

AUSTRALIAN AGRICULTURE IN 2020:
FROM CONSERVATION TO AUTOMATION

Edited by

Jim Pratley and John Kirkegaard

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PREFACE

In the 1960s and 1970s there was much concern in the Australian community about the extent of soil degradation and erosion taking place on Australian farms from over-cultivation. At that time, reduced tillage, direct drilling and early attempts at ‘chemical farming’ were taking place. Initially the availability of Spray.Seed® was enabling reduced tillage and direct drilling to be trialled as a way of reducing the need to create a cultivated seedbed. The subsequent availability of glyphosate and the option of selective weed control using new chemicals such as diclofop methyl (Hoegrass®) facilitated the evolution of conservation farming, later to be incorporated in the broader international concept of conservation agriculture.

In 1980 the Australian Society of Agronomy, now Agronomy Australia, was formed following the first agronomy conference held at Gatton Campus, now University of Queensland. Subsequent conferences have been held approximately every two years. The 4th Conference was held in Hobart and the idea of a monograph that brought together the research on the tillage ‘revolution’ was conceived.

In 1987 Peter Cornish and Jim Pratley were asked by the Australian Society of Agronomy to produce a monograph on the ‘new agronomy’ particularly about minimum tillage and its components. That monograph, *“Tillage – new Directions in Australian Agriculture”*, was an integrator of the science and technology of the time and is still relevant 30 years later. Since that publication, however, there has been a quiet revolution which has transformed the landscape to one of soil stability from the degraded soils it replaced. But this new paradigm has not been without its own challenges, and this publication provides an integrated account of the evolution of the farming systems in the last 30 years, the new agronomy of today, and the challenges beyond 2020.

The 19th Agronomy Conference in 2019 at Wagga Wagga NSW, provides the opportunity to showcase the agronomy achievements over the last thirty years, and this monograph *“Australian Agriculture in 2020: from Conservation to Automation”* records those achievements and acknowledges the research teams and farmers who have been at the heart of agronomic progress.

We, the editors, wish to thank the more than 80 contributors without whose cooperation this publication could not have happened. A special thanks goes to John Broster and Julianne Lilley for their assistance in the final stages of preparation for publication.

We also wish to express our gratitude to Agronomy Australia for funding the project which facilitates access to the works so that Australian agronomy achievements can be widely recognised and celebrated. Finally, we acknowledge Charles Sturt University for undertaking the printing and electronic preparation needed to produce both formats of the book.

We commend the contents and the story to educators and future agronomists as the first-hand version of Australian agronomy. To other researchers it is a comprehensive account, fully referenced, to assist them to capture new opportunities for agriculture in the future, and to meet its ongoing challenges.

Thank you again to all who were involved in this journey.



Jim Pratley
Charles Sturt University



John Kirkegaard
CSIRO

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PART I – CONSERVATION AGRICULTURE: THE CONTEXT



Lupin crop sown inter-row by no-till into standing wheat stubble – three pillars of conservation agriculture (Courtesy: John Kirkegaard)



**Zero-till disc seeder on 250 mm row spacing, 12 m CTF system, inter-row seeding faba beans using 2 cm GPS guidance into standing barley stubble.
(Courtesy: Greg Condon and Stephen & Michelle Hatty, Matong NSW)**

Chapter 1

Tillage: global update and prospects

Tony Fischer and Peter Hobbs

Introduction

Tillage refers to the mechanical disturbance of the soil primarily for planting of crops, but weed control and incorporation of nutrients are common secondary purposes. Modern primary tillage, principally mouldboard or disc ploughing, was developed in the 18th and 19th century, requiring substantial secondary tillage for seedbed preparation (the whole package being defined here as conventional tillage, CT). In response to the ‘dust bowl’ years in the US Great Plains in the 1940s, reduced (RT) and stubble mulch tillage, commonly called conservation tillage, that controls weeds with minimal soil disturbance and leaves at least 30% plant residue on the soil surface, was developed to combat such erosion. In the 1960s and with the development of herbicides, modern one-pass seeding systems started to appear: according to GRDC these include direct drilling (full surface disturbance), no-till (partial disturbance with narrow point), and zero-till (minimal disturbance with disc opener). These three one-pass systems approximate the definition of ‘low soil disturbance no-till’ in Kassam *et al.* (2019), and throughout our paper are together called no-till (NT).

At the time the book “Tillage: New Directions in Australian Agriculture” appeared in 1987, the “no-till revolution” was only a few years old, global NT area was small and there were few long-term experiments. Today, Kassam *et al.* (2019) estimate the area of conservation agriculture (CA), referring to NT planting systems with surface retention of crop residue and rotation of crops, to be about 180 Mha in 2015-16, or 12.5% of global crop area. This is an approximate estimate of world NT, approximate because there can be NT outside of CA, but it can be confidently stated that NT does not exceed 15% of world crop area. On the other hand, the world’s tillage literature suggests that more than 90% of the current research relates to NT (or CA). Therefore, given that there is still at least 1,200 M ha of conventional tillage (CT), this review begins by considering some current issues with CT, before passing to NT, for which many long-term results now exist. The focus is largely at a global level, leaving Australian results to later chapters.

Conventional primary and secondary tillage (CT)

CT can involve deep (15-40 cm) ploughing, and is still widely practised in the USA, Europe, North Africa and Asia. While tradition has played a role in the persistence of this intensive tillage system, other factors remain relevant, including weed control and a need to bury the copious residues in humid situations where crops follow each other with only brief fallow periods, and in cool areas where soil warming in the spring is critical; in such cases, and assuming residue burning is no longer an option, yield is often somewhat improved with CT (see later). Relief of compaction is another valid reason for deep tillage, as is tillage for burial of fertilisers and soil ameliorants. We concentrate on tillage research in temperate North America and Europe where NT is less widely adopted, the focus being on problems of CT or comparing CT to deeper loosening tillage, or to shallower tillage (RT), or to conservation tillage.

CT and energy consumption

In modern cropping, energy inputs, and their associated greenhouse gas emissions, have received much attention lately. The total energy input per ha comprises not only fuel use but also energy embodied in other inputs and activities. Energy use is dominated by N fertiliser costs, with tillage fuel usually less than 40% of the total, so reducing tillage does not have a large effect on the total energy budget. For example, in a typical irrigated maize cropping system in Nebraska a detailed survey of farmers’ energy costs found that average total input was 30 GJ/ha for a 13 t/ha grain yield (Grassini and Cassman 2012): the breakdown on energy was pumping (42%), N fertiliser (32%), grain drying (9%) and fuel for field

operations (9%), while RT saved only 6% of the total energy cost, compared with CT. The relative saving in total energy with RT (or NT) vs CT is likely to be greater in rainfed cropping, but this can be counterbalanced if herbicide use increases, since herbicides can have a high energy cost (250-500 MJ/kg a.i., compared to diesel at about 43 MJ/L), with glyphosate at the upper end of this range.

Many studies have considered reducing the energy costs of CT, which can consume 50-70 L/ha of diesel. Fuel used per ha, assuming soil moisture, tractor size and implement are optimised, is largely a function of tillage depth, soil texture and type, and degree of pulverisation of the soil, with smaller effects of speed for implements that ‘throw’ soil, and of the implement itself (McLaughlin *et al.* 2008; Lovarelli and Bacenetti 2017). Anecdotal evidence points to France and Russia as places where deep CT tillage was common, but Italy may have the strongest tradition of deep tillage, often reaching depths of 50 cm, but with recent efforts to reduce this. For example, Pezzi (2005) compared, in a silty clay typical of the Po Valley, a mouldboard plough to alternative PTO-driven rotary chisel and spading machines. Tilling to 40 cm required around 45 L/ha of diesel regardless of implement, but the alternative machines produced clods about half the size of the 24 cm mean diameter ones with the mouldboard. The spading machine was the best for energy cost corrected for the degree of pulverization. These are clearly extreme practices. While recent design research may allow small improvements in mouldboard energy efficiency (*e.g.* Ibrahim *et al.* 2017), primary tillage elsewhere is not so deep (15-25 cm) and fuel cost is closer to 20-35 L/ha of diesel (Lal 2004, McLaughlin *et al.* 2008). RT systems, whether chisel or rotovator, can save up to 40% fuel used in seedbed preparation compared to CT, depending on depth of tillage and texture.

Subsoil compaction and profile amelioration through deep loosening tillage

Compaction or dense layers can be natural but are more commonly induced by repeated tillage, in-furrow ploughing, or by heavy wheel traffic, common at harvest, and under high soil moisture. The impact and prevention of subsoil compaction has been reviewed for European Union conditions by Van den Akker *et al.* (2003) and more generally by Hamza and Anderson (2005). These authors believe that soil compaction in modern agriculture with its large and heavy machines is a major cause of soil degradation and a serious challenge to sustainability. Reduced crop yield is generally via reduced subsoil rooting in drier situations and from increased denitrification in wet, cool spring soils at higher latitudes (Van den Akker *et al.* 2003). Preventing compaction is well understood and relates to the inherent susceptibility of the soil, soil organic matter content, the moisture content when trafficked, subsoil protection by the topsoil, and the pressure applied (Spoor *et al.* 2003, Hamza and Anderson 2005). Also, on-land ploughing (all tractor wheels on the unploughed surface) significantly reduces compaction arising from in-furrow wheel traffic during ploughing. But subsoil compaction is difficult to prevent with modern heavy machinery, and negative effects on crop rooting and performance can be difficult to recognize.

Subsoil compaction is expensive to alleviate. Hamza and Anderson (2005) suggest the use of deep-rooted crops and deep incorporation of organic material and gypsum as preventative strategies. However, the accepted solution is deep subsoiling or ripping to disrupt compacted zones using forward facing points on tynes or chisels with wings, which fully or partially lift and disrupt the soil at a depth just below the compacted zone. The aim is to ease rooting in and through the compacted zone without unnecessarily loosening other parts of the profile. Spoor *et al.* (2003) discusses tyne arrangements, tillage depth and speed to achieve this, with the paraplough probably the most effective implement where compaction is not too deep. Disruption is greatest when the soil profile is dry. Spoor (2006) provided more comprehensive detail on equipment for alleviating compaction, *inter alia*, attaching loosening tynes to mouldboards to break up plough pans immediately below the normal plough depth. Deep tillage is also an opportunity for the deep incorporation of fertilisers or ameliorants such as lime, gypsum, phosphorus, and organic materials (manure, compost and the like).

Deep tillage studies have recently been comprehensively reviewed by Schneider *et al.* (2017), who considered 1530 comparisons from 67 temperate sites growing cereals around the world. However, only 22% of the sites came from publications since 1990. These authors included deep inversion (mouldboard) and mixing (rotovator) tillage along with deep loosening tillage. Deep tillage was 35 cm

or more, while control tillage averaged 19 cm. Schneider *et al.* (2017) found yield responses varied but averaged +20% for sites where root-restricting layers had been identified, a response which was significantly greater when the water supply was less. This suggests only deep loosening tillage is required. Yield effects related to all types of deep tillage and included benefits due to better nutrition when no fertiliser was used, or when fertiliser or organic material was placed deep. In addition, there was an increased risk of negative effects where topsoils had >70% silt, an effect attributed to the breakdown of natural structures and biopores.

Schneider *et al.* (2017) found that many studies contained insufficient measurements for sound interpretation of results. In all the papers cited, only Botta *et al.* (2006) working with sunflower in the western Argentine pampas came close to linking subsoiling to 45 cm with the yield response; reduced cone penetrometer readings in the compacted layer (15 to 30 cm) were associated with a doubling of root growth in this layer, a doubling of crop growth, and 25% extra yield, although no evidence was presented to attribute this to greater water use. Spoor (2006) insisted that the only way to be sure of deleterious subsoil compaction in the first place, and its proper alleviation, was visual inspection of roots in soil profiles before and after deep loosening tillage. Others propose that with automatic monitoring of soil bulk density through forces on tillage tools, the inevitable patterns of variation in soil compaction across space opens the possibility to monitor and control systems for continuous adjustment of tillage machines, in order to deliver more decompaction for less energy expended (Andrade-Sanchez and Upadhyaya 2019). Even if deep tillage alleviates compaction, it quickly returns in many soils when normal uncontrolled field trafficking continues, especially in humid climates. The only satisfactory measures of prevention with cropping in susceptible soils appear to be substantially lighter traffic, wider (softer) tyres, and/or controlled traffic. A move to autonomous vehicles may see lighter vehicles, but harvesters will likely remain heavy. Only controlled traffic can deal with this and it fits well with both till and NT systems, bringing many advantages as seen in the UK and Australian studies (*e.g.*, Godwin *et al.* 2015, Antille *et al.* 2019). To date controlled traffic cropping, now even more efficient with precision guidance, has not been widely adopted outside of Australia, and so is covered in Chapter 6.

Tillage erosion

A largely neglected feature of tillage until recently, is tillage erosion, soil movement down slope as a result of the tillage operation itself. It occurs regardless of tillage direction and leads to net erosion of convex slopes and upper field boundaries and net soil deposition in concave slopes and lower field boundaries, but no soil leaves the field (van Oost *et al.* 2006). The amount of soil moved in any operation depends on the slope curvature (rate of change of slope), as well as the tillage depth, implement and, to a lesser extent, speed. The latter factors are summarised in the tillage transport factor, which for mouldboard plowing to 40 cm ranged from 360 to 770 kg per unit slope tangent change per m of implement width.

Tillage erosion is obvious in the undulating crop lands of Mediterranean Europe, with subsoil appearing on the tops of rises. Van Oost *et al.* (2009) estimated average tillage erosion was 3.3 t/ha/y (and water erosion 3.9 t/ha/y) across arable lands in Europe. Tillage erosion was low (<1 t/ha/y) in the major agricultural plains, but high (>5 t/ha/y) in the undulating crop lands of Mediterranean and Central Europe. Rates are somewhat lower in the northern Great Plains of America at 1.1 t/ha/y (central western Minnesota) and 2.2 t/ha/y (south west Manitoba) for typical CT (Li *et al.* 2007). Lobb *et al.* (2007) estimated tillage erosion rate for Canada in 1996, concluding the 50% of the cropped land had unsustainable tillage erosion rates (> 6 t/ha/y). This was undoubtedly high because of the predominance then of CT (53%) and conservation tillage (31%); the latter was assumed to only reduce the tillage transport factor by one half. NT (16% of area) was expected by the authors to have negligible tillage erosion.

Tillage erosion is important because of net negative effects on crop yield. For example, even with a deep soil in humid Denmark, winter barley yield ranged from 6.1 t/ha (eroding areas) to 7.2 t/ha (aggrading ones) in a hummocky field with more than 100 years history of conventional tillage (Heckrath *et al.* 2005). Similar results were reported across winter wheat in an undulating field in south west England (Quine and Zhang 2002). Accumulation of nutrients in the convex low slope positions

can also contribute to nutrient loss from water overflow and drainage. Tillage erosion will remain a problem, as serious as water erosion, in all undulating lands with tillage, as there seems to be little engineering scope for its reduction, apart from shallower tillage, or NT.

Progress in no-till (NT)

The global history of NT is described by Derpsch (2016), while the most recent numbers relevant to NT come from the estimates of Kassam *et al.* (2019) of the global spread of Conservation Agriculture (CA, see above). It is assumed here that all CA involves NT, but some numbers have been adjusted to give our best estimates in Table 1. The data show that the major adopters are the Americas (mainly USA, Brazil, Argentina and Canada) but also significant acreage in Australia. The data also indicate that there has been a significant increase in area in the 7 years from 2008/09 to 2015/16 (5% p.a.), and there is a large increase in the number of countries reporting the adoption of CA (Kassam *et al.* 2019).

Table 1. No-till (NT) adoption (million ha) by region from 2008/09 to 2015/16 (adapted from Kassam *et al.* 2019, see text).

Region	NT area 2008/09	NT area in 2015/16
South America (Brazil, Argentina, Paraguay, Bolivia, Uruguay, Venezuela, Chile, Colombia)	49.56	69.90
North America (USA, Canada, Mexico)	40.00	63.18
Australia + New Zealand	12.16	22.67 ¹
European Union (EU) + Russia	1.66	8.90 ²
South Asia (India, Pakistan, Bangladesh, Nepal) ¹	1.00	4.00 ³
Central Asian States (Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan)	1.30	2.56 ⁴
China	1.33	9.00 ⁵
Sub-Saharan Africa	0.48	1.48
WANA (Algeria, Morocco, Tunisia, Sudan, Turkey, Syria, Iraq, Iran, Lebanon)	0.02	0.20
Total	107.51	181.89

¹ Mostly Australia. ² Mainly due to inclusion of Russian NT. ³ Based on recent estimates from South Asian sources. ⁴ Mostly Kazakhstan. ⁵ Much of this may not be NT, even though reported as CA (see later)

However, the question is “how much of this area is true CA (NT, permanent soil cover and rotation) and how much NT lies outside the estimated CA area?” This cannot easily be answered since many of the country statistical departments do not even collect data on NT let alone true CA. On balance, Table 1 is unlikely to overestimate the global area of NT and indicates that a significant and steadily growing number of farmers are adopting NT systems.

Advances in area of NT in last 30 years

NT in the New World NT required effective herbicides, which were developed in the UK and US in the 1950s. Chemical seed bed preparation was started in the early 1960s in Kentucky with well recognised benefits that included conservation of soil and water, and savings of time, labor, and fuel, while often producing higher yields. NT in the US increased to 2.2 million ha in 1973/74, 4.8 million 10 years later (Derpsch 2016), and just over 43 Mha in 2015/16 (Kassam *et al.* 2019).

After USA, the next push on NT came from Brazil in the early 1970s especially with the aim of reducing erosion (Derpsch *et al.* 1986). Planters were imported (from UK and Kentucky) and used to plant NT soybeans in 1972. There were initial difficulties with imported drills and limited numbers of suitable herbicides (paraquat and 2,4D) but, despite this, NT increased from 1,000 ha in 1973/74 to 400,000 ha in 1983/84. The introduction of glyphosate, a broad-spectrum herbicide in the early 1990s, and ‘Roundup ReadyTM’ herbicide-tolerant soybeans and maize in the mid-1990s, greatly facilitated NT

adoption. At the same time, Brazilian NT seeding machine manufacturers improved drills to support this revolution. Today Brazil grows soybeans, maize, wheat, barley, sorghum, sunflower, beans and green manure cover crops in rainfed agriculture using NT. Irrigated rice is also increasingly being grown with NT in southern Brazil.

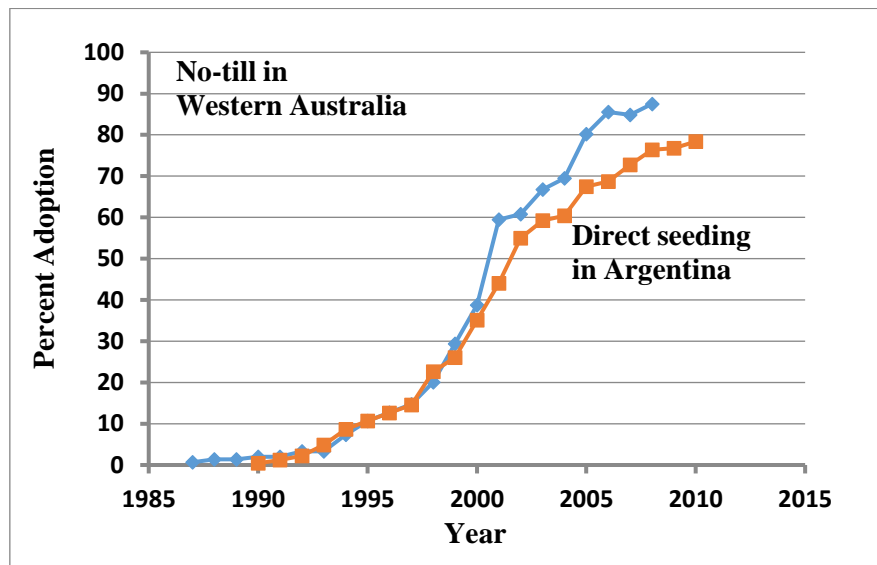


Figure 1. Adoption of no till in Western Australia (Llewellyn *et al.* 2012) and in Argentina (Apresid 2012)

Under humid but more temperate cropping of maize, soybean and wheat, Argentina, then Paraguay and Uruguay, followed quickly behind Brazil, as NT (*siembra directa* in Spanish) reached 35 Mha by 2015-16, a revolution again driven by glyphosate, glyphosate-tolerant cultivars, local machinery manufacture and innovative farmers (Ekboir and Parellada 2002). Closely paralleling the rapid adoption of no-till in Argentina was that in Australia (22 Mha in 2015-16, Kassam *et al.* 2019), illustrated in Figure 1. In Australia, NT brought additional advantages when, following herbicide fallow, there was greater pre-sowing soil water storage and earlier seeding, important under the prevailing semiarid conditions (Llewellyn *et al.* 2012). Canada also adopted rapidly, so increasing fallow water storage that continuous cropping became much more common (one crop each year), while in the US Great Plains, NT permitted farmers to eliminate the fallow year prior to wheat or sorghum to reach two crops in three years. The final NT success happened a decade later in northern Kazakhstan (although not the New World), a similar cropping system and environment to that of Saskatchewan, with similar benefits for wheat cropping.

No till in the Old World Progress with NT has clearly been slower in the rest of the world, notably in Europe, West Asia and North Africa (WANA). Management of large amounts of crop residue in the wetter parts of Europe is a major issue, but there are no biophysical reasons why NT should not be successful in southern Europe and WANA as it has been in Australia. Traditional European thinking about the value of deep ploughing, however, seems to be strongly embedded, and issues of farm subsidies stifle change. In WANA, after initial efforts in Morocco in the late 1980s and Turkey in the 1990s, work by ICARDA and ACIAR, now thwarted by unrest, confirmed that NT (promoted as direct drilling) worked well in Syria, Iraq and Morocco (Piggin *et al.* 2015, Loss *et al.* 2015). It is, however, the special efforts to promote NT in South Asia, China and Sub Saharan Africa (SSA) which are of greatest current concern, for these places bring both big benefits for NT according to experiments, but special challenges: unique cropping systems (irrigated and humid subtropics and tropics) and unique farmer typology (small holdings, especially in China, with very limited on and off-farm resources and often a dependence on crop residue for fodder or other uses).

From the late 1980s, *India and Pakistan* had steady growth in NT research on wheat in the dominant rice-wheat irrigated system (over 13.5 M ha) of the IndoGangetic Plain (IGP). Traditionally, crop residue was removed during hand harvesting (sometimes then used for feeding) leaving just the

anchored straw. Rice was transplanted into cultivated (to 15-20 cm) and puddled soil at the onset of the monsoon in June-July. After rice harvest, in October-November and removal or burning of rice straw, a seedbed was prepared by irrigation and multiple cultivations and planking (levelling), into which wheat was broadcast and covered by harrowing. Local drills for line seeding (20 cm rows) of wheat came first, followed by direct NT seeding, initially based on an imported drill from New Zealand (Hobbs *et al.* 2017), soon to be followed by locally-adapted and manufactured drills. NT wheat saved water and cultivation costs and facilitated the management of some grass weeds. There was no yield loss of NT at the same sowing date as CT, but most importantly, NT permitted earlier sowing and higher yields since the wheat avoided late season heat stress. As rice straw removal declined with the spread of mechanical harvesters and as straw burning caused serious air pollution, the next challenge was seeding without removal of the rice straw, and several innovative NT seeders were successfully developed for this purpose in India (Sidhu *et al.* 2015, see later). A further imperative, driven partly by the growing cost of rural labour, was to move rice to direct seeding into cultivated or preferably uncultivated seedbeds (Landers 2018, Hobbs *et al.* 2019); transplanting into non-puddled soils was also tried. Direct seeding of rice is challenging because of weed control difficulties, the high cost of hybrid rice seed where used, and possible seedling death due to heavy early monsoon rains (Chakraborty *et al.* 2017). Advantages, however, are that NT wheat always yields more after non-puddled rice and there were significant savings in water and labour (Hobbs *et al.* 2017). At the same time NT was being introduced, a low-cost laser leveler was developed in India and Pakistan and popularised by local custom service providers; water was saved and waterlogging reduced, especially when combined with bed planting (Naresh *et al.* 2014, but see later).

The technical developments in the IGP rice-wheat system described here, according to extensive experimentation, have led to a steady increase in profit (increased yield and reduced cost), a reduction in irrigation water use, and a reduction in overall global warming potential. This is summarised in Hobbs *et al.* (2017, 2019) and highlights the development of a double crop CA package for the rice-wheat system of the IGP. To date only the laser levelling and the NT seeding of wheat have had significant adoption by farmers; estimates put NT wheat at around 4.0 M ha (Table 1, Paroda 2018). In the IGP the main drivers of early NT adoption in wheat have been fuel costs, earlier planting and better control of herbicide-resistant grassy weeds (fewer of these weeds germinate in NT); there is little soil erosion, taking away a major incentive for NT seen elsewhere.

China has around 135 M ha arable land with much intense tillage (to 15-20 cm depth) and negative consequences especially as the system became mechanised after 1970 (Wang *et al.* 2007). Erosion was particularly bad in the drier northern and western regions. Research on conservation tillage and NT began in the late 1980s with the rainfed spring maize system in the Loess Plateau soon spreading to the winter wheat system there, and the winter wheat-summer maize double crop system in the more humid North China plain (Wang *et al.* 2007). These authors summarise numerous experiments where erosion was markedly reduced under NT (with residue retention). Yields under NT were equal to or slightly higher than those from CT, especially in dry years, because of extra stored soil water at sowing; disadvantages in wet years were related to lower soil temperatures and slower early growth. The larger meta-analysis of Wang *et al.* (2018) focused strictly on NT *versus* CT: they showed on average NT yield was only 2% above CT ($n = 275$) for wheat and 5% higher for maize ($n = 155$). Standard deviation of individual responses between diverse locations appeared, however, to be quite high (27% and 31% respectively). The only significant effect of experimental conditions was a decrease in the wheat response from +7% to +5% to -10% as mean annual precipitation increased from <400 mm to 400-600 mm and >600 mm, respectively, and a tendency for the NT yield advantage to increase after 6 years of continuous NT. A similar diversity of responses to NT was seen in a meta-analysis of rice experiments across southern China by Huang *et al.* (2015): the mean effect on grain yield was not significant (+0.4%, $n = 265$), with 7% standard deviation of individual responses. Although this variation was unrelated to establishment method (transplant, seedling throwing, direct seeding), NT, under which plants generally tillered less, was clearly superior (+5%, $n = 60$) in the low radiation humid south west (CT tended to tiller excessively) and somewhat better when fertility was higher, especially early N supply.

Notwithstanding promising early results, CT dominated in China until 2006. The jump since then in CA to over 8 Mha in 2013-14 (*e.g.* Li *et al.* 2016, also Table 1) appears to be explained by confusion in interpreting official statistics on conservation tillage as CA; the true NT area is likely smaller. This reduction in tillage is undoubtedly a move in the right direction, as confirmed by small yield increases on average in the meta-analysis of Li *et al.* 2016 (+4.5% wheat, +8.3% maize, +1.5% rice) and appears to have involved shallower tillage, greater use of rotation as strip tillage, as well as efforts to maintain residue cover. The limited move to NT, in particular CA as defined here, despite some promotion by government agencies, may reflect the diversity of cropping situations across China as emphasised in the above meta-analyses. More specifically, while most farms remain small (<1 ha), inadequate mechanisation and skills for crop residue handling continues to be a major constraint (A.D. McHugh *pers comm*). In addition, the observation of yield losses with NT (*e.g.* Wang *et al.* 2018) may be a special problem of the Loess Plateau, given the ready compactability of the generally light textured soils. For example, in an ACIAR-funded study (1992-2003) in Linfen, Shanxi Province, a single deep chiselling (30 cm), followed by NT and controlled traffic lifted winter wheat yields 10% over CT involving 20 cm deep plowing every year and no controlled traffic (Chen *et al.* 2008), with even better benefits for the yield of spring maize. A separate ACIAR project at Xifeng (Gansu), also in the Loess Plateau but without controlled traffic, found small yield reductions with NT over 10 years (winter wheat -8%, maize -7%, soybean -4%) compared with regular 30 cm chiseling, although the negative effect was less with residue retention (Li *et al.* 2018). A unique problem with crop residue in northern China is that it is used for winter heating, both in traditional houses and nowadays whole towns. Another is that plastic film mulch reduces evaporation more than residue mulch, while bringing other benefits (warming, weed control).

No-till and CA have been quite controversial in *Sub-Saharan Africa* (SSA), where some of the earliest NT experiments in the tropics were initiated at IITA in Nigeria (Lal *et al.* 1978) and in Zimbabwe and South Africa in the 1970s, mainly using tractor drawn seeding equipment, with fuel and cost efficiency as the main drivers (Wall *et al.* 2014). However, soils in SSA have had a serious decline in soil fertility and soil organic matter and become more compacted, acidic, micro- and macro-nutrient deficient and prone to erosion after many years of traditional farming (Zingore *et al.* 2005, Craswell and Flek 2013). Fallowing and opening up new land (shifting agriculture) is no longer an option. Promotion of CA on smallholder farms started in 1982/83 and intensified in 2000 (Haggblade and Tempo 2003). Tractors were not available, so CA was based on manual (jab planting into basins) and animal drawn rippers (Johansen *et al.* 2012). Crop residues are considered vital for increased soil moisture and a way to offset dry periods (Thierfelder and Wall 2009). But in much of SSA, crop residues are a scarce resource needed for animal feed or by pastoralists in the dry season (Wall 2009, Valbuena *et al.* 2012). Weed control, traditionally requiring huge labour inputs, has also been a major deterrent for adoption of CA by smallholder farmers in SSA (Muoni *et al.* 2013). Use of herbicides helped spur adoption of CA but accessibility, cost and environmental concerns led to controversies about use (Lee and Thierfelder 2017). Overall adoption of NT in SSA has been disappointingly small (Table 1).

Lessons from the global adoption experience with NT

There have been multiple drivers of farmer adoption of NT that differed between regions, and which happened rapidly after an initial lag phase in the New World (*e.g.* Figure 1). Water erosion reduction was a big driver in humid locations (*e.g.* eastern USA, southern Brazil, Argentina) while, in semi-arid areas, it was greater water conservation in herbicide fallows, which preceded NT sowing (Australia, Western Great Plains of North America, Kazakhstan), as was evident 30 or so years ago from fallowing studies (Fischer 1987). RoundupReady® varieties of maize and soybean facilitated NT adoption in the Americas.

Negative NT effects on yield were always prominent in farmers' thinking, but generally these turned out to be minor, especially with more years of NT experience and soil improvement. Yields were often higher when NT led to greater stored soil water and more timely planting of crops (Australia, South Asia and SSA). This aspect was examined by Pittelkow *et al.* (2015) in a global meta-analysis (678 studies with 6005 paired observations of NT versus CT from 50 crops and 63 countries, but dominated by high latitude, cold winter environments). They reported that latitude, crop category, aridity index,

residue management, no-till duration and N-rate were important factors influencing the overall negative yield response of 5.1%. The NT effect was greater in the tropics (-15.1%, n=521) and least in temperate zones (-3.4%, n=4824). NT yields matched CT in oilseed, cotton and legume crops but in cereals highly significant negative impacts were evident, though smaller in wheat (-2.6%, n=260) and higher in rice (-7.5%, n=31) and maize (-7.6%, n=224). NT was best under drier conditions with equal or higher yields compared with CT, when this gain was especially favoured by residue retention, at least for maize as has been also clearly shown for both rainfed and irrigated wheat-maize cropping in Mexico (Verhulst *et al.* 2009). Pittelkow *et al.* (2015) also found that, in the first two years, NT yields were lower but, from 3-10 years, tended to match CT yields, except for maize and wheat in humid climates. Moreover, these authors did find that the negative effects of NT on yields decreased with increased N-fertiliser and crop rotation. There were unraveled interactions and factor covariances in Pittelkow *et al.* (2015) and, under particular circumstances reported elsewhere in this Chapter, NT with residue retention produced consistent small positive effects on wheat and maize yields compared with CT in both Mexico and South Asia, even without benefits of extra soil stored water at planting.

A key factor in accelerating the adoption of no-till everywhere but rarely surveyed has been the steady development of appropriately-sized robust NT seed drills; the unique Indian Happy Turbo seeder is an excellent example of this. A feature especially in South America, and also Australia and India, has been the private sector working together with innovative farmers to develop a whole array of NT drills for different crops and local situations, including various versions of seeding openers (*e.g.* in Baker *et al.* 2006 and see Chapter 6). Finally, once peer pressure to stay with traditional ploughing is vanquished, and that has been a major issue everywhere, there have also been unanticipated benefits from NT, in particular farmers having more time with family and community.

Above we have described rapid NT adoption in modern agricultural situations. Its non-adoption in such situations appears related to the problem of heavy straw loads, their mechanical handling, and the depressing effect on spring soil temperature at high latitudes. The increased disease and pest problems expected with no-till and especially residue retention has not proven to be as big an issue as anticipated; this may be related to an increase in soil biodiversity and diseases suppression (see later). However regular herbicide use fostered the widespread evolution of weed resistance to herbicide, a challenge not unique to NT (discussed briefly later and in other chapters).

The slow or non-adoption of no-till in many developing countries, however, remains a huge challenge. Here cropping is characterised by small landholders, with (IGP, China) or without (SSA) substantial experience of modern agricultural technologies. A bigger role for government incentives and involvement in extension and promotion of no-till appears necessary. The closely studied IGP is illustrative. For example, Loch *et al.* (2018) explored in depth the adoption of NT wheat after rice, nowadays a well adopted NT technology, but still slower and lower adoption than expected in view of the large per ha financial benefits for adopters. They suggest that governments have not recognised the complexity of these new technologies and have failed to institute or enforce supportive policies for NT (*e.g.* enforcing no-burning laws, stopping subsidies of electricity for pumping so the extra water used in CT is felt in farmer costs). They argued that the service sector (*e.g.* custom hiring) had a key role, as it had previously fulfilled with laser levelling in the IGP. However, this was neglected by government, and the public extension services have been stretched and inadequate, especially with industry and farmer engagement, and even non-supportive of NT.

The experience in India confirmed without doubt the *sin qua non* for NT of appropriate local drills, in this case ones suited to the small four-wheel tractors of the region. The imported NZ seed drill was quickly modified by engineers from Pantnagar University in UP, India, adding its inverted-T openers to the traditional, locally manufactured wheat drill (Hobbs *et al.* 2017). This simple three-point mounted NT drill worked well in the absence of trash. However, farmers shifted to hire of combine harvesters which left loose rice residue on the soil thereby creating problems with the above fixed tyne NT drill. The farmers burnt the rice residue (whether they used NT or CT) but burning of residues plus NT has been shown to be an inferior treatment for wheat yield and is now illegal due to the extreme pollution caused. This led to the development of NT seeders that could plant into loose rice stubble. This involved researchers (local and foreign), local manufacturers and, most importantly, innovative farmers. The

result was the ‘Happy Turbo’ seeder (Sidhu *et al.* 2015), bringing equal yields and all the benefits of residue retention. These new drills were more expensive, but are now subsidised substantially by the Government, with over 10,000 produced in 2018 (H. Sidhu pers comm). The custom hire model for such drills is becoming more common. With much poorer farmers and smaller fields found in the eastern IGP, Bangladesh and SSA, even smaller machinery such as two-wheel tractors with attached drills may be key for NT adoption (Biggs and Justice 2015). At the outset of the NT revolution in Brazil, bullock drawn NT drills and hand-operated jab planters, both for maize, were successfully developed for small farmers. There are lessons from Asia for NT adoption in SSA (Baudron *et al.* 2015, Hobbs *et al.* 2019). Key suggestions include combining CA with two-wheel tractors and other complementary agronomic practices not specific to CA, and functional markets. Also included is the development of a service provider system, since farmer ownership of tractors may not be viable.

Long term effects of no till: soil physics, chemistry and biology

Tillage is well known to have many negative effects including degradation of soil physical and biological properties, and loss of soil organic carbon (SOC). NT systems were expected to reverse this. However, soil changes occur gradually, and careful long-term experiments were needed for their detection. Results on chemical, physical, and biological changes of long-term NT, both with and without crop residue retention, are now widely available, and it is SOC which is considered the key measure.

Soil organic carbon (SOC)

Thirty years ago, there was the expectation that NT, especially accompanied by residue retention, would build SOC, with multiple benefits, including C sequestration. This is a long-term issue, because:

- several years are necessary in order to accurately measure SOC changes; and
- effects on SOC are likely to become attenuated as new SOC equilibrium values are reached.

Measuring changes in SOC in NT vs CT comparisons turned out to be a complex task, requiring *inter alia* attention to adequate sampling depth and to bulk density changes (Baker *et al.* 2007).

Rothamsted Experimental Station, UK, has been at the centre of many efforts to quantify better SOC changes. Powlson *et al.* (2014) argued that the possibilities have been largely overestimated by the early proponents of NT and that proper soil sampling to depth suggests average sequestration rates to be no more than 0.3 t C/ha/y and possibly only half of this, even if SOC in the top 10 cm or so increases notably. A more recent meta-analysis of tropical cropping (IGP and SSA) found similar numbers (Powlson *et al.* 2016) as were assumed to prevail by Minasny *et al.* (2017) in their effort to promote annual global C sequestration at 4 ppm across all agricultural lands. Sapkota *et al.* (2017) found, after 7 years of NT with rice-wheat in the IGP, that returning a total of 2.1 t/ha/y of C in crop residues led to an increase in SOC of 0.5 t C/ha/y (0-60 cm, but predominantly from 0-15 cm). Martinez *et al.* (2016) in a detailed 20-year comparison in Switzerland of CT and NT under diverse crop rotations, with winter cover cropping where appropriate and crop residue retention in all treatments, found no changes in SOC (0 -50 cm). Perhaps surprisingly, in all the reviews, and in the comprehensive study of long term SOC changes at Rothamsted of Poulton *et al.* (2018) (which unfortunately lacked NT treatments), there is clearly no big C sequestration benefit from crop residue retention. A simple yet poorly appreciated explanation of this is that stable SOC, largely humus, has a relatively stable C:N:P:S nutrient ratio (Kirkby *et al.* 2016) and that C accumulation may be restricted in many circumstances by limited availability of the other nutrients (see Chapter 16).

Despite the general consensus above, higher rates of SOC accumulation under NT systems have been reported in Brazilian studies, as recently summarised in de Moraes Sá *et al.* (2017), with C sequestration rates (0-100 cm) under NT of 1.4-2.1 t C/ha/yr for tropical cropping and 0.5 to 2.0 t C/ha/y for subtropical. Several aspects of NT are unique to Brazil – high rainfall, highly weathered oxisols, recent clearing with high doses of lime to overcome the low pH and high exchangeable aluminium, and high phosphorus applications on P fixing soils. In these soils there has been a large increase in crop residue C (and associated N, P and S) returned to the soil, with SOC increases generally proportional to this surface quantity of C. Under favourable NT conditions, soil C levels to 100 cm are returning to the

levels encountered in nearby remnant native vegetation with oxisols (de Oliveira *et al.* 2016, Corbeels *et al.* 2016) and even ultisols (Diekow *et al.* 2005). Claims of such high C sequestration with NT are recognised as controversial (*e.g.* de Marais Sá *et al.* 2017), but the question now is whether SOC, once returned to the original levels, can be raised even higher under their high biomass-return NT system, although SOC is not expected to increase indefinitely.

Soil physics

The effect of surface residue on protecting bare soil from raindrop action and crusting, thereby enhancing infiltration, is a universally recognised benefit. As for other soil physical properties, the expectations regarding improvements with NT have largely been vindicated provided adequate crop residue has been returned. For example, data from a twenty-two-year experiment looked at impacts on soil physical and carbon sequestration in Central Ohio (Kahlon *et al.* 2013) are fairly typical. The data show significant positive effects of mulch and of NT on soil physical attributes; soil porosity, water infiltration rate, saturated hydraulic conductivity, mean particle size and water stable aggregates, and negative effects on penetration resistance; there was also a tendency for a beneficial interaction between mulch and NT. They conclude that “use of NT plus mulch application enhances soil quality with respect to soil mechanical, hydrological properties along with carbon concentration in the soil”. Gathala *et al.* (2011) used a 7-year rice-wheat rotation experiment in Uttar Pradesh, India, to look at soil physical properties using different crop establishment methods. Stubbles were incorporated in conventional puddling and tillage, but NT plots were seeded into standing anchored stubbles. NT treatments had lower bulk densities, lower soil penetration resistance, more water stable aggregates and higher infiltration of water compared with cultivated puddled treatments.

Soil biology

Soil biodiversity (macro and micro) is receiving more attention recently because it influences numerous ecosystem services; new molecular tools have facilitated its study (*e.g.* Kibblewhite *et al.* 2007). This is often presented under the vague label of ‘soil health’, but its connections to crop performance have rarely been elucidated. Govaerts *et al.* (2008) did look at tillage, residue management and crop rotation effects on selected soil micro-flora in a rainfed maize-wheat system long-term trial in the sub-tropical highlands of Mexico. Crop residue retention resulted in increased microbial biomass and respiration and increased populations of soil micro-flora that promote plant growth and suppress diseases. NT with residue showed equal or higher populations of beneficial micro-flora compared with CT, but no-till without residue did not. More importantly, Govaerts *et al.* (2006) showed higher populations of root rots and parasitic nematodes when residues were removed, confirming that zero-tillage without residue is clearly an unsustainable practice. Microbial diversity increased under NT with residue retention such that they suggest it is useful for biological control and integrated pest management). Parasitic nematodes were studied in Zimbabwe comparing CA under basin and rip NT with CT over two years (Mashavakure *et al.* 2018). NT had around 50% higher plant-parasitic nematode richness than CT, but maize yields were not related to this, being about 80% higher with NT. Other studies have shown that crop residue retention can favour diseases which sporulate on the residue (*e.g.* *Fusarium* in wheat, black leg in canola). Many more studies looking at specific pathogens are needed (see also Chapter 11).

Macrofauna including earthworms are an important component of the soil biota and many studies confirm that the latter are consistently favoured by NT, and usually by increased residue retention, one indirect effect of which is the development of continuous biopores, markedly enhancing water infiltration. Epigeal arthropods and beneficial soil dwelling organisms were also studied in the long term rainfed maize-wheat system using CA in central Mexico (Rivers *et al.* 2016). Higher spider populations were found in NT with residue retention and may contribute to the biological control of insect pests.

Greenhouse gas (GHG) emissions and climate change

While tillage effects on net soil CO₂ emissions are reflected largely in SOC accumulation already discussed, effects on methane and nitrous oxide (N₂O), two powerful GHGs, are less clear. Methane arises from methanogenesis of organic material under anaerobic soil conditions. Tillage systems that

encourage anaerobiosis through poor soil porosity and drainage can boost methane emissions. Thus puddled, flooded rice culture contributes approximately 1.5% of all global CO₂ emissions. Relative to this, other tillage effects on methane emissions are likely minor. N₂O, an even more powerful GHG, arises as a byproduct of both nitrification and especially denitrification, the latter favoured by anaerobiosis, associated with poor porosity and drainage and with high oxygen consumption from decomposing plant residues; anoxic microsites may also play a role. A meta-analysis by van Kessel *et al.* (2013) of experiments (excluding rice experiments) at 45 locations (239 comparisons) found that compared with CT, reduced till (62 observations) and NT (177 observations) had no significant effect on N₂O emissions (95% range of effects was from about -8% to +11%); with experiments of greater than 10 years duration N₂O was significantly reduced relative to CT (-10%); also deeper fertiliser N placement reduced NT emissions relative to CT. Chakraborty *et al.* (2017) in a global analysis of rice crops, found direct seeded NT had considerably higher N₂O emissions than CT puddled transplanted (but methane emissions were much less). Mei *et al.* (2018) conducted meta-analysis (6 out of 40 common studies with van Kessel *et al.* 2013, 9 out of 40 involving rice). Comparisons with CT showed increases in N₂O emissions with NT (+19.2%, $P < 0.05$, $n = 167$), and with reduced till (+12.3%, $P < 0.10$, $n = 45$). However, many factors, some interacting, appeared to influence this relative boost in N₂O emissions (*e.g.* reduced in longer term experiments, cooler soils, rainfed vs irrigated system, but increased with residue retention, especially where silt content was higher). A general theory for tillage, especially NT, and N₂O emissions needs more research to unravel key factors, which were likely covarying in the above meta-analyses. It is worthwhile noting that Tullberg *et al.* (2018) found N₂O emissions were reduced on average by over 50% across 6 sites in Australia with NT seeding into non-trafficked, non-compacted areas compared to the compacted traffic lane and to the randomly-trafficked control. Finally a climate component often overlooked is the cooling arising because surface residue can increase the surface albedo, commonly 0.2 for tilled soils, to around 0.3 (Davin *et al.* 2014).

New developments in no-till (NT)

Weed resistance to herbicides

In the book “Tillage” in 1987, herbicide resistance rated one page. Yet today this is probably the biggest challenge to the sustainability of modern cropping and especially NT systems (see Chapter 10); it has been exaggerated by herbicide-resistant crop cultivars but was already a growing problem before their arrival in the late 1990s, especially with fallow weed control. As well as rotating amongst suites of herbicides, use of integrated weed management (IWM) is essential, and sometimes tillage (see Chapter 7), despite the possible loss of some NT gains in useful soil traits; perhaps automated shallow precision hoeing targeting only weeds (Gerhards 2019) can lessen this need for full tillage. Sustainable cropping, especially NT cropping, will require greater weed management skills, posing special challenges for many small holders in the developing world.

Conservation Agriculture

Conservation Agriculture (CA) was a follow up to conservation tillage and then NT, having its first world congress in 2001. CA promotes the principles developed by Brazilian researchers and farmers in the latter decades of the 20th century (Kassam *et al.* 2019). CA was promoted by FAO and others to enhance the sustainability and resilience of small holder crop production systems (FAO 2011). CA counters the three components of tilled agriculture that have been shown to lead to soil and land degradation – mechanical disruption, organic matter loss, and continuous monoculture. All other components of productive agricultural systems are just as much a part of CA systems as they are of CT ones.

CA clearly represents an aspirational goal, which most agronomists would agree points to desirable outcomes, but would argue this can only be achieved gradually by applying initially only one or two of the principles. Moreover, inflexible adherence to the three principles together, as appears sometimes, can distort research agendas and dampen farmer interest in adoption of its components, which is more likely to be stepwise and must always be financially rewarding in the short term (Giller *et al.* 2015). NT plus moderate residue retention is likely to be positive and acceptable as a first step if diseases permit.

Green manure cover cropping

There has been a resurgence of interest in green manure cropping, particularly in humid subtropical Brazil and humid temperate North America and Europe, but also in Australia (see Roper *et al.* 2012). Reasons differ, as reviewed by Blanco-Canqui *et al.* (2015), but green manure cover crops are ideally suited to NT because they need to be planted as soon as possible after a main grain crop is harvested (or even relay planted before harvest); planting costs need to be kept low. A common aim is to deliver soil protection from water erosion and to reduce winter-spring drainage and nitrate leaching in humid climates. They also offer N accumulation if legumes are included, as well as unique weed control options, such as knock down herbicides (brown manure) and knife rolling just ahead of the main crop, which may also be NT sown. Apart from grazing, cover crops are by definition not harvested for grain or hay.

In southern subtropical Brazil, rainfall exceeds 1000 mm, allowing two crops per year without irrigation, usually a wheat-soybean system planted with NT. However, wheat blast (*Magnaporthe oryzae*) has become a problem and farmers have found replacing wheat with cover crops increased profits through reduced costs and increased soybean yields (Calegari *et al.* 2014). Further north in the Cerrado region, annual rainfall is even higher with a wet season of 7-8 months, still enough for a double crop of NT soybean followed by NT maize; pasture species (*e.g.* *Brachiaria* spp), interrow NT planted with the maize, are being tested as a viable grazed cover crop option for the relatively short dry period (de Moraes Sá *et al.* 2017). Reasons for cover cropping in temperate North America and Europe are more related to environmental protection (reduce nitrate pollution of waterways), and hence are often controlled by incentives and regulation.

Permanent raised bed planting systems

Permanent raised bed planting (PB) is a variation of CA that was researched in Mexico in the 1990s by Sayre *et al.* (2005), and then introduced to South Asia as a way to reduce costs and improve water productivity in irrigated systems. Essential components are laser levelling, residue retention and NT sowing of all constituent crops into the flat top of the bed; furrows may be reformed between crops, but beds are never tilled or trafficked, automatically bringing the advantages of NT and controlled traffic. Bed planting of wheat was adopted by farmers in the Yaqui Valley, Sonora, Mexico, for easier weed and water control and water savings in the 1980s, but beds were tilled and reformed with every crop (Aquino 1998). NT and permanent beds were introduced to these farmers in the 1990s (Sayre and Hobbs 2004) but never widely adopted. This system of planting was extended, largely via ACIAR projects, to South Asia and China, where small seed drills for bed planting were developed along with narrow tractor tyres to avoid bed damage (Akbar *et al.* 2016). The compacted furrows help speed the flow of water across the field and the wetting of the beds especially if furrow diking is used. This is also an appropriate way to harvest rainwater in rainfed, arid and semi-arid situations (Govaerts *et al.* 2007). Significant yield and water saving benefits have been recorded with wheat-maize double cropping on irrigated permanent (NT, residue retained) raised beds in Mexico (Hobbs and Sayre 2004), Pakistan (Akbar *et al.* 2016), northwest India (Naresh *et al.* 2014), and China (Wang *et al.* 2004, but only wheat on non-permanent beds); a special advantage is alleviation of waterlogging damage to maize in monsoonal climates. NT and permanent raised beds also worked well for rice-maize in Bihar, India (Jat *et al.* 2019), but rice has not consistently performed well on raised beds elsewhere in the IGP, probably due to mineral deficiencies in the aerobic environments.

Conclusion

Tillage has evolved: tillage that is shallower and less intense than 30 years ago now predominates. No-till, commonly with residue retention, continues to deliver many advantages, especially for the soil. Global adoption is rising rapidly, but is still no more than about 15% of global crop area, well below potential; herbicide resistance weeds probably remain the biggest concern globally for users of NT. The lagging NT adoption by small holders around the world is a special challenge, particularly with irrigated rice culture. The impact of NT plus residue retention on soil carbon sequestration is positive but less than expected, and the exact magnitude is disputed: effects on nitrous oxide emissions appear to be

variable. Permanent raised-bed NT cropping has yet to realise its early experimental promise for irrigated field cropping.

NT is expected to continue to grow rapidly but there needs to be better attention to definitions in official statistics. Also, special farmer education, extension and policy interventions will be needed with small holders. Innovations in drilling machinery will remain critical, especially as autonomous vehicles begin to appear. Weeds will be managed with integrated systems including herbicide application and mechanical removal under precision targeting, and hopefully new knockdown herbicides. Much more research is needed on soil pathogens and biota in general, in hand with efforts to increase cropping diversity, on NT effects on nitrous oxide emissions, and on strategies to manage compaction. Excessive straw amounts are likely to be handled by removal and local processing for energy, bedding, compost and feed.

References

- Aapresid (La Asociacion Argentina de Productores en Siembra Directa) (2012) Evolucion de la superficie en siembra directa en Argentina. Campanas 1977/78 a 2010/11 www.aapresid.org.ar
- Akbar G, Ahmad MM, Asif M, Hassan I, Hussain Q, Hamilton G (2016) Improved soil physical properties, yield- and water productivity under controlled traffic, raised-bed farming. *Sarhad Journal of Agriculture* **32**(4), 325-333
- Aquino P (1998) The adoption of bed planting of wheat in the Yaqui valley, Sonora, Mexico. *Wheat Special Report* 17a. CIMMYT, Mexico
- Andrade-Sanchez P, Upadhaya K (2019) Precision tillage systems. In 'Precision agriculture for sustainability' (Ed. J. Stafford) pp 273-284 (Burleigh Dodds Science Publishing: Cambridge, UK)
- Antille D, Chamen T, Tullberg J *et al.* (2019) Controlled traffic farming in precision agriculture. In 'Precision agriculture for sustainability' (Ed. J. Stafford) pp 239-272 (Burleigh Dodds Science Publishing: Cambridge, UK)
- Baker CJ, Saxton KE, Ritchie WR *et al.* (2006) 'No-tillage seeding in conservation agriculture' (Eds. Baker CJ and Saxton KE). 2nd Edition (FAO and CAB International)
- Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration – what do we really know? *Agriculture, Ecosystems and Environment* **118**, 1-5
- Baudron F, Sims B, Justice S *et al.* (2015) Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheeled tractors, conservation agriculture, and private sector involvement. *Food Security* **7**, 889-904
- Biggs S and Justice S (2015) Rural and agricultural mechanization. A history of small engines in selected Asian countries. IFPRI Discussion Paper 01443, May 2-15
- Blanco-Canqui H, Shaver TM, Lindquist JL *et al.* (2015) Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal* **107**, 2449-2474
- Botta GF, Jorajuria D, Balbuena R, *et al.* (2006) Deep tillage and traffic effects on subsoil compaction and sunflower (*Helianthus annuus* L.) yields. *Soil and Tillage Research* **91**, 164-72
- Calegari A, de Araujo AG, Costa A *et al.* (2014) Conservation agriculture in Brazil. In (Eds. RA Jat, KL Saharawat, A Kassam) 'Conservation Agriculture: Global Prospects and Challenges' pp 54-88 (CAB International: Wallingford, UK)
- Chakraborty D, Ladha JK, Rana DS *et al.* (2017) A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. *Scientific Reports* **7**, 9342
- Chen H, Bai Y, Wang Q *et al.* (2008) Traffic and tillage effects on wheat production on the Loess Plateau of China: 1. Crop yield and SOM. *Australian Journal of Soil Research* **46**, 645-651
- Corbeels M, Marchão RL, Sequiera Neto M, *et al.* (2016) Evidence of limited carbon sequestration in soils under no-tillage systems in the Cerrado of Brazil. *Scientific Reports* **6**, 21450
- Craswell ET, Vlek PLG (2013) Mining of nutrients in African soils due to agricultural intensification. In 'Principles of Sustainable Soil Management in Agroecosystems', Advances in Soil Science' (Eds. R. Lal and B.A. Stewart) pp 401-422 (CRC Press: Boca Raton, LA)
- Davin EL, Seneviratne SI, Ciais P *et al.* (2014) Preferential cooling of hot extremes from cropland albedo management. *Proceedings National Academy of Sciences* **111**, 9757-9761
- de Morais Sá J, Lal R, Cerri CC *et al.* (2017) Low carbon agriculture in South America to mitigate global climate change and advance food security. *Environmental International* **98**, 102-112
- de Oliveira Ferreira A, Amado T *et al.* (2016) Can no-till grain production restore soil organic carbon to levels natural grass in a subtropical Oxisol? *Agriculture, Ecosystems and Environment* **229**, 12-20

- Derpsch R, Sidiras N, Roth CH (1986) Results of studies made from 1977 to 1984 to control erosion by cover crops and no-tillage techniques in Parana, Brazil. *Soil and Tillage Research* **8**, 253-263
- Derpsch R. (2016) Historical review of no-tillage cultivation of crops. www.rolf-derpsch.com/en/no-till/historical-review/#c582
- Diekow J, Mielniczuk J, Knicker H *et al.* (2005) Soil C and N stocks as affected by cropping system and nitrogen fertilization in a southern Brazil Acrisol managed under no-tillage for 17 years. *Soil and Tillage Research* **81**, 87-95
- Ekboir J, Parellada G (2002) Public – private interactions and technology policy in innovation processes for zero tillage in Argentina. In ‘Agricultural Research Policy in an Era of Privatization’ (Eds. D Byerlee and R Echeverria) pp 137-154 (CABI Publishing: Wallingford)
- FAO (2011) ‘Save and Grow: a Policymaker’s Guide to Sustainable Intensification for Smallholder Crop Production’ 112 pages. ISBN 978-92-5-106871-7
- Fischer RA (1987) The responses of soil and crop water relations to tillage. In (Eds. PS Cornish JE Pratley) ‘Tillage: New Directions in Australian Agriculture’ pp 194-221 (Australian Society of Agronomy, Inkata Press: Melbourne)
- Gathala MK, Ladha JK, Kumar V, Saharawat Y, Kumar V, Sharma PK (2011) Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice-wheat rotation. *Soil Science Society of America Journal* **75** (5), 1851-1862
- Gerhards R (2019) Precision weed management systems. In ‘Precision Agriculture for Sustainability’ (Ed. J. Stafford) pp 399-420 (Burleigh Dodds Science Publishing: Cambridge, UK)
- Giller KE, Andersson JA, Corbeels M *et al.* (2015) Beyond conservation agriculture *Frontiers in Plant Science* **6**, article 870
- Godwin R, Misiewicz P, While D *et al.* (2015) Results for recent traffic systems research and the implications for future work. *Acta Technologica Agriculturae* **3**, 57-63
- Govaerts B, Mezzalama M, Sayre KD *et al.* (2006) Long term consequences of tillage, residue management and crop rotation on maize/wheat root rot and nematode populations in subtropical highlands. *Applied Soil Ecology* **32**, 305-315
- Govaerts B, Sayre KD, Lichter K *et al.* (2007) Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems. *Plant and Soil* **291**, 39-54
- Govaerts B, Mezzalama M, Sayre KD *et al.* (2008) Long term consequences of tillage, residue management and crop rotation on selected soil micro-flora groups in subtropical highlands. *Applied Soil Ecology* **38**, 197-210
- Grassini P, Cassman KG (2012) High-yield maize with large net energy yield and small global warming intensity. *Proceedings National Academy of Sciences* **109**, 1074-1079
- Hagglblade S, Tempo G (2003) Conservation farming in Zambia. EPTD Discussion Paper No. 108. 113 pp (IFPRI, Washington DC)
- Hamza MA, Anderson WK (2005) Soil compaction in cropping systems. A review of the nature, causes and possible solutions. *Soil and Tillage Research* **82**, 121-145
- Heckrath G, Djurhuus J, Quine TA *et al.* (2005) Tillage erosion and its effects on soil properties and crop yield in Denmark. *Journal of Environmental Quality* **34**, 312-324
- Hobbs P, Gupta R, Jat, RK, Malik RK (2017) Conservation agriculture in the IndoGangetic Plains of India: Past, present and future. *Experimental Agriculture*, Published online: 19 September 2017, pp. 1-19
- Hobbs P, Thierfelder C, Wall P *et al.* (2019) The role of crop and cropping system management in Conservation Agriculture systems. In (Ed. A Kassam) ‘Advances in Conservation Agriculture’ Volume 1: Systems and Science.’ Chapter 6, 29 pp. (Burleigh Dodds Science Publishing Limited: Cambridge, UK)
- Huang M, Zhou X, Cao F *et al.* (2015) No-tillage effect on rice yield in China: a meta-analysis. *Field Crops Research* **183**, 126 -137
- Ibrahim A, Bentaher H, Hamza E *et al.* (2017) 3D finite element simulation of the effect of mouldboard plough’s design on both the energy consumption and the tillage quality. *International Journal of Advances Manufacturing Technology* **90**, 473-487
- Johansen C, Haque ME, Bell RW *et al.* (2012) Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. *Field Crops Research* **132**, 18-32
- Jat RK, Singh RG, Kumar M *et al.* (2019) Ten years of conservation agriculture in rice-maize rotation of eastern Gangetic Plains of India: Yield trends, water productivity and economic profitability. *Field Crops Research* **232**, 1-10
- Kahlon MS, Lal R, Anne-Varughese M (2013) Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. *Soil and Tillage Research* **126**: 151-158
- Kassam A, Friedrich T, Derpsch R (2019) Global spread of Conservation Agriculture. *International Journal of Environmental Studies* **76**, 29-51

- Kibblewhite MG, Ritz K, Swift MJ (2007) Soil health in agricultural systems. *Philosophical Transactions of the Royal Society Series B* **363**, 685-701
- Kirkby CA, Kirkegaard JA, Richardson AE *et al.* (2011) Stable soil organic matter: a comparison of C:N:P:S ratios in Australian and other world soils. *Geoderma* **163**, 197-208
- Kirby CA, Richardson AE, Wade LJ *et al.* (2016) Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. *PLoS ONE* **11** (5).
- Lal R (2004) Carbon emissions from farm operations. *Environment International* **30**, 981-990
- Lal R, Wilson GF, Okigbo BN (1978) No-till farming after various grasses and leguminous cover crops in tropical alfisol. 1. Crop performance. *Field Crops Research* **1**, 71-84
- Landers JN (2018) Discussion paper on eliminating puddling in rice by using zero tillage. *Agriculture for Development* **35**, 23-30
- Lee N, Thierfelder C (2017) Weed control under conservation agriculture in dryland smallholder farming systems in southern Africa: A review. *Agronomy for Sustainable Development* **37** (5), 48
- Li S, Lobb DA, Lindstrom MJ (2007) Tillage translocation and tillage erosion in cereal-based production in Manitoba, Canada. *Soil and Tillage Research* **94**, 164-182
- Li H, He J, Bharucha ZP *et al.* (2016) Improving China's food and environmental security with conservation agriculture. *International Journal of Agricultural Sustainability* **14**, 377-391
- Li Z, Yang X, Cui S *et al.* (2018) Developing sustainable cropping systems by integrating crop rotation with conservation tillage practices on the Loess Plateau, a long-term imperative. *Field Crops Research* **222**, 164-179
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Lobb DA, Huffman E, Reicosky DC (2007) Importance of information on tillage practices in the modelling of environmental processes and in the use of environmental indicators. *Journal of Environmental Management* **82**, 377-387
- Loch A, Cummins J, Zuo A, Yargop R (2018) Value chain and policy interventions to accelerate adoption of zero tillage in rice-wheat farming across the Indo Gangetic Plains. Final Report to ACIAR, Canberra <http://aciarc.gov.au/publication/>
- Loss S, Haddad A, Desbiolles J *et al.* (2015) The Practical Implementation of Conservation Agriculture in the Middle East. 98 pp (ACIAR and ICARDA)
- Lovarelli D, Bacenetti J (2017) Seedbed preparation for arable crops: Environmental impact of alternative mechanical solutions. *Soil and Tillage Research* **174**, 156-168
- Martinez I, Chervet A, Weisskopf P *et al.* (2016) Two decades of no-till in the Oberacker long-term field experiment: Part 1. Crop yield, soil organic carbon and nutrient distribution in the soil profile. *Soil and Tillage Research* **163**, 141-151
- Mashavakure N, Mashingaidze AB, Musundire R *et al.* (2018) Short term impacts of tillage and fertilizer treatments on soil and root borne nematodes and maize yield in a fine textured Cambisol. *Journal of Nematology* **50**, 1-13
- McLaughlin NB, Drury CF, Reynolds WD *et al.* (2008) Energy inputs for conservation and conventional primary implements in a clay loam soil. *Transactions of American Society of Agricultural and Biological Engineers* **51**, 1153-1163
- Mei K, Wang Z, Huang H *et al.* (2018) Stimulation of N₂O emission by conservation tillage management in agricultural lands: A meta-analysis. *Soil and Tillage Research* **182**, 86-93
- Minasny B, Malone BP, McBratney AB *et al.* (2017) Soil carbon 4 per mille. *Geoderma* **292**, 59-86
- Muoni T, Rusinamhodzi L, Thierfelder C (2013) Weed control in conservation agriculture systems of Zimbabwe: Identifying economical best strategies. *Crop Protection* **53**, 23-28
- Naresh RK, Rathore RS, Yadav RB *et al.* (2014) Effect of precision land leveling and permanent raised bed planting on soil properties, input use efficiency, productivity, and profitability under maize (*Zea Mays*) – wheat (*Triticum aestivum*) cropping system. *African Journal of Agricultural Research* **9** (36), 2781-2789
- Paroda RS 2018. Reorienting Indian Agriculture: Challenges and Opportunities. Trust for Advancement of Agricultural Sciences (TAAS), India (CABI: UK)
- Pezzi F (2005) Traditional and new deep soil tillage techniques in Italy. *Transactions of the American Society of Agricultural Engineers* **48**, 13-17
- Piggin C, Haddad A, Khalil Y *et al.* (2015) Effects of tillage and time of sowing on bread wheat, chickpea, barley and lentil grown in rotation in rainfed systems in Syria. *Field Crops Research* **173**, 57-67
- Pittelkow CM, Linnquist BA, Lundy ME *et al.* (2015) When does no-till yield more? A global meta-analysis. *Field Crops Research* **183**, 156-168

- Poulton P, Johnston J, Macdonald A *et al.* (2018) Major limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology* doi: 10.1111/gcb.14066
- Powlson D, Stirling CM, Jat ML *et al.* (2014) Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* **4**, 678-683
- Powlson D, Stirling CM, Thierfelder C *et al.* (2016) Does conservation agriculture deliver climate change mitigation through carbon sequestration in tropical agro-ecosystems. *Agriculture, Ecosystems and Environment* **220**, 164-174
- Quine TA, Zhang Y (2002) An investigation of spatial variation in soil erosion, soil properties, and crop production within an agricultural field in Devon, United Kingdom. *Journal of Soil and Water Conservation* **57**, 55-65
- Rivers A, Barbercheck M, Govaerts B, Verhulst N (2016) Conservation agriculture affects arthropod community composition in a rainfed maize-wheat system in Central Mexico. *Applied Soil Ecology* **100**, 81-90
- Roper MM, Milroy SP, Poole ML (2012) Green and brown manures in dryland wheat production systems in Mediterranean-type environments. *Advances in Agronomy* **117**, 275-313
- Sapkota SP, Jat RK, Singh RG, Jat ML *et al.* (2017) Soil organic carbon changes after seven years of conservation agriculture in a rice-wheat system of the eastern Indo-Gangetic Plains. *Soil Use and Management* **33**, 81-89
- Sayre KD, Hobbs PR (2004) The raised-bed system of cultivation for irrigated production conditions. In (Eds. R Lal, P Hobbs, N Uphoff, DO Hansen) ‘Sustainable Agriculture and the Rice-Wheat System.’ Chapter 20 pp 337-355 (Ohio State University: Columbus, Ohio, USA)
- Sayre KD, Limon-Ortega A, Govaerts B (2005) Experiences with permanent bed planting systems CIMMYT, Mexico. In (Eds. CH Roth, RA Fischer, CA Meisner) ‘Evaluation and performance of permanent raised bed cropping systems in Asia, Australia and Mexico.’ pp12-25. *Proceedings of a workshop held in Griffith, Australia* (ACIAR Proc. 121)
- Schneider F, Don A, Hennings I *et al.* (2017) The effect of deep tillage on crop yield – What do we really know? *Soil and Tillage Research* **174**, 193-204
- Sidhu HS, Singh M, Singh Y, Blackwell J, Lohan SK, Humphreys E, Jat ML, Singh V, Singh S (2015) Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. *Field Crops Research*, **184**, 201-212
- Spoor G, Tijink FGJ, Weisskopf P (2003) Subsoil compaction: risk, avoidance, identification and alleviation. *Soil and Tillage Research* **73**, 175-182
- Spoor G (2006) Alleviation of soil compaction: requirements, equipment and techniques. *Soil Use and Management* **22**, 113-122
- Thierfelder C, Wall PC (2009) Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research* **46** (3), 309-325
- Tullberg J, Antille DL, Bluett C, Eberhard J, Scheer C (2018) Controlled traffic farming effects on soil emissions of nitrous oxide and methane. *Soil and Tillage Research* **176**, 18-25
- Valbuena D, Erenstein O, Homann-Kee TS *et al.* (2012) Conservation Agriculture in mixed crop-livestock systems: Scoping crop residue tradeoffs in sub-Saharan Africa and South Asia. *Field Crops Research* **132**, 175-184
- Van den Akker JJH, Arvidsson J, Horn R (2003) Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. *Soil and Tillage Research* **73**, 1-8
- Van Kessel C, Venterea R, Six J *et al.* (2013) Climate, duration, and N placement determine N₂O emissions in reduced tillage systems: a meta-analysis. *Global Change Biology* **19**, 33-44
- Van Oost K, Govers G, de Alba S, Quine TA (2006) Tillage erosion: a review of controlling factors and implications for soil quality. *Progress in Physical Geography* **30**, 443-466
- Van Oost K, Cerdan O, Quine TA (2009) Accelerated sediment fluxes by water and tillage erosion on European agricultural land. *Earth Surface Processes and Landforms* **34**, 1625-1634
- Verhulst N, Govaerts B, Verachtert, E *et al.* (2009) The importance of crop residue management in maintaining soil quality in zero tillage systems: A comparison between long-term trials in rainfed and irrigated wheat systems. *Proceedings of 4th World Congress on Conservation Agriculture*, New Delhi, India
- Wall PC (2009) Strategies to overcome the competition from crop residues in Southern Africa: Some light at the end of the tunnel. *Lead Papers, Proceedings of 4th World Congress on Conservation Agriculture*, pp 65-70 New Delhi, India
- Wall PC, Thierfelder C, Ngwira AR *et al.* (2014) Conservation agriculture in eastern and southern Africa. In ‘Conservation Agriculture: Global Prospects and Challenges’ (Eds. RA Jat, KL Sahrawat, AH Kassam) (CAB: Wallingford, UK)
- Wang F, Xuqing W, Sayre K (2004) Comparison of conventional, flood irrigated, flat planting with furrow irrigated, raised bed planting for winter wheat in China. *Field Crops Research* **87** (1), 35-42

- Wang XB, Cai DX, Hoogmoed WB *et al.* (2007) Developments in conservation tillage in rainfed regions of North China. *Soil and Tillage Research* **93**, 239-250
- Wang Y, Zhang Y, Zhou S, Wang Z (2018) Meta-analysis of no-tillage effect on wheat and maize water use efficiency in China. *Science of the Total Environment* **635**, 1372-1382
- Zingore S, Manyame C, Nyamugafata P, Giller KE (2005). Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. *European Journal of Soil Science* **56** (6), 727-736

Chapter 2

Conservation agriculture in Australia: 30 years on

Rick Llewellyn and Jackie Ouzman

Introduction

In this chapter we present a national overview of current use of conservation agriculture-related practices by Australian grain growers and the trajectories of this practice change over the past three decades. The shift to no-tillage farming represents one of the most substantial landscape changes in Australian agriculture. From initial investigations into the potential for conservation farming in Australia during the 1960s (Belotti and Rochecouste 2014, Thomas *et al.* 2007), the long process of transformation from a traditional cropping system initially involving multiple cultivations of typically fragile soil has continued into the current decade.

The importance and extended time frame of adoption of conservation agriculture-related practices in Australia means that it has received extensive research and review attention in efforts to understand and learn from the change (Cornish and Pratley 1987, Freebairn *et al.* 1993, Crabtree 2010). The aim here is not to review these studies, or the associated international literature, but to look at the more recent status of conservation agriculture application and the path it is taking across Australian cropping zones as the extent of use continues to reach its high plateau in some agro-ecological zones. Together with this ongoing establishment of no-tillage as an extensive practice in some later-adopting agro-ecological zones, we concurrently see established no-till and stubble retention acting as a platform for further major advances in cropping practice. This is the foundation for suites of practices that are together increasing water use efficiency and general management efficiency at increasing farm scales (Kirkegaard *et al.* 2014b, Fletcher *et al.* 2016) and leading to sustained levels of strong production in the face of an increasingly challenging climate (Gobbett *et al.* 2017).

The adoption of conservation farming methods is recognised as a multi-faceted, information and learning-intensive process (Young 2003, D’Emden *et al.* 2007, Gray 2010, Rochecouste *et al.* 2018), and this has been reflected in the unique role of farmer-led groups in its development and extension. We end this chapter with an examination of the associated transformation of the farm advisory network over this period of remarkable cropping change and the legacy this has left for future farming systems innovation.

Data

The chapter draws upon a mix of published and unpublished data collected from two national surveys of Australian grain growers. The main data set (from the data collection described in Llewellyn *et al.* 2016) represents 13 agro-ecological zones across northern (including northern New South Wales and Queensland), southern (including southern New South Wales, Victoria, South Australia and Tasmania) and the western zone (Western Australia), while the second data set (from Llewellyn and Ouzman 2014) represents 12 agro-ecological zones (AEZ) across southern and western Australia. This second data set is used in a supplementary manner; examining relationships with advisory support and adoption of other cropping technologies by Australian grain growers.

Data collections in both surveys involved phone interviews run in conjunction with a specialist survey data collection company, with an extensive national grower database. Growers were randomly contacted from the database until the quota for growers meeting the criteria in each AEZ was met. In both studies respondents needed to be identified as primary cropping decision makers and were screened based on their farm’s crop area being greater than 500 ha of crop, with the exception of the High Rainfall Victoria and Tasmanian zones in the 2016 study, where this was reduced to 250 ha to reflect the commonly smaller farm size in that region. In the 2016 study, the completion rate was 44%, based on the total number of primary cropping decision-makers directly approached for participation, and the

602 grower responses represent a total arable area of 2.0 million hectares. In the earlier survey study, the completion rate was 45%, with 573 growers participating.

A relatively broad definition of NT seeding is used in this chapter and the main studies cited. The working definition of NT is based around seeding with low soil disturbance and no prior cultivation, including crop seeding using either low disturbance points or ‘zero-till’ (with disc machines). The other major component of conservation cropping systems, full retention of crop residue, has been considered separately. The data present practice-change over time, showing the trends in CA-related practices, together with related factors including use of consultants and engagement with farmer groups over the last 30 years. The diffusion curves show the cumulative adoption levels based on stated times of first use by growers at the time of the study. They reflect the practice changes undertaken by the population of growers at the time of the study rather than the typically larger grower population that may have existed at the time of first use. Where possible, supplementary area-based data from the most recent farm practices survey conducted in 2016 by the Grains Research and Development Corporation (Umbers 2017) are used by way of a comparison.

Adoption and extent of use of conservation agriculture in the Australian grains industry

In this section we begin by looking at adoption and use of NT (and/or ZT practices) by Australian grain growers over the past 3 decades. Stubble retention and the use of burning is then explored as the second major component of conservation agriculture.

Adoption of no-tillage cropping

The most recent available farm practices survey data (Umbers 2017) show that the proportion of Australian grain crop area sown using no-till or zero-till reached 74% in 2016. Although this shows that NT practices have typically become ‘conventional practice’, a national perspective on time of adoption shows that growers shifting to NT for the first time has been an ongoing process into the current decade. Figure 1 shows the cumulative proportion of grain growers who have used at least some NT. It highlights the long time-frames involved in reaching peak adoption across a geographically diverse and heterogeneous population of potential adopters. At this national level, evidence of a plateauing of adoption has only become apparent in the past decade.

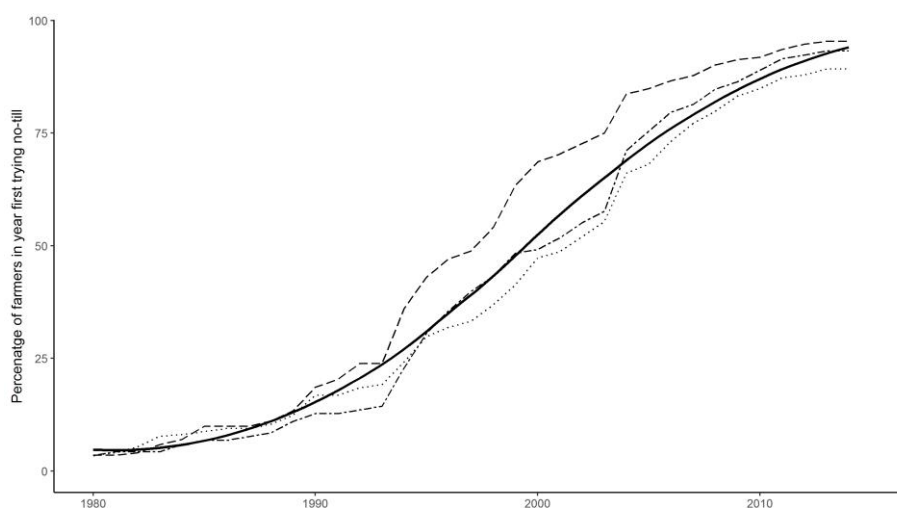


Figure 1. The cumulative proportion of Australian grain growers who had used some no-till (or zero-till) by year (solid line is national smoothed data, based on 2014 grower population, two dash line is northern, dotted is southern and long dashed is western).

When looking at the regional level, the data show the substantially faster rate of adoption of NT in Western Australia through the 1990s and an earlier slowing of adoption rates in that state (Figure 1).

Continued high adoption rates in the northern and southern regions after 2000 have led to a closing of those regional differences. Later starts to the increase in NT adoption in some agro-ecological zones such as the low-rainfall SA-Vic Mallee (including Upper Eyre Peninsula) region, and steadier rates of adoption relative to the more rapid surges in adoption experienced in agro-ecological zones such as the WA northern region, help to explain some of the regional differences and the extended period of adoption (Figure 2). Ultimately, the very large differences between agro-ecological zones in the proportion of growers who have adopted NT that was evident during the late 1990s (Figure 3) have largely disappeared, with most regions now exceeding 90% (Table 1).

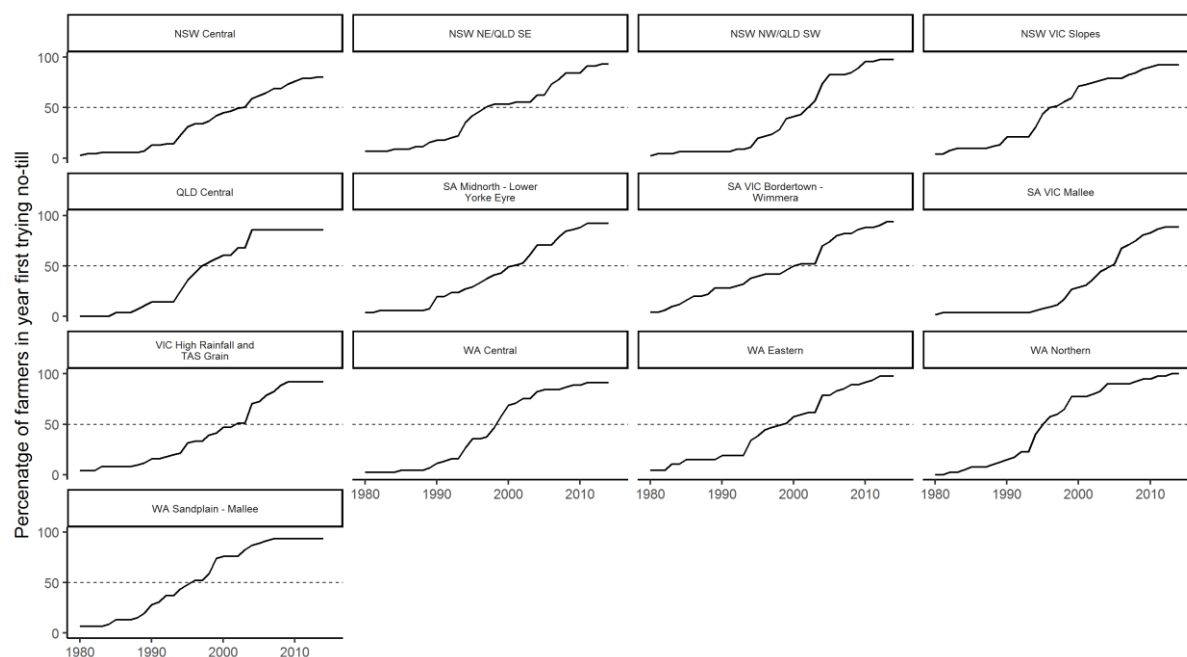


Figure 2. The cumulative proportion of grain growers by agro-ecological zone who have used some no-till (or zero-till) by year.

The extent of use of tillage

While the proportion of growers using at least some NT is typically plateauing at over 90%, the area of crop under NT (or undergoing some cultivation) still reflects more substantial differences (Table 1). On average, these 2014 season figures show 15% of cropped area sown following a prior cultivation pass. A comparable study (Umbers 2017) indicates an average 16% of the national grain crop area had received a prior cultivation pass over the years 2011-2016 with no significant change in this figure over this period. In contrast, there has been a significant reduction in the proportion of cropped area sown ‘direct-drill’ (causing greater than 30% soil disturbance in the seeding pass), indicating that gains in the crop area under NT/ZT over the past decade have come from new adopters and a shift to reduced disturbance in single pass sowing operations.

Although only small, the increases in extent of use demonstrate that the adoption process for NT adoption still may not be complete in some areas. This is more than three decades after NT began to be adopted under Australian farm conditions. The results also demonstrate that some form of tillage on relatively small areas is likely to remain a significant part of Australian cropping practice. Reasons for continued use of some tillage are explored in the next section.

Use of cultivation

While NT has become the increasingly dominant seeding system across all regions, nationally 10% of growers still choose to cultivate at least some of their land at or prior to seeding (Table 2). As a result, approximately 15% of crop area is cultivated in a particular season (Table 1). Growers choosing to perform some level of cultivation cited weed management as a main reason for cultivation prior to or

Table 1. Adoption of no-till/zero-till by Australian grain growers and extent of use

	<i>Percentage of growers</i>	<i>Average percentage of crop sown with</i>		<i>Average percentage of crop sown with</i>	
		<i><u>no prior cultivation</u></i>		<i><u>prior cultivation</u></i>	
	Used no-till or zero-till in the past	Sown with no- till or zero-till	Sown with full- cut seeding pass	Sown with no- till or zero-till implement	Sown with full- cut seeding pass
<i>Northern</i>	93%	80%	2%	9%	8%
Qld Central	86%	80%	0%	7%	13%
NSW NE/Qld SE	93%	82%	4%	8%	6%
NSW NW/Qld SW	98%	79%	2%	12%	6%
<i>Southern</i>	89%	73%	6%	10%	9%
NSW Central	76%	52%	8%	17%	21%
NSW Vic Slopes	92%	74%	6%	17%	3%
SA Midnorth – Lower Yorke Eyre	92%	85%	4%	5%	6%
SA Vic Bordertown – Wimmera	94%	76%	0%	12%	8%
SA Vic Mallee	88%	72%	10%	8%	8%
VIC high rainfall and Tas grain	92%	77%	7%	4%	12%
<i>Western</i>	96%	91%	2%	4%	3%
WA Central	91%	88%	1%	2%	8%
WA Eastern	98%	93%	3%	4%	0%
WA Sandplain – Mallee	93%	91%	2%	3%	5%
WA Northern	100%	93%	0%	6%	0%
Total / National	92%	80%	4%	8%	7%

‘Percentage of growers’ is expressed as percentage of all growers per region/zone. ‘Average percentage of cropping land’ is the average nominated proportion of cropping land (stated by the grower) sown in 2014 using this practice. Due to rounding, area numbers may not sum to 100%.

at seeding. Cultivation in the fallow period to control weeds is most common in the northern regions with 66% of growers undertaking this practice on at least some land and, on average, just under a third of their cropping land.

The application of strategic tillage (Dang *et al.* 2015, Kirkegaard *et al.* 2014a, and see Chapter 7) and the recent increase in interest and uptake of soil amelioration practices such as deep disturbance of sandy soils (Scanlan *et al.* 2019, and see Chapter 8) has further demonstrated that Australian grain growers will continue to be willing to apply targeted tillage practices where it can help to sustain a profitable cropping system. Although flexible and adaptive, Australian grain growers are also continuing to demonstrate that NT seeding systems will remain central to modern farming systems. Timeliness advantages have always been an important driver of NT adoption decisions (D’Emden *et al.* 2006) and the labour and machinery-use efficiency required for timely seeding on increasingly large farms is becoming more important (Fletcher *et al.* 2019).

Table 2. Percentage of growers cultivating at or prior to seeding in 2014 and percentage who cite weed management as main reason for cultivation.

	Southern	Western	Northern
Proportion of growers cultivating at or prior to seeding (%)	15	4	8
Cropping land cultivated prior to or at seeding (<i>i.e.</i> not under no-till) (%)	27	9	20
Average area to be cropped that is cultivated during the fallow by users of tillage (%)	31	19	28
Growers using cultivation of fallows primarily for weed control (%)	37	30	66
Growers who cite weed management as main reason for cultivation prior to seeding expressed as proportion of all growers (%)	29	15	28

Use of burning

As with tillage, despite the major shift to CA principles, use of burning as an agronomic tool is ongoing on targeted areas. While highly seasonal-dependent, over 10% of cropped land has been burnt in southern and western regions (Table 3). Similarly, the GRDC farm survey report found less than 10% of total crop area was burnt in 2016 (Umbers 2017). An increase in use of narrow windrow burning over the past decade for weed control purposes in some cases served to reduce whole-of-paddock burning but the extensive use of this practice is also likely to have led to an increase in the overall area on which some level of burning takes place, reaching 29% of crop area in the western region in 2014 (Table 3).

Nationally, burning stubble on some cropping land is common practice with over 40% of growers engaged in this practice (other than narrow windrow burning) (Table 3). The practice is most common in the southern region and less common in the northern region with 12% doing so on a small portion of their land (3%). Growers are burning crop residues for multiple reasons including: managing heavy stubble, aiding seeding and managing pest and diseases. However, for many farmers it is primarily performed for weed control, with approximately two thirds of all growers in the southern and western regions who burn stubble citing weed management as the main reason to do so (Table 3).

The evolution of narrow windrow burning has meant that burning has become more targeted and effective. Narrow windrow burning is a practice whereby chaff is placed in narrow windrows at harvest and is later burnt; the practice can remove approximately half of crop residue (Walsh and Newman 2007). Narrow windrow burning has had a rapid rise in use from a low base in early 2000 and is particularly common in the western region (Table 3, Figure 6). Although many farmers undertake narrow windrow burning in the Southern and Western regions it is estimated that this practice is undertaken on less than 5% of national cropped area (Umbers 2017).

Table 3. Percentage of growers burning stubble in 2014 and percentage who cite weed management as main reason for burning.

	Southern	Western	Northern
Growers burning stubble – whole paddock (%)	52	40	12
Cropping land burnt by users – not including windrow burning (%)	11	19	3
Growers who cite weed management as the main reason for burning (whole paddock) as a proportion of users (%)	68	66	29
Growers using narrow windrow burning (%)	28	51	4
Proportion of crop area treated with narrow windrow burning by users (%)	21	29	18

More recent innovation and shifts to harvest weed seed control practices that do not involve a burning activity (*e.g.* chaff lining, seed destruction) are not captured in this survey and thus may reduce the use of narrow windrow burning (Walsh *et al.* 2018). This reflects what appears to be an underlying, but pragmatically applied, objective of Australian growers (Kirkegaard *et al.* 2014a) to work towards no-till stubble retention systems and, not least important, practices involving less labour.

Recognising the challenges of no-till and stubble retention

As raised above, Australian growers have demonstrated a flexible approach to the core principles of CA of NT and crop residue retention, evidenced by the use of targeted burning and occasional soil disturbance. For example, area-based trends from 2008 to 2016 in retaining stubble at sowing indicate only a small increase in the proportion of cropped area sown with standing stubble (that has not been grazed, slashed or otherwise managed to remove or reduce it), with 49% of Australia's total cropped area retaining standing stubble in 2016 (Umbers 2017).

While growers express an ongoing willingness to return to the core principles of CA and while disadoption of NT is very rare (Llewellyn *et al.* 2014), there is recognition of the agronomic challenges of NT stubble retention systems. Many growers believe that under NT stubble retention systems compared with one involving cultivation and stubble burning, there will be more weeds, pest and

disease, and inputs cost are likely to be higher (Figure 3). Almost half the growers believe the efficacy of pre-emergent herbicides is less under NT stubble retention compared with a cultivation-based system without stubble retention (Figure 3). Most growers believe that weed costs are higher under a stubble retained NT system compared with one based on cultivation, with only 17% believing costs will be lower (Figure 3).

However, despite the other agronomic challenges raised, over 50% of all growers believed that wheat yield would become more reliable, including over 70% in the more fallow-dependent northern region (Figure 3). That NT stubble retained systems now dominate the modern Australian cropping landscape shows that the benefits of increased crop reliability through improved water use efficiency opportunities, and other major benefits associated with labour efficiencies, potential for scale and erosion prevention, have clearly outweighed the ongoing agronomic complexities.

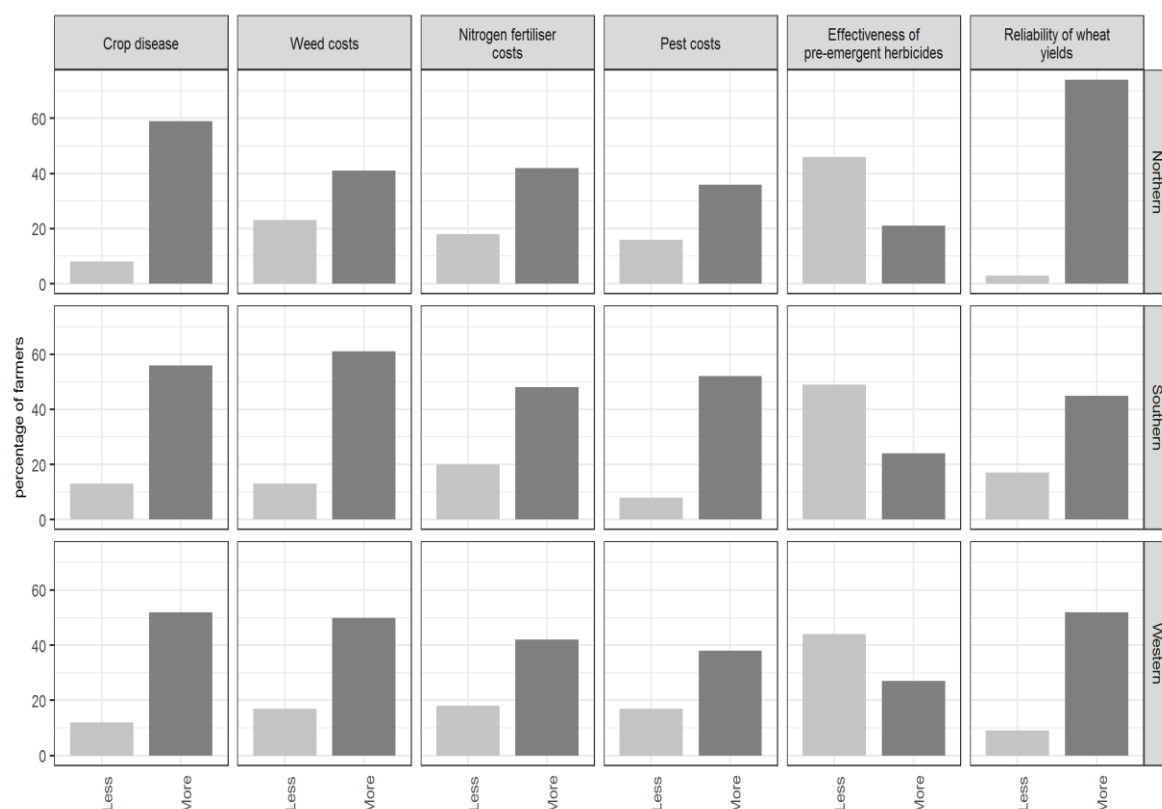


Figure 3. Grower perceptions of agronomic impacts of a no-tillage, stubble retention, continuous cropping systems compared to a cultivated system with stubble burnt on crop disease, weed, nitrogen fertiliser, weed costs, pre-emergence herbicide effectiveness and wheat yield reliability, based on 2014 responses.

Global studies have associated aridity with relatively stronger no-till performance (Pittelkow *et al.* 2015). Previous Australian studies have also shown that the likelihood of growers trying no-till for the first time rose significantly after drier than average years including droughts (D’Emden *et al.* 2007). This is attributed to: the benefits of soil water conservation; ability to seed on less rain; and erosion prevention. These aspects clearly outweighed the other agronomic challenges in those years. In the next section we explore how the farm information and advisory network has transformed to assist growers in addressing the agronomic challenges of conservation agriculture.

The changing extension environment behind the transformation to no-till

Public research agencies played a leading role in early experimentation with reduced tillage systems before farm-scale experimentation became widespread (*e.g.* Reeves 1974, Crabtree 2010, Roget *et al.* 1987, Bligh 1990). As identified by Freebairn *et al.* (1993), this early experimentation often highlighted the dilemma facing farmers: the challenge of how best to counter the negative aspects of the early

conservation tillage techniques (*e.g.* variable yields) while fully exploiting the positive aspects (*e.g.* reduced erosion risk). Meeting this challenge and the subsequent transformation of Australian grain production to NT cropping systems occurred at a time of transformation of the information and support network. This included a decline in provision of farm-specific advice by state government-based extension services and the increasing influence of support for farmer-based group activity through the National Landcare Program (Marsh and Pannell 2014, Anil 2015). As part of this change there was a remarkable rise in the role of no-till farmer associations and other farmer-led groups as partners in the development, implementation and extension of NT systems. Around the same time, the growth of the agronomy consultancy industry began, also providing practical support to farmers in addressing the additional agronomic complexities of NT, stubble retention and more intensive cropping. These developments associated with the shift to NT systems led to ongoing impact on the Australian research, development and extension network and its capacity for innovation.

No-till farming associations

The rise of no-till cropping systems through the 1990s was closely associated with the remarkable rise of farming systems groups, including the no-till farming associations. Nationally, higher participation in extension including farmer groups was significantly associated with early adoption of NT (D’Emden *et al.* 2008). In Western Australia, the Western Australian No-till Farmers Association WANTFA played an integral role in the early and rapid rise of no-till farming (Crabtree 2010, Young 2003). WANTFA formed in 1992 and recorded a remarkable 1400 members in 1999 (WANTFA pers comm). In South Australia, following the success in Western Australia, the SA No-Till Farmers Association formed in 1998 and had 1200 members by 2005 (SANTFA pers comm).

Regionally-focused farming systems groups play an ongoing and important role in the Australian grains industry research, development and extension network (Anil *et al.* 2015), together with technology-focused groups such as no-till associations and precision agriculture groups. However, it appears unlikely that the phenomenal rise of the farmer-led no-till associations will be seen again in terms of the scale of national farmer participation focused on achieving successful implementation of a particular technological change. One reason for this is the now established role of agronomy consultants on most farms.

Agronomy consultants

The use of private cropping consultants has been shown to be associated with double the likelihood of early NT adoption in Australia, although attribution of causality is difficult (D’Emden *et al.* 2006). This demand for advisory support by no-till adopters raised possible implications in regions where the ready availability of quality farm-specific advisory support was limited. An examination of the temporal relationship between increasing NT adoption and the use of paid farm advisors using data from four states (Llewellyn and Ouzman 2012) shows an interesting relationship (Figure 4).

The results show that NT adoption typically led use of paid agronomy support (Figure 5) in that the number of growers who had adopted NT was twice that of the number of growers with a private agronomy adviser. This was the case in all agro-ecological zones (data not shown), but to a greater extent in Western Australia where early NT adoption was generally ahead of the other states. In some cases this may reflect the possible availability of other information and advice sources such as retail agronomists and, initially, state government agronomists. It also demonstrates the potential ‘gap’ that no-till-focused farming systems groups such as no-till and conservation agriculture associations were able to fill.

As the extent of NT adoption and subsequent cropping intensity increased, and the agronomic challenges such as those raised in the earlier section mounted, the use of paid farm-specific agronomy advice typically rises. Although a highly significant association between use of an adviser and NT use was found (*e.g.* D’Emden *et al.* 2006), causality is difficult to ascribe from the available data. The results do suggest however that initial NT use on a farm most often occurred without the input of a farm adviser (with adviser use coming subsequently). Further, the rate of adoption of paid advisors followed

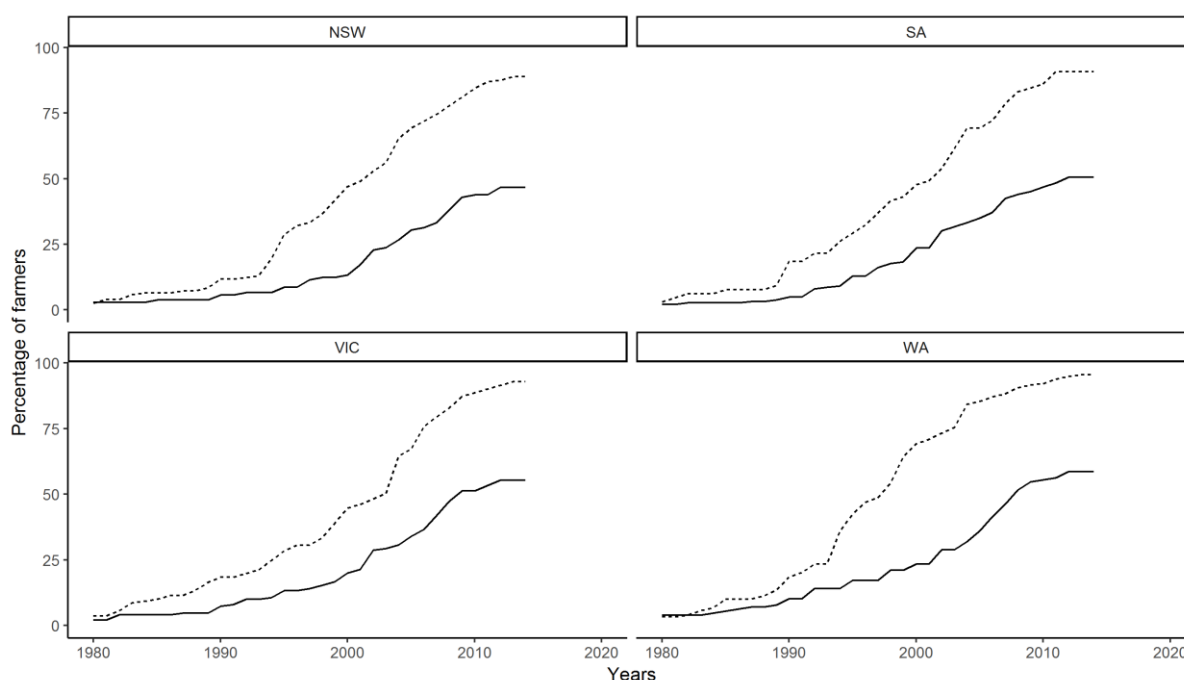


Figure 4. Percentage of farmers who have used no-till (dotted line) and use a paid agronomist (solid line) by state (no data available for Qld).

a slower rate of growth, indicating that motivation and subsequent initial farm-level decisions to adopt NT were generally not facilitated by a farm-specific advisor.

The adoption of paid agronomic advisers over the period 1990 to present has transformed how information is extended, shared and new practices introduced (Keogh and Julian 2014). By the beginning of the current decade, paid farm agronomists were the major source of farm-specific agronomic advice (Table 4).

Table 4. Major source of on-farm agronomic advice as cited by growers (showing percentage of growers citing that source in 2012)

Regions	Independent agronomist / consultant (paid)	Distributor representative agronomist (paid)	Distributor/ representative agronomist (free of charge)	State government- based agronomic adviser	Other source of advice
Southern	37	20	46	12	10
Western	51	23	36	9	16

A farm innovation and adoption legacy

Due to this rise in farm advisory services, the adoption of new practices now occurs under very different conditions from those when NT first began to be practised. In the case of current innovations, they are adopted in the presence of common on-farm agronomic advisory support. The example of the harvest weed seed control practice shown in Figure 5 highlights that, unlike the early NT adoption decision, current agronomic practice adoption decisions can now commonly be made in consultation with agronomic advisers who are in a position to learn from and share the farm experiences of a wide range of farmer clients (Kuehne and Llewellyn 2017).

The availability of cost-effective herbicide options was a major influence on the rate of adoption of NT cropping systems (D’Emden *et al.* 2006) but extensive herbicide resistance provided motivation for weed management innovation. Agronomy consultants played a key role in innovative on-farm use of herbicides (Llewellyn *et al.* 2007) and increasing attention was given to practices primarily aimed at

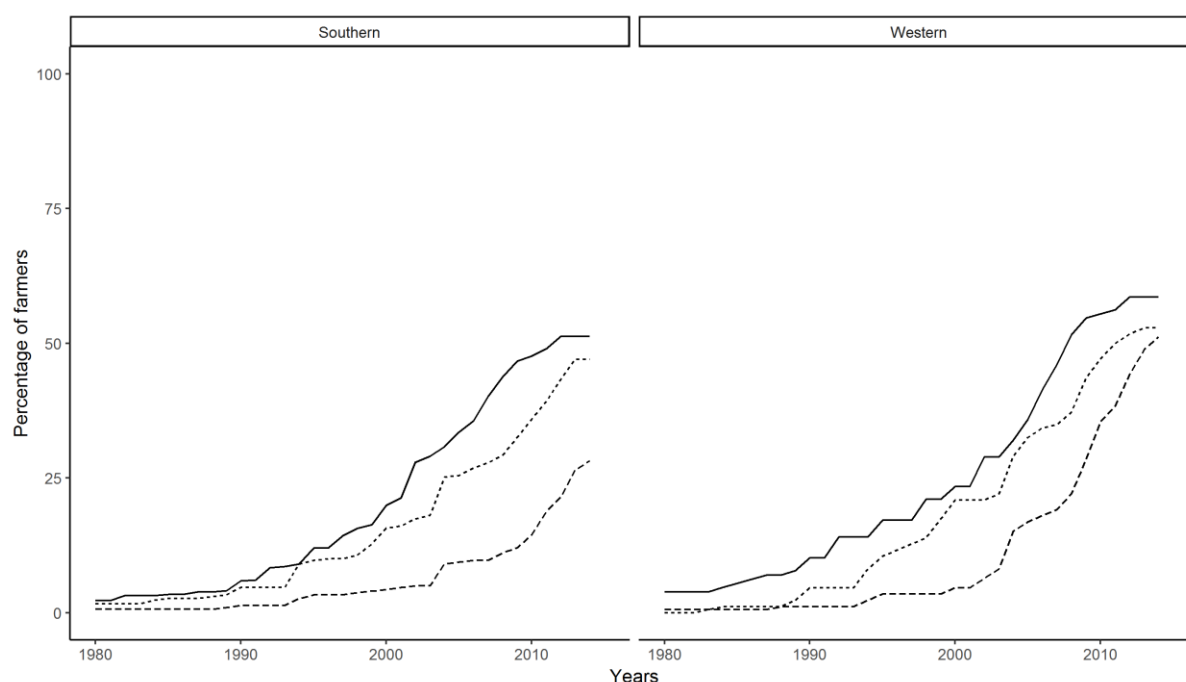


Figure 5. Percentage of farmers who have a paid cropping advisor (solid line) and harvest weed seed control practices (dotted line crop topping and dashed line narrow windrow burning)

managing weed seed set and seedbanks rather than just preventing yield loss in the year of application (Walsh *et al.* 2017).

As indicated by the cultivation and targeted burning trends described earlier, weed management demands continue to challenge some aspects of conservation agriculture practice, but at the same time are contributing to greater utilisation of more diverse crop rotations (Llewellyn *et al.* 2016) – a third key pillar to conservation agriculture. Further, Australian grain growers are recognised not only as major adopters of NT but also for their extensive and rapid adoption of harvest weed seed control practices. In many cases this has involved grower-initiated innovation in partnership with research, farming systems groups and agronomy advisers (Walsh *et al.* 2017).

Weed management provides a telling example of the farm-level innovation, adoption and extension capacity that has been developed through farmer-agronomist-researcher collaboration. The rapid rate of uptake of recent weed seed management practices shows what is now possible in the modern agricultural innovation and information network. This now also incorporates the widespread use of social media for more immediate and extensive information as well as experience sharing between farmers, their peers, advisers and researchers. Australian growers have maintained relatively low weed numbers despite severe and extensive herbicide resistance to major weeds (Llewellyn *et al.* 2009, 2016, see Chapter 10). Concurrently, they have also increased the use of early-sowing (Chapter 18) and conservation agriculture-based cropping systems in the face of drying climate trends: these are major achievements of the grains industry innovation and information system that has evolved.

Conclusion

The diffusion of conservation agriculture practices across diverse Australian cropping landscapes has been remarkable but extended. Although in some regions peak extent of use has only been reached recently, the lack of disadoption has further confirmed that NT systems are highly adoptable, adaptable, and now integral to modern cropping. Australian grain growers have achieved this through a typically flexible approach that continues to accommodate some occasional targeted soil disturbance and crop residue removal. The ongoing success of NT and its use as a platform for further major gains in agronomic and farm performance is also a result of the innovative and adaptive capacity that has developed in the grains industry over this period of change. The NT transformation involved the most

powerful example of farming systems groups as agents of change, and new farmer/farmer group-researcher partnerships were forged. The emerging complexities of implementing the new cropping systems (and the declining provision of state government-based sources of on-farm advice) resulted in the emergence of the independent agronomy advisor as a key pillar in the farm research, development and extension network. These legacies of the era, together with the widespread use of new digital tools for peer-peer sharing and learning, have created an adaptive and innovative environment that has enabled the challenges of sustaining profitable, conservation agriculture-based, cropping systems to be met. Further, the combination of the NT-based cropping system and the associated farmer, research, development and extension network that formed to support it, is now the platform for ongoing innovation in Australian cropping systems.

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References

- Anil B, Tonts M, Siddique K. (2015) Grower groups and the transformation of agricultural research and extension in Australia. *Agroecology and Sustainable Food Systems* **39** (10), 1104-1123
- Bellotti B, Rochecouste J (2014). The development of conservation agriculture in Australia – Farmers as innovators. *International Soil and Water Conservation Research* **2** (1) 21-34
- Bligh K (1990) No-till sowing using narrow-winged points or discs and press wheels. *Proceedings of Agricultural Engineering Conference* 82-87
- Crabtree B (2010) Search for sustainability with no-tillage Bill in dryland agriculture. (Crabtree Agricultural Consulting: Beckenham, WA)
- Dang Y, Seymour N, Walker S *et al.* (2015) Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: I. Drivers and implementation. *Soil and Tillage Research* **152**, 104-114
- D'Emden F, Llewellyn R, Burton M (2006) Adoption of conservation tillage in Australian cropping regions: an application of duration analysis. *Technological Forecasting and Social Change* **73**, 630-647
- D'Emden F, Llewellyn R, Burton M (2008) Factors influencing adoption of conservation tillage in Australian cropping regions. *Australian Journal of Agriculture and Resource Economics* **52**, 169-182
- D'Emden F, Llewellyn R (2006) No-till adoption decisions in southern Australian cropping and the role of weed management. *Australian Journal of Experimental Agriculture* **46**, 563-569
- Freebairn D, Loch R, Cogle A (1993). Tillage methods and soil and water conservation in Australia. *Soil and Tillage Research* **27**, 303-325
- Fletcher A, Lawes R, Weeks C (2016) Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. *Crop and Pasture Science* **67**, 1268-1280
- Gobbett DL, Hochman Z, Horan H *et al.* (2016) Yield gap analysis of rainfed wheat demonstrates local to global relevance. *The Journal of Agricultural Science* **155**, 282-299
- Gray R (2010) It all makes cents: the economics of conservation tillage. In (Eds. C Lindwall, B Sonntag) 'Landscapes Transformed: The History of Conservation Tillage and Direct Seeding' Knowledge Impact in Society, Saskatoon, Saskatchewan
- Keogh M, Julian C (2014) Optimising future extension systems in the Australian grains industry, Part 2: The public and private sector grain advisory systems in Australia. (Australian Farm Institute: Sydney) <http://farminstitute.org.au/LiteratureRetrieve.aspx?ID=141187>
- Kirkegaard J, Conyers M, Hunt J *et al.* (2014a). Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems & Environment* **187**, 133-145
- Kirkegaard JA, Hunt JR, McBeath TM *et al.* (2014b) Improving water productivity in the Australian grains industry—a nationally coordinated approach. *Crop and Pasture Science* **65**, 583-601
- Kuehne G, Llewellyn R (2017). The wisdom of farm advisors: knowing who and knowing why. Social Science Research Network, <https://ssrn.com/abstract=2897232>
- Llewellyn R, D'Emden F, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Llewellyn R, Ouzman J (2014) Adoption of precision agriculture-related practices: status, opportunities and the role of farm advisers. (CSIRO and GRDC: Canberra)

- Llewellyn R, Ronning D, Ouzman J *et al.* (2016). Impact of weeds on Australian grain production: The cost of weeds to Australian grain growers and the adoption of weed management and tillage practices. (GRDC: Kingston, ACT)
- Llewellyn R, Lindner R, Pannell D, Powles S (2007) Herbicide resistance and the adoption of integrated weed management by Western Australian grain growers. *Agricultural Economics* **36**, 123-130
- Pittelkow C, Linquist B, Lundy M *et al.* (2015) When does no-till yield more? A global meta-analysis. *Field Crops Research* **183**, 156-168
- Cornish P, Pratley J (Eds.) (1987) "Tillage: New Directions in Australian Agriculture" (Inkata: Melbourne)
- Reeves T, Ellington A (1974). Direct drilling experiments with wheat. *Australian Journal of Experimental Agriculture* **14**, 237-240
- Rochecoste J, Dargusch P, Cameron D, Smith C (2015) An analysis of the socio-economic factors influencing the adoption of conservation agriculture as a climate change mitigation activity in Australian dryland grain production. *Agricultural Systems* **135**, 20-30
- Roget D, Venn N, Rovira A (1987) Reduction of *Rhizoctonia* root rot of direct-drilled wheat by short-term chemical fallow. *Australian Journal of Experimental Agriculture* **27**, 425-430
- Scanlan C, Davies S (2019) Soil mixing and redistribution by strategic deep tillage in a sandy soil. *Soil and Tillage Research* **185**, 139-145
- Thomas G, Titmarsh G, Freebairn D, Radford B (2007). No-tillage and conservation farming practices in grain growing areas of Queensland—a review of 40 years of development. *Australian Journal of Experimental Agriculture* **47**, 887-898
- Walsh M, Newman P (2007) Burning narrow windrows for weed seed destruction. *Field Crops Research* **104**, 24-30
- Walsh M, Ouzman J, Newman P (2017) High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. *Weed Technology* **31**, 341-347
- Young N (2003) Western Australian No-Tillage Farmers Association. In (Eds. L Garda-Torres *et al.*) 'Conservation Agriculture' pp 155-158 (Kluwer Academic Publishers: Dordrecht, The Netherlands)

Chapter 3

Farms and farmers – conservation agriculture amid a changing farm sector

Ross Kingwell, Andrew Rice, Jim Pratley, Allan Mayfield and Harm van Rees

Introduction

Conservation agriculture (CA) in Australia had its beginnings in the early 1970s with the release by ICI of Spray.Seed[®], comprising paraquat and diquat (Pratley and Rowell 1987). However, it was not until 1978 with the release of diclofop (Hoegrass[®]) for post-emergent ryegrass and wild oat control and then the safer, more effective glyphosate (Roundup[®]) in 1980 by Monsanto for seedbed vegetation control that the tools were in place for adoption of direct drilling (DD) of crops. Adoption of DD was fastest in Western Australia (WA) with its large areas of sandy soils suited to DD and its larger farms and crop areas that benefited from more timely sowing.

Adoption of DD during the 1980s was due largely to the increased cost of farm labour, machinery and fuel (Pratley and Cornish 1985) rather than due to perceived beneficial effects on soils. The initial cost of glyphosate was an impediment, particularly for summer rainfall regions where multiple applications to control weeds in fallows were needed. Early adoption of DD was not without its challenges. Careful management was required to make it work and there was a delayed realisation of its farming system ramifications.

DD and related conservation practices have greatly influenced the business of farming in Australia since the late 1980s. However, identifying the separate and particular impacts of CA on farm businesses is no simple task; especially when so many other changes have contemporaneously lessened, magnified or complemented the effects of conservation practices.

Other chapters in this book provide the technical detail and experimental evidence for the benefit of CA. Our task is not to duplicate their work but rather to reveal the socio-economic change in Australian agriculture and its farm sector that formed the backdrop of farmers' use of conservation practices. We conclude our chapter by reflecting on the current challenges and opportunities facing farmers regarding their use of conservation practices.

Many factors influence the nature of farming in Australia:

- Price trends in domestic and international agricultural commodity markets signal to farmers their need to increase or diminish production of agricultural commodities;
- Technology change typically lowers real costs of production and increases agricultural production;
- Changes in government policy and government support alter the incentives farmers face to engage in agricultural production;
- Periods of climate volatility and any underlying spatial shifts in climate patterns affect production risk, and ultimately the financial risk of farming and business expansion;
- Social attitudes and expectations, within and outside of farm communities, invariably affect the nature and outcomes of farm practices and the social attractiveness of farming;
- What economists call 'path dependencies' and 'asset specificity' affect options for farm businesses. A farm business's location, soil mix, machinery, finances, access to capital, workforce and management skill are its assets. Some of these assets which cannot be quickly altered, and their history of use, their path dependency, determines what business opportunities and directions can feasibly best serve the financial interests of the farm business; and
- Innovation and investment in farming systems and their related supply chains affect the relative affordability of various farm commodities and the appeal of those commodities in processed goods.

Some of the main changes in the nature of broadacre farming in Australia since the mid-1980s, and the main causes of those changes, are described briefly in the following paragraphs.

Key changes in Australian agriculture since the 1980s

Climate variability and an apparent change in climate has affected the nature and profitability of many farm businesses (Kingwell *et al.* 2013, Stephens 2017). The change in climate is most evident in southern Australia, especially in the south-west of WA. Figures 1a and 1b illustrate the southwards and coastal drift of observed climate patterns in Australia. In southern Australia many farmers observe longer, warmer autumns and a later onset of rains to commence the winter growing season. Farmers tend to experience fewer very wet winter days and observe a decline in winter rainfall. In response to these changes, farmers adapt.

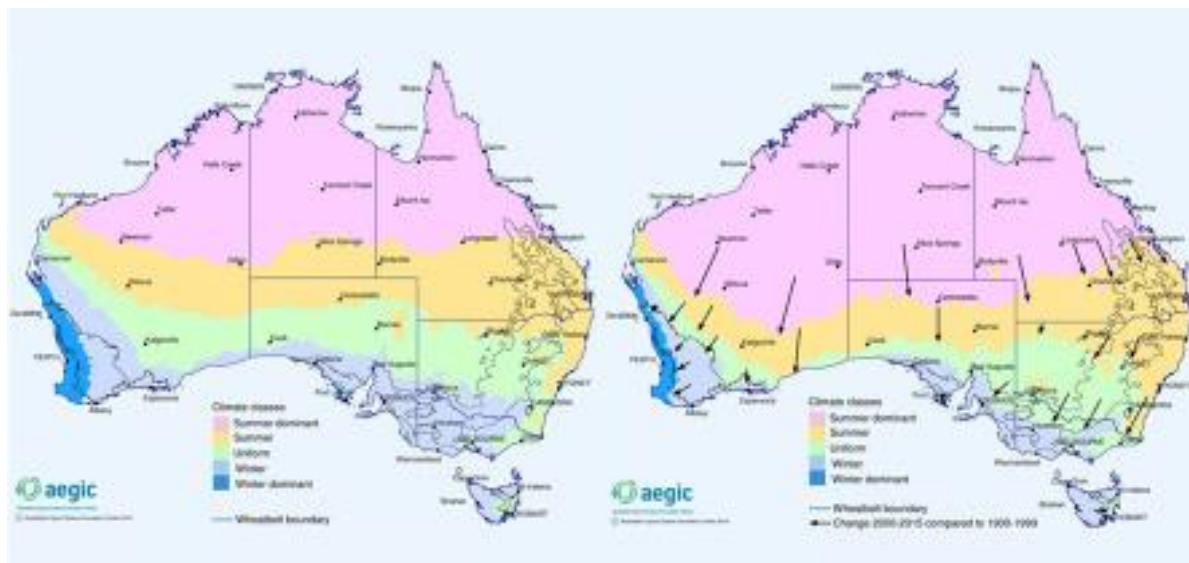


Figure 1. Australian seasonal rainfall zones based on rainfall data (a) 1990-1999, and (b) 2000-2015 (source Stephens 2016, 2017)

There is a long list of farmer adaptations to climate variability and climate change (see Ash *et al.* 2000, Howden *et al.* 2003, Kingwell 2006). The partial list includes:

- reduction in downside risk of crop production (*e.g.* staggered planting times, erosion control, minimum soil disturbance crop establishment, crop residue retention, dry-sowing, crop and varietal portfolios, soil moisture measurement);
- reduction of downside risk of animal production (selection for heat tolerance, crop-grazing, fodder and grain storage);
- seasonally tailored planting (*e.g.* tactical selection of crop portfolios, crop sequences, fields, seeding rates, row spacing, timing and rates of application of nitrogenous fertilisers and crop protection chemicals); and
- diversification of revenue streams (*e.g.* off-farm income, spatial diversification)

Since the early 1990s, Australian broadacre farming has experienced a pronounced and enduring shift into grain production, resulting in large part from the collapse, until recently, in profitability of sheep production in the 1990s. Grain production became commercially more attractive following the folly of administrators of the Reserve Price Scheme for wool (Garnaut *et al.* 1993). Their actions triggered a prolonged collapse in wool prices that weakened the profitability of sheep production. In 1987, the national sheep population was 152 million; and by 2018 the population had shrunk to under 70 million (AWI 2018).

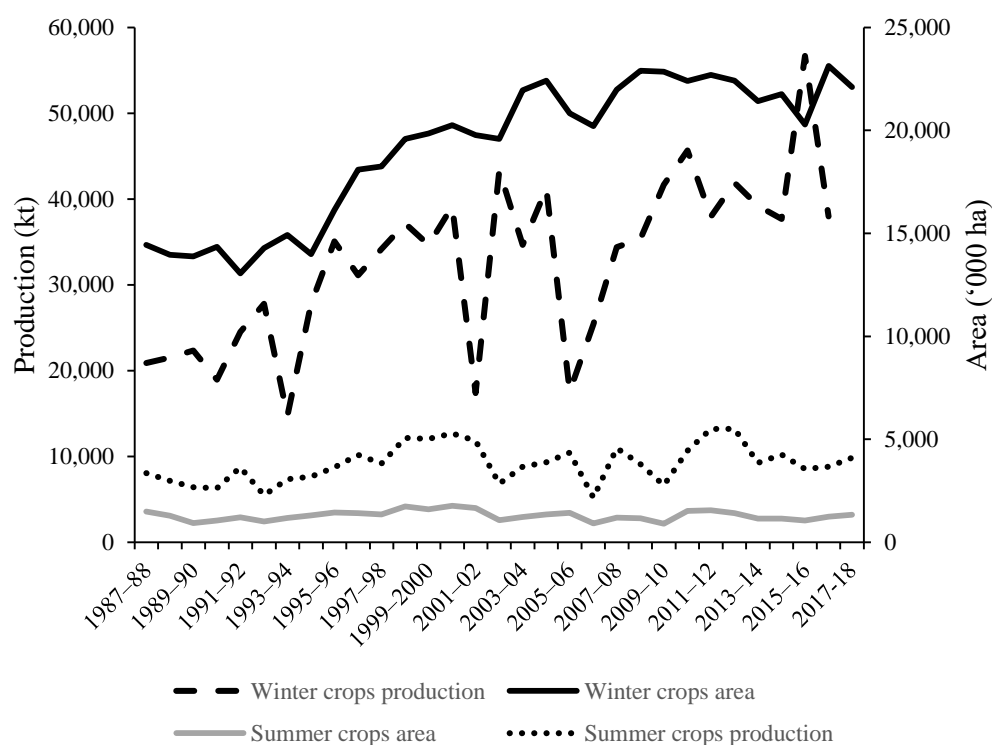


Figure 2. Changes in winter and summer crop production in Australia: 1987/8 to 2015/16
(Source: Based on Australian Commodity Statistics 2018)

Figure 2 shows the changes in the area planted to winter and summer crops in Australia and their respective production. A dominant and persistent change to winter cropping has occurred. Alternative crops to cereals such as canola and some pulses (*e.g.* lupin, faba beans and chickpeas), together with improved crop protection products, facilitated continuous cropping activity. Canola, barely grown in Australia in the late 1980s, has emerged over time as a major crop in all main grain-growing states, apart from Queensland (Figure 3). A four-year investigation (Harries *et al.* 2015) of farmers' crop use in WA showed that wheat, barley and canola, together, occupied 75% of the paddocks surveyed. Crop and pasture sequences had changed over the previous decade toward greater crop dominance and higher levels of inclusion of canola. Wheat remains the dominant crop, mostly followed by barley and then canola. These top three crops are sown often on over 80% of the total crop area in each state, except for Queensland and northern NSW with a greater area of summer crops.

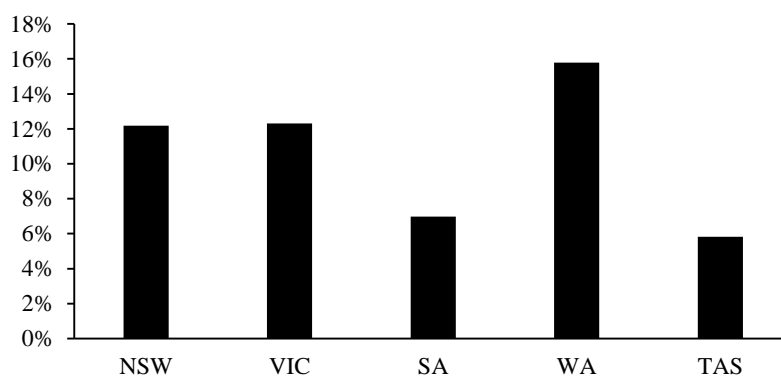


Figure 3. Percentage of the total area of crop sown to canola: 5-year average to 2017/18 (Source: Based on Australian Commodity Statistics 2018)

Farm size

Aside from the relative decline in the profitability of sheep and wool production, especially during the 1990s, many other factors encouraged the change to crop-dominant farming systems including mechanisation, labour-saving technologies, cost-effective herbicides, varietal improvement, and increases in farm size that delivered scale economies, especially to cropping. Further, in some states, the challenges to animal production of sequences of severe drought encouraged a swing into crop production. The increased focus of crop production, when combined with increases in farm sizes, transformed the asset base of broadacre farming (Figure 4).

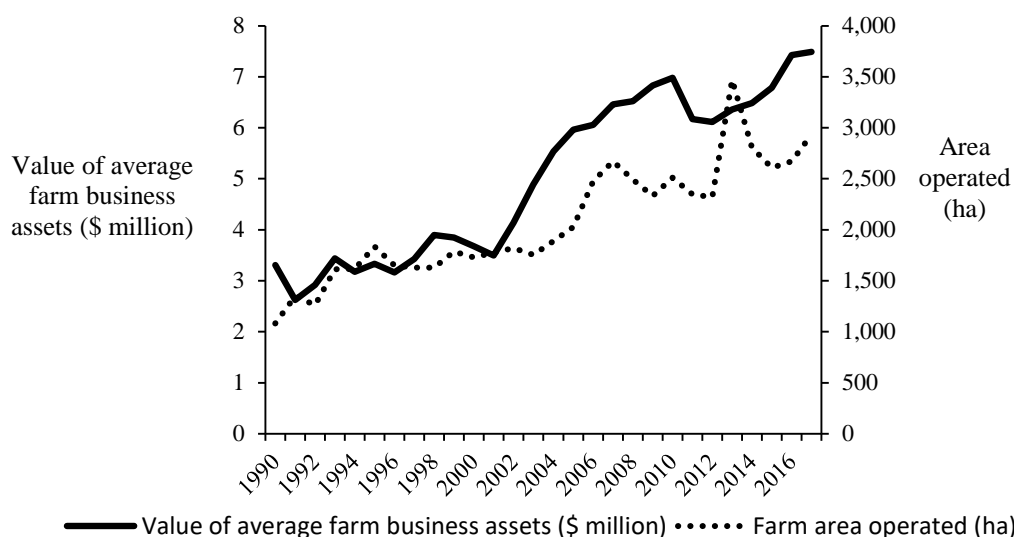


Figure 4. The average farm area operated and the value of farm business assets in the wheat and other crops industry in Australia (Source: ABARES Ag Surf data. All values are presented in constant 2017 dollar terms)

Average farm size increased markedly between 1990 and 2017, as implied by the change in area operated in Figure 4 and because the total number of wheat dominant and mixed enterprise farms declined by 40% over the period. By 2004, the largest 16% of farms accounted for around 75% of total industry output (Sheng *et al.* 2016). Larger farms generated social implications. Increasingly only the children of farmers or those with remarkable wealth were able to become sole owners and operators of a large farm business. Most others keen to engage directly in farming needed to do so via hobby or part-time farming, as farm equity partners, as farm managers or as farm workers.

The increase in the size and complexity of farm businesses (Kingwell 2011), when combined with farm families having fewer children who spend many years in education away from the farm, cause most farm businesses to increase their expenditure on purchased services (including farm labour). Use of permanent and casual labour, contractors (spraying, fencing, shearing, harvesting) and specialist services (*e.g.* grain marketing, agronomic advice, accountancy) are now common features of current farm businesses, especially cropping farms (Figure 5).

There is a positive relationship between farm size and total factor productivity. As well as outsourcing services, larger farms are better able to purchase new equipment and technology (Sheng and Chancellor 2018). Often these businesses benefit from their managers being well educated.

The increase in farm size and the commensurate decline in the farmer population, accompanied by the on-going urbanisation of Australia's population, continues to reduce the political and economic importance of the farm sector. Although farmers often draw an empathetic and sympathetic response from city consumers, the political reality is that most governments rise and fall on urban votes.

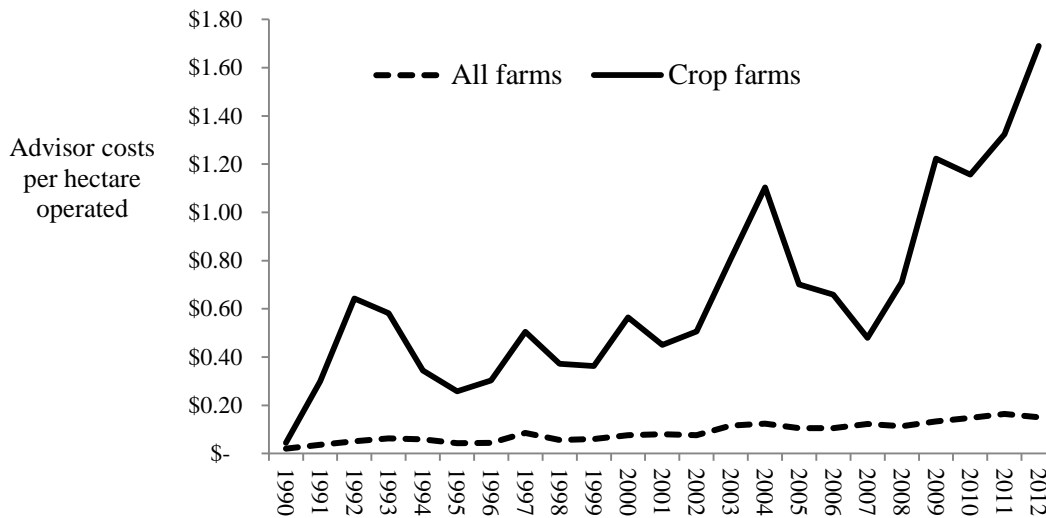


Figure 5. The increase in advisor costs for crop farms relative to all farms, 1990-2012
(Source: Keogh and Julian 2013)

Farm ownership

Although broadacre farming in Australia remains largely the province of family-owned and operated businesses, corporate farming is on the rise. Corporate and foreign ownership of Australian farmland attracts much media and political scrutiny. As at 30 June 2017, around 10% of the farmland in most mixed cropping and grazing regions of Australia were corporately-owned and at 30 June 2017, 13.6% (FIRB 2017) of Australian agricultural land was wholly or partly foreign-owned (with around half of the latter in majority Australian ownership). This compared with 5.9% of agricultural land being wholly or partly foreign-owned in 1984.

In general, there is little churn in cropping zone farmland ownership (Pritchard *et al.* 2012) which is typically around 4% per annum, suggesting most farmland is owned and operated over the long term. ABS (2018) indicates the average duration in farming is around 37 years. This longevity of familial ownership of farms gives rise to succession issues in farming being a potentially problematic business and social issue. However, farm families are having fewer children and provide their children with greater levels of education to facilitate some children pursuing careers outside of farming. However, ensuring within and across generational equity remains a general problem in farm succession.

When farmland is sold, the purchaser is usually another family farm business in the district or a corporate or family farm operation outside the district. Increasingly, family farms operate as a corporate business. Financial duress imposed by events such as the millennial drought provided investment opportunities for corporates.

Marketing arrangements

The institutional landscape has altered in conjunction with farming system and farm size changes.

- Firstly, Australia's National Competition Policy (Hilmer *et al.* 1993), actively applied after 1994, gradually, yet fundamentally, changed Australian agriculture. More than fifty statutory marketing or single desk marketing arrangements of agricultural commodities, including grains, were dismantled. For the grains industry, individual farmers became responsible for the production *and* marketing of their grains.
- Secondly, supply chain infrastructure shifted from being owned and operated by grower co-operatives into private ownership (GrainCorp, Viterro, Cargill), the exception being Cooperative Bulk Handling in WA. Most farmers, especially those in eastern states, increased

their investment in on-farm storage, in response to perceived marketing opportunities in the new deregulated environment.

- Thirdly, breeding of major crops was privatised and provision of advisory services shifted increasingly from the public sector into the private sector. Farmers increasingly received information electronically through mobile phones, portable computers and spread of the internet. As the volume of grain production grew, so did finances for grains R&D.

The need for access to real time information on markets has been accentuated by these changes and this is reflected in internet use. Gooday (2018) reports that, in 1998, 30% of farms owned a computer but 20 years later, that proportion was 90%. Broadacre farms report the major limitation of this technology to be internet access.

Education

Although the level of education in agriculture has been well below that of the general community, a phase of ‘catch-up’ has been underway since the 1980s, as Figure 6 shows. The data are skewed somewhat due to the different age distributions of the farm sector versus the general community, with farmers in 2017 having a greater average age of 57 (ABS 2018).

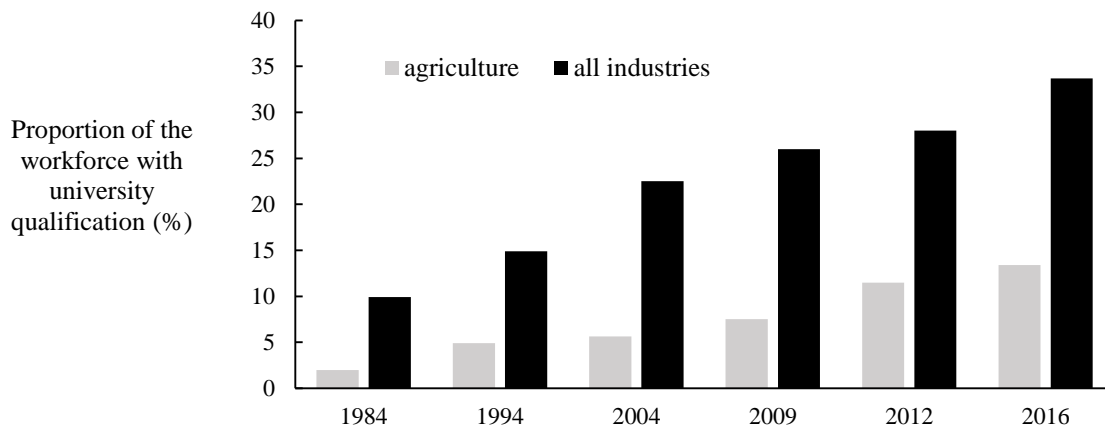


Figure 6. The trends in university education for the agriculture sector workforce in comparison with the Australian workforce (source: based on National Census data)

Further analysis specifically of the cropping industry provides clear trends of greater proportions of higher education attainment in its younger age groups and there being a smaller proportion without post-secondary qualification (Figure 7).

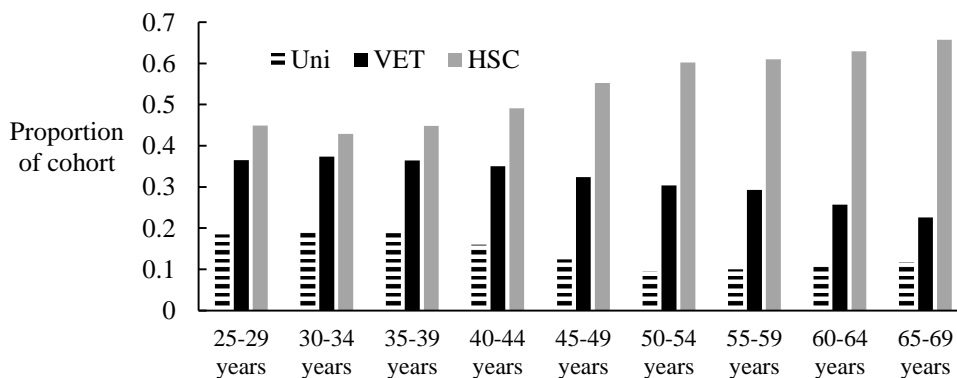


Figure 7. Highest education attainments (*i.e.* university, vocational education and training, or higher school certificate) by age cohort engaged in crop production in 2016 (Source: based on data from the National Census 2016)

During the period since the late 1980s there have been several changes in education provision and employment demands that influence farm production and management, additional to those mentioned earlier. These include:

- The closure of all professional public agriculture colleges in 1989 and their amalgamation with the university sector. Many vocational education and training (VET) level agricultural colleges also closed;
- Entry into the employment market for university graduates by distributors and resellers of agricultural goods and inputs;
- An increase in the leaving age from school from 15 to 17 years in most states in 2009;
- A decline in student numbers in agriculture from 1990 to 2012, due to the poor image of agriculture and ignorance of job and career opportunities in agriculture. However, university intake data show the number of students entering agriculture and related courses has increased each year since 2012 and, in 2016, is back at 2001 levels.

Conservation practices and farm businesses: an overview

The emergence and adoption of land and water conservation practices in Australia from the 1980s coincided with a rising community-wide sentiment regarding the need to care for rural landscapes. The National Landcare Program (NLP), initiated in 1989, encouraged farmers and other rural residents to share their knowledge, resources and their coordinated commitment to redress local or regional environmental issues (Lockie 2015). For over two decades, strong bipartisan political support for ‘landcare’ and sustainability issues persisted, allowing, for example, the national government’s ‘Caring for our Country’ program to support the Grains R&D Corporation to conduct a national survey of growers regarding their farming practices (Kearns and Umbers 2010). The survey was repeated in 2012, 2015 and 2016 (*e.g.* Umbers 2017) and complemented ABS agricultural censuses that occasionally have reported on farmers’ crop and soil management practices. The findings from these surveys reveal farmers’ adoption of the following conservation practices.

Tillage

In the early 1980s, along the south coast of WA, severe wind erosion on cultivated sandy soils reinforced the need for improved land care and prompted interest in reduced tillage that was increasingly feasible due to new increasingly effective and affordable herbicides (Crabtree 1990). WA, with its sandier soils, rapidly became the leading state for adoption of reduced tillage (RT), direct drilling (DD) and no-till (NT) (see Table 1 in Kearns and Umbers (2010) and Chapter 2). Farmer adoption of NT began to plateau in the late 2000s in most states except for NSW. By 2016, NT was commonplace across Australia, with Umbers (2017) reporting that almost three-quarters of the national crop area relied on NT.

The widespread adoption of NT, even in WA where adoption was most rapid, was not without problems and dissent. Crabtree *et al.* (2018) provide an insight into the range of issues and personalities that affected farmer uptake of NT in WA from 1990 to 2010. These authors acknowledge the dominance of NT but also concede that occasional tillage remained necessary for various reasons, including to:

- fix non-wetting soils (Hall *et al.* 2010; Roper *et al.* 2015);
- raise the pH of highly acidic subsoils (Flower and Crabtree 2011);
- manage herbicide-resistant weeds (Derksen *et al.* 1995, Ashworth *et al.* 2014);
- remove soil compaction layers or ‘hardpans’ (Hanza and Anderson 2003) and
- level paddocks.

Kirkegaard *et al.* (2014) point out that the impact of tillage systems on productivity involves a complex interaction between soil type, environment, yield potential and management system. For example, Armstrong *et al.* (2019) found tillage practice had little impact on productivity over 18 years at a site in Victoria where the soil had a naturally high structural stability.

No-till practices were typically part of a wider suite of changes in farm practices. It was the portfolio of changes in farm practices, rather than the sole uptake of NT that gradually transformed the nature of

farming systems in Australia. Accompaniments to NT were the following changes in farm practices. Whenever adoption trends or figures are quoted in the following sub-sections the source is Umbers (2017).

Precision agriculture

Bramley and Trengove (2013) outline that precision agriculture (PA) also encompasses a range of technologies. These researchers review applications of PA to Australian agriculture, noting that PA is principally applied in the grains, winegrape, sugarcane, cotton and potato industries. One component of PA is controlled traffic farming (CTF) that has followed farmer adoption of NT (Tullberg *et al.* 2007, see Chapter 6)).

Currently around 30% of Australia's grain crops area is subject to CTF, with higher rates of adoption occurring in NSW and Qld. CTF requires alignment of farm machinery wheels such that they all follow the same path in paddocks, leaving large areas of soil un-trafficked and less prone to compaction that can be problematic, especially on clay soils. The increased size and weight of some farm machinery exacerbates soil compaction (Lamande and Schjonning 2011). Hamza and Anderson (2005) show that just one pass of machinery can negatively affect all soil characteristics and crop responses. Water infiltration rate is greater in un-trafficked soils (Chyba 2012) by as much as 400% (Chamen 2011). Kingwell and Fuchsichler (2011) used whole-farm modelling to assess the profitability and role of CTF in different Australian farming systems. They found the most valuable aspect of CTF was its beneficial impact on the yield and quality of crops grown on soils most subject to compaction.

Adoption of autosteer, a component of CTF, occurred rapidly and is now a standard feature of most modern farm equipment. This technology currently is used on more than 85% of the cropped area nationally and over 90% of the crop area many regions of WA and SA. Of far less interest to farmers is variable rate technology (VRT), used on less than 7% of the national crop area. Robertson *et al.* (2012) examined VRT adoption across Australia and found the main constraints to adoption were technical issues with equipment and software, access to service provision and the incompatibility of equipment with existing farm operations.

Yield mapping, often a component of VRT, is used on about 35% of the nation's crop area. Yield mapping can involve simple monitoring of crop performance or the facilitation of crop input decisions, or as a crop diagnostic tool. McBratney *et al.* (2005) point out that although tools like yield mapping generate much data, an impediment to their utility is often the absence of accompanying decision-support systems. In other words, in order for farmers to make better decisions, the yield mapping data must be analysed and converted into information that unambiguously facilitates improved decisions from which the farm business will benefit. Robertson *et al.* (2012) also reported this lack in decision-support software.

The final technologies that form part of the suite of PA technologies (Jochinke *et al.* 2007) are remote sensing technologies such as electromagnetic sensing (most commonly being EM38 soil mapping and normalised difference vegetation index (NDVI) mapping of crop and pasture growth). EM38 soil mapping measures relative levels and depths of certain soil qualities. NDVI data helps identify plant growth and biomass levels (Abuzar *et al.* 2013). Nationally, adoption of these technologies is low, applied on only around 5% of the crop area.

Crop sequencing

The impact of crop sequences on yields of following wheat phases has been studied by Seymour *et al.* (2012) and more fully by Angus *et al.* (2015). Given the wheat dominance of farming systems in Australia it is important to know the nature and magnitude of yield effects in crop sequences. These researchers generally found that the uplift in wheat yields was greatest when the preceding crop was a pulse. In order of lessening impact was canola or linseed, followed by oats. The mean additional wheat yield after oats or oilseed break crops was independent of the yield level of the following wheat crop whereas the wheat yield response to legume break crops was not clearly independent of yield level. The yield of wheat after two successive break crops was 0.1-0.3 t/ha greater than after a single break crop.

In a sequence of wheat phases after a break crop the yield benefit decayed such that after the second consecutive wheat crop any yield increase was negligible in most situations.

Robertson *et al.* (2010) and Lawes and Renton (2015) showed that although inclusion of break crops improved farmers' potential profits, in practice farmer adoption of break crops was often less than might otherwise be expected. Harries *et al.* (2015) surveyed farmers' use of break crops over four years and concluded that crop and pasture sequences had changed, with canola as the preferred break crop. Most growers' motivations for selecting break crops involve weed management, disease management, crop nutrition and relative profitability as a cash crop.

Liming

Although rare up until the mid-2000s, apart from in southern NSW, the practice of liming has been rapidly adopted (Umbers 2017). The area of crop area limed and the rate of application of lime per hectare have both increased in the decade prior to 2016. The rationale for liming and the practicalities of how and when to lime (Gazey and Davies 2009) are now well known. The profitability of liming differs according to individual circumstances, with yield gaps due to acidity being more concentrated spatially in the high-rainfall regions of WA, Victoria and NSW (Orton *et al.* 2018). Cost benefit analyses of the amelioration of acidity, traffic hardpans, transient salinity and sodicity in various regions of WA reveal that addressing soil acidity is often the best option (Petersen 2017).

Other

Other accompaniments to no-tillage include soil water monitoring, fallowing and stubble management. Measurement of plant available water at planting is now commonplace in many parts of NSW and Qld. Umbers' (2017) national survey of grain producers revealed that almost two-thirds of growers used some fallow in their crop sequences. Up to around 10% of crop area is fallowed, mostly to assist with weed control, and use of fallow is more popular in northern NSW and southern Qld. Stubble retention, through to sowing, occurs on approximately 60% of the nation's crop area whilst stubble burning now occurs on less than 10% of the crop area. Machinery improvements now facilitate management of larger stubble loads at seeding.

Current opportunities and challenges affecting conservation farming

Opportunities

Conservation farming and the plethora of its associated technologies currently offer farmers many advantages and further opportunities are emerging (Chandra 2018). The in-built intelligence in machinery allows farmers to more confidently rely on unskilled labour. Often, unskilled, casual labour (*e.g.* backpackers) is far cheaper and more available to farm businesses than skilled labour. Skilled labour in rural regions is relatively scarce and can be expensive, especially in states with buoyant mining sectors that attract workers away from the farm sector. In the near future, autonomous vehicles will further facilitate reliance on conservation farming (Pawel *et al.* 2018, Gan and Lee 2018) and help lessen costs in some parts of agricultural supply chains.

In the current period of low interest rates and relatively high equity levels of farm businesses, especially in states less affected by drought and associated production volatility, affording machinery upgrades and land leases or purchases to capture size economies facilitates faster adoption of evolving crop production technologies. Embedded in these machinery-based technologies will increasingly be data capture and data analysis systems that facilitate crop management (Fulton and Darr 2018). Spatially targeted use of inputs as accompaniments to conservation tillage will likely become sufficiently lucrative to be commonplace.

The incoming generation of farmers and farm managers will likely be more educated and potentially more skilled as business managers than previous generations. They will probably have greater competence in labour and information management, business analysis and grain marketing. Many will have wider social networks and will have spent time away from the family farm to develop skills and

knowledge that complement farm management and ownership. Similarly, their family partners are likely to be better educated, further supporting farm business management and household decision-making. This greater human capital will facilitate the assessment and uptake of technologies and practices that will complement conservation farming.

Challenges

Although machinery intelligence provides opportunities, it also represents challenges, especially over who owns the data and the ability to transfer data across platforms. The Productivity Commission (2017) has considered rights to access digital information and potential impacts on competition. They concluded that this issue requires urgent attention by governments to maximise the economic gains potentially available from emerging digital technologies, and to reduce the risk of damage to competition. They have proposed a range of measures including a new comprehensive data right for consumers and small businesses.

Studies by Harries *et al.* (2015) and Armstrong *et al.* (2019) found no evidence that the observed sequences of crops, underpinned by conservation farming, were fundamentally unsustainable. Hence, conservation farming in the future may be resilient to most biological challenges. Other challenges, however, may unmask the sustainability of some aspects of conservation farming. The social requirement to not use certain chemicals or employ particular practices may challenge conservation farming. A swathe of social issues may in general weaken the social attractiveness of large-scale conservation farming. Issues of rural de-population, lack of diversity in rural employment, family stress, availability and affordability of education and health services in rural regions may be among the more challenging issues facing farm families. Often in farming it is not solely the biological challenges that inhibit success but rather the failure to appropriately respond to the social and economic challenges of farming.

Conservation farming has encouraged farm businesses to become more crop dominant and larger in physical and financial size. A challenge associated with these trends is that the businesses in some regions are potentially very exposed to financial damage from unforeseen prolonged drought. Drought can have long-term business consequences if the farmer's capacity to finance cropping and livestock operations during recovery is impeded (Lawes and Kingwell 2012). Kingwell (2002) observed when examining the structure of crop-dominant farming systems in Australia: "a switch into more cropping means a more capital-intensive business with greater demands for working capital. With such a business structure, a few poor seasons, especially if coupled with poor prices, can rapidly cripple a farm business". The prospect of subdued grain prices, or sustained downward pressure on grain prices, is a likely prospect over the next decade in Australia due mostly to the large volumes of affordable grains produced in the Black Sea region and in South America (Kingwell 2019). An associated challenge, as farms increase in size, are diseconomies of size when, in spite of technology and information aids, the farm manager and staff eventually are impeded in their ability to fully manage the business and its operations. Contrarily, greater crop dominance, supported by ever higher yielding crop varieties, reduces the unit costs of the bulk handling of grain thereby facilitating the competitive pricing of grain to end users. However, due to climate-induced production volatility, crop supply chains must be highly flexible to accommodate a range of sizes of grain harvests.

Increased crop dominance, supported by conservation farming, has also led to greater reliance on crop protection products. In addition, stubble retention and removal of cultivation is generating its own set of emerging issues in pest, weed and disease control. When coupled with rising direct costs (*e.g.* seed, fertiliser and crop protection products) of crop production, ensuring crop production remains profitable in the face of climate variability is a mounting challenge.

Broadacre farms are becoming larger and fewer. They are increasingly reliant on a range of professional services and external sources of innovation and research services. A challenge to these farm businesses and their service providers is how to ensure they have ongoing access to well-trained competent and affordable service providers. Answering this challenge is no simple task. Agricultural education in universities has historically been the foundation of many professional services provided to farmers.

However, in many universities, agriculture no longer has separate faculty status (Barlow *et al.* 2016) and undergraduate courses that solely focus on Australian agricultural science or agribusiness management are increasingly rare. These trends reduce the likelihood of readily available, competent personnel well versed in Australian agriculture to serve the advisory and research needs of Australian broadacre farmers. Hence, securing the future provision of competent support services to Australian farm businesses may in some regions become increasingly difficult. Such personnel are most likely to be educated in those institutions with rural campuses (Pratley and Crawley 2018).

Furthermore, many state governments have reduced support for their agricultural agencies and associated research. These agencies were often the training grounds for advisory services to farmers. Reduced training and restricted initial employment opportunities in these agencies may adversely affect the quality and quantity of future service provision to farm businesses. Moreover, infrastructure, education and social service provision in rural regions is often a poor cousin to urban investments. This reduces the attractiveness of employment in the agricultural services sector. To the extent that development and uptake of technologies and practices complementary to conservation farming depend on availability of reputable advisory and research providers, then the broadacre farm sector may not be served as well in the future.

References

- Abuzar M, Whitfield D, McAllister A, Lamb G, Sheffield K, O’Connell M (2013) Satellite remote sensing of crop water use in an irrigation area of south-east Australia. 2013 IEEE International Geoscience and Remote Sensing Symposium – IGARSS, Melbourne, VIC, 2013, pp 3269-327
- Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L, Peoples MB (2015) Break crops and rotations for wheat. *Crop and Pasture Science* **66**, 523-552
- Armstrong RD, Perris R, Munn M, Dunsford K, Robertson F, Hollaway GJ, O’Leary GJ (2019) Effects of long-term rotation and tillage practice on grain yield and protein of wheat and soil fertility on a Vertosol in a medium-rainfall temperate environment. *Crop and Pasture Science* **70**, 1-15
- Ash AJ, O’Reagan P, McKeon P and Stafford-Smith M (2000) Managing climate variability in grazing enterprises: a case study of Dalrymple Shire, north-eastern Australia. In (Eds. G.L. Hammer, N. Nichols and C. Mitchell) “Application of Seasonal Climate Forecasting in Agricultural and Natural Ecosystems” pp 253-270 (Dordrecht: Kluwer)
- Ashworth MB, Walsh MJ, Flower KC Powles SB (2014) Identification of the first glyphosate-resistant wild radish (*Raphanus raphanistrum* L.) populations. *Pest Management Science* **70**, 1432-1436
- Australian Bureau of Statistics (2018) Agricultural Commodities, Australia, 2016-17. Catalogue 7121.0 www.abs.gov.au/ausstats/abs@.nsf/latestProducts/7121.0Media%20Release%202016-17?OpenDocument
- AWI (2018) Sheep numbers by State. www.wool.com/market-intelligence/sheep-numbers-by-state/
- Barlow S, Kingwell R, Pratley J, Keating B (2016) Innovation in Australia’s agrifood systems: Are Australian universities ready for the next challenge? *Farm Policy Journal* **13**, 15-24
- Bramley R, Trengove S (2013) Precision agriculture in Australia: present status and recent developments. *Engenharia Agrícola* **33**, 575-588
- Chamen T (2011) The effects of low and controlled traffic systems on soil physical properties, yields and the profitability of cereal crops on a range of soil types. PhD thesis. Cranfield University, School of Applied Sciences
- Chandra, R (2018) FarmBeats: Automating data aggregation. *Farm Policy Journal* **15**, 7-16
- Chyba J (2012) The influence of traffic intensity and soil texture on soil water infiltration rate. MSc diss. Harper Adams University, Department of Engineering
- Crabtree WL (1990) Toward better minimum tillage for south-coastal sandplain soils. Department of Agriculture Western Australia. Division of Resource Management. Technical Report 111
- Crabtree WL, Flower K, Bligh K, Siddique K, Fogarty J (2018) Revolutionary no-tillage adoption in Western Australia from 1990-2010, Working Paper, School of Agriculture and Environment, University of Western Australia
- Derksen D, Thomas A, Lafond G, Loepky H and Swanton C (1995) Impact of post-emergence herbicides on weed community diversity within conservation-tillage systems. *Weed Research* **35**, 311-320
- Edwards J, Umbers A and Wentworth S (2012) Farm Practices Survey Report 2012 (Grains R&D Corporation, Kingston, ACT)
- Flower KC, Crabtree WL (2011) Soil pH change after surface application of lime related to the levels of soil disturbance caused by no-tillage seeding machinery. *Field Crops Research* **121**, 75-87

- Foreign Investment Review Board (2016-17) Annual Report. Commonwealth of Australia ISSN 0155-0802
- Fulton, J, Darr, M (2018) GPS, GIS, guidance, and variable-rate technologies for conservation management. In (Eds. J Delgado, G Sassenrath, T Mueller) "Precision Conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation" pp 65-81 Agronomy Monographs 59 American Society of Agronomy and Crop Science Society of America, Inc.
- Gan, H, Lee, W (2018) Development of a navigation system for a smart farm. IFAC-PapersOnLine **51**, 1-4
- Garnaut R, Bennett S, Price R (1993) Wool: Structuring for global realities. Report of the Wool Industry Review Committee to the Minister for Primary Industries and Energy, 232pp
- Gazey C, Davies S (2009) Soil acidity: A guide for WA farmers and consultants. Bulletin 4784 (Department of Agriculture and Food: WA)
- Gooday P (2018) Farm performance: Latest trends and issues affecting ICT use on farms. Outlook 2018. www.agriculture.gov.au/abares/outlook/program/gooday
- Hall DJM, Jones HR, Crabtree WL, Daniels TL (2010) Claying and deep ripping can increase crop yields and profits on water repellent sands with marginal fertility in southern Western Australia. *Australian Journal of Soil Research* **48**, 178-187
- Hamza MA, Anderson WK (2003) Responses of soil properties and grain yields to deep ripping and gypsum application in a compacted loamy sand soil contrasted with a sandy clay loam soil in Western Australia. *Australian Journal of Agricultural Research* **54**, 273-282
- Hamza MA, Anderson WK (2005) Soil compaction in cropping systems. A review of the nature, causes and possible solutions. *Soil and Tillage Research* **82**, 121-145
- Harries M, Anderson GC, Hüberli D (2015) Crop sequences in Western Australia: what are they and are they sustainable? Findings of a four-year survey. *Crop and Pasture Science* **66**, 634-647
- Hilmer F, Rayner M, Taperell G (1993) "National Competition Policy" (Australian Government Publishing Service: Canberra)
- Howden M, Ash A, Barlow S *et al.* (2003) An overview of the adaptive capacity of the Australian agricultural sector to climate change – options, costs and benefits. (CSIRO Sustainable Ecosystems, Canberra)
- Jochinke DC, Noonon BJ, Waschmann NG Norton RM (2007) The adoption of precision agriculture in an Australian broadacre cropping system – challenges and opportunities. *Field Crops Research* **104**, 68-76
- Kearns S, Umbers A (2010) 2010 GRDC Farm Practices Baseline Report www.grdc.com.au/data/assets/pdf_file/0022/209740/grdc-farm-practices-baseline-full-report-july-2010.pdf
- Keogh M, Julian C (2014) Optimising future extension systems in the Australian grains industry: Part 1. (Australian Farm Institute, Sydney)
- Kingwell R, Anderton L, Islam N *et al.* (2013) Broadacre farmers adapting to a changing climate. Final Report to National Climate Change Adaptation Research Facility, Gold Coast www.nccarf.edu.au/publications/broadacre-farmers-adapting-changing-climate
- Kingwell R (2002) Issues for Farm Management in the 21st Century: A View from the West. *Agribusiness Review* **10**, Paper 6. ISSN 1442-6951
- Kingwell R (2006) Climate change in Australia: agricultural impacts and adaptation. *Australian Agribusiness Review*, Paper 1, **14**, 30. ISSN 1442-6951
- Kingwell R (2011) Managing complexity in modern farming. *Australian Journal of Agricultural and Resource Economics* **55**, 12-34
- Kingwell R (2019) International grain supply chains: issues and implications for Australia. *AARES Annual Conference Melbourne Convention and Exhibition Centre*
- Kingwell R, Fuchsbichler A (2011) The whole-farm benefits of controlled traffic farming: An Australian appraisal. *Agricultural Systems* **104**: 513-521
- Kirkegaard JA, Conyers MK, Hunt JR *et al.* (2014) Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems and Environment* **187**, 133-145
- Lamande M, Schjonning P (2011) Transmission of vertical stress in a real soil profile: Part II: Effect of tyres size, inflation pressure and wheel load. *Soil and Tillage Research* **114**, 71-77
- Lawes RA, Kingwell RS (2012) A longitudinal examination of business performance indicators for drought-affected farms. *Agricultural Systems* **106**, 94-101
- Lawes R, Renton M. (2015) Gaining insight into the risks, returns and value of perfect knowledge for crop sequences by comparing optimal sequences with those proposed by agronomists. *Crop and Pasture Science* **66**, 622-633
- Lockie S (2015) Australia's agricultural future: the social and political context. Report to SAF07 – Australia's Agricultural Future Project (Australian Council of Learned Academies: Melbourne)
- McBratney A, Whelan B, Aneev T, Bouma J (2005) Future directions of precision agriculture. *Precision Agriculture* **6**, 7-23

- Orton T, Mallawaarachchi T, Pringle M *et al.* (2018) Quantifying the economic impact of soil constraints on Australian agriculture: A case-study of wheat. *Land Degradation and Development* (early view)
- Pawel, K, Miroslaw, Z, Marek *et al.* (2018) Evaluation of the use of autonomous driving systems and identification of spatial diversity of selected soil parameters. *Applications of Electromagnetics in Modern Techniques and Medicine (PTZE)*, Račławice pp 121-124
- Petersen E (2017) Economic analysis of the impacts and management of subsoil constraints. Report for the Grains Research and Development Corporation funded project: DAW00242 Subsoil constraints – understanding and management.
- Pratley JE, Cornish PS (1985) Conservation farming – a crop establishment alternative or a whole farm system? *Proceedings of 3rd Australian Agronomy Conference* Hobart, 95-111
- Pratley JE, Rowell DL (1987) From the First Fleet – Evolution of Australian Farming Systems. In (Eds. PS Cornish, JE Pratley) “Tillage – New Directions in Australian Agriculture” (Inkata Press: Melbourne)
- Pratley J and Crawley N (2018) Graduate destinations in agriculture. *Agricultural Science* **29/30**, 6-15
- Pritchard B, Neave M, Hickey D, Troy L (2012) Rural Land in Australia: A framework for the measurement and analysis of nationwide patterns of ownership change, aggregation and fragmentation. RIRDC Publication No. 12/038
- Productivity Commission (2017) Data Availability and Use: Overview and Recommendations, Report No. 82, Canberra.
- Renton M, Lawes R, Metcalf T, Robertson M (2015) Considering long-term ecological effects on future land-use options when making tactical break-crop decisions in cropping systems. *Crop and Pasture Science* **66**, 610-621
- Robertson MJ, Lawes RA, Bathgate A *et al.* (2010) Determinants of the proportion of break crops on Western Australian broadacre farms. *Crop and Pasture Science* **61**, 203-213
- Robertson MJ, Llewellyn RS, Mandel R *et al.* (2012) Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. *Precision Agriculture* **13**, 181-199
- Roper MM, Davies SL, Blackwell PS *et al.* (2015) Management options for water-repellent soils in Australian dryland agriculture. *Soil Research* **53**, 786-806
- Seymour M, Kirkegaard JA, Peoples MB *et al.* (2012) Break-crop benefits to wheat in Western Australia – insights from over three decades of research. *Crop and Pasture Science* **63**, 1-16
- Sheng Y, Davidson A, Fuglie K, Zhang D (2016) Input substitution, productivity performance and farm size. *Australian Journal of Agricultural and Resource Economics* **60**, 327-347
- Sheng Y, Chancellor W (2018) Exploring the relationship between farm size and productivity: Evidence from the Australian grains industry. *Food Policy* doi.org/10.1016/j.foodpol.2018.03.012
- Stephens D (2016) South-west Western Australia is losing its Mediterranean climate. GRDC Research Updates, Perth
- Stephens D (2017) Australia’s changing climate: Implications for wheat production. Guest blog for AEGIC. www.grainsinnovation.org/blog/2017/10/2/australias-changing-climate-implications-for-wheat-production
- Tullberg JN, Yule DF and McGarry D (2007) Controlled traffic farming – from research to adoption in Australia. *Soil and Tillage Research* **97**, 272-281
- Umbers A (2017) Farm Practices Survey Report 2016 (Grains Research & Development Corporation: Canberra)

Chapter 4

Evolution of conservation agriculture in winter rainfall areas

John Kirkegaard and Harm van Rees

Introduction

The southern Australian broad-acre agricultural region lies south of latitude 32°S with mainly winter rainfall in the south and west, grading to equi-seasonal in the northeast region extending into central NSW (Figure 1). The major point of contrast with systems to the north (Chapter 5) is that summers in the south are generally too dry and hot for reliable production of dryland summer crops, and most farms, though a diminishing number, retain livestock enterprises. As a result, the systems comprise annual winter crops either continuous, or phased with annual or perennial pastures (2-5 years) grazed by livestock. The soils in the vast majority of the zone are either naturally deficient or depleted in the major crop nutrients (P and N) (Isbell 2002), and average annual rainfall is generally low (<550 mm) and extremely variable by world standards. As a consequence, extensive agricultural production involves significant attention to the management of business risk, due to the probabilistic nature of the outcomes of most important management decisions.

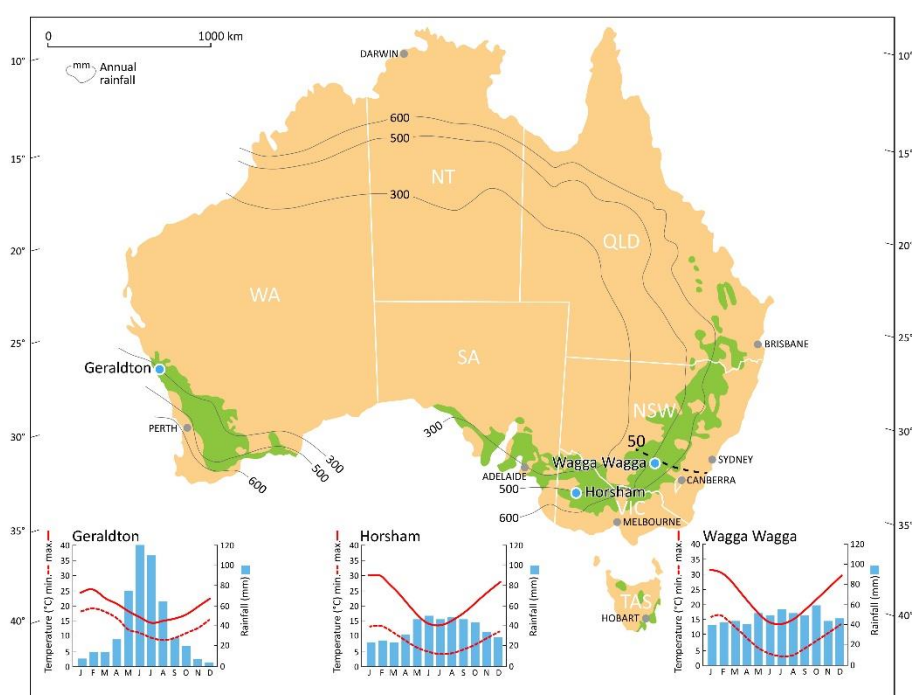


Figure 1. The distribution of broad-acre crop production in Australia (green). The southern mixed farming zones discussed in this chapter are those areas in south-eastern and Western Australia which receive 300-600 mm rainfall annually, with >50% falling during winter months (below dashed line). Patterns of rainfall and temperature are shown for three contrasting centres that represent diverse zones from which farm case studies for mixed farms and crop specialists have been prepared

The evolution of the farming system in southern Australia, from traditional mixed crop-livestock systems towards more intensive cropping, was already underway in 1987 when *Tillage – New Directions in Australia Agriculture* was published (Poole 1987). During the late 1980s the impact on the soil resource of more frequent tillage, shorter pasture and fallow periods, successive cereal crops and the expansion of cropping onto poorly structured soils was already apparent, and the impetus for the comprehensive review of crop establishment systems at the time. In the subsequent period, both the

production (yield) and productivity (yield per unit input) growth in agriculture were exceptional at around 2% p.a. in the period prior to the millennium drought (2002 to 2010), which reflected both improved crop varieties and the adoption of a range of technological advances in production (Kirkegaard *et al.* 2011). The productivity gains resulted from the increased adoption of arguably the most sustainable practices since cropping had commenced, including reduced and no-till farming systems, improved weed control using herbicides, tactical and efficient application of fertiliser, adoption of broad-leaf rotation crops and better understanding and amelioration of soil constraints including soil acidity and sodicity (Kirkegaard *et al.* 2011).

The relative frequency of crops and pastures, and the rotations practised, vary greatly between regions and individual farms in southern Australia. Around 80% of the area cropped each year is sown to wheat and other cereals, but canola and a range of winter grain legumes are now common (ABARES 2018). The predominance of cereals across the cropping zone reflects their contribution to farm profits, reduced risk and ease of marketing. The choice of other broad-leaf crops to include in the crop sequence is often based on their benefits to following cereal crops (*e.g.* weed and disease control, N contribution), although they can also be profitable in their own right (Robertson *et al.* 2010, Angus *et al.* 2015). Long fallows (plant-free for 12-18 months) were traditionally used in some semi-arid areas to conserve water and N for following crops and while the area diminished with the adoption of no-till farming systems, they are now being reconsidered in areas experiencing a drying climate (Oliver *et al.* 2010, Cann *et al.* 2019). The area of perennial pastures, particularly of lucerne (*Medicago sativa*) has increased on non-alkaline soils at the expense of annual pastures such as subterranean clover (Angus *et al.* 2001), while on alkaline soils in the Mallee vetch has expanded at the expense of medic which suffered in the Millennium drought.

A strong focus in Australian broad-acre systems has been to capture, store and use rainfall as efficiently as possible to support crop growth, while managing inputs (including N) to achieve the water-limited productivity potential and quality requirements (Kirkegaard *et al.* 2014). Benchmarking production against potential to stimulate improvement has been a powerful tool at both the crop (French and Schultz 1984) and farm level (Cary 1994). Inadequate nitrogen supply remains one of the major current causes of yield gaps in southern Australian systems (Hochman *et al.* 2018) as N application can be risky in seasons with limited spring rainfall due to ‘haying-off’ (van Herwaarden *et al.* 1998). On average, N application rates are low (approx. 40 kg/ha N), but reliance on fertiliser N has increased as pasture area declined (Angus 2001).

The productivity of Australian broad-acre agriculture has been the subject of considerable review prompted by an apparent recent slow-down in productivity trends, and food security concerns in the face of climate change (Fischer 2009, Hochman *et al.* 2009, Keating and Carberry 2010, Robertson *et al.* 2016). The recent slowdown in productivity has been variously blamed on drought (Hochman *et al.* 2017), reduced research investment and decreasing impact of new technologies (Mullen 2010) but the maintenance of production in the face of a climate induced reduction in yield potential of 27% in the period 1990 to 2015 suggests significant uptake of new technologies on-farm continues (Hochman *et al.* 2018). The success of agriculture in the southern Australian cropping zone has not come without the emergence of environmental problems such as soil acidification, dryland salinity, compaction and herbicide resistance in weeds (Kirkegaard *et al.* 2011). Addressing these issues, while maintaining crop yields, is crucial for the future.

Numerous previous reviews and subsequent chapters in this book deal in detail with the various technological innovations that have underpinned the evolution of southern farming systems during the last 30 years, and the economic, environmental and social changes that influenced their adoption. As a consequence, following a brief summary of the science and innovation underpinning those changes, a large part of this chapter is devoted to case studies on commercial farms across three diverse regions of southern Australia (Figure 1). Using crop intensification as a theme, we contrast farms in three zones that have either retained mixed crop-livestock enterprises or moved to crop-only operations to capture a brief, but important record of systems evolution at the farm level.

Science underpinning change – lessons from long-term studies

Prior to 1987 when *Tillage* was published, a convergence of enabling factors in the 1970s formed the potential for the revolution foreseen by agronomists in that publication. These were:

- Government and public focus on improved natural resource management stimulated by reports and evidence of land degradation (*e.g.* dust storms in Melbourne in 1983);
- Economic drivers related to the diminishing terms of trade with the imperative to reduce fuel and other input usage; and
- Key enabling technologies (already the subject of considerable review in 1987) including herbicides for weed control, machinery developments to enable crop establishment with less tillage and retained stubble, and profitable broad-leaf break crops.

In his review of tillage practices for winter rainfall areas in that book, Poole (1987) wisely noted that “...*Even the most promising innovations will bring attendant problems which will require solution by science if the new systems are to be embraced by farmers*”

Building on this demonstrably accurate prophecy, and as background to the farm case studies from southern Australia later in this Chapter, we briefly consider the evolution of the three pillars of CA in southern Australia – reduced tillage, retained crop residues, and diverse rotations. These elements are intimately linked and interactive in farming systems, but for ease of discussion, we briefly consider developments in each separately.

Tillage

Comprehensive reviews of the evolution of reduced tillage systems in Australia can be found elsewhere (Llewellyn *et al.* 2012, see also Chapter 2). The general trend initially was towards a reduced number of cultivations prior to seeding, reduced soil disturbance with each pass, and ultimately to one pass at seeding (direct-drilling DD), and finally reduced soil disturbance using no-till (NT, tynes) or zero-till (ZT, discs) during the seeding process itself (Umbers 2017). The evolution of machinery technology and herbicide to facilitate the transition is discussed in Chapter 6 and 10 respectively. The economic benefits in reduced fuel, time, machinery wear and labour were obvious, as were the reductions in the risk of soil erosion and improved water conservation, but reliable crop establishment and the maintenance of yield were clearly desirable.

The significant benefits in crop yield potential of the earlier-sown, direct-drilled crops we acknowledge today were often not expressed in long-term agronomic experiments (Kirkegaard 1995). This was partly due to the common sowing dates used for all treatments in the experiments, especially where crop establishment in direct-drilled treatments matched those in cultivated treatments. In drier environments, or on structurally unstable and degraded soils, improvements in soil structure and water conservation may have translated into yield benefits, but benefits from RT or NT treatments in long-term experiments were rare in southern Australia up to the mid-1990s. Kirkegaard (1995) reviewed all of the data from 33 medium and long-term experiments in Australia (26 in southern Australia) and found the yield benefit of DD *vs* RT wheat across all regions ranged from -0.18 to +0.06 t/ha. Subsequent (Heenan *et al.* 2004) and more recently published long-term experiments (Armstrong *et al.* 2019) confirmed the small or even negative impacts of RT or NT treatments where common sowing dates were used. While the undisputed environmental, economic and timeliness benefits underpinned farm adoption (Llewellyn *et al.* 2012), it remained puzzling to many soil and plant scientists why improvements in most of the ‘soil health’ indicators demonstrated in RT and NT treatments (*e.g.* aggregate stability, earthworms, macro-porosity, microbial biomass) did not translate to improved yield (Watt *et al.* 2006, Kirkegaard *et al.* 2014).

Poor early crop vigour had always been a common feature under NT with complex interactive soil physical and biological interactions involved (Simpfendorfer *et al.* 2002), though much of that could be offset in practice by the earlier sowing opportunity. Interactions with the other components of the CA system (stubble retention and crop sequence) under different soils and climates also complicated attribution of effects to tillage alone (Flower *et al.* 2017). Kirkegaard and Hunt (2010) used simulation

modelling to demonstrate the importance of the synergy between different agronomic innovations within the cropping system. For the Mallee farm considered, NT (not cultivating the soil and retaining stubble) generated only a small predicted average yield improvement if adopted alone (from 1.6 to 1.8 t/ha), but contributed to a large yield improvement (from 1.6 to 4.2 t/ha) as part of a package of synergistic innovations including improved rotation, summer fallow weed control and earlier sowing. The focus on ‘non-disturbance’ in NT systems often overlooked these true drivers of the yield benefits, but the cost savings and soil protection without yield penalty was a powerful driver for adoption (Llewellyn *et al.* 2012). Recently machinery costs have been scrutinised as a significant financial burden in risky environments (O’Callaghan 2014), and stepwise adoption and upgrading is a feature of many successful farms (see Case Studies below).

Increasingly dry autumns and the trend towards earlier sowing in recent years (Chapter 18) has provided new incentive for systems that can maintain surface soil water to capture early sowing opportunities (*e.g.* high stubble retention with disc seeding). At the same time, some strategic tillage may be required to deal with emerging issues such as herbicide resistant weeds, nutrient and pH stratification and compaction (Chapter 7). Adoption rates for ‘one pass’ tillage (ZT, NT and DD) between 2008 and 2016 have remained stable at 80 to 90% of cropped area (Umbers 2017) suggesting Australian tillage systems have matured towards pragmatic approaches tailored to specific conditions (Table 1).

Table 1. Evolution of the three current principles of conservation agriculture practice and suggested further principles (*italics*) needed to support sustainable intensification (from Giller *et al.* 2015)

CA principles (and related practices)	Past (protective)			Present (prescriptive)	Future (pragmatic)
1. Less tillage	multiple pass inversion deep	reduced pass less inversion	one pass (tine)	zero till (no disturbance)	strategic tillage
2. Retain residues	remove all early burn	later removal later burn	partial retention	full retention	managed thresholds
3. Rotation	monocultures	fallows	rotations	rotation	flexible sequences
<i>Nutrient balance</i>	<i>Exploitative Supplemental</i>			<i>None prescribed</i>	<i>Replacement</i>
<i>Pest management</i>	<i>Cultural Chemical</i>			<i>None prescribed</i>	<i>Integrated</i>

Stubble retention

The value of retaining crop residues to reduce wind and water erosion has been recognised in southern Australia since the 1920s, but by the late 1980s when *Tillage* was published, widespread adoption of stubble retention had barely commenced (Felton *et al.* 1987). The fundamental principles of water conservation were well advanced, yet the costs of stubble retention clearly outweighed the benefits at that stage, and research focused on managing crop residues to capture the benefits, while minimising constraints. The range of potential constraints in stubble-retained systems then included crop establishment, crop nutrition, and pest, weed and disease control and this has remained remarkably consistent over the subsequent 30 years (Scott *et al.* 2010, 2013). A recent 5 year research investment by the GRDC (2014-2018) to maintain profitability in stubble retained systems focused on many of the same issues, though significant improvement is clear given adoption rates of retained stubble through to planting are 60% nationally, and early stubble burning is now less than 4% of cropped area (Umbers

2017). A comprehensive account of the pathways to improved residue management is provided in Chapter 13, but a brief summary for southern Australia is provided here.

Steady improvements in machinery design, much of it involving innovative farmers, was critical to achieve adequate crop establishment in retained crop residues. These have included moving tyne ranks further apart, widening sowing rows, increasing break-out pressure, attaching clearing mechanisms to brush stubble aside, or moving to disc openers able to cut through heavier stubble. Matching harvest and post-harvest residue management to the seeding equipment available includes considerations of harvest height, and the level of residue spreading. In modern systems, harvest weed seed control (HWSC) for weed control often concentrates residues into rows for burning or onto wheel tracks for targeted spraying. The advent of satellite guidance and controlled traffic farming has facilitated inter-row sowing and further opportunities to establish crops in retained stubble.

Crop residues are invariably retained throughout most of the fire-prone summer in southern Australia as permits are required to burn, and they may be grazed on mixed farms to capitalise on spilt grain and new straw. A retained threshold of 2 to 3 t/ha minimises erosion and maximises water infiltration, while 4 to 5 t/ha of residue generally causes few problems for most current seeding equipment. Advances in post-harvest stubble management, new seeding technology and inter-row sowing have reduced the need for residue reduction, though circumstances invariably arise where pragmatic decisions to reduce weed, pest or disease-infested stubble loads make sense. Diversifying crops and practices provides the platform for success, and being flexible and pro-active to ensure stubble does not compromise timely and successful crop establishment is critical. Maintaining crop residues under continuous cropping is important as they are the major source of C input, though predicted increases in C-sequestration appear overstated (see Chapter 16). Maintaining more residue for longer near the surface in early autumn has become a focus for many farmers to capitalise on earlier and timely sowing, though dry sowing by calendar which can be problematic for weed control, is now also widespread in southern Australia (Chapter 18).

Crop diversity

Until the 1980s, southern Australia grew mainly cereals (mostly wheat, with some barley) in rotation with annual grass-legume pastures and fallow, with some areas of early-sown oats for sheep (Figure 2). In the two decades from the mid-1980s, crop area doubled (at the expense of pasture and fallow) and sheep numbers halved, and many farms or parts of farms are now continuously cropped (Kirkegaard *et al.* 2011). The degree of intensification and the main drivers (*e.g.* financial, social, logistic, bio-physical) vary between regions and with individual businesses (see Case Studies). The intensification of cropping was facilitated in part by the introduction in the 1960s and 70s of a range of legume and oilseed break crops, most notably lupins in Western Australia (Seymour *et al.* 2012), and canola across southern Australia in the 1990s (Kirkegaard *et al.* 2016). Lupins expanded in the 1980s to reach 1.2M ha prior to declining to 0.5 M ha in recent years, while canola is now the most widely grown break crop occupying 2.5 M ha in 2018 (Figure 2). The areas of other main pulse crops in southern Australia such as lentils, fababeans and field pea are generally smaller (around 230,000 each in 2017) with smaller areas of chickpea (see Chapter 19). These are often soil-type dependant, but can be significant in specific regions; lentils, for example, are concentrated in the Wimmera of Victoria and York Peninsula of South Australia. The development of these crops all relied on publicly-funded R&D programs (Maatz *et al.* 2018), which still support most pulse development, while canola breeding is now largely privatised.

The area of broad-leaf break crops can suffer from significant variation from year to year as a result of unfavourable seasons (*i.e.* considered less resilient), market and price fluctuations and disease epidemics (*e.g.* blackleg in canola and *Ascochyta* in chickpea). The area of lupins peaked in 1999 and has declined significantly since, mainly due to low prices and cost of herbicide resistant grass weed control. In contrast, canola recovered from a halving of cropped area in the millennium drought to reach a current area of around 2.5 M ha. During the prolonged millennium drought (2002-2010), cereals intensified in some areas to occupy more than 95% of cropped area in southern Australia (Figure 2).

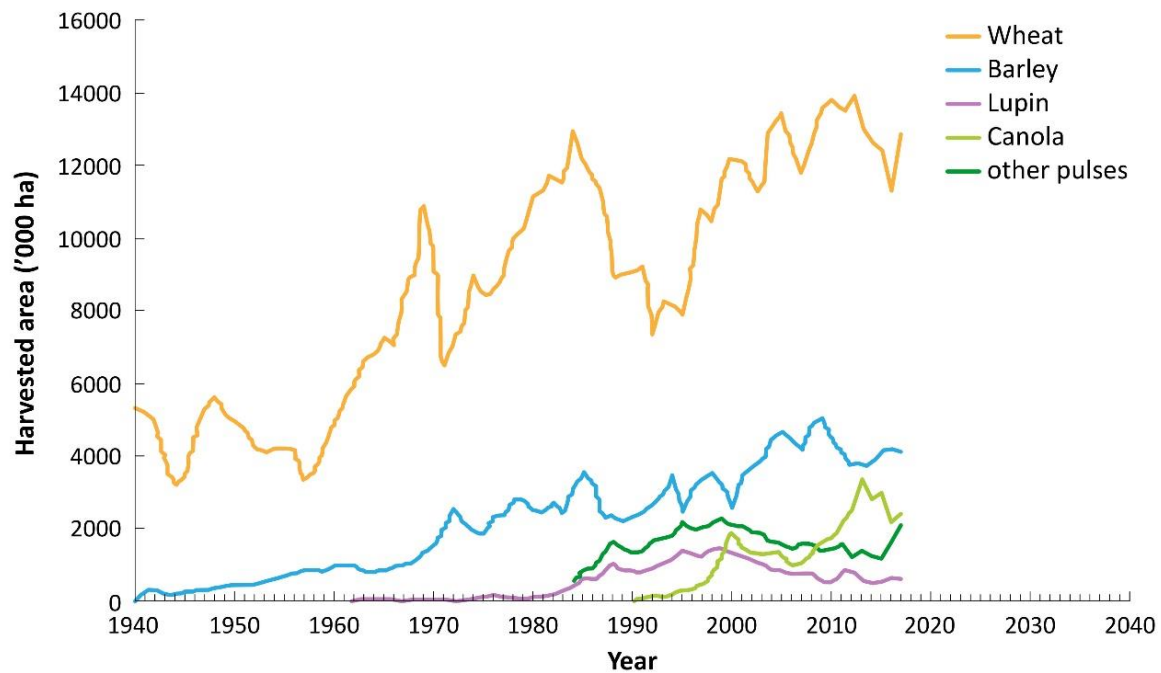


Figure 2. Area of different crops in Australia showing increasing area and diversity of broad-leaf break crops since the 1980s and the significant variability in the area of different break crops during the last 30 years.

Although the break-crop value of broad-leaf legume and oilseed crops to the yield of subsequent wheat crops is recognised (Angus *et al.* 2015), the riskiness of break crops themselves has been a deterrent to adoption. But as closer to average seasonal rainfall returned after 2010, industry-wide initiatives (*e.g.* GRDC Crop Sequencing Initiative, 2011-2016) clearly demonstrated their value to manage grass weeds, nitrogen supply and disease. Including break crops in a 3 to 4 year crop sequence was as profitable, or more profitable, than continuous cereal rotations in most cases (McBeath *et al.* 2015) (www.farmlink.com.au/project/crop-sequencing). A wider range of better adapted and herbicide tolerant canola and pulse varieties (*e.g.* for grain, grazing, hay, brown manure) are now available. On average, across southern Australia from 2011 to 2016, around 30% of cereals were planted after canola, pulses or pasture legumes although this ranged from 40 to 50% in southern NSW, mid-north of southern Australia and WA Sandplain/Mallee, but as low as 17% in central NSW (Umbers 2017).

This brief background of the evolution of the key components of conservation farming systems, provides a backdrop to case studies of that evolution on commercial farms across southern Australia. Strategies to harmonise farm performance, maximise sustainable profit and ease of management are influenced by each farmer's economic, family and risk positions. The interplay of those factors has influenced whether farms have moved towards continuous cropping or retained a significant livestock enterprise. We chart the evolution of two commercial farms in each of three diverse regions of southern Australia (Figure 1) since 1990 to exemplify the way in which technological and socio-economic factors have influenced the farm business.

Farm case studies in three zones of southern Australia

Southern NSW – mixed farmers



**Bernard (left) and Rob Hart
(Hart Brothers)**

- *Location:* Junee Reefs
50 km north of Wagga Wagga, NSW
- *Mean annual rainfall:*
525 mm, equi-seasonal
- *Soils:*
Red Kandosols, pH 4.2-4.8 (CaCl_2),
C 0.85%, N 0.09%

Enterprise description in 1990 The farm comprised 1,000 ha, with a 50:50 crop:livestock ratio. The business was managed by two brothers – Bernard (crop specialist) and Adrian (livestock). Major crops were wheat (4.0-4.5 t/ha), canola (1.8-2.0 t/ha) with smaller areas of lupin and field pea. Medium wool was produced from a self-replacing merino sheep flock. Lucerne-clover pastures were under-sown to wheat or canola in the last year of the crop phase and removed using herbicides in the spring prior to cropping. Pastures were rotationally grazing on a 4-field system supporting 15-20 DSE/ha with hay and silage produced in spring when feasible. Sequence was generally 3 years pasture, 3 years crop.

Major changes since 1990 Farm size increased by purchase and lease from 1000 ha in 1990 to 1900 ha in 1996, to 2300 ha in 2006, and to 3800 ha in 2016. The partnership between the brothers was dissolved to allow succession with Bernard's son Rob becoming a partner. Leased blocks formed two compact operations in districts 50 km apart; most leased land is suitable for continuous cropping. The business now has an advisory board, and each enterprise is examined critically each year.

Livestock A move to two flocks (self-replacing merino flock and cross-bred flock for prime lamb production) during 1990-2000 was reversed due to low profit, the cross breed flock dispersed and the merino ewes joined to terminal rams for prime lamb production. Chicory was added to the lucerne-clover pasture mix in the early 2000s to help control 'red gut' in lambs. Lucerne survived the droughts during 2000-2009 but clover consistently failed and after 2003, pastures were established in late autumn without a cover crop. In 1998, falling livestock gross margins prompted a move to 80:20 until 2002, when drought increased cropping costs and improved livestock return and the ratio returned to 65:35 by 2008. The most profitable system (from 1992 to 2002) involved pasture spring growth either grazed or sprayed out prior to cropping or cut for silage or hay. This gave excellent long-term weed control (over 3 years) and residual N benefits from lucerne to the crops. In 2008 drought had reduced stock numbers to 1100 (wool only), and all sheep were sold (low profits, reduced family labour availability, and need for cash flow). Livestock returned to the business in 2012 with improved seasonal conditions, and opportunities presented by dual-purpose crops (especially winter canola), initially using agistment. It is currently a 3,000 breeding ewe and trading operation for meat and wool production. One property currently has 600 ha exclusively using summer (millet, sorghum, winter canola) and winter (winter canola, oats, rye corn, triticale, vetch, radish, turnip) forage mixes for livestock production, with lucerne-based pastures retained in frost prone areas.

Cropping Crop performance was benchmarked using the WUE (French and Schultz 1984) and between 1998 and 2005 for wheat averaged 17 kg/ha/mm (range 10-23) compared with the benchmark of 20 kg grain/ha/mm. In 2008 following the sale of the livestock, fences were removed to improve labour efficiency in cropping. In the period from 2008 to 2012, the operation was 100% cropping and Rob also

grew the seed business. The cropping enterprise was 50:50 (break-crop:cereal) with around 50% wheat and barley, 35% canola, 15% legumes (field pea, lupin). Canola was not sown in dry years.

The tyne seeding system remained, but rows were widened from 22 to 32 cm with press wheels, and no nitrogen was added at sowing. Guidance and inter-row sowing were introduced with the aim of full stubble retention and crops were sown earlier (including dry sowing). In 2012 to 2014 work by local consultants on crop weed competition prompted a move back to 25 cm rows with a dual tyne parallelogram providing precision placement, urea upfront for extra yield and weed suppression.

The area of barley slowly increased with new varieties performing well in tough years (e.g. Hindmarsh, Latrobe, Spartacus and Planet). More crop monitoring was introduced, harvest weed seed control using windrow burning, and glyphosate spray-topped over canola gave excellent weed control.

Lentils were introduced in 2014 following on-farm research from 2012, and these replaced some of the field peas providing 2.8 t/ha yields @ \$700/t in 2016. Clearfield® lentils (resistant to imizalidinone herbicides) also fitted well with Clearfield wheat, barley and canola all available.

In 2017, a disc seeder was introduced on 16cm rows: it enabled faster sowing, maintained groundcover, managed stubble and rocks and saved the \$20-30K cost of stubble burning. The farm is not yet fully controlled traffic as three base stations would be needed for full coverage with current cost prohibitive.

Future plans There is a current focus on soils and soil fertility, maintenance of soil cover, and understanding and overcoming subsoil constraints at depths below 40 cm. The new summer and winter forage options are opening the way to increase the potential livestock numbers to 5000 ewes (season and feed dependant) and perhaps reduce the cropped area by 500 ha. The strategy will be ‘don’t breed to keep, breed to sell’ (i.e. from “mum to market”). The advisory board and the managers will maintain a focus on a business approach, on succession, and as in the past, adjust the business mix accordingly with a close eye on the latest research to continue adaptation.

Southern NSW – specialist croppers



Warwick and Di Holding

- **Location:** Yerong Creek
40 km south of Wagga Wagga, NSW
- **Mean annual rainfall:**
525 mm, equi-seasonal
- **Soils:**
Red Chromosols and Sodosols,
pH 4.4-4.9, total C 1.3 to 1.9%

Enterprise description in 1990 The 300 ha family farm was 100% arable with a 60:40 crop:livestock ratio. The main crops were wheat, lupin, canola, triticale. First-cross ewes for prime lambs were grazed on subterranean clover-annual ryegrass or lucerne-clover pastures, and there was a 40-sow piggery. The farm business was managed by Warwick’s father, but was too small to support the next generation. Warwick earned off-farm income contract spraying and haymaking and leasing land to run sheep.

Major changes since 1990 Warwick and Di began a program of expansion through land purchase, leasing and share farming from 1995. By 2009, they were farming (wheat, canola and faba-bean) on 325 ha of their own land, 965 ha leased, 320 ha share-farmed, 1100 ha contract farming, all using

controlled traffic. By 2018, with ongoing improvements to equipment and agronomy, the total area under management was 3,000 ha, all sown with a disc-seeder using CTF. The change from mixed cropping to continuous cropping was made due to concerns about surface soil damage by sheep, a personal preference for crops and the compromises in operational management and timing with livestock. The transition towards profitable and sustainable continuous cropping is described below.

Initial expansion of farming area and change to 100% cropping (1995-2002) Farming area was expanded with lease and share farming and a 40 ha 'home block' was purchased in 1997. All sheep were sold in 1998. Second hand machinery was purchased over this period to enable the expansion of the cropping program (wheat, oats, triticale, lupins and some canola).

Advances towards conservation farming (2002-2003) The total cropped area of 1,100 ha included more canola, and increased application of lime and gypsum. Crop failure in the 2002 drought prompted a change to soil management that conserved soil moisture. A new air-seeder with narrow points on 22 cm spacing was purchased: a prickle-chain allowed for 'up and back' seeding using global positioning system (GPS) guidance. Cutting and baling stubble reduced burning, and crop choice was based on disease and weed control with 2-3 year forward planning.

Precision farming (2004-2006) In 2004, Di and Warwick purchased a harvester with yield mapping capabilities and ± 10 cm GPS autosteer which took control of harvest operations and began yield and elevation mapping. Concerns about soil compaction reinforced at a CTF conference provided the impetus for further modifications. In 2006, they adopted 12 m CTF on permanent wheel tracks with wheel centres spaced 3 m apart and ± 2 cm autosteer for all operations. The sowing tyne spacing was widened from 22 to 30 cm and individual press wheels were added. They moved to block farming with each leased farm under the same crop for logistics, disease control and ease of management.

Continued 'fine tuning' of previous developments, with diversification (2007-2009) By 2007, sulphonyl urea herbicides were no longer used on cereals because of their carryover effect on canola. Stubble burning was confined to tactical weed control. Inter-row planting was introduced for cereals following cereals to reduce root disease. In 2008 they purchased 220 ha that was previously share-farmed. By 2009 they were farming 2600 ha all on controlled traffic.

Recovery from drought and floods (2010-2014) The long-term goal to buy more land was delayed by four years of drought (2006-09) and spring floods in 2010. Rising input costs were of greater concern than climate change which they believed they could adapt to. During this period, they were re-grouping financially. Drought had pushed the system to lower-risk continuous wheat, and pulses had dropped out. They slowly resumed their goal of sound rotations, with no wheat following wheat, and target crop proportions of pulses 25%, canola 25% and wheat 50%. This was achieved in 2017.

Improving weed control and timeliness of operations (2015-2017) Managing herbicide resistant weeds required numerous innovations during this period. The windrower changed from 9 m to 12 m with a sprayer added below the cutter bar for weed control at windrowing targeting seed set.

Windrow burning was adopted first by dropping the spreaders and then using a narrow chute – excellent on weeds, but hard to control the burns. A small self-propelled sprayer with high clearance dedicated to the break-crops was purchased in 2014 to improve the timeliness and logistics of spraying, especially fungicides and insecticides (*e.g.* sclerotinia/aphids in canola, heliothis in lupins).

In 2016, they commenced chaff lining (after tour of WA), and chaff-line sprayers were developed for use in the fallow (with non-selective herbicides) and in-crop (with selective herbicides – Warwick calls this 'weed-lining'). A second-hand disc-seeder was purchased in 2016 to improve crop establishment under marginal conditions enabling reliable sowing by the calendar (which has been practised since 2010), and all crops were sown with the disc seeder in 2018. The combination of stubble retention, reduced soil disturbance and lack of livestock provides more frequent opportunities for good early establishment of crops, as evident in the dry autumns of 2017 and 2018.

Novel approaches to maintain diversity, weed control and improve soil biology (2018 and beyond)

Wide-row lupins (57 cm) were trialled to maintain/improve yield with an open canopy to enable shielded inter-row application of herbicides for control of late germinating broadleaves (prickly lettuce, sow thistle) and grasses (ryegrass, wild oats).

Companion cropping involving early sowing broadleaf species grown in normal wheat rows with winter wheat on wide-rows and the companion crop (broadleaves) sprayed out during spring. The aim is to stimulate soil biology, reduce monoculture, improve the productivity of challenging shallow soils, and perhaps allow a second wheat crop in the sequence. Numerous on-farm trials are conducted using yield maps in paddock replicated strip tests to fine-tune new ideas.

Future plans Di and Warwick see that the future will focus on improving the soil, especially sub-surface acidity. Overcoming high subsoil density and balancing micro-nutrients are ongoing challenges. They believe crop and soil management is where major gains can be made, rather than relying on new genetics.

Northern Victoria – mixed farmers



John Ferrier and family

- *Location:* Birchip, NW Victoria
- *Mean annual rainfall:* 350 mm
- *Soils:*
 - 15% Birchip plains medium to heavy sodic clays;
 - 25% sandy loams over clay;
 - 65% shallow sandy clay loam over sodic clay;
 - pH 8-9, total C 1.0-1.3%

Enterprise description in 1990 John and Robyn Ferrier and John's brother Peter and wife Sue farmed in partnership on an area of 2500 ha, with a 70:30% crop to livestock ratio over the whole farm area. The main crops sown were wheat, barley and field peas and long fallowing was still practised.

Self-sown medic was the main pasture, which at times was contract harvested and sown in paddocks low in medic, and the most common rotations were medic-medic-long fallow-wheat-barley (Birchip plains); medic-medic-long fallow-wheat-barley-field peas-wheat (sandy clay loams and sandy loams).

Stubbles were heavily grazed after harvest, paddocks were sprayed with glyphosate and cultivated several times prior to sowing (less cultivation on the sodic Birchip plains due to hard-setting).

Prior to sowing, trifluralin was applied and harrowed for incorporation, leaving the soil vulnerable and exposed to wind erosion. High protein wheat was often delivered at that time.

Changes in the farm operation In the late 1990s, John and Peter started to experiment with no-till and stubble retention and made their own direct drilling points. They were also members of Farm Management 500, a farm discussion group focused on financial management, led by private consultants. John was also an inaugural board member of the Birchip Cropping Group (BCG) established in 1993. Cropping information was obtained through discussion with a private agronomist who visited the farm 5 or 6 times annually, and crop yields were routinely benchmarked using WUE principles.

Changes to the farm business structure and operations Peter and Sue left the farm after the Millennium drought (2010) and John and Robyn have since increased the size of the farm to 5,300 ha.

John now farms with his son David and daughter-in-law De-Anne. The farm no longer employs an agronomist. However De-Anne has an agronomy background and together with skills of other family

members and abilities to seek advice, they make their agronomy decisions ‘in-house’. Farm operations are carried out with two harvesters, one 18 m no-till seeder, a chaser bin, a mother bin, a self-propelled spray unit and 2 trucks. The farm also has 4000 t of on-farm storage.

Decisions to sell grain are based on decile pricing of the various commodities in October/November. For example, in 2017 chickpeas were priced at decile 10 and were all sold off the header whereas lentils were priced at decile 3 and stored on farm until at least a decile 5 price is reached.

Cropping Land is no longer long-fallowed or cultivated – all stubbles are retained and crops are planted with a no-till parallelogram seeder with precision seed placement on 30 cm row spacing. The seeder has three seed and fertiliser compartments enabling P and N rates to be blended whilst seeding.

The main crops grown are wheat, barley, canola, lentils, chickpeas and vetch (for grazing or hay). Medic in pastures did not survive the Millennium drought and is no longer planted (increased herbicide use also contributed to the demise of medic). Because there is now less medic N in the rotation, wheat protein has declined even though urea is now regularly used on cereals and canola.

The Millennium drought was a very difficult period on the farm with little or no grain produced in 2002, 2004, 2006 and 2008: 2016 was an excellent year with good rainfall and high prices, N fertiliser was applied twice during the season and the average wheat yield was 4.5 t/ha.

Crop computer simulations using APSIM was first used in 2001, in a Birchip Cropping Group (BCG) situation, and is now regularly used through ‘Yield Prophet’ to make in-crop N decisions. Cereal and canola paddocks are deep soil tested for available soil water and mineral N content prior to sowing. Yield maps and NDVI are used to identify low and high yielding zones in the paddocks to use variable fertiliser application in the future.

Weed seeking technology is being investigated, especially for summer weed spraying.

Livestock The farm now runs a reduced sheep flock (80:20 livestock to crop ratio) consisting of 1500 breeding ewes (self-replacing Dohne flock, a South African meat merino). Depending on seasonal conditions John and David also trade lambs which are grazed on stubbles. After backgrounding with cereal grain (mainly oats) in the paddock, the lambs are fattened in a feedlot. Lambing is in June which is often a tight period for sheep feed (controlling weeds with herbicides inevitably leads to reduced stock feed), and vetch hay produced on the farm is used when feed is tight. A strict policy of 70% ground cover of stubble is maintained to reduce the risk of wind erosion.

Future plans John and his family are currently happy with the scale of the farm, the family operation, skill mix and machinery ownership. John regularly updates the farm’s financial position and is involved with benchmarking services provided by AgProfit™. John highly values his membership to organisations such as FM500 and BCG, primarily because of the contact with scientists from CSIRO, Department of Agriculture and private agronomists. John looks forward to sowing long coleoptile wheats currently being trialled by wheat breeders from CSIRO to improve germination and early growth in heavy stubbles. He hopes to pass on the responsibilities of actively maintaining and updating the financials to his son and daughter-in-law in the near future.

Victorian Mallee – specialist croppers



Roy and Joan Postlethwaite

- *Location:*
South of Charlton, NW Victoria
- *Mean annual rainfall:*
420 mm
- *Soils:*
70% red brown earths (duplex);
30% black self-mulching soils (vertosols)

Enterprise description in the early 1980s The farm comprised 800 ha and had been a traditional wheat-sheep enterprise, using cultivation to control weeds, and fallowing to conserve soil moisture.

In the late 1970s Roy experimented with a continuous cropping program on one paddock to see if he could use cropping rotations to improve soil fertility. The continual use of cultivation soon ruined the soil structure and by the 1982 drought (annual rainfall, 123 mm) it was obviously not going to work. Roy attended a local farmer meeting where direct-drilling in Canada was discussed. This, together with the dust storms in 1982/83, was the trigger to rethink the operation of the enterprise. Following the drought, livestock were sold, direct drilling with stubble retention commenced and gypsum was applied to the red soils. The original farm has now been continuously cropped using no-till for over 35 years.

Developments in the cropping enterprise No-till farming has evolved over the last 3 decades, with continuous adaptation of machinery and practices as conditions changed. The current 2100 ha operation is continuously cropped on red-soils with wheat, barley, canola, lupins and vetch/oaten hay; and wheat, barley, canola and pulse crops on the black soils. The crops are sown on 30 cm spacing with tine openers with press wheels, a triple bin seeder allows urea to be placed underneath the seed at sowing. Urea is also spread in-season dependent on soil moisture and the seasonal outlook. Sowing operations start in early April, dry if it has not rained, with vetch and oats for hay, followed by canola, cereals and other pulse crops. GPS guidance is used for all operations, but controlled traffic is not practised because it leaves paddocks too rough for hay machinery. Roy prefers to sow at a slight angle to the previous year to reduce problems with stubble residues.

Challenges to the continuous cropping system On red soils the main problem is herbicide resistant ryegrass which was first recognised as a serious problem on the farm in the 1990s with full resistance to the Group A (fops and dims) herbicides. BCG had large scale herbicide resistance trials on the farm in 1998 and confirmed ryegrass resistance to fop and dim (Group A), glyphosate (Group M) and trifluralin (Group D) herbicides. A field day attended by over 400 farmers demonstrated the benefits of the double knockdown approach to ryegrass control (glyphosate followed by paraquat a few days later). Resistant ryegrass is now successfully managed through the incorporation of hay in the rotation. The farm has storage for 5000 bales of hay, which is sold into the export market and the dairy industry. The current rotation on red soils is 2 years of oats or vetch hay, followed by canola, wheat and lastly barley. However, the rotation is flexible and lupins are also grown if there is too much hay. Ryegrass is not such a problem on black soils, but some of the black soil paddocks do have banks of red soil and resistant ryegrass is slowly establishing. The rotation on black soils is chickpeas, followed by canola, wheat and then barley. Lentils have occasionally been sown but are not preferred because of difficulties with harvest. Oaten hay is now also starting to be grown on the black soils. Roy has kept paddock records since 1965 and uses these to make decisions in operations, fertiliser applications, and rotating herbicide group mode of action.

The farm employs an agronomist for advice on fertiliser and herbicide decisions. Two labourers (friends) work on the farm on a casual basis during the seeding and harvest seasons.

Future plans. Roy and Joan are in their early 70s and all operations are still done by Roy with Joan helping during hay making. Farming is in their blood and they love the lifestyle, work and challenges. They have strong feelings about good land stewardship and though Roy has a huge workload they would buy more land at the right price and location. Currently the succession plan does not involve children coming home to farm.

Western Australian Northern Sandplains – mixed farmer



John Scotney

- *Location:*
Badgingarra, WA
- *Mean annual rainfall:*
550 mm, winter dominant
- *Soils:*
Gravel 50%; sand over gravel 35%;
Yellow sandplain 10%; heavy clay 5%

Enterprise description in 1992 The original farm was 1200 ha with a 40:60 crop: livestock ratio. The cropping phase was a wheat-lupin rotation, managed using minimum tillage with one full cut pass at sowing. Wheat and lupin yield generally averaged 2-3 t/ha. The livestock operation was run on sub clover-based pastures with a sheep trading operation for meat, and a merino-based breeding component with a total flock size of 8000.

Major changes since 1992 The farm size has grown to 4,400 ha with new purchases and is currently 75:25 crop: livestock operation. The major crop sequence is canola-wheat-barley phased with two-year subterranean clover-based pasture. The initial challenges through the 1990s were water-logging in the cropping phase especially in lupins on some unsuitable (water-log prone) soils, causing bare patches with subsequent wind erosion. Leaf (septoria) and root diseases were also a problem in the cereal phase primarily due to grassy weeds in the pastures acting as hosts.

No-till farming, canola and fungicides (1992-2002) The development and adoption of no-till farming (John Ryan's DBS) and the introduction of triazine-tolerant (TT) canola in 1995, together with the adoption of an effective fungicide regime to control root and leaf diseases, all led to an increase in yields through the 1990s. Septoria was a particular constraint which was initially addressed with foliar fungicides, but seed and fertiliser treatments are now used in conjunction with foliar applications to manage fungal disease. Lupins were dropped from the rotation in the mid-1990s and replaced with TT canola primarily for improved grass weed and radish control and increased profit. During the period in the late 1990s, productivity and profitability increased, with typically 3-4 t/ha cereal yield and 2 t/ha canola yield. Improved water use efficiency in dry and average years often fell away in wetter years.

Crop expansion in the drought (2002-2010) After 2002, rainfall declined, especially the early autumn rains, and the decline was around 100 mm in annual rainfall from 550 to 450 mm. This meant cropping was more profitable and certainly less stressful than livestock, especially in the very dry years of 2006/2007. The farm area expanded with new purchases during this period in 1998 (4,860 ha), 2002 (608 ha) and 2006 (932 ha).

Addressing soil constraints During the 2000s various soil constraints emerged on the no-till cropping country and over time have been addressed. Since the early 2000s non-wetting soils emerged as an

increasing challenge initially on sandy soils but progressing to gravel soils and have been managed using several techniques including claying, spading, deep ploughing and delving and incorporation of clay. In collaboration with the West Midland Grower Group and DPIRD scientists (Dr Steve Davies) they have evaluated and adopted the most effective amelioration techniques for each soil type. Soil acidification has been addressed through application and incorporation of lime sand through this period.

Subsoil compaction also emerged and is being addressed by ripping and controlled traffic. This in turn caused erosion issues due to water harvesting into wheel tracks and a disturbed subsoil. Yield responses to soil improvements have been around 20% but vary significantly with seasonal conditions. Crop agronomy has changed, particularly with the more aggressive techniques *i.e.* mouldboard ploughing. In 2016, land area was 1200 ha. Stock numbers expanded in line with land purchases at a 70:30 ratio but stock numbers have not expanded with the latest land purchase increasing the cropping area.

Livestock enterprise changes Livestock numbers have remained fairly consistent across the years though John did experiment with higher stocking rates in 2004/2005, but the dry years of 2006/2007 caused a return to previous levels. The flock shifted from a merino based flock to a Dohne based flock with a late spring lambing, driven by higher prime lamb prices and the relatively poor wool prices through this period. This may change again to a more wool focussed breeding base if the current (2018) high wool prices are sustained. A purchase of 1215 ha in 2016 was for crop only, and the farm is currently running 70:30 crop: livestock ratio.

Future plans John is likely to be expanding the area of controlled traffic farming especially on ameliorated soils to preserve the soil benefits and will be investigating more specific VRT using new satellite and imaging techniques. He will also be continuing his experimentation with new, more productive pasture species which he sees as a driver of the system. He has experimented with biserulla, serradella, newer subterranean clovers, Teder, and is especially seeking hard-seeded varieties that can be grazed heavily in the pasture phase and persist through the cropping phase.

Western Australian Northern Sandplains – specialist cropper



Brian and Tracey McAlpine

- *Location:*
20 km west of Maya, WA
- *Mean annual rainfall:*
340 mm, winter dominant
- *Soils:*
Yellow tamma-tussock sandplain (OM 0.2%);
Pockets of gravel, red clay, salmon gum loam

Enterprise description in 1990 The McAlpines farmed 4,000 arable ha with 70:30 crop: livestock ratio. Wheat was the main crop (50% of farm area with average yields of 1.4 t/ha) with an increasing use of lupins (20%) in a very profitable wheat-lupin rotation. Crops were spread evenly around the farm for sheep grazing of stubble in summer. Sheep were run for wool and meat production on poor pastures made up of capeweed, annual ryegrass and wild radish (DSE<1/ha).

Major changes since 1990 Wheat production methods changed from cultivation to no-till by 1993 but this led to increased weeds. These were managed by intensive cropping with lupins and then triazine-tolerant (TT) canola. An interest in long-term soil health also encouraged a move to continuous cropping due to structural damage caused to the soil by livestock, and the potential to increase soil organic matter under continuous crop, no-till farming. In 1997, a gross margin analysis of paddock returns revealed low return for stock and all stock were sold.

Cropping Sowing methods changed progressively from full cultivation to direct-drilling with wide points, then inverted T points, and finally to knife points. Deep ripping, green manure, potash and lime addition were used to lift soil fertility and crop yields. Controlled traffic was introduced in 2005 as information on the benefits became available. By 2008 there were concerns about the future of controlled traffic, as it restricted machinery purchase (scale and axle stress) to keep to the width, with tramlines becoming eroded by rainfall and crop residue concentrated in the same spots. The farm area expanded with purchase of new land (937 ha in 1999; 1,466 ha in 2002; 1,836 ha in 2006). By 2005, the area under crop peaked at 6,900 ha under wheat, barley, oats, lupin and canola. Lupin and canola crops failed in the droughts of 2006 and 2007 and, although it was thought herbicide resistance could be managed, good profits from these crops were required to achieve it.

Livestock enterprise. The drought caused a trend back to livestock, as did herbicide resistant weeds and emerging salinity problems in the region which required deep-rooted perennial pasture species in the system. In 2006, after considering other livestock diversification options, Brian and Tracy introduced a 'back-grounding' cattle enterprise. This involved agisting cattle for around 6 months (winter/spring) from surrounding pastoral stations, with payment based on live-weight gain during the period. This involved no upfront purchase costs, no animal husbandry requirements and no summer feeding requirements – in contrast to the significant labour requirement of sheep enterprises when labour supply was limited by the regional mining boom. After 1997 the farm had no infrastructure for cattle, so 500 ha of arable land with intractable weed problems were partitioned into 100 ha paddocks using electric fences and troughed water. Oat fodder crops and annual pastures provided cattle feed.

In 2008, 93% of the farm was cropped and 7% was available for back-grounding cattle, actual proportions depending on feed availability. Ian ceased all backgrounding of cattle in 2010, following the live-export crisis as it became too risky. Ian became a CBH Director in 2010 which considerably increased his off-farm commitments. He established an export oaten hay enterprise for around 3 years specifically to deal with the herbicide resistant weed problems on the farm, but it was difficult to source labour and this was discontinued. The introduction of GM Roundup Ready™ canola has replaced TT canola, and barley has increased in area especially on salt-affected land, while the area of lupins has diminished due to poor performance.

Soil amelioration In recent years, the whole farm was mapped to a depth of 30 cm for pH, and he has used deep ripping to 30 cm with inclusion plates across the whole farm in a program that will repeat every 5 years. He has seen big paybacks in the dry spring seasons. He has moved from windrow burning to chaff cart for last 4 years and has now moved to chaff deck to concentrate and control weed seed banks. Currently saline land (~300 ha) is being reclaimed with deep ripping and gypsum for both surface and subsurface drainage control and cropped to barley.

Operational efficiency By 2016, the WUE of the major crops had plateaued near the perceived potential with few opportunities to increase productivity, and the focus switched to reducing costs and increasing scale. In 2016, one farm (1,200 ha) of least productive land was sold off to reduce the total crop area to 5,810 ha, which allowed the sowing program to be managed by '1 tractor unit'. The purchase of the widest seeding equipment on the market (Morris single 26.2 m bar) allows the whole farm to be sown on time with one seeder. If necessary 80% of the farm will be sown dry with the remaining sown after the autumn break. The seeder uses tynes and press wheels on 30 cm rows, and he has moved back to granular urea rather than liquid fertiliser at seeding.

Future plans Weeds are the biggest ongoing challenge, together with isolation and community decline – the farm is going well but housing will likely move to towns. Large expensive machines with large repair bills and depreciation are an issue. They will not buy more land, as successive droughts (2006/07) destroyed confidence in growing the business in the region. They have pursued balancing their personal wealth rather than having all the risk in the farm. They will continue to seek improvements and modifications to add further efficiencies to the system while protecting the resource base.

Summary

The farm case studies reinforce many of the national trends in the evolution of southern Australian farming systems over the last 30 years described earlier in the chapter, and elsewhere in this book. Equally they illustrate the diversity of individual farm enterprise response to the external drivers for change. All of the farms have increased significantly in size with the average increase of 220% for the mixed farms, 380% for the specialist crop farms but a range from 73 to 900%. It is interesting that the largest farm (6,900 ha) recently downsized, citing machinery and labour efficiency as the driver. The diversity of both crop and livestock enterprises increased in all cases from one or two main crops dominated by cereals and self-replacing wool flocks, to combinations of five or six cereal, oilseed and pulse crop options and to dual-purpose flocks, prime lamb and beef production as well as feedlots, livestock trading and agistment. The mixed farms, and even some crop specialists demonstrated the flexibility of reversible integration to adjust the crop-livestock ratio on farm according to seasonal, market and family (labour circumstances) – one farm moving between 50:50, 80:20, 65:35 and 100:0 across the 30 year period. The cropping systems on both specialist crop and mixed farms have all transitioned towards earlier sowing systems with no-till or zero-till, retained residues, controlled traffic and an increasing adoption of, or at least interest in, various precision technologies. Herbicide resistance weed management and managing soil constraints were consistently cited as ongoing issues and opportunities on most farms.

Despite these consistent trends that mirror those at national scale, the case studies also illustrate the importance of personal preference as well as family circumstances in enterprise selection and management, the value of off-farm activities, and the impacts of sudden change on individual farms when land or large equipment items are purchased, or livestock are sold. The changes were sometimes the result of long-term planning but were often triggered by changes in price, droughts, government policy or new family circumstances. Even within this relatively small set of farms, subject to similar macro-economic and climatic trends, there is enormous diversity in the specific response and fine-tuning of enterprises that needs to be acknowledged.

Interestingly there was unanimous optimism among the growers for the future with succession planning in place, a focus on sound business decisions and specific technological options for continued improvement and fine-tuning of the farming system proposed. These mostly revolved around overcoming soil constraints, better management of weeds, capitalising on new satellite and other precision technology, as well as a focus on managing personal wealth with both off-farm investments and sound farm business decisions. If they existed, concerns over the much discussed issues of rising energy and input costs, the potential impacts of climate change and slowing productivity trends were not offered voluntarily by these growers as concerns for the future. This may simply signify that these issues are considered to be a manageable extension of the negative terms of trade and climate variability that has been an accepted feature of dryland farming for this generation of Australian farmers over the last 30 years.

References

- ABARES (2018) 7121.0 agricultural commodities 2016-17 (Australian Bureau of Statistics: Canberra).
- Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L, Peoples MB (2015) Break crops and rotations for wheat. *Crop and Pasture Science* **66**, 523-552
- Angus JF (2001) Nitrogen supply and demand in Australian agriculture. *Australian Journal of Experimental Agriculture* **41**, 277-288
- Armstrong RD, Perris R, Munn M *et al.* (2019) Effects of long-term rotation and tillage practice on grain yield and protein of wheat and soil fertility on a Vertosol in a medium-rainfall temperate environment. *Crop and Pasture Science* **70**, 1-15
- Cann, DJ, Hunt, JR, Malcolm, B (2019) Long fallows can maintain whole-farm profit margins and reduce risk in semi-arid south-eastern Australia. *Agricultural Systems* (*in press*)
- Cary J, Wilkinson R (1994) An Evaluation of Farm Management 500: A Program promoting Better Business Management, The University of Melbourne, School of Agriculture and Forestry, Melbourne
- Cornish PS, Pratley JE (1987) "Tillage – New Directions in Australian Agriculture" p 7 (Inkata Press: Melbourne)

- Fischer RA (2009) Exploiting the synergy between genetic improvement and agronomy of crops in rainfed farming systems of Australia. In (Eds. V Sadras, D Calderini) "Crop Physiology: Applications for Genetic Improvement and Agronomy" (Academic: Amsterdam)
- Flower KC, Ward PR, Cordingley N *et al.* (2017) Rainfall, rotations and residue level affect no-tillage wheat yield and gross margin in a Mediterranean-type environment. *Field Crops Research* **208**, 1-10
- French RJ, Schultz JE (1984) Water use efficiency in wheat in a Mediterranean type environment: II. Some limitations to efficiency. *Australian Journal of Agricultural Research* **35**, 765-775
- Giller KE, Andersson JA, Corbeels M *et al.* (2015) Beyond conservation agriculture, *Frontiers in Plant Science*, 6 Article 870 doi: 10.3389/fpls.2015.00870
- Heenan DP, Taylor AC, Cullis BR, Lill WJ (1994) Long term effects of rotation, tillage and stubble management on wheat production in southern NSW. *Crop and Pasture Science* **45**, 93-117
- Hochman Z, Holzworth D, Hunt JR (2009) Potential to improve on-farm wheat yield and WUE in Australia. *Crop and Pasture Science* **60**, 708-716
- Hochman Z, Gobbett DL, Horan H (2017) Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology* **23**, 2071-2081
- Hochman Z, Horan, H (2018) Causes of wheat yield gaps and opportunities to advance the water limited yield frontier in Australia. *Field Crops Research* **228**, 20-30
- Isbell RF (2002) The Australian Soil Classification. (CSIRO Publishing: Collingwood)
- Keating BA, Carberry PS (2010) Emerging opportunities and challenges for Australian broad-acre agriculture. *Crop and Pasture Science* **61**, 269-278
- Kirkegaard JA (1995) A review of trends in wheat yield response to conservation cropping in Australia. *Australian Journal of Experimental Agriculture* **35**, 835-848
- Kirkegaard JA, Peoples MB, Angus JA and Unkovich M (2011) Diversity and evolution of rain-fed farming systems in southern Australia. In (Eds. P Tow, I Cooper, I Partridge, and C Birch) "Rainfed Farming Systems" pp 715-754 (Springer: Dordrecht, Netherlands)
- Kirkegaard JA, Conyers MK, Hunt JR *et al.* (2014) Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystem and Environment* **187**, 133-145
- Kirkegaard JA, Hunt JR, McBeath TM *et al.* (2014) Improving water productivity in the Australian Grains industry – a nationally coordinated approach. *Crop and Pasture Science* **65**, 583-601
- Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments *Journal of Experimental Botany* **61**, 4129-4143
- Kirkegaard JA, Lilley JM, Morrison MJ (2016) Drivers of trends in canola productivity in Australia. *Crop and Pasture Science* **67**, 1-9
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain-growing regions of Australia. *Field Crops Research* **132**, 204-212
- Maaz TM, Wulforst JD, McCracken V *et al.* (2017) Economic, policy and social trends and challenges of introducing oilseed and pulse crops into dryland wheat rotations. *Agriculture, Ecosystem and Environment* **253**, 177-194
- McBeath TM, Gupta VVSR, Llewellyn RS *et al.* (2015) Break-crop effects on wheat production across soils and seasons in a semi-arid environment. *Crop and Pasture Science* **66**, 566-579
- Mullen J (2010) Trends in investment in agricultural R&D in Australia and its potential contribution to productivity. *Australasian Agribusiness Review* **18**, 18-29
- O'Callaghan P (2014) Costs of production and enterprise mix (GRDC Updates) grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/07/cost-of-production-and-enterprise-mix
- Oliver YM, Robertson MJ, Weeks C (2010) A new look at an old practice: Benefits from soil water accumulation in long fallows under Mediterranean conditions. *Agricultural Water Management* **98**, 291-300
- Poole ML (1987) Tillage practices for crop production in winter rainfall areas. In (Eds. Cornish PS and Pratley JE) "Tillage – New directions in Australian Agriculture" (Inkata Press: Melbourne)
- Robertson MJ, Lawes RA, Bathgate A *et al.* (2010) Determinants of the proportion of break crops on Western Australian broadacre farms. *Crop and Pasture Science* **61**, 203-213
- Robertson MJ, Kirkegaard JA, Rebetzke GR *et al.* (2016) Prospects for yield improvements in the Australian grains industry: a perspective. *Food and Energy Security* **5**, 107-122
- Scott BJ, Podmore CM, Burns HM *et al.* (2013) Developments in stubble retention in cropping systems of southern Australia. www.csu.edu.au/_data/assets/pdf_file/0009/922725/Developments-in-Stubble-Retention-in-Cropping-Systems-in-Southern-Australia-11Dec2013.pdf
- Seymour M, Kirkegaard JA, Peoples MB *et al.* (2012) Break-crop benefits to wheat in Western Australia – insights from over three decades of research. *Crop and Pasture Science* **63**, 1-16

- Simpfendorfer S, Kirkegaard JA, Heenan DP, Wong PTW (2002) Reduced early growth of direct-drilled wheat in southern NSW – role of inhibitory pseudomonads. *Australian Journal of Agricultural Research* **53**, 323-331
- Umbers A (2017) GRDC Farm Practices Survey Report 2016
grdc.com.au/resources-and-publications/all-publications/publications/2018/farm-practices-survey-report-2016
- van Herwaarden AF, Farquhar GD, Angus JF *et al.* (1998) ‘Haying-off’, the negative grain yield response of dryland wheat to N fertiliser. I. Biomass, grain yield, and water use. *Australian Journal of Agricultural Research* **49**, 1067- 1081
- Watt M, Kirkegaard JA and Passioura JB (2006) Rhizosphere biology and crop productivity. *Australian Journal of Soil Research* **44**, 299-317

Chapter 5

Evolution of conservation agriculture in summer rainfall areas

Loretta Serafin, Yash Dang, David Freebairn and Daniel Rodriguez

Introduction

Over the last fifty years increases in grain yields have resulted from improvements in breeding, agronomy, soil and crop management, the cropping system, and their interactions. There is little doubt that the same drivers will be responsible for future yield gains. This suggests that identifying and adopting optimum combinations of agronomic management and cultivars that make best use of available resources *i.e.* soil water and fertility, and the seasonal conditions will continue to be the focus of research and development in the future.

Since the early 1900s wheat yields across Australia have shown periods of both rapid and slow rates of increase over time, attributed to synergistic gains from the introduction of legumes, pasture rotations, semi dwarf cultivars, and more diversified rotations that included legumes and canola as break crops (Angus 2001). Crop yield benefits from the adoption of residue retention and zero tillage have been elusive in Australia and elsewhere (Strong *et al.* 1996, Pittelkow *et al.* 2015). However, clear benefits from increased profits as a consequence of increased cropping intensities or reduced risks from conservation agriculture (CA) practices are evident when the comparison is made at the cropping system or whole farm level (Rodriguez *et al.* 2011).

CA is a farming system that promotes maintenance of permanent soil cover, minimum soil disturbance (*i.e.* no tillage), and diversification of plant species (FAO 2018, www.fao.org/conservation-agriculture/en/). In Australia, it has been promoted since mid-last century to conserve soil and water resources. Currently more than 84% of Australian farmers use some type of CA, including minimum soil disturbance, stubble retention, and/or rotations with legumes (Bellotti and Rochecouste 2014). The significant adoption of CA in Australia has been explained in response to biophysical, technological, and socio-economic drivers. Adoption across the continent has not been uniform with highest levels in Western Australia, and lowest in South Australia and Victoria. Adoption of CA in Australia's summer rainfall dominated environments, *i.e.* northern New South Wales and Queensland, has been in response to the need to manage soil and water erosion. Presently soil water retention to allow timely sowing of winter crop and early planting of summer crops as well as stabilising yields in a highly variable climate are key objectives of best management practices.

Biophysical drivers included the ubiquitous nature of Australia's fragile soils and their susceptibility to wind and water erosion, and the need to maximise the capture and use of rainfall for crop production (Serraj and Siddique 2012). Technological drivers included the introduction of glyphosate, crop disease resistance, controlled traffic, and direct seeding technologies (Llewellyn *et al.* 2012, see Chapter 2), while socio-economic drivers included cost and drudgery savings (Bellotti and Rochecouste 2014).

In this chapter we provide a re-assessment of the main drivers for the evolution of CA farming systems in the summer rainfall environments of Australia, the enabling technologies that are making it possible, and the needs for further research in view of the emergence of disruptive technologies, climate variability and change.

The environment and the farming system

Summer dominance of rainfall increases northwards of Dubbo in central New South Wales. Variants of CA dominate crop agronomy with the proportion of summer crops increasing northwards, particularly in the wetter eastern areas.

Climate in the region is characterised by unreliable rainfall, high evaporative demand (double that of rainfall in most months) and frequent intense summer storms (and associated runoff) with extended and unpredictable dry periods between rainfall events (Figure 1).

The unreliability of in-crop rainfall can make its capture as stored soil water challenging, but critical to reliable crop production. The variable nature of climate makes planting crops in the optimum window to minimise the risk of frosts and heat stress around anthesis difficult. In order to deal with such unreliable water supplies, fallowing to store water is an essential part of risk reduction. While climate change may become an issue for agronomists and farmers in coming decades, its impact is overshadowed by the challenges of dealing with seasonal variability in the short term. For example, rainfall varies from 50 to 200% of the average in any two seasons.

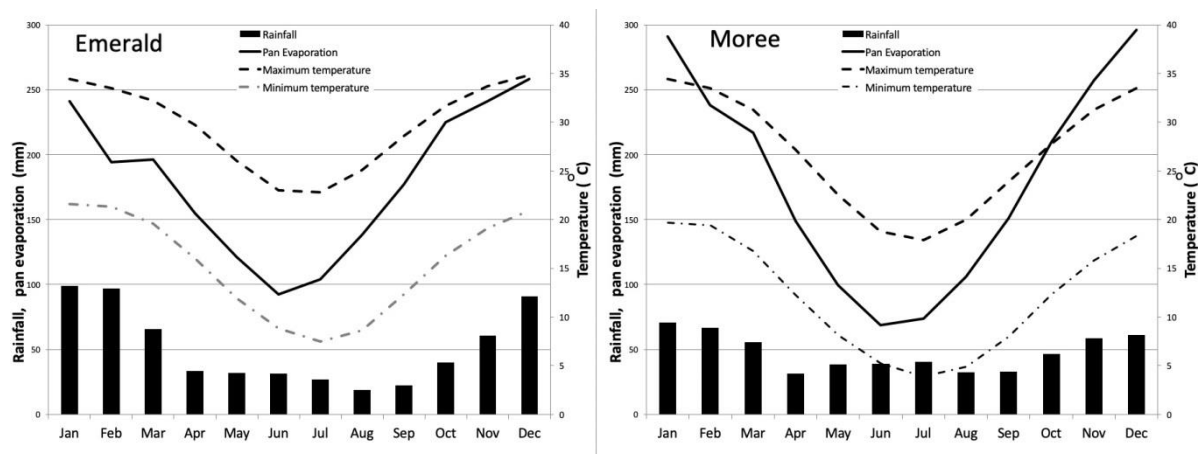


Figure 1. Average monthly rainfall, minimum and maximum temperature and evaporation potential for Emerald (AAR 600 mm, evaporation 2160 mm, Latitude 23.5° S) and Moree (AAR 595 mm, evaporation 2180 mm, Latitude 29.5° S)

Typical crop rotations are based around wheat (winter) or sorghum (summer). For example, wheat to chickpea or wheat, then a long fallow to sorghum or double crop to chickpea are common rotations in northern New South Wales and southern Queensland. Fallows of 12-15 months are also common during the transition between summer to winter crops (*e.g.* sorghum harvested in autumn, with wheat, chickpea or barley sown in winter the following year). In the drier western cropping areas, fallows may need to be 12-24 months for sufficient fallow water accumulation as fallow efficiencies of 15-25% require time and effective rainfall.

However, given the likelihood of heat stress and dry spells around flowering (Singh *et al.* 2015), there is increasing interest in winter sown sorghum. Winter sown sorghum crops aim to avoid the overlap between flowering and extreme high temperature days that cause flower sterility (Singh *et al.* 2015). Grain filling takes place at more favorable temperatures thereby reducing screenings and increasing yields. Crops can be harvested as soon as early January which allows the opportunity for the fields to be double cropped into chickpea after a short summer fallow.

Further north in Queensland, the importance of grain sorghum and other summer crops such as maize and mungbean increases together with the dominance of summer rainfall (Rodriguez and Sadras 2007). In response to the large variability of summer rainfall (*ca.* 30% coefficient of variation), northern cropping systems are highly opportunistic, in contrast to fixed rotations (Freebairn *et al.* 1997, Rodriguez *et al.* 2011). Further west, rainfall and soil quality decline significantly, reducing cropping

intensities of predominantly mixed crop-livestock farming systems (Rodriguez *et al.* 2014), reflecting the need to spread risk with lower and more variable production.

Impact of conservation agriculture in the summer rainfall zone

Research conducted in the late 1970s and 1980s provided strong initial evidence to support the adoption of stubble retention in the summer rainfall zone and helped demonstrate the value of efficient fallows through improved water storage. Numerous studies in the region reported increases in water storage with crop residue cover in no-till (NT) systems compared with residue removed by tillage in conventional tillage (CT) systems (Marley and Littler 1989, Norwood 1994, Felton *et al.* 1995, Radford *et al.* 1995, O’Leary and Connor 1997a, Li *et al.* 2007, Thomas *et al.* 2007b).

More recently Thomas *et al.* (2007) reviewed results from 120 experiment years and showed that NT systems generally resulted in higher soil water storage in fallows due to better infiltration and possibly reduced evaporation associated with crop residues providing soil cover. Greater infiltration rates of NT soils was also attributed to an increase in macropores improving water movement into the soil profile (Chan and Mead 1988, McGarry 2000). Residue cover in NT systems also reduces wind speed and soil temperature, thereby helping to reduce water loss through evaporation (Jones *et al.* 1994, O’Leary and Connor 1997a).

The dependence of winter crops on starting soil water at three locations; Greenethorpe (southern NSW), Moree (northern NSW) and Dalby (southern Queensland) is shown in Figure 2 to demonstrate changes in the importance of fallows for different climates. For example, just to the south of the Northern region at Greenethorpe, 20% of a winter crops’ water supply is provided through fallow moisture (proportion of the crops water supply derived from soil water at planting). This value increases to 60% for a winter crop at Dalby. Improved rainfall capture and reduced evaporation has shown significant yield and cropping system profits, particularly during the Millennium Drought that affected eastern and southern Australia during the early 2000s.

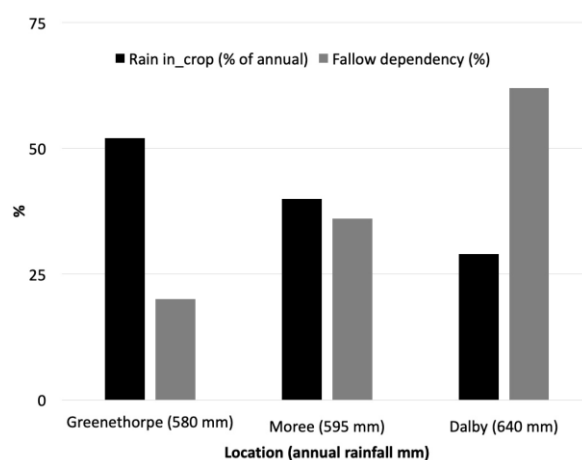


Figure 2. Percentage of in-crop rainfall and ‘fallow dependency’ (the proportion of the crop’s water supply derived from soil water at planting) for winter crops at three locations.

Marley and Littler (1989) showed average fallow efficiency values for four tillage treatments at a long-term trial near Warwick, Qld (Figure 3). An extra 9% of rainfall was captured when stubble was retained in NT systems, compared with cultivation and no stubble. Similarly, starting soil water measured over three years at three sites in northern NSW was 30 mm higher in NT with stubble compared with tilled and stubble burnt (Felton *et al.* 1995). However, in both these studies, wheat yields did not reflect these gains in starting soil water, indicating the complex dynamics between resource availability at the time of planting and the yield formation dynamics (Angus 2001, Pittelkow *et al.* 2015).

The full benefit of implementing NT is often not evident until later, in many instances greater than 5 years (Pittelkow *et al.* 2015). The reasons for this are mixed; for example, Radford and Thornton (2011)

found that a yield penalty associated with aggressive tillage lasted three years after a NT regime was implemented over the whole trial (Table 1). It is notable that there were no yield differences between the three ‘stubble retained’ treatments and that crop type was varied depending on planting opportunities.

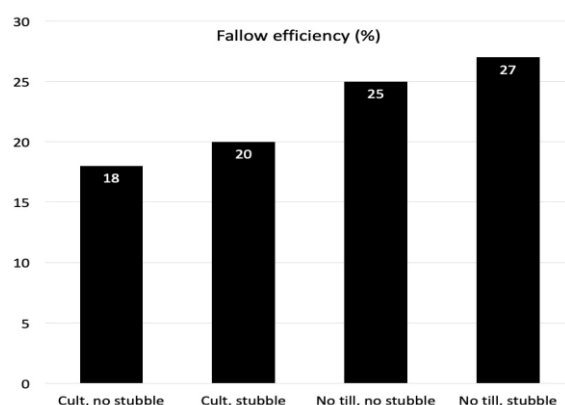


Figure 3. Average fallow efficiency (% of fallow rainfall stored in soil at planting) for four tillage/stubble treatments at the Hermitage Research Station near Warwick 1968-79 (11 years) (Marley and Littler 1989)

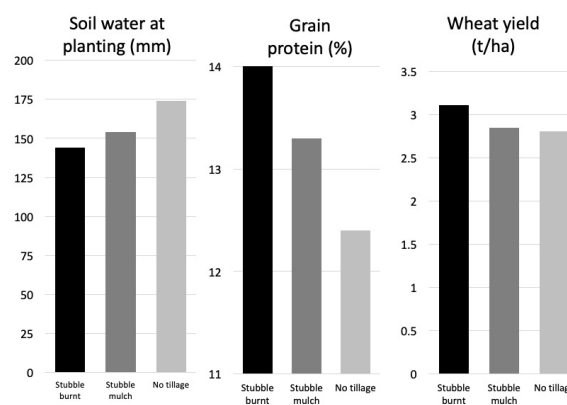


Figure 4. Average yield over 3 years for three fallow management strategies at Warialda, Croppa Creek and Breeza, 1986-88 (Felton *al et.* 1995). All treatments received basal fertiliser plus 50 kg/ha N

Table 1. Average grain yield (t/ha) over 20 years for four fallow management options and yield when all plots were managed for the subsequent 3 years (Radford and Thornton 2011)

Treatment	Mean Yield for 20 Years (t/ha)	Mean Yield for 3 years Post-treatment (t/ha)
Disc/scarifier tillage	2.15	1.43
Stubble mulch tillage	2.66	2.73
Reduced till	2.77	2.83
No-till	2.79	2.71

Drivers for the adoption of conservation agriculture practices

The combination of research, development and extension activities, together with a range of biophysical, socio, and economic drivers have led to the fast adoption of conservation farming practices across Australia’s summer rainfall areas. For example, in the span of ten years, the percentage of cropping land under NT increased from less than 5% in 1999 to 65% in 2010 (Llewellyn *et al.* 2012, Dang *et al.* 2018).

Biophysical drivers

As knowledge on the importance of capturing rainfall and retaining soil water developed, practices that promoted improved fallow efficiency allowed for earlier planting and increased the reliability of cropping (Rodriguez *et al.* 2011, Sadras *et al.* 2016). Today, soil conservation practices such as crop residue and NT are seen as crucial to manage dryland cropping (Belloti and Rochecoste 2014).

Socio-economic drivers

Socio-economic factors that favoured the adoption of CA practices included the limited availability of labour in remote communities, land consolidation into larger farms, and the availability of drudgery and cost saving technologies such as auto-steer, controlled traffic and larger machinery. The CA practices and soil water retention brought increased opportunities to diversify crop rotations and double cropping. Whole farm simulation studies suggest that increased cropping frequency is possible with an opportunity cropping strategy combined with direct drill, controlled traffic systems (Chudleigh *et al.* 2002, Rodriguez *et al.* 2011, 2014). This increased cropping frequency is reliant on stored soil moisture to dictate rules for sowing.

Benefits are particularly notable in the more marginal environments where the ability to retain stubble *in situ* allowed for the expansion of cropping activities into previously sole grazing, or mixed cropping and grazing farms. The opportunity to increase the area under crop in recent years has been forgone as meat prices have increased and annual rainfall has been below average.

Soil organic carbon and biology

Soil organic carbon (SOC) levels of NT soils have frequently exceeded CT soils with a pronounced stratification of SOC in the top 0-0.15 m soil depth (Luo *et al.* 2010, Soane *et al.* 2012, and see Chapter 16). Results from experiments conducted in the summer rainfall region comparing CT with NT have been mixed, with some NT treatments reporting small increases in SOC stocks calculated on depth increments in the surface soil layers (Dalal *et al.* 2011), while others reported that NT management has little or no impact (Fettell and Gill 1995, Armstrong *et al.* 2003).

In the semi-arid sub-tropical environments of north-eastern Australia, many studies observed greater SOC concentrations under NT systems; however, this is primarily due to NT simply decreasing the rate of decline relative to CT management (Doran *et al.* 1998, Olson 2010, Chan *et al.* 2011, Page *et al.* 2013). The crops are grown following a fallow period in order to accumulate soil moisture and the crop biomass production is generally insufficient to lead to any overall gain in total SOC (Fettell and Gill 1995, Franzluebbers and Arshad 1997, Chan *et al.* 2003, Hoyle and Murphy 2006).

An analysis of 40 years of SOC data at the Hermitage, Queensland site showed that SOC stocks measured over time showed a decrease (0.29 Mg/ha/year to 0.3 m soil profile) across the experiment and more so in the top 0.1 m under stubble burnt (SB) and NT as compared with stubble retained (SR) and NT (Page *et al.* 2013).

Similar to SOC, several studies have reported greater soil biological activity in NT systems when compared with CT systems (Wildermuth *et al.* 1997, see Chapter 15) with greater abundance and diversity at the soil surface and with minimal difference at lower depths. This is attributed largely to a more favourable soil environment because of increased quantity and diversity of organic material, increased moisture, improvements in soil structure and, in some instances, a more favourable temperature (Wardle 1995, Lupwayi *et al.* 2001). Wardle (1995) showed that there was a wide range of responses between different species, although most organism groups had greater abundance or higher soil microbial biomass (SMB, defined as mass of living microbial tissues) in NT soil than in CT soil. Large organisms in general are more sensitive to tillage than smaller organisms due to longer life cycles, combined with physical disruption of the soil and habitat destruction (Wardle 1995). Earthworm populations have increased markedly in the region under NT, and are adversely affected by cultivation (Robertson *et al.* 1994).

Weeds in conservation agriculture systems

Prior to the advent of effective herbicides, tillage was the primary method of controlling weeds that interfered with the crop sowing operation and then competed with the emerging crop for limited available water and nutrients (Pratley *et al.* 1999). Tillage influences weed populations by the combined effect of mechanical destruction of weed seedlings and by changing the vertical distribution of weed seeds in soil (Peigné *et al.* 2007). Practices such as residue burning are also known to destroy weed

seeds and decrease weed infestations (Heenan *et al.* 1990). In the absence of residue burning, NT has led to increases in the population of some weed species (Buhler *et al.* 1994, Chauhan *et al.* 2012, Lyon *et al.* 1998,) and reduction in others (Pratley 1995).

The weed flora in the summer rainfall areas of Australia have been documented in several field surveys (Felton *et al.* 1994, Osten *et al.* 2007, Rew *et al.* 2005, Walker *et al.* 2005, Werth *et al.* 2010, Wicks *et al.* 2000). Multiple studies have shown a significant shift in both weed population densities and species. Weeds with wind dispersed seeds and glyphosate-tolerant species have become more prevalent. Essentially a small number of species tend to dominate in NT cropping including the summer grasses, such as *Echinochloa* spp. and liverseed grass (*Urochloa panicoides*), and weeds with wind dispersed seeds, such as sowthistle (*Sonchus oleraceus*), and increasingly windmill grass (*Chloris truncata*) and fleabane (*Conyza bonariensis*).

Alternative methods for weed control have emerged in response to the changing suite of weeds and resistance to herbicides. Strategic tillage and weed seeker technology have been combined with agronomic practices such as higher seeding rates and altering row orientation to improve crop competition with weeds and reduce weed seed set (Dang *et al.* 2018). These methods could be further exploited. Future options may include the use of microwave and robotic technology to increase the control of weeds. Desiccation of crops, primarily sorghum and chickpea using glyphosate as the sole or base active ingredient has become accepted practice to prevent further crop growth and use of soil water, as well as allowing late season weed control. Further information is available in Chapter 10.

Diseases in conservation agriculture systems

Reduced soil disturbance associated with residue retention in NT systems generally results in higher soil moisture and reduced temperature, which creates a more favourable environment for many plant pathogens and encourages disease persistence (Bockus and Shroyer 1998, Cook and Haglund 1991, Wildermuth *et al.* 1997,). Retained stubble residue retention also offers a food and inoculum source for many diseases. The most common soil- and residue-borne diseases in the Australian summer dominated rainfall region include: crown rot of cereals caused by *Fusarium pseudograminearum*; yellow spot of wheat caused by *Pyrenophora tritici-repentis*; net and spot forms of net blotch of barley (*Hordeum vulgare*) caused by *Pyrenophora teres* f. *teres* and *Pyrenophora teres* f. *maculata* Smedeg., respectively; ascochyta blight of chickpea (*Cicer arietinum*) caused by *Ascochyta rabiei*; and stalk diseases of sorghum (*Sorghum bicolor*) caused by *Fusarium moniliforme*. Root-lesion nematodes (*Pratylenchus thornei* and *Pratylenchus neglectus*) are also major pests and host on several crop species important in the region including wheat, chickpea and sorghum. Residue retention has been the main driver in increasing stubble borne diseases prompting increased focus on crop rotations and technologies such as inter-row sowing. Further information is available in Chapter 11.

Technologies that have enabled conservation agriculture

Over the last 30 years the level of technology has increased; tractors are a good example of the changes. Major changes to the internal and external design and functionality of tractors has made them more user friendly and automated as well as providing efficiency gains in the field. Tractor power has increased, wheel base sizes have expanded, more complex software and operating platforms to incorporate GPS technology have been widely adopted.

Sowing and spraying equipment have also changed in response to the requirements of farming operations with wider planters and improvements in seed placement and singulation. Precision planters are standard for summer crops, and some winter crops such as chickpea. Controlled traffic has reduced soil compaction, and overlaps creating savings in seed, fertiliser and herbicides (Tullberg 2010, see Chapter 6).

The introduction of GPS linked with Geographic Information Systems (GIS) has enabled capabilities such as auto steer, precision agriculture and variable rate technology. The use of real time Kinematic (RTK) navigation systems at a 2 cm level of accuracy has given producers the ability to collect and utilise more information about their fields and their crop performances. These systems have extended

the working hours of operators as utilising auto steer extends the time which one employee can manage in a shift as well as the conditions in which tractors can be operated; for example, in low visibility such as at night or in fog. This technology has also elevated the skill set of producers; each tractor driver now requires advanced computing skills.

There has been a greater focus on reducing the ‘footprint’ of tractors across fields. The use of track machines and controlled traffic tramlines has helped to concentrate soil compaction to a smaller area of the field through reducing the area over which a tractor wheel passes. The next stage in technology innovations is the inclusion of remote sensing, many as independent platforms, but some also linked to tractors and spray rigs such as weed seekers and green seekers.

Planter improvements

Planting equipment has developed in complexity and adaptability to manage variable conditions. Capital investment in machinery is expensive and can have a significant influence on profitability (Vogt and Verrall 2018). However, crop establishment is critical to final crop yields. The focus of planter developments has been largely in seed placement and seed metering.

Use of precision planters has increased over the last 30 years, particularly for summer crops. The increase in hybrid varieties has increased seed costs leading to greater emphasis on planting less seed more precisely to keep establishment costs lower. Parallelogram planters with improved ability to follow soil contours and attention on reducing seed bounce and better placement has also become more important.

Seed singulation improvements have helped to ensure seed metering is more accurate and the occurrence of doubles or missed seeds is minimised. Through ensuring both seed spacing and singulation are optimised, even plant stands can be established to reduce intraspecific competition, improve crop evenness at maturity and assist in uniformity to aid management of weeds, pests and crop desiccation timing.

The combination of soil mapping, multi hybrid planters and connective software has now made it possible for farmers to plant more than one variety and apply more than one agronomy (*i.e.* plant population, nutrition) within a field on the go. This allows for zones within fields to be defined and optimum combinations of hybrids and agronomic management applied (Rodriguez *et al.* 2018).

The discussion on disc versus tyne implements continues with each system having its merits. Typically disc planters provide less soil disturbance but have less soil penetration capacity, limiting their usefulness in moisture seeking situations compared with a tyne. A tyne implement has better ability to ‘plant to moisture’ and establish a crop in otherwise too dry conditions and with more ‘soil throw’, which can be useful to incorporate herbicides for improved effectiveness.

Row spacing (skip row, wide row, twin row)

Varying row spacing is a management practice which is used to match the crop design better to the availability of resources or expected seasonal conditions. In winter cereals, wide row spacings (*e.g.* 50 cm) are used in marginal environments with narrow row spacings of 25–37.5 cm used in more favourable rainfall zones. Studies have demonstrated that yield decreases in winter cereals once row spacing moves wider than 30 cm (McMullen 2014). To gain efficiencies from investments in planters, many growers adopted the use of 37.5 cm winter crop row spacing and 75 cm summer crop row spacing, thus utilising this equipment for both winter and summer planting. Purchasing of precision planting equipment has become more typical for summer crops allowing adoption of more specialised row spacing suited to each crop in the rotation.

In summer broadacre cropping, the use of skip row technology has become common place in the marginal environments or where planting is proposed on fallows and soil moisture is lower than the ideal near full profile. Wide rows or skip rows provide an effective bigger soil mass and moisture supply during grain fill. Initially, single (plant two miss one row) or double skip (plant two, miss two rows)

was favoured during 2000-2010, although wide rows (120-150 cm) have gained favour in recent years (Serafin and McMullen 2015).

Conversely, the need to maximise yields in more favourable environments has brought consideration of narrow row spacings (≤ 50 cm) or the use of twin rows. The need for additional planter units and the difficulty in managing high stubble loads have been challenges to adopting a narrow row planting design. In contrast, twin rows provide the ability to mitigate some of these issues.

Row placement: on row/ off previous crop row

The use of 2 cm RTK guidance systems and auto steer has meant the possibility of inter or on row sowing, *i.e.* planting in between the previous crops rows or planting back on the previous crop rows. Inter row sowing is an option for handling high stubble loads as well as disease management (*e.g.* crown rot) by minimising the contact which emerging seedlings have with previous crop residue. In contrast, sowing on the row of previous crop stubble allows seedlings to access old crop root channels and biopores which trap water better than the inter row area.

Adapting to heat and stress in the summer rainfall zone – looking forward

Across the summer dominant rainfall region, managing heat and moisture stress around flowering remains the focus of crop adaptation and systems agronomy. The main adaptation strategy farmers have to reduce yield loss is to avoid the overlap between stress events and flowering by targeting optimum flowering windows and managing canopy size. However, to fit the flowering of sorghum around a low risk window for heat and water stress for example, the crop would need to be sown into soil temperatures lower than the recommended 16°C, with a higher frost risk. Achieving rapid and uniform sorghum emergence is essential under these less ideal conditions; however it is a balancing act between the potential benefits of reduced stress around flowering and the higher risk of crop damage or loss due to frost damage at the early seedling stage.

These are some of the challenges farmers face to respond to an increasingly hotter and drier environment. Ongoing research has shown that sorghum crops sown into soil moisture as early as August take longer to emerge, though are harvested during mid to late December, potentially increasing cropping frequency and production. However, numerous questions require answers before widespread adoption of this practice.

Earlier summer crop establishment Present sowing recommendations indicate that sorghum “should be planted when the soil temperature at the intended seed depth is at least 16°C (preferably 18°C) for 3-4 consecutive days and the risk of frosts has passed” (Kneipp and Serafin 2006). However, initial results suggest that crops could be successfully established on colder soils (~12°C at planting depth) with good moisture and ground cover that reduces evaporative losses. Other factors likely to be important include seed quality, crop residue cover, soil moisture, soil type, and hybrid genetic differences.

Improved definition of frost risk Air temperature thresholds (intensity) and duration of damaging frosts in sorghum during early vegetative stages have not been clearly established. There is a need for better prediction of the likelihood of early frost damage so that early sowing decisions can be better informed. Other factors likely to affect frost damage include crop residue cover, soil moisture, soil type and hybrid.

Stresses around flowering, grain yields and risk of uneconomical crops There is a need to produce information on how alternative hybrid and agronomy combinations, including early sowings, change the frequency of stress environments around flowering, and how these changes impact on likely yields and risks of uneconomic crops across the region. This information needs to be packaged and delivered in a way that can be used to inform farmers’ decisions.

Cropping system benefits Initial simulations with APSIM show potential increases in the likelihood of double cropping a winter crop after a longer summer fallow. For example, a crop planted in early August at Warra Qld would take 100 days to reach flowering, and be harvested during mid or late December,

leaving a longer fallow period into the next winter crop. The magnitude of the benefits and risks across the region need to be properly quantified following on from previous work in 1976 (Berndt and White 1976). Questions remain on how often this is likely to happen and the implications on subsequent crops, profits and risks.

What knowledge is missing for the future?

Although the adoption of CA has progressed steadily, further adoption appears to be hindered by several issues:

- the increase in herbicide-resistant weed species;
- the build-up of soil- and stubble-borne diseases;
- the stratification of organic matter and nutrients in the top layers of the soil, and the depletion of subsoil layers *i.e.* particularly phosphorus and potassium;
- the build-up of soil insects, and the limited number of management options to control insects that have a below-ground pupal stage (*e.g. Helicoverpa spp.*); and
- the environmental and health concerns about the effects of herbicides on- and off-site.

The importance of crop rotation and disease ‘break crops’ is accepted, although the role of soil biology on soil processes is poorly understood beyond ‘soil organic matter is good’. Cover crops have shown possibilities but there has been little follow up until recently to explore where this practice fits into farming systems (Erbacher *et al.* 2019). While this area may be considered high risk, future improvements in system performance will be harder to find.

Weed control remains a high cost component of grain production and herbicide resistance presents a growing threat to CA. Herbicides are valuable management tools and their efficacy needs to be maintained, suggesting the need to combine multiple weed control strategies, including strategic tillage.

Future productivity gains across Australia’s summer rainfall dominant cropping systems are likely to continue to accumulate from improvements in farmers’ capacity to identify optimum combinations of crops and varieties (Genotype), agronomic management (Management), cropping systems (Cropping System) and whole farm management strategies across its diverse climate and soil environments (E). Large benefits are expected to arise from improvements in our capacity to characterise expected seasonal conditions in our variable climate.

Farm case studies in northern NSW and Queensland

Northern NSW



Darryl (left) and Sara Bartelen

“Optimising the full potential of your soil is the key to farming in northern NSW”

- *Location:* “Krui Plains” 60 km north of Moree, NSW
- *Mean annual rainfall:* 552 mm
- *Soils:* Grey vertosol

Darryl and Sara Bartelen brought fresh ideas and a lot of enthusiasm to implement conservation farming practices when they took over operations from Sara’s parents at “Krui Plains” north of Moree 24 years ago. Today, the 4,300 ha cropping and steer backgrounding family farm operates under the management of Darryl, Sara, their daughter Catie and one full time employee.

In the mid-1990s, Darryl commenced implementing changes to the conventional farming practices that had included multiple tillage operations, round and round paddock traffic and grazing sheep. Sheep were replaced with a steer backgrounding enterprise where grazing was mainly confined to the non-cropped area and weeds were controlled by herbicides.

Darryl watched and listened to neighbours, agronomists, leading district growers and his father-in-law to glean information to improve the efficiency of the farm. Initially it was the simple step of spraying fallows for weed control instead of cultivating.

The dawn of the dry new decade in 2001 convinced him to try NT. He converted an old John Shearer trash worker into a no till planter and in 2001 sowed their first no till crop to improve moisture storage and reduce soil erosion, following the wet seasons in the late 1990s. The modified planter was used for all winter crops until 2013 when they purchased a 12 m disc planter. The disc planter soon proved unsuitable in their conditions; insufficient penetration excluded moisture seeking, and excessive stubble pinning occurred in heavy stubbles. Darryl reverted to their modified planter until 2017 when he purchased an 18 m tined parallelogram planter on 37.5 cm row spacings. Their summer crops had benefited from the purchase of a precision planter in 2005.

“Krui Plains Pastoral Co” maintains a rotation of wheat /chickpea/barley/sorghum, with a 25% split in area between these four crops. Their crop rotation has changed little over time, except addition of barley in 2002 to expand feed grain market and reduced yield impact of crown rot. Opportunistic crops such as mungbean, sunflower and corn have been grown but they have returned to their core grain crops.

Currently they use 12 and 18 m planters and 12 m headers, all with a common 3 m wheelbase on a controlled traffic guidance system with 2 cm accuracy. A strong focus on conserving and retaining moisture means fallow weeds are controlled. Weeds are controlled in a timely manner using a WEEDit™, purchased in 2014, and a self-propelled 36 m spray rig purchased in 2017.

No-till has resulted in herbicide resistance and a new suite of weeds *e.g.* windmill grass. Glyphosate-resistant barnyard grass (species) evolved as a challenge but is now under control through using a multi-pronged approach of herbicides and crop rotation.

Darryl and Sara are conscious of the need to measure impacts of the changes they make. They use a mix of productivity, economic and sustainability indicators to monitor the impact of their decisions. For example, on a productivity basis, long term average wheat yields have lifted from 1.5 to 2.7 t/ha. From an economic viewpoint the WEEDit™ has reduced their chemical costs by \$50,000/year and improved their sustainability by reducing the area sprayed in fields on average to 10%, extending the useful life of herbicide chemistry

In the most recent 2018-2019 drought, Darryl felt he had set up the farm to be in the best position to succeed, basing decisions on the amount of stored soil moisture and striving to improve efficiency of all aspects of their cropping operation.

In future Darryl predicts continued challenges with conservation farming, such as controlling multiple herbicide resistant weeds and an increasingly hot, dry and variable climate. For future weed control, he envisages a multipronged attack; expanding herbicide chemistry groups used, the WEEDit™, possibly an autonomous weed chipper and using new “green on green” variable rate spray rigs.

The Bartelen’s are already scanning the horizon for the next efficiency improvement, recently engaging the services of a company to utilise the plethora of data they have collected through yield maps and remote imagery since 2003. This information will be verified and zones of crop performance established across their property. This zoning will be used to implement a variable rate program, initially for fertiliser, but ultimately for crop inputs such as seeding rates, variety choice and even crop selection.

Central Queensland



Paul Murphy

“Combining conservation agriculture and organic production in central Queensland”

- *Location:* “Kevricia” 40 km north of Emerald, Qld
- *Mean annual rainfall:* 600 mm
- *Soils:* Brigalow Yellow wood

Paul Murphy is an organic grain producer who manages the family farm “Kevricia”, in Central Queensland, with his wife Cherry and two adult children. The property consists of 1400 ha dryland crops and 500 ha of native pastures. Paul began managing the property in the early 1980s alongside his parents, who had cleared and developed the farm. A decade later, Paul and his wife took ownership of the property with the aim of supplying produce in response to the growing social demand of reducing chemical inputs. This led Paul to obtain organic certification for the farm and to utilise ‘natural’ means of soil and crop enhancement and a residue-free end product. The Murphy farm business focuses on selling organic cereals and pulses for niche markets, and their ‘chemical free’ products attract premium prices. Typically, yields of organic farming systems are lower than conventional practices, but this is currently offset by significant price premiums.

Driven by the vagaries of the Central Queensland climate, the cropping program is highly opportunistic. Organic management practices use rotations that comprise five years of cropping followed by two years of green manuring and field revegetation by legumes and grasses. The crop sequence and intensity are driven by planting opportunities (*i.e.* availability of soil moisture) and field history. Other influencing factors include the selling prices of multiple cropping alternatives including a range of speciality wheats, chickpeas and linseed in winter, and mungbeans, sunflower, sorghum, soybean and corn in summer. A key component is the green manuring with *Dolichos lablab*, *Sesbania*, and naturalised grasses during the revegetation periods, as well as stubble retention during the cropping phase. Opportunistic ‘cash crops’ only take place following cultivation with full soil moisture profiles. Weeds are the predominant constraint and are managed using strategic tillage and crop rotations.

During the 1980s, “Kevricia” was managed under conventional tillage with no chemical usage. Under Paul’s ownership, organic crops have been produced using minimum strategic tillage. Strategic tillage and weed control continue to be evolving issues. Nowadays the farm is managed through control traffic on 18 m rows for the tillage and planting operations. However, harvesting is unable to follow the tram tracking system due to operational constraints. Critical to success has been identifying optimum soil moisture levels for any tillage operation. Maintaining crop and stubble cover, building soil organic matter and improving soil structure to increase rainfall harvesting have been key elements to prosperity. Crop nutrition is managed with the contribution from green manures and native legume species, in combination with composts and animal-based manures. The effects of green manuring and the revegetation periods can be observed for up to five years depending on conditions, and determine the length of the cropping and revegetation phases. Paul is also experimenting with the use of organic and inorganic soil amendments based on basalt rock dust to enhance soil structure and fertility.

An important driver for change on the management of the farm has been the observation of soil constraints, particularly compacted soil layers that have produced smaller rooting systems that result in poor rainfall infiltration. Improvements include the adoption of reduced tillage to preserve soil structure, reduce erosion and increase rainfall infiltration through larger root systems. The adoption of controlled traffic has helped to reduce compaction and increase efficiencies. Despite higher profits from selling

differentiated produce in niche markets at higher prices, weed control remains the most important and difficult challenge.

The focus of the business remains to increase returns on assets. Driven by the lack of specifically adapted hybrids to perform reliably in the hot, dry conditions of the Central Queensland cropping region of ca. 160,000 ha, Paul has been heavily involved with the creation and growth of Radicle Seeds Australia™, a farmer-owned sorghum and maize breeding company. This helps to diversify sources of income. The Company's objective is to fill the space of smaller higher value seed markets, and to provide value propositions to clients and regional communities.

The main challenge for dryland cropping in Central Queensland is the trend towards increases in the intensity of management and rotation systems, and a reduction in the frequency of rainfall events. This together with hot summers makes the maintenance of crop and stubble cover paramount to the reliability, profitability and sustainability of crop production. Labour constraints and the need for strategic and localised tillage in organic systems leads Paul's cropping system towards the adoption of robotic technologies for weed control. Paul also looks to future developments on the availability of autonomous precision planting and field management systems that automatically changes genetics (*i.e.* hybrid type) and management (*i.e.* agronomy and nutrition) on the go across contrasting management zones, or that mechanically take weeds while retaining stubble where it needs to be.

References

- Angus J (2001) Nitrogen supply and demand in Australian agriculture. *Australian Journal of Experimental Agriculture* **41**, 277-288
- Armstrong RD, Millar G, Halpin NV *et al.* (2003) Using zero tillage, fertilisers and legume rotations to maintain productivity and soil fertility in opportunity cropping systems on a shallow Vertosol. *Australian Journal of Experimental Agriculture* **43**, 141-153
- Bellotti B, Rochecoste JF (2014) The development of conservation agriculture in Australia—Farmers as innovators. *International Soil and Water Conservation Research* **2**, 21-34
- Berndt RD, White BJ (1976) Simulation-based evaluation of three cropping systems on cracking-clay soils in a summer-rainfall environment. *Agricultural Meteorology* **16**, 211-229
- Bockus WW, Shroyer JP (1998) The impact of reduced tillage on soilborne plant pathogens. *Annual Review of Phytopathology* **36**, 485-500
- Buhler DD, Stoltenberg DE, Becker RL, Gunsolus JL (1994) Perennial weed populations after 14 years of variable tillage and cropping practices. *Weed Science* **42**, 205-209
- Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture: A review. *Crop Protection* **38**, 57-65
- Chan KY, Conyers MK, Li GD *et al.* (2011) Soil carbon dynamics under different cropping and pasture management in temperate Australia: Results of three long-term experiments. *Soil Research* **49**, 320-328
- Chan KY, Heenan DP, So HB (2003) Sequestration of carbon and changes in soil quality under conservation tillage on light-textured soils in Australia: a review. *Australian Journal of Experimental Agriculture* **43**, 325-334
- Chan KY, Mead JA (1988) Surface physical properties of a sandy loam soil under different tillage practices. *Australian Journal of Soil Research* **26**, 549-559
- Chudleigh FC, Cox HW, Chapman VJ (2002) Modelling profitable and sustainable farming systems in Central Queensland. *Proceedings 46th Annual Conference of Australian Agricultural and Resource Economics Society Inc.* Adelaide (CD-ROM)
- Cook RJ, Haglund WA (1991) Wheat yield depression associated with conservation tillage caused by root pathogens in the soil not phytotoxins from the straw. *Soil Biology and Biochemistry* **23**, 1125-1132
- Dalal RC, Allen DE, Wang WJ *et al.* (2011) Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. *Soil and Tillage Research* **112**, 133-139
- Dang YP, Balzer A, Crawford M *et al.* (2018) Strategic tillage in conservation agricultural systems of north-eastern Australia: why, where, when and how? *Environmental Science and Pollution Research* **25**, 1000-1015
- Doran JW, Elliott ET, Paustian K (1998) Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management. *Soil and Tillage Research* **49**, 3-18
- Erbacher A, Lawrence D, Freebairn D *et al.* (2019) Cover crops can boost soil water storage and crop yields. GRDC Update, Goondiwindi

- Felton WL, Marcellos H, Martin RJ (1995) A comparison of three fallow management strategies for the long-term productivity of wheat in northern New South Wales. *Australian Journal of Experimental Agriculture* **35**, 915-21
- Felton, WL, Wicks GA, Welsby SM (1994) A survey of fallow practices and weed floras in wheat stubble and grain sorghum in northern New South Wales. *Australian Journal of Experimental Agriculture* **34**, 229-236
- Fettell N, Gill HS (1995) Long-term effects of tillage, stubble and nitrogen management on properties of a red brown earth. *Australian Journal of Experimental Agriculture* **35**, 923-928
- Franzluebbers AJ, Arshad MA (1997) Soil microbial biomass and mineralizable carbon of water-stable aggregates. *Soil Science Society of America Journal* **61**, 1090-1097
- Freebairn DM, Connolly RD, Dimes J, Wylie PB (1997) Crop sequencing. In (Eds. AL Clarke, PB Wylie) "Sustainable Crop Production in the Subtropics-an Australian Perspective" pp 289-305 (Queensland Department of Primary Industries: Toowoomba, Qld)
- Heenan DP, Taylor AC, Leys AR (1990) The influence of tillage, stubble management and crop rotation on the persistence of great brome (*Bromus diandrus* Roth). *Australian Journal of Experimental Agriculture* **30**, 227-230
- Jones OR, Hauser VL, Popham TW (1994) No-tillage effects on infiltration, runoff, and water conservation on dryland. *Transactions of the ASAE* **37**, 473-479
- Hoyle FC, Murphy DV (2006) Seasonal changes in microbial function and diversity associated with stubble retention versus burning. *Australian Journal of Soil Research* **44**, 407-423
- Kneipp J, Serafin L (2006) Grain sorghum: NSW planting guide 2006-07. Primefact 266 (NSW Department of Primary Industries: Orange)
- Li YX, Tullberg JN, Freebairn DM (2007) Wheel traffic and tillage effects on runoff and crop yield. *Soil and Tillage Research* **97**, 282-292
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Llewellyn RS, D'Emden F, Gobbett D (2009) Adoption of no-till and conservation farming practices in Australian grain growing regions: current status and trends. Report for SA No-till Farmers Association and CAAANZ, 41pp
- Luo ZK, Wang EL, Sun OJ (2010) Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: A review and synthesis. *Geoderma* **155**, 211-223
- Lupwayi NZ, Arshad MA, Rice WA, Clayton GW (2001) Bacterial diversity in water-stable aggregates of soils under conventional and zero tillage management. *Applied Soil Ecology* **16**, 251-261
- Lyon DJ, Stroup WW, Brown RE (1998) Crop production and soil water storage in long-term winter wheat-fallow tillage experiments. *Soil and Tillage Research* **49**, 19-27
- Marley JM, Littler JW (1989) Winter cereal production on the Darling Downs – an 11 year study of fallowing practices. *Australian Journal of Experimental Agriculture* **29**, 807-827
- McGarry D, Bridge BJ, Radford BJ (2000) Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. *Soil and Tillage Research* **53**, 105-115
- McMullen G, (2014) Row spacing in winter crops – the cost of wider rows. Grains Research Update Northern Region, Issue 75
- Norwood C (1994) Profile water distribution and grain yield as affected by cropping system and tillage. *Agronomy Journal* **86**, 558-563
- O'Leary GJ, Connor DJ (1997a) Stubble retention and tillage in a semi-arid environment: 1. Soil water accumulation during fallow. *Field Crops Research* **52**, 209-219
- O'Leary GJ, Connor DJ (1997b) Stubble retention and tillage in a semi-arid environment: 2. Soil mineral nitrogen accumulation during fallow. *Field Crops Research* **52**, 221-229
- Olson KR (2010) Impacts of tillage, slope, and erosion on soil organic carbon retention. *Soil Science* **175**, 562-567
- Osten VA, Walker SR, Storrie A *et al.* (2007) Survey of weed flora and management relative to cropping practices in the north-eastern grain region of Australia. *Australian Journal of Experimental Agriculture* **47**, 57-70
- Page KL, Dalal RC, Pringle MJ *et al.* (2013) Organic carbon stocks in cropping soils of Queensland, Australia, as affected by tillage management, climate, and soil characteristics. *Soil Research* **53**, 596-607
- Peigné J, Ball BC, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? A review. *Soil Use and Management* **23**, 129-144
- Pittelkow CM, Linquist BA, Lundy ME *et al.* (2015) When does no-till yield more? A global meta-analysis. *Field Crops Research* **183**, 156-168
- Pratley JE (1995) Long-term investigations of the effect of tillage practices on crop production at Wagga Wagga, New South Wales. *Australian Journal of Experimental Agriculture* **35**, 885-892

- Pratley J, Urwin N, Stanton R *et al.* (1999) Resistance to glyphosate in *Lolium rigidum*. I. Bioevaluation. *Weed Science* **47**, 405-411
- Radford BJ, Key AJ, Robertson LN, Thomas GA (1995) Conservation tillage increases soil water storage, soil animal populations, grain yield and response to fertiliser in the semi-arid subtropics. *Australian Journal of Experimental Agriculture* **35**, 233-32
- Radford BJ, Thornton C (2011) Effects of 27 years of reduced tillage practices on soil properties and crop performance in the semi-arid subtropics of Australia. *International Journal of Energy, Environment and Economics* **19**, 565-588
- Rew LJ, Medd RW, Van de Ven R *et al.* (2005) Weed species richness, density and relative abundance on farms in the subtropical grain region of Australia. *Australian Journal of Experimental Agriculture* **45**, 711-723
- Robertson LN, Kettle BA, Simpson GB (1994) The influence of tillage practices on soil macrofauna in a semi-arid agroecosystem in northeastern Australia. *Agriculture, Ecosystems and Environment* **48**, 149-156
- Rodriguez D, Cox H, deVoil P, Power B (2014) A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. *Agricultural Systems* **126**, 50-61
- Rodriguez D, de Voil P, Hudson D *et al.* (2018) Predicting optimum crop designs using crop models and seasonal climate forecasts. *Science Report* **8**, 1-13
- Rodriguez D, deVoil P, Power B *et al.* (2011) The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. *Field Crops Research* **124**, 157-170
- Rodriguez D, Sadras VO (2007) The limit to wheat water-use efficiency in eastern Australia. I. Gradients in the radiation environment and atmospheric demand. *Australian Journal of Agricultural Research* **58**, 287
- Sadras VO, Hayman PT, Rodriguez D *et al.* (2016) Interactions between water and nitrogen in Australian cropping systems: physiological, agronomic, economic, breeding and modelling perspectives. *Crop and Pasture Science* **67**, 1019-1053
- Serafin L, McMullen G (2015) Sorghum agronomy to manage risk and improve yield in the western zone. www.grdc.com.au/resources-and-publications/grdc-update-papers
- Serraj R, Siddique KHM (2012) Conservation agriculture in dry areas. *Field Crops Research* **132**, 1-6
- Singh V, Nguyen CT, van Oosterom EJ *et al.* (2015) Sorghum genotypes differ in high temperature responses for seed set. *Field Crops Research* **171**, 32-40
- Soane BD, Ball BC, Arvidsson J *et al.* (2012) No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil and Tillage Research* **118**, 66-87
- Stinner, BR, House, GJ (1990) Arthropods and other invertebrates in conservation tillage agriculture. *Annual Review of Entomology* **35**, 299-318
- Strong WM, Dalal RC, Weston EJ *et al.* (1996) Sustaining productivity of a vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes. 2. Long-term fertiliser nitrogen needs to enhance wheat yields and grain protein. *Australian Journal of Experimental Agriculture* **36**, 665-674
- Thomas GA, Titmarsh GW, Freebairn DM, Radford BJ (2007) No-tillage and conservation farming practices in grain growing areas of Queensland – a review of 40 years of development. *Australian Journal of Experimental Agriculture* **47**, 887-898
- Tullberg J (2010) Tillage, traffic and sustainability – A challenge for ISTRO. *Soil and Tillage Research* **111**, 26-32
- Tullberg JN (2000) Wheel traffic on tillage draught. *Journal of Agricultural Engineering Research* **75**, 375-382
- Vogt S, Verrall G (2018) Utilising machinery to increase profit. GRDC Groundcover supplement: Profit Drivers, Issue 132
- Wardle DA (1995) Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices. *Advances in Ecological Research* **26**, 105-185
- Walker SR, Taylor IN, Milne G, Osten VA, Hoque Z, Farquharson RJ (2005) A survey of management and economic impact of weeds in dryland cotton cropping systems of sub-tropical Australia. *Australian Journal of Experimental Agriculture* **45**, 79-91
- Webb AA, Grundy MJ, Powell B, Littleboy M (1997) The Australian sub-tropical cereal belt: soils, climate and agriculture. In (Eds. AL Clarke and PB Wylie) "Sustainable Crop Production in the Sub-tropics: An Australian Perspective" pp 8-23 (Queensland Department of Primary Industries: Brisbane)
- Wicks GA, Felton WL, Murison RD, Martin RJ (2000) Changes in fallow weed species in continuous wheat in northern New South Wales, 1981-90. *Australian Journal of Experimental Agriculture* **40**, 831-842
- Wildermuth GB, Thomas GA, Radford BJ *et al.* (1997a) Crown rot and common root rot in wheat grown under different tillage and stubble treatments in southern Queensland, Australia. *Soil Tillage Research* **44**, 211-224

PART II – MANAGING SOIL AND STUBBLE



Bad old days: Mouldboard ploughing in clay soils (year) – sheen of polished surfaces that bake hard and require ‘defensive tillage’ (Courtesy: Jim Pratley)



On the journey: Direct drilling at Wagga Wagga (year) after a clean burn (Courtesy: Jim Pratley)



Compromises: Cool, late stubble burn Wagga Wagga (year) for summer cover but less issues with stubble at seeding with stubbles (Courtesy: Jim Pratley)



Challenges: Stubble trouble with high residue load (around 7 t/ha), long straw and inadequate machinery clearance (Courtesy: Jim Pratley)

Chapter 6

Machinery evolution for conservation agriculture

Jack Desbiolles, Chris Saunders, James Barr, Glen Riethmuller, Gary Northover, Jeff Tullberg and Diogenes Antille

Introduction

Australia lies among the top five countries worldwide to adopt *en masse* conservation agriculture (CA) farming systems (Kassam *et al.* 2015). No-till (NT) practice is still growing having reached 80-90% of crop area in many regions (Llewellyn *et al.* 2012, see also Chapter 2). This unprecedented rate of change has led to a rapid evolution in machinery for CA systems. This chapter reviews the evolution of machinery for CA systems witnessed in Australia over the last 30 years. It is structured around 4 key groups of machinery, namely tractors as the power source, crop seeding/planting, spraying and harvesting machinery covering the key phases a crop establishment, protection and grain harvesting. A final section also covers the topic of controlled traffic farming (CTF) and associated machinery adaptations, as CTF plays an increasing role in Australian cropping, occupying an estimated 22% (6.75 M ha) of grain cropping area (ABS 2017).

Tractor market evolution in Australia 1989-2017

Some 23% of farms now crop more than 1,200 ha (ABARES 2018). While 25% of cropping farmers are rated as high innovators, CA cropping equipment is shown to be the most common type of innovation adopted by Australian farmers (Nossal and Lim 2011). Australia's agricultural machinery market has undergone significant changes over the last 30 years and has been subjected to the various highs and lows of the cropping industry. Tractor demand is often considered the litmus test for the health of the agricultural sector by the machinery industry at large and, over the last ten years, the industry has shown record demand in Australia for new tractors. The agricultural machinery industry currently separates tractor sales below and above 60 horsepower (HP) – 44 kilowatt (kW) – segregating the rapidly evolving hobby farm/lifestyle market from the traditional farming sector, respectively. Table 1 depicts selected trends within the >60HP tractor market, highlighting the increasing diversity of models, the predominant role of front wheel assist tractors and the decrease in average size in the top 10 selling tractors since the mid-2000s, explained by the increasing availability of lower priced tractors originating from Asia.

The range of tractor brands has not changed greatly over the past 30 years (Table 1), but there have been several mergers and consolidations, one of which includes the gradual merging of tractor brands under CNH Global such as Ford-New Holland (1986), Fiatagri (1991), Case-IH and Steyr (1999), restructured in 2013 under the *New Holland Agriculture* brand, part of the CNH Industrial Group. Similarly, AGCO Corporation purchased a large number of farm machinery companies, including Massey Ferguson (1994), Fendt (1997), Challenger (2002) and Valtra (2004) tractors. Smaller mergers in Europe have included the SDF company created in 1995, from a gradual merging of SAME Trattori with Lamborghini Trattori (1973), Hürlimann (1979) and Deutz-Fahr (1995) tractor brands. These mergers have consolidated manufacturing locations for these brands and intensified dealership sales, service and backup activities. Over the period, new brands have also appeared on the market, particularly lower cost brands from Eastern Europe and later from Asia.

In 2017, the Australian tractor market stood at \$1.32b (TMA 2017), remaining above the \$1b threshold for the 10th year in a row: 36.5% (=4,632) of the total number of tractors (=12,674) were dedicated to the lifestyle market sector (less than 60 HP), which continues to increase annually at a rate of 5-10%. In the traditional farming sector, the average tractor size continues to rise, *e.g.* from 131 HP in 2007 to 163 HP in 2017. The average cost of horsepower in this sector increased from \$801 (2008) to \$888 (2017), in contrast with the lifestyle market sector, where the average cost per HP, fell from \$731 (2003) to \$657 (2017).

Table 1. Snapshot at 5-year intervals of tractor sales and key market features in Australia

Year	>60HP market units	annual size,	Type: % 2WD / FWA / 4WD (track)	HP of top 10 selling tractors	Notes
1989	6,382		24% / 70% / 6% (-)	77	14 brands (295 models)
1994	5,083		13% / 78% / 8% (-)	109	14 brands (301 models), track machines appear and show promise
1999	6,484		5% / 84% / 8% (4%)	140	17 brands (326 models)
2004	7,633		2% / 91% / 6% (1%)	161	13 brands (392 models) – market adjusting to post-brand merger period
2009	7,864		1.5% / 93% / 5% (1%)	128	16 brands (458 models) – new brands appear, stronger demand for lower power row crop and high-end utility tractors
2014	6,411		1% / 91% / 4% (4%)	102	17 brands (496 models) – increased model customization via direct factory ordering. 60-100 HP utility market demand continues
2018	7,909		2% / 92% / 3% (3%)	103	15 brands (535 models) – Above trends continue

Source: Tractor Machinery Association State of the Industry reports, for the respective years shown

Keys: 2WD: 2-wheel drive, FWA: Front wheel assist, 4WD: 4 equal wheel drive, HP: Horsepower

Evolution in tractor technology

Tractors with diesel engines provide the main power source in CA systems. The features of modern tractors provide a far more adaptable and functional unit than in the past, with technologies that assist in driver comfort, safety and farm management. Overall, tractors have become more powerful for their weight and size and can run longer on a given tank of fuel; they are cleaner for the environment and have also become mechanically more reliable.

Engines

The 1990s brought a boom in engine improvements, transmission features, and use of electronics along with many other evolutionary advancements that have made tractors what they are today. Engines have become more powerful, more energy efficient, less noisy and smoother running; in part due to the introduction of electronic common rail direct injection technology, using high-pressure fuel rail and computer controlled electronic injectors able to promote complete and accurate fuel combustion. While the emission control strategies and tail pipe emission standards of agricultural vehicles lags behind those of road transport vehicles (Kubsh 2017), current US based Tier-IV regulations (Equivalent to EU based stage IV regulations) for non-road diesel engines used in agriculture, gradually phased in since 2008, have forced manufacturers to achieve a 90% reduction in particulate material and 50% reduction in nitrogen oxides over Tier I levels of the mid-1990s. This was achieved using dedicated control technologies (*e.g.* John Deere 2019a).

In the Agriculture sector, there is currently no cost-effective substitute for diesel power which allows Australian agriculture to produce more output with less energy inputs. New Holland have commercially available tractors (T6.140 and T6.180) using *FTP Industrial* engines that run on methane or biogas, which is most economical where it can be produced on-farm (New Holland Agriculture 2019).

Transmissions

A tractor transmission converts power from the engine into useful tractive effort on the ground, and most R&D efforts have aimed to reduce losses due to friction and heat, and optimise the transmission ratios available in the key implement operating speeds to keep the engine running at peak performance, including minimal fuel consumption.

The main advance in recent years has been in the development of continuously/infinately variable transmission (CVT, IVT) and hybrid power shift transmissions that provide a much greater (or infinite) choice of ground speed for all field and road operations. In 1995, Fendt introduced the world's first tractor with continuously variable transmission, and this set a benchmark for user control. In 2012, John Deere released its direct-drive transmission which combines the efficiency benefits of a manual shift transmission with the ease of operation of the IVT™ transmission (Figure1).

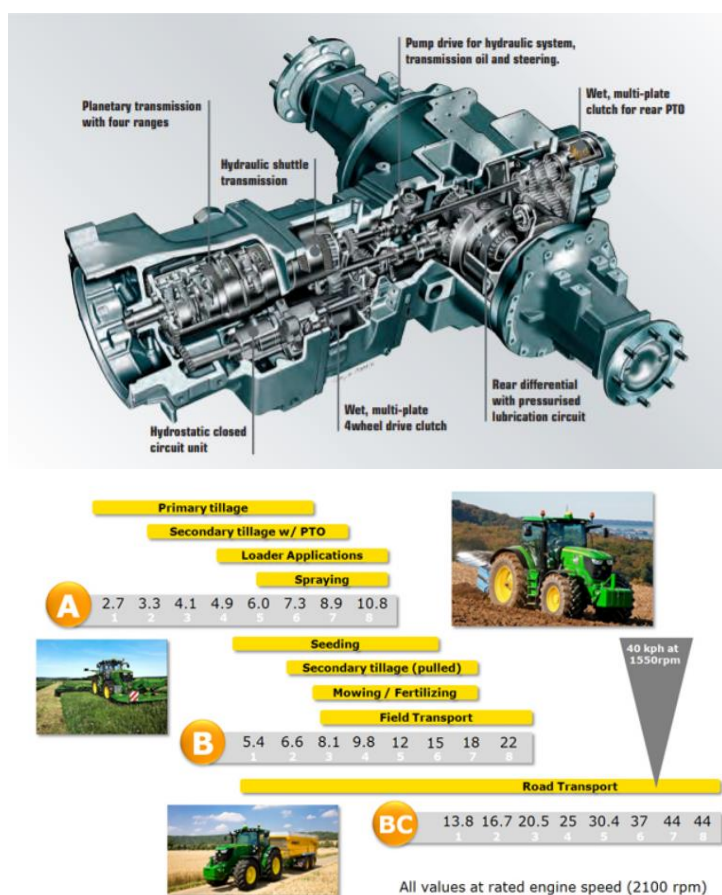


Figure 1. CVT/IVT transmissions have revolutionised tractor operational efficiency:

Top: TTV 610 drive train from ZF/Deutz-Fahr integrating stepless hydrostatic powershuttle offering automatic, PTO and manual driving strategies over 0-50 km/h speed range (graphic illustration courtesy of Deutz-Fahr);

Bottom: 8 automatic powershift gears over 3 ranges offered by the direct drive IVT from John Deere (diagram courtesy of John Deere)

In addition to improvements in the working gear range, transport speeds have also increased rapidly since the 1980s. With the introduction of the JCB FastTrack which was capable of travel speeds of ≈ 70 km/h, most tractor manufacturers have now increased their road speeds to 40-50 km/h. Such travel speeds have been accompanied by suspension and braking improvements to meet regulations and safety standards and allow for increased productivity of such activities as spraying and fertiliser application, along with lighter service activities and road carting, indirectly improving the overall tractor use productivity.

The improvements in transmission technology have led to efficiency improvements in the field, allowing either the farmer to intervene with gear change under load, or the tractor to automatically choose the optimum gear ratio to maintain optimum engine performance; the operational speed is kept at its targeted optimum (power or fuel consumption) by a dedicated control system with a user-friendly interface, improving operator comfort.

Tyres and tracks

Critical aspects of a tractor are its tractive performance and ground pressure affecting the extent of traffic-induced compaction, especially in CA systems where compaction removal by tillage is often not an acceptable option. As the size, weight and power of tractors have steadily increased, the need to support this weight and transmit higher power to the ground has amplified. Commonly, the number of tyres per axle can be increased while also reducing their inflation pressure. This increases the overall footprint of the tractor and adds extra load to each axle. An alternative exists in the rubber track system, which was first introduced as the Mobile-Trac System by Caterpillar in 1986. Evaluation of the benefits of tracks over dual wheels sustained strong marketing debates across the tractor industry over the ensuing three decades. In 1996, Case IH introduced their Quadtrac system, for articulated tractors giving more traction and less ground pressure than 12 tyres (x3 per wheel hub) on a 4WD tractor and eliminated power hop to provide a smoother ride. Today, many manufacturers offer competing tracked versions or alternatives, some with narrower profile and footprint adoptable for controlled traffic systems, many of which can now be specified on particular centre spacing to suit a chosen CTF system. The benefits of track systems have also been extended to trailers, air-seeder carts and harvesters, to reduce soil compaction.

In conventional front wheel assist tractor configurations, an alternative to tracks is to reduce the ground pressure under the tractor via a central tyre inflation system (*e.g.* Tigges 2015). Fendt have integrated this technology (VarioGrip) as standard on the latest 1000 Vario series tractors powered with up to 517 HP. In conjunction with Michelin tyre development, PTG launched in 2018 a fully ISOBUS compatible retrofit system that can automatically reduce and increase tyre pressure on the go from 0.4 bar to 2.0 bar suitable for optimum traction and minimum compaction in field operations and for optimum road transport efficiency, respectively (Figure 2).



Figure 2. *Left:* Track suspension technology improving the riding stability in rough terrain (*e.g.* ATI Inc. Power-Flex Trax™ with Terraform™ suspension), *Right:* New adaptive tyre technology (*e.g.* Michelin EvoBib) maximising footprint under field setting (0.4 bar) vs optimum road footprint at 1.8 bar via the use of a central tyre inflation system (pictures courtesy ATI and Michelin, respectively)

Cabin technology

With cropping areas continuously increasing, the time spent by farmers on tractors has increased the demand for greater cabin comfort. In a similar way that the car industry has increased the comfort and safety of cars over the past 20 years, a similar standard is now expected in tractors, to provide better working conditions and reduce operator fatigue. In 1987, Renault became the first tractor manufacturer to introduce the *hydrostable* cab, a full cabin suspension with coil springs dampers and anti-roll bars; this was a system employed on their trucks and was claimed to reduce cab vibration by 35% (Henley 2017). Cab suspension is now commonplace throughout modern tractors, and front axle suspension is considered standard in front wheel assist tractors. New means of adding suspension comfort to fully tracked tractors is also becoming more common, *e.g.* the TerraformTM suspension, which improves load distribution, uniformly follows ground contours and greatly reduces vibration (Figure 2).

System controls

Electronics have played a significant role to increase the efficiency of CA over the past decade and have been pivotal in many areas of tractor development and improvement. Key areas such as engines, transmission, hydraulics and linkage control and, most recently, headland management have improved tractor operations. Additionally, the key area of differential global positioning systems (DGPS) guidance with Real Time Kinematic (RTK) accuracy, autosteering control and many other associated precision agricultural functions have added to the tractor ease of functionality. This technology is at a stage where pre-prescribed areas and operations can be pre-programmed by the manager and the tasks completed with minimal input from the operator. The driver is there to monitor and provide redundant safety in case of system error. This is a natural interim step before fully autonomous tractors become common place. A key electronic advancement is embodied in the ISO 11783 Standard (ISOBUS) specifying a serial data network for control and communications between tractor and implement, and the associated message-based protocol for Controller Area Network (CANBUS) applications. This standardised communication protocol into pairing any tractor and implement increases the practical functionality and safety, allows more automated connection, set-up and operation to maximise productivity while minimising the user input.

As the amount of work that needs completing in a timely manner increases at the farm level, the impact of technology breakdown is becoming much greater. The development of telematics and tractor sensing systems allows monitoring of tractors and attached equipment in the field from a remote site or location. This has become more common over recent years for applications such as fleet logistics and scheduling preventive maintenance (*e.g.* John Deere 2019b). In the latter, trends in operating conditions can be logged and predictions of potential failures can be made, reducing the risk of untimely breakdown and optimising the productivity of tractor operations. This means that components and parts that are suspect or near to end-of-life or replacement period can be swapped or replaced preventively during scheduled down-time before the next critical period of work to help guarantee reliability and productivity.

Look into the future

Although FPT Industrial, the supplier of engines to both CASE and New-Holland tractors, have had methane and biofuel running engines used in trucks throughout Europe since 2016, such technology is unlikely to make a big impact in the Australian sector. EU Stage V certified engine technologies have recently appeared in the tractor markets, ‘kick-started’ by the Deutz TTCD engines in 2017.

In 2016, John Deere introduced its SESAM (Sustainable Energy Supply for Agricultural Machinery) prototype technology in a world first fully battery operated electric high-performance tractor, with 174 HP of continuous power, 400 HP maximum output, and an autonomy of up to 4 hours depending on the operations conducted, including the ability to recharge from restoring energy source (Agri-Machinery News 2017). New Holland Agriculture and Fendt have concepts for electric/hybrid tractors, but this is unlikely to replace completely the power needed for current agricultural practices. If practice change can come about (*e.g.* through automation) then smaller lighter electric tractors may become an attractive

proposition. In the short term, markets are not quite ready for this still limited technology (*e.g.* Kanicki 2017), especially in the Australian context of large farms.



Figure 3. *Left:* DOT autonomous tractor and no-till seeder tested in Canada since 2017; *Right:* CNH industrial autonomous tractor concept (pictures courtesy of Norbert Beaujot, SeedMaster, and CNH respectively)

In 2017, DOT Technology Corp. of SeedMaster in Canada unveiled a U shape, autonomous powered platform concept, designed to slide on and off a range of dedicated implements (DOT 2017). This world-first concept of fully autonomous tractor and implement system was developed as a holistic answer to the future of farming including considerations of reduced field machinery weight. A 163 HP engine powers a standard DOT unit, incorporates safety halting features, relies on remote control by the operator for swapping implements and RTK GPS positional information to follow farmer-approved path-plans for field operations. The operator reviews progress in real time and can manage multiple units to suit the farm size. While it was first equipped with a 9 m wide precision seeder implement for field testing (Figure 3), mainstreaming this concept requires a full suite of DOT-ready implements, yet to be developed with existing manufacturers.

Similarly, in 2016, CNH announced their autonomous tractor concept (CNH Industrial 2016 – see Figure 3) featuring advanced obstacle detection technology. Initially suitable for integrating within existing operator-based machinery fleets, including as autonomous support vehicles, the concept aims to move towards increased autonomy over time, offering full control and optimisation via big data management.

An automated ‘whole of system’ approach, starting with autonomous tractors, and following through the implements, fleets and tendering machines to enable non-stop 24/7 operations with little to no human intervention, are likely to be most beneficial to Australian broad-acre CA systems. The barriers to such autonomous systems currently lie beyond the tractor and with the equipment attached. ISOBUS international standards go some way towards ensuring consistent communication between the implement and the tractor; more sensors and feedback are needed from the implement to the tractor in the absence of a human operator to check the quality and safety of work being carried out. The second barrier will always be the human and industry acceptance, as well as the regulation and legalisation around a completely autonomous farm.

The future of tractor development and functionality is likely to be driven from the main markets to which the manufacturers supply, *i.e.* USA and Europe. In these regions the regulations around emissions, fuel type availability and any autonomy restriction will probably drive the demand and therefore supply of these future technologies.

Evolution of no-till seeder technology

Overview

The crop seeding operation in Australian CA systems has been optimised over the last 40 years, from the early years of ‘trash farming’, aiming to reduce tillage and promote residual residue cover on the surface. Two of the three key principles of CA have the most direct impacts on seeder technology requirements, namely:

- minimising soil disturbance, via no pre-seeding cultivation and low soil disturbance at seeding; and
- permanent soil cover, including dedicated cover crops, intercrops and/or previous crop residue, with least disturbance or burial occurring at seeding.

The terminology around CA systems was addressed in the mid-1990s by the Western Australian No-Tillage Farmers Association in its early years of activities, leading to the following Australian framework followed to this day, despite not being matched internationally:

- *Direct seeding*: a one pass seeding operation into stubble, using a ‘full cut’ soil disturbance down to seeding depth;
- *No-till seeding*: a one pass seeding operation using a tyne seeder fitted with narrow openers creating distinct narrow furrows between undisturbed inter-row zones; and
- *Zero-till seeding*: A one pass seeding operation using a disc seeder to minimise furrow disturbance, soil throw and disruption to crop residue.

During this time, the evolution in seeder technology has benefited from an increased momentum of research, dedicated to optimising the performance of the seeding system, gradually recognising the significant impact of machinery on no-till (NT) crop performance. The seeding system is defined by the components of the seeder engaging with soil and residue, and responsible for the optimum delivery of furrow inputs, including seeds and fertiliser. The principles driving its performance have been described as independent of seeder scale (Desbiolles and Kleemann 2003) and commonly, five key functions are considered in a research setting: a) residue handling, b) furrow opening, c) fertiliser placement, d) seed placement, and e) furrow closing/ pressing. Over time, the seeding system technology quickly evolved, reflecting the advance in CA cropping systems, to encompass extra functions, such as: seed pressing, pre-emergence herbicide incorporation by sowing, row placement of other nutrients (*e.g.* trace elements), amendments (*e.g.* soil wetters, soil inoculants) and pesticides (*e.g.* fungicides, insecticides...), enabled in particular by the development of accurate liquid application technology, and stubble row relative positioning via GPS (*e.g.* inter-row and on-row).

Key milestones in seeding system evolution

Initially the need to address the physical context of i) high soil strength and ii) surface residue load drove the early focus of seeder machinery modifications. While the fundamental approach to crop seeding – *i.e.* continuous furrow systems – did not change in the transition from CT to NT, some key milestones of seeder technology development over the last 30 years can be recognised. These steps occurred initially under a process of low-cost upgrades of conventional (combine) seeders under a low risk approach to experiment with NT farming. A persistent process of trial and error, which underpinned the gradual improvements of NT seeder capacity and performance, was a common endeavour for many adopting farmers, who thereby played a key role in machinery innovation contributing to the success of NT farming in Australia. Overseas seeding technologies also underwrote the diversity of choice, most notably from Canada and the USA.

In winter grain cropping, the development in seeding system technology and capabilities included the following step-changes, some introduced in different forms at various times over the last 30 years (Kondinin 1993a, 2000):

- removing tilling tynes and re-distributing seeding tynes on combine drills;
- fitting narrow openers to minimise furrow disturbance;
- increasing the seeding tyne break-out rating;
- modifying the tyne layout by increasing the seed row spacing and the number of tool bars;
- matching seed banding boots to narrow furrow openers;
- maximising opener wear life and wear shape via cast steel, tungsten carbide tile and hardfacing technologies;
- implementing deeper furrows with sub-seed disturbance, to break-up the hard pan and address increasing *Rhizoctonia solani* root disease pressure;
- adapting furrow press-wheels to optimise crop establishment into stored soil moisture, including adaptation to maximise water harvesting potential of furrows;
- optimising tyne design and increasing frame layout clearances to maximise residue handling capacity;
- separating seed and fertiliser banding to enable higher nutrition inputs at seeding;
- hydraulic tyne release systems to improve reliability and longevity in harsh and stony soil conditions;
- adapting paired row and ribbon seeding for higher seedbed utilisation, to compensate for wider row spacing, maintain higher yield potential and greater competition against weeds;
- more accurate seed placement with independent press-wheel regulated seed boots;
- tyne opener adaptation for furrow moisture seeking down to 250 mm depth;
- controlled soil throw to optimise weed control efficacy and crop safety under pre-emergence herbicides incorporated by sowing (IBS);
- increased role of disc seeder technologies for higher quality CA systems;
- development of split banding options for disc seeders;
- technology enhancement for sticky soil conditions, including self-cleaning press-coils;
- mainstreaming of contour-following seeding tynes to ensure row accuracy on increasingly wider seeders;
- liquid application technologies for in-furrow nutrition, amendment and disease/pest management at seeding; and
- high-speed compatible, low soil throw (bentleg) tyne opener technology (Barr *et al.* 2016, 2019).

Evolution in seed and fertiliser dispensing

When initially converting to NT seeding, the seed/fertiliser hoppers on combine drills were raised to accommodate the larger underframe tyne layouts, and splitter cups were adapted to accommodate dual banding arrangements (Kondinin 1993a). However, it is the air-seeding configurations, where seeds and fertiliser were centrally metered, and conveyed by air to furrow openers across the seeding implement, which achieved the necessary capacities required on large farms (Figure 4). Air-seeding technology arose from an Australian invention by Albert Fuss in 1956, who thereafter founded the Gyrall Implements company in Dalby, Qld. Today's air-seeder technologies can reach up to 47 m³ in volume capacity and have the ability to meter up to seven products (*e.g.* seeds, liquid/granular fertilisers, inoculants, amendments), including granular and liquids. The air-carts exist as frame-mounted, tow-between or tow-behind models, while their latest features include auto-section control, GPS controlled variable rate, self-adjusting calibration, fast-fill auger/conveyor system, track-axle option, monitoring cameras, and fast hopper clean-out.

The centralised metering of air seeders requires splitting in multiple stages to reach individual seeding rows, leading to variable splitting accuracies. In contrast, fast metering seed-row specific roller technology has been extended to air seeders to improve the delivery rate uniformity across seed rows and also contribute to more uniform distribution along the seed row when combined with low speed downslope air-assist delivery to row openers (*e.g.* Ultra-Pro II metering system, SeedMaster 2017). The row by row control of metering technology has recently taken a new dimension with the CX6 Smart



Figure 4. Large scale air seeder CA equipment for broadacre crops are commonly 12-24 m wide, set at 220-300 mm seed row spacing and can sustain effective work rates in the range of 15-25 ha/hr (picture by Jack Desbiolles)

Seeder, launched in 2017 by Canadian innovation company *Clean Seed Capital Group*. It offers simultaneous electronic metering of up to 6 products above each opener, GPS based corrections for overlap and curve sowing compensation. The 45 tonne, 18.7 m wide air-seeder bar also features an innovative triple shoot opener and offers a unique flexibility to deliver a wide range of furrow configurations under high resolution prescriptions row by row across the paddock (Clean Seed Capital Group 2019).

In parallel, the development of CA seeder bar implements has continually increased in width, reaching up to 27 m with double fold option for transport, and up to 65 m with end-tow transport mode. Various implement features, such as floating hitch, flexible sectional frames, parallel lift, fixed frames with rising openers, and centralised depth adjustment provide a range of specific benefits able to improve the efficacy and efficiency of crop seeding operations, such as improved contour following, high floatation, adjustable furrow till depth ‘on the go’, and swapping versatility between single/double row spacing. The scale of Australian seeders is perhaps best illustrated by the Guinness world record achieved in 2010 by the John Coggan Family in Meandarra, Qld, using a 36 m wide Multi-Planter to sow 905.5 ha of wheat in 24 hours.

Tyne versus disc seeding systems

In the Australian context, the dominant seeder technology over the last 30 years has remained the tyne seeders, whereby the ‘narrow point + press-wheel’ system (*e.g.* Figure 5a) has been widely acknowledged as the cornerstone of Australian NT farming. Its key features include the ability to till below the seed zone and separate seeds from fertiliser within the furrow to improve seedling vigour and control risks of fertiliser toxicity (GRDC 2011). The tyne-press wheel system has also been adapted to maximise the water harvesting capabilities of NT furrows, to achieve deeper moisture seeking and to increase the seedbed utilisation by the use of paired row or band sowing attachments (Moodie and Desbiolles 2016). Tyne-press wheel systems have enabled the safe application of pre-emergence herbicides immediately prior to sowing and mechanically incorporated by the seeding system. This technique developed in Australia requires physical separation of the herbicide from the seed zone to be successful, which is commonly achieved in the process of furrow opening from the associated lateral soil throw over the inter-row under a controlled speed (Haskins 2012). Such requirements emphasise the need to control the furrow opener soil disturbance characteristics in order to achieve uniform incorporation for reliable weed control and maintain high levels of crop safety.



Figure 5. (a) A majority of CA seeders in Australia use tyne seeding systems, (b) Recent interest in disc seeding systems is especially increasing among long term CA farmers (pictures from Jack Desbiolles)

In contrast, the interest in zero-till (ZT) disc seeders (*e.g.* Figure 5b) has resulted in a period of significant development over the last 12-15 years, mainly in line with a focus on reduced soil disturbance to improve CA ‘quality’. Disc seeding systems include single, double and/or triple disc blade assemblies as well as hybrid disc-blade systems, and their benefits relative to tyne systems have been reviewed by Ashworth *et al.* (2010). Incentives to adopt ZT include the ability to reduce soil and residue disturbance, maximise work rates and facilitate full crop residue retention (Desbiolles 2011). The fundamental differences in furrow opening process between a narrow point and a disc blade means crop safety is not easily achieved with pre-emergence herbicides, most of which are not registered for use with disc seeders. Research has demonstrated that crop safety is highest with triple disc seeders or when using row cleaners to remove herbicide contaminated surface soil over a narrow band ahead of the seeding disc blade (Kleemann *et al.* 2014).

RTK auto-steering: A significant tool assisting CA

Tractor GPS guidance with RTK differential correction delivers repeatable 2 cm auto-steering accuracy across the farm, season after season, and enables several ‘precise row sowing’ strategies, such as:

- *Inter-row sowing* (Figure 6a): sowing centrally between existing stubble rows to solve implement blockage (tyne seeder) and residue hair-pinning (disc seeder) issues. This technique also provides several valuable agronomic benefits such as improved crop establishment and grain yield, lower crown rot disease (*Fusarium* pathogens) incidence, better harvestability of low-lying pulses and greater efficacy of pre-emergence herbicides (McCallum 2007); and
- *Edge row sowing* (Figure 6b): close to the side of existing stubble rows to benefit from the improved soil moisture, nutrition and biology present within the old furrow, while keeping the standing stubble intact. This technique ideally uses side-banding seeding systems with a row-based guidance system, but is often practiced with paired-row sowing under GPS guidance for ease of adoption. Edge row sowing is critical for establishing uniform CA crops in low fertility, water repellent sands.
- *On-row sowing*: is an alternative technique to edge row sowing, easier to implement at the paddock level with mainstream seeding systems and GPS guidance, but with the key drawback of uprooting and bunching existing standing stubble.

Research is currently investigating the impact of cumulative edge row sowing within a permanent row zone, as a way to enhance the seed row fertility and productivity on deep sands (Desbiolles *et al.* 2017). Where the seeder tracking behind the tractor is not sufficiently stable, some passive and active implement steering options exist to guide the implement more precisely onto the intended path (Desbiolles 2017).



Figure 6. Example inter-row sowing (a) and ‘edge row’ sowing (b) of barley crops into wheat stubble. Both techniques require GPS autosteer guidance with RTK accuracy, and may benefit from additional GPS steering of the implement (pictures from Jack Desbiolles)

Innovation in residue cutting technology

A novel approach to crop residue handling at sowing has been the commercial development, led by the South Australian No-Till Farmers Association, of the *Aqua-Till™* ‘liquid coulters’ (Figure 7), which uses ultra-high pressure (UHP) waterjet cutting technology to slice very large amounts of surface residue ahead of a disc or tyne seeding system. Recent evaluation by Taki *et al.* (2018) showed residue cutting was most effective under wet and compressed conditions. Liquid herbicides have also been successfully applied under the *Jetacide™* adaptation of the technology for the termination of cotton ratoons after harvest (Butler 2018), enabling rapid NT establishment of follow-up winter grain crops. A current research adaptation of UHP liquid-jet technology focusses on the banding of amendments (*e.g.* gypsum, lime, and nano-carbon liquids) below furrow depth in order to mitigate specific constraints at the furrow scale.



Figure 7. Recent research showed the Aqua-Till™ waterjet cutting capacity of wheat residue is proportional to the nozzle orifice area, and exceeds 35 t/ha with a 0.3 mm nozzle size (picture from Greg Butler)

Precision planter technologies

Precision planters used for summer grain crops on up to 1 m row spacing have evolved significantly since the 1980s, when mechanical singulation technology was still competing with early versions of single row vacuum pick-up plate and pressurised drums, and mechanical ground drives combined

sprocket ratios with plate hole numbers to adjust seed population per ha (Kepner *et al.* 1986). While double disc openers have remained the common basis of most planter row units, today's technology incorporates many innovations which play an active role to maximise performance and efficiency of wide row crop planting in CA systems. These include:

- High speed capable, vacuum or pressure-assist seed singulation systems, coupled with assisted delivery into the furrow to achieve consistent plant-to-plant spacing on every row;
- Singulation plates optimised for many seed types and sizes, increasingly including winter grain crops;
- Hydraulic over mechanical drive upgrade with GPS based control systems enabling ground drive equivalence, variable rate by prescription zone and row level swath control via individual clutches, for row auto shut-off to cancel overlap over headlands;
- Electric drive on individual row units enabling similar row by row variable rate control GPS-based, with additional benefits such as self-adjusting individual feed rate to maintain constant plant spacing when planting on curves;
- Controlled down pressure to achieve constant furrow depth across variable strength soil types, and ensure consistent seed placement;
- Controlled down force over furrow closing to tailor to the seed agronomic requirements in soil specific conditions; and
- Most recently, 'on-the-go' sensing of in-furrow data (*e.g.* *Smart FirmerTM*, Precision Planting 2019) such as organic matter, moisture, temperature, cation exchange capacity and residue content to optimise – in true-time – furrow uniformity (via adjustable residue managers), seed placement depth into moisture (via self-adjusting gauge wheels) and seed/fertiliser rates matched to soil zone potential.

The precision management of seeding operations for winter grain crops is a recent innovation, which involves extending and adapting precision planter technologies (Figure 8) in particular to suit narrower spacing down to the 25-38 cm spacing range. The resulting uniform crop establishment at a consistent plant spacing on the row, combined with precision placement within the furrow, allows significant seed cost savings, especially when using high vigour graded (hybrid) seeds (*e.g.* 40-60% seed savings per ha achievable with hybrid canola). For the narrower row spacing broadacre applications, various bulk fill systems have been developed to integrate a centralised high capacity seed hopper, designed to continuously recharge the buffering mini-hoppers within each row singulation unit.



Figure 8. Precision planting technology adapted for winter grain crop sowing is the new frontier of CA mechanisation in Australia (picture from Jack Desbiolles)

Look into the future

The mechanisation of crop seeding continues to evolve in line with the expanding knowledge of successful CA cropping systems in Australia, and the ability to improve operational and agronomic efficiencies via greater integration of real time sensing and automation, in a precision agriculture framework. The current trends point to providing each individual seed (of calibrated vigour and potential) with an optimised furrow environment, row by row, with a view to maximise the yield performance of each individual plant across the whole paddock.

Innovation in sprayer technology

Without tillage, CA remains dependent on chemical applications to control weeds and pests. For weed control alone, farmers typically spray weeds before seeding as a non-selective ‘knock down’, immediately prior to seeding with soil applied pre-emergence chemicals, and during the season with multiple post-emergence sprays. The constant battle to conserve moisture in Australian conditions has also led to summer weed spraying becoming standard practice, with entire farms being sprayed (often multiple times) after major summer rainfall events. In addition, in-season pesticide, fungicide and foliar fertiliser applications, as well as end-of-season spray topping, make the sprayer arguably the most used implement in CA. The evolution of sprayer technology over the last 30 years was driven by the following requirements (GRDC 2017):

- Need for *timely applications* and therefore higher work rates (exacerbated by increased cropping area);
- *Minimise crop damage* leading to yield loss, especially from over-application due to overlaps, cross contamination of chemical mixtures between sprays and trafficking damage during in-season sprays;
- *Maximise application efficacy*, whereby the issue of herbicide resistance has become severe in Australian CA and any under-application or poor application quality can accelerate the selection for herbicide resistant weeds (Broster *et al.* 2019, see also Chapter 10);
- *More sophisticated chemistries*, providing a toolbox for selecting weeds in crop, and managing the development of herbicide resistance. However, with this sophistication came cost and as such, now every litre of chemical is monitored closely;
- *Sensitive cropping areas* (such as vineyards and cotton fields) in proximity to urban areas and organically grown farms requiring even more effectively controlled spray drift, especially during night-time spraying (enabled by tractor autosteer guidance and required by ever more demanding spraying programs), when high risk of surface temperature inversion occurs; and
- *Operator safety*, particularly with the handling of chemicals in the mixing processes.

Modern sprayer technology offers drastic improvements in work rates from a typical 30-40 ha/hr in the early 1990s to 80-90 ha/hr today; improved efficacy to minimise both under and over-application; high clearance machines, safe chemical handling processes and better controlled droplet size. Technology advances are summarised below by major components of a sprayer.

Trailed vs self-propelled

As little as 15 years ago, trailed boom sprayers dominated the Australian market, and a range of tanks and boom sizes were available to suit different farms. Self-propelled (SP) sprayers have now taken a major share in sales of the large farm-scale market, with growers chasing specific benefits including high work rates associated with larger tanks, wider booms, high effective speed through dedicated suspension systems, and minimised crop damage with high clearance chassis design. The 2017 estimated sales of SP sprayers alone in Australia was over \$250 M or 12% of the total major new machinery sales (TMA 2017). However, the significantly higher cost of self-propelled units currently limits their adoption on low to mid-scale farms.

Nozzle technologies

The nozzle function on a sprayer is to control liquid flow, convert (via atomisation) the spray liquid into suitable size droplets, and disperse the droplets in a specific pattern for the target application. Conventional *flat fan nozzles* (Figure 9a) with a spray angle between 80-110 degrees have been the most commonly used nozzles in CA and ISO standards (ISO 1984-2018) have been in place since the 1980s linking recommended flow rates, operating pressures and droplet sizes with standardised nozzle colours and physical dimensions. Recent developments in flat fan nozzles has seen the pressure range increase, enabling lower pressures to generate coarser droplets and reduce drift. Reductions in spray drift risk has best been achieved with *pre-orifice* ‘low-drift’ nozzles and *air induction nozzles*. Pre-orifice nozzles (Figure 9b) contain a relatively large exit orifice compared with conventional flat fan nozzles and a smaller metering orifice close to inlet of the nozzle which causes a pressure drop and pre-atomisation. The combination of a pressure drop and large exit orifice minimise the atomisation of smaller droplets and therefore narrow the range of droplet sizes created to a coarser range. Air induction nozzles (Figure 9c) additionally draw air into a mixing chamber via a venturi effect. This creates larger air filled droplets, less prone to spray drift, which shatter on impact with the target to create smaller droplets. Nozzle orientation can also have an impact on spray drift and coverage. *Twinjet* (Figure 9d) and *dual pattern* nozzles, and fore/aft nozzle arrangements (Figure 10), improve coverage on vertical surfaces within the canopy, through standing rows of stubble and on rough surfaces.

The vast majority of spray nozzles come in fixed sizes, where pressure adjustments vary the flow rate to account for speed variations in the field. This can be achieved through the spray control unit, although droplet size and nozzle performance are very sensitive to pressure. Low pressures cause inconsistent spray patterns resulting in poor coverage. High pressures increase the proportion of fine particles, increasing the risk of spray drift (GRDC 2017).

Multi-tier nozzles (double, triple and quad – e.g. Figure 10) have been developed and paired with electronic control systems to swap automatically between nozzles, increasing the effective range and providing a level of optimisation to suit the impact of variable operating speed on desired droplet size. *Pulse-width modulation* (PWD) is an alternative approach to control flow rate at the nozzle (Giles *et al.* 1996). PWD technology pulses a solenoid to actuate a diaphragm, closing flow from the nozzle based on an inputted duty cycle. The duty cycle typically can close the nozzle up to 10 times per second limiting the flow to between 20-100% of its full capacity and providing the ability to limit the rate of chemical application ‘on-the-go’ as speed varies. Importantly this can be achieved with minimal change to the pressure, providing a consistent droplet size and spray pattern. Having such sophistication at the nozzle level increases cost but enables variable rates for site specific management, or the ability to shut off nozzles for a high resolution section control.

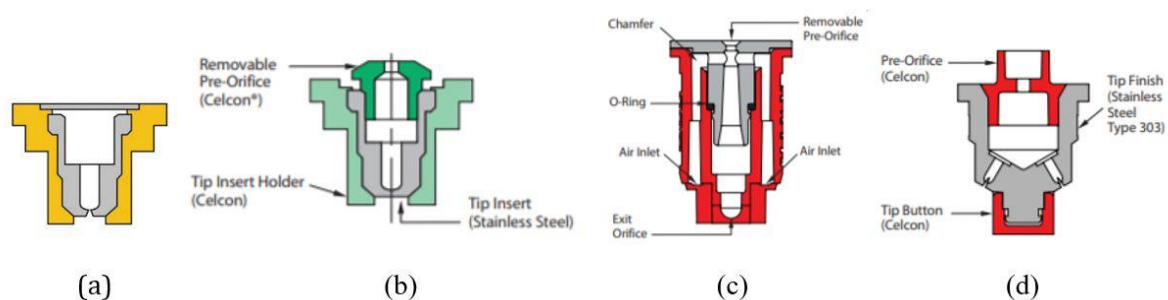


Figure 9. Example flat fan nozzle technologies: conventional (a), pre-orifice low-drift (b), air-induction (c), twin-jet (d) (diagrams courtesy of Teejet Technologies).



Figure 10. Fore/aft dual (left) and multi-tier (right) nozzle arrangements (pictures courtesy of Teejet Technologies)

Boom design and height control

Boom stability while cornering and navigating across the paddock is critical for spray accuracy. Height movements in the boom from vertical movement or a rolling action reduces spray quality – in the worse cases leaving unsprayed strips, concentrating chemicals in hot spots, generating boom damage from ground strikes, or increasing the risk of spray drift (Heidary *et al.* 2014). The acceleration of the boom tips while turning can induce yaw in the boom and cause speed differentiations over the boom length, therein reducing spray quality. With the demand for higher work rates driving boom widths up to 54 m and operating speeds in excess of 30 km/h, maintaining a stable boom is a challenge. Modelling research by Langenakens *et al.* (1999) showed spray deposits could vary between 0-760% under large sprayer boom rolling motion and vertical deformations, due to excessive speed.

Boom stability has been greatly improved by isolating its movement relative to the chassis. This has been achieved by minimising total chassis movement via improved axle suspension and through height control systems. Passive boom height control has been achieved with flexible boom centres in the form of fully supported, suspended and semi-suspended designs which have been available in the market for years (Kondinin 2001). Active boom height control is now being widely adopted, taking measurements of downforce on boom gauge wheels or, more commonly, through ultrasonic sensors to provide real time control over boom height uniformity. Unlike ground wheels, ultrasonic sensors cause no crop damage and are able to sense an often variable crop canopy height – a key advantage for in-season applications. Initial adoption of active boom height control was slow due to cost and the sampling frequency and response of the booms limiting performance at speeds above 20 km/h. However, these issues have largely been addressed and such sensors are almost a standard feature on newly purchased sprayers. The design of wider booms, more heavily loaded with nozzles, control units and sensors has forced manufacturers to investigate lighter and stronger materials to maintain structural integrity and boom stability. As a result, manufacturers are opting to move to aluminium truss booms – reducing boom weight by as much as 50%, and adopting the light, stiff and strong carbon fibre mast technology from the yachting industry.

Transfer systems

Mixing, pouring and loading chemicals onto the sprayer traditionally places the operator at risk. Closed loop transfer systems, which use suction to pump chemical from the commercial drum and mix into the main spray tank (sometimes via an induction hopper) safely isolate the operator from chemical exposure (Kondinin 2001). Chemical suppliers have adapted to safer operations by supplying re-fillable drums with quick fit attachments and measurement scales printed on the side. Re-fillable drums also save time in the cleaning process and eliminate environmental risks associated with disposal of non-refillable chemical drums.

Pumps and plumbing

At the heart of the spray technology is the pump which is used to pressurise and draw liquid from a tank. The liquid is pumped in two paths, to the boom section and nozzles, and back to tank to provide agitation and bypass return when the boom section is turned off. In its basic principle, the spray pump

technology has not changed in decades, although the capacity has grown to match increasing work rates. Rather, the technology advancements have come from the plumbing quality and functionality between tanks, pumps and nozzles – offering a range of options to control the flow of liquid and output at the nozzles, and options to mitigate the risk of contamination between mixes.

Sprayers now split wide booms into many sections, with liquid feeding centrally into each section reducing the extent of internal pressure drop. When paired with solenoid control valves and GPS technologies, this arrangement enables sectional shut off to reduce overlap in headlands: more sections, down to single nozzle level, increase the resolution and further minimise overlap. Flushing and rinsing between spray mixtures is typically achieved by opening a valve at the end of each spray section. Clean water flush tanks and recirculating booms have also been incorporated onto sprays booms to streamline this process for efficiency and efficacy.

Direct injection (DI) systems mix chemical and clean water in-line and enable the primary tank to contain water alone. This results in faster more efficient mixing, less chemical waste and a quicker cleaning process after spraying (Figure 11). The popularity of these systems is growing, driven primarily by the need to minimise cross contamination between chemical mixtures. However the cost, particularly when multiple products are commonly used, the inability to mix granular formulas, and the risk of exposure to concentrated chemicals during maintenance continue to limit adoption on a broad scale.

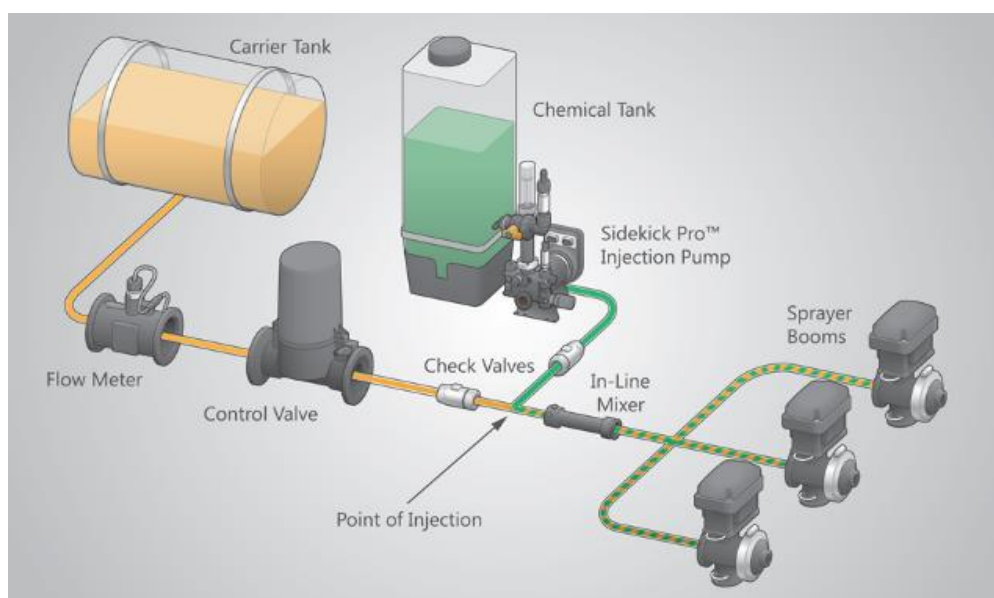


Figure 11. Example direct injection concept in sprayers – *Diagram courtesy of Teejet Technologies*

Weather Stations

The weather, in particular the temperature, water evaporation rate (ΔT) and wind speed, has a major influence on spray drift risk and application efficacy. Many product labels, and state or territory legislation, require operators to record wind speed, wind direction, temperature and humidity at the site of application for accountability and traceability. Hand-held weather stations are common place for this application, with more and more on farm weather stations, and tractor mounted weather stations being adopted. Regional weather station networks are being established within the farm community to record weather conditions at ground level, but also at a 10 m height for predicting temperature inversions, which drastically increase the risk of long-distance (2 km+) spray drift. These farmer-initiated infrastructures have been established with the intent to stay ahead of their duty-of-care to neighbouring industries and communities, and therefore reduce the risk of important chemistries becoming banned (PIRSA 2018).

Sensing

In an attempt to cut down the high chemical costs in blanket applications, sensors have been, and continue to be, developed for targeted weed spraying applications. The *WEEDit* (Figure 12) and WeedSeeker sensors, which use electro-optical sensors to detect plant chlorophyll and activate individual spray nozzles via electrical solenoids, have found commercial success and are currently being used in spot spraying applications of summer weeds. Major benefits for the CA systems are significantly reduced chemical use and the possibility to afford higher chemical dose improving the weed control efficacy and lowering the risk of weeds evolving herbicide resistance. Weed sensing technology can similarly be paired with actuators and mechanical weeding devices (rather than solenoids and spray nozzles), offering a chemical-free alternative (*e.g. Weed Chipper*) for ‘spot’ weed control (GRDC 2019).

A greater challenge is to detect weeds in the growing crop and to selectively apply chemicals. New sensor developments, such as the H-sensor by Agricon are combining red, near infrared and plant shape factors to achieve this. This technology has been tested in Australian conditions (Dimos *et al.* 2018) and can identify grasses within broadleaf species, but identifying individual species remains a challenge. Further, as the detection algorithms use shape factors, its field of view also limits performance and detection is only viable prior to canopy closure. The “green on green” sensor fitted as a limited release on the Agrifac 48 m sprayer is also being developed and uses a RGB camera and artificial intelligence with deep learning to target broadleaf weeds in cereal crops (Jourdain 2019). Despite the current issues, the importance of such technology should not be understated. With growing herbicide resistance issues and the diversity of effective herbicide mixes dwindling, the significance of in-crop weed sensing applications is becoming increasingly important.



Figure 12. *WEEDit* sensing light footprint under sprayer boom during night spraying of summer weeds (picture courtesy of Bulla Burra farm)

Harvester technology

Older harvesters in Australia tended to have a comb or closed front, which left long straw protecting the soil from wind and water erosion. This concept originated from the original stripper design pulled by horses where the crop heads were taken off between long extended fingers, which were ideal for low yielding crops (Quick and Buchele 1978). A 1986 Kondinin Group survey (Kondinin 1993b) conducted across all of Australia’s grain cropping areas with a 24% response rate highlighted that 51% of the 1692 recorded harvesters were closed front type, and 49% open front type. Today, modern harvesters in Australia use open fronts and are principally manufactured in the USA or Europe, where much higher crop biomass levels are common. The open front can cut the crop close to the ground and get weed seeds into the harvester for treatment as part of an integrated weed management system, increasingly valuable in modern CA cropping systems (see Chapter 10).

Harvester power, front width, grain tank capacity and weight have increased significantly over the last 30 years. Modern harvesters are currently categorised into a class system which is broadly based on engine power (Eckelkamp 2011), namely Class 4 up to 160 kW; Class 5, 161kW to 199kW; class 6, 200kW to 240kW; class 7, 241kW to 279kW; class 8, 280kW to 300kW; class 9, above 345kW; and class 10, above 373kW.

Traditional open fronts use a screw auger to move material sideways towards the centre feeder house which takes the crop into the harvester for threshing and separation. To use the full capacity of the larger headers in lower rainfall zones, open front widths now commonly reach 11-12 m, with up to 18 m available. These fronts commonly rely on air-bag floatation systems to float along, aiming to keep the cutting height constant across the paddock, while wide front stability at speed is improved by the use of adjustable, spring-loaded side gauge wheels. Draper belt fronts are now the most common alternative as they feed the crop more evenly, are lighter weight and can cut the crop even closer to the ground. Flexing draper fronts (e.g. Figure 13) are a recent development for harvesting very low crops such as lentils whereby the cutting knife can additionally flex to better follow ground contours across the width and maximise crop harvestability.

Harvester front technology



Figure 13. Flexi-belt fronts can follow ground contours across their width with a 225 mm flex range (e.g. Claas Convio Flex front, picture by Jack Desbiolles)

Stripper fronts were first commercialised in 1989 in the UK and are increasingly popular in Australia as a way to maximise the quantity of anchored stubble in CA systems. They use rows of stripping fingers fitted on a counter-rotating barrel over the full width of the front. They are designed to remove the grain heads from the crop, which is achieved most efficiently on thick and even crops (Figure 14). They have the advantage of increased capacity and efficiency, as well as improved performance in high moisture and weed infested crops, since mostly pre-threshed grain and chaff with only limited straw material are taken into the harvester, while the bulk of the straw remains as anchored stubble. Stripper fronts integrate best with disc seeders due to the straw length, while there is some evidence that the long straw may also reduce summer weed problems. Stripper fronts generally are limited in width due to their weight, and efficiently picking up lodged crops can be a problem.



Figure 14. Stripper fronts use multiple rows of stripping fingers (inset) and help maximise the proportion of anchored residue retained in CA systems, e.g. Shelbourne Reynolds (picture by Glen Riethmuller)

Crop threshing and separating components

Conventional harvesters have a rotating drum located transverse to the direction of travel and threshing the grain against a stationery and adjustable concave, followed by a separation process, commonly over alternating straw walkers or multi-separation rotors. While add-on drums can improve both feed and threshing efficiency, this concept tends to limit throughput but can handle damp straw very well. A majority of current harvesters in Australia use single or twin rotors oriented in the same direction as travel, first introduced in 1977 by International Harvesters as the *Axial Flow* concept, which offers the advantage of gentler threshing over a larger concave area and a more efficient straw-grain separation further along the rotor. These rotary harvesters tend to break the straw more, due to the longer processing path around the rotor, which reduce its quality for baling and handling but makes sowing into stubble with tyne seeders easier. Hybrid systems also exist to combine the relative benefits of transverse drum threshing with efficient rotary separation.

Technologies for integrated weed management

When the maturity of weed and crop coincide well, weed seeds can be collected effectively during the crop harvesting process, so harvest weed seed control (HWSC) methods have been developed (Walsh *et al.* 2013, see also Chapter 10) to assist with herbicide resistant weeds. Their success depends largely on how successful the weed seeds can enter the harvester and be streamlined on exit. The various harvester modification options (Weed Smart 2019) include the following:

- *Windrow burning* became common for weed seed control by simply taking the straw spreaders off to allow careful burning of harvested windrows. Beside the high labour intensity, this method has the risk of the field catching fire, especially in high residue crops such as cereals.
- *Chaff carts* are towed behind the harvester to catch the material off the sieves. When carts are full the material can be dumped in the paddock for either later burning, grazed by stock or removed for disposal or use.
- *Chaff lining* is a low-cost approach where a chute is added to the back of the harvester to concentrate the chaff material into a thin band, usually onto a wheel track, that can rot down with rainfall. Even if some weed seeds survive, the resulting weeds are concentrated in area and therefore can be targeted with herbicide. At best, the chaff lines are kept permanent across seasons, to reinforce the effect. In a controlled traffic system, the chaff is best dropped onto the wheel tracks (using a *chaff deck*), where vehicle traffic additionally contributes to weed control. This option also helps reduce soil dust in summer spraying operations.
- *The Glenvar Bale Direct™ system* has a straw baler attached behind the harvester to capture all material residues coming out of the harvester into bales. These bales have a high string number to

help hold the fine material in the bale and then can be removed for uses such as stock feed (as there is some grain in it) or pelletised with other ingredients for confined stock feeding.

- **Weed Seed Destruction Mills** (Figure 14). The *Harrington Seed Destructor* (HSD) was initially a trailed machine behind the harvester with its own power source. It was designed to mill the chaff and weed seed material off the sieves using a cage mill. Dedicated research underpinning later designs developed by the University of South Australia (Berry *et al.* 2014, 2015), suited to high class harvesters, have impact destruction mills integrated into the back of, and powered by, the harvester, and were commercialised as the *iHSD*. One drawback was measuring sieve losses as all the material goes through the mill. The later designs developed by De-Bruin Engineering (SA) and McIntosh Distribution (WA) have two vertical mills at the ends with an auger taking material into them; this auger has a removable floor so grain loss can be assessed and foreign objects can be captured and removed. They are also powered directly from the harvester shafts via belts which are more energy efficient than hydraulic motors. The *Seed Terminator* is an alternate design which first introduced a mechanical drive solution and uses a multistage hammer mill. Major harvester manufacturers are now also working on different weed seed destruction mechanisms, which will further advance the technology and aid CA. On-going R&D for all of these systems is focussed on reducing power usage while maintaining high levels of weed seed kill. The benefit with such systems is that the pulverised material is returned to the paddock and not burnt or nutrients removed, but a side effect is that the fine dust can become a harvester fire risk if not carefully managed.



Figure 15. Weed seed destruction at harvest is a recent Australian innovation that is a game changer for sustainable weed management in CA systems . *Left:* close-up view of *iHSD* early prototype with hydraulic drive (picture by Chris Saunders) *Right:* Seed Terminator unit in operation below a conventional straw chopper (picture courtesy of Seed Terminator)

Controlled traffic farming (CTF) is increasing Australia-wide (Tullberg *et al.* 2007) but spreading the straw evenly is a problem for wide fronts – now out to 18 m width. Nufab have developed a limited release of a double conveyor and spinner system to help spread the straw to 18 m but more work needs to focus in this area. Modern straw chopper/spreaders claim spreading capabilities up to 12-15 m wide (Kondinin 2018).

A Global Positioning System (GPS) for automatic steering and crop output mapping is now commonly used on harvesters and this reduces overlap for greater field efficiency and is also required for CTF. Yield mapping is common on most harvesters, where the grain flow is monitored and recorded along with GPS position. Grain moisture is measured on the go together with yield, and increasingly with protein level, which can guide the next season nitrogen input using variable rate application.

Chaser bins pulled by tractors increase harvester field efficiency and many now have a system where the harvester controls the tractor speed to facilitate easier unloading ‘on the go’.

Adaptation to manage snails in crops

Snail contamination of grain is a continuing problem in southern areas of Australia, exacerbated by residue retention, and some management options have extended to harvester modifications (Leonard *et al.* 2003). These include *dislodger bars*, mechanically knocking snails off the crop ahead of the harvester front, and *fixed aperture screens* for separating snails from grain within the harvester. Field research showed the stripper fronts are able to minimise the intake of snails into the harvester.

Machinery integration into CTF systems

History

In Australia, Adem and Tisdall (1984) demonstrated the benefits of ‘permanent bed’ cropping systems. Tullberg (1988) confirmed the energy effects of controlling traffic, noting that a few Queensland grain growers were also doing this with conventional tractors modified to 3-m track gauge to match the harvester. Controlled Traffic Farming (CTF) was developed and defined as a package in a participatory research, development and extension program in the 1990s (Yule *et al.* 2000). Large-scale adoption followed. The Australian Controlled Traffic Farming Association Inc. (ACTFA, www.actfa.net/) has defined as the fundamentals of CTF:

- All machinery has the same or modular working and track gauge width, which allows establishment of permanent traffic lanes;
- All machinery is capable of precise guidance along the permanent traffic lanes; and
- Farm, paddock and permanent traffic layout arranged to optimise surface drainage and logistics.

In practice, it is usually combined with RT or NT, greater surface residue retention, opportunity cropping, and more precise placement of inputs. Over the past 25 years, the percentage of Australian grain cropping land under CTF increased to 15% in 2008 and 29% in 2016. It has also been adopted by an unknown, but substantial number of cotton and sugarcane growers, and some horticultural producers. Adoption is driven by grower perceptions of the benefits, which vary with region, soil type and cropping system, but can be grouped into those related directly to the management of soil compaction, and those which might be described as ‘system’ benefits. The latter includes the environmental benefits associated with the perceived overall improvements in soil health and function. Although significant, these benefits are more difficult to quantify than the soil and agronomic benefits that result in improved yield, and water and fertiliser use efficiency.

Compaction-related benefits of CTF

Compaction damage occurs almost instantly under traffic on relatively soft soil conditions, and one pass of a farm vehicle may cause up to 90 % of the maximum compaction. Compaction is probably endemic in Australian systems where each crop involves traffic on more than 40% of field area by 10-35 t machines. Compaction reduces porosity and increases soil strength, impeding root exploration of the profile, and increasing the risk of run-off and soil erosion, and therefore nutrient losses to the environment and watercourse pollution. It adversely affects soil biota, water and fertiliser use efficiency, constraining yield and irrigation intervals (Antille *et al.* 2015). Mechanical amelioration of compaction is energy-demanding and expensive, and soil recovery through natural processes is slow or non-existent in some soils (Pollard and Webster 1978, see Chapter 8). CTF restricts all heavy traffic to permanent traffic lanes, occupying 10-25% of crop area, allowing most crop production to occur in soil unaffected by wheel compaction. Direct effects of CTF compared with non-CTF systems have been demonstrated in a wide variety of soils and cropping systems:

- Increased water infiltration into the soil (Li *et al.* 2007);
- Increased plant available water capacity (McHugh *et al.* 2009);
- Increased soil biological activity (Pangnakorn *et al.* 2003);
- Reduced run-off and nutrient loss (Rohde and Yule 1995); and
- Reduced risk of denitrification and soil emissions of greenhouse gases (Tullberg *et al.* 2018).

These effects all facilitate more sustainable and productive cropping, and CTF is usually associated with reduced production costs and improved yields (Chamen *et al.* 2015).

Indirect ‘system’ benefits of CTF

A significant proportion of equipment power (and fuel) is used to create compaction. This power to overcome motion resistance can be very large in soft, cultivated soils in ‘seedable’ condition, and smaller on hard, dry soil. Motion resistance reductions of 20–40% have been reported for travel on permanent lanes, instead of crop beds. This improved trafficability enhances timeliness allowing more rapid start (or resumption of work) after rainfall events, an important effect noted by McPhee *et al.* (1995). There is also a significant energy penalty involved in mechanical disturbance of wheeled soil (Luhai *et al.* 2017). Other indirect benefits of CTF are matters of grower observation, such as:

- A slow improvement in paddock, and consequently crop, uniformity is often noted from the elimination of traffic-induced soil variability developing from random field traffic;
- Greater precision is possible in the more uniform soil conditions of CTF, facilitating more precise placement of seeds, fertilisers and crop chemicals; and
- CTF growers note the convenience of having only two soil, crop and weed conditions to manage (crop beds and permanent traffic lanes), with both in a consistent spatial relationship with their equipment.

Machinery integration into CTF systems

Most grain growers have been able to develop compatible CTF systems by integrating the modification of some units with their normal equipment replacement cycle, often at little additional cost. Conversion from a conventional mechanisation system, with unmatched machinery and track gauge widths, to CTF should consider the steps listed below. Decision support systems (*e.g.* CTF Calculator, www.ctfcalculator.org/) have been developed to calculate and illustrate the relative footprint of a given mechanisation system, and to assist growers with CTF designs as they transition from a conventional system to CTF. By providing information on the machinery modifications required, an economic evaluation can then be undertaken to assist decision-making. Such decision support systems can also be used to assess compaction management options (*e.g.* deep tillage) based on estimates of field cropped area affected by traffic. Similarly, tools are available to plan the layout of CTF systems such as aerial photogrammetry coupled with digital elevation models used in combination with soil type and historic yield maps (Antille *et al.* 2019). The key components of CTF systems are (Isbister *et al.* 2013):

- *Guidance system*: global navigation satellite systems with real-time kinematic (RTK) ± 0.02 m correction;
- *Machinery matching*: decide on imperial or metric system, select the operating width (*e.g.* 3:1 or 2:1 ratio sprayer-combine harvester and planter), match wheel track spacing (*e.g.* 3 m);
- *Design of permanent traffic lanes*: cropped or bare, and width; and
- *Layout considerations*: optimisation of in-field routing and orientation to minimise risk of erosion and runoff.

CTF adoption can be more challenging in other (non-grain) cropping systems, but there are many successful examples in cotton (Antille *et al.* 2016), sugarcane (Braunack and McGarry 2006) and horticulture (McPhee and Aird 2013). The one common theme of almost all successful CTF adoption has been careful, long-term planning (see grower Case Studies, Chapter 4).

Conclusions

Over the last 30 years, the evolution of cropping machinery for CA systems has been remarkable, leading to major steps in field productivity improvements, machine reliability, energy efficiency, ergonomics and operator safety. A fundamental contributor has been the standardisation of communication protocols via ISOBUS and CANBUS, mainstreamed over the last 15 years. This has improved user-friendliness, integration, compatibility and functionality of plug-and-play control system technologies. In the highly mechanised, large cropping farm context of Australia, the integration of GPS

geolocation into mapping and control systems has perhaps made the most notable difference to the adoption of controlled traffic farming and the development of precision agriculture, underpinning the successful implementation of effective and efficient CA systems. The logical progression in machinery evolution lies in further innovation around powering technology, real-time sensing within soil-plant-machine systems, machine to machine wireless communication, data management platforms and automation of machine tasks removing operator control, with a focus maintained on improving the productivity of both the operator and the grain producing plant. While cropping system and operator productivity will continue to be a major focus, we can also expect an increased emphasis on minimising the environmental impacts – both on and off-farm – of equipment system operation.

References

- ABARES (2018) Australian Farm Surveys and Analysis: Report of the Farm Physical Characteristics for the Grains Industry 2015-17 (ABARES, Department of Agriculture and Water Resources: Canberra) www.agriculture.gov.au/abares/research-topics/surveys
- ABS (2017) Australian Bureau of Statistics Land Management and Farming in Australia 2015-16. Catalogue no. 4627.0 www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4627.02015-16?OpenDocument
- Adem H H, Tisdall JM (1984) Management of tillage and crop residues for double-cropping in a fragile soil. *Soil and Tillage Research* **4**, 577-589
- Agri-Machinery News (2017) John Deere SESAM Electric Tractor www.youtube.com/watch?v=kxLm2XnQixk
- Antille DL, Bennett JMCL, Jensen TA (2016) Soil compaction and controlled traffic considerations in Australian cotton-farming systems. *Crop and Pasture Science* **67**, 1-28
- Antille DL, Chamen T, Tullberg JN *et al.* (2019) Controlled traffic farming in precision agriculture. In (Ed. JV Stafford) "Precision Agriculture for Sustainability, Part 2: Delivery Systems" Chapter 10 pp 239-270, Burleigh Dodds Series in Agricultural Science No.52 (Burleigh Dodds Science Publishing Limited: Cambridge, UK)
- Antille DL, Chamen WCT, Tullberg JN, Lal R (2015) The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in arable land: a critical review. *Transactions of the ASABE* **58**, 707-731
- Ashworth M, Desbiolles J, Tola E (2010) Disc seeding in zero-till farming systems: A review of technology and paddock issues (West Australian No-Tillage Farmers Association: Northam, Western Australia)
- Barr JB, Desbiolles J, Fielke J (2016) Minimising soil disturbance and reaction forces for high speed sowing using bentleg furrow openers. *Biosystems Engineering* **151**, 53-64
- Barr JB, Desbiolles JMA, Fielke JM, Ucgul M (2019) Development and field evaluation of a high speed no-till seeding system. *Soil and Tillage Research* (in press)
- Berry NK, Fielke JM, Saunders C (2014) Determination of impact energy to devitalise annual ryegrass (*Lolium rigidum*) seed from one impact using double and single sided impacts. *Biosystems Engineering* **118**, 138-146
- Berry NK, Fielke JM, Saunders C (2015) A Mastercurve to predict annual ryegrass (*Lolium rigidum*) seed devitalisation when exposed to multiple single sided impacts. *Biosystems Engineering* **133** 56-63
- Braunack MV, McGarry D (2006) Traffic control and tillage strategies for harvesting and planting of sugarcane (*Saccharum officinarum*) in Australia. *Soil and Tillage Research*, **89**, 86-102
- Broster JC, Pratley JE, Ip RHL *et al.* (2019) A quarter of a century of monitoring herbicide resistance in *Lolium rigidum* in Australia. *Crop and Pasture Science* **70**, 283-293
- Butler G (2018) Cotton ratoon termination with AquaTill injecticide. *The Australian Cottongrower*, Dec 2018/Jan 2019, 20-22
- Chamen WCT, Moxey AP, Towers W *et al.* (2015) Mitigating arable soil compaction: A review and analysis of available cost and benefit data. *Soil and Tillage Research* **146**, 10-25
- Clean Seed Capital Group (2019) CX-6 Smart Seeder <http://www.cx6smartseeder.com>
- CNH Industrial (2016) The CNH Industrial Autonomous Tractor Concept www.youtube.com/watch?v=T7Os5Okf3OQ
- Desbiolles J and Kleemann S (2003) Seeding system factors influence no-till cropping results. *Proceedings of 16th Triennial International Soil Tillage Research Organisation Conference*, University of Queensland, Brisbane pp 364-372
- Desbiolles J (2011) Disc seeders in Australian Agriculture: An Australian survey. *Proceedings of 5th World Congress on Conservation Agriculture* Brisbane, Australia
- Desbiolles J (2017) Seeder Tracker and guidance for precise row sowing. *Ag Contractor and Large Scale Farmer*, **99**, 16-18

- Desbiolles J, McBeath T, MacDonald L *et al.* (2017) Testing the concept of fertility strips to increase productivity on deep sand. (Mallee Sustainable Farming)
www.msfp.org.au/testing-concept-fertility-strips-increase-productivity-deep-sand
- Dimos N, Trengrove S, Sherriff S *et al.* (2018) The H Sensor: a weed ID and mapping system, SAGIT Research Summary, SPAA114
- DOT (2017) Meet the Future of Agriculture. www.seedotrun.com/index.php
- Eckelkamp M (2011) What gives a combine its class? *AgWeb Farm Journal*, 30 September
www.agweb.com/article/what_gives_a_combine_its_class
- GRDC (2011) Fertiliser toxicity factsheet: Care with fertiliser and seed placement (Grains Research and Development Corporation: Canberra) : www.grdc.com.au/_data/assets/pdf_file/0019/203635/fertiliser-toxicity.pdf.pdf
- GRDC (2017) Grow Notes: Spray application manual for grain growers (Grain Research and Development Corporation: Canberra)
www.grdc.com.au/resources-and-publications/grownotes/technical-manuals/spray-application-manual
- GRDC (2019) Mechanical chipper added to weeds arsenal. *Groundcover* **138**, p3
- Giles DK, Henderson GW, Funk K (1996) Digital control of flow rate and spray droplet size from agricultural nozzles for precision chemical application. In (Eds. PC Robert, RH Rust, WE Larson) "Precision Agriculture" pp 729-738 (American Society of Agronomy, Crop Science Society of America, Soil Science Society of America: Madison WI, USA)
- Haskin B (2012) Using pre-emergent herbicides in conservation farming systems. Weed Management Report (NSW Department of Primary Industries: Orange) 20pp
https://www.dpi.nsw.gov.au/_data/assets/pdf_file/0003/431247/Using-pre-emergent-herbicides-in-conservation-farming-systems.pdf
- Heidary M, Al Douzals JP, Sinfort C, Vallet A (2014) Influence of spray characteristics on potential spray drift of field crop sprayers: A literature review. *Crop Protection* **63**, 120-130
- Henley S (2017) NOSTALGIA: A look back at the tractor 'legends' of the 1990s. *Farmers Guardian*, Insights 25 July www.fginsight.com/vip/vip/nostalgia-a-look-back-at-the-tractor-legends-of-the-1990s-23400
- Isbister B, Blackwell P, Riethmuller G, Davies S, Whitlock A, Neale T (2013) Controlled traffic farming technical manual (Northern Agricultural Catchments Council: Geraldton, Western Australia)
www.nacc.com.au/wpcontent/uploads/2015/05/NACC_Controlled_Traffic_Farming_Technical_Manual.pdf
- ISO (1984-2018) Standards catalogue 65.060.40 – Plant care equipment. International Organisation for Standardization www.iso.org/ics/65.060.40/x/
- Langenakens JJ, Clijmans L, Ramon H, De Baerdemaeker J (1999) The effects of vertical sprayer boom movements on the uniformity of spray distribution. *Journal of Agricultural Engineering Research* **74**, 281-291
- John Deere (2019a) Making history by leaving little behind – A powerful story of diesel innovation
www.deere.com.au/en/campaigns/engines-and-drivetrain/diesel-engine-technology
- John Deere (2019b) Telematics: smart machines for increased productivity
www.deere.com/en/electronic-solutions/telematics/
- Jourdain G (2019) Green on green camera spraying – a game changer on our doorstep? *Grains Research Updates*, Perth www.giwa.org.au/2019researchupdates
- Kanicki D (2017) Which has more potential, autonomous or electric tractors? *Ag-Equipment Intelligence*, March
- Kassam A, Friedrich T, Derpsch R, Kienzle J (2015) Overview of worldwide spread of conservation agriculture. *Field Action Science Reports* **8** (on-line) www.journals.openedition.org/factsreports/3966
- Kepner RA, Bainer R, Barger EL (1982) "Principles of Farm Machinery" 3rd edition (AVI Publishing Company, Inc.: Wesport CT, USA) 527pp
- Kleemann S, Desbiolles J, Preston C, Gill GS (2014). Influence of disc seeding systems on pre-emergence herbicide control of annual ryegrass (*Lolium rigidum*) in wheat. *Proceedings of 19th Australasian Weeds Conference* Hobart, Tasmania
- Kondinin (1993a) "The seeding edge – The Australian seeding and tillage manual" Revised edition (Eds. M Casey, S Boyle) 376pp (Kondinin Group: Belmont, Western Australia)
- Kondinin (1993b) "The reapers digest – The essential harvesting manual" Revised edition (Eds. M Casey and S Boyle) 384pp (Kondinin Group: Belmont, Western Australia)
- Kondinin (2000) "Min-Till Drill – A guide to minimum tillage cropping systems" (Ed. S. Wallwork) 340pp (Kondinin Group: Belmont, Western Australia)
- Kondinin (2001) "Spraying Solutions" (Ed. T Nugent) 240pp (Kondinin Group: Belmont, Western Australia)
- Kondinin (2011) Chemical transfer systems. Issue Report. *Farming Ahead Magazine* **228** 15-28.
- Kondinin (2018) Residue management at harvest. Research Report No 097, *Farming Ahead*, February 23pp

- Kubsh J (2017) Managing emissions from non-road vehicles. Report prepared for the International Council on Clean Transportation. 24pp www.theicct.org/publications/managing-emissions-non-road-vehicles
- Leonard E, Baker G, Hopkins D (2003) Bash'em burn'em bait'em: Integrated snail management in crops and pastures. (GRDC: Canberra) www.grdc.com.au/GRDC-Snails-BashBurnBait
- Li YX, Tullberg JN, Freebairn DM (2007) Wheel traffic and tillage effects on runoff and crop yield. *Soil and Tillage Research* **97** (2), 282-292
- Llewellyn RS, FH D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Luhaib AAA, Antille DL, Tullberg JN *et al.* (2017) Effect of controlled traffic farming on energy saving in Australian grain cropping systems. Paper 1700583 *ASABE Annual International Meeting*, American Society of Agricultural and Biological Engineers St. Joseph, MI doi: 10.13031/aim.201700583
- McCallum M (2007) Multiple benefits from Inter-row sowing with 2cm RTK GPS. *Proceedings 5th Controlled Traffic Farming Conference*, Perth WA www.actfa.net/actfa-conferences/ctf07-conference/
- McHugh AD, Tullberg JN, Freebairn DM (2009) Controlled traffic farming restores soil structure. *Soil and Tillage Research* **104**, 164-172
- McPhee J, Aird E (2013) Controlled traffic for vegetable production: part 1. Machinery challenges and options in a diversified vegetable industry. *Biosystems Engineering* **116**, 144-154
- McPhee JE, Braunack MV, Garside AL *et al.* (1995). Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 3, Timeliness and trafficability. *Journal of Agricultural Engineering Research* **60**, 191-199
- Moodie M, Desbiolles J (2016) Seeding systems for variable Mallee soils. FarmTalk factsheet No 45. Mallee Sustainable Farming www.msfp.org.au/farmtalk-45-seeding-systems-variable-mallee-soils
- New Holland Agriculture (2019) New Holland T6 methane power tractor prototype makes a statement at SIMA 2017 www.agriculture.newholland.com/eu/en-uk/about-us/whats-on/news-events/2017/t6-methane-power
- Nossal K, Lim K (2011) Innovation and productivity in the Australian grains industry. ABARES research report 11.06, Canberra
- Pangnakorn U, George DL, Tullberg JN, Gupta ML (2003) Effect of tillage and traffic on earthworm populations in a Vertosol in Southeast Queensland. *Proceedings of 16th ISTRO Conference* Brisbane pp 881-885
- PIRSA (2018) Reducing spray drift with Mid North Mesonet. *PIRSA News*, Edition 1, p26 www.pir.sa.gov.au/data/assets/pdf_file/0015/332061/PIRSA_News_-_Edition_1_-_2018.pdf
- Pollard F, Webster R (1978) The persistence of the effects of simulated tractor wheeling on sandy loam subsoil. *Journal of Agricultural Engineering Research* **23**, 217-220
- Precision planting (2019) www.precisionplanting.com/products/all-products
- Quick G, Buchele W (1978) The Grain Harvesters (American Society of Agricultural Engineers: St. Joseph, MI, USA) 269pp
- Rohde K, Yule D (1995) Land management systems including controlled traffic, erosion control and crop rotations for dryland cotton. *Proceedings of 1st ACTFA Conference*, Yeppoon, Qld www.actfa.net/actfa-conferences/1995-ctf-conference
- SeedMaster (2017) www.seedmaster.ca/ultrapro.php
- Taki O, Desbiolles J, Butler G (2018) Waterjet cutting of crop residue using the Aqua-Till liquid coulters – A laboratory evaluation. Paper 207, *Proceedings of 21st International Conference of the International Soil Tillage Research Organisation* 2017, Paris, France
- Tigges M (2015) Central tire inflation systems for agricultural vehicles. *Proceedings of 2015 Agricultural Equipment Technology Conference* Louisville, KY USA
- TMA (2017) Agriculture tractors and equipment – The state of the industry. July (Tractor and Machinery Association of Australia)
- Tullberg J N (1988) Controlled traffic in subtropical grain production. *Proceedings of 11th ISTRO Conference*, Edinburgh, UK **1**, 323-326 www.istro.org/index.php/publications/proceedings
- Tullberg JN, Antille DL, Bluett C *et al.* (2018) Controlled traffic farming effects on soil emissions of nitrous oxide and methane. *Soil and Tillage Research* **176**, 18-25
- Tullberg JN, Yule DF, McGarry D (2007) Controlled traffic farming – From research to adoption in Australia. *Soil and Tillage Research* **97**, 272-281
- Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. *Weed Technology*, **27**, 431-436
- Weed Smart (2019) Harvest Weed Seed Control Tools. www.weedsmart.org.au/resources/hwsc
- Yule DF, Cannon RS, Chapman WP (2000) Controlled traffic farming – Technology for sustainability. *Proceedings of 15th Conference*, Fort Worth, Texas www.istro.org/index.php/publications/proceedings

Chapter 7

Strategic tillage within conservation agriculture

Mark Conyers, Yash P. Dang and John Kirkegaard

Introduction


The three pillars of modern conservation agriculture (CA) are reduced tillage, soil cover by stubble retention and diverse rotations (FAO 2015). The significant efforts to reduce tillage from the multiple passes practised in Australia up to the 1980s underpinned the publication of *Tillage, New Directions in Australian Agriculture* in 1987. Since that time Australia has led the world in the development and adoption of reduced tillage (RT) systems, but several recent reviews have questioned the drive for a complete absence of tillage (Kirkegaard *et al.* 2014, Dang *et al.* 2015a, Giller *et al.* 2015) and promoted its strategic use in cropping systems. The strategic use of tillage, primarily restricted to the surface soil and seedbed, is the subject of this chapter.

The first records of an animal drawn plough are from Mesopotamia in about 3000 BC (Hillel 1991). Tillage has been used in various forms and for various reasons over the millennia, primarily to control weeds and to prepare a seed bed (Cornish and Pratley 1987, Lal 2009). After 5000 years, has the recent progress in chemical weed control made ploughing redundant? Despite the high uptake of CA practice in Australia (Llewellyn *et al.* 2012), tillage has remained as a tool *within* CA practice (see Chapter 2). This is due to a number of factors including the need to incorporate limestone into acidic soils and the role tillage can play in integrated pest and weed management. The use of any form of tillage within CA can be controversial on philosophical grounds (Grandy *et al.* 2006, Giller *et al.* 2009), or with respect to the loss of soil C (see Chapter 16). However challenges to the complete abandonment of tillage are increasingly common (Pierce *et al.* 1994, Dick 1997, Giller *et al.* 2015) and questions about the fit of complete no-till have been asked in Africa (Giller *et al.* 2009), South America (Bolliger *et al.* 2006, Dominguez *et al.* 2010, Nunes *et al.* 2017), and North America (Baan *et al.* 2009, Wortmann *et al.* 2010) as well as in Australia (Kirkegaard *et al.* 2014, Crawford *et al.* 2015, Dang *et al.* 2015a, 2015b, 2018).

Since the replacement of the bullock, donkey and horse there have been many developments in the mechanisation of both the draft and the implement. Mechanised draft in the form of tractors has slowly increased in size and energy requirements, while implements have grown wider and deeper. The diversity of implements has also increased. The impact on the soil itself therefore came to exceed the simpler expectations of weed control and a good seed bed. Tillage machinery and purposes have evolved (see Chapter 6) along with the principles of CA. Mechanisation will continue to evolve to meet the needs of CA: modified points that cultivate below the seed rather than across the row is an example; weed sensing technology that supports spot chipping by scarifiers is a recent example. The major characteristics that we can use to best describe these various forms of surface soil tillage are their depth and degree of mixing (Table 1, see Chapter 1). Use of inversion tillage with implements such as the mouldboard plough is rare in Australia, except to ameliorate soils with significant constraints (see Chapter 8). Most growers use non-inversion, shallow tillage based on tyne and disc implements that do not fully invert the soil (Dang *et al.* 2018). The degree and depth of mixing can vary with the range of modern implements. Further, the frequency of tillage has decreased over the last two generations, as conventional tillage (CT) decreased from regular ploughing between harvest and seeding in the 1950s, to RT with just two or three passes to control summer weeds by the 1980s, at the time that Cornish and Pratley (1987) compiled their review.

In this chapter, we consider the role of various depths and degrees of tillage of surface soil within modern CA in Australia (see Chapter 2), and how this has evolved since 1987. We do not cover the placement of amendments at depth (limestone, gypsum, manure, composts) nor the displacement of clay from B horizons into sandy and/or non-wetting surface soils (see Chapter 8).

Table 1. Characterising tillage implements for varying degree and depth of soil mixing

Depth	Increasing mixing of soil 	Inversion
shallow	Diamond harrows Prickle chains Speed tillers	
Beyond-seed placement depth	Tyned implements ^a Offset discs Rotary hoe	Mouldboards

^a Tyned implements can generally penetrate deeper than offset discs or rotary hoe but are classified here with respect to mixing of surface soil only.

The use of tillage within CA

Table 2 summarises the ‘pros and cons’ of tillage within CA in a broad range of agro-ecological scenarios. The usual trade-offs are evident and nearly every action can be beneficial or detrimental depending on the circumstances.

With regard to soil chemical properties, the only situation where the net benefit of tillage is clear is in the need to incorporate limestone on acidic soils. Limestone’s dissolution, reaction with acidity and movement are so slow and spatially limited that in a semi-arid cropping environment (350 to 600 mm annual average rainfall), such as the southern Australian wheat-belt, liming is a poor investment without soil incorporation by tillage (Conyers *et al.* 2003a, Scott and Coombes 2006). We expand on this topic later. In addition to the need to neutralise acidifying soils, the stratification of immobile nutrients such as P (Franzluebbers 2002) and alkalinity (Paul *et al.* 2003), with high concentrations in the surface few cm of soil, can limit their availability in dry and hot conditions and may accentuate off-site effects if erosion occurs. The loss of C from soil due to tillage is also a common concern and we also expand on this topic later.

In managing soil physical conditions (Table 2), sodic soils clearly represent situations where any form of tillage needs careful consideration due to a likely increase in dispersibility (Emerson 1983). For all soils, the risk of erosion by wind or water is another area of concern (Melland *et al.* 2017, Dang *et al.* 2018), so that slope, groundcover, soil moisture and the risk of storms must be considered. Any proposed strategic tillage should be left as late as possible before sowing in the southern grain-growing region of Australia. In the northern region of Australia, where both summer and winter cropping is practised, the timing of tillage needs to consider not only the risk of storms, but conservation of stored soil water (Dang *et al.* 2018). While stored water is important throughout Australian grain cropping (Hunt and Kirkegaard 2011), winter crops in the northern region are especially reliant on stored water from the wetter summer season. The structure and porosity of compacted subsurface soils could also be ameliorated by tap-rooted crops (*e.g.* safflower) rather than ploughing (Knights 2010); surface soil crusting only requires light harrows (*i.e.* shallow working, little mixing) for amendment, and uneven seed beds might require only a shallow disturbance for levelling. Livestock compaction by sheep, although of concern to growers using no-till (NT) in mixed farming systems, may not require amendment (Hunt *et al.* 2016) as it is generally shallow and with limited impacts on water supply to crops. Controlled traffic lanes which can become compacted represent only a small proportion of a field, whatever depth or degree of mixing is selected for renovation after wet, damaging seasons. These examples demonstrate that the type of tillage and the proportion of the field covered in a strategic tillage operation should not be likened to the multiple passes of a field to 10 cm depth or more that characterised the CT of the mid-20th century. Recent data from southern NSW indicate that a one-off tillage with scarifiers or offset disc does minimal damage to wet aggregate stability and to infiltration rates, with recovery times of zero to four years (generally one to two years) depending on the severity of the tillage and the rate of addition of fresh residues (Kirkegaard *et al.* 2014, Conyers *et al.* 2019). Effects of tillage on soil physical properties are considered in more detail later.

Off-site effects from tillage practice (Table 2), other than erosion, can be beneficial or detrimental and are generally small or variable in direction (Dang *et al.* 2015b). Hence the management of off-site effects is rarely a trigger for a strategic tillage operation.

Table 2. The pros and cons of the use of strategic tillage, covering a broad range of agro-ecological considerations (based on Dang *et al.* 2015a, b and Conyers *et al.* 2019)

Consideration	Pro	Con
Soil chemical properties		
NPKS stratification	High soil surface temperature & evaporation rates means less availability of stratified nutrients; <i>Deep placement of nutrients & amendments to replenish depleted subsurface soils (see Chapter 8);</i>	Early seedling growth possibly enhanced by stratification in mild conditions
pH	Limestone has limited solubility, requiring incorporation;	
C	<i>Inversion (without pulverisation) improves subsurface C stores;</i>	Tendency to decrease profile stores of C
Soil physical conditions		
Crusting	Breaking surface crusts to improve infiltration vs run-off	Sodic soil dispersion is enhanced
Uneven seed bed	<i>Levelling of surface for small seeded crops</i>	
Compacted subsurface	Reduce compaction for improved aeration. infiltration & root growth	Sodic soil dispersion is enhanced
Wet season compaction	<i>Compacted controlled traffic lanes needing renovation along strips</i>	<i>Sodic soil dispersion is enhanced</i>
Erosion		Decreased K_{sat} on vertosols and hence increased run-off rates
Off-site effects		
P pollution	Dilution of P enriched surface strata.	No-till favours less risk of run-off
GHG emissions		
CO_2	<i>Removal of agronomic constraints improves net C fixation</i>	<i>Increase in short term production/loss of CO_2</i>
CH_4	Variable and small impacts.	Variable, small impacts
N_2O	<i>Variable impacts reported</i>	<i>Variable impacts reported</i>
Plant diseases		
Crown rot (<i>Fusarium</i>), wheat	Stubble incorporation can increase decomposition	Loss of water can slow stubble decomposition
Bare patch (<i>Rhizoctonia</i>), wheat	<i>Minimises the spread and survival of the fungus</i>	Tillage can spread stubble & fungus more evenly across a field
Yellow spot (<i>Pyrenophora</i>), wheat	Minimised by stubble incorporation by discs	
Blight (<i>Ascochyta</i>), chickpea	<i>Burial of stubble reduces spread of spores</i>	
Stalk diseases (<i>Fusarium</i>), sorghum	Burial of stubble reduces pathogen build-up.	
Soil fauna		
Root lesion nematodes (<i>Pratylenchus</i>)	Reduces populations	
<i>Helicoverpa</i> spp.	<i>Reduces populations</i>	
Predatory insects (e.g. beetles, ants)		Reduces populations.
Earthworms		Reduces populations.
Molluscs (snails, slugs)	Reduces habitat and dilutes food sources.	
Pests		
Rodents, especially mice	Reduces habitat and dilutes food sources.	
Weeds		
Wind-dispersed seeds	<i>Prevalence increased by no-till</i>	
Herbicide resistance	New seeds can be buried beyond coleoptile length e.g. annual ryegrass (<i>Lolium</i>)	Long lived buried seeds can be brought to the surface e.g. fleabane (<i>Conyza</i>).

K_{sat} =saturated hydraulic conductivity, GHG = greenhouse gases

Plant diseases interact with tillage primarily through the management of stubble although they are mostly influenced by other forms of stubble management (grazing, cutting, burning, Scott *et al.* 2010, Dang *et al.* 2015a). The soil-borne fungal pathogen *Rhizoctonia solani* (AG8) which causes bare patch in cereals appears to be a disease where tillage has beneficial effects through soil disturbance alone (Rovira 1986) and this could also be true for inhibitory pseudomonads (Simpfendorfer *et al.* 2001, see also Chapter 11). Soil faunal populations are generally reduced by tillage, and this is beneficial in the case of pests such as slugs, snails (Pomeroy 1969, Voss *et al.* 1998, Glen and Symondson 2003) and plant parasitic nematodes (Rahman *et al.* 2007) but detrimental in the case of earthworms and predatory insects (Dang *et al.* 2015b, Table 2). Rodent pests burrow in soil and eat remaining grain after harvest, so tillage can assist control by both destroying habitat and burying food sources (Johnson 1986). However, baiting also needs to be used to control existing populations, so tillage is part of an integrated solution, not a stand-alone cure. The management required for effective control of standing weeds is very different to the management required for the weed seed bank stored in the soil (Table 2, Crawford *et al.* 2015, Owen *et al.* 2017). For Integrated Weed Management (IWM) where herbicide options are limited, grazing, manure crops, silage and hay cutting, harvest weed seed management and tillage are all options to be considered in the management mix (Chauhan *et al.* 2006, Edwards *et al.* 2012, see also Chapter 10).

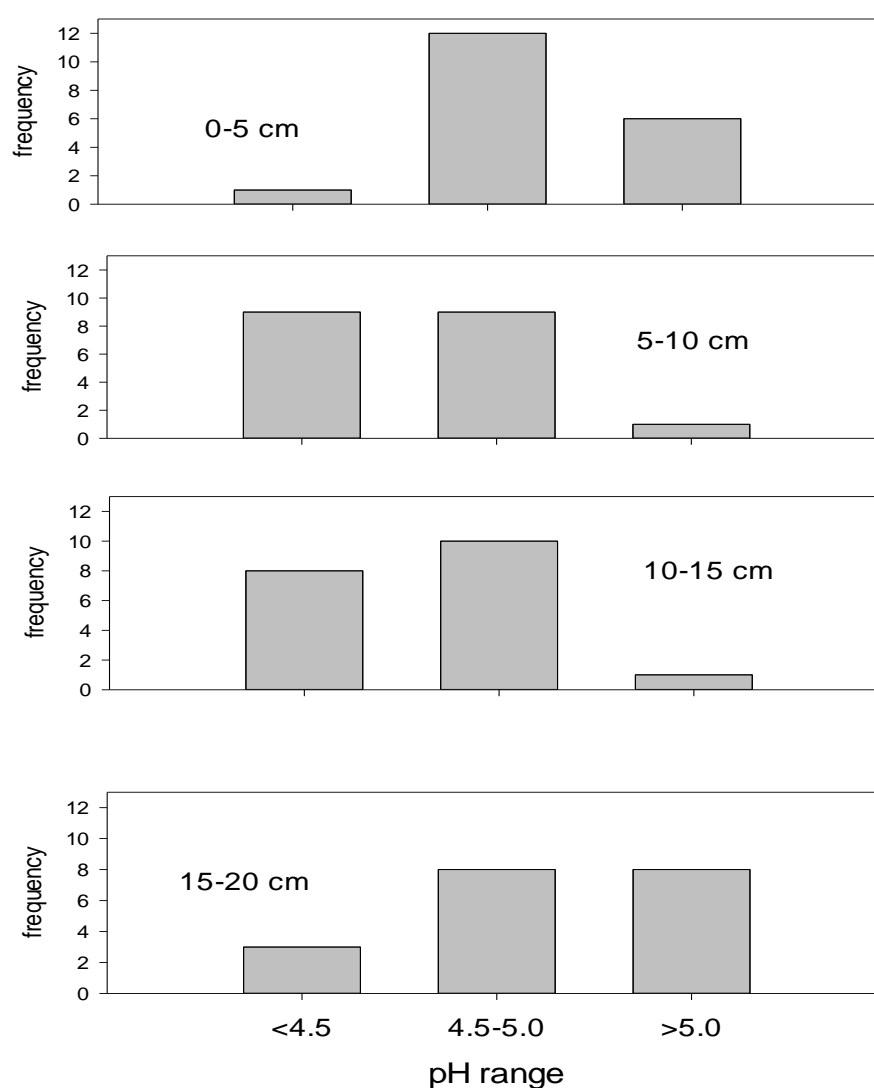


Figure 1. The frequency distribution of soil pH (CaCl₂) from 19 field sites over 4 depths on red kandosols near to the long-term rotation experiment (SATWAGL) at Wagga Wagga in 1996

Strategic tillage and acidity

Stratification of soil acidity (pH), together with the limited depth of penetration of applied limestone, was identified in the 1980s (Conyers and Scott 1989), shortly after soil acidity became recognised as a problem in southern Australia. The obvious influence of tillage on pH stratification was noted subsequently (Conyers *et al.* 1996) on a long-term field experiment. At this time there was concern as to how well the long-term field experiment might reflect what was occurring on commercial farms. Nineteen commercial fields were surveyed within 100 km of the experiment on the same red Kandosol soil type as for the long-term experiment reported by Conyers *et al.* (1996). Figure 1 shows the frequency distribution of soil pH (CaCl₂) at four depths for these 19 fields (Scott *et al.* 2017). The three pH ranges are based on where soil acidity was not likely to be a problem (pH >5) and where the acidity constraint was likely to be serious (pH <4.5).

There was a tendency for pH to be stratified and for the acidity to be worse at 5 to 15 cm depth. This implied that emerging seedlings were experiencing more stressful acidity than might be indicated by a standard 0-10 cm soil test. Over the subsequent two decades subsurface acidity under NT management has become a very common and sometimes damaging issue on commercial fields of faba beans (Burns *et al.* 2017) and possibly for other acid-sensitive species. Currently the problem is limiting the expansion of high value legumes (*e.g.* lentils, chickpeas) in some areas as the amount of limestone required to remediate the soils for adequate legume nodulation to 20 cm depth (of the order of 3.5 t/ha), combined with the need for deep incorporation (to about 15 cm), is seen as a costly investment.

Strategic tillage and soil C

It is generally recognised that tillage results in a loss of soil organic matter since it promotes mineralisation. However any improvement in plant growth, particularly for roots, is likely to increase the addition of C to soil over the season that follows. The extent of C loss from soil due to tillage varies with other management factors such as NPS inputs (Kirkby *et al.* 2014, 2016), stubble management (Heenan *et al.* 2004), as well as the proportion of pasture phase within the rotation (Helyar *et al.* 1997).

Most importantly, the rate of loss of soil C needs to be considered. In a comparison of NT by direct drilling (knife points) with annual tillage (two or three passes) by scarifiers or offset discs over 21 years, Heenan *et al.* (2004) found that the rate of loss of soil C from surface soil (red Kandosol) due to tillage was 191, 146, 189 kg C/ha/year under three different rotations. Comparing three long-term trials in the southern rainfall environment, including the trial of Heenan *et al.* (2004), Chan *et al.* (2011) found that annual losses and gains of soil C to 30 cm depth ranged from -278 to +552 kg/ha/year. In the northern grain region on a Vertosol, Dalal *et al.* (2011) found that the difference in C stock at 0-10 cm between NT and CT was < 0.4 t C/ha after 40 years. The SOC sequestration rates were initially 100-120 kg C/ha/year in the first decade but declined to an average of 45 kg C/ha/year over 40 years. At 0-30 cm depth the effect of tillage on SOC stock was not significant. These rates of change in soil C are not dramatic when compared with the large annual above-ground biomass production of the order of 10,000 kg DM/ha/year.

Given the slow loss rate of soil C due to annual tillage, involving two or three passes per year, it is likely that a single strategic tillage event implemented occasionally would have limited impact on stores of soil C (Conyers *et al.* 2015). Further, it appears that these losses of soil C due to tillage can be minimised, eliminated or even reversed by applying supplementary nutrients, NPS, to the stubble prior to decomposition (Kirkby *et al.* 2014, 2016). Adding supplementary nutrients to crop stubbles at the time of incorporation increased soil C levels over a 6-year period by 5.5 t/ha at one site, while stubble retention alone reduced soil C by 3.2 t/ha (Kirkby *et al.* 2016). The issue is considered in Chapter 16.

Strategic tillage and soil physical properties

Grandy *et al.* (2006) found a 35% decrease in mean weight diameter of aggregates in the surface 20 cm of soil following mouldboard ploughing of a grassland in Michigan. Most of the decrease was due to loss of macro-aggregates ($>250\ \mu\text{m}$). However Quincke *et al.* (2007) found that a single tillage, regardless of implement (including a mouldboard) did not affect aggregate stability nor grain yield at two sites under corn or sorghum in Nebraska. Infiltration rate was increased at one site by mouldboard plough but decreased at the other. Wortmann *et al.* (2010), also in Nebraska, found that water stable aggregates were not affected by a single tillage at two sites except for an increase in aggregation at 5-10 cm depth under mouldboard inversion at one site. There were no effects on grain yield at either site. Pierce *et al.* (1994) found that a single tillage at a site in Michigan decreased bulk density and increased macroporosity but decreased microporosity. After four to five years the soil properties had generally returned to those of the NT treatment. In Saskatchewan, Baan *et al.* (2009) compared three intensities of a single cycle of tillage at three sites and found no effect on soil aggregation (dry sieving) or crop production except at one site where grain yield was decreased in one year. Conyers *et al.* (2019) in southern New South Wales found no effect of a single tillage on saturated hydraulic conductivity at three sites, but initial minor decreases in wet aggregate stability (0-14%) generally recovered within the first two years.

It appears then, with the exception of Grandy *et al.* (2006) on a grassland, that a single tillage of long-term NT system either causes no damage, or minimal damage to the various measures of soil physical properties. Recovery times, *i.e.* returning to equivalence with a NT system, generally took from zero to two years but up to four years in some circumstances.

Adoption of strategic tillage

Adoption of strategic tillage to deal with a suspected issue will be driven by profitability, which is influenced by the relative value of the perceived lost grain yield, the cost of tillage and the degree to which the yield constraint is amended by tillage. Clearly, with diseases, insect pests, molluscs and rodents, there are very specific circumstances to consider. Similarly, with herbicide resistance, the full agronomic situation of herbicide and crop rotation also needs to be assessed. Any use of tillage needs to be considered in conjunction with other practices to influence the ecology of the specific biological constraints to grain yield.

The impact of tillage on soil moisture at sowing depends on the rainfall and temperatures between the tillage event and sowing, which is beyond the control of the farmer. Previously, the risk of a dry seed bed was generally greater for winter crops in northern Australia than in the winter dominant rainfall region in the south (Dang *et al.* 2015a, b). However, the recent trend for earlier sowing systems in southern and western Australia (Chapter 18) has re-ignited interest in the need to conserve fallow rainfall and to maintain high stubble loads with minimal soil disturbance using disc seeders.

Probable drivers for strategic tillage will include soil physical and chemical properties and the need to control weeds. There are many common soil physical limitations: a surface crust that inhibits emergence, a hard pan that inhibits root exploration, surface pugging or wheel tracks that create an uneven and partly compacted seed bed. A common soil chemical constraint is acidity, especially in the subsurface soil that will inhibit root development and nodulation by N-fixing microorganisms and cannot be easily ameliorated without lime incorporation. The periodic need for *integrated* weed management is also likely to be a major driver, with around 30-66% of farmers nominating weed management as the reason for pre-sowing cultivation (see Chapter 2). The most appropriate type of tillage will depend on the nature of the main issue. For example, a surface crust will only require a superficial working with an implement such as diamond harrows; a hard pan will require a tined implement but minimal mixing; soil acidity will require mixing of limestone into the soil to below the depth of seed placement by an implement such as off-set discs; surface pugging could be remedied by a scarifier with minor soil disturbance; and wheel tracks might require a deeper working and some mixing but only to strips across the field. No *inversion* of the soil would be required in these instances for soil management but might be necessary to bury herbicide resistant weed seeds (Chauhan *et al.*

2006). A combination of NT, limited or no grazing, and wider row spacing might favour weeds such as fleabane (*Conyza* spp). Any loss of herbicide tolerance for summer weeds would also apply pressure to a NT system. Slug, snail and mouse plagues are more episodic features of our farming systems. In future however, tillage need not always be extensive but could be spot specific and triggered by sensors.

The practical issues to be addressed then, are to determine how much disturbance is required to address the problems identified: the depth, degree of mixing and frequency of tillage that was most appropriate. The potential downsides and their persistence must be weighed against the yield constraints being addressed.

On the basis of existing Australian data, the following guidelines for strategic tillage are offered:

- Commercial application rates of 2 to 3 t/ha of limestone will last for about 10 years before re-application and incorporation is necessary (Conyers *et al.* 2003b), possibly shortened where rates of N fertiliser exceed 100 kg/ha/yr or where long-term surface applications without tillage has caused stratification and subsurface acidification. The limestone can be top-dressed onto the paddock anytime during the autumn. Discing will achieve better incorporation than scarifying (Scott and Coombes 2006).
- Small reductions in wet aggregate stability due to tillage generally can be expected to recover within two years depending on the severity of the tillage and the rate of return of fresh residues to the soil (Conyers *et al.* 2019).
- Losses of soil organic C in cultivated systems are of the order of 0 to 300 kg C/ha/yr in southern Australia, on a stock of 13 to 30 tonnes (Chan *et al.* 2011), while in Vertosols in the north the loss due to tillage can be even less on similar stocks (Dalal *et al.* 2011). Adding supplementary nutrients (NPS) to crop stubbles at the time of incorporation could enhance stores of soil C or at least minimise the loss (Kirkby *et al.* 2016). Maintaining balanced nutrition generally is required to decrease the mining of soil organic matter to provide nutrients for crop growth.
- In the northern grain region, where winter crops rely on stored summer rain, as much as 10 mm of water over 30 cm depth can be lost from the seed zone after a strategic tillage (Crawford *et al.* 2015). Such losses of water might reduce sowing opportunities. This issue might increase in importance in other regions as the issue of stored water for earlier sowings into drier seedbeds becomes more prominent.
- The purpose of the strategic tillage will determine the best timing; however, the timing and intensity of rainfall after tillage dictates the risk of erosion and/or the loss of stored soil water. Local climate data on rainfall and storm frequency are therefore critical background information (Yu and Rosewell 1996, Dang *et al.* 2015a, b).
- To minimise erosion risk we recommend the usual guidelines: the ribbon test for soil moisture, slope assessment, and pending rainfall forecasts. For southern Australia we recommend leaving the tillage as late as possible before sowing.
- Further general guidelines to implement tillage within no-till systems for the northern grains region are summarised in Table 12 of Dang *et al.* (2018).

Conclusions

Strategic tillage is a flexible option that has been adopted by Australian farmers within the context of near full adoption of NT systems. It is a sensible and pragmatic approach to maintain profitability while protecting the soil resource base. Within the context of the trade-offs outlined, best management practice should not be an uncritical adherence to a tillage or stubble management philosophy. The best approach is a field-by-field evaluation each year to take account of the stubble load, weed burden, disease history, pest history, soil physical state and soil test results. There is a wide range of implements available to optimise the tillage required, with varying depths of reach and degrees of soil mixing. Such evaluation and planning is generally within the skills of the modern farmer and their advisor.

References

- Baan CD, Grevers MCJ, Schoenau JJ (2009) Effects of a single cycle of tillage on long-term no-till prairie soils. *Canadian Journal of Soil Science* **89**, 521-530
- Bolliger A, Magi J, Amado TJC *et al.* (2006) Taking stock of the Brazilian “Zero-Till revolution”: a review of landmark research and farmers’ practice. *Advances in Agronomy* **91**, 47-110
- Burns H, Norton M, Tyndall P (2017) Reduced nodulation of faba bean on acidic soils; the role of topsoil pH stratification. *Proceedings of Australian Agronomy Conference*. Ballarat, Australia
- Chan KY, Conyers MK, Li GD, Helyar *et al.* (2011) Soil carbon dynamics under different cropping and pasture management in temperate Australia: Results of three long term experiments. *Soil Research* **49**, 320-328
- Chauhan BS, Gill GS, Preston C (2006) Tillage system effects on weed ecology, herbicide activity and persistence: A review. *Australian Journal of Experimental Agriculture* **46**, 1557-1570
- Conyers MK, Heenan DP, Poile GJ *et al.* (1996) Influence of dryland agricultural management practices on the acidification of a soil profile. *Soil and Tillage Research* **37**, 127-141
- Conyers MK, Heenan DP, McGhie WJ, Poile GJ (2003a) Amelioration of acidity with time by limestone under contrasting tillage. *Soil & Tillage Research* **72**, 85-94
- Conyers MK, Mullen CL, Scott BJ *et al.* (2003b) Long-term benefits of limestone applications to soil properties and to cereal crop yields in southern and central New South Wales. *Australian Journal of Experimental Agriculture* **43**, 71-78
- Conyers MK, Liu DL, Kirkegaard J *et al.* (2015) A review of organic carbon accumulation in soils within the agricultural context of southern New South Wales, Australia. *Field Crops Research* **184**, 177-182
- Conyers MK, Scott BJ (1989) The influence of surface incorporated lime on subsurface soil acidity. *Australian Journal of Experimental Agriculture* **29**, 201-207
- Conyers MK, van der Rijt V, Oates A *et al.* (2019) The strategic use of tillage within conservation agriculture in southern New South Wales, Australia. *Soil & Tillage Research* **193**, 17-26
- Cornish PS, Pratley JE (Eds.) (1987) “Tillage: New Directions in Australian Agriculture”. (Inkata Press: Melbourne)
- Crawford MH, Rincon-Florez V, Balzer A *et al.* (2015) Changes in the soil quality attributes of continuous no-till farming systems following a strategic tillage. *Soil Research* **53**, 263-273
- Dalal RC, Allen DE, Wang WJ *et al.* (2011) Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. *Soil & Tillage Research* **112**, 133-139
- Dang YP, Seymour NP, Walker SR *et al.* (2015a) Strategic tillage in no-till farming systems in Australia’s northern grains-growing regions: 1. Drivers and implementation. *Soil & Tillage Research* **152**, 104-114
- Dang YP, Moody PW, Bell MJ *et al.* (2015b) Strategic tillage in no-till farming systems in Australia’s northern grains-growing regions: 11. Implications for agronomy, soil and environment. *Soil & Tillage Research* **152**, 115-123
- Dang YP, Balzer A, Crawford M *et al.* (2018) Strategic tillage in conservation agricultural systems of north-eastern Australia: why, where, when and how? *Environmental Science and Pollution Research* **25**, 1000-1015
- Dick WA (1997) Tillage system impacts on environmental quality and soil biological parameters. *Soil & Tillage Research* **41**, 165-167
- Dominguez A, Bedano JC, Becker AR (2010) Negative effects of no-till on soil macrofauna and litter decomposition in Argentina as compared with natural grasslands. *Soil & Tillage Research* **110**, 51-59
- Edwards J, Umbers A, Wentworth S (2012) Farm Practices Survey Report 2012 (Grains R&D Corporation: Canberra)
- Emerson WW (1983) Inter-particle bonding. In “Soils: an Australian Viewpoint.” Chapter 31 pp 477-498 (CSIRO:Melbourne)
- FAO (2015) “Conservation Agriculture” www.fao.org/ag/ca/index.html
- Franzluebbers AJ (2002) Soil organic matter stratification ratio as an indicator of soil quality. *Soil & Tillage Research* **66**, 95-106
- Giller KE, Andersson JA, Corbeels M *et al.* (2015) Beyond conservation agriculture. *Frontiers in Plant Sciences* **6**, 1-14
- Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: The heretics’ view. *Field Crops Research* **114**, 23-34
- Glen DM, Symondson WOC (2003) Influence of soil tillage on slugs and their natural enemies. In (Ed. Adel El Titi) “Soil Tillage in Agroecosystems” pp 208-222 (CRC Press: Boca Raton)
- Grandy AS, Robertson GP, Thelen KD (2006) Do productivity and environmental trade-offs justify periodically cultivating no-till cropping system? *Agronomy Journal* **98**, 1377-1383

- Heenan DP, Chan KY, Knight PG (2004) Long-term impact of rotation, tillage and stubble management on the loss of soil organic carbon and nitrogen from a Chromic Luvisol. *Soil & Tillage Research* **76**, 59-68
- Helyar KR, Cullis BR, Furniss K *et al.* (1997) Changes in the acidity and fertility of a red earth soil under wheat-annual pasture rotations. *Australian Journal of Agricultural Research* **48**, 561-586
- Hillel DJ (1991) "Out of the Earth" (The Free Press: New York)
- Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop and Pasture Science* **62**, 915-929
- Hunt JR, Swan AD, Fettel NA *et al.* (2016) Sheep grazing on crop residues do not reduce crop yields in no-till, controlled traffic farming systems in an equi-seasonal rainfall environment. *Field Crops Research* **196**, 22-32
- Johnson RJ (1986) Wildlife damage in conservation tillage agriculture: a new challenge. *Proceedings of 12th Vertebrate Pest Conference*, University of California, Davis
- Kirkby CA, Richardson AE, Wade LJ *et al.* (2014) Nutrient availability limits carbon sequestration in arable soils. *Soil Biology and Biochemistry* **68**, 402-409
- Kirkby CA, Richardson AE, Wade, LJ *et al.* (2016) Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. *PLOS One* **11**, 1-17
- Kirkegaard JA, Conyers MK, Hunt JR *et al.* (2014) Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems and Environment* **187**, 133-145
- Knights S (2010) Raising the bar with better safflower agronomy. (GRDC: Canberra). <https://bit.ly/2Yx9aKL>
- Lal R (2009) The plow and agricultural sustainability. *Journal of Sustainable Agriculture* **33**, 66-84
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Melland AR, Antille, DL, Dang YP (2017) Effects of strategic tillage on short term erosion, nutrient loss in runoff and greenhouse gas emissions. *Soil Research* **55**, 201-214.
- Nunes MR, da Silva AP, Denardin JE *et al.* (2017) Soil chemical management drives structural degradation of Oxisols under a no-till cropping system. *Soil Research* **55**, 819-831
- Owen MJ, Walsh MJ, Llewellyn RS, Powles SB (2007) Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (*Lolium rigidum*) populations. *Crop and Pasture Science* **58**, 711-718
- Paul KI, Black AS, Conyers MK (2003) Development of acidic subsurface layers of soil under various management systems. *Advances in Agronomy* **78**, 187-214
- Pierce FJ, Fortin MC, Staton MJ (1994) Periodic plowing effects on soil properties in a no-till farming system. *Soil Science Society America Journal* **58**, 1782-1787
- Pomeroy DE (1969) Some aspects of the ecology of the land snail, *Helicella virgata*, in South Australia. *Australian Journal of Zoology* **17**, 495-514
- Quincke JA, Wortmann CS, Mamo M *et al.* (2007) One-time tillage of no-till systems: soil physical properties, phosphorus runoff, and crop yield. *Agronomy Journal* **99**, 1104-1110
- Rahman L, Chan KY, Heenan DP (2007) Impact of tillage, stubble management and crop rotation on nematode populations in a long-term field experiment. *Soil & Tillage Research* **95**, 110-119
- Rovira AD (1986) Influence of crop rotation and tillage on Rhizoctonia bare patch of wheat. *Ecology and Epidemiology* **76**, 669-673
- Scott BJ, Conyers MK, Burns HM *et al.* (2017) Stratification of acidity in the shallow soil surface – experiences in the cropping areas of southern and central NSW: doing more with less. *Proceedings of 18th Australian Agronomy Conference*, Ballarat, Australia 24-28
- Scott BJ, Coombes NE (2006) Poor incorporation of lime limits grain yield response in wheat. *Australian Journal Experimental Agriculture* **46**, 1481-1487
- Scott BJ, Eberbach PL, Evans J, Wade LJ (2010) "Stubble retention in cropping systems in Southern Australia: benefits and challenges." EH Graham Centre Monograph No.1
www.csu.edu.au/research/grahamcentre
- Simpfendorfer S, Kirkegaard JA, Heenan DP, Wong PTW (2001) Involvement of root inhibitory *Pseudomonas* spp. in the poor early growth of direct drilled wheat in intact cores. *Australian Journal of Agricultural Research* **52**, 845-853
- Voss MC, Ulber B, Hoppe HH (1998) Impact of reduced and zero tillage on activity and abundance of slugs in winter oilseed rape. *Journal of Plant Diseases and Protection* **105**, 632-640
- Wortmann CS, Drijber RA, Franti TG (2010) One-time tillage of no-till crop land five years post-tillage. *Agronomy Journal* **102**, 1302-1307
- Yu B, Rosewell CJ (1996) An assessment of a daily rainfall erosivity model for New South Wales. *Australian Journal of Soil Research* **34**, 139-152

Chapter 8

Soil Constraints: A Role for Strategic Deep Tillage

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Introduction

Despite grains productivity improvements arising from CA, the gap between yields in growers' paddocks and the physiologically determined water limited yield potential throughout many cropping regions remains large (Hochman *et al.* 2016). Although a variety of factors are responsible for this, many areas of the Australian grain belt with the largest proportional yield gaps contain a range of physicochemical soil constraints (Adcock *et al.* 2007, Dang *et al.* 2010, MacEwan *et al.* 2010, Page *et al.* 2018, Van Gool 2016, see Table 1). These constraints can result in significant reductions in grain yield potential by restricting root growth and access to soil water and nutrient supplies or directly inhibit growth via toxicities. Often a variety of constraints occur simultaneously and can be present in either the top or subsoils (or both) and are associated with both fine and coarser textured soils. In this chapter we have defined 'subsoil' as the part of the profile below normal depth of sowing or routine cultivation for weed control (ca. 0.1 m). Whilst some subsoil constraints reflect the inherent nature of the soil, those occurring in the top 0.5 m of the profile, such as acidity or compaction from machinery, result from agricultural management practices.

A range of strategies have been proposed to manage these soil constraints including:

- 'genetic solutions' involving increased tolerance to soil toxicities;
- agronomic management to maximise profitability rather than productivity;
- 'amelioration', almost inevitably involving some form of physical intervention and/or application of an amendment (Sumner *et al.* 1986, Adcock *et al.* 2007, Gill *et al.* 2008, 2012, Davies *et al.* 2015a, b).

'Biological drilling' ('primer plants') involving use of plant roots to modify subsoils has been assessed (Yunusa and Newton 2003, McCallum *et al.* 2004, Nuttall *et al.* 2008), but in recent years there has been increased attention on strategic deep tillage, which is one-off or occasional tillage typically to depths of 0.3 m or more. Strategic deep tillage includes deep ripping (Hamza and Anderson 2005), deep soil mixing (Scanlan and Davies 2019), soil inversion (Davies *et al.* 2013), deep placement, or clay spreading and delving with deep incorporation (Cann 2000, Rebbeck *et al.* 2007, Hall *et al.* 2010). The size and reliability of yield responses associated with strategic deep tillage differ across soil types and regions, but they can have significant and sustained profitability benefits (Davies *et al.* 2015b, Sale and Malcolm 2015, Davies *et al.* 2018).

If the constraint is chemical, such as sodicity, acidity or a nutrient deficiency, some form of amendment is required, either inorganic (*e.g.* gypsum or lime) or organic (*e.g.* manures, compost). Such amendments have typically been applied to the topsoil (*e.g.* Armstrong *et al.* 2007, Li *et al.* 2019) but direct placement into subsoil is gaining interest (Davies *et al.* 2008, Condon *et al.* 2018, Sale *et al.* 2019), although the mechanisms of yield improvements appear to vary with soil type and seasonal conditions and are contested (Celestina *et al.* 2018, Gill *et al.* 2019). Many subsoil amelioration practices have a high cost to implement and so are strategic in application and need to have a long residual benefit to make economic sense.

Soil constraints

In Australian dryland cropping systems, soil constraints typically align with broad soil types (Table 1). Low water holding capacity, topsoil water repellence, compaction, soil acidity and associated aluminium and manganese toxicity, and poor fertility are common on deep sands, sandy earths and sandy A-horizons of duplex (texture contrast) soils. High alkalinity, sodicity and chemical toxicities such as boron, chloride, bicarbonate and salt are common on finer textured loamy earth and clay subsoils and in the clay B-horizon of duplex profiles (Table 1).

Table 1. Association of common constraints of agricultural soils and the Australian Soil Classification soil orders (Isbell and National Committee on Soil and Terrain 2016). Dominant soil texture is shown include sand (S), texture contrast (TC), loam (L) and clay (C)

Australian Soil Classification SOIL ORDER		Tenosols	Rudosols	Kandosols	Calcarosols	Sodosols	Kurosols	Chromosols	Vertosols	Dermosols	Ferrosols
Soil Texture		S	S	L	S, TC	TC	TC	TC	C	C	C
COMMON SOIL CONSTRAINTS	Water repellence	x	x	x	x	x		x			
	Low water holding capacity	x	x		x		x				
	Subsoil compaction	x	x	x	x	x		x	x		
	Poorly structured dense subsoil	x	x	x	x	x	x	x		x	x
	Poor subsoil fertility	x	x	x	x	x	x				α
	Acidity (Al and Mn toxicity)	x	x	x			x	x			x
	Alkalinity				x	x				x	
	Sodicity					x	x		x		
	Temporary water logging					x	x	x	x	α	
	Boron toxicity				x	x			x		
	Other toxicities (e.g. Chloride)				x	x			x	x	

x = commonly occurring; α = variable occurrence

Soil water repellence occurs when hydrophobic organic compounds and waxes of plant and fungal origin coat topsoil sand particles resulting in slow and uneven water infiltration (Chan 1992, Franco *et al.* 1995, 2000, Doerr *et al.* 2000, Unkovich 2014). It is most common on sandy-topsoils with low clay content (<5 %) and has been recognised as a major constraint since land clearing in the late 1940s (Bond 1964, Roberts and Carbon 1971). Water repellence results in uneven and slow soil wetting causing:

- poor and delayed crop establishment;
- staggered weed germination;
- susceptibility to wind and water erosion;
- high leaching risk due to preferential flow; and
- inefficient use of rainfall (King 1981, Blackwell 2000, Roper *et al.* 2015).

Concentration of organic matter at the soil surface through reduced tillage (Chan 1992), a shift towards earlier and dry seeding (Fletcher *et al.* 2016), and smaller, less reliable break-of-season rainfall events, have likely contributed to increased expression of soil water repellence (Roper *et al.* 2015).

Subsoil compaction, plough pans and inherent hard layers as a result of cementation (Needham *et al.* 2004a) have long been recognised as significant soil constraints (Hamblin and Tennant 1979, Henderson *et al.* 1988). Growth in the scale of cropping enterprises has led to the use of larger, heavier machinery with resultant higher axle loads causing deeper, more severe, compaction (Henderson *et al.* 1988, Hagan *et al.* 2015, Isbister *et al.* 2016). Current agricultural machinery such as harvesters, air carts, tractors, sprayers and chaser bins have axle loads exceeding 10 tonnes, resulting in deeper compaction to 0.4 m or more (Isbister *et al.* 2016). Degree of compactibility for soils with less than 20% clay is related to the particle size distribution (Needham *et al.* 2004b). Soils with more even (well-graded) distribution of soil particles can be more susceptible to compaction than poorly-graded sand, though these may still have high bulk density (Needham *et al.* 2004b).

Agricultural practices have acidified soils. Soil acidity is a common soil constraint in cropping zones of south eastern and Western Australia (WA) and occurs in both coarse and fine textured soils. The acidification rate has increased as cropping has intensified, with higher inputs of N fertilisers and increased product export (Mason *et al.* 1994, Dolling and Porter 1994, Dolling *et al.* 1994). Where lime applications have been inadequate, there has been extensive development of subsurface acidity (Williams 1980, Tang *et al.* 2000, Tang 2004, Gazey *et al.* 2013) and associated aluminium and manganese toxicity. Whilst lime application can ameliorate acidity within the 0-10 cm layer, the slow dissolution and movement of lime limits the effectiveness of surface-applied lime to address deeper, subsoil acidity (and see Chapter 7).

Grain production in the low and medium rainfall regions of Australia is mostly conducted on neutral to alkaline soils (Adcock *et al.* 2007, Dang *et al.* 2010, van Gool *et al.* 2018). Clay content typically increases with depth (to more than 60%), often concurrent with an increase in the severity of a range of physicochemical subsoil constraints. These limit crop productivity via impeding subsoil root growth and function, leading to poor utilisation of subsoil water and nutrients (Nuttall *et al.* 2003). Lack of available water is the principal yield constraint in these environments and subsoil constraints tend to restrict grain yields in seasons with 'dry finishes' (Nuttall and Armstrong 2010) when the crop is more reliant on subsoil water reserves to complete grain fill. Most subsoils contain multiple constraints, the most common being sodicity and salinity, but many also have toxic concentrations of boron (B), chloride (Cl⁻), bicarbonate (HCO₃⁻) and potentially aluminium (Al) arising from high pH, as well as reduced nutrient availability (Adcock *et al.* 2007, Dang *et al.* 2010, Brautigan *et al.* 2012). Poor subsoil structure and high soil strength resulting from both sodicity (Shaw *et al.* 1994) and compaction (McGarry 1993, Hamza and Anderson 2005) is common. Poor subsoil structure often leads to restricted drainage, temporary water logging and restricted aeration (Rengasamy *et al.* 2003). Many texture contrast soils can also have alkaline clay-rich B-horizons that are sodic, poorly structured and may also be saline (Hall *et al.* 2009), restricting crop root growth and nutrient availability (Tennant *et al.* 1992, Belford *et al.* 1992).

Strategic deep tillage tools and approaches

Deep ripping, also known as subsoiling, involves the loosening of soils for the purpose of removing hardpans, either natural or induced, and loosening dense subsoils to improve soil structure, porosity and water infiltration (Spoor 2006). Deep ripping is undertaken using deep working tynes which may be rigid or have high-breakout pressure. Typically, deep rippers do not intentionally incorporate much topsoil into the subsoil (Scanlan and Davies 2019). The type and geometry of the deep ripper can influence soil mixing as rippers with parabolic, wider or angled chisel-point tynes can delve and mix the soil more than narrow-tynd rippers (Spoor 2006). Addition of wings or wider points can also result in more breakout and soil disturbance, depending on working depth and soil conditions, especially moisture content (Spoor 2006). Narrow-tynd rippers can incorporate around 5-10% of the topsoil into soil layers below 0.1 m, but this would typically only be to a maximum depth of 0.15 m (Scanlan and Davies 2019; Table 2). This 'mixing' is passive with topsoil falling into temporary voids around and behind the ripping tynes as they pass through the soil.

In Australia, deep ripping has been practised for more than 40-years (Jarvis 1983, 1986a, Ellington 1986) and has long included the possibility of incorporating or deep placing soil amendments, such as lime, nutrients and organic matter (Robertson *et al.* 1957, Parr 1959). In continuous or intensive grain cropping systems of WA, deep sandy-textured soils have been the most responsive to deep ripping (Jarvis 1986b) and consequently the most commonly ripped soils. Ripping depths have traditionally been 0.3-0.4 m (Jarvis 1986b) but in recent years ripping depths on deep sands and sandy earths have increased to 0.7-0.8 m (Blackwell *et al.* 2016). The move to even deeper ripping has been driven by:

- recognition of deeper and more severe compaction layers arising from larger and heavier machinery (Isbister *et al.* 2016) coupled with increased cropping intensity;
- increased availability of high horsepower tractors and deeper working rippers; and
- larger yield and potential profit benefits when used on responsive soil types.

Table 2. Summary of strategic deep tillage approaches, working depth, incorporation characteristics, soil constraints addressed and approximate cost

Strategic deep tillage method	Implement working depth (m)	Implement impact on incorporation of soil amendment and/or topsoil	% topsoil buried below 0.1 m*	Constraints addressed	Approximate cost (\$/ha)
Deep ripping	0.3-0.7	Minimal incorporation, depending on ripper type. Backfill to 0.15 m.	5-10	Compaction Hardpans	\$45-100
Deep ripping with topsoil slotting	0.3-0.7	Topsoil slots from surface typically to depths of 0.35-0.40 m, but ripping depths can extend to 0.70 m. Can partially incorporate surface spread amendments (<i>e.g.</i> lime, nutrients, organic matter).	10-15	Compaction Hardpans Subsoil acidity Subsoil sodicity	\$55-120
Deep subsoil placement, using ripper	0.3-0.7	Direct deep placement of amendments (<i>e.g.</i> organic matter, lime, gypsum, nutrients) in bands at depths up to 0.70 m.	5-15	Compaction Hardpans Subsoil acidity Subsoil fertility	\$300-1400
Subsoil clay Delving + incorporation	0.6-1.2	Backfill likely due to wide tynes and high disturbance, subsequent clay incorporation will mix soils to 0.15-0.45 m. Soil amendments can be mixed into soil profile by incorporation process.	n.m.	Water repellence Compaction Fertility of A-horizon	\$300-450
Soil mixing – large offset discs	0.2-0.3	Offsets throw soil one way then back again, mixing of topsoil and surface spread amendments, (<i>e.g.</i> lime, subsoil clay, organic matter) typically occurs between 0.15-0.25 m.	n.m.	Subsoil acidity Water repellence Compaction	\$50-70
Soil mixing - one pass tillage	0.3-0.35	Mixing of topsoil and surface spread amendments to 0.15 m and some deeper inclusion to 0.30 m possible depending on tyne design.	n.m.	Subsoil acidity Compaction	\$70-100
Soil mixing – rotary spader	0.35-0.4	Mixes to maximum working depth of 0.35-0.40 m. Can incorporate a range of surface spread amendments (<i>e.g.</i> lime, gypsum, organic matter, subsoil clay, nutrients etc.)	50-60	Subsoil acidity Compaction Water repellence Fertility of A-horizon	\$120-150
Soil inversion - mouldboard plough	0.35-0.45	Buries a layer typically between 0.15-0.40 m. Can bury surface applied amendments (<i>e.g.</i> lime, organic matter, nutrients etc.) at depth. For subsoil acidity low pH subsoil brought to the surface after ploughing will need to be limed.	80-90	Water repellence Compaction Subsoil fertility Weeds	\$100-150
Soil inversion – modified one way disc plough	0.3-0.4	Buries topsoil or surface applied amendments, such as lime or organic matter, in an arc from surface down to a depth of 0.25-0.35 m.	60	Water repellence Compaction Subsoil fertility Weeds	\$40-60

* The proportion of topsoil buried below 0.1 m based on Scanlan and Davies 2019, Ucgul *et al.* 2017, 2018, 2019. n.m. = not measured.

Costs of ‘deeper’ ripping are considerably higher with greater fuel use as a result of increased draft force, reduced work rate with narrower rippers and slower operating speeds and greater wear and fatigue of engines and machinery components working under high load (Blackwell *et al.* 2016, Isbister *et al.* 2016). Blackwell *et al.* (2016) found that fuel use at least doubled when ripping to 0.55 m on sand compared with ripping to 0.3 m. Shallow leading tynes can reduce the deeper ripping draft force and fuel use compared with conventional ripping and provide more effective removal of deep compaction

(Hamza *et al.* 2013). Depending on the tyne arrangement, shallow-leading tynes were shown to reduce draft by up to 11-25% on deep loamy sand and by up to 18% on a clay soil (Hamza *et al.* 2013).

Other developments in deep ripping include topsoil slotting (Blackwell *et al.* 2016, Davies *et al.* 2015a, Parker *et al.* 2017) and direct deep placement of amendment (Gill *et al.* 2008, Davies *et al.* 2008, Sale *et al.* 2019). Topsoil slotting is achieved through placement of an opener behind the ripping tyne which operates just below the topsoil, holding the subsoil open to allow loosened topsoil and surface applied amendment to fall into slots (Davies *et al.* 2015a, Blackwell *et al.* 2016, see Figure 1). Deeper inclusion of surface organic matter to depths up to 0.35-0.40 m may help maintain the ripping slot in softer condition for a longer time (Blackwell *et al.* 2016).

Direct placement of organic or other soil amendments directly into the subsoil typically involves placement of pipes directly behind deep ripper tynes (Gill *et al.* 2008, Davies *et al.* 2008). Large diameter pipes are used for deep placement of dry, sometimes pelletised, amendments which flow via gravity or are blown into the subsoil (Gill *et al.* 2008, Davies *et al.* 2008). Liquid amendments can be pumped through smaller diameter tubes, although the volume of amendment that can be applied is restricted (Anderson and Hendrick 1983).

Clay delving, like deep ripping, uses deep working tynes to interact with the subsoil. In this instance tynes are fixed, often angled at ~45°, broad-faced and typically work at depths of at least 0.6 m or more, typically with only 2-3 tynes spaced about 1 m apart (Desbiolles *et al.* 1997, Bailey and Hughes 2012, Betti *et al.* 2015). Delving tynes penetrate the clay B-horizon of texture contrast, or duplex, soils and lift clay-rich subsoil into the sandy A-horizon (Bailey and Hughes 2012) while at the same time physically breaking up compacted and cemented layers (Figure 1). Following delving, soils are typically worked with offset discs or a rotary spader (described below) to mix further and incorporate the clay (Bailey and Hughes 2012). Increasing the clay content of sandy topsoils can reduce soil water repellence and improve soil wettability (Betti *et al.* 2015, 2016), while also improving fertility (Hall *et al.* 2010), soil carbon storage (Schapel *et al.* 2017, 2018) and crop yield (Bailey *et al.* 2010, Hall *et al.* 2010, Betti *et al.* 2017).

Deep soil mixing involves occasional cultivation of soils to depths of 0.2 m or more (Scanlan and Davies 2019), as opposed to traditional ploughing or cultivation practices that are shallower and were traditionally practised regularly, rather than as a strategic or one-off practice. Deep soil mixing can be beneficial by reducing topsoil water repellence and partial weed seed burial (Davies *et al.* 2013). Deep mixing can also be effective to incorporate stubbles and place surface organic matter and associated nutrients deeper into the soil profile. In Australia, deep mixing is typically undertaken using large, deep working, offset disc ploughs, one-pass tillage system implements or, more recently, rotary spaders (Davies *et al.* 2010, 2013, 2015a, see Table 2).

One-pass tillage implements combine a series of tillage tools on the one implement, typically a leading set of shallow working offset discs followed by ripping tynes and then levelling discs or harrows and a soil packer (Davies *et al.* 2015a). While they may have a working depth of 0.3-0.35 m, depth of incorporation is often 0.25 m or less. Large offset discs can also have disc diameters up to 0.8-1.0 m and work as deep as 0.3 m; however effective incorporation of the surface often only occurs to a depth of 0.2-0.25 m (Davies *et al.* 2015a, see Table 2). Rotary spading typically follows deep ripping and has a working depth of 0.35-0.4 m (Scanlan and Davies 2019, Ucgul *et al.* 2018, see Table 2).

Rotary spaders have a shaft which rotates, typically at ~90 revolutions per minute in the direction of travel. Attached are sets of curved tynes, on the end of which are, typically, triangular-shaped spades that help bury topsoil at depth while also lifting some subsoil to the surface (Scanlan and Davies 2019, Ucgul *et al.* 2018). Incorporation by a spader is not uniform; rather the spades bury deeper 'pockets' of topsoil (Figure 1) in a grid pattern when viewed from above, through various soil layers (Ucgul *et al.* 2018). Rotary spaders typically bury about 50-60% of the topsoil (Ucgul *et al.* 2018, Scanlan and Davies 2019, see Table 2).



Figure 1. Images demonstrating a range of strategic deep tillage implements and the impact they have on the soil profile. Note incorporation dark coloured topsoil caused by each implement (Photos: Stephen Davies, Department of Primary Industries and Regional Development WA and Erin Cahill, agVivo image modified one-way plough).

Soil inversion is perhaps the most extreme strategic deep tillage option, resulting in the topsoil being nearly completely buried underneath a layer of subsoil 0.15-0.35 m deep (Figure 1). This provides an opportunity to:

- bury water repellent topsoil and lift wettable subsurface soil to the surface;
- incorporate lime, deeper into the soil profile;
- redistribute topsoil nutrients and organic matter into the crop root zone; and
- lift higher clay content subsoil to the surface, depending on soil type (Davies *et al.* 2013).

The principal advantage of inversion over soil mixing is more effective amelioration of topsoil water repellence (Roper *et al.* 2015) and the near complete burial of weed seeds (Peltzer and Matson 2006, Davies *et al.* 2010, Newman and Davies 2010, Aulakh *et al.* 2012) which can slow the evolution of herbicide resistance (Renton and Flower 2015). Soil inversion is typically undertaken with a mouldboard or ‘square’ plough but more recently modified one-way disc ploughs have also been used. The modifications involve removal of every second disc and fitment of larger and often more concave discs, increased break-out pressure on the jump arms and may involve adding more weight to the

plough, depending on the model used. These modifications allow deeper working, more space for soil to turn over and a greater degree of inversion. Mouldboard ploughs provide the most complete inversion (Ucgul *et al.* 2017, Scanlan and Davies 2019), but square and one-way ploughs are cheaper to purchase and effective with good setup and soil conditions (Ucgul *et al.* 2019), though weed seed burial is inferior to the mouldboard plough. Mouldboard ploughs typically bury 80-95% of the topsoil below the top 0.1 m (Ucgul *et al.* 2017, Scanlan and Davies 2019, see Table 2) while one-way ploughs bury 60-75% of the topsoil (Scanlan and Davies 2019, Ucgul *et al.* 2019, see Table 2).

Strategic deep tillage practices are often implemented in combination, either at the same time or in series over several years (Davies *et al.* 2018). The most common combinations involve deep ripping together with either soil mixing or inversion (Davies *et al.* 2018) or clay delving with subsequent incorporation. Timing of this ripping after inversion can vary, but generally occurs within 2-4 years. Use of controlled traffic farming systems can increase the longevity of soil loosening benefit from strategic deep tillage by confining machinery compaction to permanent wheel-tracks (Ellington 1986, Chan *et al.* 2006). However, some subsoils naturally 're-compact' after loosening and may require occasional deep ripping (Needham *et al.* 2004a).

Effects on crop growth and yield

Deep ripping to alleviate subsoil hardpans is most beneficial on deep sands and deep sandy duplex soils (Jarvis 1986b, Hamza and Anderson 2003), with responses on heavier-textured soils more variable and less reliable (Ellington 1986, Kirkegaard *et al.* 2008, Armstrong *et al.* 2009). Yield benefits from ripping result from improved root growth extension rates and final rooting depth which contribute to subsoil water access and more efficient nitrogen capture (Delroy and Bowden 1986). In sandy soils, deep ripping typically results in substantial increases in grain yield, of the order of 20-40% in the first season after ripping (Hamza and Anderson 2003, Armstrong *et al.* 2009). Yield benefits from deep ripping typically decline substantially in subsequent seasons. Despite yield increases of 19% in the year of ripping (sandy duplex), Hamza and Anderson (2003) report that by the third year the yield benefit had disappeared. Reasons for a neutral or negative response to ripping include:

- enhanced vegetative crop growth driving greater water use with insufficient moisture left for grain filling (Delroy and Bowden 1986);
- bringing excessive clay or hostile subsoil to the surface on heavier-textured soils (Kirkegaard *et al.* 2008, Armstrong *et al.* 2009, Blackwell *et al.* 2016);
- loss of soil structure; or
- not fully overcoming compaction or other soil constraints present, such as acidity (Coventry *et al.* 1987).

On deeper sands, increasing ripping depth up to 0.8 m to remove deeper compaction can substantially increase the crop yield benefit in situations where traditional ripping depths of 0.3-0.4 m have not improved yield (Blackwell *et al.* 2016, Isbister *et al.* 2016, Davies *et al.* 2018). Blackwell *et al.* (2016) reported yield increases of 83-137% following ripping to 0.55 m, compared with minimal response following ripping to 0.3 m.

Crop response to ripping with topsoil slotting to incorporate surface organic matter and amendments deeper into the profile have been mixed (Blackwell *et al.* 2016, Davies *et al.* 2015a). Blackwell *et al.* (2016) reported that, for deep ripping to 0.55 m following spreading of surface-applied lime on deep sand and sandy duplex sites, wheat yield benefits from topsoil slotting ranged from 16-32% over deep ripping with no slotting. Lime addition improved the benefit at several of the more acidic sites, consistent with previous research (Coventry *et al.* 1987, Davies *et al.* 2008). In contrast Davies *et al.* (2018) found no significant benefit to wheat yields (-12-10%) from topsoil slotting across two sites and two ripping depths compared with ripping alone. Parker *et al.* (2017) reported reduced yields from topsoil slotting for lupin in the second season, noting that the soil opener which facilitates topsoil slotting had also acted to re-compact the soil between the tynes. On heavier soil types, including a calcareous loam, loamy duplex and grey clay, crop yield response to topsoil slotting showed no positive

yield responses in the first year (Blackwell *et al.* 2016) but on the grey clay in the second season increased barley yield by 0.67 t/ha over ripping only (Parker *et al.* 2017).

Broad-faced ripping tynes can delve (lift) clay-rich subsoil within the 0.3-0.6 m layer into the sandy textured surface A-horizon of duplex (texture contrast) soils. This results in benefits from deep subsoil loosening and removal of hardpans and topsoil water repellence but can also improve the fertility, pH and moisture holding of the sandy A-horizon (Bailey *et al.* 2010, Bailey and Hughes 2012, Betti *et al.* 2015, 2016, 2017). Variability in crop response to delving has been attributed to differences in the machinery used, the depth and extent of mixing between the soil horizons, and the timing of operation.

Cereal grain yields are increased by around 50% on average in the first two years following rotary spading on deep sands and deep sandy duplex soils (Davies *et al.* 2019). This represents a yield increase of 0.42-0.73 t/ha depending on soil type. Growth and yield increases are in part driven by increased mineralisation of organic matter, leading to greater nutrient supply, along with nutrient redistribution, establishment, soil loosening and soil pH benefits. Once these effects subside, residual yield responses appear soil type dependent, falling to 11% (0.22 t/ha) on average for pale deep sands but remaining at 33% (0.55 t/ha) for stronger deep sands, sandy earths and deep duplex soils (Davies *et al.* 2019). Current research indicates that benefits from rotary spading can last at least 4-5 years on better sands but may be more limited on infertile and low clay content deep sands (Davies *et al.* 2019).

Crop grain yield responses to soil inversion can be large and sustained for 8 or more years (Davies *et al.* 2015b, Davies *et al.* 2019). Soil inversion on average increases cereal grain yield by 30-60% (0.54-0.88 t/ha) in the first 2-years depending on soil type (Davies *et al.* 2019). As with deep soil mixing, responses tend to be lower on low fertility deep sands, and higher on deep sandy duplex and repellent gravel soils. Residual cereal yield benefits average 21-27% (0.51-0.68 t/ha) for most soils. For pale deep sands residual yield benefits typically decline after several years except for severely repellent deep sands where the untreated condition is particularly poor (Davies *et al.* 2019).

While benefits of ameliorating sands through deep soil mixing and soil inversion are apparent, there are numerous substantive risks, including:

- acute short-term wind erosion risk with complete stubble burial;
- surface crusting from lifting higher clay content subsoil to the surface with low organic matter;
- increased activity of pre-emergent herbicides resulting in greater risk of crop damage (Edwards *et al.* 2018) as well as opportunity for improved weed control;
- loss of soil organic carbon from tillage effect;
- poor seed depth control on loosened soils;
- re-compaction, especially if traffic is not controlled; and
- run-down of soil fertility.

These risks can be managed by growers but highlight the complexity and management required to achieve an 'optimal' outcome.

Strategic deep tillage with soil amendments

For soils with a combination of soil physicochemical constraints, soil amendments together with strategic deep tillage may be needed to address the interacting constraints, stabilise or improve soil structure or improve subsoil fertility all of which may improve the size and longevity of the amelioration benefit (Ellington 1986, Coventry *et al.* 1987, Hamza and Anderson 2003).

Lime incorporation into acidic subsoils

Movement of lime to depth is influenced by soil properties (texture, initial pH, pH buffering capacity), rainfall (duration and intensity) and lime (quality, particle size and rate of application, Whitten *et al.* 2000) but is generally very slow without physical intervention (Li *et al.* 2019). Conyers and Scott (1989) demonstrated that application rates of 8 t/ha were required to increase pH several centimetres below the depth of incorporation in loam topsoil of a southern NSW duplex soil. However, the mechanism of

alkali movement is related to the pH following liming and not the rate of lime itself (Scott and Conyers 1995). They recommended liming to a $\text{pH}_{\text{Ca}} > 5.5$ to facilitate alkali movement below the incorporation layer to the 0.1-0.2 m layer in their example. However long-term field experimentation demonstrates that the rate of subsoil pH increase remains slow, 0.04 pH units per year in the 0.1-0.2 m layer (Li *et al.* 2019).

Use of tillage to incorporate liming products to greater depth allows for more immediate amelioration of soil acidity in the subsoil. On acidic deep sandy textured soils with low pH buffering capacity, compaction and minimal subsoil structure, surface liming followed by incorporation using strategic deep tillage is an effective amelioration intervention (Gazey and Davies 2009). Rotary spaders, large offset discs and mouldboard ploughs have been used to incorporate lime into acidic sands (Davies *et al.* 2015a). The interaction of soil inversion with a mouldboard plough and lime application improved barley yield and reduced ryegrass biomass in a replicated experiment on deep yellow sand in WA, eight seasons after the amelioration was applied (Figure 2, Davies *et al.* 2015b).

For soils with higher clay content, deep tillage to depths of 0.3-0.4 m requires large energy inputs, can damage soil structure and increase erosion risk, especially if poorly structured A_2 horizons are brought to the soil surface (Kirchhof *et al.* 1995). For example, broadcasting lime at high rates (20 t lime/ha) prior to ripping or delving was shown to have limited benefit in ameliorating subsoil acidity (Kirchhof *et al.* 1995, see Figure 3a). Thus, deep tillage to incorporate lime into bulk soil is not commonly used on the loam and clay soils of south-eastern Australia, though beneficial interactions have been measured (Coventry *et al.* 1987). On sandy clay loam with a dense hardpan and subsoil acidity in north-east Victoria, lime application was necessary to achieve a deep ripping response and the ripping was still effective after 4-years (Coventry *et al.* 1987).

Where deep tillage of bulk soil may be uneconomic or impractical, techniques that amend specific portions of the soil profile or areas under or adjacent to seeding rows have been assessed (*e.g.* Davies *et al.* 2008, Blackwell *et al.* 2016, Sale *et al.* 2019). Lime slotting by mechanically cutting slots, 0.15 m wide and 0.8 m deep, in the profile to remove soil, mixing that soil with lime at 20 t lime/ha and then replacing the amended soil back to the slot, was effective in increasing soil pH (Figure 3a) in the slot (Kirchhof *et al.* 1995) and resulted in 46% of the yield of a completely amended soil (Jayawardane *et al.* 1995). However the use of such high lime rates and specialised intensive machinery limit the practicality of this method in dryland cropping systems.

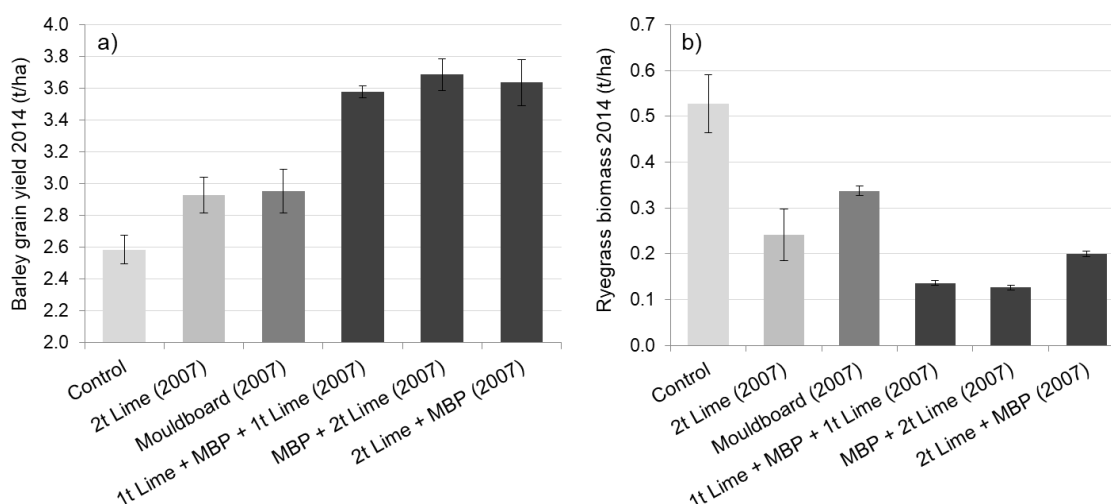


Figure 2. Impact of lime application and mouldboard ploughing (MBP) applied in 2007 on: a) barley grain yield (t/ha); b) above-ground ryegrass biomass (t/ha, right) in 2014. For treatments with lime, all were surface applied at total rate of 2 t/ha either without incorporation (2t Lime); split with half (1 t/ha) before and after MBP (1t + MBP + 1t); all applied before MBP (2t + MBP); or all applied after MBP (MBP + 2t). Bars show standard error of the mean of 4 replicates (adapted from Davies *et al.* 2015b)

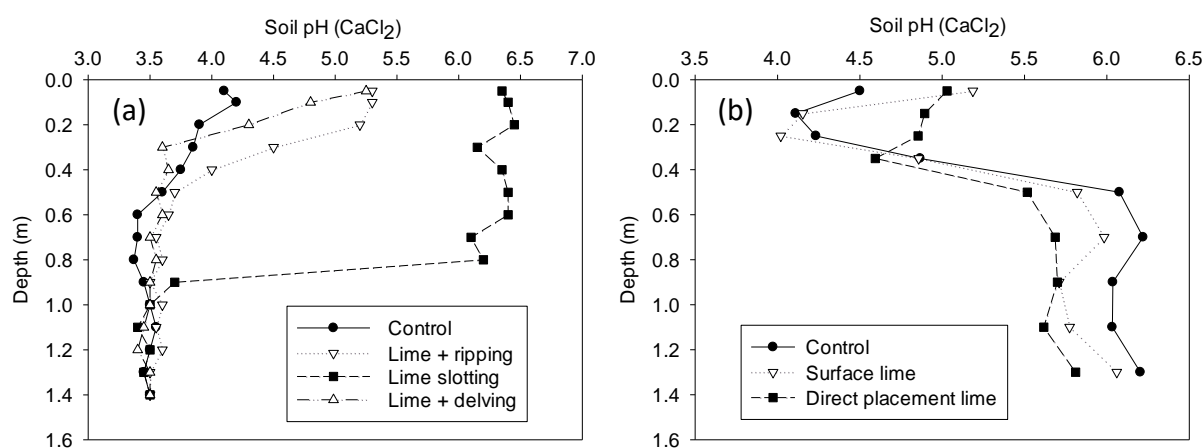


Figure 3. Impact of lime application and placement on soil pH profiles for: a) a yellow Podsol showing untreated (control), lime followed by ripping or delving and slotting of lime amended soil (adapted from Kirchhof *et al.* 1995); and b) a Chromosol at Rutherglen, Victoria, showing untreated (control), surface lime and direct deep (0.3 m) lime placement (adapted from Condon *et al.* 2018)

Direct placement of lime has been achieved with modified deep rippers, fertiliser spreaders and air delivery systems to create machines that blow lime into subsoil seams to a depth of 0.3 to 0.4 m (Davies *et al.* 2008, Li and Burns 2016). This machinery can ameliorate subsoil acidity to the depth of placement (Figure 3b) and also decrease soil strength (Davies *et al.* 2008, Li and Burns 2016, Condon *et al.* 2018). Yield responses from this approach have been mixed, with crop yields failing to respond at a range of sites in southern NSW (Swan *et al.* 2011, Li and Burns 2016) but was shown to increase wheat yield by 20-30% in WA deep sands with acidic subsoils (Davies *et al.* 2008, Gazey and Davies 2009). For the southern NSW sites, drought conditions experienced during the trial years 2007-9 may have limited the opportunity for a crop response (Swan *et al.* 2011). Direct lime placement and partial amelioration of acidic subsoils enables lime application rates to be decreased, potentially to economically viable rates.

Application rates of dolomite or lime of 2.3 and 2.5 t/ha, respectively, ameliorated the acidity in the 10-30 cm of a Chromosol at Rutherglen, Victoria (Figure 3b) resulting in more than a 10% increase in canola yield compared with an unlimed control (Condon *et al.* 2018). Some versions of direct placement equipment can apply organic material and other inorganic amendments to specific layers of the soil, allowing amelioration of acidity and provision of subsoil nutrition, thereby addressing multiple crop productivity constraints (Condon *et al.* 2018). Apart from the need of specialised equipment and slow application process, a major limitation to success of direct deep lime placement is poor vertical distribution and a discontinuity of the ameliorated subsoil which would likely limit the benefit obtained.

Clay spreading and incorporation on sands

Addition of clay-rich subsoil to sands, known as claying, was first trialled in 1968 by South Australian farmer, Clem Obst, near Bordertown. After spreading a clay-rich subsoil on a sandy rise following excavation of a new dam, Obst (1994) recalls an immediate and long-lasting improvement in soil wettability, successfully growing clover and lucerne on clay-spread areas in following years. It is now estimated that 0.16 Mha of land have been clay modified in southern and Western Australia (Churchman *et al.* 2014).

Where available, incorporation of clay subsoil provides a permanent amelioration of soil water repellence but can also modify soil pH, nutritional status, moisture dynamics, carbon sequestration, soil stability and biological activity. Improved plant nutrition, particularly potassium from the applied clay, and greater water infiltration are key factors behind improved productivity on clayed soils (Hall *et al.* 2010). Substantial benefits (up to 22 t/ha increases) to soil organic carbon (SOC) stocks (0-30 cm) have also been associated with increased clay content (Schapel *et al.* 2017, 2018), although the benefits of

this on improved biological fertility and nutrient retention and supply have been poorly quantified to date.

Surface spreading of clay is undertaken when clay B-horizon subsoils are too deep to be delved effectively. Clay spreading involves excavation and broadcast spreading of a clay-rich subsoil from a large pit over deep, typically repellent, sands (Davenport *et al.* 2011). Spreading is typically undertaken using carry graders, purpose-built spreaders or heavy-duty multi-spreaders. Once spread, a range of deep cultivation approaches (*e.g.* tynes, off-set discs, harrows, rotary hoe) are used to incorporate the clay into the top 0.1 to 0.2 m. Subsoil clays are typically spread at rates of 100-300 t/ha, aiming to increase the topsoil clay content to the 3-6% clay required to overcome repellence (Hall *et al.* 2010, Davenport *et al.* 2011). High rates (200 t/ha or more) can be difficult to incorporate effectively and can lead to negative impacts, such as soil sealing, poor emergence and restricted root development (Davenport *et al.* 2011). Implements for deeper incorporation, such as rotary spaders and large-diameter deep working offset discs help minimise this risk.

Although expensive, claying practices have been shown to double crop yields, with an expectation of permanence (Cann 2000). Yield increases of 0.3-0.6 t/ha have been reported on a WA sandplain soil (Hall *et al.* 2010).

Incorporation of organic amendments

Organic amendments have the potential to provide benefits over and above their nutritional value alone including altering:

- physical condition through changing structural stability, porosity and bulk density, which impact root growth and water dynamics;
- chemical condition through changing pH buffering, cation exchange capacity, and chelation which affect nutrient supply and retention; and
- biological functions including nutrient cycling rates, and the balance between beneficial and pathogenic organisms.

The use of organic amendments in agriculture has been reviewed previously (Edmeades 2003, Quilty and Cattle 2011, Abbott *et al.* 2018). In general, these reviews focus on results from surface application of amendments, often in terms of disposal of ‘wastes’, where there has been a focus on nutrient budgets. These overseas studies have often failed to account for other potential benefits to productivity by using these organic amendments if soil physicochemical constraints are present. A recent Australian study (Celestina *et al.* 2018) compared surface and subsoil application of organic amendments or additional matching inorganic fertiliser applications and found that over the first two years following application the yield response could generally be attributed to additional nutrient supply, particularly nitrogen. The impact of any amendment in overcoming a physicochemical constraint in the subsoil will be negated if there is either no subsoil water, as occurs in very low rainfall years, or when the crop can rely on water in the topsoil and so can be highly season-dependant (Nuttall and Armstrong 2010). Similarly, no long-term beneficial effect of the amendments will occur if there are no physical constraints present, such as occurs on many well-structured soils, such as vertosols. Furthermore, it may take several years for the benefits of organic amendments to become evident, as they result not only from the short-term direct nutrient effects, but longer-term indirect effects. Indirect effects include those resulting from altered root growth and distribution, as well as enhanced aggregation resulting from microbial processes (hyphal binding, extracellular polymer binding, Six *et al.* 2004, Tisdall and Oades 1978). This has been demonstrated in recent research targeting poorly structured sodic subsoils where subsoil manuring (chicken litter placed at 0.3-0.4 m) improved grain yields through both improved crop nutrition and soil structure (Gill *et al.* 2019, Sale *et al.* 2019). Gill *et al.* (2019) demonstrated seasonal impacts on response with no difference between surface and subsoil manuring at one site in an ‘average’ rainfall season but a significant advantage of subsoil manuring over surface manuring in a season with a dry spring, where the crop was reliant on subsoil water reserves during grain filling. Transport and application costs can be challenging for profitability of organic amendments although, where successfully applied to overcome subsoil constraints, the potential for profitable outcomes has been demonstrated (Sale and

Malcolm 2015, Trengove and Sherriff 2018, Gill *et al.* 2019). Further work appears necessary to attribute growth and yield impacts from deep organic amendments to nutritional or other mechanisms and to assess economic feasibility (Gill *et al.* 2019, Celestina *et al.* 2018, 2019).

In sands, rotary spading, topsoil slotting, soil inversion or direct deep placement can be used to incorporate organic amendments into the profile. In South Australia (SA) the combination of deep ripping to 0.3 m with surface applied chicken litter (5 t/ha) and/or high fertiliser rates has been evaluated (Trengove and Sherriff 2018). The outcomes demonstrate strong seasonal and rotational effects, with barley (2016) responding to increased nutrition, and lentils (2017) responding to ripping. Overall, the cumulative three-year yield gains for a wheat-barley-lentil rotation above the 4.4 t/ha control were +3 t/ha, +2.4 t/ha, and +2 t/ha under high annual fertiliser rates, deep ripping and chicken litter treatments, respectively. The costs associated with high fertiliser treatments, compared with lower costs of ripping or chicken litter, result in ripping alone having the highest return on investment, followed by ripping with chicken litter (Trengove and Sherriff 2018).

For neutral-to-alkaline soils with clay subsoils and multiple physicochemical constraints, it is generally necessary to ameliorate chemically these subsoils using amendments such as gypsum or nutrient-rich organic matter. Purely physical amelioration of these soils, such as deep ripping, are often ineffective (Nuttall *et al.* 2005, Armstrong *et al.* 2009). Use of nutrient-rich organic matter has proven effective but the processes underpinning this remains unclear. Improved productivity is associated with additional nutrition (Celestina *et al.* 2018) and increased use of subsoil water from improvements in both physical structure and fertility of the subsoil (Gill *et al.* 2012, Gill *et al.* 2019). Yield responses of 27 up to 250% over an untreated control have been achieved in the Victorian High Rainfall Zone (Sale *et al.* 2019, Gill *et al.* 2019). These yield increases arising from deep placement of amendments generally last several years, which is an important consideration when needing to offset high upfront costs of implementation (Sale and Malcolm 2015).

Economic consequences of strategic deep tillage

For the purpose of understanding the economic impacts of strategic deep tillage, tillage treatments have been categorised as either deep ripping or soil mixing/inversion.

Deep ripping is most effective on deep sandy-textured soils and less effective on heavy clay soils. Armstrong *et al.* (2009) provides a summary of yield responses to deep ripping by soil type. On responsive soils, average wheat yield responses were found to be 33% in New South Wales, 10-23% in SA, 23-25% in Victoria and 20-47% in WA.

Deep ripping generally costs \$40-100/ha depending on soil type (Table 2), with benefits lasting about 3 seasons (Isbister 2017). Deep ripping is generally not cost-effective unless conducted on a soil with high productive potential, or in conjunction with other amelioration options to address other soil constraints, such as acidity, nutrient deficiency or toxicity, sodicity or topsoil water repellence (Armstrong *et al.* 2009, Petersen *et al.* 2019).

Soil mixing or inversion provides long-term and reliable benefits for most repellent soils. Davies *et al.* (2019) reviewed trial data from WA during 2009-2018 and found that cereal responses to soil mixing/inversion range from 56-86% in the first and second year after treatment, and 11-49% in the third and subsequent years. Yield response for canola was approximately 24%, and that for lupin 20-50%. Field research results in SA are similar, although soil mixing/inversion resulted in very high yield increases (200%) on some soils with low (0.5 t/ha) control yields (Fraser *et al.* 2016, Macdonald *et al.* 2019).

Soil mixing/inversion can cost \$50-150/ha depending on the soil type and technique (Table 2) and benefits last more than 10 years (Davies *et al.* 2015b). Soil mixing or inversion is generally worthwhile even when yield potential is low and other soil constraints are present.

Significantly higher benefits are generated when strategic deep tillage and other amelioration options are combined to address limiting constraints within a soil. This may include use of more than one

strategic deep tillage method (*e.g.* deep ripping as well soil mixing/inversion) as well as incorporating amendments such as fertilisers, clay, lime, and/or organic matter.

Recent research in Victoria on a Sodosol in a High Rainfall environment (550 mm annual rainfall) showed deep ripping alone to have little impact on yields, but deep ripping in conjunction with gypsum, nutrients, wheat straw+ nutrients or chicken manure resulted in yield responses of 12-16% on high yielding soils (mean grain yield of control = 6.3 t/ha, unpublished data). Even higher yield responses (up to 200%) have been recorded following application of nutrient-rich organic matter to clay soils in high rainfall environments in South Australia and southern NSW (unpublished data). Assuming a \$300/t grain price, this is a gross benefit of \$225-300/ha. Sale and Malcolm (2015) found amending sodic soils by subsoil manuring (20 t/ha) to be expensive (\$1,300-\$1,400/ha) but cost effective, generating a net present value over 4 years of \$1,390-\$1,810/ha. The question about whether similar or better returns could be achieved with improved nutrition alone remains open (Celestine *et al.* 2019).

Higher profits are generally gained by spending a limited budget addressing all constraints within an area of the farm, rather than addressing one constraint over a larger area. This is because the full yield benefit of any one soil amelioration technique cannot be realised until other limiting constraints are addressed. However, it can also be profitable to undertake low cost and easy to implement partial-amelioration options if they can be applied to larger areas of the farm in a given year, and still provide a portion of the yield benefit (Blackwell *et al.* 2014). Prioritising constraints to be addressed, or regions of the farm to ameliorate, depends on local soil conditions, the cost of amelioration, the attainable yield and the price of grain. The WA Department of Primary Industries and Regional Development have developed a decision tool called ROSA (Ranking Options for Soil Amelioration) to help consultants and farmers make this comparison (Petersen *et al.* 2019).

ROSA can be used to illustrate the benefits of addressing multiple constraints rather than single constraints in WA. For example, a sandy or deep sandy duplex soil with significant topsoil water repellence, subsoil compaction and acidity (pH: 0-0.1 m = 4.8, pH: 0.1-0.3 m = 4.5) issues. The net present value (NPV) over a five-year period of addressing single constraints of water repellence (through soil mixing/inversion) or subsoil compaction (through deep ripping) is approximately \$140/ha and \$30/ha, respectively. However, addressing multiple constraints of water repellence, subsoil compaction and acidity (through soil mixing, deep ripping and liming) results in a 5-year NPV of approximately \$1,440/ha.

It is important to note that the benefits and costs of strategic deep tillage differ significantly across regions of Australia; these examples should be considered as indicative only of the benefits that can be gained from strategic deep tillage for soil amelioration.

Future directions in strategic deep tillage

Strategic deep tillage, often in conjunction with an amendment, can be used successfully to overcome a range of soil physicochemical constraints. The high cost of such approaches are a barrier and grain growers need greater confidence that the interventions will likely result in profitable productivity increases over the medium to long-term. Following amelioration with strategic deep tillage, management strategies based on long-term controlled traffic, no-till and stubble retention will enable the improved yield potential from overcoming soil constraints to be maximised and sustained and reduce the risk of negative environmental impacts.

The most convincing current evidence for strategic deep tillage exists for deep sandy-textured soils or texture contrast soils with deep A-horizons. On these soils, improved rooting depths can be obtained by removal of constraints and the weakly developed soil structure is less susceptible to damage from deep tillage intervention. There is a need to better understand how soil fertility and biological activity can be improved and maintained following amelioration to sustain higher potential yields on these soils. Soil amelioration may provide an opportunity to build soil organic carbon levels as more of the soil profile becomes biologically active, soils are mixed and production of above- and below-ground plant biomass

increases. However, apart from clay addition to sands, a cost-effective system or strategy to build soil carbon on many dryland cropping soils remains elusive.

The nature of physicochemical constraints associated with higher clay content neutral-alkaline soils used for grain production presents particular challenges. High clay content, combined with low rainfall and high evaporation environments, results in high soil strengths and increased energy costs to physically alter the subsoils. Furthermore, many of the constraints are chemical, such as high sodicity, leading to dispersion and poor structure when soils are wet and high penetrometer resistance when dry. The severity also usually increases with depth. Amelioration then almost always requires amendment addition, likely at depth, further increasing cost and reducing the feasibility of such approaches. In regions with higher, more reliable rainfall, large increases in yields may sometimes justify the initial significant financial investment required, but there remains considerable uncertainty in predicting when such interventions will improve yield and profit. Targeted subsoil interventions and the promise of stimulating further ‘biological’ improvement of the subsoil condition following intervention requires further research. Where amelioration is not financially or logistically feasible, growers will need use better adapted, more tolerant crop varieties or species and manage agronomic inputs to match the constrained yield potential.

Amelioration of soil constraints can, in part, enable a reduction in the gap between current and potential water limited grain yields but capturing and sustaining this benefit will require the simultaneous implementation of a range of management strategies to reduce the range of abiotic and biotic constraints that limit grains productivity.

References

- Abbott LK, Macdonald LM, Wong MTF *et al.* (2018) Potential roles of biological amendments for profitable grain production – A review. *Agriculture, Ecosystems and Environment* **265**, 34-50
- Adcock D, McNeill AM, McDonald GK, Armstrong RD (2007) Subsoil constraints to crop production on neutral and alkaline soils in south-eastern Australia: A review of current knowledge and management strategies. *Australian Journal of Experimental Agriculture* **47**, 1245-1261
- Anderson DL, Hendrick JG (1983) Subsoil lime injector. *Soil Science Society of America Journal* **47**, 337-339
- Armstrong RD, Eagle C, Jarwal SD (2007) Application of composted pig bedding litter on a Vertosol and Sodosol soil. 1. Effect on crop growth and soil water. *Australian Journal of Experimental Agriculture* **47**, 689-699
- Armstrong RD, Davies SL, Kirkegaard JA (2009) Deep ripping not appropriate for all soil types. Deep Ripping Factsheet (Grains Research and Development Corporation: Canberra) www.grdc.com.au/resources-and-publications/all-publications/factsheets/2009/06/grdc-fs-deepripping
- Aulakh JS, Price AJ, Enloe SF *et al.* (2012) Integrated Palmer amaranth management in glufosinate-resistant cotton: I. Soil inversion, high residue cover crops and herbicide regimes. *Agronomy* **2**, 295-311
- Bailey G, Hughes B, Tonkin R *et al.* (2010) Gross soil modification of duplex soils through delving and spading. *Proceedings of 19th World Congress of Soil Science*, Brisbane, Queensland p 4
- Bailey G, Hughes B (2012) An observational study of clay delving and its impact on the A2 horizon in sand over clay soils. *Proceedings of 5th Joint Australian and New Zealand Soil Science Conference* Hobart, Tasmania
- Belford RK, Dracup M, Tennant D (1992) Limitations to growth and yield of cereal and lupin crops on duplex soils. *Australian Journal of Experimental Agriculture* **32**, 929-945
- Betti G, Grant C, Churchman G, Murray R (2015) Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia. *Soil Research* **53**, 125-136
- Betti G, Grant CD, Murray RS, Churchman GJ (2016) Size of subsoil clods affects soil-water availability in sand-clay mixtures. *Soil Research* **54**, 27-290
- Betti G, Hall D, Davies S, Edwards T (2017) Clay delving for the amelioration of water repellent soils: first year results from a site near Esperance. *GRDC Grains Research Updates*, Perth, Western Australia www.giwa.org.au/2017researchupdates
- Blackwell PS (2000) Management of water repellency in Australia, and risks associated with preferential flow, pesticide concentration and leaching. *Journal of Hydrology* **231-232**, 384-395
- Blackwell P, Hagan J, Davies S *et al.* (2014) Smart no-till furrow sowing to optimise whole-farm profit on non-wetting soil. *Agribusiness Crop Updates*, Perth, Western Australia (Department of Agriculture and Food WA and Grains Research and Development Corporation) www.giwa.org.au/2014-crop-updates

- Blackwell PS, Isbister B, Riethmuller G *et al.* (2016) Deeper ripping and topsoil slotting to overcome subsoil compaction and other constraints more economically: way to go! *GRDC Grains Research Updates* Perth, Western Australia www.giwa.org.au/2016researchupdates
- Bond RD (1964) The influence of the microflora on the physical properties of soils. II. Field studies on water repellent sands. *Australian Journal of Soil Research* **2**, 123-131
- Brautigan DJ, Rengasamy P, Chittleborough DJ (2012) Aluminium speciation and phytotoxicity in alkaline soils. *Plant and Soil* **360**, 187-196
- Cann MA (2000) Clay spreading on water repellent sands in the south east of South Australia – promoting sustainable agriculture. *Journal of Hydrology* 231-232, 333-341
- Celestina C, Midwood J, Sherriff S *et al.* (2018) Crop yield responses to surface and subsoil applications of poultry litter and inorganic fertiliser in south-eastern Australia, *Crop and Pasture Science* **69**, 303-316
- Celestina C, Hunt JR, Sale PWG, Franks AE (2019) Attribution of crop yield responses to application of organic amendments: A critical review. *Soil and Tillage Research* **186**, 135-145
- Chan KY (1992) Development of seasonal water repellence under direct drilling. *Soil Science Society of America Journal* **56**, 326-329
- Chan KY, Oates A, Swan AD *et al.* (2006) Agronomic consequences of tractor wheel compaction on a clay soil. *Soil and Tillage Research* **89**, 13-21
- Churchman GJ, Noble A, Bailey G *et al.* (2014) Clay addition and redistribution to enhance carbon sequestration in soils. In (Eds. A Hartemink, K McSweeney) “Soil Carbon”, Progress in Soil Science (Springer: Cham)
- Condon JR, Moroni JS, Zander A *et al.* (2018) Deep ripping incorporation of novel amendments to ameliorate subsurface acidity. *Proceedings of National Soils Conference* Canberra, ACT
www.soilscienceaustralia.org.au/media/content/files/Proceedings_Natl_Soil_Sci_Conf-Canberra_18-23_Nov_2018_FINAL_reduced_size.pdf
- Conyers MK, Scott BJ (1989) The influence of surface incorporated lime on subsurface soil acidity. *Australian Journal of Experimental Agriculture* **29**, 201-207
- Coventry DR, Reeves TG, Brooke HD *et al.* (1987) Increasing wheat yields in north-eastern Victoria by liming and deep ripping. *Australian Journal of Experimental Agriculture* **27**, 679-685
- Dang YP, Dalal RC, Buck SR *et al.* (2010) Diagnosis, extent, impacts, and management of subsoil constraints in the northern grains cropping region of Australia. *Australian Journal of Soil Research* **48**, 105-119
- Davenport D, Hughes B, Davies S, Hall D (2011) Spread, delve, spade, invert: a best practice guide to the addition of clay to sandy soils. (Grains Research and Development Corporation and the Agricultural Bureau of South Australia Incorporated)
www.grdc.com.au/resources-and-publications/all-publications/bookshop/2011/09/grdc-booklet-spreaddelvespadeinvert
- Davies SL, Gazey C, Gartner D (2008) Long-term effect of lime incorporated directly into acid subsoils on soil properties and growth of wheat. *Proceedings of Australia and New Zealand Soil Societies Conference*. Massey University, Palmerston North, NZ
- Davies SL, Newman P, Best B (2010) Impact of soil inversion, soil dilution and claying on non-wetting sandplain soils. *Proceedings of 2010 Agribusiness Crop Updates* Perth Western Australia (Department of Agriculture and Food, Western Australia and Grains Research and Development Corporation)
- Davies SL, Blackwell PS, Bakker DM *et al.* (2013) Deep soil cultivation to create improved soil profiles for dryland crop production. *Proceedings of 2013 Society for Engineering in Agriculture (SEAg) Conference* Mandurah, Western Australia.
- Davies SL, Gazey C, Parker W *et al.* (2015a) Lime incorporation into acidic soils: assessing cost, efficacy, value and novel approaches. *Proceedings 2015 Agribusiness Crop Updates* Perth Western Australia
www.giwa.org.au/2015-crop-updates
- Davies SL, Hagan J, Reynolds C *et al.* (2015b) Long-term responses to soil amelioration – benefits will last more than 10 years! *Proceedings 2015 Agribusiness Crop Updates* Perth Western Australia
www.giwa.org.au/2015-crop-updates
- Davies S, Boyes T, Reynolds C *et al.* (2018) Understanding the impact of a comprehensive range of deep tillage practices on crop performance and soil properties for two water repellent soil types. *GRDC Grains Research Updates*, Perth, Western Australia www.giwa.org.au/2018researchupdates
- Davies S, Betti G, Edwards T, McDonald G *et al.* (2019) Ten years of managing water repellent soils research in Western Australia – a review of current progress and future opportunities. *GRDC Grains Research Updates*, Perth, Western Australia. www.giwa.org.au/2019researchupdates
- Delroy ND, Bowden JW (1986) Effect of deep ripping the previous crop, and applied nitrogen on the growth and yield of a wheat crop. *Australian Journal of Experimental Agriculture* **26**, 469-479
- Desbiolles JMA, Fielke JM, Chaplin P (1997) An application of tine configuration to obtain subsoil delving for the management of non-wetting sands. *Proceedings of Third International Conference on Soil Dynamics* (ICSD III) Tiberias, Israel pp. 201-210

- Doerr SH, Shakesby RA, Walsh RPD (2000) Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth Science Reviews* **51**, 33-65
- Dolling PJ, Porter WM (1994) Acidification rates in the central wheatbelt of Western Australia. 1. On a deep yellow sand. *Australian Journal of Experimental Agriculture* **34**, 1155-1164
- Dolling PJ, Porter WM, Rowland IC (1994) Acidification rates in the central wheatbelt of Western Australia. 2. On a sandy duplex soil. *Australian Journal of Experimental Agriculture* **34**, 1165-1172
- Edmeades DC (2003) The long-term effects of manures and fertilisers on soil productivity and quality: a review. *Nutrient Cycling in Agroecosystems* **66**, 165-180
- Edwards T, Davies S, McDonald G *et al.* (2018) Understanding interactions between pre-emergent herbicides and inversion tillage. *GRDC Grains Research Updates*, Perth, Western Australia
www.giwa.org.au/2018researchupdates
- Ellington A (1986) Effects of deep ripping, direct drilling, gypsum and lime on soils, wheat growth and yield. *Soil and Tillage Research* **8**, 29-49
- Fletcher A, Lawes R, Weeks C (2016) Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. *Crop and Pasture Science* **67**, 1268-1280
- Franco CMM, Tate ME, Oades JM (1995) Studies on non-wetting sands. I. The role of intrinsic particulate organic matter in the development of water-repellency in non-wetting sands. *Australian Journal of Soil Research* **33**, 253-263
- Franco CM, Clarke PJ, Tate ME, Oades JM (2000) Hydrophobic properties and chemical characterisation of natural water repellent materials in Australian Sands. *Journal of Hydrology* **231-232**, 47-58
- Fraser M, Davenport D, Bartel B, Wilhelm N (2016) Overcoming constraints on sandy soils – amelioration strategies to boost crop production. *GRDC Grains Research Updates* www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/overcoming-constraints-on-sandy-soils-amelioration-strategies-to-boost-crop-production
- Gazey C, Davies S (2009) “Soil acidity: a guide for WA farmers and consultants” Bulletin 4784 (Department of Agriculture and Food, Western Australia, Perth)
- Gazey C, Andrew J, Griffen E (2013) Soil acidity. In “Report card on sustainable natural resource use in agriculture” (Department of Agriculture and Food, Western Australia) www.agric.wa.gov.au/climate-land-water/resource-assessment/report-card-conditions-and-trends
- Gill JS, Sale PWG, Tang C (2008) Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. *Field Crops Research* **107**, 265-275
- Gill JS, Clark GJ, Sale PW *et al.* (2012) Deep placement of organic amendments in dense sodic subsoil increases summer fallow efficiency and the use of deep soil water by crops. *Plant and Soil* **359**, 57-69
- Gill JS, Sale PW, Peries RR, Tang C (2019) Crop responses to subsoil manuring. II. Comparing surface and subsoil manuring in north-eastern Victoria from 2011 to 2012. *Crop and Pasture Science* **70**, 318-326
- Hagan J, Blackwell P, Davies S, Isbister B (2015) Tools and planning to ease the transition to Controlled Traffic Farming. *Proceedings 2015 Agribusiness Crop Updates* Perth Western Australia. (Department of Agriculture and Food, WA and Grains Research and Development Corporation) www.giwa.org.au/2015-crop-updates
- Hall DJM, Jones HR, Crabtree WL, Daniels T (2010) Claying and deep ripping can increase crop yields and profits on water repellent sands with marginal fertility in southern Western Australia. *Australian Journal of Soil Research* **48**, 178-187
- Hall JAS, Maschmedt DJ, Billing NB (2009) The soils of southern South Australia. The South Australian Land and Soil Book Series, Volume 1; “Geological Survey of South Australia” Bulletin 56 (Department of Water, Land and Biodiversity Conservation: Government of South Australia)
- Hamblin AP, Tennant D (1979) Interaction between soil type and tillage level in a dryland situation. *Australian Journal of Soil Research* **17**, 177-189
- Hamza MA, Anderson WK (2003) Responses of soil properties and grain yields to deep ripping and gypsum application in a compacted loamy sand soil contrasted with a sandy clay loam soil in Western Australia. *Australian Journal of Agricultural Research* **54**, 273-282
- Hamza MA, Anderson WK (2005) Soil compaction in cropping systems: a review of the nature, causes and possible solutions. *Soil and Tillage Research* **82**, 121-145
- Hamza MA, Riethmuller GP, Anderson WK (2013) Experimental subsoiling by in-line and shallow deep tines. *Soil Research* **51**, 477-483
- Henderson C, Levett A, Lisle D (1988) The effects of soil water content and bulk density on the compactibility and soil penetration resistance of some Western Australian sandy soils. *Australian Journal of Soil Research* **26**, 391-400
- Hochman Z, Gobbett D, Horana H, Navarro Garcias J (2016) Data rich yield gap analysis of wheat in Australia. *Field Crops Research* **197**, 97-106

- Isbell RF and National Committee on Soil and Terrain (2016) "The Australian Soil Classification" Second Edition (CSIRO Publishing: Canberra)
- Isbister B, Hagan J, Blackwell PS (2016) The changing options for soil compaction management in the WA wheatbelt. *GRDC Grains Research Updates*, Perth, Western Australia
www.giwa.org.au/2016researchupdates
- Isbister B (2017) Deep-ripping explained. *Ground Cover* Issue 126 www.grdc.com.au/resources-and-publications/groundcover/ground-cover-issue-126-january-february-2017/deep-ripping-explained
- Jarvis RJ (1983) Deep ripping produces wheat yield responses. *Australasian Field Crops Newsletter* **18**, 104-106
- Jarvis RJ (1986a) The history of deep tillage research in Western Australia. In (Ed. MW Perry) "A review of deep tillage research in Western Australia" Report 3, pp 1-5 (Department of Agriculture and Food: Perth, Western Australia)
- Jarvis RJ (1986b) Crop response to deep tillage. In (Ed. MW Perry) "A review of deep tillage research in Western Australia" Report 3 pp 40-51 (Department of Agriculture and Food: Perth, Western Australia)
- Jayawardane NS, Barrs HD, Muirhead WA *et al.* (1995) Lime-slotting technique to ameliorate subsoil acidity in a clay soil II. Effects on medic root-growth, water extraction and yield. *Soil Research* **33**, 443-459
- King PM (1981) Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Australian Journal of Soil Research* **19**, 275-285
- Kirchhof G, Jayawardane NS, Blackwell J, Murray E (1995) Lime-slotting technique to ameliorate subsoil acidity in a clay soil 1. Effects on soil-pH and physical characteristics. *Soil Research* **33**, 425-441
- Kirkegaard JA, Angus J, Swan T *et al.* (2008) Ripping yarns: 25 years of variable responses to ripping clay soils in south-eastern Australia. *Proceedings of 14th Australian Agronomy Conference* Adelaide, South Australia agronomyaustraliaproceedings.org/index.php/2008
- Li GD, Burns H (2016) Managing Subsoil Acidity: 3-D Ripping Machine. GRDC DAN00206, NSW Department of Primary Industries www.dpi.nsw.gov.au/agriculture/soils/acidity
- Li GD, Conyers MK, Heylar KR *et al.* (2019) Long-term surface application of lime ameliorates subsurface soil acidity in the mixed farming zone of south-eastern Australia. *Geoderma*, **338**, 236-246
- Macdonald L, McBeath T, Moodie M *et al.* (2019) Underperforming sandy soils – targeting constraints for cost effective amelioration. *GRDC Grains Research Updates* Adelaide, South Australia
- MacEwan RJ, Crawford DM, Newton PJ, Clune TS (2010) High clay contents, dense soils, and spatial variability are the principal subsoil constraints to cropping the higher rainfall land in south-eastern Australia. *Australian Journal of Soils Research* **48**, 150-166
- Mason MG, Porter WM and Cox WJ (1994) Effect of an acidifying nitrogen fertiliser and lime on soil pH and wheat yields 1. Soil effects. *Australian Journal of Experimental Agriculture* **34**, 237-246
- McCallum MH, Kikegaard JA, Green T *et al.* (2004) Evidence of improved macro-porosity following perennial pasture on a duplex soil. *Australian Journal of Experimental Agriculture* **44**, 299-307
- McGarry D (1993) Degradation of soil structure. In (Eds. G McTinish, W Boughton) "Degradation Processes in Australia" pp 271-305 (Longman Cheshire: Australia)
- Needham P, Scholz G, Moore G (2004a) Hard layers in soils. In (Ed. G Moore) "Soilguide. A handbook for understanding and managing agricultural soils" Bulletin 4343 (Department of Agriculture, Western Australia) pp 111-115
- Needham P, Moore G, Scholz G (2004b) Subsurface compaction. In (Ed. G Moore) "Soilguide. A handbook for understanding and managing agricultural soils" Bulletin 4343 (Department of Agriculture, Western Australia) pp 116-124
- Newman PD, Davies SL (2010) Mouldboard plough continues to kick goals. *2010 Agribusiness Crop Updates*, Perth (Western Australia. Department of Agriculture and Food Western Australia and Grains Research and Development Corporation)
- Nuttall, JG, Armstrong, RD, Connor DJ, Matassa VJ (2003) Interrelationships between soil factors potentially limiting cereal growth on alkaline soils in NW Victoria *Australian Journal of Soil Research* **41**, 277-292
- Nuttall JG, Armstrong RD, Connor DJ (2005) The effect of boron tolerance, deep ripping with gypsum, and water supply on subsoil water extraction of cereals on an alkaline soil. *Australian Journal of Agricultural Research* **56**, 113-122
- Nuttall JG, Davies SL, Armstrong RA, Peoples MB (2008) Testing the primer-plant concept: wheat yields can be increased on alkaline sodic soils when an effective primer phase is used. *Australian Journal of Agricultural Research* **59**, 331-338
- Nuttall JG, Armstrong RD (2010) Impact of subsoil physicochemical constraints on crops grown in the Wimmera and Mallee is reduced during dry seasonal conditions. *Australian Journal of Soil Research* **48**, 125-139
- Obst C (1994) Non-wetting soils: management problems and solutions at 'Pineview', Mundulla. *Proceedings of 2nd National Water Repellency Workshop*, Perth, Western Australia pp 137-139 (Grains Research and Development Corporation and the Western Australian Department of Agriculture)

- Page KL, Dalal RC, Wehr JB *et al.* (2018). Management of the major chemical soil constraints affecting yields in the grain growing region of Queensland and New South Wales, Australia – a review. *Soil Research* **56**, 756-779
- Parker W, Isbister B, Hall D *et al.* (2017) Longevity of deep ripping and topsoil inclusion in soils under traffic farming; evidence from the second season. *GRDC Grains Research Updates*, Perth, Western Australia. www.giwa.org.au/2017researchupdates
- Parr JF (1959) Effects of vertical mulching and subsoiling on soil physical properties. *Agronomy Journal* **51**, 412-414
- Peltzer SC, Matson P (2006) Windrow management for annual ryegrass control: bury, burn or bomb? *Proceedings 15th Australian Weed Conference*, Adelaide, South Australia www.weedinfo.com.au/bk_15awc.html
- Petersen EH, Lemon J, Xayavong V (2019) Ranking Options for Soil Amelioration spreadsheet (ROSA). (Department of Primary Industries and Regional Development) www.agric.wa.gov.au/managing-soils/ranking-options-soil-amendments-tool
- Quilty JR, Cattle SR (2011) Use and understanding of organic amendments in Australian agriculture: a review. *Soil Research* **49**, 1-26
- Rebbeck M, Lynch C, Hayman PT, Sadras VO (2007) Delving of sandy surfaced soils reduces frost damage in wheat crops. *Australian Journal of Agricultural Research* **58**, 105-112
- Rengasamy P, Chittleborough D, Helyar K (2003) Root-zone constraints and plant-based solutions for dryland salinity. *Plant and Soil* **257**, 249-260
- Renton M, Flower K (2015) Occasional mouldboard ploughing slows evolution of resistance and reduces long-term weed populations in no-till systems. *Agricultural Systems* **139**, 66-75
- Roberts FJ, Carbon BA (1971) Water repellence in sandy soils of south-western Australia. 1. Some studies related to field occurrence. *Field Station Record Division of Plant Industry, CSIRO* **10**, 13-20
- Robertson WK, Fiskell JGA, Hutton CE *et al.* (1957) Results from subsoiling and deep fertilization of corn for 2 years. *Soil Science Society of America Journal* **21**, 340-346
- Roper MM, Davies SL, Blackwell PS *et al.* (2015) Management options for water-repellent soils in Australian dryland agriculture. *Soil Research* **53**, 786-806
- Sale P, Malcolm B (2015) Amending sodic soils using sub-soil manure: economic analysis of crop trials in the high rainfall zone of Victoria. *AFBM Journal* **12**, 22-31
- Sale PW, Gill JS, Peries RR, Tang C (2019) Crop responses to subsoil manuring. I. Results in south-western Victoria from 2009 to 2012. *Crop and Pasture Science* **70**, 44-54
- Scanlan CA, Davies SL (2019) Soil mixing and redistribution by strategic deep tillage in a sandy soil. *Soil and Tillage Research* **185**, 139-145
- Schapel A, Davenport D, Marschner P (2017) Increases in organic carbon concentration and stock after clay addition to sands: validation of sampling methodology and effects of modification method. *Soil Research* **55**, 124-133
- Schapel A, Marschner P, Churchman J (2018) Clay amount and distribution influence organic carbon content in sand with subsoil clay addition. *Soil and Tillage Research* **184**, 253-260
- Scott BJ, Conyers MK (1995) Magnesium nutrition and lime movement down the profile. “*Making better fertiliser, lime & gypsum recommendations*” (Eds. IG Fenton, PW Orchard) pp 1-18 (Agricultural Research Institute: Wagga Wagga, Australia)
- Shaw RJ, Brebber L, Ahern CR, Weinand MMG (1994) A review of sodicity and sodic soil behaviour in Queensland. *Australian Journal of Soil Research* **32**, 143-172
- Spoor G (2006) Alleviation of soil compaction: requirements, equipment and techniques. *Soil Use and Management* **22**, 113-122
- Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between microaggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research* **79**, 7-31
- Sumner ME, Shahandeh H, Bouton J, Hammel J (1986) Amelioration of an acid profile through deep liming and surface application of gypsum. *Soil Science Society of America Journal* **50**, 1254-1258
- Swan T, Kirkegaard J, Angus J *et al.* (2011) Potential impacts of subsoils constraints on canola production in southern NSW. *Proceedings of 17th Australian Research Assembly on Brassicas (ARAB)*, Wagga Wagga, NSW www.australianoilseeds.com/conferences_workshops/ARAB/arab_2011
- Tang C, Raphael C, Rengel Z, Bowden JW (2000) Understanding subsoil acidification: effect of nitrogen transformation and nitrogen leaching. *Australian Journal of Soil Research* **38**, 837-849
- Tang C (2004) Causes and management of subsoil acidity. *SuperSoil 2004: 3rd Australian New Zealand Soils Conference* University of Sydney, Australia www.regional.org.au/au/asssi/supersoil2004
- Tennant D, Scholz G, Dixon J, Purdie B (1992) Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. *Australian Journal of Experimental Agriculture* **32**, 827-843

- Tisdall JM, Oades JM (1978) Organic matter and water-stable aggregates in soils. *Journal of Soil Science* **33**, 141-163
- Trengove S, Sherriff S (2018) Amelioration of sandy soils – opportunities for long term improvement. *GRDC Grains Research Updates* Adelaide, South Australia www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/past-update-proceedings/2018/grdc-grains-research-update-adelaide-2018
- Ucgul M, Saunders C, Fielke JM (2017) Discrete element modelling of top soil burial using a full scale mouldboard plough under field conditions. *Biosystems Engineering* **160**, 140-153
- Ucgul M, Saunders C, Li P *et al.* (2018) Analyzing the mixing performance of a rotary spader using digital image processing and discrete element modelling (DEM). *Computers and Electronics in Agriculture* **151**, 1-10
- Ucgul M, Saunders C, Desbiolles JMA *et al.* (2019) Improving the effectiveness of overcoming constraints by optimising soil amelioration practices. GRDC Grains Research Updates Perth, Western Australia. (Grains Research and Development Corporation) www.giwa.org.au/2019researchupdates
- Unkovich M (2014) A review of the potential constraints to crop production on sandy soils in low rainfall south-eastern Australia and priorities for research. Report for GRDC Low Rainfall Zone Regional Cropping Solutions Network (Grains Research and Development Corporation) www.grdc.com.au/research/reports/report?id=5999
- van Gool D (2016) Identifying soil constraints that limit wheat yield in South-West Western Australia. Resource Management technical report 399 (Department of Agriculture & Food, Western Australia, Perth) www.agric.wa.gov.au/managing-soils/soil-constraints-limit-wheat-yield-south-west-western-australia
- van Gool D, Stuart-Street A, Tille P (2018) Distribution of classified soils in south-west Western Australia. Resource Management Technical Report 401 (Department of Primary Industries and Regional Development: Perth) www.agric.wa.gov.au/identifying-wa-soils/soil-classification
- Whitten MG, Wong MTF, Rate AW (2000) Amelioration of subsurface acidity in the south-west of Western Australia: downward movement and mass balance of surface-incorporated lime after 2-15 years. *Soil Research* **38**, 711-728
- Williams CH (1980). Soil acidification under clover pasture. *Australian Journal of Experimental Agriculture and Animal Husbandry*. **20**, 561-67
- Yunusa IA, Newton PJ (2003) Plants for amelioration of subsoil constraints and hydrological control: the primer-plant concept. *Plant and Soil* **257**, 261-281

Chapter 9

Advances in crop residue management

Ken Flower, Yash Dang, Phil Ward

Introduction

In broad-acre dryland farming systems, crop residues are a useful resource with many benefits within a farming operation, largely associated with soil and water conservation and soil fertility. Consequently, retention of crop residue has been adopted in both the summer and winter crop growing areas, as farmers, supported by research, have developed techniques to manage the residues and minimise the downsides. In this chapter, we discuss the evolution of residue management in Australia, highlighting the benefits and challenges, including the effects on the soil. The optimum amount of retained crop residue and how this can change over time is evaluated, as well as the techniques currently used in Australia to manage crop residues successfully.

Residue quantity and dynamics

Grain production in Australia is dominated by cereals, particularly wheat, which has a harvest index of about 0.4 (residue quantity is about 1.5 times grain yield). An estimate of residue quantity ‘available’ across Australia was made from wheat yields, using average regional yields for the period 2012-2017 (data from the Australian Bureau of Statistics). Average residue quantity available varies from around 3 t/ha in the drier parts of Western Australia (WA) and the South Australian (SA)/Victorian Mallee, to as much as 10 t/ha in Tasmania (Figure 1). With a recommended level of at least 2 t/ha of residue for erosion control (Scott *et al.* 2010, 2013), there are areas in Australia where adequate residue is not produced in some seasons, and there are also areas where excess residue is often produced (Scott *et al.* 2013).

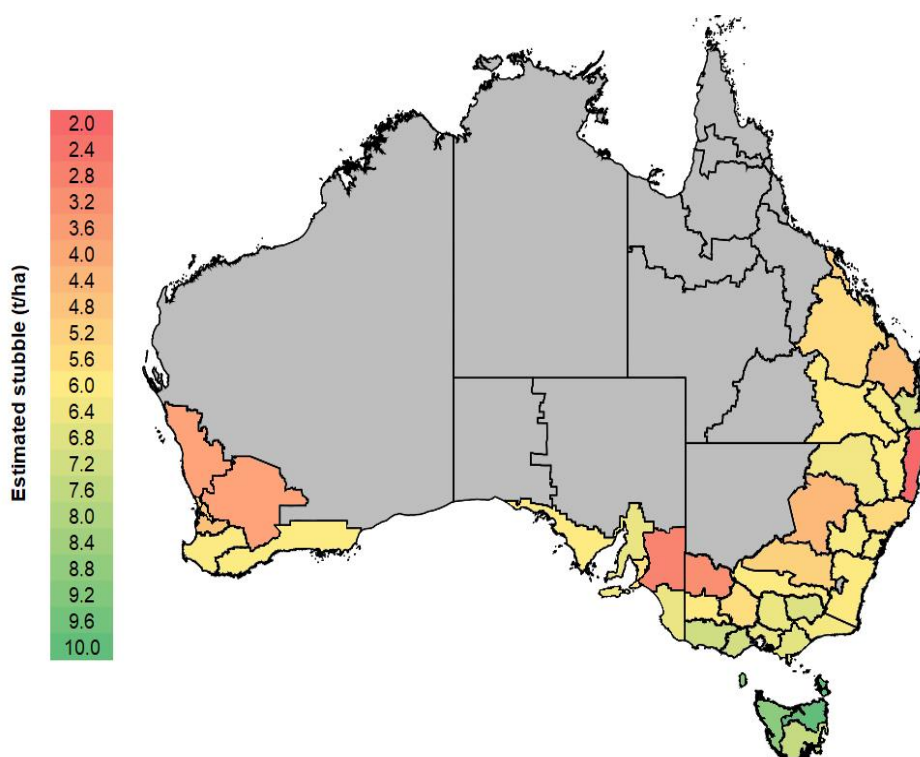


Figure 1. Estimated residue quantity available, based on regional average wheat yields for the period 2012-2017

The amount of crop residue present on the soil surface in NT systems fluctuates over time, building up and then declining according to crop type and seasonal conditions. This was demonstrated in a long-term NT experiment at Cunderdin, a relatively low rainfall area of the wheat belt of Western Australia (Figure 2). Residue levels were typically lowest towards the end of the growing season (around anthesis) and highest immediately after harvest. There was a relatively small change in residue dry-mass over summer (between post-harvest and pre-seeding – Figure 2). As expected, rotations with more cereals generally had higher residue levels. A severe drought at Cunderdin in 2010 produced little change in residue dry mass from post-harvest 2009 through to the same period in 2010, after which the remaining residue decomposed relatively quickly to reach very low levels by anthesis 2011 (Figure 2). The fallow as a ‘break’ from the cereals was included in the trial in 2014, resulting in residue levels declining to their lowest point at anthesis in 2015 (Figure 2).

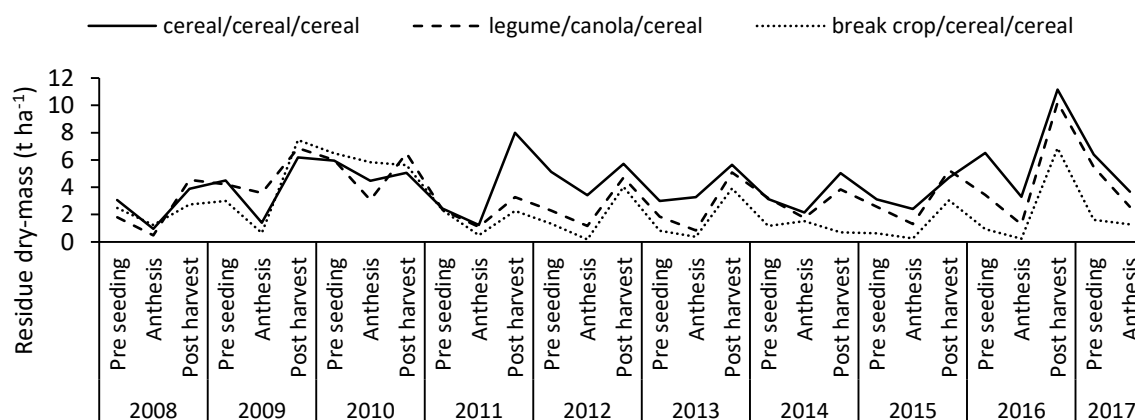


Figure 2. Crop residue dry-mass from 2008 to 2017 in a long-term NT trial at Cunderdin (WA). The legume/canola/cereal rotation started with the legume in 2008, 2011, 2014 and 2017. The break crop/cereal/cereal rotation had legume as the break crop in 2008 and 2011 and fallow in 2014 and 2017 (unpublished information courtesy of Neil Cordingley, WANTFA, and Phil Ward, CSIRO).

In the Mediterranean-style climate of southern Australia, residue breakdown generally occurs relatively slowly; it is not unusual to see residue from several years present in the same field (Figure 3). However, in northern Australia where summer rainfall is more common, residue breakdown occurs much more rapidly (Freebairn *et al.* 1991), due to the coincidence of higher temperatures and moisture availability. For this reason, higher rates of residue immediately after harvest are more manageable in northern grain-producing regions of Australia.



Figure 3. Crop residue shortly after harvest in a trial at Cunderdin, WA. Residue from the previous cereal crop (12 months since its harvest) is clearly visible between the fresh stubble rows

Is there an optimum level of crop residue?

Ideally, there should be enough residue present to prevent erosion, maintain or improve soil organic carbon, maximise infiltration of water into the soil and contribute to crop yield and quality, particularly under water stress conditions. Recent estimates suggest that 2-3 t/ha is sufficient to achieve these benefits (Kirkegaard *et al.* 2014, Giller *et al.* 2015). Residue should not decrease crop yield. Beyond this, the concept of ‘optimum’ residue is complex to unravel and will depend on the growing environment and farm conditions. Higher levels of crop residue may provide additional benefits, particularly in soil microbial activity (see Chapter 15) and smothering of weeds (not many using this strategy due to Harvest Weed Seed Control – HWSC). Conversely, high levels of crop residue can have negative impacts, mainly related to tie-up of nitrogen (Kirkegaard 2018), physical impairment to seeding operations and crop establishment (Scott *et al.* 2010, Flower *et al.* 2017) or in rare cases allelopathic chemicals in the stubble. For example, Flower *et al.* (2017) showed that crop yield was reduced when the amount of cereal crop residue present at seeding exceeded about 3.5 to 4 t/ha. The crop yield reduction was thought to be largely caused by poor spreading of the residue at harvest and physical impairment of seeding machinery and subsequent crop establishment. These were largely machinery issues, related to poor spreading of residue by the harvester and inability of the seeder to manage high residue amounts. However, the yield reduction did not occur with similar amounts of canola or legume residue present, as these residue pieces, usually stems, are generally larger and tend to smother less crop. In general, the capacity to manage crop residues will vary from farm to farm, with some farmers developing their systems to enable seeding into heavy residues.

In other research, crop residues mainly have a positive effect on yield in dry environments, due to the water conservation aspects (Farooq *et al.* 2011, Pittelkow *et al.* 2015). This was confirmed by Kirkegaard *et al.* (2018) at two sites in southern NSW, where yield response to crop residue was positive or neutral at relatively low growing season rainfall, up to about 300 mm (Figure 4). The negative impact of residue on yield in the higher rainfall seasons was thought to be related to nitrogen tie-up during the winter (Kirkegaard *et al.* 2018) which may be less likely when following a diverse rotation including legumes. Nonetheless, more research is required to understand and avoid the negative effects of crop residue on yield under high rainfall/yield conditions, especially the disease and nutritional aspects as well as stubble handling at seeding in cereal dominated rotations.

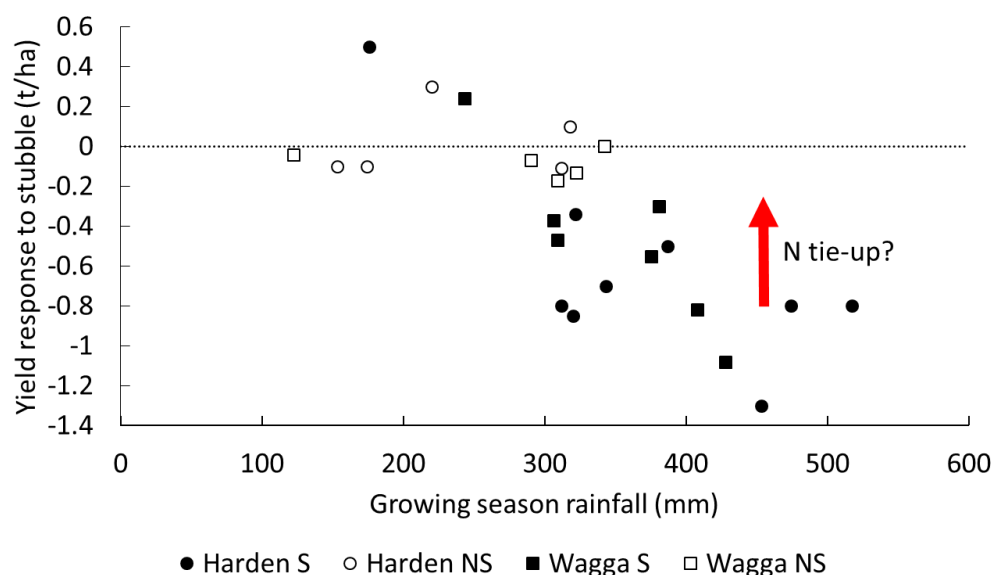


Figure 4. Yield response to crop residue (stubble) with different amounts of growing season rainfall at two sites in southern NSW (after Kirkegaard *et al.* 1994, Heenan *et al.* 1994, Giller *et al.* 2015) Solid circles represent seasons where differences between stubble retained and stubble burnt were significant (S), open symbols where not significant (NS). Recent experiments suggest the large yield gap can be closed somewhat with added N fertiliser at sowing (Kirkegaard *et al.* 2018)

Evolution of residue management

Farming, at least in the conventional sense, commenced in Australia in the late 18th century with the arrival of European settlers. Initially, farming practices were imported exclusively from the UK, but these practices quickly proved unsuitable for the Australian environment (Pratley and Rowell 1987). Residue management at this stage mainly focussed on removal of the residue by burning (Pratley and Rowell 1987), to allow tillage for seedbed preparation for the next crop.

During the 20th century, crop residue management diverged between the northern grain-growing regions, with summer-dominant rainfall (see Chapter 5), and the southern grain growing regions where winter rainfall is more dominant (see Chapter 4). In areas where summer rainfall dominates, rainfall tends to occur as intense thunderstorms, with large quantities of rain falling in a short time (Leeper 1970). The situation was exacerbated by frequent tillage (for weed control), and residue removal. By the middle of the century, erosion was becoming recognized as a serious issue for crop production. Residue retention was known to reduce the water erosion risk, but managing the residue during seeding of the next crop was proving difficult. Nevertheless farmers were experimenting with methods of residue retention in the 1950s (Hallsworth *et al.* 1954, Holland *et al.* 1987). However, it was not until the late 1960s that research into methods to manage retained stubble commenced (Fawcett 1975, Marley and Littler 1989). Despite these slow beginnings, residue retention was common in the region from the early 1980s (Chamala *et al.* 1983, Watt 1983) and the practice has been pivotal in controlling the erosion risk.

In most of southern Australia, winter rainfall dominates, and rainfall intensity is much lower than in northern Australia. Therefore, the threat from water erosion has been perceived to be lower. However, frequent cultivation resulted in soils of poor stability, and wind and water erosion became common. With the arrival of herbicides in the 1960s and 1970s, cultivation became less important for weed control, and residue retention over summer became more common (Poole 1987). Despite this, residue burning prior to seeding was still common, because the available seeding machinery could not cope with retained residue loads. It was only during the 1990s, with the rapid adoption of NT farming and availability of suitable machinery (D'Emden *et al.* 2006, 2008, Llewellyn *et al.* 2012), that stubble burning became less common than stubble retention. More recently, the increase in herbicide-resistant weeds has brought limited burning of harvester windrows back into use, as one way to control the weed seed bank (Walsh and Powles 2007, see Chapter 10). Recent estimates suggest that crop residues are currently retained on between 49 to 60% of cropped land (Umbers 2017, Etherton 2018).

Crop residue management

There are a wide range of crop residue management practices, depending upon the cropping system, amount of crop residue present, machinery availability and individual farmer approach. Retaining crop residues within the farming system has several implications for machinery choice (*e.g.* harvester, seeder) and pest management (*e.g.* weeds, insects, disease). The three key stages for management of the crop residues are (i) harvest, (ii) post-harvest, and (iii) seeding. Each stage can be managed in isolation although, for maximum benefits, an integrated approach starting from harvest through to seeding of the crop is required.

Harvest management

Effective crop residue management starts at harvest by cutting at the appropriate height and spreading residue as evenly as possible across the harvested area (not if using windrow burning). As harvester cutting fronts get wider, it is becoming more difficult to achieve an even spread of residue, which in turn can create problems at seeding. For residues up to 5 t/ha, a cutting height of 20 cm or less allows tyne machines to operate with fewer blockages (GRDC 2011). Desbiolles (2007) emphasised that residue height should be kept to 60–65% of the total height of the lowest obstruction of the seeding bar. However, another recent approach is to cut the residue relatively high (30 cm), thereby reducing the amount of residue lying on the soil, and then use high accuracy GPS guidance to place the new crop row between the previous residue rows at seeding.

Cutting crop residue short has implications as more material passes through the harvester and needs to be spread. Harvest costs are increased when the cutting height is reduced and lower comb height reduces the evenness of the spread of the residue. Use of a second cutter bar fitted to a harvester can reduce the residue height as well as improve the uniformity of residue spread (as less residue is processed by the harvester), without reducing harvest speed, but can be damaged by rocks (Scott *et al.* 2013). Several spreader designs are commercially available with improved technologies including maximum air velocity chopper/blower, adjustable single paddle disc spreader and power cast tailboard behind the chopper. Some spreader options include either chaff only or chaff and residue spreading choices (Ashworth *et al.* 2010). Associated with this are a number of adaptations for HWSC (See Chapter 6 and 10).

Post-harvest management

Post-harvest residue management strategy depends upon the amount of residue left on the field and the amount of residue that the seeding machinery can handle (Scott *et al.* 2013). The presence (or absence) of livestock in the farming system is also a factor, although grazing on residues with low stocking rates of sheep appears to do little damage to the soil and have no detrimental impact on the yield of the following crop (Hunt *et al.* 2016, Allan *et al.* 2016, see Chapter 7). Some machines have been designed to reduce residue height and to promote faster decomposition including harrows, prickle chains, disc chains, off-set discs and machines that ‘smash up’ the stubble (GRDC 2011). The effectiveness of these machines depends on soil type and conditions. Reducing residue through strategies of mulching, windrowing, grazing, baling, burning, harrowing or partial removal can minimise difficulties encountered from heavy stubble loads at seeding (Rainbow and Derpsch 2011). Traditionally, residue incorporation involved significant and repeated mixing and inversion of the soil to bury residues and create a suitable seedbed. Incorporating residues can also help mix the soil and prevent the nutrient stratification that may develop over the long term in NT systems (Bockus and Shroyer 1998, Scott *et al.* 2010).

Table 1. Some advantages and disadvantages of different residue management strategies (derived from Singh *et al.* 2018)

Residue Management	Advantages	Disadvantages
Surface retention	<ul style="list-style-type: none"> ↓ erosion ↑ soil moisture ↑ soil organic matter and nutrient reserves ↑ soil physical and biological quality ↓ prevalence of some weed and disease species. 	<ul style="list-style-type: none"> ↓ ease of planting and crop establishment ↓ nutrient availability due to stratification and/or immobilization ↓ air temperatures (frost) ↑ in some weed and disease species ↓ effectiveness of pre-emergence herbicides
Incorporation	<ul style="list-style-type: none"> ↑ ease of seeding operations ↑ speed of nutrient cycling and crop availability ↓ nutrient stratification ↓ prevalence of some weed and disease species. ↑ effectiveness of pre-emergence herbicides 	<ul style="list-style-type: none"> ↑ rates of organic matter decomposition ↓ soil physical and biological quality ↓ soil moisture ↑ erosion
Removal (baling, burning)	<ul style="list-style-type: none"> ↑ ease of seeding operations ↓ prevalence of some disease species. ↑ effectiveness of pre-emergence herbicides 	<ul style="list-style-type: none"> ↑ nutrient loss ↓ soil physical and biological quality ↓ soil moisture ↑ erosion

However, these must be weighed against the benefits of retaining stubble as summarised briefly in Table 1. Clearly, long term removal of residue will lead to a net loss of organic-C and plant nutrients, which leads to a reduction in soil quality and productivity (Mandal *et al.* 2004, Blanco-Canqui and Lal 2009, Scott *et al.* 2010, Agegnehu and Amede 2017).

Seeding management

Large residue loads can interfere with seeding machinery (Lyon *et al.* 2004, Scott *et al.* 2010, Avci 2011). Blockage of the seeding implement is one of the major challenges to residue retention, especially when residue loads from the previous crop are high (>3 t/ha) or tall, or chaff and residue has not been chopped and spread evenly (Vanclay and Glyde 1994, Umbers 2017). Desbiolles (2007) found that the ability to establish sensitive crops reliably in heavy stubble in NT cropping was a major issue for most farmers, but in recent surveys (Umbers 2017) farmers appear to be slowly adopting higher levels of residue retention. There are several ways to cope with heavy residue at seeding including planting between the previous stubble rows (inter-row seeding), use wider crop row spacing and modifying the seeding machinery.

Increasing row spacing improves seeding operations by allowing greater residue flow and reduced risk of blockage, along with a reduction in tractor draft. Seeding in wider rows reduces power and seeder costs and reduces the risk of herbicide being thrown into the adjacent crop rows at seeding. The use of wider rows of about 25 to 30 cm as compared with 15 to 20 cm has become popular in residue retained farming systems, although it may result in a yield penalty in the higher rainfall areas. A yield loss as high as 1% for every centimetre widening of row space from a 18 cm row spacing has been reported (Amjad and Anderson 2006, Scott *et al.* 2013). Agronomic practices that maximise yield at conventional row spacing are also effective at wider row spacings, but are unlikely to offset the yield loss associated with wider rows (Scott *et al.* 2013).

Inter-row seeding is particularly useful to handle heavy residues. When compared with in-row seeding (into the previous residue rows), inter-row seeding improves establishment by 27% (McCallum 2006). A coulter can cut through residue, and minimise soil throw on tyned planters. To ensure consistent seeding depth, depth control across the implement is extremely important for good tracking. Inter-row seeding generally requires Real Time Kinetic (RTK) precision guidance with ± 2 cm accuracy and autosteer on the tractor (McCallum 2006) (See Chapter 22). It is important to keep the same row spacing year after year and best to sow in the same direction each year for each run. Controlled traffic farming enables inter-row seeding with potential of widespread additional benefits such as reduced compaction, improved trafficability, ease of operations and reduced dust (Rainbow and Derpsch 2011).

Both tyne and disc (opener) seeding implements have advantages and disadvantages in terms of residue handling ability, soil disturbance and cost. Many farmers, with either tyne or disc seeders, have set up their systems to successfully seed into high residue loads without having to incorporate/reduce residues. This requires consideration of all aspects of the machinery set up from harvest and seeding as well as crop aspects such as rotation and row spacing.

Tyned seeders are often less expensive than disc seeders, but generally handle less stubble. These seeders cause some soil disturbance which can be useful to manage hard-to-kill weeds, herbicide resistant weeds, soil and stubble-borne disease and nutrient stratification (Dang *et al.* 2015). On the other hand, disc seeders handle heavier residue loads but can result in hair-pinning (pushing residue into the seeding groove) reducing seed/soil contact, resulting in poor germination and emergence. This problem is more common in old disc seeders that rely on the weight of the machine for soil penetration, but newer models are set on a sharper angle so discs slice through the soil and cut stubble rather than rely on the machine weight (Ashworth *et al.* 2010, Scott *et al.* 2013). Recently, farmers have also shown renewed interest in disc seeders, especially set at narrow row spacings, to increase crop competition against weeds. Row-cleaner residue managers move stubble away from disc openers and improve the residue handling ability of disc openers to reduce hair-pinning and enhance soil/seed contact (Ashworth *et al.* 2010). Disc implements disturb soil less than tyne-implements resulting in less water loss, but the lack of soil throw in a disc system means the effectiveness of pre-emergent herbicides that work by

incorporation may be compromised. Coulter discs attached to the front of seeders also help to manage stubble at seeding and can be used to increase soil throw for herbicide incorporation.

Several modifications and recommendations have been developed from research and grower experience. Mead and Qaisrani (2003) and GRDC (2011) suggested some guidelines to improve residue flow through tyne seeders, including:

- a ‘stubble tube’ placed around tyne shanks;
- a straight vertical shank with rounded cross section; and
- matching inter-tyne spacing with a minimum of twice the residue length, creating a tyne layout that minimises the number of clump interactions with following tynes.

Machinery evolution continues apace and the most recent innovations and directions for the future are discussed in more detail in Chapter 6.

Effects of crop residue

Crop residue retention is one of the key aspects of CA, but because of the wide range of methods in which CA can be implemented, there are few general rules regarding optimum amounts of residue (Kitonyo *et al.* 2018). Target levels of 70% ground cover have been recommended to minimise soil erosion (Scott *et al.* 2010, 2013). The effects of crop residue can also vary, depending on local conditions.

Soil and water conservation

The benefit of crop residue retention to control erosion is well known, with the amounts of stubble required varying with soil and landscape characteristics, and type and orientation of residue (standing or horizontal). For example, 50% soil cover by residue reduced wind erosion by 85% and approximately 1 t/ha of cereal stubble, 2 t/ha of lupin stubble and 3 t/ha of canola stubble achieves 50% ground cover (Anderson 2009, Leonard 1993). Felton *et al.* (1987) maintained that approximately 2.5 t/ha of close-growing crops (*e.g.* wheat) or 4 t/ha of tall coarse crops (*e.g.* grain sorghum) were required to achieve 90% interception of raindrops. As a general rule, 2 t/ha of wheat stubble as a surface mulch provides adequate protection against soil erosion (Felton *et al.* 1987).

Crop residues also increase water capture, which is crucial in our rainfed cropping systems. Residues increase infiltration and reduce soil water evaporation, especially soon after rainfall events (Verberg *et al.* 2012). The result is increased soil water content, which is particularly important early in the growing season, where crops can be established earlier and survive for longer, should dry conditions follow. However, evaporation over long, dry periods will often result in soil water near the surface declining to similar levels as with no stubble present (Ward *et al.* 2009, 2012). The distribution of soil water after rainfall, especially light rains, is affected by the amount of standing and horizontal residue. Generally, bare soil has the highest evaporation and horizontal residues the lowest, with standing residue intermediate (Flerchinger *et al.* 2003). Nonetheless, Swella *et al.* (2015) found an 11% increase in soil water in the stubble row and adjacent area compared with the inter-row. In addition, the effect was greatest with taller-cut stubble (cut at 0.25-0.3 m compared with 0.05 m height) and at least 2 t/ha of horizontal residue between the residue rows. Hence under dry conditions, farmers can seed following crops adjacent to the standing residue row, to access the increased soil water. Good weed control is crucial to reap the soil water conservation benefits of crop residues, especially during the summer fallow (Hunt *et al.* 2013).

Soil and air temperature

In the USA, crop residues have been shown to reduce soil temperature, seed emergence and early crop growth where crops are grown in spring, soon after thawing of the soil (Fortin 1993, Boomsma *et al.* 2010). Generally, crop residue has a moderating effect on soil temperatures, being cooler during the day and warmer at night (Bruce *et al.* 2006). This has a positive effect on seedling growth in Australian NT systems, where crops are often seeded into warm/hot soil (Abrecht and Bristow 1990), especially

when seeded early. Nonetheless, high amounts (6 t/ha) of wheat stubble were shown to reduce canola emergence and yield (Bruce *et al.* 2006). Residue orientation also affects soil temperature, with Swella (2013) showing that taller standing residue had a greater moderating effect than shorter residue, and that horizontal residue had a greater effect than standing residue. The latter was also observed by Flerchinger *et al.* (2003).

The effect of crop residue on air temperature differs from that on soil temperature. Swella (2013) found that residue increased air temperature 0.05 m above the soil during the day and decreased it at night. The residue effectively ‘blankets’ the soil, reducing soil heat loss during the night; consequently air temperature above mulched soil is decreased (GRDC 2016). In some environments, like southern Australia, frost at anthesis or soon after can reduce crop yields, and its severity may be increased with heavy stubble loads (Jenkinson and Biddulph 2016).

Nutrition

Crop residues vary greatly in their nutrient content depending on crop type, soil fertility, fertiliser applications and the growing conditions. For example, Schultz and French (1976) found that the nitrogen concentration of wheat residue varied from 1.6 to 11.5 mg/kg, phosphorus varied from 0.2 to 1.5 mg/kg and potassium from 6.9 to 25.5 mg/kg. It was estimated by Pluske and Bowden (2004) that up to 90% of the nitrogen in stubble is lost through burning, compared with 10% for phosphorus, 10% for potassium and 25% for sulphur, although these estimates are likely to vary considerably. Nonetheless, it is considered that, in most years, 75% of the potassium in stubble would leach into the soil (Anderson 2009).

There has been much research on the contribution of different types of residue to the nitrogen requirements of following crops. Green residues decompose rapidly with up to 40% of residue mineralised within 12 months. A slower rate of decomposition occurs in mature residues that possess a greater C:N ratio, and greater lignin:N ratio and/or polyphenol:N ratios. Where legume phases are followed by a crop phase, 10-20% of previously green legume residue N is typically used by the first succeeding crop, while less than 10% of N in mature pasture residue is normally taken up in the first following crop (Fillery 2001). Between 70-150 kg N/ha can be mineralised after a legume phase.

Leaching of available N (derived from the previous legume or in-crop fertilisers) below the root zone can occur in sandy soils. As such, low quality residues (like high C:N ratio cereal residue) have been suggested as a way to improve the synchronisation between N supply and crop demand (Palm *et al.* 2001, Vanlauwe *et al.* 2001). Murphy *et al.* (2016) showed that residue retention enhanced the recovery of fertiliser-N in the plant-soil system over the short term.

In current NT systems with residue retention, residues from successive crops of different ages are present (Craig 2016). Therefore, it is more difficult to predict the potential contribution of the residue to subsequent crop nutrition, although Kirkegaard *et al.* (2018) and Gupta *et al.* (2018) both suggest that little crop N is sourced directly from residue breakdown. Craig (2016) showed that, in the absence of applied nitrogen fertiliser, up to 32 kg N/ha was mineralised in both monoculture wheat and wheat rotated with canola and a grain legume (*i.e.* mixed residue types). Nonetheless, when nitrogen fertiliser was applied, more N was immobilised in the monoculture wheat system compared with the rotated system. This suggests that in some situations, particularly with heavy cereal residues, additional nitrogen (deep placed in the soil away from the residues) may be required. Indeed, Kirkegaard (2018) reported that surface-retained cereal stubble in modern no-till systems can immobilise N, constrain young crops and reduce yields by 0.3-0.5 t/ha.

Crop residue also contributes to soil organic matter, although it has been shown that a lack of nutrients can limit carbon sequestration from residue (Kirkby *et al.* 2014). Following on, it has been demonstrated that the addition of nutrients (NPS) can increase the rate of stubble decomposition and carbon sequestration (Kirkby *et al.* 2016, and see Chapter 16).

Diseases, insects and other pests

Residue-borne diseases can have a significant impact on following crops in NT systems, particularly when similar crops are grown in succession; disease increases with successive crops (see Chapter 11). Crop rotation/physical separation is the best way to reduce residue-borne disease levels. Providing a single year break in Western Australia reduced the amount of septoria nodorum blotch (*Parastagonospora nodorum*) and yellow spot (*Pyrenophora tritici-repentis*) significantly in wheat and the infectivity of 18 month old wheat residue was similar to that of the nil residue treatment (Bhathal and Loughman 2001). By contrast, wheat yellow leaf spot lasts longer in eastern Australia and a two to three year break was recommended for stubble retention systems (Summerell and Burgess 1989, Bhathal and Loughman 2001).

Nonetheless, in many stubble-retained systems, the diseases can be managed adequately using a variety of techniques such as resistant varieties, fungicides applied to the fertiliser or seed, seeding between the previous crop rows to avoid the residue and use of row cleaners to move the residue away from the emerging seedlings (see Chapter 11). For example, Verrell *et al.* (2017) found that moving the residue (source of inoculum) away from the sown row reduced the incidence of crown rot in wheat by 3.7% and white heads by 13.6%. Also, seeding between the stubble from the previous crop rows led to a 12% reduction in incidence of crown rot. Placing the residue from the harvester in a narrow windrow and burning significantly reduced residue load by between 40-60% (Flower *et al.* 2017) and also killed *Sclerotinia sclerotiorum* sclerotia in canola residues (Brooks *et al.* 2018). However, the effectiveness of windrow burning to reduce *S. sclerotiorum* sclerotia varied from 48% to 74%, depending on the pollination type (open pollinated or hybrid), crop row spacing and harvester cutting height (Brooks *et al.* 2018). By contrast, windrow burning had little effect on stubble borne diseases in cereals such as wheat and barley (Flower *et al.* 2019).

No-till cropping systems with residue retention have higher levels of ground dwelling arthropods and beneficial insects compared with cultivated systems with no residue (Witmer *et al.* 2003). Overall, there is little evidence that NT increases arthropod pests (Hammond 1997, Stingli and Bokor 2008), although Andersen (2003) showed that pests and beneficial insects react differently to no-till systems. For example, field slugs were more common in reduced tillage systems, where weeds were not adequately controlled (Andersen 1999). In addition, where land-snails are a problem, some form of stubble management (such as rolling) is sometimes required to knock the standing residue and snails down to reduce the recruitment of juveniles the following year (see Chapter 12).

Weed control efficacy

Crop residues can smother some weeds to provide partial weed control. However, crop residues can also intercept much of the applied herbicides, potentially reducing their efficacy. This is particularly so with pre-emergence herbicides, which are applied before or soon after seeding. As expected, the amount of herbicide intercepted increases with the level of ground cover; the same amount of cereal residue will intercept more herbicide than coarser residue types, like lupin or canola, because of greater surface coverage by the cereal residue. The age of the residue has only a small effect on interception with year-old residue intercepting less herbicide than the same amount of fresh residue, largely because of slightly reduced surface coverage (Khalil *et al.* 2018). Increased herbicide efficacy with crop residues can be achieved by using higher water volumes. Borger *et al.* (2013) demonstrated increased spray coverage from 5% to 32% and improved weed control efficacy from 53% to 78% by increasing spray carrier volume from 30 L to 150 L. The use of medium sized droplets also improved spray coverage but had little effect on weed control efficacy.

When large amounts of herbicide are intercepted, subsequent weed control relies on rainfall or irrigation to wash some of the herbicide off the residues into the soil. Most herbicide will be washed off the residue into the soil, to provide weed control, when rainfall or irrigation occurs soon after herbicide application. The higher the amount of rainfall the greater the amount washed into the soil, although the intensity of rainfall has been shown to have no effect (Khalil *et al.* 2019). The amount of herbicide washed off the crop residue into the soil varies with the different chemicals. Khalil *et al.* (2019) showed

that pyroaxsulfone leached easily from residue into the soil for at least two weeks after application of the herbicide; prosulfocarb was intermediate and trifluralin leached the least, mainly due to loss by volatilisation. Therefore, careful selection of herbicide should be made when high levels of residue are present.

Conclusions

Crop residue retention is one of the three key components of CA as it provides soil protection, water conservation, and contributes to the maintenance of soil organic matter and soil fertility. However, it must be managed to avoid compromising timeliness of sowing, target plant populations, effective weed, pest and disease control and crop nutrition, all which may affect crop yield (Swan *et al.* 2018). Fortunately, the first few t/ha of stubble provide most of the benefits with few issues, and numerous options exist to manage heavier stubbles well (Kirkegaard *et al.* 2014, Swan *et al.* 2018).

Residue management starts at harvest and continues through to seeding of the crop. The optimal way to manage crop residues will vary across farms and paddocks, and a systems approach is required that takes into consideration crop rotation, residue condition (*e.g.* type, age, dry or wet), residue amounts, disease risk, weed spectrum/herbicides and available machinery (*e.g.* ability of harvester to spread residue evenly across the whole cutting width, ability of seeding machinery to handle residue). Australian farmers now fully burn fewer than 4% of fields prior to seeding (Umbers 2017) which represents an enormous transition from the farming systems described in *Tillage* 30 years ago in which little stubble was retained. As the precision of seeding equipment improves, and the strategies for effective pest, weed and disease control broaden in diverse cropping systems, stubble retention will continue to underpin sustainable cropping systems in Australia.

References

- Abrecht DG, Bristow KL (1990) Maize seedling response to the soil environment at varying distances from a mulched soil bare soil boundary. *Soil & Tillage Research* **15**, 205-216
- Agegnehu G, Amede T (2017) Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: A review. *Pedosphere* **27**, 662-680
- Allan CJ, Jones B, Falkiner S *et al.* (2016) Light grazing of crop residues by sheep in a Mediterranean-type environment has little impact on following no-tillage crops. *European Journal of Agronomy* **77**, 70-80
- Amjad M, Anderson WK (2006) Managing yield reductions from wide row spacing in wheat. *Australian Journal of Experimental Agriculture* **46**, 1313-1321
- Andersen A (1999) Plant protection in spring cereal production with reduced tillage. II. Pests and beneficial insects. *Crop Protection* **18**, 651-657
- Andersen A (2003) Long-term experiments with reduced tillage in spring cereals. II. Effects on pests and beneficial insects. *Crop Protection* **22**, 147-152
- Anderson G (2009) The impact of tillage practices and crop residue (stubble) retention in the cropping system of Western Australia. (Western Australian Agriculture Authority, South Perth, Western Australia) 6151 <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.541.5372&rep=rep1&type=pdf>
- Ashworth M, Desbiolles J, Tola EK (2010) "Disc Seeding in Zero-Till Farming Systems: A Review of Technology and Paddock Issues" (West Australian No-Tillage Farmers Association: Northam, Western Australia: Perth)
- Avci M (2011) Conservation tillage in Turkish dryland research. *Agronomy for Sustainable Development* **31**, 299-307
- Bhathal JS, Loughman R (2001) Ability of retained stubble to carry-over leaf diseases of wheat in rotation crops. *Australian Journal of Experimental Agriculture* **41**, 649-653
- Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. *Critical Reviews in Plant Sciences* **28**, 139-163
- Bockus WW, Shroyer JP (1998) The impact of reduced tillage on soilborne plant pathogens. *Annual Review of Phytopathology* **36**, 485-500
- Boomsma CR, Santini JB, West TD *et al.* (2010) Maize grain yield responses to plant height variability resulting from crop rotation and tillage system in a long-term experiment. *Soil & Tillage Research* **106**, 227-240
- Borger CPD, Riethmuller GP, Ashworth M *et al.* (2013) Increased carrier volume improves preemergence control of rigid ryegrass (*Lolium rigidum*) in zero-tillage seeding systems. *Weed Technology* **27**, 649-655

- Brooks KD, Bennett SJ, Hodgson LM, Ashworth MB (2018) Narrow windrow burning canola (*Brassica napus* L.) residue for *Sclerotinia sclerotiorum* (Lib.) de Bary sclerotia destruction. *Pest Management Science* **74**, 2594-2600
- Bruce SE, Ryan MH, Kirkegaard JA, Pratley J (2006) Improving the performance of canola in retained wheat stubble. *Australian Journal of Agricultural Research* **57**, 1203-1212
- Chamala S, Coughenour CM, Keith KJ (1983) Study of conservation cropping on the Darling Downs – A basis for extension programming. (University of Queensland, Department of Agriculture: Brisbane)
- Craig NW (2016) Assessing soil nitrogen supply in wheat monoculture under no-tillage in Western Australia. PhD Thesis, The University of Western Australia
- D’Emden FH, Llewellyn RS, Burton MP (2006) Adoption of conservation tillage in Australian cropping regions: An application of duration analysis. *Technological Forecasting and Social Change* **73**, 630-647
- D’Emden FH, Llewellyn RS, Burton MP (2008) Factors influencing adoption of conservation tillage in Australian cropping regions. *Australian Journal of Agricultural and Resource Economics* **52**, 169-182
- Dang YP, Seymour NP, Walker SR *et al.* (2015) Strategic tillage in no-till farming systems in Australia’s northern grains-growing regions: I. Drivers and implementation. *Soil & Tillage Research* **152**, 104-114
- Desbiolles J (2007) Stubble still a challenge. Groundcover Supplement. GRDC Issue 64
www.grdc.com.au/resources-and-publications/groundcover/ground-cover-supplements/ground-cover-issue-64-notill-supplement/stubble-still-a-challenge
- Etherton A (2018) A profitable stubble system. Groundcover Supplement. GRDC Issue 135, 2
www.grdc.com.au/resources-and-publications/groundcover/ground-cover-supplements/groundcover-issue-135-stubble/a-profitable-stubble-system
- Farooq M, Flower KC, Jabran K *et al.* (2011) Crop yield and weed management in rainfed conservation agriculture. *Soil & Tillage Research* **117**, 172-183
- Fawcett RG (1975) Water penetration and storage in relation to wheat growth on swelling clays. CSIRO Land Resources Laboratories No. Discussion paper No 1
- Felton WL, Freebairn DM, Fettell NA, Thomas JB (1987) Crop residue management. In (Eds. PS Cornish, JE Pratley) “Tillage: New Directions in Australian Agriculture” pp 171-193 (Inkata Press: Melbourne)
- Fillery IRP (2001) The fate of biologically fixed nitrogen in legume-based dryland farming systems: a review. *Australian Journal of Experimental Agriculture* **41**, 361-381
- Flerchinger GN, Sauer TJ, Aiken RA (2003) Effects of crop residue cover and architecture on heat and water transfer at the soil surface. *Geoderma* **116**, 217-233
- Flower KC, Hüberli D, Collins SJ *et al.* (2019) Progression of plant parasitic nematodes and foliar and root diseases under no-tillage with different crop rotations and residue management *Soil & Tillage Research* **191**, 18-28
- Flower KC, Ward PR, Cordingley N, Micin SF, Craig N (2017) Rainfall, rotations and residue level affect no-tillage wheat yield and gross margin in a Mediterranean-type environment. *Field Crops Research* **208**, 1-10
- Fortin MC (1993) Soil temperature, soil water and no-till corn development following in-row residue removal. *Agronomy Journal* **85**, 571-576
- Freebairn DM, Littleboy M, Smith GD, Coughlan KJ (1991) Optimising soil surface management in response to climatic risk. In (Eds. RC Muchow, JA Bellamy) “Climatic risk in crop production: models and management for semiarid tropics and subtropics” pp 283-305 (CAB International: Wallingford, UK)
- Giller KE, Andersson JA, Corbeels M *et al.* (2015) Beyond conservation agriculture. *Frontiers in Plant Science* **6**, 1-14
- GRDC (2011) “Stubble management”. Monograph 9 (Grains Research and Development Corporation: Canberra, Australia)
- GRDC (2016) Managing Frost Risk: Case studies of growers in Western Australia (Grain Research and Development Corporation: Canberra)
- Gupta V, Kirkegaard J, McBeath T *et al.* (2017) The effect of stubble on nitrogen tie-up and supply – The Mallee experience. 8pp (Mallee Sustainable Farming) <http://www.msfp.org.au/wp-content/uploads/The-effect-of-stubble-on-nitrogen-tie-up-and-supply-Vadakattu-Gupta-Full.pdf>
- Hallsworth E, Gibbons F, Lemerle T (1954) The nutrient status and cultivation practices of the soils of the North-West wheat belt of NSW. *Australian Journal of Agricultural Research* **5**, 422-447
- Hammond RB (1997) Long-term conservation tillage studies: Impact of no-till on seedcorn maggot (Diptera: Anthomyiidae). *Crop Protection* **16**, 221-225
- Heenan DP, Taylor AC, Cullis BR, Lill WJ (1994) Long term effects of rotation, tillage and stubble management on wheat production in southern N.S.W. *Australian Journal of Agricultural Research* **45**, 93-117
- Holland JF, Doyle AD, Marley JM (1987) Tillage practices for crop production in summer rainfall areas. In (Eds. PS Cornish, JE Pratley) “Tillage: New directions in Australian agriculture” (Inkata Press: Melbourne)

- Hunt JR, Browne C, McBeath TM *et al.* (2013) Summer fallow weed control and residue management impacts on winter crop yield through soil water and N accumulation in a winter-dominant, low rainfall region of southern Australia. *Crop and Pasture Science* **64**, 922-934
- Hunt JR, Swan AD, Fettel, NA *et al.* (2016) Sheep grazing on crop residues do not reduce crop yields in no-till, controlled traffic farming systems in an equi-seasonal rainfall environment. *Field Crops Research* **196**, 22-32
- Jenkinson R, Biddulph B (2016) Role of stubble management on the severity and duration of frost and its impact on grain yield. *GRDC Grains Research Updates*. Perth <http://www.giwa.org.au/2016researchupdates>
- Kempster V, Charwat S (2003) Soil surface temperature and mortality in land snails: implications for successful management. *Australian Journal of Experimental Agriculture* **43**, 1351-1356
- Khalil Y, Flower K, Siddique KHM, Ward P (2018) Effect of crop residues on interception and activity of prosulfocarb, pyroxasulfone, and trifluralin. *PLoS ONE* **13**, e0208274. doi. org/10.1371/journal.pone.0208274
- Khalil Y, Flower K, Siddique KHM, Ward P (2019) Rainfall affects leaching of pre-emergent herbicide from wheat residue into the soil. *PLoS ONE* **14**(2): e0210219. www.doi.org/10.1371/journal.pone.0210219
- Kirkby CA, Richardson AE, Wade LJ *et al.* (2014) Nutrient availability limits carbon sequestration in arable soils. *Soil Biology and Biochemistry* **68**, 402-409
- Kirkby CA, Richardson AE, Wade LJ *et al.* (2016) Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. *PLoS ONE* **11**, e0153698 doi:10.1371/journal.pone.0153698
- Kirkegaard JA, Angus JF, Gardner PA, Müller W (1994) Reduced crop growth and yield of wheat with conservation cropping I Field studies in the first year of the cropping phase. *Australian Journal of Agricultural Research* **45**, 511-528
- Kirkegaard JA, Conyers MK, Hunt JR *et al.* (2014) Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems and Environment* **187**, 133-145
- Kirkegaard J (2018) Why do stubble-retained systems need more nitrogen? Ground Cover Supplement – Stubble (July-August) pp 8-9 (Grains Research and Development Corporation: Canberra)
- Kirkegaard J, Vadakattu G, Hunt J, Jones K (2018) The effects of stubble on nitrogen tie-up and supply. *GRDC Updates* www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/02/the-effects-of-stubble-on-nitrogen-tie-up-and-supply
- Kitonyo OM, Zhou Y, Coventry DR, Denton MD (2018) Canopy development and grain yield of dryland wheat is modified by strategic nitrogen supply and stubble management. *European Journal of Agronomy* **99**, 195-205
- Leeper GW (1970) "The Australian Environment" (CSIRO and Melbourne University Press: Melbourne)
- Leonard L (1993) "Managing for Stubble Retention" Bulletin 4271. Department of Agriculture Western Australia. <https://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1137&context=bulletins>
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Lyon D, Bruce S, Vyn T, Peterson G (2004) Achievements and future challenges in conservation tillage. *Proceedings of 4th International Crop Science Congress*, Brisbane, Australia pp. 1-19 [www.cropscience.org.au](http://www.cropsscience.org.au)
- Mandal KG, Misra AK, Hati KM *et al.* (2004) Rice residue-management options and effects on soil properties and crop productivity. *Journal of Food Agriculture and Environment* **2**, 224-231
- Marley J, Littler J (1989) Winter cereal production on the Darling Downs – an 11 year study of fallowing practices. *Australian Journal of Experimental Agriculture* **29**, 807-827
- McCallum M (2006) Inter row sowing and no-till – a good marriage. GRDC Online Farm trials. 2006 Trial Report Precision Agriculture <https://www.farmtrials.com.au/trial/13886>
- Mead JA, Qaisrani R (2003) Improving stubble flow through tines on agricultural machinery. *Biosystems Engineering* **85**, 299-306
- Murphy RP, Montes-Molina JA, Govaerts B *et al.* (2016) Crop residue retention enhances soil properties and nitrogen cycling in smallholder maize systems of Chiapas, Mexico. *Applied Soil Ecology* **103**, 110-116
- Palm CA, Gachengo CN, Delve RJ *et al.* (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems & Environment* **83**, 27-42
- Pittelkow CM, Linquist BA, Lundy ME *et al.* (2015) When does no-till yield more? A global meta-analysis. *Field Crops Research* **183**, 156-168
- Pluske W, Bowden B (2004) Stubble management impacts on soil nutrients. *Farming Ahead* pp 38-40 (Kondinin Group, Perth)

- Poole ML (1987) Tillage practices for crop production in winter rainfall areas. In (Eds. PS Cornish, JE Pratley) "Tillage: New Directions in Australian Agriculture" pp 24-47 (Inkata Press: Melbourne)
- Pratley JE, Rowell DL (1987) From the first fleet – evolution of Australian farming systems. In (Eds. PS Cornish, JE Pratley) "Tillage: New Directions in Australian Agriculture" pp. 2-23 (Inkata Press: Melbourne)
- Rainbow R, Derpsch R (2011) Advances in no-till farming technologies and soil compaction management in rainfed farming systems. In (Eds. P Tow, I Cooper, I Partridge I, C Birch) "Rainfed Farming Systems" pp 991-1014 (Springer: Dordrecht)
- Schultz JE, French RJ (1976) Mineral content of herbage and grain of Halberd wheat in South Australia. *Australian Journal of Experimental Agriculture* **16**, 887-892
- Scott BJ, Eberbach PL, Evans J, Wade LJ (2010) "Stubble Retention in Cropping Systems in Southern Australia: Benefits and Challenges" EH Graham Centre Monograph No. 1
<https://www.csu.edu.au/research/grahamcentre>
- Scott BJ, Podmore CM, Burns HM *et al.* (2013) Developments in stubble retention in cropping systems in southern Australia. Report to GRDC on Project DAN 00170 pp 103 (Department of Primary Industries: Orange NSW) pp 103. <https://bit.ly/2YbPdda>
- Singh BP, Bijay-Singh, Noack SR, Fang Y, Mehra P, Page K, Dang YP (2018) Crop residue management for improving soil carbon storage, nutrient availability and fertilizer use efficiency. *Advances in Soil Science* in review
- Stingli A, Bokor A (2008) Effect of conservation tillage and nutrient rate on the occurrence of certain insect groups in winter wheat. *Cereal Research Communications* **36**, 1699-1702
- Summerell BA, Burgess LW (1989) Factors influencing survival of *Pyrenophora tritici-repensis*: stubble management. *Mycological Research* **93**, 38-40
- Swan T, Francis J, Kirkegaard J *et al.* (2018) Flexible stubble management – how to reap returns to the bottom line. *GRDC Updates Wagga Wagga* grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/08/flexible-stubble-management
- Swella GB (2013) Managing crop residues to improve wheat growth and yield. PhD Thesis, The University of Western Australia
- Swella GB, Ward PR, Siddique KHM, Flower KC (2015) Combinations of tall standing and horizontal residue affect soil water dynamics in rainfed conservation agriculture systems. *Soil & Tillage Research* **147**, 30-39
- Vanclay F, Glyde S (1994) Land degradation and land management in central NSW: Farmers' knowledge, opinion and practice. A Report to the New South Wales Department of Agriculture and the Department of Conservation and Land Management <https://catalogue.nla.gov.au/Record/1916499>
- Vanlauwe B, Wendt J, Diels J (2001) Combined application of organic matter and fertilizer. In (Ed. WA Dick) "Sustaining Soil Fertility in West Africa" pp 247-280 (Soil Science Society of America, Inc.: Madison, Wisconsin, USA)
- Verberg K, Bond WJ, Hunt JR (2012) Fallow management in dryland agriculture: Explaining soil water accumulation using a pulse paradigm. *Field Crops Research* **130**, 68-79
- Verrell AG, Simpfendorfer S, Moore KJ (2017) Effect of row placement, stubble management and ground engaging tool on crown rot and grain yield in a no-till continuous wheat sequence. *Soil & Tillage Research* **165**, 16-22
- Umbers A (2017) GRDC Farm Practices Survey Report 2016. GRDC
www.grdc.com.au/FarmPracticesSurveyReport
- Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. *Weed Technology* **21**, 332-338
- Ward PR, Flower KC, Cordingley N *et al.* (2012) Soil water balance with cover crops and conservation agriculture in a Mediterranean climate. *Field Crops Research* **132**, 33-39
- Ward PR, Whisson K, Micin SF *et al.* (2009) The impact of wheat stubble on evaporation from a sandy soil. *Crop and Pasture Science* **60**, 730-737
- Watt LA (1983) Effects of land use changes on soil erosion in the western Gwydir area. *Journal of Soil Conservation, New South Wales* **39**, 142-147
- Witmer JE, Hough-Goldstein JA, Pesek JD (2003) Ground-dwelling and foliar arthropods in four cropping systems. *Environmental Entomology* **32**, 366-376

PART III – PROTECTING THE CROP



A cloud over pesticide use (Courtesy: Michael Walsh)



Crown rot in wheat becomes a challenge in stubble retained systems (Courtesy: Steven Simpfendorfer)



**Herbicide resistant ryegrass in lupins at Wagga Wagga, 1988
(Courtesy: Jim Pratley)**



First recorded case of glyphosate resistance (1995): in annual ryegrass from a farm at Echuca, Victoria (Courtesy: Jim Pratley)

Chapter 10

Weed control in cropping systems – past lessons and future opportunities

Michael Walsh, John Broster, Bhagirath Chauhan, Greg Rebetzke and Jim Pratley

The weed control environment

Weed control in Australian crops has been through a revolution over the last three decades, transforming from a dependency on cultivation, with associated soil degradation issues, to herbicide reliance in conservation agriculture (CA) systems. The resulting dramatic change in the crop production environment has resulted in a similarly significant impact on weed control practices. The adoption of CA is underpinned by the availability of highly efficient, selective herbicides, but the absence of alternate weed control technologies has led to an overreliance on herbicides. The widespread evolution of herbicide resistance now threatens the sustainability of CA systems (Powles and Yu 2010).

Australian farmers, like those elsewhere, are continually confronted by weeds that impact crop yields, quality and profitability (Oerke 2006). A study by Llewellyn *et al.* (2016) determined that the cost of weeds to Australian grain growers was \$3.3 billion per year due to a combination of lost production (\$0.75 billion) and weed control expenditure (\$2.57 billion). Herbicide resistance is already a significant component of weed control costs (\$187 million) and with no new herbicides in the foreseeable future this cost will continue to escalate (Llewellyn *et al.* 2016).

Historical perspective on weed control in cropping systems

Cropping systems and weed control prior to 1980s

The impact of weeds on crop yields has been a challenge since crop production began. Initially it was addressed by shifting agriculture from place to place and then, as implements became available, by cultivation practices to destroy weeds (Pratley and Rowell 1987). Some weeds, notably skeleton weed (*Chondrilla juncea*) readily adapted to this and fields were converted to pasture for a period to enable livestock to control weeds (Cuthbertson 1967, Wells 1970) – a stimulus for ‘ley farming’ in the 1930s.

Weed seed collection was a part of the harvest operation for years prior to 1987 and well before the introduction of the current harvest weed seed control (HWSC) technologies. Harvesting equipment used during this period allowed the collection of some weed seed as well as small and broken grain via the screening of grain as it entered the grain tank. This material, referred to as ‘seconds’ was subsequently collected in an additional storage tank. This technology was relatively effective in that the seconds were ‘bagged-off’ and fed to the farm poultry or otherwise disposed of. This capability became obsolete from the 1970s with changes in harvester threshing and cleaning systems that enabled increased processing efficiency, and therefore harvester capacity. Weed seeds, however, were dispersed with the chaff back onto the soil.

Cropping systems and weed control 1980s – 2020

The need to improve soil structure, retain nutrients and conserve soil moisture has driven the widespread adoption of conservation cropping practices based on reduced tillage and stubble retention (FAO 2015, Kassam *et al.* 2012, Llewellyn *et al.* 2012). The introduction and development of conservation cropping practices in Australia began in the 1970s and was initially based on the restricted use of cultivation prior to, and at seeding. During this period there was much experimenting with the use of ‘knockdown’ herbicides paraquat plus diquat (Spray.Seed®) and glyphosate. Adoption rates were initially low but rapidly increased through the 1990s as seeding implement technology developed and the benefits of this approach was realised. Subsequently, tillage operations were further restricted at seeding with knife-point fitted tynes or disc seeding systems.

During the first half of this period the availability of highly effective herbicides for pre-seeding weed control and selective in-crop weed control became a significant driver in the success of conservation cropping systems (D'Emden *et al.* 2008). The most important of these were acetyl coenzyme A carboxylase (ACCase) inhibitors, *e.g.* dichlofop methyl (Hoegrass®), and acetolactase synthase (ALS) inhibitors, *e.g.* chloresulfuron (Glean ®), (Powles and Howat 1990) which for the first time provided highly effective control (up to 99%) of the dominant grass (annual ryegrass and wild oats) and broadleaf (wild radish) weeds. The success of these herbicides paved the way for a proliferation of in-crop selective herbicides that, in most cases, were highly effective, easy to use and readily adopted by farmers.

The adoption of CA has improved soil condition and structure as well as allowing more frequent and timely access to fields with farm equipment for crop planting, crop protection treatments and harvest. Crop planting delays due to wet soils were substantially reduced. More timely herbicide applications have increased efficacy by targeting weeds at their most vulnerable growth stage. Planting on time, or even early, provides for a more vigorous establishment with improved weed competition (see Chapter 18).

Prior to the adoption of CA, crop stubbles were usually burnt in autumn to remove residues for ease of sowing and to control stubble-borne diseases, pest and weeds. Stubble burning can reduce the viability of annual ryegrass seed present on the soil surface by 80%. Temperatures of burning stubbles are higher above the soil (20 cm) than at the surface reducing seed viability if the seed is retained in the seed head (Walsh and Newman 2007). The value of soil cover for erosion minimisation and soil moisture retention prompted delays in burning closer to sowing. Ultimately, burning was largely replaced by stubble retention with the introduction of seeding systems with stubble handling capability.

Herbicide resistance in Australian cropping systems

Before the 1970s/1980s herbicide revolution, tillage and, to a lesser extent, residue burning were the major methods of weed control in Australian cropping systems. The availability of the non-selective herbicides, paraquat/diquat and glyphosate, allowed efficient pre-seeding weed control (Matthews 2018) thereby reducing or removing the need for tillage (Pratley and Rowell 1987). The development of the ACCase and ALS inhibiting herbicides enabled highly effective in-crop weed control with little or no effect on crop growth and development (Matthews 2018). Their control of many grass weeds in cereal crops led to marked increases in herbicide use. The use of herbicides for pre- and post-seeding weed control removed the need for tillage and residue burning to control weeds, facilitating the development of CA.

The efficacy of herbicides has been integral to the success of CA but the subsequent overreliance has placed strong selection pressure on weed populations for resistance evolution. Through most of the 20th century, livestock production dominated the current cropping region and annual ryegrass (*Lolium rigidum*) pastures were established as a valuable source of forage. Thus, by the 1970s, when crop production and herbicide use intensified, annual ryegrass was well established in large, naturalised populations throughout the grain production regions (Donald 1965, Kloot 1983). While highly productive as a pasture species, annual ryegrass possesses the key attributes of a resistance-prone weed species (*i.e.* high genetic variability, obligate out-crossing, high seed production and rapid seed bank turnover) that has resulted in it becoming the world's most resistance-prone weed. The strong selection pressure imposed by the highly effective ACCase and ALS inhibiting herbicides on large populations of this species was a 'perfect recipe' for the widespread evolution of multi-resistant populations.

The first case of evolved herbicide resistance in Australia was reported in 1982 following just six applications of diclofop-methyl to an annual ryegrass population (Heap and Knight 1982). This population was also found to be cross resistant to a range of ACCase and ALS inhibiting herbicides (Heap and Knight 1986, 1990). Despite the clear warning of this first case of resistance, the message was largely ignored and within a relatively short period (5-10 years) the evolution of herbicide resistant weed populations began to impact on the viability of conservation cropping systems (Powles *et al.* 1997).

Table 1 Herbicide resistant weeds of Australian cropping (adapted from Heap 2019)

Species with evolved herbicide resistance	First reported	Herbicide family/site of action
<i>Arctotheca calendula</i> (capeweed)	1986	Synthetic auxins, PS1
<i>Avena fatua</i> (wild oats)	1985	ACCase
<i>Avena ludoviciana</i> (wild oats)	1989	ACCase, ALS, Unknown
<i>Brachiaria eruciformis</i> (sweet summer grass)	2014	EPSPS
<i>Brassica tournefortii</i> (wild turnip)	1992	ALS
<i>Bromus diandrus</i> (great brome)	1999	ACCase, ALS, EPSPS
<i>Bromus rigidum</i> (rigid brome)	2007	ACCase, ALS
<i>Bromus rubens</i> (red brome)	2014	EPSPS
<i>Chloris truncata</i> (windmill grass)	2010	EPSPS
<i>Chloris virgate</i> (feathertop Rhodes grass)	2015	EPSPS
<i>Conyza bonariensis</i> (flaxleaf fleabane)	2010	PS1, EPSPS
<i>Conyza sumatrensis</i> (tall fleabane)	2018	PS1
<i>Cyperus difformis</i> (small umbrella flower sedge)	1994	ALS
<i>Damosonium minus</i> (starfruit)	1994	ALS
<i>Digitaria sanguinalis</i> (large crab grass)	1993	ACCase, ALS
<i>Diplotaxis tenuifolia</i> (Lincoln weed)	2004	ALS
<i>Echinochloa colona</i> (awnless barnyard grass)	2004	PS11, EPSPS
<i>Echium plantagineum</i> (Paterson's curse)	1997	ALS
<i>Eleusine indica</i> (goosegrass)	2015	PS1
<i>Erharta longiflora</i> (annual veldt grass)	2014	ACCase
<i>Fallopia convolvulus</i> (climbing buckwheat)	1993	ALS
<i>Fumaria densiflora</i> (fumitory)	1999	Microtubule inhibitors
<i>Galium tricornutum</i> (three horn bedstraw)	2012	ALS
<i>Gamochaeta pensylvanica</i> (cudweed)	2015	PS1
<i>Hordeum glaucum</i> (wall barley grass)	1982	ACCase, ALS, PS1, EPSPS
<i>Hordeum leporinum</i> (barley grass)	1988	ACCase, PS1
<i>Lactuca saligna</i> (wild lettuce)	2017	EPSPS
<i>Lactuca serriola</i> (prickly lettuce)	1994	ALS, EPSPS
<i>Lolium rigidum</i> (annual ryegrass)	1982	ACCase, ALS, PS11, Microtubule inhibitors, Lipid synthesis inhibitors, VLCFA inhibitors, PS1, EPSPS, Carotenoid biosynthesis inhibitors (unknown target)
<i>Mitracarpus hirtus</i> (tropical girdlepod)	2007	PS1
<i>Nassella trichotoma</i> (serrated tussock)	2002	Lipid synthesis inhibitors
<i>Pentzia suffruticosa</i> (Calomba daisy)	2004	ALS
<i>Phalaris minor</i> (lesser canary grass)	2012	ACCase
<i>Phalaris paradoxa</i> (hood canary grass)	1997	ACCase, ALS
<i>Poa annua</i> (winter grass)	2009	ALS, PS11, Microtubule inhibitors, EPSPS, Unknown
<i>Rapistrum rugosum</i> (turnip weed)	1996	ALS
<i>Raphanus raphanistrum</i> (wild radish)	1997	ALS, PS11, PDS inhibitors, Synthetic auxins, EPSPS
<i>Sagittaria montevidensis</i> (arrowhead)	1994	ALS
<i>Sinapis arvensis</i> (wild mustard)	1996	ALS
<i>Sisymbrium orientale</i> (Indian hedge mustard)	1990	ALS, PS11, PDS inhibitors, Synthetic auxins
<i>Sisymbrium thellungii</i> (African turnip weed)	1996	ALS
<i>Solanum nigrum</i> (blackberry nightshade)	2015	PS1
<i>Sonchus oleraceus</i> (sow thistle)	1990	ALS, Synthetic auxins, EPSPS
<i>Sporobolus fertilis</i> (giant Parramatta grass)	2004	Lipid synthesis inhibitors
<i>Tridax procumbens</i> (tridax daisy)	2016	EPSPS
<i>Urochloa panicoides</i> (liverseed grass)	1996	PS11, EPSPS
<i>Urtica urens</i> (stinging nettle)	2002	PS11
<i>Vulpia bromoides</i> (silver grass)	1990	PS11, PS1

Herbicide-resistant weed populations have evolved throughout the world's cropping regions (Heap 2019), but multiple resistance evolution has been most extensive across the Australian grain production region (Table 1). Susceptibility in annual ryegrass populations is now rare with the predominant scenario being ACCase inhibiting and/or ALS inhibiting herbicide resistance (Owen *et al.* 2014, Boutsalis *et al.* 2012, Broster and Pratley 2006, 2019, Broster *et al.* 2013b, see Table 2). This weed has

evolved resistance to eleven modes of action (MOA); ACCase inhibitors (Heap and Knight 1982), ALS inhibitors (Heap and Knight 1986), PSII inhibitors (Burnet *et al.* 1991), microtubule inhibitors (McAlister *et al.* 1995), mitosis inhibitors (Heap 2019), bleachers (Burnet *et al.* 1991), fat synthesis inhibitors (Brunton *et al.* 2018), VLFCA inhibitors (Heap 2019), PSI inhibitors (Heap 2019), EPSP synthase inhibitors (Pratley *et al.* 1996) and carotenoid biosynthesis inhibitors (Burnet *et al.* 1991). The frequency and distribution of multi-resistant annual ryegrass populations ensures that this species now dominates weed management decisions on the majority of Australian farms.

Table 2. Frequency of herbicide resistance in randomly collected annual ryegrass (*Lolium rigidum*) populations collected across Australia's crop production regions

Herbicide	Herbicide family/ site of action	WA	NSW	SA	Vic	Tas
Diclofop	ACCase	96	64	58	73	46
Sethoxdim	ACCase	79	-	-	-	-
Clethodim	ACCase	65	10	9	8	8
Chlorsulfuron	ALS	-	-	70	71	-
Sulfometuron	ALS	98	57	-	-	16
Imazamox/imazapyr	ALS	-	53	58	31	20
Trifluralin	VLCFA	27	9	57	8	8
Simazine	PSII	-	0	-	-	-
Atrazine	PSII	2	-	-	-	-
Glyphosate	EPSPS	7	3	3	2	0
Paraquat	PSI	0	-	-	-	-

Data from (Broster *et al.* 2013b; Owen *et al.* 2014) and J. Broster and P. Boutsalis pers. comm.

WA values are populations with $\geq 1\%$ survival, NSW and Tasmania are for $>10\%$ survival and Vic and SA values are for $\geq 20\%$ survival at recommended rate

— Indicates herbicide not used in screening.

The extent of herbicide resistance in other major weed species of Australian cropping (*e.g.* wild oats, wild radish, sowthistle, fleabane) is less severe than that of annual ryegrass, but significant, nonetheless. A 2010 survey of the WA wheatbelt found 71% of randomly collected wild oat populations were resistant to the ACCase inhibiting herbicide, diclofop-methyl (Owen *et al.* 2014, Owen and Powles 2016). Similar surveys of southern NSW identified 38% and 20% of wild oats were resistant to diclofop-methyl (Broster *et al.* 2011a, 2011b, 2013b). In WA over 80% of wild radish populations were resistant to sulfonylurea herbicides (Owen *et al.* 2015b) compared with 15% in NSW (J Broster unpublished data). In WA there are also significant frequencies of multi-resistant populations with 30% resistant to three MOA. Results from a survey in 2010 indicated that only 7% of randomly collected populations remained herbicide susceptible (Owen *et al.* 2015b). In southern NSW where sowthistle is more commonly found, over 50% of populations were resistant to sulfonylurea herbicides while glyphosate resistance is common in northern NSW (Broster *et al.* 2012, unpublished data, Jalaludin *et al.* 2018). Resistance to multiple MOA has been reported for both brome grass and barley grass. In WA 13% of brome grass populations were reported to be resistant to sulfonylurea herbicides (Owen *et al.* 2015a). In the South Australian Mallee, western Victoria and western NSW, where brome grass is more prevalent, the extent of resistance was greater with resistance to the sulfonylurea herbicides in 45%, 37% and 28% of populations respectively (Boutsalis *et al.* 2014, J. Broster unpublished data). Barley grass resistance is lower with occasional populations resistant to ACCase and ALS inhibiting herbicides although paraquat resistant populations have been reported in both NSW and Tasmania, the majority being in established lucerne pastures (J Broster unpublished data).

The role of glyphosate and other herbicide tolerance traits

The growth of glyphosate resistance globally is of particular concern with over 40 species now confirmed with resistance to this herbicide (Preston 2019). Resistance was first identified in the late 1990s in Australian annual ryegrass populations (Pratley *et al.* 1996, Powles *et al.* 1998, Pratley *et al.* 1999). Since this initial discovery the frequency of glyphosate resistance in Australia has continued to increase (Broster *et al.* 2019, Preston 2019), while globally much of the growth in frequency of glyphosate resistant species (Figure 1) has occurred since the commercial availability of Roundup Ready™ crop varieties, notably in soybean, corn and cotton.

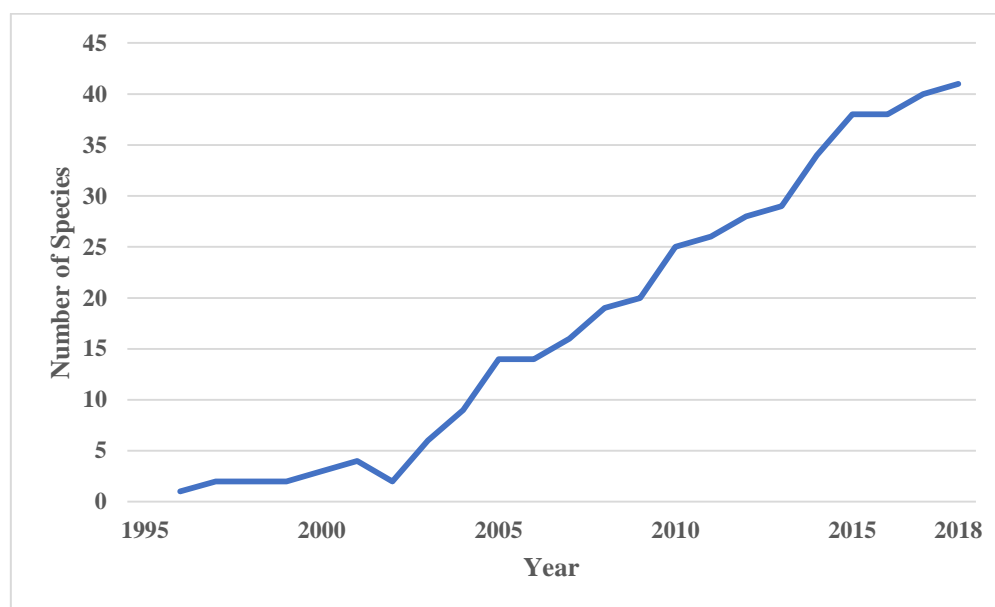


Figure 1. Increase in glyphosate resistant weeds globally, 1990 to 2015 (Heap 2019)

Glyphosate has been, and remains, fundamental to conservation cropping systems, globally. Recent technologies have increased dependency through the inclusion of glyphosate tolerance traits in some crops, notably canola in Australia. Glyphosate resistance traits are now the basis for the gene stacking approach where, in an attempt to combat herbicide resistance evolution, multiple herbicide resistance traits are being combined within single biotypes of some crops. This phenomenon of multiple herbicide-tolerances through gene stacking has been reviewed by Gressel *et al.* (2017). The use of glyphosate tolerance traits has dominated the development of herbicide tolerant crops and is now universally used when traits are stacked and has dramatically changed the use pattern of glyphosate from solely a knockdown herbicide (*i.e.* pre-planting seedbed vegetation control) to a broad-spectrum, in-crop selective herbicide. In doing so, it frequently is the last herbicide used in the growing season and so any survivors will contribute to resistance evolution. In Australia, to date, the glyphosate resistance traits have been confined to cotton (registered from 1996) and subsequently canola (registered from 2003 but grown only in NSW and Victoria since 2008 and in WA since 2010). The incidence of glyphosate resistance in Australia is shown in Figure 2 indicating its spread since 2005 across the southern cropping belt of Australia where canola is grown.

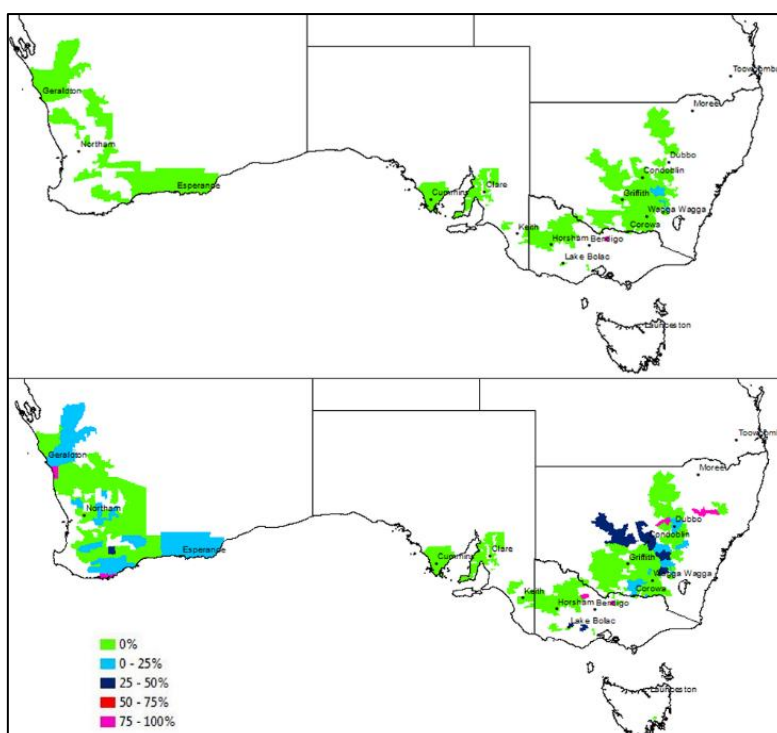


Figure 2. Increase in incidence of glyphosate resistance in the Australian southern cropping zone 2005 (top) to 2018 (bottom) (Broster *et al.* 2019)

Weed control environment of conservation cropping systems

Crop establishment and residual herbicides The widespread adoption of CA incorporating minimal cultivation and stubble retention (Llewellyn *et al.* 2012) has many benefits including soil cover and reduced moisture loss but provides some challenges in weed control measures (Figure 3). The retention of residues creates an artificial emergence depth for crop seedlings that requires extended hypocotyls *e.g.* canola (Bruce *et al.* 2006b) and the micro-environment can be 2-3 °C colder in winter, both of which can reduce the vigour of emerging crop seedlings relative to that of the competing weeds (Bruce *et al.* 2006a).



Figure 3. The presence of cereal stubble interfering with the capability of canola seedlings to establish at Harden NSW (Bruce *et al.* 2006c)

Crop residues act as a physical barrier and can intercept and absorb a large proportion of soil active herbicides which reduces the quantity reaching the soil surface and can compromise the efficacy on weed populations (Banks and Robinson 1982, Chauhan *et al.* 2006c). This absorbed herbicide may also be released later from the degrading stubbles to impact on subsequent susceptible crops (*e.g.* Pratley 1992).

A seedbank focus for annual weed control The impact of weeds on crops is largely a function of numbers – depleting the seedbank is an obvious management tactic to restrict crop weed infestations (Buhler *et al.* 1997). While the methods by which farmers address the weed challenge have evolved in conjunction with the adoption of CA, the dominant weeds of Australian cropping systems are annual species that are reliant on a viable seedbank for persistence and interference in annual cropping systems. Similar to the approaches used in previous, less conservative systems, weed management programs in conservation cropping systems remain focussed on practices aimed at depleting weed seedbanks. In general, seedbanks are depleted by minimising recruitment and by encouraging seedbank decline. Alternatively, some weed species can be encouraged to germinate by a light cultivation of the surface soil. In winter crops, annual ryegrass and fumitory respond in this way enabling control through a follow-up herbicide or further cultivation at the seedling stage prior to sowing. In CA, cultivation has been discouraged but occasional strategic tillage may be helpful (see Chapter 7)

Impact of reduced tillage In NT systems, most weed seeds remain on or near the soil surface after crop planting. Vertical weed seed distribution in these systems is mainly influenced by sowing depth and the type of sowing points. In a southern Australian study, a NT system retained 56% of annual ryegrass seeds in the top 1 cm soil layer, whereas only 5% seeds were found in this layer in a CT system (Chauhan *et al.* 2006b). The adaptation to NT also changed the weed spectrum with Paterson's curse (*Echium plantagineum*) and *Vulpia* spp. (Forcella 1984) apparently better adapted to the lack of soil disturbance, but fumitory and to some extent annual ryegrass (Pratley 1995) for a time were less-well adapted. The differential seed distribution in the soil profile can affect weed population dynamics by affecting soil temperature, soil moisture, light conditions and predator activity (Buhler 1997). Seeds present on or near the soil surface are prone to predation and rapid decay due to unfavourable weather conditions (Mohler 1993). Higher levels of decay have been reported for seeds present on the soil surface compared with buried seeds (Chauhan *et al.* 2006a), suggesting CA systems provide the opportunity to deplete the seed bank more rapidly.

CT systems favour larger-seeded weed species that can emerge from depths of >5 cm, while small-seeded species are favoured by NT as more seeds are at or near the soil surface. Some of the favoured weed species are African turnip weed, common sowthistle, feathertop Rhodes grass, flaxleaf fleabane, Indian hedge mustard and windmill grass. Small-seeded species commonly have a light requirement for germination and so those seeds present on the soil surface in NT systems are prone to germination in response to the break in the season. Where available, a light irrigation could be used to stimulate weed seed germination. Emerged seedlings can then be killed using a non-selective herbicide prior to crop planting. Hard-seeded species, such as marshmallow and bladder ketmia, generally require scarification to germinate. These species have an impermeable seed coat, which increases their persistence if buried in the soil. In NT systems, seeds present on the soil surface experience fluctuating temperature and moisture conditions to make seedcoats brittle, thereby helping to break dormancy in hard-seeded species. Fire can also break dormancy and stimulate germination in hard-seeded species. The seed bank of hard-seeded species potentially can be depleted faster in CA systems compared with CT systems.

Weed seeds present on or near the soil surface are also susceptible to seed predators (Hulme 1994, Norton 2003) and environmental damage (*e.g.* Moore *et al.* 2014 with annual ryegrass). In WA, an average of 48% predation was reported for annual ryegrass, wild oats and wild radish, – higher for annual ryegrass than the other two species (Spafford Jacob *et al.* 2006). Seed size and ease of consumption were suggested as possible factors influencing predator preference. In an earlier study, predation of awned barnyard grass (*Echinochloa crus-galli*) reduced seedbank inputs from 2000 to less than 400 seeds/m² (Cromar *et al.* 1999). The type and amount of crop residue may affect seed predation. A Canadian study showed seed predation was higher in maize residue (31%) compared with wheat (21%) and soybean (24%) residues (Cromar *et al.* 1999). The authors suggested the type of residue was

more important than total residue biomass. However, a WA study concluded that residue cover *per se* did not affect seed predation but suggested that management practices that increased the activity of seed predators (e.g. minimising tillage and insecticide use and retention of standing crop stubble) could be incorporated into an integrated weed management program (Spafford Jacob *et al.* 2006). When combined with other weed control tools, seed predation and seed decay in conjunction with NT may help to minimise herbicide use, risk and costs (Westerman *et al.* 2003) by reducing the seed bank and density of weed seedlings emerging in the following season.

The need for alternative weed management options

Herbicidal weed control has been fundamental to the success of Australian conservation cropping systems over the last three decades. However, a lack of effective herbicides now threatens the viability of these systems. Herbicide resistance (Boutsalis *et al.* 2012, Broster *et al.* 2013a, Owen *et al.* 2015b) and the restricted introduction of new herbicides (Duke 2012) have combined to severely restrict the availability of effective herbicide options for weed control in Australian cropping. There is an urgent need for alternative weed control technologies and approaches suitable for use in these systems (Walsh 2017).

Routine weed control options for conservation cropping systems

At present there are very few alternatives to herbicides that can be routinely used to control weeds in conservation cropping systems. The options that are available, crop competition and harvest weed seed control, are inferior to herbicides and, therefore, need to be used together and in conjunction with other weed management treatments, principally herbicides.

Enhanced crop competition through agronomic manipulation Crop competition is a pragmatic approach to manage problematic weeds, especially herbicide-resistant weeds. In the absence of control, weeds compete with crops for essential resources (Roush and Radosevich 1985). Enhancing crop competition improves resource use (water, nutrients and light) by the crop. Although crop competition occurs throughout the growing season, enhancing the competitive effects of crops are predominantly implemented at sowing. Agronomic practices such as seed size, seeding rate, row spacing, row orientation, crop cultivar (see later), and fertiliser placement can all be adjusted to ensure establishing crop seedlings have a competitive advantage over the weeds (Lemerle *et al.* 2001, Blackshaw 2004, Lemerle *et al.* 2004, Yenish and Young 2004, Zerner *et al.* 2008, Borger *et al.* 2009, Lutman *et al.* 2013, Andrew *et al.* 2015). Enhanced crop competition offers the potential for substantial weed control advantages and, importantly, yield increases. In Australia, increased crop competition through higher wheat plant densities (150 to 200 plants/m²) has consistently resulted in substantial (>50%) reductions in growth and seed production of the dominant weed species, annual ryegrass (Lemerle *et al.* 2004), wild radish (Walsh and Minkey 2006), wild oats (Radford *et al.* 1980) and brome grass (Gill *et al.* 1987). Typically, enhanced wheat crop competition through an increase in plant densities has a positive impact on grain yield without compromising grain quality (Anderson *et al.* 2004). Similarly, the use of narrow row spacing improves crop-weed competition in favour of the crop by developing faster canopy cover and allowing less light penetration through its leaves. Likewise, changing the row orientation may help to enhance crop-weed competition and suppress problematic weeds.

Enhanced crop competition cannot be considered a standalone weed control treatment. When combined with other weed control practices, the additional impact on weed populations can be critical for weed control. For example, enhanced wheat crop competition routinely increase the efficacy of selective herbicides in controlling crop-weed populations (Kim *et al.* 2002). Importantly, this competition can lead to the control of weed populations that are resistant to the applied herbicide. For example, a 2,4-D resistant wild radish population was controlled when 2,4-D was applied at the recommended rate to resistant plants present within a competitive wheat crop (Walsh *et al.* 2009). As well as complementing herbicide activity, enhanced crop competition will likely improve the efficacy of harvest weed seed control (HWSC) strategies (Walsh *et al.* 2018a). Annual weed species infesting global wheat production systems are typically not shade tolerant (Gommers *et al.* 2013) and as indicated from competition studies, grow poorly when shaded (Zerner *et al.* 2008).

When competing with wheat for light, the likely response for shade intolerant weed species is a more upright growth habit (Morgan *et al.* 2002, Vandenbussche *et al.* 2005). This erect growth habit will undoubtedly lead to higher proportions of total seed production being located above harvester cutting height and increasing subsequent exposure to HWSC methods. Clearly then, the combined benefits of higher yield potential and enhanced weed control ensure that agronomic weed management should be standard practice throughout global wheat production systems.

Harvest weed seed control The biological attribute (weakness) of seed retention at maturity in annual ryegrass, wild radish and other annual weed species means that, at crop maturity, seed heads remain intact and at a height that enables weed seeds to be ‘harvested’ during grain crop harvest (Figure 4). For example, in field crops a large proportion (~60-100%) of the total seed production of the dominant annual weed species, annual ryegrass, wild radish, brome grass and wild oats can be collected during grain harvest (Blanco-Moreno *et al.* 2004, Walsh and Powles 2014, Walsh *et al.* 2018a). The efficient operation of a grain harvester expels the collected weed seed from the harvester, typically in the chaff fraction of harvest residues (Broster *et al.* 2016). Innovative Australian growers recognised the weed control opportunity of collecting the weed seeds to prevent the replenishment of weed seed banks. Subsequently, harvest weed seed control (HWSC) systems have been developed to destroy weed seeds during commercial grain crop harvest (Walsh *et al.* 2013). These include:

- chaff collection and subsequent burning;
- grazing or mulching (chaff cart);
- concentration in a narrow windrow with straw residues for subsequent burning (narrow windrow burning) (Walsh and Newman 2007);
- concentration of chaff into narrow rows (chaff lining);
- chaff collected and baled along with straw residues (Bale Direct System); and
- mechanical destruction during harvest (integrated Harrington Seed Destructor and Seed Terminator) (Walsh *et al.* 2012, 2018) (Figure 5).



Figure 4. Upright and intact annual ryegrass seed heads in mature cereal crop

HWSC is an established and effective weed control practice with Australian crop producers. It is estimated that almost one-third of Australian growers routinely use some form of HWSC to target their crop weed problems. However, although these systems have proven their efficacy on annual ryegrass and wild radish (Walsh *et al.* 2013) their efficacy on the other dominant weed species of Australian cropping, *i.e.* wild oats and brome grass, may be limited by poor seed retention at crop harvest (Walsh and Powles 2014). Given that HWSC is now a routine form of weed control, the challenge for researchers and the industry is to increase the efficacy of these systems for other weed species.



Figure 5. Current forms of harvest weed seed control (A) chaff cart, (B) narrow windrow burning, (C) bale direct system, (D) impact mill, (E) chaff lining and (F) chaff tramlining

Strategic weed control options

The strategic approach involves the use of a highly disruptive technique when weed populations reach a pre-determined critical level (*e.g.* >5.0 plant/m²) where the aim is for maximum impact on these populations over the shortest period of time. In all weed management programs, there will be instances when weed densities increase to a level that places undue pressure on the sustainability of weed control practices as well as the production system. The greatest influence on weed control efficacy is climate and there is a wide range of seasonal conditions that can reduce the efficacy of weed control practices (*e.g.*, drought, waterlogging, frost, high temperatures). Because the threat of resistance evolution to all weed control practices increases with increasing weed densities then a major, disruptive weed control tactic is required that quickly delivers substantially lower weed numbers. When the weed population is markedly lower (*e.g.* <1 plant/10 m²) regular crop production, including the use of routine control practices, can be resumed.

Hay, silage, manure crops and pasture phases Excessively high weed populations and the absence of effective in-crop herbicide treatments can force growers to move away from continuous cropping for one or more years enabling the use of more vigorous approaches to reduce a weed population. Techniques such as hay, silage (Gill and Holmes 1997) or manure crops (Flower *et al.* 2012) can substantially reduce annual ryegrass populations, often within one season, to quickly allow the resumption of continuous cropping. Pasture management and use of livestock provide a range of options to achieve this including spray-grazing for broadleaf weed control, spray-topping of pastures for grass

weed control, pasture cleaning with paraquat or simazine (*e.g.* for *Vulpia* spp. control) in the season or two before the cropping phase, or some form of fodder conservation (hay or silage). Timing of fodder conservation can be critical to determine impact on subsequent weed population. Bowcher (2002) at Wagga Wagga in southern NSW showed that, in pastures containing *Vulpia* spp., Paterson's curse and annual ryegrass, cutting times were critical to determine weed control. An early spring cut minimised *Vulpia* spp. regrowth and seed rain whereas the other two species continued to grow and produce seed. Cutting later in the spring reduced the regrowth and seed rain of these species.

Fallow phase, cover crops and mulches Implementing a season-long fallow phase provides the opportunity to reduce weed populations significantly, typically through herbicide use, as well as to conserve soil moisture and provide a disease break (Dolling *et al.* 2006, Passioura and Angus 2010, Hunt and Kirkegaard 2011). This practice is particularly popular across the marginal rainfall areas of Australia's cropping regions where soil moisture storage is the priority during this phase (Hunt *et al.* 2013). Weeds present during the fallow phase can use significant amounts of soil moisture and so weed control throughout this period is imperative to maximise soil water storage (Hunt *et al.* 2009). Available nitrogen levels typically increase during this phase and contribute to significant yield responses in following crops (Hunt *et al.* 2013). As weeds can also benefit from the increased availability of nitrogen during the fallow phase, they must be controlled to ensure the crop yield responses. Weeds in fallow phases host crop diseases and must be removed to ensure that there is an effective 'disease break' between crops (Angus *et al.* 2015). In conservation cropping systems, tillage is not a desirable option for weed control in fallow phases: herbicides, specifically glyphosate, is relied on for weed-free fallow phases. The consequence is the widespread evolution of glyphosate resistance in several weed species (as described above) particularly in areas where fallows are a common component of cropping rotations, *e.g.* summer fallows in northern NSW and southern Qld.

Cover crops are established at the start of a fallow phase (short or long) to provide soil surface cover and replace lost biomass (Bolliger *et al.* 2006, Ruis and Blanco-Canqui 2017). Cover crop species are selected for their ability to cover the soil surface quickly as well as to produce large quantities of biomass (Fageria *et al.* 2005). Depending on the growing season and available soil moisture, cover crops are typically terminated by mowing, rolling or with herbicides well before planting a subsequent major crop (Creamer and Dabney 2009). The resulting mulch cover can suppress weed germination and emergence (Mohler and Teasdale 1993, Chauhan *et al.* 2012, Latif *et al.* 2019). In WA, black oat (*Avena strigosa* Schreb.) used as a cover crop suppressed growth of several weeds, including annual ryegrass (Flower *et al.* 2012). High biomass-producing cover crops as mulch can be a useful tool for weed suppression in CA systems (Fleet *et al.* 2018). Crops with allelopathic properties could also provide substantial weed suppression (Putnam and DeFrank 1983, Holmes *et al.* 2017). Sorghum (*Sorghum bicolor* L.), for example, releases the allelochemical sorgoleone and therefore, could be used successfully as a cover crop in CA systems (Dayan *et al.* 2010, Lee and Thierfelder 2017). Residue retention as part of CA practices could help reduce weed infestations although higher quantities than normally found in Australian dryland cropping systems are needed to substantially suppress weed germination. The use of water and N, otherwise available to the subsequent crop must be considered when contemplating the use of cover crops in semi-arid environments such as Australia.

Strategic Tillage Initially, tillage was used routinely to improve conditions for crop establishment and weed control. However, the advent and successful adoption of NT systems incorporating chemical weed control demonstrated that tillage is unnecessary for weed control (Zimdahl 2013). The greater reliance on herbicides, however, increases the prospect of herbicide-resistant weeds in these NT systems. In Australia, for example, *L. rigidum*, *Sonchus oleraceus*, *R. raphanistrum*, *Echinochloa colona*, *Conyza bonariensis*, and *Urochloa panicoides* have already evolved resistance to glyphosate (Heap 2019). However, despite the risk of evolution of herbicide resistance, these highly productive NT cropping systems need to be sustained. Strategic tillage has thus been receiving great attention among researchers and farmers in several countries, including Australia (Kirkegaard *et al.* 2014, Dang *et al.* 2015, Melander *et al.* 2015, Renton and Flower 2015, see also Chapter 7).

A strategic deep tillage used occasionally, once every 5-10 years, as a whole field or targeted at weed patches can reduce weed seedling emergence. The aim of this approach is to bury the weed seeds to a

depth from which they cannot emerge (Cussans and Moss 1982) and is particularly effective against smaller weed species that cannot emerge from relatively shallow depths of burial (*i.e.* >5 cm) and have a short seedbank life. In the northern cropping region of Australia, lower densities of *C. bonariensis*, *R. raphanistrum*, *Rapistrum rugosum* and *Avena fatua* were reported in the first year following a strategic chisel tillage operation (Crawford *et al.* 2015). Similarly, another study in Queensland reported 61-90% reduced emergence of *Chloris virgata*, *Chloris truncata* and *C. bonariensis* after occasional tillage with harrow, gyral and offset discs compared with a NT system (McLean *et al.* 2012).

Mouldboard ploughing has also been re-considered. Here soil inversion buries the shallow weed seed banks established under long-term conservation cropping systems to a depth from which there is no emergence (*i.e.* >30 cm, Reeves and Smith 1975, Code and Donaldson 1996). Prior to the widespread adoption of conservation cropping practices, mouldboard ploughing was routinely used for weed control across the world's cropping regions (Mas and Verdú 2003, Ozpinar 2006, Cirujeda and Taberner 2009, Lutman *et al.* 2013). Strategic mouldboard ploughing is now being used as an effective weed control practice to target weed seed banks in conservation wheat production systems. An occasional tillage of the whole field can be a useful weed control technique and when used sparingly the positive effects of NT systems on soil condition can be retained (Dang *et al.* 2015). The strategic disruptive weed control, although a major interference to crop production, reduces the selection pressure on routine chemical control practices with the aim of preserving their use for the long term. This is discussed further in Chapter 8.

Development of additional weed control opportunities

Competitive crop cultivars Cereal species and varietal differences in crop competitiveness with weeds has provided the impetus to use breeding for genetic improvement of in-crop weed control (Andrew *et al.* 2015). In wheat, comparisons across an historic 100-year set of varieties highlighted that older varieties were more competitive with weeds (Vandeleur and Gill 2004) presumably reflecting selection for improved performance in the absence of in-crop herbicides. Overseas studies have demonstrated a reduction in herbicide use of up to 50% when using weed-competitive wheats (Travlos 2012, Andrew *et al.* 2015): a broader benefit is the integration of competitive varieties with cultural management (*e.g.* weed seed harvest and tillage) to reduce herbicide use and slow herbicide resistance.

Competitiveness can be considered as the partial-to-complete suppression of competing weeds to increase crop yield, or the ability of a variety to tolerate a competitor to maintain higher yields. Selection for greater tolerance of pests is a breeding strategy used for many crop insects and diseases but is of less value in weed management owing to the ongoing growth and development of the weed, and release of seed into the weed bank. Breeding of competitive crops has focused on selection of genotypes with improved access to light, water and nutrients which suppresses the growth of neighbouring weeds (Worthington *et al.* 2015). However, owing to the complex nature of plant-to-plant competition, weed suppression as a breeding strategy will likely require integration across multiple traits (Andrew *et al.* 2015). Greater early vigour, rapid leaf area development and biomass at stem elongation and altered root architecture are mechanisms used in natural plant communities (Aerts 1999). Root exudates are also used in plant defence to slow the growth of neighbouring competitors (Belz 2007).

In targeting traits of weed-competitive crop varieties, genetic modification of below-ground growth is slow and challenging owing to low heritability (*i.e.* correlation of phenotype with the underlying genotype) and difficulty in phenotyping large populations (Wasson *et al.* 2014). The simplest approach is selection for more rapid early growth as this can be done quickly and inexpensively in large breeding populations with visual assessments of leaf size (Rebetzke and Richards 1999), LiDAR-based biomass, and Greenseeker®-based NDVI and percentage ground cover (Jimenez-Berni *et al.* 2018). Particular quantitative trait loci (QTL) have also been linked to genes associated with greater early vigour and weed competitiveness in marker-assisted selection (Coleman *et al.* 2001).

In cereals, greater leaf size and rapid early leaf area development are associated with larger seed embryos, higher specific leaf area, and use of gibberellin-sensitive dwarfing genes to reduce stem height (Rebetzke *et al.* 2004, 2014). Unfortunately, commercial wheat varieties selected for increased yield

potential are ubiquitously conservative for early growth. A global survey identified 30 wide-leaved, wheat donors subsequently used in an S1 recurrent selection program to accumulate favourable genes to increase early vigour (see Chapter 17). High vigour lines derived from this program have been used to develop wheats with capacity to suppress the growth of ryegrass by up to 50% (Zerner *et al.* 2016). Ongoing breeding with these and other sometimes displaced genetic resources including landraces will be of significant value in selection away from traditional breeding objectives (*e.g.* yield potential, Rebetzke *et al.* 2018). A focus on breeding lines that are higher-yielding but also profitable and environmentally sustainable, such as occurs with weed-competitive crops, will require broader consideration of traits and alleles not present in existing breeding populations.

Impact of crop residues on weeds In stubble retention systems the role of the crop residue needs to be considered for its impact on weed establishment in subsequent crops. In the USA, Russian vetch (*Vicia villosa*) and rye (*Secale cereal*) residues were found to reduce weed density by more than 75% compared with the no-residue treatment (Mohler and Teasdale 1993). In a recent pot study in Queensland, the addition of 6 t/ha of wheat residue reduced the emergence of African turnip weed (*Sisymbrium thellungi* O.E. Schulz) by 64-75% compared with no residue (Mahajan *et al.* 2018). In similar studies, sorghum and wheat residue retention on the soil surface reduced seedling emergence of windmill grass (*Chloris truncata*) and common sowthistle, respectively (Chauhan *et al.* 2018, Manalil *et al.* 2018). Other studies have shown that the variety of the residue can determine which weeds are impacted and the effect can be influenced by seasonal conditions prior to germination (J Pratley, unpublished). The break in the season at germination time is likely to cause a bigger effect. As well as reducing weed seedling emergence, residue retention may also delay seedling emergence (Chauhan and Abugho 2013). Late emerging weed seedlings would be at a competitive disadvantage relative to the crop and thus have less impact on crop growth.

Self-weeding capability Plants have the capability to control their competition by exuding a range of chemicals into the soil environment, a process called allelopathy. Sorghum (*Sorghum bicolor*), for example, releases the allelochemical sorgoleone and therefore can be successfully used as a cover crop in CA systems (Dayan *et al.* 2010, Lee and Thierfelder 2017). Some chemicals from allelopathy have been developed as commercial herbicides (*e.g.* Callisto™ in North America and now Australia) thereby demonstrating their potency and selectivity.

While much literature exists on allelochemicals and their capability, little has been done to take advantage of them commercially (Rice 1979, Wu *et al.* 2001, Asaduzzaman *et al.* 2014). In China, allelopathic rice varieties are now commercially available (Kong *et al.* 2011) and this capability is being incorporated into rice varieties in the US (Gealy *et al.* 2014).

In most crop species, allelopathic capability has largely been bred out of commercial varieties: Bertholdsson (2004) showed for barley that capabilities of landrace lines were significantly higher in bioactivity than are modern varieties. However, some breeding lines do retain allelopathic capability but this has not been evaluated, as these lines are developed under weed free conditions and are commercially grown with the support of herbicides.

In Australia, the range of allelopathic capability of genotypes on weed species has been shown in wheat (Wu *et al.* 2001) and rice (Seal *et al.* 2004). Asaduzzaman *et al.* (2014) also showed that canola varieties had a range of allelopathic impacts (Figure 6) with consistent results in field trials over three seasons (Figure 7). It remains to be seen whether herbicide resistance will cause a rethink on the commercial possibilities of the self-weeding capabilities in crop varieties.

Mechanical weed control The opportunity for substantial cost savings, combined with the potential for introducing novel weed control technologies, is driving the demand for site-specific weed management control. However, this approach requires suitable weed detection and identification technologies that currently are not commercially available for in-crop use. The options available are based on spectral reflectance that with reasonable accuracy detect green leaf material (Scotford and Miller 2005). These systems are not suitable for in-crop use but have been successfully used for many years to control weeds in fallows. Another limitation to the adoption of site-specific weed management is that this approach

only becomes economically viable once low weed densities (<1 plant/m²) have been achieved. However, a strong focus on weed control efficacy driven by diminishing herbicide resources is helping to deliver lower than ever weed population densities in Australian dryland cropping systems. For example, in-crop wild radish populations across many areas of the WA wheat belt are well below 1 plant/10 m² with some farmers opting to hand weed areas in preference to applying herbicides. Thus, for these growers the demand is now for effective site-specific weed management systems.

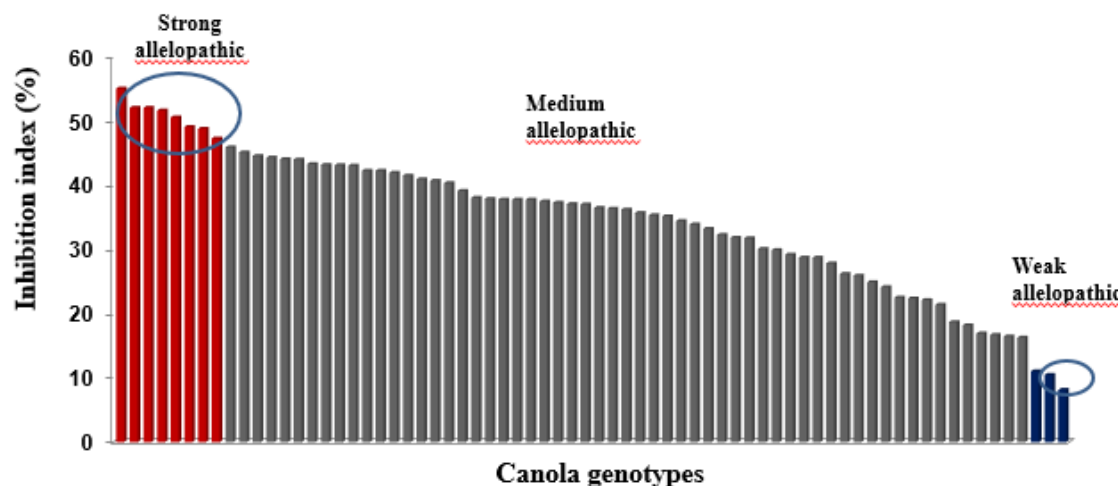


Figure 6. Inhibition index of 80 canola genotypes on root length of annual ryegrass (Asaduzzaman *et al.* 2014) with strongly allelopathic lines to the left and poorly allelopathic lines to the right



Figure 7. Impact of highly allelopathic canola genotype, Av-Opal (Left), and a poorly allelopathic genotype, Barossa (Right), on weed control (Asaduzzaman *et al.* 2014).

In low weed density situations, because of the small areas involved, and therefore the reduced impact on crop yields, detected weeds can be aggressively targeted with significant cost savings. For example, non-selective herbicides, tillage treatments, even hand weeding all become viable options. Additionally, the ability to strategically target low weed densities creates the potential for the introduction of more novel and unique weed control technologies such as electrocution (Vigneault *et al.* 1990), flaming (Bond *et al.* 2007, Hoyle *et al.* 2012), microwaves (Brodie *et al.* 2012), infrared (Ascard 1998) and lasers (Marx *et al.* 2012). There is now considerable investment in weed identification and mapping on many fronts, ranging from vehicle-mounted to UAV and even satellite systems.

The opportunity to use of range of alternate control tactics on low density weed populations within a crop is reliant on accurate detection, identification and characterisation (*i.e.* weed type, species, growth stage of the weeds). Several studies have highlighted the potential for site-specific weed control where weed detection and mapping have been separated from weed control (López-Granados 2011, Berge *et al.* 2012, de Castro *et al.* 2012).

Summary

Weed control in Australian cropping systems has undergone more dramatic changes in the last three decades than during the previous history of crop production in Australia. This period commenced with the herbicide revolution where introductions of highly effective selective and non-selective herbicides were providing excellent control of the dominant cropping weeds. These herbicides facilitated the adoption of CA and the end of tillage-based weed control systems. However, in the late 1980s there were reports of herbicide resistance, principally in annual ryegrass populations collected from intensively cropped fields. These cases heralded the start of a proliferation of herbicide resistant weed populations throughout the entire Australian cropping region during the 1990s and 2000s. The extent and severity of this phenomenon dramatically changed forever weed management and cropping practices across this region, such that from the 2000s onwards the focus has been on the conservation of diminishing herbicide resources and the development of alternative weed control technologies.

The introduction and adoption of HWSC combined with a renewed focus on crop competition have reduced somewhat the selection pressure on the few remaining herbicide resources. These combined with ‘intervention type’ weed control options for when weed populations begin to escalate have allowed growers, for the time being, to continue with conservation cropping systems. The challenge remains though for the development of highly effective alternatives to herbicides for routine use in these production systems. As we move into the next era, the expectation is that advancements in sensing, vision and computing technologies will deliver site-specific control capabilities and the potential for the use of an array of alternate approaches to weed control.

References

- ABARES (2019) ‘Australian Commodity Statistics.’ Available at <http://www.daff.gov.au/abares>
- Aerts R (1999) Interspecific competition in natural plant communities: mechanisms, trade-offs and plant-soil feedbacks. *Journal of Experimental Botany* **50**, 29-37
- Anderson WK, Sharma DL, Shackley BJ, D’Antuono MF (2004) Rainfall, sowing time, soil type and cultivar influence optimum plant population for wheat in Western Australia. *Australian Journal of Agricultural Research* **55**, 921-930
- Andrew IKS, Storkey J, Sparkes,DL (2015) A review of the potential for competitive cereal cultivars as a tool in integrated weed management. *Weed Research* **55**, 239-248
- Angus JF, Kirkegaard JA, Hunt JR *et al.* (2015) Break crops and rotations for wheat. *Crop and Pasture Science* **66**, 523-552
- Asaduzzaman M, Pratley JE, An M, Luckett DJ, Lemerle D (2014) Canola interference for weed control. *Springer Science Reviews* **2**, 63-74
- Ascard (1998) Comparison of flaming and infrared radiation techniques for thermal weed control. *Weed Research* **38**, 69-76
- Banks PA, Robinson EL (1982) The influence of straw mulch on the soil reception and persistence of metribuzin. *Weed Science* **30**, 164-168
- Belz R (2007) Allelopathy in crop/weed interactions — an update. *Pest Management Science* **63**, 308-326
- Berge TW, Goldberg S, Kaspersen K, Netland J (2012) Towards machine vision based site-specific weed management in cereals. *Computers and Electronics in Agriculture* **81**, 79-86
- Bertholdsson NO (2004) Variation in allelopathic activity over 100 years of barley selection and breeding. *Weed Research* **44**, 78-86
- Blackshaw RE (2004) Application method of nitrogen fertilizer affects weed growth and competition with winter wheat. *Weed Biology and Management* **4**, 103-113
- Blanco-Moreno JM, Chamorro L, Masalles RM *et al.* (2004) Spatial distribution of *Lolium rigidum* seedlings following seed dispersal by combine harvesters. *Weed Research* **44**, 375-387
- Bolliger A, Magid J, Amado JCT *et al.* (2006) Taking stock of the Brazilian “Zero-Till Revolution”: A review of landmark research and farmers’ practice. *Advances in Agronomy* **91**, 47-110

- BOM (2019) Bureau of Meteorology Weather and Climate Statistics www.bom.gov.au
- Bond W, Davies G, Turner RJ (2007) A review of thermal weed control. (HDRA, Coventry, UK: Ryton Organic Gardens)
- Borger CPD, Hashem A, Pathan S (2009) Manipulating crop row orientation to suppress weeds and increase crop yield. *Weed Science* **58**, 174-178
- Boutsalis P, Gill GS, Preston C (2012) Incidence of herbicide resistance in rigid ryegrass (*Lolium rigidum*) across southeastern Australia. *Weed Technology* **26**, 391-398
- Boutsalis P, Kleemann SGL, Gill GS, Preston CM (2014) A hidden threat: widespread Group B herbicide resistance in brome across south-eastern Australia. *Proceedings of 19th Australasian Weeds Conference* Hobart, Tasmania www.caws.org.au/awc/2014/awc201412021.pdf
- Bowcher, AJ (2002) Competition between temperate perennial pasture species and annual weeds: the effect of pasture management on population dynamics and resource use. PhD thesis, Charles Sturt University, Wagga Wagga
- Brodie G, Ryan C, Lancaster C (2012) Microwave technologies as part of an integrated weed management strategy: A review. *International Journal of Agronomy* **2012**, Article ID 287608,14
- Broster JC, Koetz EA, Wu H (2011a) Herbicide resistance in wild oats (*Avena* spp.) in southern New South Wales. *Plant Protection Quarterly* **26**, 106-110
- Broster JC, Koetz EA, Wu H (2011b) Herbicide resistance levels in annual ryegrass (*Lolium rigidum* Gaud.) in southern New South Wales. *Plant Protection Quarterly* **26**, 22-28
- Broster JC, Koetz EA, Wu, H (2012) Weed species present in cereal crops in southern New South Wales. *Proceedings of 18th Australasian Weeds Conference*. Melbourne, Vic
- Broster JC, Koetz EA, Wu H (2013a) Herbicide resistance levels in annual ryegrass (*Lolium rigidum* Gaud.) and wild oat (*Avena* spp.) in southwestern New South Wales. *Plant Protection Quarterly* **28**, 126-132
- Broster JC, Koetz EA, Wu H (2013b) Herbicide resistance levels in annual ryegrass (*Lolium rigidum* Gaud.) and wild oats (*Avena* spp.) in south-western New South Wales. *Plant Protection Quarterly* **28**, 126-132
- Broster JC, Pratley JE (2006) A decade of monitoring herbicide resistance in *Lolium rigidum* in Australia. *Australian Journal of Experimental Agriculture* **46**, 1151-1160
- Broster JC, Walsh MJ, Chambers AJ (2016) Harvest weed seed control: the influence of harvester set up and speed on efficacy in south-eastern Australia wheat crops. *Proceedings of 20th Australasian Weeds Conference*. Perth, WA 38-41 www.caws.org.au/awc/2016/awc201610381.pdf
- Broster JC, Pratley JE, Ip RH *et al.* (2019) A quarter of a century of monitoring herbicide resistance in *Lolium rigidum* in Australia. *Crop and Pasture Science* **70**, 283-293
- Bruce SE, Kirkegaard JA, Pratley J, Howe G (2006a) Growth suppression of canola through wheat stubble I. Separating physical and biochemical causes in the field. *Plant and Soil* **281**, 203-218
- Bruce SE, Ryan MH, Hely S *et al.* (2006b) Growth suppression of canola through wheat stubble II. Investigating impacts of hypocotyl elongation using simulated stubble. *Plant and Soil* **281**, 219-231
- Bruce SE, Ryan MH, Kirkegaard JA, Pratley J (2006c) Improving the performance of canola in retained wheat stubble. *Australian Journal of Agricultural Research* **57**, 1203-1212
- Brunton DJ, Boutsalis P, Gill GS, Preston C (2018) Resistance to multiple PRE herbicides in a field-evolved rigid ryegrass (*Lolium rigidum*) population. *Weed Science* **66**, 581-585
- Buhler DD (1997) Effects of tillage and light environment on emergence of 13 annual weeds. *Weed Technology* **11**, 496-501
- Buhler DD, Hartzler RG, Forcella F (1997) Implications of weed seedbank dynamics to weed management. *Weed Science* **45**, 329-336
- Burnet MWM, Hildebrand OB, Holtum JAM, Powles SB (1991) Amitrole, triazine, substituted urea, and metribuzin resistance in a biotype of rigid ryegrass (*Lolium rigidum*). *Weed Science* **39**, 317-323
- Chauhan BS, Abugho SB (2013) Effect of crop residue on seedling emergence and growth of selected weed species in a sprinkler-irrigated zero-till dry-seeded rice system. *Weed Science* **61**, 403-409
- Chauhan BS, Gill G, Preston C (2006a) Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (*Lolium rigidum*) seed bank. *Weed Science* **54**, 669-676
- Chauhan BS, Gill G, Preston C (2006b) Seedling recruitment pattern and depth of recruitment of 10 weed species in minimum tillage and no-till seeding systems. *Weed Science* **54**, 658-668
- Chauhan, BS Gill, GS Preston C (2006c) Tillage system effects on weed ecology, herbicide activity and persistence: A review. *Australian Journal of Experimental Agriculture* **46**, 1557-1570
- Chauhan BS, Manalil S, Florentine S, Jha P (2018) Germination ecology of *Chloris truncata* and its implication for weed management. *PLoS ONE* **13**, e0199949
- Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture: A review. *Crop Protection* **38**, 57-65
- Cirujeda A, Taberner A (2009) Cultural control of herbicide-resistant *Lolium rigidum* Gaud. populations in winter cereal in Northeastern Spain. *Spanish Journal of Agricultural Research* **7**, 146-154

- Code GR, Donaldson TW (1996) Effect of cultivation, sowing methods and herbicides on wild radish populations in wheat crops. *Australian Journal of Experimental Agriculture* **36**, 437-442
- Coleman RK, Gill GS, Rebetzke GJ (2001) Identification of quantitative trait loci for traits conferring weed competitiveness in wheat (*Triticum aestivum* L.). *Australian Journal of Agricultural Research* **52**, 1235-1246
- Crawford MH, Rincon-Florez V, Balzer A *et al.* (2015) Changes in the soil quality attributes of continuous no-till farming systems following a strategic tillage. *Soil Research* **53**, 263-273
- Creamer NG, Dabney SM (2009) Killing cover crops mechanically: Review of recent literature and assessment of new research results. *American Journal of Alternative Agriculture* **17**, 32-40
- Cromar HE, Murphy SD, Swanton CJ (1999) Influence of tillage and crop residue on postdispersal predation of weed seeds. *Weed Science* **47**, 184-194
- Cussans GW, Moss SR (1982) Population dynamics of annual grass weeds. In (Ed. D Farnham) "Brighton Crop protection symposium-Decision Making for the Practice of Crop Protection" Brighton, UK pp 91-98 (BCPC)
- Cuthbertson EG (1967) Skeleton weed: distribution and control. Bulletin 68:(NSW Dept of Agriculture)
- D'Emden FH, Llewellyn RS, Burton MP (2008) Factors influencing adoption of conservation tillage in Australian cropping regions. *Australian Journal of Agricultural and Resource Economics* **52**, 169-182
- Dang YP, Moody PW, Bell MJ *et al.* (2015) Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: II. Implications for agronomy, soil and environment *Soil and Tillage Research* **152**, 115-123
- Dayan FE, Rimando AM, Pan Z *et al.* (2010) Sorgoleone. *Phytochemistry* **71**, 1032-1039
- de Castro AI, Jurado-Expósito M, Peña-Barragán JM, López-Granados F (2012) Airborne multi-spectral imagery for mapping cruciferous weeds in cereal and legume crops. *Precision Agriculture* **13**, 302-321
- Dolling PJ, Fillery IRP, Ward PR *et al.* (2006) Consequences of rainfall during summer/autumn fallow on available soil water and subsequent drainage in annual-based cropping systems. *Australian Journal of Agricultural Research* **57**, 281-296
- Donald CM (1965) The progress of Australian agriculture and the role of pastures in environmental change. *Australian Journal of Science* **27**, 187-198
- Duke S (2012) Why have no new herbicide modes of action appeared in recent years? *Pest Management Science* **68**, 505-512
- Fageria NK, Baligar VC, Bailey BA (2005) Role of cover crops in improving soil and row crop productivity. *Communications in Soil Science and Plant Analysis* **36**, 2733-2757
- FAO (2015) "Introduction to conservation agriculture (its principles & benefits)" www.teca.fao.org/technology/introduction-conservation-agriculture-its-principles-benefits
- Fleet B, Malone, J Preston, Gill, G (2018) Target-site point mutation conferring resistance to trifluralin in rigid ryegrass (*Lolium rigidum*). *Weed Science* **66**, 246-253
- Flower KC, Cordingley N, Ward PR, Weeks C (2012) Nitrogen, weed management and economics with cover crops in conservation agriculture in a Mediterranean climate. *Field Crops Research* **132**, 63-75
- Forcella F (1984) Size and structure of silvergrass (*Vulpia* spp.) populations in direct drilled wheat. *Australian Weeds* **3**, 3-5.
- Gealy DR, Anders M, Watkins B, Duke S (2014) Crop performance and weed suppression by weed-suppressive rice cultivars in furrow- and flood-irrigated systems under reduced herbicide inputs. *Weed Science* **62**, 303-320
- Gill G, Poole M, Holmes J (1987) Competition between wheat and brome grass in Western Australia. *Australian Journal of Experimental Agriculture* **27**, 291-294
- Gill GS, Holmes JE (1997) Efficacy of cultural control methods for combating herbicide-resistant *Lolium rigidum*. *Pesticide Science* **51**, 352-358
- Gommers CMM, Visser EJW, Onge KRS *et al.* (2013) Shade tolerance: when growing tall is not an option. *Trends in Plant Science* **18**, 65-71
- Gressel J, Gassmann AJ, Owen MD (2017) How well will stacked transgenic pest/herbicide resistances delay pests from evolving resistance? *Pest Management Science* **73**, 22-34
- Heap IM (2019) 'International survey of herbicide resistant weeds.' www.weedscience.com
- Heap IM, Knight R (1986) The occurrence of herbicide cross-resistance in a population of annual ryegrass, *Lolium rigidum*, resistant to diclofop-methyl. *Australian Journal of Agricultural Research* **37**, 149-156
- Heap IM, Knight R (1990) Variation in herbicide cross-resistance among populations of annual ryegrass, *Lolium rigidum*, resistant to diclofop-methyl. *Australian Journal of Agricultural Research* **41**, 121-12
- Heap JW, Knight R (1982) A population of ryegrass tolerant to the herbicide diclofop-methyl. *Journal of the Australian Institute of Agricultural Science* **48**, 156-157
- Holmes AA, Thompson AA, Wortman SE (2017) Species-specific contributions to productivity and weed suppression in cover crop mixtures. *Agronomy Journal* **109**, 2808-2819

- Hoyle JA, McElroy JS, Rose JJ (2012) Weed control using an enclosed thermal heating apparatus. *Weed Technology* **26**, 699-707
- Hulme PE (1994) Post-dispersal seed predation in grassland: Its magnitude and sources of variation. *Journal of Ecology* **82**, 645-652
- Hunt JR, Browne C, McBeath TM *et al.* (2013) Summer fallow weed control and residue management impacts on winter crop yield though soil water and N accumulation in a winter-dominant, low rainfall region of southern Australia. *Crop and Pasture Science* **64**, 922-934
- Hunt JR, Cousens RD, Knights SE (2009) *Heliotropium europaeum* only germinates following sufficient rainfall to allow reproduction. *Journal of Arid Environments* **73**, 602-610
- Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop and Pasture Science* **62**, 915-929
- Isbell RF (2016) "The Australian Soil Classification" (Ed. RF Isbell and the National Committee on Soil and Terrain) (CSIRO Publishing: Clayton South, Vic)
- Jalaludin A, Widderick MJ, Broster JC *et al.* (2018) Glyphosate and 2,4-D amine resistance in common sowthistle (*Sonchus oleraceus*) and fleabane (*Conyza bonariensis*) in the northern grain growing region of Australia. *Proceedings of 21st Australasian Weeds Conference* Sydney, NSW
- Jimenez-Berni J, Deery D, Rozas-Larraondo P *et al.* (2018) High throughput determination of plant height, ground cover and above-ground biomass in wheat with LiDAR. *Frontiers in Plant Science* **9** doi.org/10.3389/fpls.2018.00237
- Kassam A, Friedrich T, Derpsch R *et al.* (2012) Conservation agriculture in the dry Mediterranean climate. *Field Crops Research* **132**, 7-17
- Kim DS, Brain P, Marshall EJP, Caseley JC (2002) Modelling herbicide dose and weed density effects on crop:weed competition. *Weed Research* **42**, 1-13
- Kloot PM (1983) The Genus *Lolium* in Australia. *Australian Journal of Botany* **31**, 421-435
- Kong CH, Chen XH, Hu F, Zhang SZ (2011) Breeding of commercially acceptable allelopathic rice cultivars in China. *Pest Management Science* **67**, 1100-1106
- Latif S, Gurusinghe S, Weston P *et al.* (2019) Performance and weed-suppressive potential of selected pasture legumes against annual weeds in south-eastern Australia. *Crop and Pasture Science* **70**, 147-158
- Lee N, Thierfelder C (2017) Weed control under conservation agriculture in dryland smallholder farming systems of southern Africa. A review. *Agronomy For Sustainable Development* **37**, 48
- Lemerle D, Cousens RD, Gill GS *et al.* (2004) Reliability of higher seeding rates of wheat for increased competitiveness with weeds in low rainfall environments. *Journal of Agricultural Science* **142**, 395-409
- Lemerle D, Gill GS, Murphy CE *et al.* (2001) Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. *Australian Journal of Agricultural Research* **52**, 527-548
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Llewellyn RS, Ronning, D Ouzman J *et al.* (2016) Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices. Report for GRDC (CSIRO, Australia)
- López-Granados F (2011) Weed detection for site-specific weed management: mapping and real-time approaches. *Weed Research* **51**, 1-11
- Lutman PJW, Moss SR, Cook S, Welham SJ (2013) A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*. *Weed Research* **53**, 299-313
- Mahajan G, George-Jaeggli B, Walsh M, Chauhan BS (2018) Effect of soil moisture regimes on growth and seed production of two Australian biotypes of *Sisymbrium thellungii* O. E. Schulz. *Frontiers in Plant Science* **9** doi.org/10.3389/fpls.2018.01241
- Manalil S, Ali HH, Chauhan BS (2018) Germination ecology of *Sonchus oleraceus* L. in the northern region of Australia. *Crop and Pasture Science* **69**, 926-932
- Marx C, Barcikowski, S, Hustedt M *et al.* (2012) Design and application of a weed damage model for laser-based weed control. *Biosystems Engineering* **113**, 148-157
- Mas, MT, Verdú AMC (2003) Tillage system effects on weed communities in a 4-year crop rotation under Mediterranean dryland conditions. *Soil and Tillage Research* **74**, 15-24
- Matthews GA (2018) "A history of pesticides" (CABI: Boston, USA)
- McAlister FM, Holtum JAM, Powles SB (1995) Dintroaniline herbicide resistance in rigid ryegrass (*Lolium rigidum*). *Weed Science* **43**, 55-62
- McLean AR, Widderick MJ, Walker SR (2012) Strategic tillage reduces emergence of key sub-tropical weeds. *Proceedings of 18th Australian Weeds Conference*. Melbourne, Australia
- Melander B, Lattanzi B, Pannacci E (2015) Intelligent versus non-intelligent mechanical intra-row weed control in transplanted onion and cabbage. *Crop Protection* **72**, 1-8

- Mohler CL (1993) A model of the effects of tillage on emergence of weed seedlings. *Ecological Applications* **3**, 53-73
- Mohler CL, Teasdale JR (1993) Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. *Weed Research* **33**, 487-499
- Moore JR, Pratley JE, Mace WJ, Weston LA (2014) The effect of summer heat and stubble load on endophyte viability in annual ryegrass. *Proceedings of 19th Australasian Weeds Conference*. Wagga Wagga, Australia
- Morgan PW, Finlayson SA, Childs KL *et al.* (2002) Opportunities to improve adaptability and yield in grasses: Lessons from sorghum. *Crop Science* **42**, 1791-1799
- Norton GM (2003) Understanding the success of fumitory as a weed in Australia. PhD thesis Charles Sturt University Wagga Wagga
- Oerke E (2006) Crop losses to pests. *The Journal of Agricultural Science* **144**, 31-43
- Owen MJ, Martinez NJ, Powles SB (2014) Multiple herbicide-resistant *Lolium rigidum* (annual ryegrass) now dominates across the Western Australian grain belt. *Weed Research* **54**, 314-324
- Owen MJ, Martinez NJ, Powles SB (2015a) Herbicide resistance in *Bromus* and *Hordeum* spp. in the Western Australian grain belt. *Crop and Pasture Science* **66**, 466-473
- Owen MJ, Martinez NJ, Powles SB (2015b) Multiple herbicide-resistant wild radish (*Raphanus raphanistrum*) populations dominate Western Australian cropping fields. *Crop and Pasture Science* **66**, 1079-1085
- Owen MJ, Powles SB (2016) The frequency of herbicide-resistant wild oat (*Avena* spp.) populations remains stable in Western Australian cropping fields. *Crop and Pasture Science* **67**, 520-527
- Ozpinar S (2006) Effects of tillage systems on weed population and economics for winter wheat production under the Mediterranean dryland conditions. *Soil and Tillage Research* **87**, 1-8
- Passioura JB, Angus JF (2010) Improving productivity of crops in water-limited environments. *Advances in Agronomy* **106**, 37-75
- Powles SB, Howat PD (1990) Herbicide-resistant weeds in Australia. *Weed Technology* **4**, 178-185
- Powles SB, Lorraine-Colwill DF, Dellow JJ, Preston C (1998) Evolved resistance to glyphosate in rigid ryegrass (*Lolium rigidum*) in Australia. *Weed Science* **46**, 115-128
- Powles SB, Preston C, Bryan IB, Jutsum AR (1997) Herbicide resistance: impact and management. *Advances in Agronomy* **58**, 57-93
- Powles SB, Yu Q (2010) Evolution in action: plants resistant to herbicides. *Annual Review of Plant Biology* **61**, 317-347
- Pratley J (1992) Herbicide carryover in wheat stubbles. *Proceedings of 6th Australian Agronomy Conference*. Armidale NSW pp 318-321
- Pratley J (1995) Long term investigations of the effect of tillage practices on crop production at Wagga Wagga, New South Wales. *Australian Journal of Experimental Agriculture* **35**, 885-892
- Pratley J, Baines P, Eberbach P *et al.* (1996) Glyphosate resistance in annual ryegrass. *Proceedings of 11th Annual Conference of the Grassland Society of New South Wales*, Wagga Wagga NSW
- Pratley J, Urwin N, Stanton R *et al.* (1999) Resistance to glyphosate in *Lolium rigidum*. I. Bioevaluation. *Weed Science* **47**, 405-411
- Pratley JE, Rowell DL (1987). From the first fleet: evolution of Australian farming systems. In (Eds. PS Cornish and JE Pratley) "Tillage – New Directions in Australian Agriculture" pp 2-23 (Inkata Press, Melbourne)
- Preston, C (2019) The Australian Glyphosate Sustainability Working Group.
<http://www.glyphosateresistance.org.au/>
- Putnam AR, DeFrank J (1983) Use of phytotoxic plant residues for selective weed control. *Crop Protection* **2**, 173-181
- Radford BJ, Wilson BJ, Cartledge O, Watkins FB (1980) Effect of wheat seeding rate on wild oat competition. *Australian Journal of Experimental Agriculture and Animal Husbandry* **20**, 77-81
- Rebetzke GJ, Botwright TL, Moore CS *et al.* (2004) Genotypic variation in specific leaf area for genetic improvement of early vigour in wheat. *Field Crops Research* **88**, 179-189
- Rebetzke GJ, Jimenez-Berni, J, Fischer, RA *et al.* (2018) Review: High-throughput phenotyping to enhance the use of crop genetic resources. *Plant Science* **282**, 40-48
- Rebetzke GJ, Richards RA (1999) Genetic improvement of early vigour in wheat. *Australian Journal of Agricultural Research* **50**, 291-302
- Rebetzke GJ, Verbyla AP, Verbyla KL *et al.* (2014) Use of a large multiparent wheat mapping population in genomic dissection of coleoptile and seedling growth. *Plant Biotechnology Journal* **12**, 219-230
- Reeves TG, Smith IS (1975) Pasture management and cultural methods for the control of annual ryegrass (*Lolium rigidum*) in wheat. *Australian Journal of Experimental Agriculture and Animal Husbandry* **15**, 527-530
- Renton M, Flower KC (2015) Occasional mouldboard ploughing slows evolution of resistance and reduced long-term weed populations in no-till systems. *Agricultural Systems* **139**, 66-75
- Rice EL (1979) Allelopathy: An Update. *Botanical Review* **45**, 15-109

- Roush ML, Radosevich SR (1985) Relationship between growth and competitiveness of four annual weeds. *Journal of Applied Ecology* **22**, 895-905
- Ruis SJ, Blanco-Canqui, H (2017) Cover crops could offset crop residue removal effects on soil carbon and other properties: a review. *Agronomy Journal* **109**, 1785-1805
- Scotford IM, Miller PCH (2005) Applications of spectral reflectance techniques in northern European cereal production: A review. *Biosystems Engineering* **90**, 235-250
- Seal A, Haig T, Pratley J (2004) Evaluation of putative allelochemicals in rice root exudates for their role in the suppression of arrowhead root growth. *Journal of Chemical Ecology* **30**, 1663-1678
- Spafford Jacob HS, Minkey DM, Borger C, Gallagher RH (2006) Variation in post-dispersal weed seed predation in a crop field. *Weed Science* **54**, 148-155
- Travlos IS (2012) Reduced herbicide rates for an effective weed control in competitive wheat cultivars. *International Journal of Plant Production* **6**, 1-13
- Vandeleur RK, Gill GS (2004) The impact of plant breeding on the grain yield and competitive ability of wheat in Australia. *Australian Journal of Agricultural Research* **55**, 855-861
- Vandenbussche F, Pierik R, Millenaar FF *et al.* (2005) Reaching out of the shade. *Current Opinion in Plant Biology* **8**, 462-468
- Vigneault C, Benoit DL, McLaughlin NB (1990) Energy aspects of weed electrocution. *Reviews of Weed Science* **5**, 12-26
- Walsh MJ (2017) Weed management in dryland cropping systems. In (Eds. M Farooq, KHM Siddique) "Innovations in Dryland Agriculture" (Springer: Cham)
- Walsh MJ, Broster JC, Aves C, Powles SB (2018a) Influence of crop competition and harvest weed seed control on rigid ryegrass (*Lolium rigidum*) seed retention height in wheat crop canopies. *Weed Science* **66**, 627-633
- Walsh MJ, Broster JC, Powles SB (2018b) iHSD mill efficacy on the seeds of Australian cropping system weeds. *Weed Technology* **32**, 103-108
- Walsh MJ, Harrington RB, Powles SB (2012) Harrington seed destructor: A new nonchemical weed control tool for global grain crops. *Crop Science* **52**, 1343-1347
- Walsh MJ, Maguire N, Powles SB (2009) Combined effects of wheat competition and 2,4-D amine on phenoxy herbicide resistant *Raphanus raphanistrum* populations. *Weed Research* **49**, 316-325
- Walsh MJ, Minkey DM (2006) Wild radish (*Raphanus raphanistrum* L.) development and seed production in response to time of emergence, crop topping and sowing rate of wheat. *Plant Protection Quarterly* **21**(1), 25-29
- Walsh MJ, Newman P (2007) Burning narrow windrows for weed seed destruction. *Field Crops Research* **104**, 24-40.
- Walsh MJ, Newman P, Powles SB (2013) Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. *Weed Technology* **27**, 431-436
- Walsh MJ, Powles SB (2014) High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. *Weed Technology* **28**, 486-493
- Wasson AP, Rebetzke GJ, Kirkegaard JA *et al.* (2014) Soil coring at multiple field environments can directly quantify variation in deep root traits to select wheat genotypes for breeding. *Journal of Experimental Botany* **65**, 6231-6249
- Wells G (1970) Skeleton weed (*Chondrilla juncea*) in the Victorian Mallee. 2. Effect of legumes on soil fertility, subsequent wheat crop and weed population. *Australian Journal of Experimental Agriculture* **10**, 622-629
- Westerman PR, Hofman A, Vet LEM, van der Werf W (2003) Relative importance of vertebrates and invertebrates in epigeal weed seed predation in organic cereal fields. *Agriculture, Ecosystems and Environment* **95**, 417-425
- Worthington M, Reberg-Horton SC, Brown-Guedira G *et al.* (2015) Relative contributions of allelopathy and competitive traits to the weed suppressive ability of winter wheat lines against Italian ryegrass. *Crop Science* **55**, 57-64
- Wu H, Pratley J, Lemerle D, Haig T (2001) Allelopathy in wheat (*Triticum aestivum*). *Annals of Applied Biology* **139**, 1-9
- Yenish JP, Young FL (2004) Winter wheat competition against jointed goatgrass (*Aegilops cylindrica*) as influenced by wheat plant height, seeding rate, and seed size. *Weed Science* **52**, 996-1001
- Zerner MC, Gill GS, Vandeleur RK (2008) Effect of height on the competitive ability of wheat with oats. *Agronomy Journal* **100**, 1729-173
- Zerner MC, Rebetzke GJ, Gill GS (2016) Genotypic stability of weed competitive ability for bread wheat (*Triticum aestivum*) genotypes in multiple environments. *Crop and Pasture Science* **67**, 695-702
- Zimdahl RL (2013) "Fundamentals of Weed Science" (Academic Press: California, USA)

Chapter 11

New approaches to crop disease management in conservation agriculture

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Changes in disease profiles following adoption of CA

Importance of key wheat pathogens in Australia

The economic importance of wheat diseases in Australia was estimated in 1988 (Brennan and Murray 1989), 1998 (Brennan and Murray 1998) and 2008 (Murray and Brennan 2009). The value of wheat and area sown has changed over time, but the expression of yield losses as a percentage of the production enables comparisons between surveys (Table 1). Estimates were made for the northern (central and northern NSW plus Qld), southern (southern NSW, Victoria and SA) and western (WA) grain growing regions of Australia. Five key diseases, reported to increase in prevalence with the adoption of CA, have all steadily risen in their importance across all three regions (Table 1). The cereal root disease Take-all (*Gaeumannomyces tritici*) has generally declined in estimated importance over time. This may reflect the intensification of cropping over this period which has seen a reduction in the area of annual grass-legume pastures. The grass component in ley pastures is known to significantly contribute to elevated levels of take-all in following cereal crops as they serve as an alternate host for the causal pathogen (MacLeod *et al.* 1993).

Table 1. Average potential annual yield loss (%) of key wheat diseases estimated in 1988, 1998 and 2008 by cropping region

Disease	Northern			Southern			Western		
	1988	1998	2008	1988	1998	2008	1988	1998	2008
Yellow spot	3.3	2.0	19.0	1.0	1.6	3.9	5.0	9.3	12.9
Crown rot	3.0	13.0	22.2	0.4	6.6	10.5	0.1	0.3	1.5
Rhizoctonia	0.2	0.1	0.0	3.7	4.7	4.1	0.5	1.4	4.5
RLN <i>Pt</i> ^A	2.8	12.3	11.6	0.0	0.9	2.4	0.0	0.0	0.6
RLN <i>Pn</i> ^B	0.0	1.0	2.4	0.0	2.8	5.6	0.0	0.3	7.8
Take-all	0.8	0.6	0.0	9.5	13.6	3.6	10.0	3.0	1.4

^ARLN = root lesion nematode *Pratylenchus thornei*, ^B*P. neglectus*

Consistent with the trends presented in Chapter 2, Ugalde *et al.* (2007) explored changes in tillage and stubble management practices used by Australian cereal producers between 1995 and 2000. They showed that some form of aggressive tillage was common across nearly all Australian farming systems and regions in 1995, consisting of one, two or multiple cultivations and that there were only isolated pockets of NT or RT in each grain-growing region. However, over the next five years there were substantial shifts in land management with a significant increase in the adoption of conservative tillage practices. The shift was particularly noticeable in the western region where by 2005 more than 85% of the total cropped land was subject to no-till (NT) cropping practice (see Chapter 2).

The changes in tillage practices affected management of cereal stubble. The areas where stubble was incorporated decreased greatly between 1995 and 2000, especially in the northern and southern regions (Ugalde *et al.* 2007). In many parts of the southern region, incorporation was replaced by burning; in the northern and western regions there was a greater tendency to leave the stubble intact.

Changes in practices associated with adoption of CA between 1995 and 2000 are most likely to be key drivers in the prevalence of stubble-borne diseases of wheat between 1998 and 2008 (Table 1). Yellow leaf spot (*Pyrenophora tritici-repentis*) increased significantly over this period in the northern and western regions, but stubble burning in the southern region is likely to have limited infections. Crown

rot (*Fusarium pseudograminearum*) increased significantly in importance between 1998 and 2008, but this was not reflected in the western region (Table 1), even though it had the most adoption of CA (Ugalde *et al.* 2007). This highlights a potential weakness in the approach used by Murray and Brennan (2009) which is based on subjective estimates of incidence, severity and yield loss caused by wheat pathogens by only a limited number (18) of expert pathologists. Differences in the knowledge and awareness of the importance of specific diseases may exist between pathologists which may not reflect the actual disease incidence in a region.

The incidence of crown rot in cereal crops was objectively measured through laboratory plating of 1774 stubble samples collected at harvest across grain-growing regions between 2014-2017. High infection levels (>26%) occurred in 31%, 21% and 15% of paddocks in the northern, western and southern regions respectively (Simpfendorfer, unpublished). This indicates that the importance of crown rot (Murray and Brennan 2009), particularly in the western region, are probably underestimated. Future estimates of the economic importance of crop diseases in Australia would benefit from objective and quantitative data of disease incidence and severity.

Disease incidence in CA systems in Australia

Significant changes in the prevalence of specific plant pathogens are often observed following the adoption of CA. The increased retention of plant residues provides stubble-borne pathogens with an extended opportunity to survive between crops when host plants are absent during both fallow periods and rotations with non-host species (Bockus and Shroyer 1998). Some stubble-borne pathogens can survive multiple years in crop residues. For example, *Fusarium pseudograminearum* (*Fp*), the primary cause of crown rot (CR) in cereals, survives as mycelium for up to three years in infected cereal residues (Summerell and Burgess 1988), and *Bipolaris sorokiniana* (*Bs*), the cause of common root rot (CRR) in cereals, survives on wheat residues at the soil surface for at least two years (Duczek *et al.* 1999). In CT systems, the burial and increased rate of decomposition of crop residues reduces the survival of stubble-borne pathogens (Bockus and Shroyer 1998). Reduced soil disturbance, increased soil moisture and lowering of soil temperatures can also create a more favourable soil environment for many plant pathogens and encourage disease persistence (Bockus and Shroyer 1998). Under favourable climate and soil conditions, CA can increase the prevalence of some diseases and deleterious rhizobacteria (Simpfendorfer *et al.* 2002) while other diseases decrease in the prevalence (Table 2).

Interpretation of disease effects can be complicated by the differential effect of tillage and stubble retention practices on pathogen levels and disease expression. For instance, under a NT system, the incidence of CR (*Fp*) was significantly higher where stubble was retained (32.2%) than where it was removed (4.7%) but under disc tillage, there was no significant difference in disease level between stubble treatments (12-17%) (Wildermuth *et al.* 1997). However, the expression of whiteheads caused by CR was lowest in the NT plots (4.3%) and highest in the RT (19.3%) and CT (disc) (12.2%) stubble-retained treatments. Available soil water (depth of 1.2 m) at sowing and anthesis was highest in the NT plots and lowest in the CT (disc) plots. Moisture stress around anthesis exacerbates the effect of *Fp* necrosis on the vascular system of cereal plants which led to the expression of conspicuous whiteheads (Beddis and Burgess 1992). So, although CA systems can increase the incidence of CR infection, they also favour greater water retention in the soil profile which can reduce plant stress during anthesis and consequently decrease the expression of whiteheads associated with CR infection.

Indirect impacts of CA on plant diseases

Reduced spread of disease The retention of cereal stubble reduces the incidence of some diseases during the pulse phase of crop rotations. Infection of lupin leaves with brown leaf spot (*Pleiochaeta setosa*) in Western Australia was reduced when cereal stubble mulch was retained, compared with stubble removal (Sweetingham *et al.* 1993). The authors proposed that the retention of cereal mulch limited the rain splash of soil-borne *P. setosa* spores into the upper canopy of the lupin crop. The benefit of cereal stubble retention in reducing brown leaf spot in lupins was supported by observations in southern NSW (Simpfendorfer *et al.* 2004).

Table 2. Examples of crop diseases that increase and decrease with CA in Australia

Crop	Disease and causal organism	Selected references
<i>Diseases that increase with CA</i>		
Cereal	Rhizoctonia root rot (<i>Rhizoctonia solani</i>)	de Boer and Kollmorgen (1988), Roget <i>et al.</i> (1996)
	Crown rot (CR; <i>Fusarium</i> spp.)	Dodman and Wildermuth (1989), Wildermuth <i>et al.</i> (1997)
	Yellow spot (<i>Pyrenophora tritici-repentis</i>)	Summerell and Burgess (1989), Bhathal <i>et al.</i> (2003)
	Take-all (<i>Gaeumannomyces graminis</i> var. <i>tritici</i> , Ggt)	Pankhurst <i>et al.</i> (1995a); Roget <i>et al.</i> (1996),
	Eyespot (<i>Oculimacula yallandae</i>)	de Boer <i>et al.</i> (1993), Murray <i>et al.</i> (1991)
	Pythium root rot (<i>Pythium</i> spp.)	Pankhurst <i>et al.</i> (1995b)
	Septoria tritici blotch (<i>Zymoseptoria tritici</i>)	Goodwin (2007)
	Root lesion nematodes (RLN; <i>Pratylenchus</i> spp.)	Rahman <i>et al.</i> (2007); Thompson <i>et al.</i> (2008)
	Net blotch (<i>Pyrenophora teres</i>)	Lehmensiek <i>et al.</i> (2007)
Canola	Septoria nodorum blotch (<i>Parastagonospora nodorum</i>)	Bhathal <i>et al.</i> (2003)
	Blackleg (<i>Leptosphaeria maculans</i>)	Barbetti and Khangura (1999), West <i>et al.</i> (2001)
Pulse	Rhizoctonia bare-patch (<i>Rhizoctonia solani</i>)	Sweetingham (1986)
	Ascochyta blight (<i>Ascochyta</i> spp.)	Davidson <i>et al.</i> (2007)
<i>Disease that decrease with CA</i>		
Cereal	Cereal cyst nematode (CCN; <i>Heterodera avenae</i>)	Rovira 1990, Vanstone <i>et al.</i> (2008)
	Common root rot (CRR; <i>Bipolaris sorokiniana</i>)	Wildermuth <i>et al.</i> (1997), de Boer <i>et al.</i> (1991)
Pulse	Sclerotinia stem rot (<i>Sclerotinia sclerotiorum</i>)	Simpfendorfer <i>et al.</i> (2004)
	Brown leaf spot (<i>Pleiochaeta setosa</i>)	Sweetingham <i>et al.</i> (1993), Simpfendorfer <i>et al.</i> (2004)

Virus incidence in pulse crops also can be reduced by the retention of cereal stubble in CA systems. The final incidence of cucumber mosaic virus (CMV) in narrow-leafed lupins was reduced 25-40% in seven field experiments where cereal stubble was spread on the soil surface (Bwye *et al.* 1999). Inter-row planting into standing wheat stubble halved the incidence of beet western yellows virus (BWYV) in chickpea when compared to the same amount of stubble flattened on the soil surface (Moore *et al.* 2014). The mechanism for these differences is unclear but both CMV and BWYV are spread by aphid vectors and aphid numbers were lower with retained stubble treatments in the lupin study (Bwye *et al.* 1999). Retained cereal stubble can deter the landing of migrant aphid vectors.

A similar association has been found with reduced incidence of barley yellow dwarf virus (BYDV) in wheat and barley in the UK with CA practices. The combined effect of RT plus retention of cereal stubble was shown to provide a 21% yield advantage over CT without stubble. The yield benefit was associated with up to 48% reduction in aphid numbers and 71% decrease in the incidence of BYDV in the RT treatment compared with CT (Kennedy *et al.* 2010).

Earlier sowing opportunities Retention of stubble on the soil surface under CA increases surface moisture at sowing time, and allows an earlier and/or extended sowing window, particularly in dry seasons. Earlier sowing can improve crop water use efficiency and increase wheat yield (Kirkegaard and Hunt 2010) but can increase the incidence of some diseases. Earlier sowing tends to increase the risk of BYDV (McKirdy and Jones 1997) and wheat streak mosaic virus (WSMV) in cereal crops (Coutts *et al.* 2008) due to warmer temperatures in early autumn favouring activity of aphid or mite vectors that transmit these viruses. Earlier planting can also increase levels of stripe rust (*Puccinia striiformis*) at early crop stages due to warmer temperatures in early autumn, favouring rust cycling (Murray *et al.* 2005). Earlier sowing has also been shown to increase ascochyta blight in field peas (McDonald and Peck 2009). However, with the exception of ascochyta blight in field peas, delayed sowing is not generally recommended to reduce risk from these pathogens as the yield penalty associated with later sowing has been shown to generally outweigh the yield benefit from decreased disease severity and growers have options for disease control in early-sown crops.

Deeper planting to access stored soil moisture at sowing Crop yields in the northern region are generally more reliant on stored soil water than in other regions due to the predominance of higher clay content soils with increased plant available water holding capacity and a summer dominant rainfall pattern. However, dry conditions in autumn can limit planting opportunities so growers are often forced

to increase sowing depths with cereals and chickpeas to access deeper soil moisture to establish crops earlier in the planting window. Deeper sowing lengthens the sub-crown internode in cereals which increases susceptibility to CRR (Duczek and Piening 1982). Soil temperatures greater than 20-30°C favour *Bs* infection with yield losses between 7 and 24% reported from CRR in bread wheat (Wildermuth *et al.* 1992). The trend to deeper and earlier sowing of cereals into warmer soils is associated with an increased prevalence of CRR across Australia, especially in the northern region.

Bipolaris sorokiniana was recovered from 52%, 31% and 29% of 1774 cereal crops surveyed in the northern, western and the southern region respectively between 2014 and 2018. Medium to high (>11%) infection levels occurred in 13%, 8% and 5% of paddocks in the northern, western and southern region respectively (Simpfendorfer, unpublished). Consideration of integrated management options for CRR appears to be an increasing priority for Australian cereal growers. Importance is heightened by potential interaction between *Bs* and other soil- or stubble-borne diseases such as CR which can exacerbate yield loss (Simpfendorfer 2016a).

New management approaches for crop disease control in CA systems

Although the adoption of CA is associated with an increased incidence of some diseases, Australian researchers have been developing a range of innovative strategies to assist growers to minimise losses. These include pre-plant testing to determine levels of pathogen risk, technology and engineering innovations at sowing, breeding tolerant varieties and improving fungicide efficacy. Novel approaches, such as the potential of microwave radiation to reduce the survival of stubble-borne pathogens, are also currently being explored in Australia.

Value of PREDICTA® B to determine disease risk prior to sowing

A quantitative DNA-based soil testing service, PREDICTA® B, is available in Australia to assist grain growers to predict the likely risk of soil-borne diseases by measuring pathogen levels prior to planting. Growers have the option of changing cultivars or modifying cropping programs in situations where the risk of crop loss is high. The service was launched in 1997 with the initial focus on soil-borne pathogens of wheat and barley. Since then the range of pathogens covered has grown steadily and has expanded to include stubble-borne pathogens and cover a broader range of crops including pulses and oilseeds (Ophel-Keller *et al.* 2008). PREDICTA B has provided growers with a transformational change in their ability to quantify the risk of various diseases within their farming systems.

The key advantage of these DNA based assays is their ability to quantify a broad range of soil- and stubble-borne pathogens affecting cereals and pulses in a single soil sample. PREDICTA B results compiled and mapped to the nearest town highlight higher risk cropping areas for different diseases prior to sowing, and this can be used to inform industry (Figure 1).

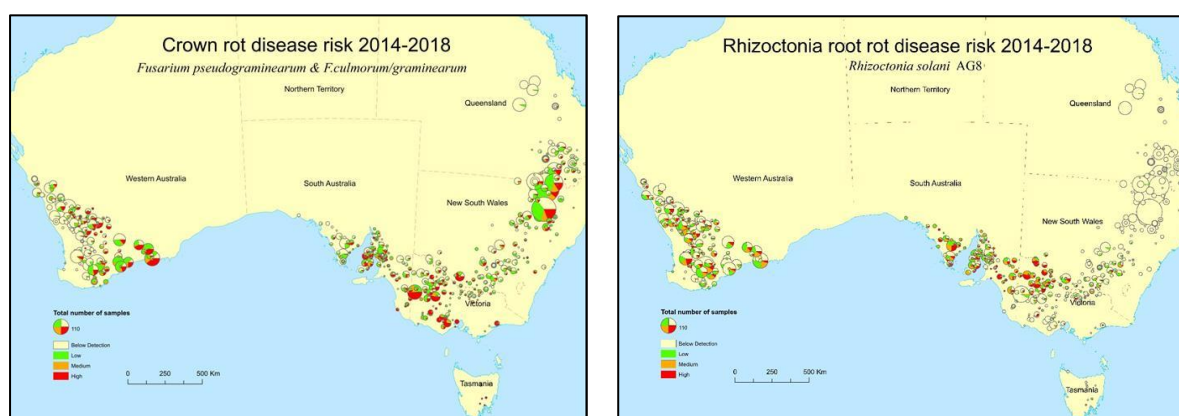


Figure 1. Distribution and levels of *Fusarium spp.* associated with causing crown rot (left) and *Rhizoctonia solani* (AG8; right) detected by PREDICTA B in grower paddocks and NVT sites prior to seeding 2014-2018 (N.B. the size of each pie chart is proportional to the number of samples mapped to the town and the numbers of low, medium and high disease risk samples are presented as green, orange and red sectors, respectively)

PREDICTA B results indicated that CR (Figure 1, left) is the most important soil/stubble-borne disease nationally, followed by root lesion nematodes. However, rhizoctonia root rot (Figure 1, right) and take-all also pose significant risks and other less common diseases may be important locally. A comprehensive range of maps is available at

http://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b.

Over time these results reveal the effects of changing cropping practices on pathogen levels. For example, the dramatic impact of the adoption of cereal cyst nematode (CCN) resistant cereal varieties and rotation with non-host crops on CCN soil levels is evident between 2002 and 2018 (Figure 2).

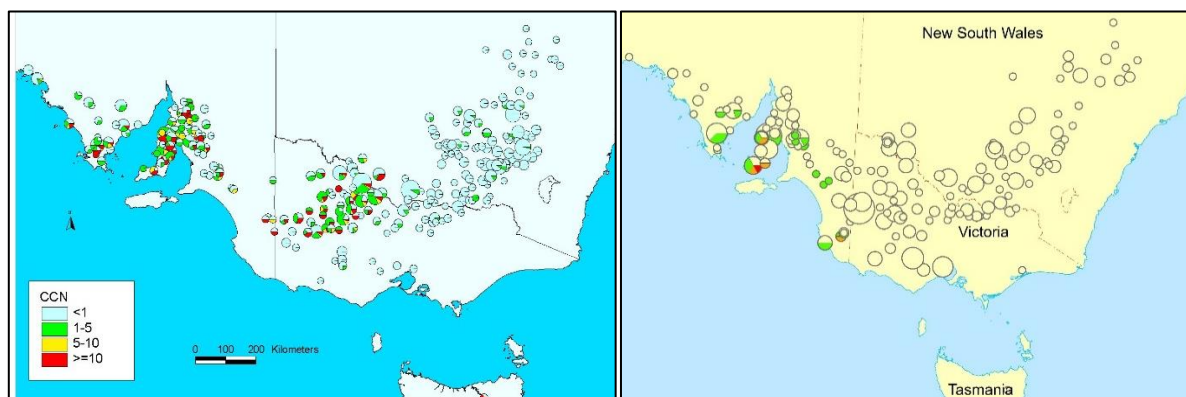


Figure 2. Distribution and levels of cereal cyst nematode detected by PREDICTA B in grower paddocks prior to seeding in 2002 (left) and 2018 (right)

The continued inclusion of new tests within the PREDICTA B system is valuable to determine the changing distribution, epidemiology and importance of a wide range of pathogens associated with the new CA practices across Australia. Use of PREDICTA B by growers and researchers has raised awareness of the risks posed by soil- and stubble-borne pathogens across regions. This technology is also allowing researchers to examine the impact of cropping practices on multiple soil- and stubble-borne pathogens, research which was previously considered too complex. PREDICTA B is also supporting development of improved management strategies to limit losses from diseases under CA.

Inter-row sowing and disease

The adoption of inter-row sowing using GPS guidance is a relatively recent innovation in CA in Australia to improve stubble handling. *Fp* is a stubble-borne pathogen, so inoculum becomes concentrated in the previous cereal rows with CA. Paddock surveys across 44 sites in the northern region in 2005 reported an average 45% reduction in the incidence of *Fp* infection and 51% decrease in the severity of CR with inter-row sowing (Simpfendorfer 2012). In replicated small plot experiments inter-row sowing reduced *Fp* incidence and CR severity resulting in 27% fewer whiteheads and a 6% yield benefit in bread wheat-durum wheat cycles over three seasons (Verrell *et al.* 2017).

The main value of inter-row sowing is that it reduces the rate of *Fp* inoculum build-up in a cereal/pulse or oilseed crop sequence. This benefit is not evident in continuous cereal production because inoculum survives too long in the inter-row spaces. Inter-row sowing is a useful component of an integrated disease management system for CR when combined with rotation of non-host crops. In the northern region, rotation of cereals with non-host oilseed and pulse crops reduced crown rot infection (by 3.4-41.3%) and increased wheat yield (by 0.24-0.89 t/ha) compared with a cereal-wheat rotation (Kirkegaard *et al.* 2004). Further research combining crop sequencing with inter-row sowing, found that using mustard-wheat and chickpea-wheat rotations increased wheat yield by 40-44% compared with continuous wheat with a further 11-16% yield benefit from inter-row sowing, depending on the row placement sequences (Verrell 2014).

A combined crop sequence and row placement strategy is now recommended for CA in the northern region. The strategy has two simple principles:

- sow break crops (oilseed or pulse) between standing wheat rows which need to be kept intact; and
- sow the following wheat crop *directly over* the row of the previous seasons break crop.

This ensures a four-year gap between wheat crops sown on the same row, resulting in decreased incidence of CR in wheat and improved germination of the break crops.

Take-all, caused by *Ggt*, was less severe as the distance of seed placement to the inoculum source increased (Kabbage and Bockus 2002). Mathematical modelling suggested that sowing parallel to and between previous cereal rows would reduce yield loss to *Ggt* (Garrett *et al.* 2004). Field experiments in South Australia confirmed that inter-row sowing improved yield in the presence of take-all (McCallum 2007). In summary, inter-row sowing, using precision row placement can limit the impact of pathogens such as *Fp* and *Ggt* with CA where inoculum is predominantly confined to the previous cereal rows.

Impact of seeding equipment on soil-borne diseases

It is well established that different soil openers (tynes or discs) used when sowing crops have a significant influence on the severity of rhizoctonia root rot (Rovira 1990). Disturbance below seeding depth using knife-points disrupts the hyphal network of rhizoctonia in the soil surface, assisting crop roots to escape early infection and reduce disease impact. Rhizoctonia risk is generally considered greater when sowing using single disc seeders than knife-points. Preliminary studies in South Australia in 2015 examined the potential of a specifically engineered ‘sweep’ (Figure 3b) mounted in-front of a single disc to excavate the top 2-3 cm of soil, where rhizoctonia inoculum was concentrated, away from the seeding row. The crop established well with no signs of bare-patches, although rhizoctonia recovered by mid-winter to cause severe disease on the crown roots (P. Bogacki pers. comm.).

In a CR infested site, planting using a tyne resulted in better plant establishment, higher tiller density and improved grain yield compared with a disc opener (Verrell *et al.* 2017). This yield advantage was considered to be due to the ‘excavating’ effect of the tyne, removing *Fp* inoculum from the seed furrow. Moving cereal stubble away from the sown row using a row cleaner in front of a single disc (Figure 3a) also reduced the incidence of *Fp* (by 3.7%) and whiteheads (by 13.6%) but did not increase yield (Verrell *et al.* 2017).

Improving the efficacy of fungicide strategies

Targeted fungicide application for crown rot CR infection is concentrated below ground and at the base of infected tillers which is likely to limit the activity of foliar fungicide applications. Simpfendorfer *et al.* (2014) showed that across 22 field sites in northern NSW in 2013/14, targeted fungicide application at the base of tillers using inter-row droppers with angled nozzles (Figure 4a) provided an average 5 % yield benefit (0.19 t/ha) in the absence of CR inoculation and a 15 % (0.37 t/ha) yield benefit in the CR inoculated treatment. However, the average level of benefit remained 0.98 t/ha less than uninoculated control plots. Normal foliar fungicide application 50 cm above the crop canopy did not provide any yield benefit. Targeting the in-crop application of fungicides at the base of infected wheat plants provided a minor (5-15 %) yield improvement but may be a useful addition to an integrated control strategy to manage CR.

Liquid banding of fungicide for Rhizoctonia Rhizoctonia is still a major constraint to cereal production in low to medium rainfall districts in the southern and western regions of Australia (Figure 1). Improved integrated management including early sowing, grass free canola, pulse and pastures (Gupta *et al.* 2012), knife point seeding systems and fungicides has reduced the impact of rhizoctonia root rot. These

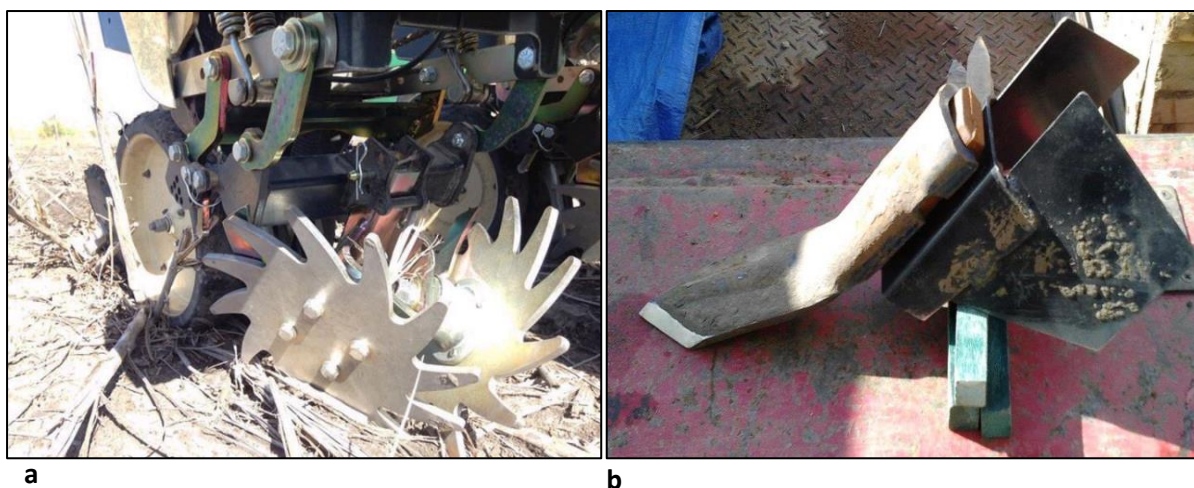


Figure 3. Row cleaner used to move cereal stubble away from sowing row (a); sweep used to shift surface soil and stubble out of planting row (b);



Figure 4. Inter-row droppers used to target fungicide application at the base of wheat tillers to improve in-crop control of crown rot (a); liquid application system used to apply fungicide above (b) and below the seed (c) at sowing to manage *Rhizoctonia* root rot (photos: Jack Desbiolles, Uni SA)

changes in agronomy have resulted in a significant shift in the symptomology of *rhizoctonia* root rot from ‘bare patches’ due to seedling infection to development of uneven growth in mid-winter due to infection of crown roots when soil temperatures drop to $<10^{\circ}\text{C}$. Infection can then continue to develop on the root system until the crop matures, and can spread to the seminal root system, limiting water uptake in periods of high evapotranspiration.

Several fungicide seed treatments are registered in Australia for the control of *rhizoctonia* in cereal crops. However, extensive field evaluation in the southern and western region found that on average seed treatments only provided an average 5% (0 to 18%) yield benefit in wheat and barley (McKay *et al.* 2014). Rainfall post sowing is needed to move fungicide applied to seeds into the root zone with roots growing outside the fungicide zone being unprotected.

The fungicides azoxystrobin + metalxyl-m (Uniform®, Syngenta) and penflufen (EverGol Prime®, Bayer CropScience) have recently been registered for liquid streaming to control *rhizoctonia*. Twenty-one fungicide efficacy trials comparing seed treatments with liquid streaming in either barley or wheat were conducted in SA and WA from 2011-2013. These experiments found that application via dual

banding, in-furrow 3-4 cm below the seed (Figure 4b) and on the surface behind the press wheel (Figure 4c), provided the most consistent yield (0.20 to 0.53 t/ha in wheat and 0.37 to 0.87 t/ha in barley) and root health benefits across seasons (McKay *et al.* 2014).

Liquid streaming fungicides is a significant development in the control of rhizoctonia root rot in CA and provides several benefits compared with applying fungicides as seed or fertiliser treatments. These benefits include a greater capacity to target placement to improve protection of both the crown and seminal root systems from rhizoctonia root rot, greater flexibility to vary fungicide application rate and to target areas of the paddock that will provide the greatest return on investment, and the ability to not apply fungicides to areas where run-off may contaminate water courses. The decision to apply fungicides to a specific paddock can be delayed until seeding which eliminates the risk of contaminating trucks and augers that will be used later in the season to transport grain. An additional expense is required with liquid systems which can be a barrier to adoption. However, due to flexibility in liquids which can be applied this has seen more rapid adoption in the western than the southern region where these systems were already being used for nutrient application.

Newer modes of action Fungicide management of foliar diseases in Australia has traditionally been based on the use of demethylation inhibitor (DMI, Group 3) triazole fungicides. However, evolving issues with the development of fungicide resistance to DMIs in Australia and availability of new modes of action including quinone outside inhibitors (QoI or strobilurins, Group 11) and succinate dehydrogenase inhibitors (SDHI, Group 7) has driven a re-evaluation of fungicide management strategies.

Spot-form of net blotch (SFNB), caused by the fungus *Pyrenophora teres f. maculata*, is a common foliar disease of barley across Australia due to the widespread cultivation of susceptible varieties, stubble retention and favourable climatic conditions (McLean *et al.* 2009). The SDHI seed treatment, fluxapyroxad (Systiva®, BASF) was registered in Australia for the control of a range of fungal diseases in barley, including SFNB, in 2015. In two field experiments conducted in the northern region in 2016, Systiva® was found to have similar efficacy as a first node (GS31) application of foliar fungicides when both strategies were backed up by a second foliar fungicide application at awn peep (GS49) (Simpfendorfer and Street 2017). Systiva® provided useful levels of SFNB suppression post GS49 under moderate disease pressure at Tamworth but activity waned by this growth stage under higher disease pressure at Dubbo in 2016. Foliar application of bixafen + prothioconazole (SDHI + DMI; Aviator® Xpro®, Bayer CropScience) was also included in this study and provided improved control of SFNB and reduced yield loss compared with azoxystrobin + cyproconazole (QoI + DMI, Amistar Xtra® Syngenta) which was then better than propiconazole (DMI, Tilt®250 Syngenta) in these experiments (Simpfendorfer and Street 2017). Similar findings on the value of Systiva® for early control of SFNB in barley have been produced in the southern region (McLean and Hollaway 2015).

Recent Australian studies have also found that the inclusion of these newer QoI or SDHI actives in fungicide management strategies has improved the control of yellow spot and septoria tritici blotch in wheat along with net-blotch (both net-form and SFNB), scald and powdery mildew in barley (Poole and Wylie 2017), blackleg in canola (Horbury 2016) and ascochyta blight in chickpeas (K Moore, pers. comm.) compared with existing DMI only standards.

Disease forecasting models Disease forecasting models can assist in determining the risk of disease occurrence as well as the probability that the intensity of the infection will increase (Campbell and Madden 1990). Reliable and timely crop disease forecasts can assist growers to manage disease especially by guiding appropriate and/or timely application of fungicides. Disease forecasts can prevent or reduce the unnecessary application of fungicides in seasons when climatic conditions are not conducive to pathogen development or infection.

In Australia, this has been well demonstrated through the development and application of the 'Blackspot Manager' model in the management of ascochyta blight in field peas in the Western Australia, South Australia, Victoria and southern NSW (Galloway 2018). Blackspot Manager calculates when the majority of spores (~60%) have been released from field pea stubble and the risk of infection is reduced

to low levels. Growers can then decide to delay sowing field peas until their region is designated as having low disease risk or, if sowing when risk is high, they can plan a foliar fungicide program to reduce the severity of *Ascochyta* blight.

A similar model to predict the maturity of *Leptosphaeria maculans* ascospores on canola residues from previous crops based on weather conditions has been developed in Western Australia (Pratt and Salam 2018). The model aims to improve blackleg management in canola, including fungicide timing, and was released for use by growers in both western and eastern Australia in 2018. Further disease forecasting models are currently under development in Australia for yellow spot (*Pyrenophora tritici-repentis*) in wheat crops and sclerotinia stem rot (*Sclerotinia sclerotiorum*) in canola.

Breeding for tolerance to soil- and stubble-borne diseases

A tolerant cultivar is defined as one that loses significantly less yield or quality compared with other cultivars, when exposed to an equivalent level of pathogen burden (van den Berg *et al.* 2017). Tolerance in wheat to the root lesion nematode *Pratylenchus thornei* (*Pt*) was first identified in 1984 with an on-going breeding and selection program in Australia (Thompson *et al.* 2008). Nationally, the adoption of wheat varieties with moderate or higher levels of tolerance to *Pt* has risen from 24% in 2010 to 62% in 2016 (Murray and Brennan, unpublished data). This has significantly reduced yield losses, especially in the northern region where this plant pathogenic nematode is endemic, and highlights the potential value of this approach to limit the impact of soil-borne pathogens which increase in CA systems.

No major genes for CR resistance exist (Liu and Ogbannaya 2015). However, wheat varieties differ in both their levels of tolerance and resistance to CR; these are separate mechanisms both of which can reduce the extent of yield loss (Forknall *et al.* 2019). Recent research has established the relative ‘tolerance’ of different bread wheat, barley and durum varieties to CR in Victoria and SA (Evans and Hollaway 2017), WA (Hüberli *et al.* 2017), southern NSW (Milgate and Baxter 2018), central/northern NSW and southern Qld (Simpfendorfer *et al.* 2016b). Growers can adopt cereal varieties with improved yield performance in the presence of CR infection as proven in their region to minimise losses. In a relatively short period of time the yield benefit of switching between wheat varieties in the presence of CR infection has risen from 5-10% in 2007 (Daniel and Simpfendorfer 2008) to 20-40% in 2015 (Simpfendorfer 2016b).

A key limitation to resistance and tolerance breeding for CR remains a lack of research and knowledge of the genetic basis of the mechanisms which confer tolerance. An understanding is required of the underlying mechanism(s) which confer improved tolerance (*e.g.* resistance to the pathogen, root architecture, heat stress tolerance, tolerance of abiotic factors such as salinity or sodicity) to refine further and target breeding efforts. Heat tolerance traits such as waxy leaves and leaf rolling have been reported to enhance the water use efficiency of wheat crops (Richards *et al.* 2010) which may also reduce the expression of CR.

Breeding for desirable root architectural traits, such as narrow root angle and high root number (Manschadi *et al.* 2006), which improve access to stored moisture deep in the soil, may also reduce the impact of CR under terminal drought conditions which are frequently experienced in the northern region of Australia. However, in environments with shallow soils where the crop relies on sporadic rainfall in-season (*e.g.* western and southern regions), a wider root growth habit and shallow root system may be preferable to maximise soil water uptake (Alahmad *et al.* 2018).

Selection for tolerance may be a better strategy to improve yield and raise the pathogen threshold before losses occur where major genes for disease resistance are not available. Priority diseases for improving crop tolerance under CA include rhizoctonia root rot and take-all in cereals as well as root lesion nematodes (*Pratylenchus* spp.) in pulses and oilseeds, which can be exposed to high populations when grown following susceptible wheat cultivars. Preliminary research has been conducted on the value of more rapid root replacement in chickpea cultivars to improve tolerance to phytophthora root rot (S Bithell pers. comm.).

Microwave radiation – a novel approach to manage stubble-borne pathogens

New microwave field applicator prototypes are being developed in Australia for the control of weeds in paddocks (Brodie *et al.* 2015). Microwave radiation may also offer a rapid and chemical-free approach to reduce the survival of stubble-borne pathogens in crop residues and allow them to remain intact. Preliminary laboratory research has demonstrated that microwave radiation is an effective method for significantly reducing the survival of *Fp* in durum wheat stubble (Petronaitis *et al.* 2018). To date, the practical adoption of microwave radiation to control soil- and stubble-borne pathogens within paddocks has largely been limited by the availability of suitable large-scale equipment. More research is required, including consideration of alternate radiation sources such as infrared, before such technology can be used to manage stubble-borne pathogens under field conditions.

Challenges to reduce disease risk in CA systems

There are several inherent challenges associated with managing crop diseases under CA systems. These include likely impacts of future climate change predictions, issues around weeds and crop intensification and the continuing evolution of pathogen populations.

Climate change

It is widely acknowledged that the increased adoption of CA systems will be critical in growers adapting to future climate change scenarios including increased temperatures, elevated CO₂, greater variability in rainfall and increased frequency of droughts. Crop production will become more reliant on the stored soil water benefits associated with adoption of CA to buffer against these climatic changes. The potential impact of climate change on a wide range of crop diseases has been modelled in various studies as reviewed by Luck *et al.* (2011). This review concluded that the importance of necrotrophic wheat diseases such as yellow spot, septoria tritici blotch and septoria nodorum blotch in wheat are likely to decrease with climate change.

Crown rot infection in cereal crops is predicted to increase in significance with climate change. Increasing atmospheric CO₂ concentration has been shown to directly increase the production of *Fp* biomass in wheat tissue (Melloy *et al.* 2010). The production and survival of CR inoculum in retained stubble is predicted to increase as a consequence. Furthermore, reduced reliability of rainfall and elevated temperatures, especially during grain filling, are further likely to increase the severity and yield loss from CR. It has even been suggested that CR would be a good indicator of global climate change (Moya-Elizondo 2013).

Changes in rainfall patterns and increased frequency of droughts are further likely to increase the longevity of stubble-borne pathogens in CA systems by reducing the rate of residue decomposition. These conditions are also likely to alter the rate of spore maturity and release from residues over time with necrotrophic stubble-borne pathogens such as *Pyrenophora* spp., *Septoria* spp. and *Ascochyta* spp. which may alter the timing of currently recommended management strategies.

Weeds as alternate hosts for plant pathogens

CA systems rely on herbicides to replace cultivation for the control of weeds. This has led to the evolution of herbicide resistant weeds across Australian cropping areas (see Chapter 10). Resistance to glyphosate alone, the main herbicide which has underpinned the adoption of NT globally, has been recorded in ten grass weed species and seven broadleaf species in Australia (Preston 2019). Many of these weeds are alternate hosts of different crop pathogens which can undermine recommended disease management strategies. The impact of weeds on disease can be two-fold in some instances, such as with grass weeds and CR. The reported hosts of *Fp* include 15 grass species including ryegrass, black oats and barley grass (Alahmad *et al.* 2018) which can be important sources of inoculum especially during break crop periods. These weeds can further reduce stored soil water levels during fallow periods and/or provide in-crop competition with cereal plants for moisture which can increase stress during grain-filling and exacerbate the expression of whiteheads in CR infected tillers (Alahmad *et al.* 2018).

Furthermore, some herbicides have been shown to increase the severity of disease such as the pre-sowing application of sulphonylurea with rhizoctonia root rot (Rovira 1990).

Increased cropping intensification

The adoption of CA facilitates the intensification of cropping often with the removal of longer pasture ley phases. This can increase disease incidence by reducing the time for inoculum levels to decline between susceptible crop species. However, even when rotations are implemented the shared host range of some pathogens can still result in increased disease incidence. For instance, bread wheat, durum wheat, barley, sorghum and maize are all hosts of *Fusarium graminearum* and when grown in close rotation increase the risk of fusarium head blight (FHB), especially in durum wheat which is very susceptible (Obanor *et al.* 2013). *Sclerotinia sclerotiorum* has an even wider host range including winter pulse crops (chickpea, lentils, lupins and faba beans), winter oilseeds (canola) and summer broad leaf crops (sunflowers, mungbeans, soybean and cotton). These limit rotation options, especially with the increasing intensification of high value pulse crops such as chickpeas and lentils in Australia. The widespread adoption of wheat-chickpea-wheat rotations in the northern region supports *Pt* populations while wheat-canola-wheat rotations in the southern and western regions will promote *Pn* populations due to the growth of successive susceptible hosts to these different RLN species.

The increased intensification of canola and pulses in different regions further means that previous recommendations around only growing these crops once every three years in the same paddock to limit the incidence of disease are no longer practical. Buffer zones of around 500 m between current canola or pulse crops with residues of these same species from the previous season are also recommended to limit the development of fungal pathogens such as *Ascochyta* spp. and *Leptosphaeria maculans* which have limited wind-borne dispersal. These recommendations were useful over a decade ago when these industries were starting to develop in the different regions but have become impractical with the increased intensification of canola and/or pulse production.

Fungicide resistance

Recent findings on the improved efficacy of Qol and SDHI based fungicides are promising for improved disease management in Australian cereal and pulse crops, especially given that most of these diseases are known to increase with the adoption of CA (Table 2). However, Qol fungicides are considered at high risk of resistance evolution within fungal pathogens and the risk of resistance to SDHI fungicides is considered medium to high (FRAC 2018). This is concerning given that DMI fungicides are only considered to be at medium risk yet multiple instances of DMI fungicide resistance have been recorded in Australia for a range of pathogens (Anon. 2016). To prolong the activity of Qol and SDHI fungicides along with existing triazole products, they need to be used judiciously and in combination with other management strategies. Australian growers are urged to use integrated disease management (IDM) strategies to limit losses from crop diseases such as crop rotation, cultivar resistance, inoculum monitoring and disease forecasting; with fungicides being only one component. IDM will reduce disease pressure and the reliance on fungicides as the sole management tool but importantly also delays the development of resistance to these valuable chemical options.

‘Breakdown’ of host resistance genes by fungal pathogens

Canola production is challenged by the fungal pathogen *Leptosphaeria maculans* having a high evolutionary potential which means that extensive sowing of a cultivar in a region can lead to blackleg resistance bred into a cultivar becoming ineffective within three years (Sprague *et al.* 2006). The ability of *L. maculans* to evolve rapidly to ‘break down’ disease resistance bred into canola cultivars makes it a high-risk pathogen within Australian cropping systems (Van de Wouw *et al.* 2014). Marcroft *et al.* (2012) showed that rotating canola cultivars with different resistance genes minimised blackleg pressure by manipulating *L. maculans* populations. Annual monitoring of avirulence allele frequencies in *L. maculans* populations across Australia provides power to anticipate which cultivars will be most successful in future growing seasons (Van de Wouw *et al.* 2017). Growers can rotate canola cultivars from different blackleg resistance groups when required to reduce the severity of blackleg and

prolonging effectiveness of resistance genes. Ultimately, this process has allowed the continued expansion of canola production in Australia (Van de Wouw *et al.* 2017).

Pyrenophora teres f. *teres* (*Ptt*), the cause of net-form of net blotch (NFNB) in barley, is a highly variable pathogen with thirteen different pathotypes identified in Australia (Platz *et al.* 2000). This is challenging for the management of this stubble-borne pathogen. Sexual reproduction in *Ptt* means that progeny of crosses that carry increased virulence to different resistance genes present in cultivars are selected for overtime by the successive production of an individual barley variety. This has seen increased severity of NFNB on the barley varieties, Commander and Shepherd, in the northern region in recent years through their selection for previously rare *Ptt* pathotypes (Fowler and Platz 2017).

Conversely, the Australian *Ascochyta rabiei* (syn. *Phoma rabiei*) population, cause of ascochyta blight in chickpeas, has low genotypic diversity with only one mating type detected to date. This potentially precludes substantial genetic diversity through recombination which may result in the evolution of new pathotypes of the pathogen (Mehmood *et al.* 2017). However, isolates of *A. rabiei* which cause increased disease severity on widely adopted 'resistant' host genotypes such as Genesis090 and PBA HatTrick have been identified. A greater frequency of highly aggressive isolates within the ARH01 haplotype group appear to have created 'super isolates' with the highest pathogenicity ranking. This represents a significant risk to the Australian chickpea industry – not only are the isolates widely adapted across diverse geographical environments, but there are a disproportionately large number of aggressive isolates, indicating fitness to survive and infect the best Australian resistance sources (Mehmood *et al.* 2017).

Conclusion

Australian growers have persisted with CA and increased adoption, especially in the western region, despite the associated increased challenges with disease management. A range of new innovations in disease management under CA systems continue to support this trend. Pragmatism with occasional tillage and stubble burning can form part of a more resilient and integrated approach, and as climate shifts continue pathologists will need to be alert to the potential for emerging problems and work closely with agronomists and breeders to develop solutions.

References

- Alahmad S, Simpfendorfer S, Bentley AR, Hickey LT (2018) Crown rot of wheat in Australia: *Fusarium pseudograminearum* taxonomy, population biology and disease management. *Australasian Plant Pathology* **47**, 285-299
- Anonymous (2016) Sampling report annual review 2016: Fungicide resistance group. Centre for Crop and Disease Management. www.ccdm.com.au/wp-content/uploads/2017/06/FRG-Annual-Report-2016.pdf
- Barbetti MJ, Khangura RK (1999) Managing blackleg in the disease-prone environment of Western Australia. *Proceedings of 10th International Rapeseed Congress*, Canberra, Australia
www.regional.org.au/au/gcirc/3/8.htm
- Beddis AL, Burgess LW (1992) The influence of plant water stress on infection and colonization of wheat seedlings by *Fusarium graminearum* Group 1. *Phytopathology* **82**, 78-83
- Bhathal JS, Loughman R, Speijers J (2003) Yield reduction in wheat in relation to leaf disease from yellow (tan) spot and septoria nodorum blotch. *European Journal of Plant Pathology* **109**, 435-443
- Bockus WW, Shroyer JP (1998) The impact of reduced tillage on soilborne plant pathogens. *Annual Review of Phytopathology* **36**, 485-500
- Brennan JP, Murray GM (1989) Australian wheat diseases: Assessing their economic importance. *Agricultural Science* **2**, 26-35
- Brennan JP, Murray GM (1998) *Economic Importance of Wheat Diseases in Australia*. (NSW Agriculture: Wagga Wagga)
- Brodie G, Gixti M, Hollins E *et al.* (2015) Assessing the impact of microwave treatment on soil microbial populations. *Global Journal of Agricultural Innovation, Research and Development* **2**, 25-32
- Bwyre AM, Jones RA, Proudlove W (1999) Effects of different cultural practices on spread of cucumber mosaic virus in narrow-leaved lupins (*Lupinus angustifolius*). *Australian Journal of Agricultural Research* **50**, 985-996
- Campbell CL, Madden LV (1990) *Introduction to Plant Disease Epidemiology*. (John Wiley and Sons: New York)

- Coutts BA, Strickland GR, Kehoe MA *et al.* (2008) The epidemiology of wheat streak mosaic virus in Australia: case histories, gradients, mite vectors, and alternative hosts. *Australian Journal of Agricultural Research* **59**, 844-853
- Daniel R, Simpfendorfer S (2008) The impact of crown rot on winter cereal yields. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2008/06/the-impact-of-crown-rot-on-winter-cereal-yields
- Davidson JA, Kimber RBE (2007) Integrated disease management of ascochyta blight in pulse crops. In (Eds. B Tivoli, A Baranger, FJ Muehlbauer, BM Cooke) "Ascochyta Blights of Grain Legumes" (Springer: Dordrecht)
- de Boer RF and Kollmorgen, JF (1988) Effects of cultivation and stubble retention on soil- and stubble-borne pathogens of wheat in Victoria – an overview. *Plant Protection Quarterly* **3**, 3-4
- de Boer RF, Kollmorgen JF, Macauley BJ, Franz PR (1991) Root rot and yield of wheat in the Victorian Mallee. *Australian Journal of Experimental Agriculture* **31**, 367-372
- de Boer RF, Steed GR, Kollmorgen JF, Macauley BJ (1993) Effects of rotation, stubble retention and cultivation on take-all and eyespot of wheat in northeastern Victoria, Australia. *Soil & Tillage Research* **25**, 263-280
- Dodman RL, Wildermuth GB (1989) The effect of stubble retention and tillage practices in wheat and barley on crown rot caused by *Fusarium graminearum* Group 1. *Plant Protection Quarterly* **4**, 98-99
- Duczek LJ, Piening LJ (1982) Effect of seeding depth, seeding date and seed size on common root rot of spring barley. *Canadian Journal of Plant Science* **62**, 885-891
- Duczek L, Sutherland K, Reed S *et al.* (1999) Survival of leaf spot pathogens on crop residues of wheat and barley in Saskatchewan. *Canadian Journal of Plant Pathology* **21**, 165-173
- Evans M, Hollaway G (2017) Varieties an escape route in heavy disease years. GroundCover issue 128 May-June www.grdc.com.au/resources-and-publications/groundcover/groundcover-issue-128-may-june-2017/varieties-an-escape-route-in-heavy-disease-years
- Forknall CR, Simpfendorfer S, Kelly AM (2019) Using yield response curves to measure variation in the tolerance and resistance of wheat cultivars to *Fusarium* crown rot. *Phytopathology* (accepted) doi.org/10.1094/PHYTO-09-18-0354-R
- Fowler R, Platz G (2017) Increased levels of net form of net blotch in Commander and Shepherd. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/increased-levels-of-net-form-of-net-blotch-in-commander-and-shepherd
- FRAC (2018) FRAC Code List ©*2018: Fungicides sorted by mode of action (including FRAC Code numbering) www.frac.info/docs/default-source/publications/frac-code-list/frac_code_list_2018-final.pdf?sfvrsn=6144b9a_2
- Galloway (2018) Finding the safe planting window for blackspot. Department of Primary Industries and Rural Development www.agric.wa.gov.au/n/5582
- Garrett KA, Kabbage M, Bockus WW (2004) Managing for fine-scale differences in inoculum load: seeding patterns to minimize wheat yield loss to take-all. *Precision Agriculture* **5**, 291-301
- Goodwin SB (2007) Back to basics and beyond: increasing the level of resistance to *Septoria tritici* blotch in wheat. *Australasian Plant Pathology* **36**, 532-538
- Gupta VVSR, McKay A, Diallo S *et al.* (2012) *Rhizoctonia solani* AG8 inoculum levels in Australian soils are influenced by crop rotation and summer rainfall. *Proceedings of 7th Australasian Soilborne Diseases Symposium*, Fremantle p33
- Horbury R (2016). Control of blackleg with soil and foliar fungicides. www.farmtrials.com.au/trial/18665
- Hüberli D, Gajda K, Connor A, Van Burgel A (2017) Choosing the best yielding wheat and barley variety under high crown rot. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/choosing-the-best-yielding-wheat-and-barley-variety-under-high-crown-rot
- Kabbage M, Bockus, WW (2002) Effect of placement of inoculum of *Gaeumannomyces graminis* var. *tritici* on severity of take-all in winter wheat. *Plant Disease* **86**, 298-303
- Kennedy TF, McDonald JG, Connery J, Purvis G (2010) A comparison of the occurrence of aphids and barley yellow dwarf virus in minimum-till and conventional-till autumn sown cereals. *The Journal of Agricultural Science* **148**, 407-419
- Kirkegaard JA, Hunt JR (2010). Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- Kirkegaard JA, Simpfendorfer S, Holland J *et al.* (2004). Effect of previous crops on crown rot and yield of durum and bread wheat in northern NSW. *Australian Journal of Agricultural Research* **55**, 321-334
- Lehmensiek A, Platz GJ, Mace E *et al.* (2007) Mapping of adult plant resistance to net form of net blotch in three Australian barley populations. *Australian Journal of Agricultural Research* **58**, 1191-1197

- Liu C, Ogonnaya FC (2015) Resistance to *Fusarium* crown rot in wheat and barley: a review. *Plant Breeding* **134**, 365-372
- Luck J, Spackman M, Freeman A *et al.* (2011) Climate change and diseases of food crops. *Plant Pathology* **60**, 113-121
- MacLeod WJ, MacNish GC, Thorn CW (1993) Manipulation of ley pastures with herbicides to control take-all. *Australian Journal of Agricultural Research* **44**, 1235-1244
- Manshadi AM, Christopher J, deVoil P, Hammer GL (2006). The role of root architectural traits in adaptation of wheat to water-limited environments. *Functional Plant Biology* **33**, 823-837
- Marcroft SJ, Van de Wouw AP, Salisbury PA *et al.* (2012) Effect of rotation of canola (*Brassica napus*) cultivars with different complements of blackleg resistance genes on disease severity. *Plant Pathology* **61**, 934-944
- McCallum M (2007). Multiple benefits from inter-row sowing with 2 cm RTK GPS. *Proceedings of 5th Australian Controlled Traffic and Precision Agriculture Conference*, University of Western Australia pp 118-121
- McDonald GK, Peck D (2009). Effects of crop rotation, residue retention and sowing time on the incidence and survival of *ascochyta* blight and its effect on grain yield of field peas (*Pisum sativum* L.). *Field Crops Research* **111**, 11-21
- McKay A, Bogacki P, Desbiolles J *et al.* (2014) Rhizoctonia control improved by liquid banding of fungicides. Grains Research Australia Adviser Update, Adelaide South Australia pp 245-249
www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/02/rhizoctonia-control-improved-by-liquid-banding-of-fungicides
- McKirdy SJ, Jones RAC (1997) Effect of sowing time on barley yellow dwarf virus infection in wheat: virus incidence and grain yield losses. *Australian Journal of Agricultural Research* **48**, 199-206
- McLean MS, Howlett BJ, Hollaway GJ (2009) The epidemiology and control of spot form of net blotch (*Pyrenophora teres f. maculata*) of barley: a review. *Crop and Pasture Science* **60**, 303-315
- McLean M, Hollaway G (2015) Spot form of net blotch yield loss and management in barley using fungicides and resistance in Victoria. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/02/spot-form-of-net-blotch-yield-loss-and-management
- Mehmood Y, Sambasivam P, Kaur S *et al.* (2017) Evidence and consequences of a highly adapted clonal haplotype within the Australian *Ascochyta rabiei* population. *Frontiers in Plant Science* **8**, article 1029
doi.org/10.3389/fpls.2017.01029
- Melloy P, Hollaway G, Luck J *et al.* (2010) Production and fitness of *Fusarium pseudograminearum* inoculum at elevated carbon dioxide in FACE. *Global Change Biology* **16**, 3363-3373
- Milgate A, Baxter B (2018) Management of crown rot in southern NSW farming systems. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/02/management-of-crown-rot-in-southern-nsw-farming-systems
- Moore K, Verrell A, Aftab M (2014) Reducing risk of virus disease in chickpea through management of plant density, row spacing and stubble – 2013 trials in northern NSW. GRDC Grains Research Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/03/reducing-risk-of-virus-disease-in-chickpeas
- Moya-Elizondo EA (2013) *Fusarium* crown rot disease: biology, interactions, management and function as a possible sensor of global climate change. *Ciencia Investigacion Agraria* **40**, 235-25
- Murray GM, Brennan JP (2009) Estimating disease losses to the Australian wheat industry. *Australasian Plant Pathology* **38**, 558-570
- Murray GM, Heenan DP, Taylor AC (1991) The effect of rainfall and crop management on take-all and eyespot of wheat in the field. *Australian Journal of Experimental Agriculture* **31**, 645-651
- Murray GM, Welling C, Simpfendorfer S, Cole C (2005) Stripe rust: understanding the disease in wheat. (NSW Department of Primary Industries: Orange)
- Obanor F, Neate S, Simpfendorfer S *et al.* (2013) *Fusarium graminearum* and *Fusarium pseudograminearum* caused the 2010 head blight epidemics in Australia. *Plant Pathology* **62**, 79-91
- Ophel-Keller K, McKay A, Hartley D *et al.* (2008) Development of a routine DNA-based testing service for soilborne diseases in Australia. *Australasian Plant Pathology* **37**, 243-253
- Pankhurst CE, Hawke BG, McDonald HJ *et al.* (1995a) Evaluation of soil biological properties as potential bioindicators of soil health. *Australian Journal of Experimental Agriculture* **35**, 1015-1028
- Pankhurst CE, McDonald HJ, Hawke BG (1995b) Influence of tillage and crop rotation on the epidemiology of *Pythium* infections of wheat in a red-brown earth of South Australia. *Soil Biology and Biochemistry* **27**, 1065-1073
- Petronaitis T, Forknall C, Simpfendorfer S (2018) Microwave radiation reduces survival of *Fusarium pseudograminearum* in durum wheat stubble. *Australasian Plant Pathology* **47**, 375-378

- Platz GJ, Bell KL, Rees RG, Galea VJ (2000) Pathotype variation of the Australian net blotch population. *Proceedings of 8th International Barley Genetics Symposium III*, 160-162
- Poole NF, Wylie T (2017) New fungicides and disease management strategies for wheat and barley. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/03/new-fungicides-and-disease-management-strategies-for-wheat-and-barley
- Pratt J, Salam K (2018) Canola blackleg spore maturity forecast for Western Australia www.agric.wa.gov.au/n/6989
- Preston C (2019) The Australian Glyphosate Sustainability Working Group www.glyphosateresistance.org.au/
- Rahman L, Chan KY, Heenan DP (2007) Impact of tillage, stubble management and crop rotation on nematode populations in a long-term field experiment. *Soil & Tillage Research* **95**, 110-119
- Richards RA, Rebetzke GJ, Watt M *et al.* (2010) Breeding for improved water productivity in temperate cereals: phenotyping, quantitative trait loci, markers and the selection environment. *Functional Plant Biology* **372**, 85-97
- Roget DK, Neate SM, Rovira AD (1996) Effect of sowing point design and tillage practice on the incidence of rhizoctonia root rot, take-all and cereal cyst nematode in wheat and barley. *Australian Journal of Experimental Agriculture* **36**, 683-693
- Rovira AD (1990) The impact of soil and crop management practices on soil-borne root diseases and wheat yields. *Soil Use and Management* **6**, 195-200
- Simpfendorfer S (2012). Inter-row sowing reduces crown rot in winter cereals. *Proceedings of First International Crown Rot Workshop for Wheat Improvement* Narrabri, NSW
- Simpfendorfer S (2016a) Impact of common root rot and crown rot on wheat yield. NSW DPI Northern Grains Research Results, Tamworth NSW p125
- Simpfendorfer S (2016b) Crown rot – does cereal crop or variety choice matter? GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/crown-rot-does-cereal-crop-or-variety-choice-matter
- Simpfendorfer S, Street M (2017) Evaluation of fungicide management strategies to control spot form of net blotch in barley. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/evaluation-of-fungicide-management-strategies-to-control-spot-form-of-net-blotch-in-barley
- Simpfendorfer S, Kirkegaard JA, Heenan DP, Wong PTW (2002) Reduced early growth of direct drilled wheat in southern New South Wales: Role of root inhibitory pseudomonads. *Australian Journal of Agricultural Research* **53**, 323-331
- Simpfendorfer S, Heenan DP, Kirkegaard JA *et al.* (2004) Impact of tillage on lupin growth and the incidence of pathogenic fungi in southern New South Wales. *Australian Journal of Experimental Agriculture* **44**, 53-56
- Simpfendorfer S, Fensbo F, Shapland R (2014) Targeted application improves efficacy of in-crop fungicides against crown rot in wheat. *Proceedings of 8th Australian Soilborne Diseases Symposium*, Hobart
- Sprague SJ, Marcroft SJ, Hayden HL, Howlett BJ (2006) Major gene resistance to blackleg in *Brassica napus* overcome within three years of commercial production in south-eastern Australia. *Plant Disease* **90**, 190-198
- Summerell BA, Burgess LW (1988) Stubble management practices and the survival of *Fusarium graminearum* Group 1 in wheat stubble residues. *Australasian Plant Pathology* **17**, 88-93
- Summerell BA, Burgess LW (1989) Factors influencing survival of *Pyrenophora tritici-repentis*: stubble management. *Mycological Research* **93**, 38-40
- Sweetingham MW (1986) Research into lupin root diseases. *Journal of the Department of Agriculture, Western Australia, Series 4* **27** (2), Article 4 www.researchlibrary.agric.wa.gov.au/journal_agriculture4/vol27/iss2/4
- Sweetingham MW, Loughman R, Porritt SE (1993) Cereal stubble mulching protects lupins from brown spot (*Pleiochaeta setosa* [Kirchn.] Hughes). *Australian Journal of Experimental Agriculture* **33**, 469-473
- Thompson JP, Owen KJ, Stirling GR, Bell KL (2008) Root-lesion nematodes (*Pratylenchus thornei* and *P. neglectus*): a review of recent progress in managing a significant pest of grain crops in northern Australia. *Australasian Plant Pathology* **37**, 235-242
- Ugalde D, Brungs A, Kaebnick M *et al.* (2007) Implications of climate change for tillage practices in Australia. *Soil & Tillage Research* **97**, 318-330
- van den Berg F, Paveley ND, Bingham IJ, van den Bosch F (2017) Physiological traits determining yield tolerance of wheat to foliar diseases. *Phytopathology* **107**, 1468-1478
- Van de Wouw AP, Marcroft SJ, Ware A *et al.* (2014) Breakdown of resistance to the fungal disease, blackleg, is averted in commercial canola (*Brassica napus*) crops in Australia. *Field Crops Research* **166**, 144-151
- Van de Wouw AP, Howlett BJ, Idnurm A (2017) Changes in allele frequencies of avirulence genes in the blackleg fungus, *Leptosphaeria maculans*, over two decades in Australia. *Crop and Pasture Science* **69**, 20-29

- Vanstone VA, Hollaway GJ, Stirling GR (2008) Managing nematode pests in the southern and western regions of the Australian cereal industry: continuing progress in a challenging environment. *Australasian Plant Pathology* **37**, 220-234
- Verrell A (2014) Managing crown rot through crop sequencing and row placement. GRDC Update www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/07/managing-crown-rot-through-crop-sequencing-and-row-placement
- Verrell AG, Simpfendorfer S, Moore KJ (2017) Effect of row placement, stubble management and ground engaging tool on crown rot and grain yield in a no-till continuous wheat sequence. *Soil & Tillage Research* **165**, 16-22
- West JS, Kharbanda PD, Barbetti MJ, Fitt BDL (2001) Epidemiology and management of *Leptosphaeria maculans* (phoma stem canker) on oilseed rape in Australia, Canada and Europe. *Plant Pathology* **50**, 10-27
- Wildermuth GB, Tinline RD, McNamara RB (1992) Assessment of yield loss caused by common root rot in wheat cultivars in Queensland. *Australian Journal of Agricultural Research* **43**, 43-58
- Wildermuth GB, Thomas GA, Radford BJ *et al.* (1997) Crown rot and common root rot in wheat grown under different tillage and stubble treatments in southern Queensland, Australia. *Soil & Tillage Research* **44**, 211-224

Chapter 12

New approaches to manage invertebrate pests in conservation agriculture systems – uncoupling intensification

Michael Nash, Dusty Severtson and Sarina Macfadyen

Invertebrate threats to broadacre agriculture in Australia

A large diversity of invertebrate species has been recorded on broad-acre grain farms across Australia, both pests and beneficials (natural enemies, pollinators and nutrient-cyclers). Many have the potential to cause economic damage, but often do not reach high enough densities, or only infrequently feed on commercial crops. Likewise, some species are considered beneficial in certain contexts but cause crop damage in others (*e.g.* earwigs, Horne and Edward 1995). Overall direct economic losses from invertebrate pests have been estimated at \$359 million annually (Murray *et al.* 2013). Factors, such as the evolution of resistance, withdrawal of pesticides from registration and market access, all have the potential to make management of pests costlier.

Changes to management practices, such as the widespread uptake of Conservation Agriculture (CA) (see Chapter 2) have contributed to shifts in pest complexes over the last 30 years (Hoffmann *et al.* 2008, Nash and Hoffmann 2012). The negative perception of increased pest problems in CA contrasts with the potential for increased biodiversity (Loreau *et al.* 2003), ecosystem services (Gurr and Wratten 2004) and increased production (Tilman *et al.* 1996). In this chapter we consider why pests (*e.g.* slugs and snails) may become problems in CA in Australia, or with the intensification of agriculture that is facilitated by CA (*e.g.* aphids). We explore why they become problems for farmers by considering the processes impacting the population dynamics of these species, and new technologies that can help to maintain sound pest management principles within CA systems.

Foundational pest management concepts that rely on invertebrate monitoring

Attributing damage to specific pest species under a variety of management and climatic conditions is difficult given the diversity of potential pest species. Furthermore, conclusively demonstrating that increased or decreased risk of a pest outbreak is due to adoption of one or more CA practices is challenging given the many factors involved. A review by Macfayden *et al.* (2019) concluded “*The ability to predict when and where pests will cause yield loss in grain crops across Australia is limited.*” This is due to a lack of knowledge about:

- individual species distribution;
- pest interaction with crop plants, and physiology, that influence population increase;
- the interactions between invertebrate species under different environmental conditions; and
- *ad-hoc* monitoring of invertebrates in broad-acre farming systems

We suggest the attribution of increased pest threats to CA is weak and suspect that in the case of Australian grain production systems, current pest outbreaks are more an issue of availability of resources, mainly moisture (Nash and Hoffmann 2012) and farm labour. That is, broad-acre farmers do not have time to monitor large areas at key times (establishment) and agronomists used for crop scouting are not paid enough to monitor crops more than once a fortnight. Therefore, the population build-up that precedes a pest outbreak is not well documented, and the contributing factors are often not clear.

Integrated Pest Management (IPM) as a concept was pioneered by Stern *et al.* (1959) and adopted in some farming systems in Australia. It is based on an understanding of pest and beneficial dynamics, economic thresholds, monitoring of pest and natural enemy populations to select appropriate control methods, and avoidance of the use of broad-spectrum pesticides. These guidelines have been adopted cautiously by a small proportion of grain growers (Horne *et al.* 2008). Ideally, pest control decisions

should take place within the context of the entire agro-ecosystem (Smith 1962), using “sound ecological information about pests and their crop environment” (Kogan 1998). A more limited IPM paradigm, heavily reliant on monitoring and management responses based on thresholds that limit disruption to natural enemies (Dent 1995), has been extended by the Australian grains industry to growers.

Precision Pest Management, is an extension of Precision Agriculture (PA), that makes soil and crop management decisions to fit the specific conditions found within each field (Strickland *et al.* 1998). The accurate and precise application of pesticides made possible within PA aims to reduce over-use, leaching, runoff, and non-target impacts (Brenner *et al.* 1998). This should, in theory, reduce negative environmental effects and thus most importantly improve environmental stewardship (Strickland *et al.* 1998).

Pesticides – are agrochemicals applied to protect crops from weeds diseases and invertebrates. We refer to **Insecticides** specifically as agrochemicals that control insect pests, as are other ‘-cides’ for specific invertebrate groups.

The theory versus the practice of CA and pest control

In theory, adoption of CA (Chapter 1 for definition) should lead to reduced crop losses from pests, a reduction in agro-chemical use and, therefore, more profitable farming systems. In practice, pest problems frequently are reported to limit yields in CA systems around the world (Fanadzo *et al.* 2018). If CA is implemented fully, this management approach would include a diversity of tactics to reduce pest populations including:

- use of diverse crop rotations, including cover crops;
- use of cultivars resistant to, or tolerant of, pests;
- careful selection of planting dates (see Chapter 18) and planting density; and
- shrewd use of pesticides (Figure 1).

Crop rotation has been effectively used for many years to break the life-cycles of pests. By planting non-host crops, pests are denied a food source during a critical life stage. However, the diversity in crop rotation choices in some parts of Australia is somewhat limited. Cover crops and crop residues may be important for increasing the populations of natural enemies. However, soil-dwelling pests such as slugs, snails, cutworms and rodents can also benefit from residue retention and therefore prevention from desiccation. Finally, cooler ground conditions due to retained stubble (see below changes to microclimate) cause slower seedling emergence rates allowing pests more time to cause damage to emerging crops. There are many interactions between the adoption of CA practices, the consequences of the change to the crop environment, and pest population dynamics (Figure 1). We illustrate some of these trade-offs and complexities of CA and pest management using specific pest species below.

Specific pest interactions with CA

Slugs and snails Molluscs are associated with farming systems that retain stubble and reduce tillage (Glen and Symondson 2003, Figure 1). Several exotic snail and slug species of European-Mediterranean origin have established in Australia and become significant pests of grain crops (Baker 2002). These include: common white snail [*Ceratomyxa virgata* (Da Costa)], pointed snail [*Cochlicella acuta* (Müller)], small pointed snail [*Priocella barbara* (L.)] (Hygromiidae), white Italian snail [*Theba pisana* (Müller) (Helicidae)], blacked keeled slug [*Milax gagates* (Draparnaud) (Milacidae)], grey field slug [*Deroceras reticulatum* Müller) (Agriolimacidae)] (Micic *et al.* 2008), and brown field slug (*D. invadens* Reise)). The main threat from snails is related to market access, with *C. virgata* included in formal import standards (February 2015) for wheat and barley set prior to the China-Australia Free Trade Agreement. The Chinese market is worth AU\$1.5 billion (ABARES 2014) to Australia and is estimated to increase the price for barley growers from AU\$20 to AU\$40 per tonne. Previous contamination issues (*e.g.* Korea 2012) highlight the potential cost snails pose to the grains industry, when a major market restricts access due to a quarantine breach. Slugs are particularly damaging to establishing canola (Gu *et al.* 2007), with yield losses in untreated areas of field trials of up to 80% (GRDC report DAS00134). It has been demonstrated that slug numbers are greater in the absence of

natural enemies (Nash *et al.* 2008). The over-use of insecticides and soil tillage reduce the numbers of large generalist predators such as carabid and rove beetles (Nash *et al.* 2008). Therefore, CA systems that reduce negative impacts on beneficial species, in theory should experience fewer problems from slugs and snails due to higher mortality from natural enemies. However, this has not been the experience of many grain producers in Australia, and there are case studies where pesticides have been implicated in crop losses due to slugs (Hill *et al.* 2017).

Green Peach Aphid It has been estimated that, for aphid species found in Australian crops, direct feeding and virus injuries result in potential economic costs of \$AU241 and \$AU482 million per year, respectively (Valenzuela and Hoffmann 2015). We focus on the green peach aphid [*Myzus persicae* Sulzer (1776) (Hemiptera: Aphididae)] as, economically, it is the most important aphid crop pest worldwide (van Emden and Harrington 2007). Several factors have enhanced its status as a pest, including its wide distribution, host range, mechanisms of plant damage, life cycle, capacity to disperse and ability to evolve resistance to insecticides (Bass *et al.* 2014). Green peach aphid reproduces asexually under Australian conditions and, combined with a short generation time, this allows populations to increase rapidly under favourable conditions to quickly reach damaging numbers (Vorburger *et al.* 2003). In addition, this mode of reproduction has significant implications for population genetics (Wilson *et al.* 2002) and the continuing evolution of insecticide resistance (de Little and Umina 2017). Grain farmers manage the risk of plant viruses vectored by green peach aphid using aphidicides; either seed treatments or sprays once the crop has emerged. The control of green peach aphid on many crops has relied almost exclusively on the use of chemicals, with intensive use over the last 50 years leading to the evolution of widespread and multiple forms of resistance (Bass *et al.* 2014). Resistance is now confirmed for most classes of aphidicides registered for use in Australia, including the organophosphates, carbamates, pyrethroids, and neonicotinoids (Umina *et al.* 2018). Insecticide resistance management strategies (IRM) that are implemented by agricultural industries, are essential if the utility of current and future insecticides is to be preserved (Sparks and Nauen 2015). We believe CA practices can provide growers with a production system that facilitates the shift away from intensive agro-chemical usage, thus mitigating current threats posed by pests that evolve quicker than the development of new chemical classes and pesticide products. However, to achieve this the adoption of CA practices needs to be uncoupled from the use of pesticides and implemented with IPM.

Pest management remains one of the greatest challenges for the adoption and continued use of CA practices and, in most farming systems, the adoption of CA practices leads to greater use of agro-chemicals. Although CA does not automatically necessitate the greater use of pesticides, this may arise where integrated pest or weed management is not practised within the CA system and therefore a heavy reliance on pesticides exists (Figure 1). Often full adoption of CA is unlikely to occur (or only partially occurs) in situations where there is little or no access to cost-effective pesticides that work. For example, in small-holder farms across Africa the adoption of CA practices has been low due to limited access to pesticides to prevent losses from pests, especially weeds (Thierfelder *et al.* 2018). In contrast, in systems with easy access to low cost pesticides (*e.g.* Australia), over-use has exacerbated pest issues through resistance evolution (Gould *et al.* 2018) and secondary pest outbreaks (Hill *et al.* 2017) due to loss of natural enemies.

Other factors that lead to variable outcomes in relation to CA practices include time since adoption and how this interacts with the response of individual species to the removal of tillage. It may take some years for populations of pests in a no-till (NT) field to increase to a level where they ultimately cause crop damage. Even then, it may only be in specific environmental conditions (*e.g.* warm, dry) in which pests feed on crop plants. Furthermore, both pest and natural enemy species can respond differently to tillage. For example, Marti and Olson (2007) recorded more aphids, ants and ladybeetles with less tillage, while lacewings, spiders and fungal pathogens showed no difference between tillage treatments. Petit *et al.* (2017) showed that cereal fields that adopted CA over four years prior had high abundance of beneficial, predatory carabid beetles. These examples suggest that CA should lead to benefits for farmers, but this is not always the case. For example, Brainard *et al.* (2016) in the US, showed in a vegetable system that complete adoption of CA resulted in greater pest and cover crop management costs.

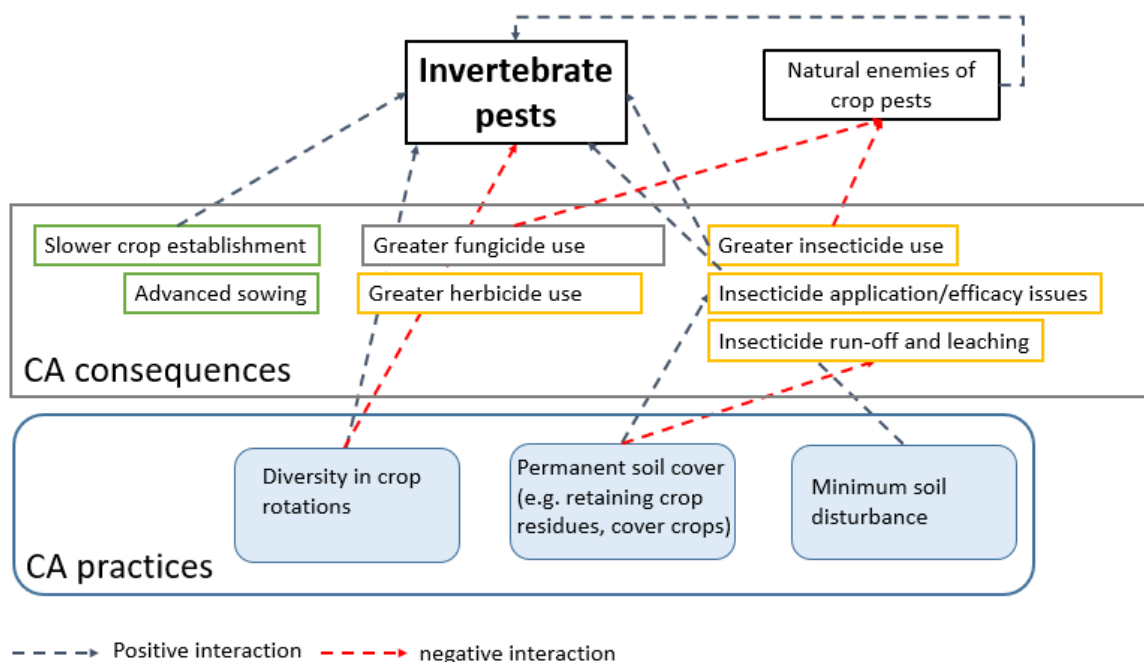


Figure 1. The potential impact of conservation agriculture on invertebrate pest management. Note that the conservation agriculture practices themselves and other changes to the system that often occur in response to adoption both have impacts on pests and natural enemies

Changes in crop environment and how they interact with CA and pest management

Changes in climate and microclimate

Along with increased adoption of reduced tillage and stubble retention, there have been fundamental changes to climate, crop rotations used by farmers and pesticide use patterns. These may all interact and impact pest populations. Efficient water use is critical to the success of dryland farms in water limited environments, *i.e.* most areas of Australia (Nash and Hoffmann 2012). Likewise, many Australian invertebrate pest species have become adaptive strategists that can use and respond successfully to low and unpredictable water resources (Greenslade 1983). The influence of climate change on pest species has been examined in various farming systems (Thomson *et al.* 2010, Macfadyen *et al.* 2018), with a consensus that there will be a change in species threatening crops, not only between seasons but over longer timeframes. Farm management continues to respond to climate change generating the ongoing need for adaptive management of pests in this context (Sutherst *et al.* 2011).

Retaining stubbles influences the microclimate experienced by invertebrates through cooler soil temperatures (Malhi and O'Sullivan 1990), and therefore slower establishing crops (Figure 1). Slow crop establishment leads to seedlings being exposed to herbivory for greater periods of time (Gu *et al.* 2007). In the case of pest-sensitive crops such as canola (*Brassica napus*), IPM recommendations often include:

- selection of cultivars that have vigorous seedling growth (*e.g.* hybrid cultivars);
- sowing larger seed (canola >2 mm); and
- avoidance of some seed treatments that slow establishment (*e.g.* Cosmos® BASF containing fipronil 500 g/L).

Conversely, stubble retention aids moisture conservation near the soil surface (Monzon *et al.* 2006) enabling crops to be sown earlier (see Chapter 18). Early, dry sowing, due to a less reliable seasonal break and autumn/winter rainfall decline (Cai and Cowan 2013), has some benefits for crop growth:

deeper roots, improved seedling vigour in warmer soils, greater weed competition, greater radiation interception and reduced evaporation have all been recorded.

Crop establishment in conservation agriculture

Timely application of pest control during a busy sowing program can be problematic. Growers are therefore naturally drawn towards cost effective prophylactic application of agro-chemicals (Nash and Hoffmann 2012). For example, pest earth mites (*e.g.* red-legged earthmite, RLEM [*Halotydeus destructor* (Tucker)]) are generally considered a key establishment pest of canola (Gu *et al.* 2007), yet Umina *et al.* (2015) only observed significantly greater yield in one small plot experiment in a canola field, out of a total of four experiments. Hill *et al.* (2017) found no benefit in applying miticides despite pest mite presence in a south west Victorian field and lower numbers of carabid and rove beetles were observed in areas treated with a broad-spectrum insecticide, resulting in subsequent higher slug numbers. However, overall yield responses were not conclusive (Hill *et al.* 2017). That study highlights that growers often ignore invertebrate communities when considering sowing times; yet changing planting date would reduce canola exposure to pests at the key establishment stage. For example, slugs become active in mid-May when canola has been sown traditionally; with soil moisture above 25% v/v canola seedlings are more susceptible to herbivory and slower to establish than when sown in April. The current shift to earlier sowing of canola crops in Australia has enabled them to establish quicker and be at a less susceptible growth stage (*i.e.* GS 1.4-1.6) by the time slugs become active (M Nash *personal observations*). Conversely, early sowing of canola, in April, may lead to increased risk of virus transmission due to actively migrating green peach aphids (Henry and Aftab 2018).

Current pesticide use-patterns

Theoretically, the adoption of CA practices should not necessitate greater use of pesticides. In practice, adoption of NT can lead to a greater reliance on herbicides to control weeds, and in some cases a greater use of insecticides and fungicides in response to greater pest populations (Figure 2). Over the last 30 years, an increase in use of low cost agro-chemicals has been observed (Gould *et al.* 2018) across large geographic scales. The challenge is to support growers to limit inputs, enabling them to take advantage of premium markets that stipulate low or below detectable minimum chemical residue limits (MRLs) in products. In line with international trends, data compiled from the Australian Pesticides and Veterinary Medicines Authority (APVMA) suggest an increase in total agricultural chemical sales, year on year, of AU\$40 million. Specific pest reports in relation to adoption of CA are not clear. However, some pests have increased in association with pesticide use with the worldwide trend of agricultural intensification (Tilman *et al.* 2002) through reduction in biodiversity and biological control (Geiger *et al.* 2010). To understand further if the ecosystem service of pest control by natural enemies is being maintained in CA first we must answer the question: Has insecticide usage in Australia increased since the inception of CA in Australia?

To examine the changes in insecticide usage in Australia expenditure records from APVMA are presented in Figure 2. Total expenditure in Australia for 2016/17, to protect all agricultural crops from invertebrate pests, including horticulture, grazing and broadacre, was AU\$613 million. There has been a decline in insecticide sales since the early 2000s, due in large part to insecticide reductions applied to cotton to control cotton bollworm following release of GM Bollgard II® cultivars in 2003. At this time, selective insecticides were available, economic validation occurred, and an industry-wide extension campaign led to widescale adoption of IPM in cotton (Wilson *et al.* 2018). If data prior to full uptake of new cotton technologies are excluded (Bollgard II®), then expenditure on insecticides has increased since 2006/07 by AUD\$20 million, year on year (Figure 2). APVMA data support previous studies that suggest that pest control in arable farming systems is still reliant on broad-spectrum insecticides (Nash and Hoffmann 2012, Macfadyen *et al.* 2014); many growers have not adopted IPM despite heavy investments into research and extension by the grains industry (Macfadyen *et al.* 2014) and the ever-increasing threat of resistance (Umina *et al.* 2018).

Despite mites (Acari: Penthaleidae), including red legged earth mite and blue oat mite [*Penthaleus* spp.] being considered a significant pest in pastures and other broadacre enterprises (Murray *et al.* 2013),

miticide expenditure has declined since 1999 by AU\$1 million year on year (Figure 2). The extremely variable expenditure (AU\$15,149,239-AU\$72,632,850) is most likely due to these pests causing economic damage only occasionally; often control is not required (Hill *et al.* 2017).

Insecticides are applied as seed treatments to prevent damage from aphids, which transmit viruses and suppress mites, and lucerne flea activity [*Sminthurus viridis* (Collembola: Sminthuridae)]. The APVMA data suggest that expenditure on seed treatments has remained relatively stable across time (Figure 2). However, expenditure jumped in 2016/17 by AU\$17 million (34%) and remained so in 2017/18, despite a decrease in the price growers paid for imidacloprid, the dominant insecticide applied to seed, and fluquinconazole, a fungicide applied to canola seed, due to generic products becoming available on the Australian market. We suspect the increased expenditure is in response to imidacloprid being applied to cereals to protect plants from the Russian wheat aphid (Kirkland *et al.* 2018), which first appeared in Australian cereal fields in 2016 (Yazdani *et al.* 2018).

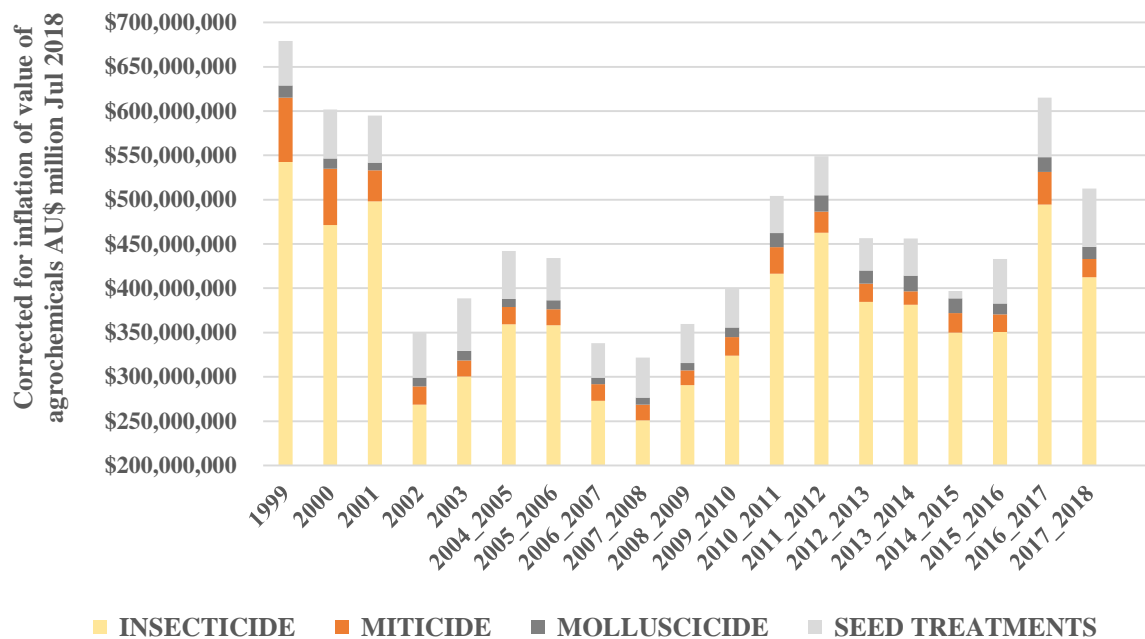


Figure 2. Value of pesticides applied to protect crops in Australia from Invertebrates presented as a yearly breakup of agricultural chemical sales into various APVMA classes (APVMA data accessed 28 Mar2019) since 1999, corrected for inflation. Note reporting of data changed in 2003 from end of year to end of financial year. Drought occurred in many regions of Australia from 2001-2009

Molluscicides applied to control slugs and snails are separated in the APVMA data, and expenditure has increased consistently across time (Figure 2). We believe slugs and snails are adapting to the adoption of CA and, in some areas (*e.g.* south west Victoria), are forcing growers to use tillage and burning for cultural control of these pests. The impacts of over-reliance on pesticide application in biological communities (Geiger *et al.* 2010) in fields managed under CA needs to be separated from invertebrate responses arising from CA (see Figure 1). Otherwise this may lead to dis-adoption of CA in contexts where changes to pesticide use alone may have beneficial effects.

Solutions to pest challenges in conservation agriculture

Along with the adoption of CA over the past four decades (see Chapter 2), there has been an increasing reliance on broad-spectrum synthetic insecticides to protect crops from economic damage caused by arthropod pests (Macfadyen *et al.* 2014, Figure 2). However, the evolution of resistance and the non-target impacts to beneficials have led to advances in pest management tactics; *i.e.* strategies that target pest species and minimise adverse effects on non-target species (Horowitz and Ishaaya 2013). Several studies have demonstrated that the adoption of sampling plans for pests in field crops has led to a

reduction in pesticide usage and improved pest management (Serra *et al.* 2013, Stubbins *et al.* 2014). It is important that broad-acre farmers in CA systems realise the value of this new suite of monitoring and decision support tools to manage pests sustainably. The rise of digital technologies (see Chapter 24) will aid farm management generally, although we only consider technologies specific to monitoring pests here.

Pest patchiness

Van Helden (2010) described the spatial and temporal dynamics of arthropod pests in arable crops in the context of precision pest management. Spatial heterogeneity of arthropod distributions in field crops are driven by a wide range of factors including plant phenology, *e.g.* leaf age (Kennedy and Booth 1951) and growth stage (Ferguson *et al.* 2003), as well as land topography (Hill and Mayo 1980), distance from crop edge (Severtson *et al.* 2015), host plant chemistry (Nowak and Komor 2010) and host plant sensory cues (Powell *et al.* 2006). An example of this spatial variability at the field level is provided in Figure 3. In a single field in Western Australia we measured, at a fine resolution, canola plant density and plant growth characteristics, as well as the spatial distribution of multiple aphid species. The distribution of cabbage aphids and green peach aphids differed between pest species and by sampling technique (visual inspection on leaves and racemes and sweep netting – Figure 3vi-xi). The patterns seen across the field (Figure 3) show strong edge effects where aphids were more abundant around the edge of the field. This information could be used to the advantage of the field operator by targeting pest scouting to areas where the arthropod pests are most likely to occur first.

Characterisation of spatial distribution patterns of arthropod pests in large-scale agricultural fields is important because it affects the sampling effort needed to estimate their population density. Some methods include Spatial Analysis by Distance IndicEs (SADIE), the sequential probability by ratio test (SPRT) and geographic information systems (GIS). SADIE was developed to detect and measure the degree of heterogeneity in spatial patterns of insect populations (Perry 1998); it has been used to identify factors which determine their spatial distribution (Ferguson *et al.* 2003, Cocu *et al.* 2005) and to improve sampling plans for pests in crops (Nansen *et al.* 2005, Reay-Jones 2014, Severtson *et al.* 2016). The SPRT has been employed to develop sequential sampling plans with reduced sampling effort and increased accuracy compared with fixed sample size methods (Severtson *et al.* 2016). GIS and geostatistics have also improved understanding of the spatial patterns of insect pests and their influence on sampling and optimisation of insecticide application (Liebhold *et al.* 1993, Dmini *et al.* 2010).

Remote sensing to improve monitoring

While manual sampling of arthropod pests is crucial to identify infestation levels, recent advances in remote sensing technology may provide methods to automate detection of plants experiencing pest-induced stress. Furthermore, advances in insect trapping technologies provide early warning of pest migration into crops before or while the insects are being colonised. Knowledge of the timing of the arrival of low densities of colonising aphids can be important to prevent the spread of crop diseases vectored by aphids, and to target surveillance activities to the fields that have been colonised.

Since the emergence of precision agriculture in the mid-1980s, technologies such as global navigation and satellite systems (GNSS) and GIS, as well as improved computing systems, have led to the site-specific or variable rate application of products, especially fertilisers (Gebbers and Adamchuk 2010). These technologies have allowed farmers to move away from ‘blanket’ or whole-of-field application of single-rate fertilisers to site-specific, variable rate application so that products are applied where they are required. Significant cost savings associated with reduced fertiliser inputs drove this technology to adoption. Site-specific or variable rate application of insecticides or other control methods have potential for similar reasons, particularly if arthropod pests can be detected early before populations cause economic damage or when minimal insecticide is required to target smaller areas of infestation. These early infestations could also be targeted with release of biological control agents. However, significant challenges to identify the arthropod pest species has slowed the development of variable-

rate insecticide applications based on pre-defined GIS files produced from canopy reflectance data acquired from remote sensors (*e.g.* drones or satellites).

Jones and Vaughan (2010) explained how abiotic (such as water stress or mineral deficiency/toxicity) and biotic stress (*i.e.* pests and diseases) cause similar responses in plants; *e.g.* decreased chlorophyll content, altered growth/biomass and stomatal closure. Classification of the plant canopy reflectance data from the main sensor platforms (thermal, spectral, fluorescence, multiangular, lidar and microwave) has been successful and with good accuracy, but the stressed plants detected often required ground-truthing to diagnose the causal agent. Diagnosing the causal agent in pest management programs is important as many arthropod pests in agriculture require insecticides with different modes of action and rates of product; more than one arthropod pest species may be present.

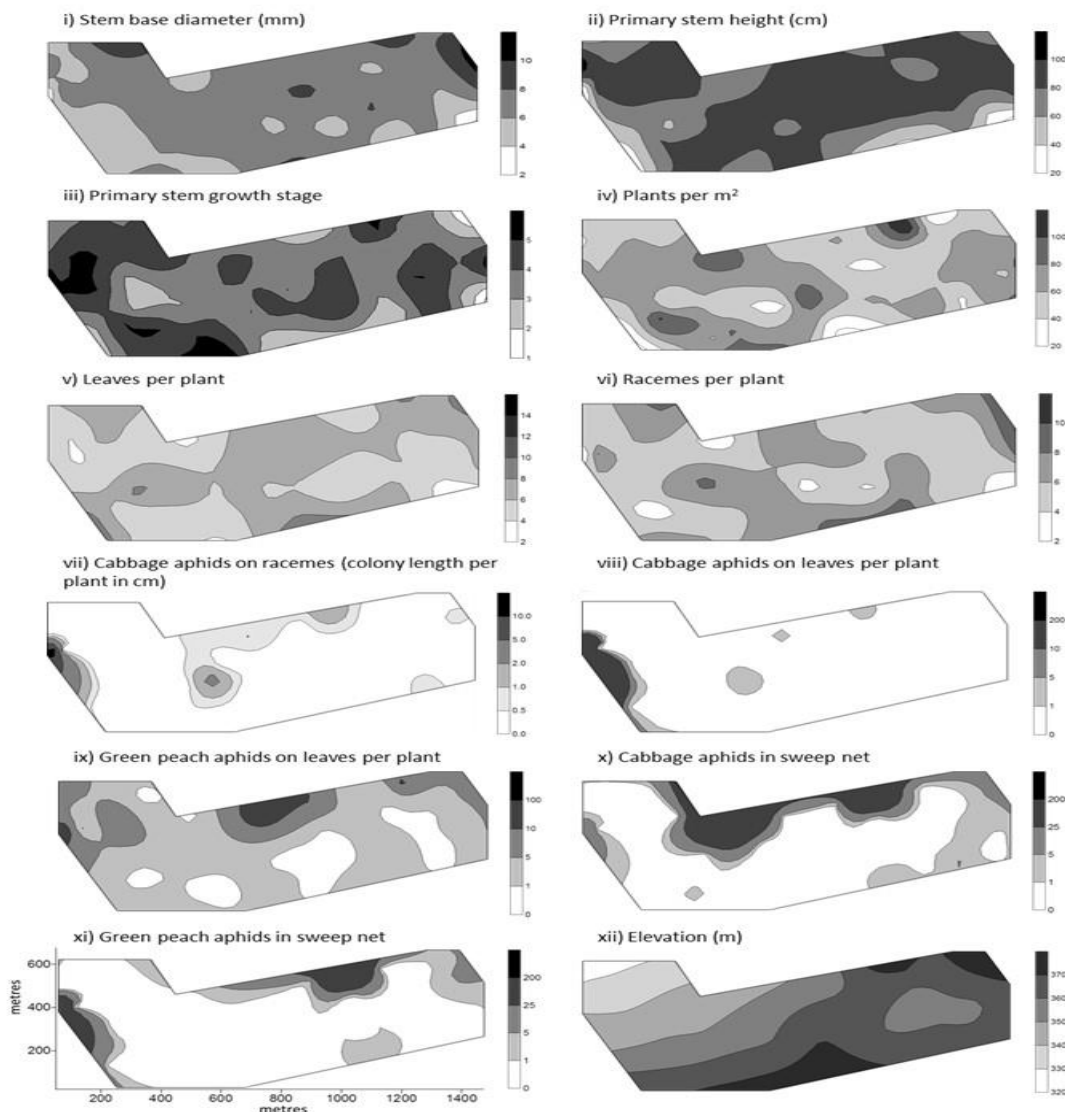


Figure 3. Spatial patterns seen in a large single field of canola near York, Western Australia, August 2013. The maps show the spatial variability in a number of factors related to plant phenology(i-vi), cabbage aphid abundance on plants and in sweep nets (vii, viii, x), green peach aphid abundance on plants and in sweep nets (ix, xi), and elevation across the field (m asl)

Machine learning and artificial intelligence may provide useful outcomes in terms of detecting specific pests responsible for plant stress reflecting complex spectral signatures without the need for ground validation (Bouroubi *et al.* 2018). Nonetheless, canopy reflectance data, such as Normalised Difference Vegetation Index (NDVI), can target pest scouting and crop monitoring efforts to parts of the crop which are experiencing stress. This is most likely to be infested with a pest, disease or other causal agent which can be strategically ground-truthed. Such targeted crop scouting of stressed regions ultimately increases detection accuracy by accounting for spatial aggregation of arthropod pests and reduces the labour required to scout field crops.

Smart traps – agriculture utilising digital technologies

Another type of technology aiding crop monitoring and decision support for arthropod pest management in CA has been termed ‘smart’ trapping. Smart trapping often refers to some sort of technology which is ‘smarter’ than a traditional manual method of trapping such as:

- The Limacapt (Anon. 2019a) system helps to count and monitor the activity of slugs throughout the night. This tool, which is more efficient than manual refuge traps (Archard *et al.* 2004), enables highly detailed analysis of the risks caused by this pest and hence provides information to enable more informed decision-making;
- The DTN Smart Trap® (Anon. 2019b) uses established pheromone lures for specific pest moth species and traditional sticky material housed within a delta-type trap. It is enhanced using remote imaging infrastructure with deep-learning algorithms to detect pests in near real-time and transmit the information via existing telecommunications networks to mobile and web platforms; and
- The Trapview® (Anon. 2019) uses a similar infrastructure with imaging and automated pest detection using algorithms and comprises a sticky conveyer belt that can be moved remotely to reveal a new round of sticky paper.

Together with remote pest detection and automated counting, predictive models are being developed which quantify the risk of caterpillar damage using the temporal moth counts and climate data. These digitally based technologies are considered a breakthrough in monitoring of highly variable pest populations when labour for scouting is limited.

Pheromone traps

The development of pheromones and semiochemicals, which attract specific insect species, has greatly improved the way field technicians trap pests (*e.g.* moths) and provide presence data as an early warning as the pest migrates into crops (El-Sayed 2018). Pheromone trapping has the benefit of being species-specific thereby saving time on specimen sorting and diagnostics. However, some groups of arthropod pests such as aphids require manual trapping via suction traps or sticky traps; this brings with them a suite of other arthropods that require sorting and diagnostics. To improve field intelligence and decision support around temporally targeted insecticide application (or not to apply in low risk scenarios), engineers have developed in-field molecular diagnostics machines which rapidly diagnose aphid species and the presence of viruses they vector prior to the aphids colonising the crop using their nucleic acids. One of these new technologies is called Loop Mediated Isothermal Amplification (LAMP). It has been used successfully to detect from yellow sticky traps green peach aphids and turnip yellows virus (TuYV) in the aphids as the canola crops were being initially colonised, providing growers with information on the risk of virus epidemics (Congdon *et al.* 2019).

Increased diversity in cropping systems

The benefits of plant diversity relative to strict monoculture include improved pest suppression and increased pollination services leading to increase yield. In some environments, mixed species cover cropping may offer a new approach in the Australian context to increase biodiversity. Previous research has focused on increasing landscape heterogeneity (Schellhorn *et al.* 2008, Thomson and Hoffmann 2010), often through the provision of diverse ‘shelterbelts’ (Tsitsilas *et al.* 2006). Provision of services from small margins into relatively large fields needs to be questioned, and the value of in-field resources

quantified further (Nash and Hoffmann 2012). Previous research indicates biodiversity needs to be provided within productive landscapes at relevant spatial scales to provide pest control. For example, in viticulture planting of native plant species between vines improved pest suppression (Danne *et al.* 2010); pollination services from bees placed every 200 m within faba bean crops increased yield by 17% (Cunningham and Le Feuvre 2013); and the inclusion of habitat for predators within UK fields improved pest control, *i.e.* beetle banks (Thomas *et al.* 2002). However, in Australia, when plantings were not at the appropriate scale beetles were not found to be greater in abundance, whereas other predators such as spiders increased (Tsitsilas *et al.* 2011). More research is needed to understand the value of increasing biodiversity for Australian farmers under the context of cost benefits for pest management and other ecosystem services.

The inclusion of polycultures, such as inter-cropping or cover cropping, may have multiple benefits under Australian conditions where fields are large, and there is a need to diversify crop cultivars, type and flowering time to minimise the risk of crop failures in dryland systems (Nash and Hoffmann 2012). An example of intercropping is the practice of sowing canola and peas together (peaola), which has been successfully used in higher rainfall zones of Australia since the 1980s and is receiving attention again (Fletcher *et al.* 2016). The growing of mixed species crops that are not harvested for grain, known as cover cropping, is a key component of some farming systems overseas (Sarrantonio and Gallandt 2003), but is yet to be adopted widely in southern Australia, mainly due to the water used by the cover crop reducing the following cash crop yield. A variant of this is pasture cropping where cash crops are sown into established native pastures, but significant impacts on grain yield reduced gross margins, but also lowered input cost and risk associated with crop failure (Millar and Badgery 2009). Historically the sowing of cereals (*e.g.* oats or barley) as cash crop into mature lucerne stands to compete with grass weeds has anecdotally been used successfully in mixed farming systems across southern Victoria and parts of NSW, but again yields are often reduced (Harris *et al.* 2007). However, few studies have linked the increased crop diversity to pest suppression or reduced risk of pest outbreaks. In one such study, there was a reduction in the number of times economic thresholds for heliothine caterpillars were exceeded in crimson clover and rye was less compared to control plots. The build-up of predators in the cover crops subsequently resulted in reduction in the level of heliothines in no-till cotton (Tillman *et al.* 2004). The provision of increased crop diversity must be quantified to link the perceived benefits of pest control to both economic and environmental outcomes.

Concluding remarks

To increase grower acceptance of invertebrates in fields, a greater understanding is required of crop damage under different management practices, and the resulting impacts on yield. The benefits provided by invertebrates can be harnessed to decrease agro-chemical usage, increase water infiltration, nutrient cycling and pollination of pulse crops, whilst improving access to premium markets. For growers to harness the benefits of CA they must also have knowledge of, and access to, a diversity of pest management approaches. Here we have outlined some of the solutions to the pest management challenges created by (or the consequence of) CA practices, including novel monitoring approaches, smart traps and ways to increase crop diversity. We emphasise that the adoption of CA practices in theory should not necessitate the greater use of pesticides, although in practice this trend is occurring in Australian systems. Uncoupling these intensification practices from CA practices is the next challenge.

References

- Anon. (2019a) www.diesel-international.com/newsmakers/sima-2019-innovations/
- Anon. (2019b) www.dtn.com/about/resource/dtn-smart-trap-brochure/
- Anon. (2019c) www.trapview.com/v2/en/
- Archard G, Bohan DA, Hughes L, Wiltshire CW (2004) Spatial sampling to detect slug abundance in an arable field. *Annals of Applied Biology* **145**, 165-173
- Baker GH (2002) Helicidae and Hygromidae as pests in cereal crops and pastures in southern Australia. In (Ed. GM Barker) "Molluscs Crop Pests" pp 193-215 (CABI Publishing: Oxon)

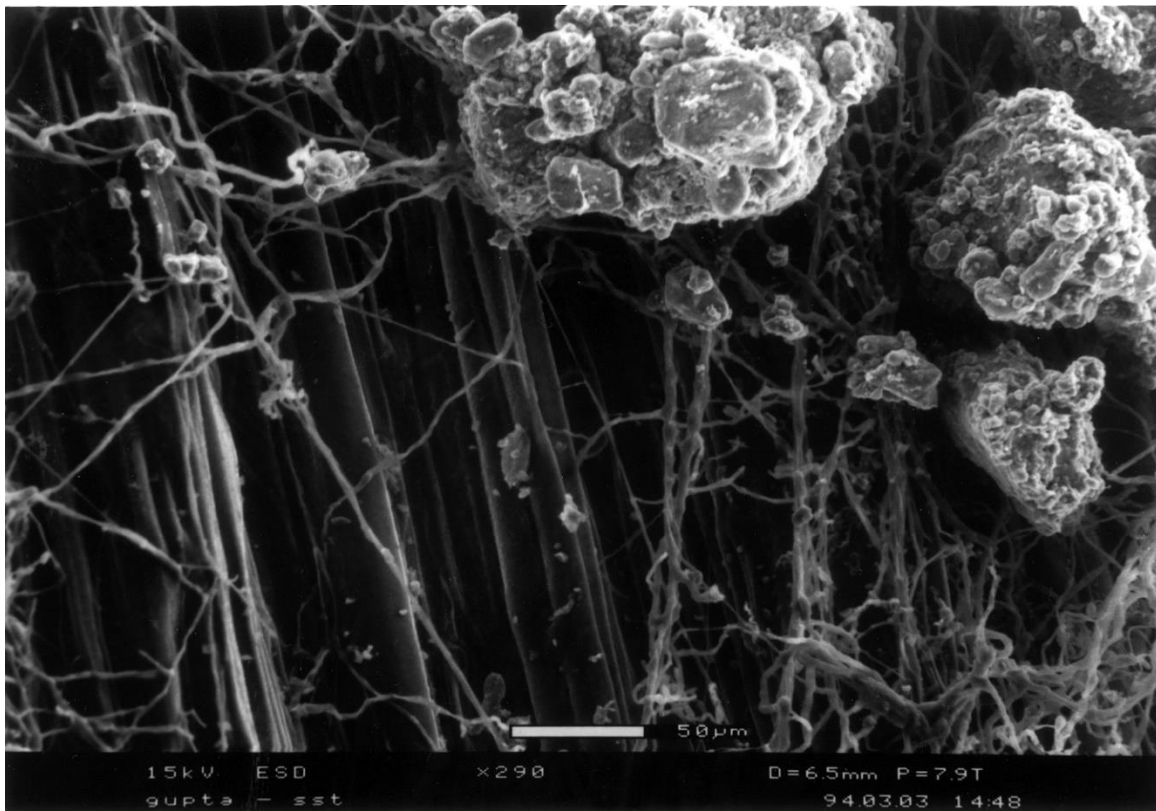
- Bass C, Puinean AM, Zimmer CT *et al.* (2014) The evolution of insecticide resistance in the peach potato aphid, *Myzus persicae*. *Insect Biochemistry and Molecular Biology* **51**, 41-51
- Bouroubi Y, Bugnet P, Nguyen-Xuan T *et al.* (2018) Pest detection on UAV Imagery using a deep convolutional neural network. *Proceedings of International Society of Precision Agriculture*: Montreal, Canada
- Brainard DC, Bryant A, Noyes DC *et al.* (2016) Evaluating pest-regulating services under conservation agriculture: A case study in snap beans. *Agriculture, Ecosystems & Environment* **235**, 142-154
- Cai W, Cowan T (2013) Southeast Australia autumn rainfall reduction: a climate change-Induced poleward shift of ocean-atmosphere circulation. *Journal of Climate* **26**, 189-205
- Cocu N, Conrad K, Harrington R, Rounsevell MDA (2005) Analysis of spatial patterns at a geographical scale over north-western Europe from point-referenced aphid count data. *Bulletin of Entomological Research* **95**, 47-56
- Congdon BS, Kehoe MA, Filardo FF, Coutts BA (2019) In-field capable loop-mediated isothermal amplification detection of turnip yellows virus in plants and its principal aphid vector *Myzus persicae*. *Journal of Virological Methods* **265**, 15-21
- Cunningham SA, Le Feuvre D (2013) Significant yield benefits from honeybee pollination of faba bean (*Vicia faba*) assessed at field scale. *Field Crops Research* **149**, 269-275
- Danne A, Thomson LJ, Sharley DJ *et al.* (2010) Effects of native grass cover crops on beneficial and pest invertebrates in Australian vineyards. *Environmental Entomology* **39**, 970-978
- Dent D (1995) "Integrated Pest Management" pp 356. (Chapman & Hall: London).
- Dmini I, Kozina A, Bazok R, Barcic JI (2010) Geographic information systems (GIS) and entomological research: A review. *Journal of Food, Agriculture & Environment* **8**, 1193-1198
- Henry F, Aftab M (2018) Viruses in spring-sown dual-purpose canola in the high rainfall zone of southern Victoria. *GRDC Updates* <https://bit.ly/2YetEsj>
- El-Sayed AM (2018) The Pherobase: Database of pheromones and semiochemicals. *Pherobase Database Pheromones Semiochem* www.pherobase.com/
- Fanadzo M, Dalicuba M, Dube E (2018) Application of conservation agriculture principles for the management of field crops pests. *Sustainable Agricultural Reviews* **28**, 125-152
- Ferguson AW, Klukowski Z, Walczak B *et al.* (2003) Spatial distribution of pest insects in oilseed rape: implications for integrated pest management. *Agriculture, Ecosystems & Environment* **95**, 509-521
- Fletcher A, Peoples MB, Kirkegaard JA *et al.* (2016) Prospects of utilising intercrops and crop variety mixtures in mechanised, rainfed, temperate cropping systems. *Crop and Pasture Science* **67**, 1252-1267
- Gebbers R, Adamchuk VI (2010) Precision agriculture and food security. *Science* **327**, 828-831
- Geiger F, Bengtsson J, Berendse F *et al.* (2010) Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. *Basic and Applied Ecology* **11**, 97-105
- Glen DM, Symondson WOC (2003) Influence of tillage on slugs and their natural enemies. In (Ed. A El Titi) "Soil Tillage Agroecosystems" pp 207-227 (CRC Press: Boca Raton, FL)
- Gould F, Brown ZS, Kuzma J (2018) Wicked evolution: Can we address the sociobiological dilemma of pesticide resistance? *Science* **360**, 728-732
- Greenslade PJM (1983) Adversity selection and the habitat templet. *The American Naturalist* **122**, 352-365
- Gu H, Fitt GP, Baker GH (2007) Invertebrate pests of canola and their management in Australia: a review. *Australian Journal of Entomology* **46**, 231-242.
- Gurr GM, Wratten SD, Altieri MA (2004) "Ecological Engineering for Pest Management: Advances in Habitat Manipulation for Arthropods" pp 256 (CSIRO: Victoria)
- Gupta SC, Larson WE, Linden DR (1983) Tillage and surface residue effects on soil upper boundary temperatures 1. *Soil Science Society of America Journal* **47**, 1212-1218
- van Helden M (2010) Spatial and temporal dynamics of arthropods in arable fields. In (Eds. EC Oerke, R Gerhards, G Menz, RA Sikora) "Precision Crop Protection – the Challenge and Use of Heterogeneity" pp 51-61 (Springer: Netherlands)
- van Emden H, Harrington R (2007) "Aphids as Crop Pests" pp 700 (CABI: Oxfordshire UK)
- Harris RH., Hirth JR, Crawford MC *et al.* (2007) Companion crop performance in the absence and presence of agronomic manipulation. *Australian Journal of Agricultural Research* **58**, 690-701
- Hill MP, Macfadyen S, Nash MA (2017) Broad spectrum pesticide application alters natural enemy communities and may facilitate secondary pest outbreaks. *PeerJ* **5**, e4179 doi:10.7717/peerj.4179
- Hill RE, Mayo ZB (1980) Distribution and abundance of corn rootworm species as influenced by topography and crop rotation in eastern Nebraska. *Environmental Entomology* **9**, 122-127
- Hoffmann AA, Weeks AR, Nash MA *et al.* (2008) The changing status of invertebrate pests and the future of pest management in the Australian grains industry. *Australian Journal of Experimental Agriculture* **48**, 1481-1493
- Horne PA, Edward CL (1995) Phenology and food preferences of *Labidura truncata* Kirby (Dermaptera: Labiduridae) in Western Victoria. *Journal of the Australian Entomological Society* **34**, 101-04

- Horne PA, Page J, Nicholson C (2008) When will integrated pest management strategies be adopted? Example of development and implementation of integrated pest management strategies in cropping systems in Victoria. *Australian Journal of Experimental Agriculture* **48**, 1601-1607
- Horowitz AR, Ishaaya I (2013) Advanced technologies for managing insect pests: An overview. In (Eds. I Ishaaya, SR Palli, AR Horowitz) "Advanced Technologies for Managing Insect Pests" pp 1-11 (Springer Netherlands: Dordrecht)
- Jones HG, Vaughan RA (2010) Integrated applications. In "Remote Sensing of Vegetation. Principles, Techniques, and Applications" pp 271-331 (OUP: Oxford)
- Kennedy JS, Booth CO (1951) Host alternation in *Aphis fabae* Scop. I. Feeding preferences and fecundity in relation to the age and kind of leaves. *Annals of Applied Biology* **38**, 25-64
- Kirkland LS, Pirtle EI, Umina PA (2018) Responses of the Russian wheat aphid (*Diuraphis noxia*) and bird cherry oat aphid (*Rhopalosiphum padi*) to insecticide seed treatments in wheat. *Crop and Pasture Science* **69**, 966-973
- Liebholt AM, Rossi RE, Kemp WP (1993) Geostatistics and geographic information systems in applied insect ecology. *Annual Review of Entomology* **38**, 303-327
- de Little SC, Umina PA (2017) Susceptibility of Australian *Myzus persicae* (Hemiptera: Aphididae) to three recently registered insecticides: Spirotetramat, Cyantraniliprole, and Sulfoxaflor. *Journal of Economic Entomology* **110**, 1764-1769
- Loreau M, Mouquet N, Gonzalez A (2003) Biodiversity as spatial insurance in heterogeneous landscapes. *Proceedings of National Academy of Sciences* **100**, 12765-12770
- Kogan M (1998) Integrated pest management: perspectives and contemporary developments. *Annual Review of Entomology* **43**, 243-270
- Macfadyen S, Hardie DC, Fagan L *et al.* (2014) Reducing insecticide use in broad-acre grains production: An Australian study. *PLOS ONE* **9**, e89119. doi:10.1371/journal.pone.0089119
- Macfadyen S, McDonald G, Hill MP (2018) From species distributions to climate change adaptation: Knowledge gaps in managing invertebrate pests in broad-acre grain crops. *Agriculture, Ecosystems & Environment* **253**, 208-219
- Macfadyen S, Moradi-Vajargah M, Umina P *et al.* (2019) Identifying critical research gaps that limit control options for invertebrate pests in Australian grain production systems. *Austral Entomology* **58**, 9-26
- Malhi SS, O'Sullivan PA (1990) Soil temperature, moisture and penetrometer resistance under zero and conventional tillage in central Alberta. *Soil and Tillage Research* **17**, 167-172
- Marti OG, Olson DM (2007) Effect of tillage on cotton aphids (Homoptera: Aphididae), pathogenic fungi, and predators in south central Georgia cotton fields. *Journal of Entomological Science* **42**, 354-367
- Millar GD, Badgery WB (2009) Pasture cropping: a new approach to integrate crop and livestock farming systems. *Animal Production Science* **49**, 777-787
- Monzon JP, Sadras VO, Andrade FH (2006) Fallow soil evaporation and water storage as affected by stubble in sub-humid (Argentina) and semi-arid (Australia) environments. *Field Crops Research* **98**, 83-90
- Murray DA, Clarke MB, Ronning DA (2013) Estimating invertebrate pest losses in six major Australian grain crops. *Australian Journal of Entomology* **52**, 227-241
- Nansen C, Weaver DK, Sing SE *et al.* (2005) Within-field spatial distribution of *Cephus cinctus* (Hymenoptera: Cephidae) larvae in Montana wheat fields. *The Canadian Entomologist* **137**, 202-214
- Nash MA, Hoffmann AA (2012) Effective invertebrate pest management in dryland cropping in southern Australia: The challenge of marginality. *Crop Protection* **42**, 289-304
- Nash MA, Thomson LJ, Hoffmann AA (2007) Slug control in Australian canola: monitoring, molluscicidal baits and economic thresholds. *Pest Management Science* **63**, 851-859
- Nash MA, Thomson LJ, Horne PA *et al.* Hoffmann AA (2008a) *Notonomus gravis* (Chaudoir) (Coleoptera: Carabidae) predation of *Deroceras reticulatum* Muller (Gastropoda: Agriolimacidae), an example of fortuitous biological control. *Biological Control* **47**, 328-334
- Nash MA, Thomson LJ, Hoffmann AA (2008b) Effect of remnant vegetation, pesticides and farm management on abundance of the beneficial predator *Notonomus gravis* (Chaudoir) (Coleoptera: Carabidae). *Biological Control* **46**, 83-93
- Nowak H, Komor E (2010) How aphids decide what is good for them: experiments to test aphid feeding behaviour on *Tanacetum vulgare* (L.) using different nitrogen regimes. *Oecologia* **163**, 973-984
- Perry JN (1998) Measures of spatial pattern and spatial association for counts of insects. *Proceedings of ecology and population dynamics section, 20th International Congress of Entomology*, Florence Italy, 25-31
- Petit S, Trichard A, Biju-Duval L *et al.* (2017) Interactions between conservation agricultural practice and landscape composition promote weed seed predation by invertebrates. *Agriculture, Ecosystems & Environment* **240**, 45-53
- Powell G, Tosh CR, Hardie J (2006) Host plant selection by aphids: Behavioral, evolutionary, and applied perspectives. *Annual Review of Entomology* **51**, 309-330

- Reay-Jones FPF (2014) Spatial distribution of stink bugs (Hemiptera: Pentatomidae) in wheat. *Journal of Insect Science* **14**, 1-22
- Sarrantonio M, Gallandt E (2003) The role of cover crops in North American cropping systems. *Journal of Crop Production*. **8**, 53-74
- Schellhorn NA, Macfadyen S, Bianchi FJJA *et al.* (2008) Managing ecosystem services in broadacre landscapes: what are the appropriate spatial scales? *Australian Journal of Experimental Agriculture* **48**, 1549-1559
- Serra GV, Porta NCL, Avalos S, Mazzuferi V (2013) Fixed-precision sequential sampling plans for estimating alfalfa caterpillar, *Colias lesbia*, egg density in alfalfa, *Medicago sativa*, fields in Córdoba, Argentina. *Journal of Insect Science* **13**, 1-19
- Severtson D, Flower K, Nansen C (2015) Nonrandom distribution of cabbage aphids (Hemiptera: Aphididae) in dryland canola (Brassicales: Brassicaceae). *Environmental Entomology* **44**, 767-779
- Severtson D, Flower K, Nansen C (2016) Spatially-optimized sequential sampling plan for cabbage aphids *Brevicoryne brassicae* L. (Hemiptera: Aphididae) in canola fields. *Journal of Economic Entomology* **109**, 1929-1935
- Smith RG (1962) Integration of biological and chemical control. *Bulletin of the Entomological Society of America* **8**, 188-189
- Sparks TC, Nauen R (2015) IRAC: Mode of action classification and insecticide resistance management. *Insecticide and Acaricide Modes of Action and their Role in Resistance and its Management* **121**, 122-128
- Stubbins FL, Seiter NJ, Greene JK, Reay-Jones FPF (2014) Developing sampling plans for the invasive *Megacopta cribraria* (Hemiptera: Plataspidae) in soybean. *Journal of Economic Entomology* **107**, 2213-2221
- Sutherst RW, Constable F, Finlay KJ *et al.* (2011) Adapting to crop pest and pathogen risks under a changing climate. *Wiley Interdisciplinary Reviews: Climate Change* **2**, 220-237
- Symondson WOC, Glen DM, Wiltshire CW *et al.* (1996) Effects of cultivation techniques and methods of straw disposal on predation by *Pterostichus melanarius* (Coleoptera: Carabidae) upon slugs (Gastropoda: Pulmonata) in an arable field. *Journal of Applied Ecology* **33**, 741-753
- Thierfelder C, Baudron F, Setimela P *et al.* (2018) Complementary practices supporting conservation agriculture in southern Africa. A review. *Agronomy for Sustainable Development* **38**, 16
- Thomas SR, Noordhuis R, Holland JM, Goulson D (2002) Botanical diversity of beetle banks: Effects of age and comparison with conventional arable field margins in southern UK. *Agriculture Ecosystems & Environment* **93**, 403-412
- Thomson LJ, Hoffmann AA (2010) Natural enemy responses and pest control: Importance of local vegetation. *Biological Control* **52**, 160-166
- Thomson LJ, Macfadyen S, Hoffmann AA (2010) Predicting the effects of climate change on natural enemies of agricultural pests. *Biological Control* **52**, 296-306.
- Tillman G, Schomberg H, Phatak S *et al.* (2004) Influence of cover crops on insect pests and predators in conservation tillage cotton. *Journal of Economic Entomology* **97**, 1217-1232
- Tilman D, Cassman KG, Matson PA *et al.* (2002) Agricultural sustainability and intensive production practices. *Nature* **418**, 671-677
- Tsitsilas A, Hoffmann AA, Weeks AR, Umina PA (2011) Impact of groundcover manipulations within windbreaks on mite pests and their natural enemies. *Australian Journal of Entomology* **50**, 37-47
- Tsitsilas A, Stuckey S, Hoffmann AA *et al.* (2006) Shelterbelts in agricultural landscapes suppress invertebrate pests. *Australian Journal of Experimental Agriculture* **46**, 1379-1388
- Umina PA, McDonald G, Maino J *et al.* (2018) Escalating insecticide resistance in Australian grain pests: contributing factors, industry trends and management opportunities. *Pest Management Science* **75**, 1494-1506
- Umina PA, Jenkins S, McColl S *et al.* (2015) A framework for identifying selective chemical applications for IPM in dryland agriculture. *Insects* **6**, 988-1012
- Valenzuela I, Hoffmann AA (2015) Effects of aphid feeding and associated virus injury on grain crops in Australia. *Austral Entomology* **54**, 292-305
- Vorburger C, Lancaster M, Sunnucks P (2003) Environmentally related patterns of reproductive modes in the aphid *Myzus persicae* and the predominance of two 'superclones' in Victoria, Australia. *Molecular Ecology* **12**, 3493-3504
- Wilson ACC, Sunnucks P, Blackman RL, Hales DF (2002) Microsatellite variation in cyclically parthenogenetic populations of *Myzus persicae* in south-eastern Australia. *Heredity* **88**, 258-266
- Wilson LJ, Whitehouse MEA, Herron GA (2018) The management of insect pests in Australian cotton: An evolving story. *Annual Review of Entomology* **63**, 215-237

Yazdani M, Baker G, DeGraaf H *et al.* (2018) First detection of Russian wheat aphid *Diuraphis noxia* Kurdjumov (Hemiptera: Aphididae) in Australia: a major threat to cereal production. *Austral Entomology* **57**, 410-417

PART IV – MANAGING THE RESOURCES



Fungal hyphal network on cereal stubble in no-till systems
(Courtesy: Vadakattu Gupta)



**Stabilizing flowering time in wheat for improved water use efficiency
(Courtesy: Bonnie Flohr)**



**Compacted soil limits resource capture in wheat (water and N) while
ripping (background) increases root access to resources
(Courtesy: Victor Sadras)**

Chapter 13

Water use in rainfed systems: physiology of grain yield and its agronomic implications

Victor Sadras, John Kirkegaard and James Hunt

Introduction

Managing climate variability and its effects on water supply to dryland crops has always been a central theme for agriculture in the driest continent on earth. As we write in mid-2019, Australia has already dealt with catastrophic floods in north Queensland, unprecedented droughts and bushfires in Tasmania, and fish kills due to low rainfall and water levels in the Murray Darling river system. In 1987, when *Tillage* was published, there were many references to water conservation, infiltration and erosion, and an implicit understanding of the importance of efficient water use for agricultural production. Yet there was not one reference to the now classic work of French and Schultz (1984a, b) on water use efficiency, linking wheat yield to seasonal water use and growing season rainfall. French and Schultz' biophysically strong benchmark, intuitively relates yield and water, and became a hallmark of the next 30 years in Australian agriculture. Whereas more refined benchmarks have been advanced to account for some of the original simplifications (Sadras *et al.* 2015), the core principle remains: there is an upper limit of yield for a given availability of water, termed water-limited yield potential, and differences between actual and water-limited yield potential reveal yield gaps. The yield gap concept now drives diagnosis and agronomy to address the factors responsible for the failure of crops to achieve water-limited yield potential (Hochman *et al.* 2012, van Ittersum *et al.* 2013, van Rees *et al.* 2014, Hochman and Horan 2018).

Growers rely on two linked sets of principles to increase farm-level production and profit, and to manage risk in the face of variable rainfall and extreme events including frost and heat. One is the management of individual crops, primarily supported by crop science and agronomy. The other is the arrangement of crops (or more broadly, land use) in space and time, supported by farming system research. The core of this chapter outlines principles of crop science and agronomy linked to efficient water use at the paddock-scale with direct implications for management. We conclude with an example of scaling these principles to the farming system level.

First, we show the role of rainfall in shaping patterns of land use and cropping options, emphasising the importance of amount, seasonality and size of rainfall events. Next, we focus on the upper boundary of yield in relation to water use, and the main sources of variation of this boundary including variety, management and environment. Rather than focus on specific agronomy, we analyse growth in terms of capture and efficiency in the use of resources, the central role of grain number to accommodate environmental variation, and the link between grain number and growth rate in a species-specific critical window in the context of timing, intensity and duration of drought episodes. We briefly consider how the elements of CA can be considered through this lens, as can the opportunities provided by novel agronomy, including the management of legacies of water and N use across a cropping sequence.

We believe that better integration of (and in a sense rediscovering) these physiological principles into agronomy at both the crop and farm level will be central to improve water-limited yield potential, closing yield gaps and increasing farm productivity and profitability.

Rainfall patterns set the limits and opportunities for cropping

There are three features of rainfall relevant to agriculture: amount, seasonality and size of events (Figure 1). The amount of rainfall sets the boundary for major patterns of land use, with cropping feasible above a certain annual rainfall, and rangelands in the riskier, lower-rainfall environments (Figure 1A). Seasonality sets three cropping environments in Australia (Figure 1B): the summer-rainfall region of

Queensland and northern New South Wales, the winter-rainfall regions of south-eastern and south-western Australia, and a transition zone lacking seasonality between the northern and southern region. For the same amount of annual rainfall, the summer regime allows for a greater crop diversity and higher cropping intensity, whereas winter rainfall has favoured an autumn-sown spring cereal (wheat, barley) system in rotation with pastures, legumes, and more recently canola. Driven by the winter-rainfall regime, the cropping systems of south-eastern and south-western Australia have evolved in convergence with the ancient wheat-pulse system of the Mediterranean basin; in this regard, much of Australian agriculture is Levantine rather than European (Sadras and Dreccer 2015).

Seasonality also has a major impact on the proportion of water available from pre-season and in-season rainfall, with implications for management and risk. In the winter-rainfall regions, wheat relies primarily on in-season rainfall, compared with a larger contribution of stored soil moisture in summer-rainfall regimes (Figure 1C). The frequency of large rainfall events increases from south to north (Figure 1D). For the same amount of rainfall, large events favour deep drainage and runoff as sources of inefficiency, whereas small events favour soil evaporation losses (Sadras 2003, Sadras and Baldock 2003, Monzon *et al.* 2006, Verburg *et al.* 2012).

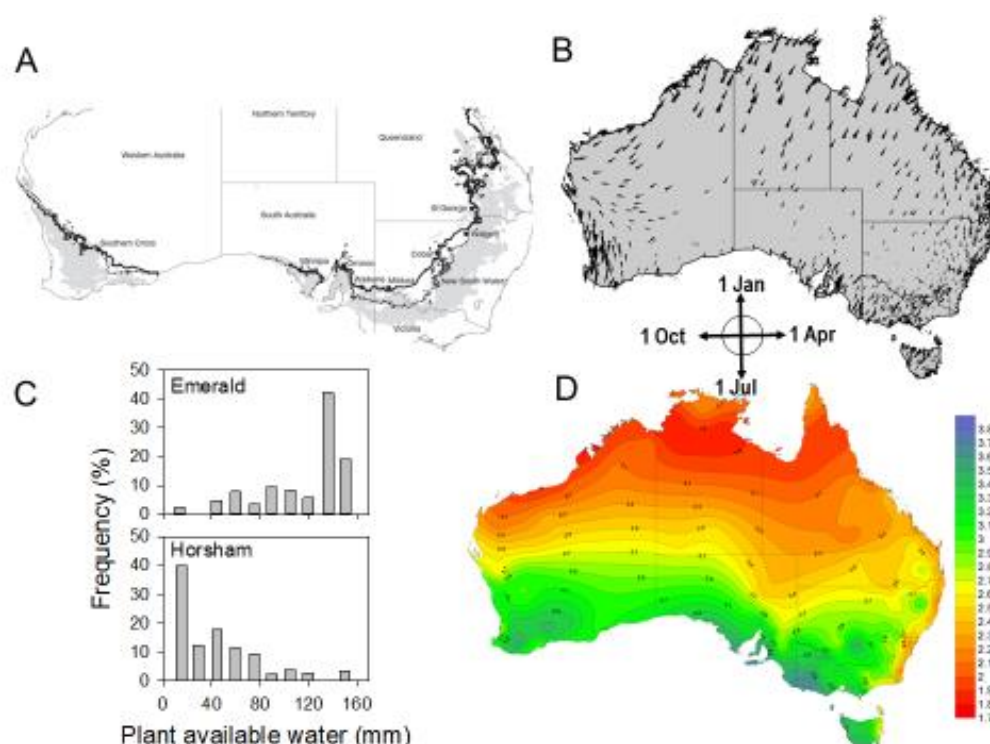


Figure 1. Amount, seasonality and size of rainfall events set boundaries and opportunities for cropping and influence the fate of water. (A) The amount of rainfall marks the transition from cropping into extensive grazing in Australia. The dotted line is the April-October 220 mm isohyet; the solid line is the 0.26 precipitation: evaporation ratio isopleth, and the grey area is the wheat growing region. (B) The seasonality of rainfall shapes cropping options. The length of Markham's vectors represents the intensity of seasonality and their direction in the 360° dial indicates the time of the year with the greatest rainfall concentration. For example, the vector is large indicating strong seasonality and points towards early January in northern Queensland, is large and points towards mid-July in the southern and western region, and is small highlighting lack of seasonality in most of NSW (C) Seasonality of rainfall influences the contribution of stored water at sowing to total water availability – modelled soil plant available water at sowing for wheat at Emerald, a summer-rainfall location, and Horsham, a winter-rainfall location; (D) The size of rainfall events influences the fate of water, *e.g.* small events favour soil evaporation. The map shows power law coefficient of rainfall for the winter semester in Australia. Power law coefficients are the unitless slope of the relationship between frequency and size of non-zero rainfall events on a log-log scale; colour-coded coefficients indicate increasing dominance of larger events from blue to red. Sources and further details: (A) Nidumolu *et al.* (2012), (B, D) Williamson (2007), (C) Sadras and Rodriguez (2007)

Crop yield per unit evapotranspiration is agronomically and biophysically bounded

For wheat crops encompassing common sources of variation (namely soil, weather and management) yield-rainfall plots are scattered; seasonal rainfall typically accounts for about one-third of the variation in the yield of wheat in south-eastern Australia. In this context, French and Schultz (1984a, b) insightfully drew a boundary line capturing the upper limit of wheat yield for a given evapotranspiration; this boundary was later shown to hold for other rainfed systems (Figure 2).

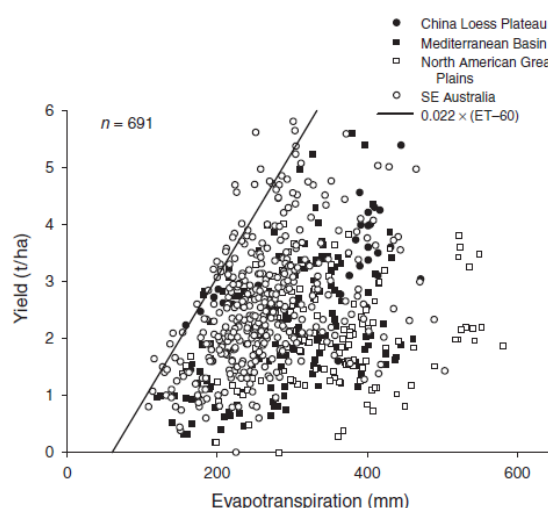


Figure 2. Relationship between yield and evapotranspiration for wheat crops in south-eastern Australia, Mediterranean basin, China Loess Plateau, and North American Great Plains. The boundary line has a slope of 22 kg/ha/mm and the x-intercept is 60 mm (source: Sadras and Angus 2006)

Two agronomic parameters define this boundary: the x-intercept, commonly interpreted as seasonal soil evaporation, and the slope of the line, representing the water-limited yield potential. It is important to make the distinction between the conceptual model, with robust theoretical and empirical support, and the parameters that need adjustment to account for variation with soil, climate and technology. Soil evaporation is not fixed, as noted by French and Schultz and others, but varies with soil, rainfall and management (Figure 3). Whilst French and Schultz inferred these parameters, they were shown to be in close agreement with subsequent empirical measurements (Unkovich *et al.* 2018).

In a north-south transect in eastern Australia, soil evaporation increases southwards in parallel to the greater proportion of in-season rainfall dominated by an increasing frequency of small events wetting the top soil more often (Figure 3). Management practices that increase the rate of canopy cover (*e.g.* high fertiliser rate, narrow rows, high sowing density, earlier sowing) would normally reduce soil evaporation, as illustrated in Figure 3B, D and Box 1 for nitrogen. The slope of the line increases southwards, in parallel to the reduction in vapour pressure deficit. Further, the slope initially set at 20 kg/ha/mm for south-eastern locations with technology of the early 1970s, including pre-Green Revolution cultivars, has increased to about 25 kg/ha/mm with newer, higher yielding varieties in these environments (Sadras and Lawson 2013). The concept of the boundary water use efficiency was first used in Australia, and more recently expanded to other crops worldwide as a practical benchmark for yield-gap analysis (Rattalino Edreira *et al.* 2018).

Crop growth depends on four resources and modulating abiotic and biotic factors

Crop biomass depends on the ability of the canopy to capture radiation and carbon dioxide, and on the ability of the root system to capture nutrients and water. Weather, soil, weeds, pathogens and herbivores modulate the rate of capture of these four resources, and the efficiency in the use of resources to produce biomass.

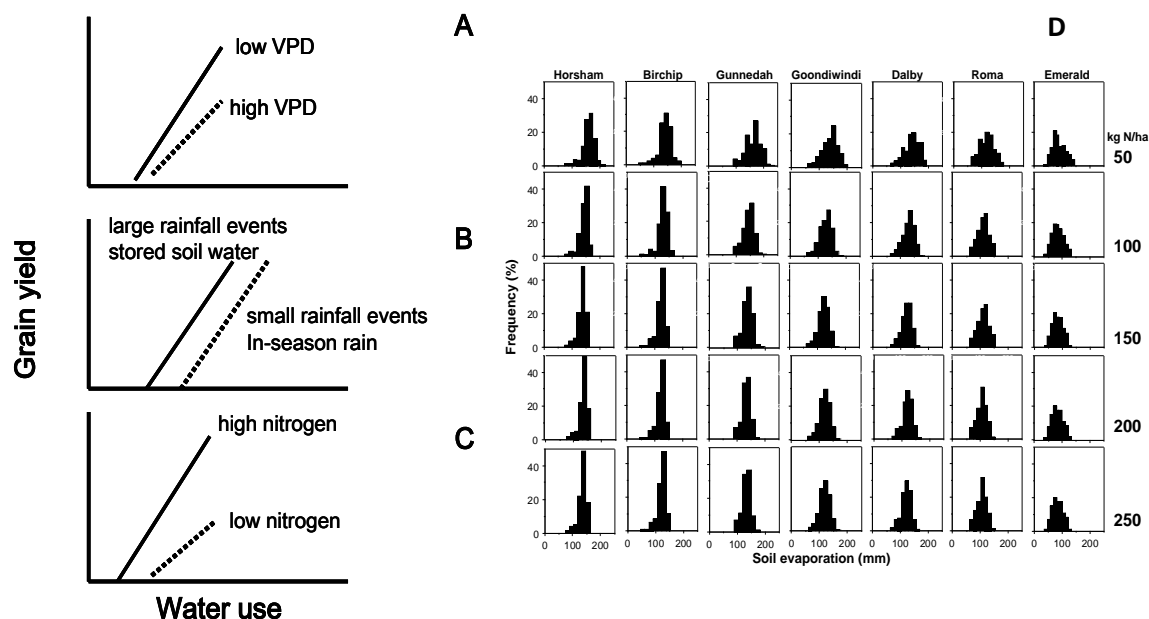


Figure 3. Influence of climate and nitrogen supply in the parameters of the French and Schultz benchmark. (A) Reduction in slope with increasing vapour pressure deficit. Vapour pressure deficit is a measure of air dryness; it increases inland and northwards, and it also increases with late sowings. (B) Increased soil evaporation with increasing frequency of small rainfall events and crop dependence on in-season rainfall as opposed to dominance of large rainfall events and crop reliance on stored soil water. (C) Nitrogen deficiency reduces the slope and increases soil evaporation. (D) Modelled soil evaporation highlighting: the declining evaporation from south (Horsham) to north (Emerald), the declining evaporation with increasing nitrogen supply, and the season-to-season variation in evaporation captured in the distribution of frequencies (source of histograms in D: Sadras and Rodriguez 2010)

Box 1 Effects of nitrogen on soil evaporation and water use efficiency

Norton and Wachsmann (2006) measured the response of canola to nitrogen rate from zero in controls up to 210 kg ha⁻¹ in the Victorian Wimmera. In response to increasing nitrogen, shoot dry matter and yield increased (Table 1). High nitrogen increased the amount of water used by the crop by about 30 mm, and reduced wasteful soil evaporation by about 40 mm. In total, more nitrogen improved the water economy of the crop by 70 mm. High nitrogen, as a consequence, increased the water use efficiency of the crop from 17 to 28 kg dry matter ha⁻¹ mm⁻¹, and from 5 to 8 kg grain ha⁻¹ mm⁻¹. The fertiliser efficiency dropped from 35 kg grain ha⁻¹ kg N⁻¹ with 70 units of fertiliser to 13 kg grain ha⁻¹ kg N⁻¹ with 240 units of fertiliser. Comparison of yield per unit water use and yield per unit nitrogen fertiliser shows a universal trade-off: more nitrogen means higher water use efficiency and lower nitrogen use efficiency.

Table 1. Effect of nitrogen rate on canola yield, shoot dry matter, water use, soil evaporation, dry matter per unit water use, yield per unit water use, and yield per unit nitrogen fertiliser (source: Norton and Wachsmann 2006)

N rate (kg/ha)	Grain Yield (t/ha)	Shoot dry Matter (t/ha)	Water Use (mm)	Soil evaporation (mm)	Dry matter per unit water use (kg/ha.mm)	Yield per unit water use (kg/ha.mm)	Yield per unit N (kg/kg N)
0	1.6	5.2	307	128	17.1	5.3	
70	2.5	8.8	349	112	25.3	7.1	35.3
140	2.5	8.7	344	91	25.2	7.3	17.9
210	2.8	9.5	335	87	28.4	8.4	13.4

To illustrate crop growth analysis based on capture and efficiency in the use of resources, we consider the effect of soil compaction in a sandy Mallee soil as shown in Figure 4. Soil stress impairs root growth and function. This leads to:

- Reduced ability to capture water and nutrients;
- Reduced capture of water and nutrients closes a loop of reduced root growth;
- Reduced capture of water and nutrient compromises canopy growth and function (e.g. stomata close under water deficit);
- A smaller, less effective canopy captures less radiation and carbon dioxide (i.e. less photosynthesis);
- Reduced capture of radiation and carbon dioxide closes a loop of reduced canopy growth;
- Reduced capture of radiation and carbon dioxide closes a loop of reduced root growth.

Hence, all four resources limit crop growth in compacted soil. In a comparison of crops on compacted soil, and soil where deep-ripping (three-tine ripper with 0.6-m-depth tynes spaced at 0.45 m) removed compaction, removal of soil stress improved root growth and canopy size with a 2-fold increase in capture of radiation from 18 to 40%. Increased transpiration and interception of radiation fully accounted for the increase in crop growth associated with alleviation of soil compaction. Control crops yielded between 1.2 and 2.9 t/ha and yield improvement from ripping ranged from nil to 43% depending on season and position in the landscape (Sadras *et al.* 2005).

In agriculture, the notion of a single limiting factor has dominated since von Liebig's law of the minimum. The inadequacy of the law of the minimum has been demonstrated, particularly in factorial experiments of fertilisation. For two resources A and B, the law of the minimum predicts yield isolines with two segments parallel to the A and B axis, and a break point when the crop shifts from A to B limited (Figure 5). For many reasons, actual responses do not conform to this pattern, *i.e.* actual yield

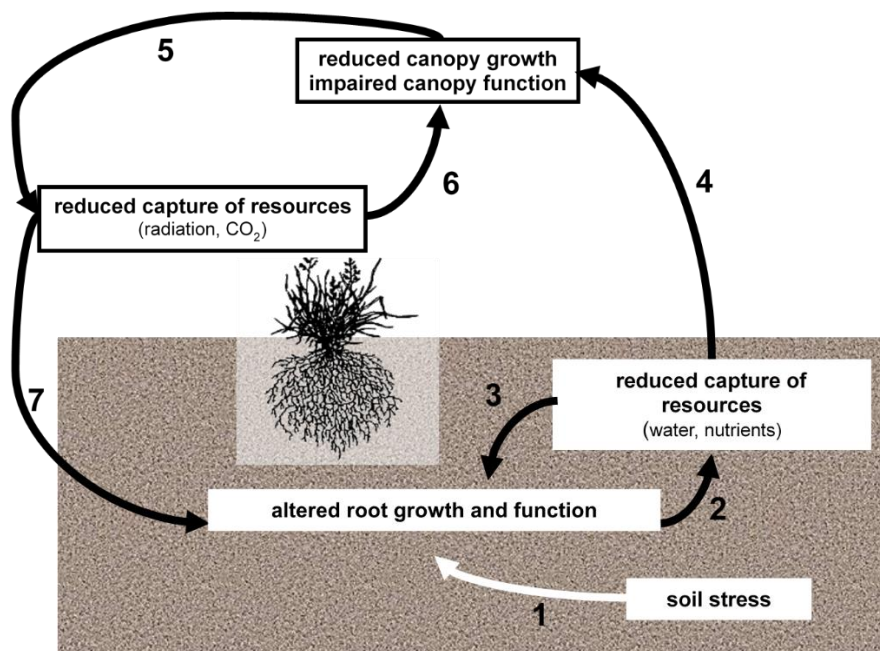


Figure 4. Effect of soil compaction on crop capture of soil and above-ground resources highlighting reinforcing loops. 1. Soil stress impairs root growth and function; this leads to 2) reduced ability to capture water and nutrients. 3) Reduced capture of water and nutrients closes a loop of reduced root growth. 4) Reduced capture of water and nutrient compromises canopy growth and function (e.g. stomata close under water deficit). 5) A smaller, less effective canopy captures less radiation and carbon dioxide (i.e. less photosynthesis). 6) Reduced capture of radiation and carbon dioxide closes a loop of reduced canopy growth. 7) Reduced capture of radiation and carbon dioxide closes a loop of reduced root growth (source: Sadras *et al.* 2005)

isolines are curvilinear (Figure 5). For example, a crop with very low N supply can still respond to P that stimulates root growth and enhances capture of N, and vice-versa. Duncan *et al.* (2018) showed higher yield per unit fertiliser N (relative to unfertilised control) in wheat crops with co-application of P, K and S.

Cossani and Sadras (2018) updated the theory of resource co-limitation, and outlined the underlying mechanisms with an emphasis on water and nitrogen. They define co-limitation as “the simultaneous limitation of yield per unit area by multiple resources over the agronomically relevant time scale (*e.g.* season, between cuts in forages) or developmentally relevant critical period.” Theory predicts that for a given intensity of stress, growth is maximised under resource co-limitation; this prediction has been supported in field studies with wheat, barley, canola and maize where high yield associates with high water-N co-limitation. The improvement in wheat yield over the last five decades has been linked to increased nitrogen-water co-limitation (Cossani and Sadras 2019). Measures of crop water and nitrogen status with remote sensing could be integrated in a co-limitation framework for management applications (Cossani and Sadras 2018).

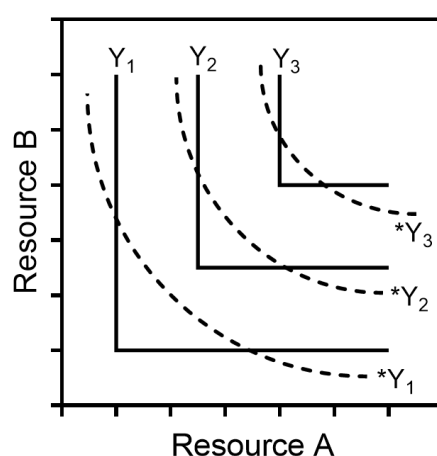


Figure 5. Response of crop yield to availability of two resources A, B. Solid lines are yield isolines (Y) expected from the law of the minimum, and dashed lines are yield isolines (Y*) resulting for interactions between resources, as supported by experiments. Subscripts 1 to 3 indicate increasing yield (source: Cossani and Sadras 2018)

Crops accommodate environmental variation through grain number

Across sources of variation, yield is primarily a function of grain number (Figure 6). Grain weight is important for quality and screenings are certainly undesirable, but large improvement in yield, say from 2 to 4 t/ha or from 3 to 6 t/ha, depends on grain number. Evolutionary and agronomic selection for conserved seed size explain the robust relationship between yield and grain number (Sadras 2007, Sadras and Denison 2009, Sadras and Slafer 2012, Slafer *et al.* 2014). Grain number can be seen as the ‘coarse’ regulator of yield and grain weight as the ‘fine’ regulator (Slafer *et al.* 2014).

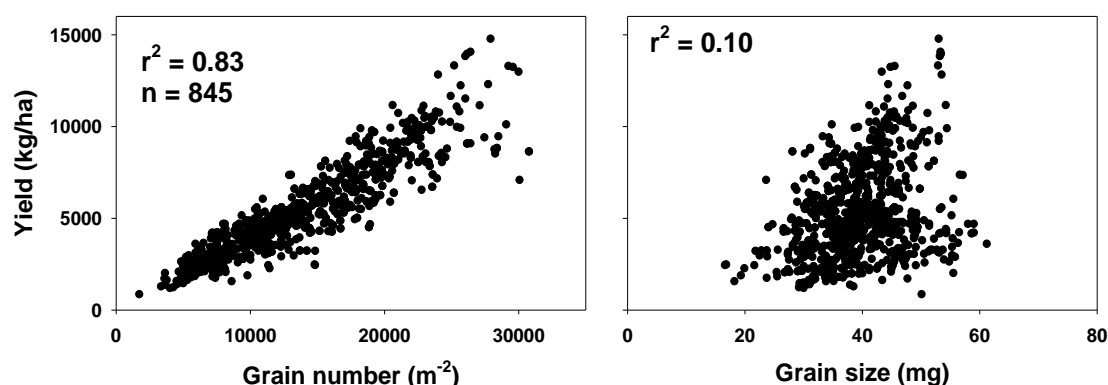


Figure 6. Crops accommodate environmental variation through grain number (left), whereas grain weight (right) is a secondary source of variation in yield (source: Slafer *et al.* 2014)

Despite the well-established relationship between yield and grain number, practices such as canopy management or nitrogen fertilisation often emphasise grain filling. Under some combinations of soil, water supply and phenology, over-fertilisation can lead to *haying-off* (van Herwaarden *et al.* 1998a, b, c). The asymmetric response to nitrogen of grain number and grain weight, however, reinforces the notion that management aimed at ensuring grain filling needs to account for the risk of nitrogen deficiency severely compromising grain number.

Figure 7 illustrates this asymmetry: excess nitrogen (nitrogen nutrition index, $NNI > 1$) can reduce grain weight at a rate of 26% per unit NNI, but nitrogen deficit ($NNI < 1$) can reduce grain number at 168% per unit NNI (Figure 7). Box 2 outlines the calculation and interpretation of the nitrogen nutrition index NNI. The asymmetric response to nitrogen of biomass and harvest index leads to the same conclusion: excess nitrogen can reduce harvest index at 16% per unit NNI whereas nitrogen deficit can reduce biomass at 157% per unit NNI (Figure 7).

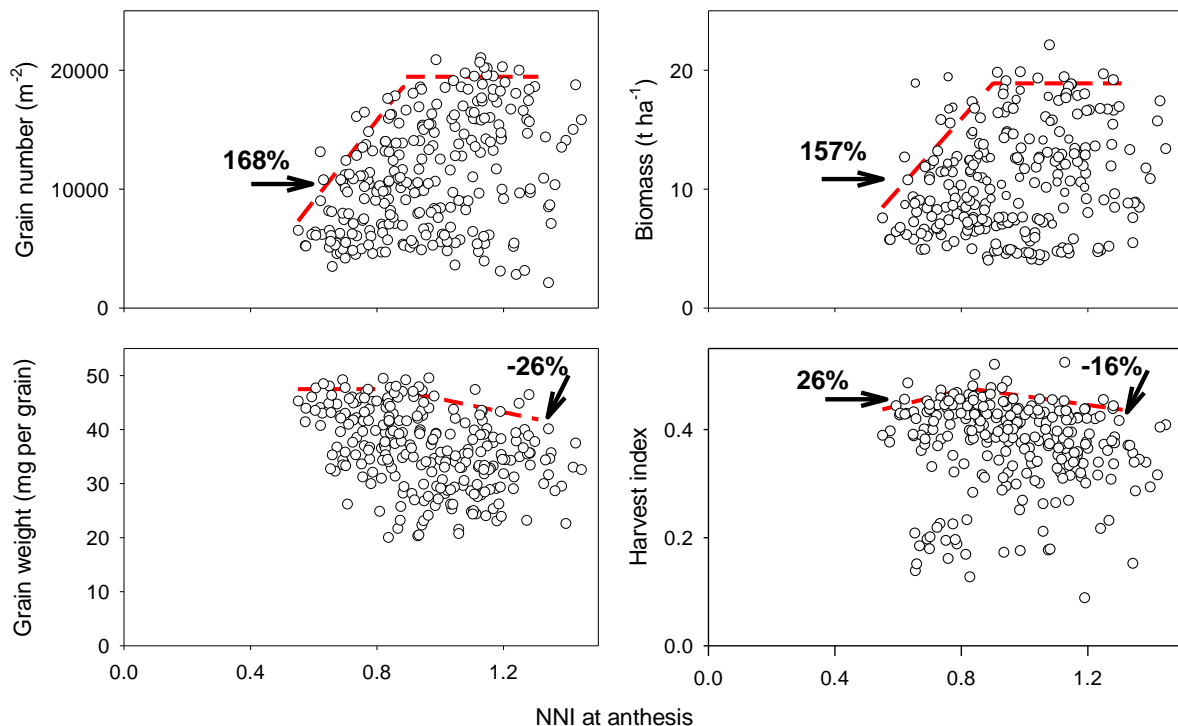


Figure 7. Relationships between wheat yield components and the nitrogen nutrition index NNI at anthesis. Red lines are boundary functions, and percentages are slopes on relative scales. Data from experiments, grower fields, and National Variety Trials in South Australia (source: Hoogmoed *et al.* 2018)

Grain number is defined in a species-specific developmental window

The general notion that grain number, and therefore grain yield, is most sensitive to stress at flowering is partially right. Detailed experiments to establish the most vulnerable stages show a wider window, from approximately stem elongation to about 10 days after flowering for wheat, barley and oat, with the most sensitive stage shortly before flowering (Figure 9A). For field pea, chickpea, lupin and canola, the most vulnerable stage is displaced towards pod set, or about 200 °Cd after flowering (Figure 9A). Critical periods have also been established for maize, sunflower and soybean

The importance of the critical period for crop management is three-fold. First, crop yield is proportional to the duration of the critical period, and the critical period shortens with lower photothermal quotient, defined as the radiation-to-temperature ratio (Fischer 1985). This partially explains the larger yield potential (*i.e.* with no extreme temperature or other stresses) in early-flowering crops.

Box 2 Nitrogen nutrition index

A nitrogen dilution curve describes the relationship between shoot nitrogen concentration and shoot biomass (Figure 8). Nitrogen in crop biomass dilutes for two reasons. First, the leaf-to-stem ratio of the crop declines with crop age; as leaves contain more nitrogen than stems, the concentration of nitrogen in shoot declines. Second, nitrogen moves from shaded leaves at the bottom of the canopy to well-lit leaves at the top with increasing ground cover. These dilution curves therefore assume two crop components, leaf and stem, and are therefore used only for the pre-flowering period, before significant spike growth.

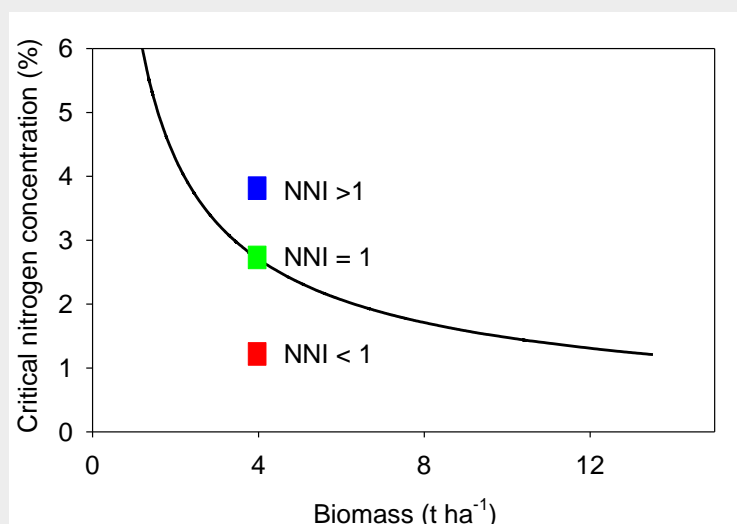


Figure 8. Critical nitrogen dilution curve for wheat under South Australian conditions. The curve, nitrogen concentration = $6.75 \times \text{biomass}^{-0.66}$, represents the minimum nitrogen concentration to achieve maximum biomass. The nitrogen nutrition index NNI is the ratio between actual and critical nitrogen concentration at a given biomass, where points below the curve ($\text{NNI} < 1$) indicate nitrogen deficit and points over the curve ($\text{NNI} > 1$) indicate excess nitrogen. The curve was derived in crops of Axe, Trojan, Mace, and Scout grown in six environments with fertiliser rate from nil to 240 kg N/ha (source: Hoogmoed and Sadras 2018)

An important implication of nitrogen-biomass dilution curves is that nitrogen concentration cannot be used as indicator of crop nitrogen status, unless it refers to a given biomass. Experiments with nitrogen rates are used to parametrise a ‘critical’ dilution curve, corresponding to the minimum nitrogen concentration required to achieve maximum biomass. At a given biomass, nitrogen can be insufficient ($\text{NNI} < 1$), sufficient ($\text{NNI} = 1$) or excessive ($\text{NNI} > 1$) for maximum growth. (Hoogmoed *et al.* 2018) illustrate the use of NNI to benchmark commercial crops and NVT in SA.

Second, grain number is proportional to crop growth rate in the critical window. This relationship is widespread and robust; it has been verified in wheat (Figure 10), field pea and chickpea (Figure 11), maize, sunflower and soybean (Andrade *et al.* 2005). In wheat, chickpea and soybean, the relationship between grain number and crop growth rate is linear. Linearity means that more grains are set per unit increase in growth rate with improving growing conditions; there is no morphological limit. Wheat accommodates better conditions with more tillers and more grains per head, whereas chickpea and soybean branch and set more pods with further growth. In maize and sunflower, the relationship is non-linear and grain number and yield level off at high growth rates; in these species, only one or two ears (maize) or a single head (sunflower) impose a morphological limit to yield under more favourable conditions.

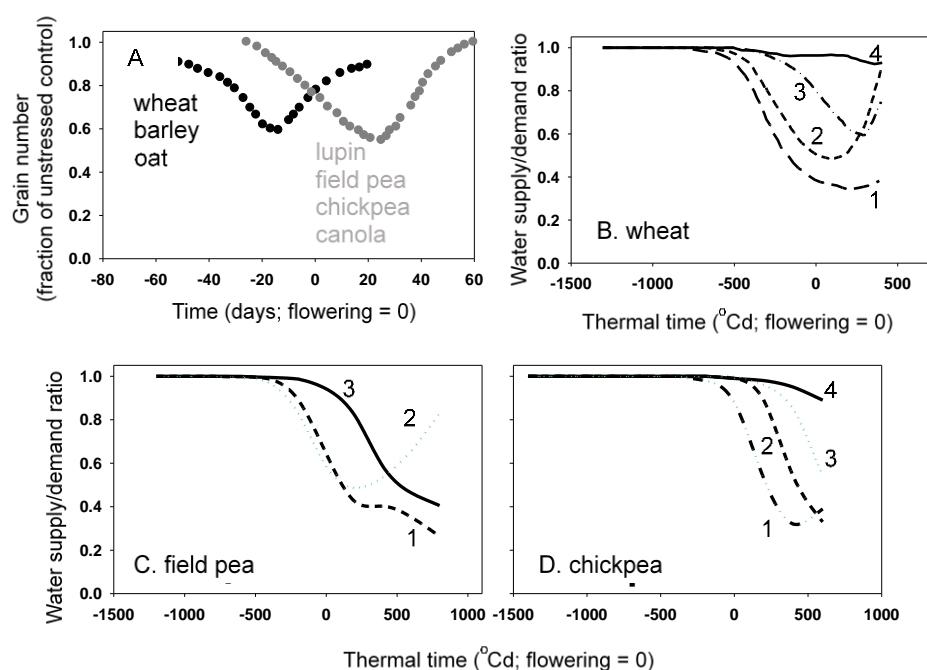


Figure 9. (A) The critical developmental window for the definition of grain number in cereals, pulses and canola. Patterns of water supply and demand in (B) wheat, (C) field pea, and (D) chickpea. Sources: (A) critical period of wheat, Fischer (1985); barley Arisnabarreta *et al.* (2008); oat, Mahadevan *et al.* (2016); lupin and fieldpea, Sandaña (2012); chickpea, Lake and Sadras (2014); canola, Kirkegaard *et al.* (2018). Drought patterns of (B) wheat, Chenu *et al.* (2013); (C) field pea, Sadras *et al.* (2012a), and (D) chickpea, Lake *et al.* (2016). Patterns of drought are numbered from 1 for early onset, progressively more severe water deficit during the season, to 3-4 for less severe or no water deficit.

Hence, two patterns – linear and non-linear – emerge for the relationship between grain number and crop growth rate. Field pea is interesting because we could have expected a chickpea-like linear pattern – more growth, more pods. Instead, field pea in South Australia shows a maize-like pattern where yield levels off at high growth rate (Figure 10). Growth and yield are decoupled in field pea under favourable growing conditions, setting a limit to yield potential. This can be tackled genetically, by selecting lines with a chickpea-type response. The reasons for the decoupling of growth and yield in field pea are unknown, but pod abortion in dense canopies might relate to the light microclimate (Heindl and Brun 1983, Myers *et al.* 1987). If so, agronomic solutions may be found by shifting from highly rectangular to a square crop configuration; precision seeding might help to ‘straighten’ the yield-growth relationship in field pea. The relationships between grain set and crop growth rate are unknown in lentil and fababean, but anecdotal evidence suggest it would be field pea-like, rather than linear as in chickpea. Third, crop management that seeks to avoid severe water stress during the critical period would improve yield. This requires a quantitative characterisation of the patterns of water stress in terms of timing, duration and intensity.

Yield peaks when crop critical windows are aligned with favourable conditions; hence the importance of managing flowering time with appropriate combinations of sowing date and selection of variety (Anderson *et al.* 1996, Flohr *et al.* 2017). Crop simulation has allowed optimal flowering periods to be identified for different environments across Australia for both wheat (Flohr *et al.* 2017) and canola (Lilley *et al.* 2019).

Many of the historic advances in Australian wheat yield have been due to better alignment of crop critical windows with favourable conditions. This includes the release of the faster developing Federation (Pugsley 1983), the development of no-till which allowed earlier sowing (Stephens and Lyons 1998, Flohr *et al.* 2018), and the century-long trend for breeders to produce faster developing cultivars (Eagles *et al.* 2009). Flohr *et al.* (2018) identified that wheat critical windows and optimal period for growth were well aligned at least in leading farmers’ fields, and opportunities for further yield gains via this mechanism are limited.

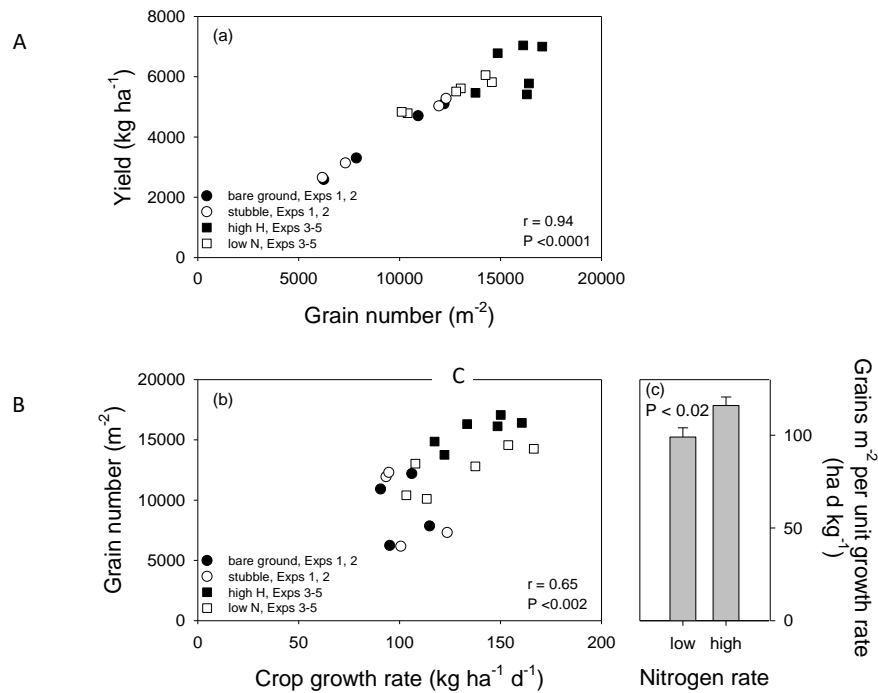


Figure 10. Relationship between (A) yield and grain number, and (B) grain number and crop growth rate in the critical window of wheat crops grown in South Australia with a combination of stubble and nitrogen rates. (C) Grain number per unit growth rate in crops with high and low nitrogen supply. Source: Sadras *et al.* (2012b)

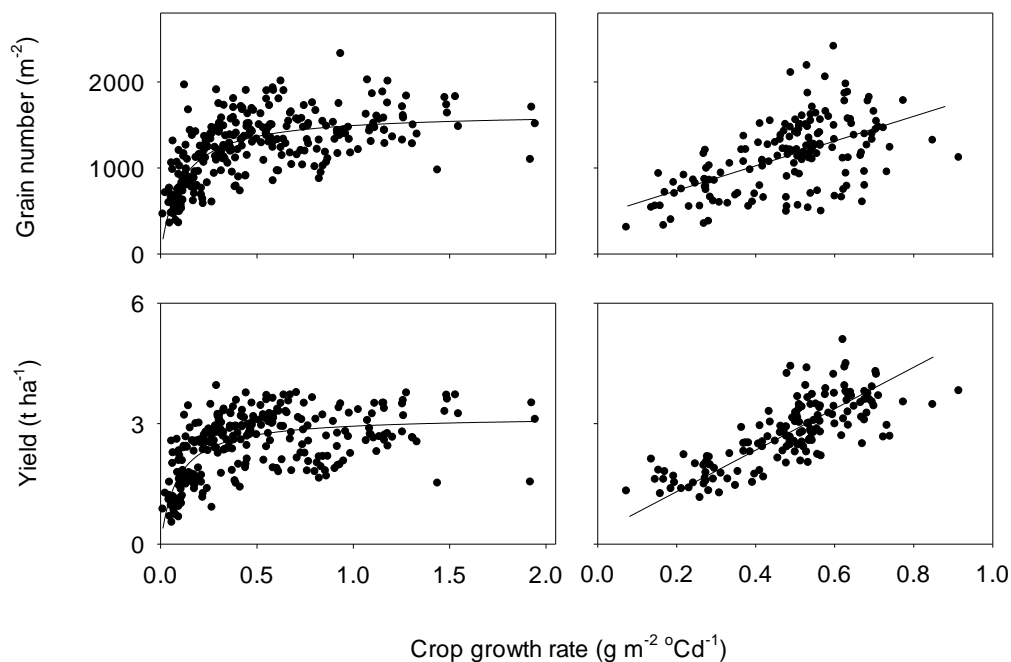


Figure 11. Relationship between crop growth rate in the critical window and grain number and yield of field pea (left) and chickpea (right) in South Australia (sources: field pea, Sadras *et al.* 2013; chickpea, Lake and Sadras 2016)

Effect of water deficit depends on the timing, duration and intensity of stress in relation to the critical window

‘Terminal drought’, ‘dry finish’, ‘dry spring’ are common descriptors of growing conditions in Australian regions. These descriptors are qualitative, vague and often do not reflect actual patterns. We suggest that this perception of ‘terminal drought’ has biased crop management towards the preservation of grain filling at the expense of grain number. Daily estimates of water supply and demand have been used to derive quantitative, probabilistic patterns of drought for major crops in Australia. Chapman and his colleagues pioneered this approach for sorghum in the northern region (Chapman *et al.* 2000), and drought patterns were later quantified and mapped for maize (Chauhan *et al.* 2013), wheat, field pea and chickpea (Figure 9BCD).

For wheat, drought pattern 1 in Figure 9B has an onset about 500 °Cd before flowering. Stress intensifies gradually, and the supply of water at flowering is only 40 % of the demand. This is the most severe drought, and many locations feature this pattern in about one third of seasons (Chenu *et al.* 2013). This pattern of stress largely overlaps with the critical period of grain set (Figure 9A). Thus, although stress is severe after flowering, most of the damage has occurred by the time the crop reaches grain filling, and it relates to grain number. The onset is slightly later and less intense for drought pattern 2, which recovers with rainfall late in the season. Drought pattern 3 is closer to ‘terminal drought’ as it develops after flowering and affects both grain set and filling.

The drought patterns 1, 2 and 3 for field pea are similar to those for wheat (Figure 9C vs 9B). Pattern 1 is the most severe, with an early onset and low supply/demand ratio at the critical period of pod set. Pattern 2 has an early onset, a gradual intensification of stress until pod set, and recovery following rainfall during grain fill. The similarity in the patterns of drought for wheat and field pea derive from soil-climate combinations that are common to both crops; for this reason, we expected similar patterns for chickpea in overlapping sites. However, the patterns for chickpea are different; pre-flowering stress is not evident, and drought of varying intensity develops with onset close to or shortly after flowering. It has been speculated that the lack of severe water stress before flowering relates to slow growth typical of chickpea at low winter temperature (Lake *et al.* 2016). Thus, similar soil-rainfall conditions where dry spells cause water deficit in vigorous wheat and pea crops, might be less likely to stress smaller chickpea canopies severely. Breeding efforts to improve growth under low temperature might shift the drought patterns of chickpea towards those of field pea and wheat.

Physiological principles support farming systems agronomy

An understanding of the ways in which agronomic management ultimately influences crop yield can be improved significantly by applying these crop physiological principles, at both the crop and system level. A good recent example is the work of Kitonyo *et al.* (2017) in South Australia who took a physiological approach to understand the impacts of no-till management (tillage, stubble and N supply and timing) on wheat through the lens of resource supply at critical growth periods. Tillage had little impact on resource supply at the critical period or, as a consequence, on yield. In contrast, fine-tuning stubble rates and the timing of N supply had significant impacts on N and water supply at the critical period; resultant effects on crop growth rate and radiation use efficiency between stem elongation and flowering explained impacts on grain yield.

The benefits of earlier sowing systems in wheat (Hunt *et al.* 2019) and canola (Kirkegaard *et al.* 2016) can also be explained in terms of the improved supply of water and efficiency of water use through deeper rooting, reduced evaporative loss and increased transpiration efficiency, combined with alignment of the critical window with seasonally favourable periods for growth (see Chapters 18 and 23). Critical to the success of these systems is the preceding agronomy of sound crop sequences to reduce weed seed banks and root disease and potentially to fix nitrogen and preserve water, along with strict weed control and maintenance of surface cover to maximise capture and storage of summer rainfall (Kirkegaard and Hunt 2010, Kirkegaard *et al.* 2014).

In dryland farming systems it makes sense to consider the water use efficiency across the crop sequence, rather than focusing on individual crops, because the legacies of water and N supply (along with weeds and disease) influence the performance of subsequent crops and consequently the profitability and efficiency of the sequence. In the northern grain region, Hochman *et al.* (2014) found that only 30% of the crop sequences surveyed in 94 paddocks were achieving >75% of predicted potential, much lower than for individual crops. Kirkegaard (2019) used a simulation study validated against a 30-yr field experiment in southern NSW to investigate the potential legacies of introducing both early-sown winter wheat and early-sown winter canola into the crop sequence in place of the later sown (May-June) spring crops that had been grown at the site. At the high rainfall site with relatively light textured soil, the simulation predicted significant yield increases for both crops, and small legacy effects on subsequent crops in the sequence, when firstly winter wheat, and then winter canola were introduced (Table 2). However, the higher yielding crop responded significantly to increased N supply (extra 50 kg/ha N as winter top-dressing), as the N rates applied to the spring crops were insufficient to support the higher yielding winter crops.

Table 2. The predicted impacts of sequential changes to management on the long-term mean yield of wheat and canola (t/ha) at the Harden long-term tillage site (source: Kirkegaard 2019)

Crop	Baseline (measured)	Weed Control	Weed control Early wheat	Weed control Early wheat Early canola	Weed control Early wheat Early canola +50 kg N/ha/yr
Wheat	4.5	4.7	5.6	5.5	6.0
Canola	2.9	3.1	2.9	3.3	5.0

This example demonstrates the potential to improve the water use efficiency (yield per mm annual rainfall) of the entire sequence; the early-sown winter crops were using water that was otherwise evaporated or leached in this high rainfall environment.

Conclusion

The physiological principles that underpin grain yield inform crop science and farming system agronomy, which in turn deliver increasing productivity of individual crops and crop sequences. Yield is a primary function of grain number, and grain number is defined in a crop-specific window. Extended critical windows associated with high radiation-to-temperature ratio are typical of early flowering and high latitudes and altitudes, which therefore favour yield potential. Management to increase growth rate in the critical window generally improves yield. For some combinations of crop and environment, growth and yield can be decoupled. This decoupling can be neutral (*e.g.* field pea) or negative (*e.g.* wheat haying off) for yield. The asymmetry between the responses of grain number and grain weight to management are important.

In a crop sequence, capturing the potential of higher-yielding, early sown crops requires pre-crop management that ensures increased supply of resources to the crop in the critical period. The legacies of reduced profile water and N following high yielding crops must be managed in environments where soil profiles may not refill. At both the crop and system level, novel agronomic management should be carefully considered in light of the underpinning physiology, rather than by agronomic recipes, especially in light of increasing climate variability.

References

- Anderson WK, Heinrich A, Abbotts R (1996) Long-season wheats extend sowing opportunities in the central wheat belt of Western Australia. *Australian Journal of Experimental Agriculture* 36, 203-208
- Andrade FH, Sadras VO, Vega CRC, Echarte L (2005) Physiological determinants of crop growth and yield in maize sunflower and soybean: their application to crop management modelling and breeding. *Journal of Crop Improvement* 14, 51-101
- Arisnabarreta S, Miralles DJ (2008) Critical period for grain number establishment of near isogenic lines of two- and six-rowed barley. *Field Crops Research* 107, 196-202

- Calviño PA, Monzon JP (2009) Farming systems of Argentina: yield constraints and risk management. In (Eds. VO Sadras DF Calderini) "Crop physiology: applications for genetic improvement and agronomy" pp 55-70 (Academic Press: San Diego)
- Chapman SC, Hammer GL, Butler DG, Cooper M (2000) Genotype by environment interactions affecting grain sorghum. II. Frequencies of different seasonal patterns of drought stress are related to location effects on hybrid yields. *Australian Journal of Agricultural Research* **51**, 209-221
- Chauhan YS, Solomon KF, Rodriguez D (2013) Characterization of north-eastern Australian environments using APSIM for increasing rainfed maize production. *Field Crops Research* **144**, 245-255
- Chenu K, Deihimfard R, Chapman SC (2013) Large-scale characterization of drought pattern: a continent-wide modelling approach applied to the Australian wheatbelt – spatial and temporal trends. *New Phytologist* **198**, 801-820
- Cossani CM, Sadras VO (2018) Water-nitrogen co-limitation in grain crops. *Advances in Agronomy* **150**, 231-274
- Cossani CM, Sadras VO (2019) Increasing co-limitation of water and nitrogen drives genetic yield gain in Australian wheat. *European Journal of Agronomy* **106**, 23-29
- Duncan EG, O'Sullivan CA, Roper MM *et al.* (2018) Influence of co-application of nitrogen with phosphorus potassium and sulphur on the apparent efficiency of nitrogen fertiliser use grain yield and protein content of wheat: Review. *Field Crops Research* **226**, 56-65
- Eagles HA, Cane K, Vallance N (2009) The flow of alleles of important photoperiod and vernalisation genes through Australian wheat. *Crop and Pasture Science* **60**, 646-657
- Fischer RA (1985) Number of kernels in wheat crops and the influence of solar radiation and temperature. *Journal of Agriculture Science* **105**, 447-461
- Flohr BM, Hunt JR, Kirkegaard JA, Evans JR (2017) Water and temperature stress define the optimal flowering period for wheat in south-eastern Australia. *Field Crops Research* **209**, 108-119
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018) Fast winter wheat phenology can stabilise flowering date and maximise grain yield in semi-arid Mediterranean and temperate environments. *Field Crops Research* **223**, 12-25
- French RJ, Schultz JE (1984a) Water use efficiency of wheat in a Mediterranean type environment. I. The relation between yield water use and climate. *Australian Journal of Agricultural Research* **35**, 743-764
- French RJ, Schultz JE (1984b) Water use efficiency of wheat in a Mediterranean type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research* **35**, 765-775
- Heindl JC, Brun WA (1983) Light and shade effects on abscission and c-14 photoassimilate partitioning among reproductive structures in soybean. *Plant Physiology* **73**, 434-439
- Hochman Z, Gobbett D, Holzworth D *et al.* (2012) Quantifying yield gaps in rainfed cropping systems: A case study of wheat in Australia. *Field Crops Research* **136**, 85-96
- Hochman Z, Horan H (2018) Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. *Field Crops Research* **228**, 20-30
- Hoogmoed M, Neuhaus A, Noack S, Sadras VO (2018) Benchmarking wheat yield against crop nitrogen status. *Field Crops Research* **222**, 153-163
- Hoogmoed M, Sadras VO (2018) Water stress scatters nitrogen dilution curves in wheat. *Frontiers in Plant Science* **9**, 406
- Hunt JR, Lilley JM, Trevaskis B *et al.* (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change* **9**, 244-247
- Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- Kirkegaard JA, Hunt JR, McBeath TM *et al.* (2014) Improving water productivity in the Australian grains industry – a nationally coordinated approach. *Crop and Pasture Science* **65**, 583-601
- Kirkegaard JA, Lilley JM, Brill RD *et al.* (2018) The critical period for yield and quality determination in canola (*Brassica napus* L.). *Field Crops Research* **222**, 180-188
- Kirkegaard JA (2019) Incremental transformation: success from farming systems synergy. *Outlook on Agriculture* **48**, 105-112.
- Lake L, Chenu K, Sadras VO (2016) Patterns of water stress and temperature for Australian chickpea production. *Crop and Pasture Science* **67**, 204-215
- Lake L, Sadras VO (2014) The critical period for yield determination in chickpea (*Cicer arietinum* L.) *Field Crops Research* **168**, 1-7
- Lake L, Sadras VO (2016) Screening chickpea for adaptation to water stress: Associations between yield and crop growth rate. *European Journal of Agronomy* **81**, 86-91
- Lilley JM, Flohr BM, Whish JPM *et al.* (2019) Defining optimal sowing and flowering periods for canola in Australia. *Field Crops Research* **235**, 118-128

- Mahadevan M, Calderini D, F Zwer PK, Sadras VO (2016) The critical period for yield determination in oat (*Avena sativa* L.). *Field Crops Research* **199**, 109-116
- Monzon JP, Sadras VO, Andrade FH (2006) Fallow soil evaporation and water storage as affected by stubble in sub-humid (Argentina) and semi-arid (Australia) environments *Field Crops Research* **98**, 83-90
- Myers RL, Brun WA, Brenner ML (1987) Effect of raceme-localized supplemental light on soybean reproductive abscission. *Crop Science* **27**, 273-277
- Nidumolu UB, Hayman PT, Howden SM, Alexander BM (2012) Re-evaluating the margin of the South Australian grain belt in a changing climate. *Climate Research* **51**, 249-260
- Norton R, Wachsmann N (2006) Nitrogen use and crop type affect the water use of annual crops in south-eastern Australia. *Australian Journal of Agricultural Research* **57**, 257-267
- Pugsley AT (1983) The impact of plant physiology on Australian wheat breeding. *Euphytica* **32** 743-748
- Rattalino Edreira JI, Guilpart N, Sadras V *et al.* (2018) Water productivity of rainfed maize and wheat: A local to global perspective. *Agricultural and Forest Meteorology* **259**, 364-373
- Sadras VO (2003) Influence of size of rainfall events on water-driven processes I. Water budget of wheat crops in south-eastern Australia. *Australian Journal of Agricultural Research* **54**, 341-351
- Sadras VO (2007) Evolutionary aspects of the trade-off between seed size and number in crops. *Field Crops Research* **100**, 125-138
- Sadras VO, Angus JF (2006) Benchmarking water use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research* **57**, 847-856
- Sadras VO, Baldock JA (2003) Influence of size of rainfall events on water-driven processes. II. Soil nitrogen mineralisation in a semi-arid environment. *Australian Journal of Agricultural Research* **54**, 353-361
- Sadras VO, Cassman KG, Grassini P *et al.* (2015) "Yield gap analysis of rainfed and irrigated crops: Methods and Case Studies" (FAO: Rome)
- Sadras VO, Denison RF (2009) Do plant parts compete for resources? An evolutionary perspective. *New Phytologist* **183**, 565-574
- Sadras VO, Dreccer MF (2015) Adaptation of wheat barley canola field pea and chickpea to the thermal environments of Australia. *Crop and Pasture Science* **66**, 1137-1150
- Sadras VO, Lake L, Chenu K *et al.* (2012a) Water and thermal regimes for field pea in Australia and their implications for breeding. *Crop and Pasture Science* **63**, 33-44
- Sadras VO, Lake L, Leonforte A *et al.* (2013) Screening field pea for adaptation to water and heat stress: Associations between yield crop growth rate and seed abortion. *Field Crops Research* **150**, 63-73
- Sadras VO, Lawson C (2013) Nitrogen and water-use efficiency of Australian wheat varieties released between 1958 and 2007. *European Journal of Agronomy* **46**, 34-41
- Sadras VO, Lawson C, Hooper P, McDonald GK (2012b) Contribution of summer rainfall and nitrogen to the yield and water use efficiency of wheat in Mediterranean-type environments of South Australia. *European Journal of Agronomy* **36**, 41-54
- Sadras VO, O'Leary GJ, Roget DK (2005) Crop responses to compacted soil: capture and efficiency in the use of water and radiation. *Field Crops Research* **91**, 131-148
- Sadras VO, Rodriguez D (2007) The limit to wheat water use efficiency in eastern Australia. II. Influence of rainfall patterns. *Australian Journal of Agricultural Research* **58**, 657-669
- Sadras VO, Rodriguez D (2010) Modelling the nitrogen-driven trade-off between nitrogen utilisation efficiency and water use efficiency of wheat in eastern Australia. *Field Crops Research* **118**, 297-305
- Sadras VO, Slafer GA (2012) Environmental modulation of yield components in cereals: Heritabilities reveal a hierarchy of phenotypic plasticities. *Field Crops Research* **127**, 215-224
- Sandaña P, Calderini DF (2012) Comparative assessment of the critical period for grain yield determination of narrow-leaved lupin and pea. *European Journal of Agronomy* **40**, 94-101
- Slafer G, Savin R, Sadras VO (2014) Coarse and fine regulation of wheat yield components in response to genotype and environment. *Field Crops Research* **157**, 71-83
- Stephens DJ, Lyons TJ (1998) Variability and trends in sowing dates across the Australian wheatbelt. *Australian Journal of Agricultural Research* **49**, 1111-1118
- Unkovich M, Baldock J, Farquharson R (2018) Field measurements of bare soil evaporation and crop transpiration and transpiration efficiency for rainfed grain crops in Australia – A review. *Agricultural Water Management* **205**, 72-80
- van Herwaarden AF, Farquhar GD, Angus JF *et al.* (1998a) 'Haying-off' the negative grain yield response of dryland wheat to nitrogen fertiliser I. Biomass grain yield and water use. *Australian Journal of Agricultural Research* **49**, 1067-1082
- van Herwaarden AF, Angus JF, Richards RA, Farquhar GD (1998b) 'Haying-off' the negative grain yield response of dryland wheat to nitrogen fertiliser II. Carbohydrate and protein dynamics. *Australian Journal of Agricultural Research* **49**, 1083-1094

- van Herwaarden AF, Richards RA, Farquhar GD, Angus JF (1998c) ‘Haying-off’ the negative grain yield response of dryland wheat to nitrogen fertiliser. III The influence of water deficit and heat shock. *Australian Journal of Agricultural Research* **49**, 1095-1110
- van Ittersum MK, Cassman KG, Grassini P *et al.* (2013) Yield gap analysis with local to global relevance—A review. *Field Crops Research* **143**, 4-17
- van Rees H, McClelland T, Hochman Z *et al.* (2014) Leading farmers in South East Australia have closed the exploitable wheat yield gap: Prospects for further improvement. *Field Crops Research* **164**, 1-11
- Verburg K, Bond WJ, Hunt JR (2012) Fallow management in dryland agriculture: Explaining soil water accumulation using a pulse paradigm. *Field Crops Research* **130**, 68-79
- Williamson G (2007) “Climate and root distribution in Australian perennial grasses; implications for salinity mitigation” PhD Thesis, The University of Adelaide.

Chapter 14

Nutrient-management challenges and opportunities in conservation agriculture

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Introduction

Massive changes have taken place in the nutrient management of Australian crops and pastures in the past three decades. Before then the supply of nutrients had been mostly from soil reserves (apart from phosphorus fertiliser, which has been routinely applied in the south), but during the three decades those reserves have declined and plant demand is increasingly met by fertilisers. Additional amounts of nutrients are needed to meet the requirements of higher yielding crops, the increased crop area stimulated by conservation agriculture (CA) and the reduced area of pastures and their supply of residual nitrogen from biological fixation. The three macronutrients considered in this chapter (nitrogen - N, phosphorus - P and potassium - K) show different patterns of decline in cropping soils:

- There has been a national decrease in the soil N reserves of cropping soils averaging 2-3% per annum (Angus and Grace 2017);
- For P, low inherent fertility meant that acute deficiency occurred after a few years without P fertiliser in southern farming areas, while northern Vertosols had higher indigenous P fertility and deficiencies took longer to appear;
- South-eastern soils generally contain high K levels, but deficiency is now widespread in the lighter western soils (Brennan and Bell 2013) and increasingly in the north (Bell *et al.* 2012).

Crops recover a small proportion of the macronutrients in the year they are applied in fertilisers – about 45% in the case of N (Angus and Grace 2017), and there are similar low efficiencies for P and K (McLaughlin *et al.* 2011). More of the fertiliser is recovered in the second and later seasons but the total recovery is generally less than half. The three decades that are the subject of this chapter are a transition period as Australian agriculture starts to pay for nutrients that were previously mined from soil. If trends continue, fertiliser will supply most of the macronutrients and will supplement more of the other 12 essential nutrients.

CA concentrates P and K in the topsoil because of their low mobility ('stratification'), and this process is often accompanied by depletion of those nutrients in the subsoil and the emergence of subsurface acidity on some soil types. In both instances, the lack of thorough soil mixing with tillage means fertilisers and lime are no longer thoroughly incorporated into a deeper cultivated soil layer but remain concentrated in the upper layers that are prone to drying. The use of 'challenge' in the title emphasises the need to balance CA practices with fertiliser and lime placement. An example is introducing strategic tillage as an occasional rather than annual practice aimed at redistributing nutrients and lime (see Chapter 7). Nutrient supply and demand vary greatly across Australian agricultural environments and we aim to recognise the diversity of the dryland crop and pasture land; here we use 'west' to mean Western Australia, 'south-east' to mean South Australia, Victoria and NSW south of the Macquarie Valley, 'south' to include 'west' and 'south-east' and 'north' to mean from the Macquarie Valley to central Queensland.

Crops

In the last 30 years there has been a tripling of crop production, most of which has been due to increased yield rather than crop area (Table 1). The increased production has required large increases in inputs of N fertiliser and lime, with the latter information relating only to NSW, which is the only state with long-term data on agricultural lime. Unlike N, there has been little net change in P input, reflecting less input of single superphosphate to pasture offset by increased application of compound fertilisers to crops.

The doubling of K fertiliser is mostly due to increased applications to crops in the west and north. By 2017, the input of fertiliser N and P exceeded the estimated output in crops, but K removal exceeded input.

The size of dryland farms and the crop area per farm are increasing (Chapter 3), and both changes are facilitated by CA. Farmers want to minimise the number of times that implements pass over their crops and so welcome opportunities to combine inputs into a single pass or at least move application dates to off-peak periods. They want to increase the speed of operations without compromising their efficiency. Management of nutrients and acidity must fit with such logistics.

Pastures

Pastures grown in rotation with crops and permanent pastures represent a large part of the extensive non-cropping land on Australian farms (Table 1). Rotational pastures benefit from the nutrients and lime applied to crops. Cultivation during the cropping phase, even when it only consists of direct drilling, helps to mix nutrients and lime into the topsoil. From the start of ‘sub & super’ in the 1950s, improved permanent pastures based on subterranean clover were regularly topdressed with superphosphate. Since this practice concentrated P on the soil surface it was not readily available in dry conditions (Cornish and Myers 1977). However the practice persisted until the wool price crash and superphosphate bounty ended in the 1970s. Many graziers then reduced or abandoned topdressing with superphosphate. In the high-rainfall zone topdressing pastures is an efficient method of applying P (McLaren *et al.* 2017) and the graziers in this environment who persisted with annual superphosphate topdressing obtained profitable responses.

There are no data on the amount of lime applied to acid soils that support permanent pastures, but observations suggest that it is less than to crops with similar levels of acidity. It is generally unprofitable to apply lime where the main pasture species, subterranean clover, is acid-tolerant so the surface and subsurface soils on livestock farms in the high-rainfall zone are acidifying more rapidly than those in crop and mixed crop-livestock farms where lime is being applied. Since 2013-2015, increased prices for meat and wool have boosted the profitability of permanent and rotational pasture systems in the south and will perhaps lead to more sustainable systems through better management of pasture species, lime and P.

Table 1. Production and area of Australian crops and pastures, nutrient inputs in fertiliser, nutrient outputs in grain and animal products, and input of agricultural lime in NSW in 1987 and 2017.

	Amount in 1987	Amount in 2017	Ratio 2017:1987
Crop production (M t)*	28	69	2.5
Crop area (M ha)*	16	20	1.3
Non-crop area (M ha)*	65	55	0.85
<i>Input**</i>			
Fertiliser N (M t)***	0.34	1.49	4.4
Fertiliser P (M t)***	0.39	0.43	1.1
Fertiliser K (M t)***	0.11	0.22	2.0
Lime (M t)****	0.05	1.10	22
<i>Output §</i>			
N (M t)	0.55	1.44	2.6
P (M t)	0.10	0.30	3.0
K (M t)	0.13	0.38	2.9

*Dryland grains, oilseeds and pulses plus cotton (lint and seed), raw sugar and irrigated cereal grain.

Datasource www.apps.daff.gov.au/AGSURF/agsurf.asp

** Fertiliser input to pastures and intensive crops as well as to dryland crops

*** www.fertilizer.org.au

****Lime data are for NSW only: data source: NSW mining royalties

§Calculated from crop production and estimated average nutrient concentrations in product and residue.

Pastures in the Brigalow Belt bioregion face even more serious nutritional problems because of low and decreasing levels of available soil P and inadequate applications of P fertiliser (Peck *et al.* 2015). This report concluded that P fertiliser was a profitable investment for beef production in the ~40 M ha of this region, but there has been little research on the optimal methods to apply P. McIvor *et al.* (2011) report similar problems of P deficiency across the extensive rangelands of northern Australia where the most promising way to supply P is as a feed supplement to grazing cattle. The low P inputs to the Brigalow pastures and the difficulty in P management of crops in the north (discussed below) are reflected in the relatively small proportion of nutrient supplied as P in Queensland (Table 2).

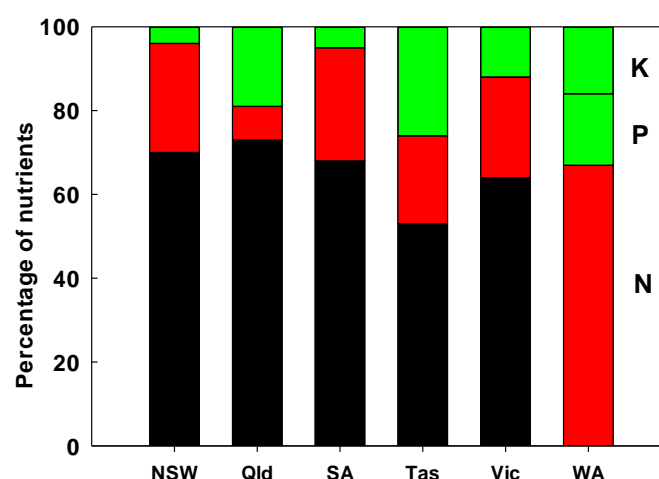


Table 2. Percentages of macronutrients in fertilisers applied during 2016 in Australian states (data courtesy of Fertilizers Australia)

Dual-purpose crops

Cereals and canola crops can be grazed by sheep and cattle in the vegetative stage before they regrow and produce grain. The practice has increased steadily in the south since 2005-10. Nutrients removed during grazing are not available for grain production and N fertiliser is normally applied after grazing to replace the amount removed. The N use efficiency (NUE) of this system is consistently lower than for ungrazed crops with fertiliser applied under the same conditions (Sprague *et al.* 2019). It appears that N-demand is temporarily reduced in small grazed plants and microbial immobilisers assimilate much of the fertiliser N before the plants grow large enough to compete with immobilisers. Livestock also graze stubbles on mixed farms and Hunt *et al.* (2016) showed that grazing increased accumulation of soil mineral N in pre-crop sowing measurements. Their explanation was reduced immobilisation resulting from less stubble as well as N cycling through manure and urine.

Interactions between nutrition and conservation agriculture

The practices of direct drilling and stubble retention have increased wheat yields in the north because of soil water conservation (Thomas *et al.* 1997). In the south these practices have had mixed effects, with increased yield in dry seasons reflecting the northern results, and reduced yield in wet seasons, partly due to microbial inhibition of root growth (Giller *et al.* 2015 and see Chapter 9). The other key component of conservation agriculture, rotation of cereals with broadleaf crops and pastures, also increases yield. Regardless of the cause, increases in crop yield potential lead to extra crop nutrient demand.

Conservation agriculture also affects nutrient supply, particularly the supply of mineral N, with stubble retention leading to increased immobilisation and deficiency of crop N early in the growing season. The degree to which immobilisation influences early N supply is determined by stubble load, climatic conditions and inherent soil N fertility. Stubble loads of 1-3 t/ha are unlikely to alter the optimum N

fertiliser rate, but at higher stubble loads, the optimal N rate tends to be higher under stubble retention due to immobilisation (Mason 1992).

Soil disturbance is known to increase mineralisation by improving microbial access to parts of the soil that are relatively rich in organic matter. While overseas research has generally shown that tillage increases mineralisation (and hence accelerates long-term depletion of soil N), nutrients retained in stubble are a significant benefit of CA. Taking N in wheat stubble as an example, the average quantity of N contained in retained stubble is 15 kg N/ha, estimated from average yield (2.1 t/ha), harvest index (40%) and the nutrient concentration of stubble (0.5% N). This represents one third of the 45 kgN/ha applied as fertiliser to dryland crops (Angus and Grace 2017) but a smaller proportion of crop-N recovery. About 10% of stubbles were burnt in 2016, as reported by graingrowers to a GRDC (2017) survey. There is loss of N and, depending on the fire temperature and wind, other nutrients from these stubbles. In the 90% of stubbles that are retained, N represents a significant component of the N cycle. No directly comparable data about nutrients retained in stubble are available from 30 years earlier when average Australian wheat yield was ~30% lower and so, presumably, were stubble nutrient amounts. In previous decades, more stubble nutrients were recycled by livestock grazing in the mixed crop-livestock systems that then predominated, and sowing equipment could not operate without blockages by stubble after high-yielding cereal crops. In the future, nutrients are likely to be retained in all but the heaviest stubbles and if these are managed with a ‘cool burn’ there is unlikely to be large nutrient loss.

Matching nutrient demand and supply

Nutrients are managed efficiently when their supply from soil and fertiliser closely matches the demand by the crop. With increasing productivity, nutrient supply must increase to meet crop demand and to avoid nutrient deficiency or surplus. Formal supply-demand models and rules of thumb give a prognosis of nutrient response and machine learning has promise as a predictive tool to include several data sources (Lawes *et al.* 2019). We should not forget ‘test strips’ which were widely used by Australian farmers or advisers in a previous generation (Schroder and Curnow 1977). In this system single-element fertilisers were added to, or deleted from, a strip of crop or pasture. Decisions about fertiliser requirements were then made from a visual inspection of the growth response. The system is now reinvented as ‘N-rich strips’ and used in conjunction with a proximal sensor for variable rate N-fertiliser application (Colaço and Bramley 2018).

Nutrient demand

Crop productivity and nutrient demand depend on a combination of crop management, environment and genetics. Crop management practices that have increased yield are early sowing with long-season wheat (Hunt *et al.* 2019) and the use of break crops. Legumes provide not only a disease break but also residual N and a separate growth stimulus to following crops by the process of hydrogen fertilisation (Peoples *et al.* 2008). In a meta-analysis Angus *et al.* (2015) showed that the combined effect of these processes increased wheat yield by 1.2 t/ha more than wheat after wheat. Overcoming soil-compaction by deep ripping consistently lifts potential yield and increases wheat-yield response to N in the west (see Chapter 8), first shown by Delroy and Bowden (1986), and on sandy soils elsewhere in the south. Deep ripping gives inconsistent results in the south-east (Kirkegaard *et al.* 2008).

In the south, where growing-season rainfall provides the main water supply for winter crops, nutrient demand cannot be forecast accurately until relatively late in the growing season. With adequate N until tillering (from soil and sowing fertiliser), in-season N inputs can be estimated by a tactical approach based on a revised yield expectation, emerging seasonal conditions, empirical tests of crop N-status and grain price and protein premium. Yield responses to in-season N are more reliable in high-rainfall than low-rainfall regions, but can be highly profitable in exceptional seasons in semi-arid regions. In-season application is inappropriate for less-mobile nutrients that should be applied at or before sowing. Cropping areas in north-eastern Australia are less reliant on in-season rainfall than on moisture stored in the soil profile during summer and/or winter fallows. In these systems, soil moisture available at sowing provides a guide to the minimum yield potential and seasonal forecasts of in-crop rainfall can be used to estimate any additional productivity. In these systems, all nutrients are supplied at or before

sowing, with one of the critical success factors for effective nutrient management being coincidence of water, nutrients and active roots in the same part of the soil profile.

The combination of improved crop management and breeding has increased Australian grain yields by annual rates varying from 1.1% for wheat to 2.1% for sorghum (Potgeiter *et al.* 2016). Genetic improvements in crop yield potential affects nutrient demand through nutrient uptake and/or internal nutrient utilisation efficiency. Selection for high wheat yield over many decades has simultaneously increased NUE (Cossani and Sadras 2019). Examples of more specific genetic effects are that semi-dwarf wheat cultivars require more N than tall cultivars (Syme *et al.* 1976) and long-duration cultivars also require more N than short-duration cultivars, provided that the water supply is adequate (Flohr *et al.* 2018). In sorghum, ‘stay-green’ genotypes have increased yields under terminal drought stress (Borrell *et al.* 2014). The use of molecular genetics for the development of cultivars with increased nutrient uptake has shown promise in laboratory studies (Krapp 2015) but has not yet shown increased NUE in the field. Breeding for nutrient efficiency may have benefits if it reduces nutrient losses but otherwise will simply deplete soil nutrient reserves more rapidly and lead to greater fertiliser requirement in later years.

Soil nutrient supply

Nutrients in the soil may originate from the pre-agricultural era, from residues of fertilisers and manures applied previously and from the biologically fixed N from legume crops and pastures. There is also a small amount from atmospheric deposition. Soil N is mostly found in organic forms, requiring microbial processes to convert to inorganic forms for plant uptake. In contrast, K (and in some instances P) in soil is mostly found in inorganic pools with differing solubility and bioavailability to plants. Examples of the cycles of N, P and K for wheat crops producing average yields in Australia are shown in Figure 1.

The largest source of crop N is from mineralisation, defined as the conversion of organic to mineral N (Figure 1a). The reverse process and second largest flux consist of immobilisation of mineral N that has not been taken up by the plant plus rhizodeposition, which consists of roots and root exudates (Wichern *et al.* 2008). The net N supply is mainly controlled by topsoil temperature, water content and the amount and quality of organic matter. Soil disturbance has been shown to increase mineralisation in overseas research, resulting in accelerated long-term depletion of soil N, but Australian experiments have shown little or no increase in mineralisation due to tillage or stubble retention (Angus *et al.* 2006). The difference is likely to be the different tillage methods: mouldboard ploughing to depths >0.2 m in many overseas farming systems, but in Australia scarifying with narrow tynes to a depth of <0.1 m (see Chapter 1).

Soil reserves provide a greater supply of P to the crop than fertiliser and crop residues (Figure 1). Isotope dilution studies have shown that between 73 and 85% of P taken up by the crop is from soil reserves (McLaughlin *et al.* 1988, McBeath *et al.* 2012) and that between 7.5 and 22% of crop P taken up is from fertiliser (McBeath *et al.* 2012). P supply from crop residues depends upon residue type; in the medium rainfall region in the west, estimated P supplies from green manure, canola, legume crop and wheat residues were 11, 0.9, 0.4 and 0.3 kg P/ha/year (Damon *et al.* 2014).

Soil K is present in several distinct pools which have been simplified in Figure 1 and are explained in detail in Bell *et al.* (2017b). The main source of solution K is from desorption of the ion from mineral surfaces and some clay interlayers. However, slower K release (or in some cases fixation) can occur from clay-mineral interlayers, while dissolution of K minerals can also occur under the action of plant roots. Most of the K in cereals is returned to the soil surface in residues from which it is leached by rain into the topsoil (Rossolem *et al.* 2017), so uneven straw distribution during harvest can increase the spatial variability in plant-available K.

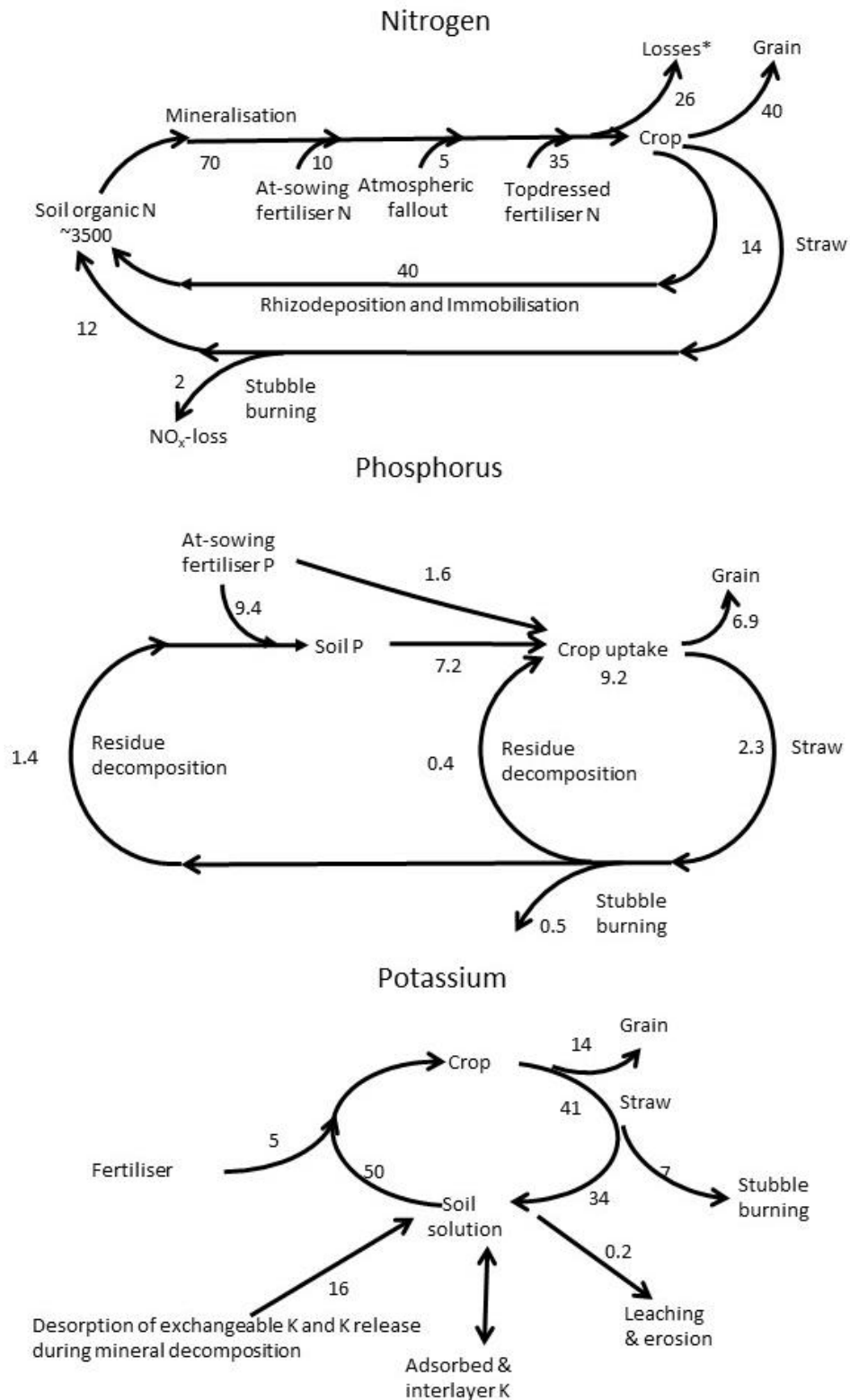


Figure 1. Annual cycles of N, P and K (kg/ha) for an average Australian wheat crop yielding 2.1 t/ha with a grain protein concentration of 10.5% and with grain removal of 3.3 ± 0.7 kg P/t and 4.6 kg K/t (Norton 2012)

Nutrient supply from fertiliser

The framework for discussing the supply of nutrients from fertiliser is the 4 Rs system (Snyder 2017) – right placement, timing, source and rate.

Fertiliser placement

Before the mid-1980s, single superphosphate was the main fertiliser applied to Australian crops and it was almost entirely banded with the seed. Compound fertilisers, such as monoammonium phosphate (MAP), that became available in the 1980s were, and still are, applied in the same way. Since the high ammonia concentration from such fertilisers damages germinating seeds, other application methods were needed to apply high N rates. One was to broadcast urea onto the soil surface and incorporate it by sowing (IBS). Another was to apply N to growing crops, either as broadcast granular urea or as liquid urea ammonium nitrate (UAN) sprayed on the soil and foliage.

In situations where P reactions in soil are dominated by sorption, banding P fertiliser near the seed can improve P fertiliser recovery (McLaughlin *et al.* 2011). This provides an additional advantage in cereal crops, with the close proximity to the developing root system providing an easily accessible source of P at floral initiation, when potential grain number is determined. The value of deep soil P to crop P nutrition is increasingly recognised (Bell *et al.* 2012, Lester *et al.* 2017, McBeath *et al.* 2012). A meta-analysis by Nkebiwe *et al.* (2016) suggests that deep subsurface placement of fertiliser could offer a significant benefit in stratified soils, in particular soils where stratified fertiliser is positioned in the layer most vulnerable to frequent drying during the growing season. Deep P placement has increased yield by 5-25% compared to conventional P placement (Bell *et al.* 2015, 2016, Lester *et al.* 2017), with an optimum depth of ~20 cm and band spacing ≤ 50 cm.

Similarly, deep placement of K also seems to offer significant productivity benefits in northern Vertosols, especially in seasons where topsoils are dry for extended periods (Bell *et al.* 2015). Responses are often smaller than responses to deep P and are not observed unless P supply is adequate, suggesting that P is the primary limitation. In sandy soils there is much greater flexibility in K application strategies because the typically low CEC results in a very limited capacity to sorb K on the exchange surfaces. In this situation (*e.g.* sandy soils in the west), K broadcast onto the soil surface can ultimately leach into the subsoil.

Fertiliser timing

Nitrogen applied before sowing or at the early stages of crop development tends to increase yield and have little effect on grain protein concentration. Early N can even reduce grain protein due to dilution by additional yield. Excessive N applied early can lead to ‘haying-off’, the disorder of cereals in terminal drought leading to reduced yield and low quality grain (van Herwaarden *et al.* 1998). Canola crops do not hay-off as much as cereals (Norton 2016). Later N applications tend to increase grain protein concentration relatively more than yield but seldom cause haying off. Mineral N leached into the subsoil during a fallow also tends to increase grain protein because it is not accessed by the roots until late in crop development (Lotfollahi *et al.* 1997).

For environments where there is reliable rainfall during the growing season, applying N to the growing crop has advantages of delaying expenditure on fertiliser until there is more information on seasonal conditions, crop-N status, grain prices and protein premiums. N-fertiliser top-dressed onto alkaline surfaces of retained stubble or ash from burnt stubble is at risk of ammonia volatilisation. However, the model of Fillery and Khimashia (2016) predicted little or no N loss when N fertiliser is injected into the soil or top-dressed before rain. Fertiliser N applied onto a dry surface soil or into a dry topsoil, provided it is not dissolved in dew, is neither available to crops nor prone to loss.

The other pathways of N-loss, leaching and denitrification, are most active when the soil is very wet and contains a large amount of nitrate. In some situations, soil saturation can be reduced by land levelling and high concentrations of nitrate can be avoided with split fertiliser applications, both at

considerable cost. With the development of autonomous robots, it may be possible to apply N in numerous splits at low cost.

The response of wheat to fertiliser P banded with the seed varies strongly with the date of sowing. Batten *et al.* (1999) showed that yield of crops sown in April required much less fertiliser P to maximise yield than those sown later, but higher P removal rates must ultimately lead to greater depletion of soil P reserves and potentially greater P-fertiliser requirement in later years. Many cropping soils in the south have accumulated sufficient available P to now require only maintenance P applications.

Placement and timing interactions

The fertiliser products listed in the *Placement* section can be applied before, during and after sowing. Application before sowing can cause a yield penalty because sowing is delayed. With dry sowing (see Chapter 18), nutrients on or near the soil surface are unavailable to crops but in winter-rainfall environments the topsoil is likely to wet up within a few weeks so that the nutrients become available. In the north, fertiliser applied just before sowing or at sowing is often ineffective because the topsoil remains dry after sowing. The solution may be deep-drilling of fertilisers containing N, P, K and micronutrients during the fallow period. In this system, nutrients are drilled at a depth of at least 0.2 m where the soil is likely to remain moist enough for nutrient uptake to meet crop demand (Bell *et al.* 2012). The residual effects of deep placement applications made early in the fallow period can persist for 4-6 years (Bell *et al.* 2016), and applications are made early during a winter or summer fallow so that subsequent rainfall can replace any tillage-induced moisture loss. The fertiliser N drilled in this system is normally leached into the subsoil as the soil water refills and the bulge of mineral N in the subsoil normally results in an N supply to the crop that is more synchronous with peak nutrient demand than when it is applied at or just before sowing. The option to apply N fertiliser well before sowing a winter crop is more suited to well-buffered clays and other alkaline soils than to light soils that are prone to nitrate leaching and acidification.

Applying N fertiliser in mid-row bands as part of a one-pass sowing operation separates seed from fertiliser and prevents seedling damage from ammonia. A one-pass sowing operation also minimises soil disturbance. The agronomic advantage of mid-row banding at sowing of winter crops is that urea or anhydrous ammonia, when placed at high concentrations ($>500 \mu\text{g N/g}$) suppresses nitrification and immobilisation and can remain in the ammonium form for several months. The high ammonium concentrations are achieved with one band of fertiliser between every second seed row, so that each seed row has access to one fertiliser band. Mid-row banding has given greater NUE than other application methods in several experiments (Angus *et al.* 2014, Sandral *et al.* 2017). An alternative to mid-row banding is side banding using tynes that deliver seed behind the ‘boots’ and fertilisers to the side of the crop row, far enough from the seed to minimise damage to germinating seedlings (Barr *et al.* 2016). More than half the N applied to dryland crops in Canada, for example, is applied at sowing in side or mid-row bands and PAMI (2015) reported no significant difference between the methods.

Mid-row banding of N fertiliser during crop growth is another promising method of application provided there is highly precise guidance using GPS. Wallace *et al.* (2016) showed that this system was more efficient than in-crop application of solid or liquid fertiliser to the soil surface. The probable reason for the higher NUE was that N was neither stranded on dry soil nor lost by ammonia volatilisation. There have not yet been comparisons between mid-row banding during crop growth and one-pass mid-row banding at sowing.

Form – inorganic fertilizer: implications for CA

Fertiliser price, nutrient concentration and convenience influence the form of nutrient applied. Urea dominates the N market because it is cheaper per unit N than alternatives such as liquid UAN, granular ammonium sulphate or ammonium nitrate. Ammonium nitrate often gives greater ‘agronomic efficiency’ (AE) than urea but the additional yield does not usually justify the additional cost. The N in UAN is also more expensive than in urea but it has advantages that justify the additional cost in some circumstances. The AE for UAN may be slightly greater than for urea (Loss and Appelbee 2006) and it

can be applied uniformly and rapidly through a spray boom. Little UAN is applied in the north or south-east but it makes up half the fertiliser N applied in the west. Anhydrous ammonia is also convenient to use but the cost of transport and storage vessels is high unless spread over high yields, or two crops per year. Enhanced efficiency N fertilisers (EEF) contain urease and/or nitrification inhibitors and/or a coating such as polyethylene and epoxy resin that slows dissolution of nutrients. The effect of all EEFs is to retain soil N in the form of urea or ammonium so that less N is lost through ammonia volatilisation, nitrate leaching or denitrification. There is good evidence that nitrification inhibitors reduce emissions of the greenhouse gas N₂O but little evidence of consistently increased yield (Rose *et al.* 2018).

Most P fertiliser for crops consists of granular ammonium phosphates while, for pastures, graziers still apply single superphosphate, partly because of the additional sulfur. In most cases the solid-P sources (single superphosphate, MAP and DAP) perform quite similarly except in calcareous soils where the solubility of superphosphate and DAP is poor (Lombi *et al.* 2005). On highly calcareous soils (>15% CaCO₃ w/w) liquid P fertilisers, although expensive, can be more cost-effective than granular phosphates but there is no individual liquid P product that is consistently superior to the others on these soils (McBeath *et al.* 2007). Foliar application of liquid P is an attractive option because it allows for tactical applications of P in response to the season. However, while it has been shown to be absorbed by foliage, it has not given consistent yield responses (Noack *et al.* 2010). While soil-banded liquid P has not been shown to lead to a yield disadvantage compared with granular, foliar applied liquid P that has not been absorbed will land on the soil surface where roots have minimal access, potentially reducing P availability compared with soil application. Applying two or more nutrients in a band can increase the efficiency with which crops recover each. In a K-deficient soil in the west, co-locating P and K fertilisers in a band soil increased root proliferation in the band and increased K uptake by crops (Ma *et al.* 2011). Similar results have been reported in a northern Vertisol (Bell *et al.* 2017a), but high concentrations of co-located P and K fertilisers were needed to stimulate additional K uptake.

Form – manures and residues

Beef feedlots and dairy farms produce ~4 M t/yr of manure (Bunemann *et al.* 2006). Most feedlots are in the north, while poultry and pig manure are applied to croplands in the south close to the source. Most dairy manure is applied on the farms where it is produced. Nutrients in manures vary considerably in concentration, depending on feed rations, age of the manure and the duration of stockpiling (Beegle *et al.* 2008). Nutrient concentrations are typically low and are not in the correct ratios to match crop requirements or balance nutrient removal, so manures should form part of a sustainable nutrient management plan (Abbott *et al.* 2018). The low concentrations also result in high transport costs/kg of nutrient, resulting in distribution patterns centred within a <50 km radius of the source.

Most manure is broadcast onto the soil surface and generally not incorporated. This reduces efficiency of manure nutrient use, with N loss through ammonia volatilisation and positional unavailability of immobile elements. Beegle *et al.* (2008), in a survey of 89 experiments, found that the average NUE of manure was 39±21% of inorganic fertiliser in the year of application, when applied at the same rate and in the same conditions. Celestina *et al.* (2018) found that applying high rates of manures and other organic amendments into slots in dense subsoils increased yield of winter crops, mainly due to increased N supply.

Long-term stubble retention has little effect on soil carbon (C) because the humification is limited by low levels of N, P and sulfur (see Chapter 16). Manures generally contain sufficient N, P and S to increase soil C, but when applied sporadically at commercial application rates (1-5 t/ha), provide small C inputs. Incorporating manure to supply crop nutrients also limits the longevity of any potential C benefit. Added C is less persistent in sands than in finer textured soil.

Rate – paddock averages

Nitrogen fertiliser decisions can be made at or before sowing, and, in winter-rainfall regions, during crop growth. When N is applied at sowing, soil tests of mineral N to an appropriate depth (60 cm in the south and 90 cm in the north) are inputs to a supply-demand equation

$$F = (D - SE_{\text{soil}}) / E_{\text{fert}}$$

where F is fertiliser requirement, D is demand calculated from expected yield, grain protein and the proportion of N the grain, S is the supply of nutrients from soil and E is efficiency, expressed as the proportion of nutrient from soil or fertiliser that is taken up by the crop. Where it is feasible to apply N during crop growth the yield target can be adjusted as the season unfolds. In these regions a useful measure of crop-N status is shoot density at the start of tillering. This is closely related to the mass of above-ground N and yield response to applied N. The mass of N in the crop is a better predictor of yield response to fertiliser than above-ground N concentration, apparently because self-dilution of tissue N tends to compress the range of concentrations (Angus 1995). Foliar cover of vegetative crops is also closely related to the mass of N which justifies the use of remote and proximal sensors for variable rate application (Li *et al.* 2010). The limitation of relying on canopy cover alone is that it may be related to soil constraints as well as nutrient status. Where canopy cover is low because of N deficiency more fertiliser is needed but where low canopy cover is due to soil constraints there is less need for N (Angus *et al.* 2010).

For nutrients applied at sowing, the critical values for macronutrients have been developed in the ‘Better Fertilisers Decision Framework’ (N - Bell *et al.* 2013b, P - Bell *et al.* 2013c, K - Brennan and Bell 2013), and the utility of different soil testing methods has been evaluated for P (Speirs *et al.* 2013). The critical nutrient concentration may vary with management practices and, for example, much more P may be required for crops supplied with high levels of N fertiliser than is estimated from established critical values (Duncan *et al.* 2018).

The supply-demand approach is inappropriate for P (Bell *et al.* 2013a, c) and K (Brennan and Bell 2013) because the critical soil test values are not closely related to crop yield, and for P are more related to the buffer capacity of the soil and application method (Moody 2007). The CEC and resulting K buffer capacity influence the optimum K application rate (Bell *et al.* 2017a).

For P and K, applications are typically made at or before sowing. Given the lack of quantitative relationships between yield and P/K demand, the appropriate rate will be determined by the efficiency with which the crop exploits the applied fertiliser. This will primarily be determined by positional availability in the soil profile in interaction with the amount and distribution of seasonal rainfall.

Rate – variable

Spatial sensing of soil constraints and crop conditions provides information that can be used to vary inputs of fertiliser and lime. Variable P application can be prescribed to replace P removed in grain, as estimated from a yield monitor. Variable lime application to neutralise surface soil acidity (but not subsurface acidity) can be prescribed using a pH sensor (*e.g.* www.veris.com). Variation in target yield due to subsoil salinity or sodicity can be estimated by electromagnetic induction (*e.g.* www.geonics.com). But the greatest interest in variable rate technology is with N fertiliser.

Only about 20% of Australian grain growers adopt variable N inputs based on soil-specific management (Robertson *et al.* 2012), despite significant yield and profit benefits being demonstrated in distinctly variable environments, for example between sand dunes and clay loam swales (Monjardino *et al.* 2013). Sensors of crop-N status, which in turn inform variable fertiliser application strategies, have significantly evolved in the last 20 years, although several constraints to their widespread adoption remain. Colaço and Bramley (2018) suggest that the limitations lie within the experimental approaches used, the implementation of the N application algorithms in farmers’ fields and the ability to deliver consistent and profitable outcomes. They conclude that further development via the integration of a range of sensors is likely to improve the adoptability of the technology.

Nutrient and pH stratification

Positional availability of nutrients

Soil sampling in Australia has usually been to a depth of 10 cm which is too shallow to identify nutrient-depleted subsoils or stratification of immobile nutrients and subsurface acidity. Sampling the 10-20 cm layer identifies presence of an ‘acid throttle’ (a soil layer sandwiched between a limed topsoil and a naturally neutral or acidic subsoil) and, in the north, sampling the 10-30 cm layer identifies nutrient depletion (Moody *et al.* 2010). In sand-surfaced soils in the west there was an economic benefit from sampling the subsoil when exchangeable K was near-adequate (40-60 mg/kg) in deep sands, or when it was less than 40 mg/kg in duplex soils (Scanlan *et al.* 2015).

Crops extract nutrients from moist topsoils and subsoils, and the latter can supply up to 70% of the N, P and K accumulated by crops in temperate climates (McBeath *et al.* 2012, Kautz *et al.* 2013). Where the topsoil is dry and crops are reliant on subsoil moisture for extended periods, root access to the nutrient-rich topsoil layers is limited and stratified nutrient reserves in these layers are effectively unavailable. In such conditions, crops rely more on subsoil nutrients if they are present. In the west, P accumulates in subsoils when P fertiliser has been repeatedly applied in excess of crop demand (Weaver and Wong 2011). In such circumstances, a test of P concentration in the topsoil underestimates the supply of P from the whole soil profile (Bell *et al.* 2013a). In clay soils in the north there is evidence of P depletion at soil depths >10 cm and <60 cm (Norrish 2003), and of increased yield in response to deep banding P and K fertiliser (Bell *et al.* 2015, 2016, Lester *et al.* 2017).

Nutrient stratification and subsoil depletion can be addressed by periodic ‘strategic tillage’ to redistribute nutrients concentrated in the topsoil into deeper soil, or by direct placement of nutrients into the depleted subsoil layers (see Chapter 7). The ‘strategic tillage’ option of cultivation every 5-10 years is considered by some to be inconsistent with conservation tillage because it leads to temporary reduction in surface cover, accelerated soil C loss and disruption of microbial communities. However there are situations where periodic tillage is already occurring to control herbicide-resistant weeds, to incorporate lime, increase topsoil clay content or reduce the severity of hydrophobicity. These operations also redistribute stratified nutrients through larger soil volumes (Scanlan and Davies 2019). The balance between these benefits and costs associated with tillage needs further research (Dang *et al.* 2015). The value of the alternative approach, to inject nutrients directly into depleted subsoil layers, depends on seasonal conditions (Bell *et al.* 2012).

Reversing subsurface acidification

In situations where no lime has been applied, the topsoil becomes acidified and the acid layer spreads down and becomes thicker, retarding penetration of roots of acid-sensitive species to reduce yield. Applying lime to the topsoil layers without incorporation by tillage leads to development of an ‘acid throttle’. This pH profile is an increasingly common occurrence in cropping land in the high and medium rainfall regions of the south. Surface lime applied at normal rates moves slowly through loam-textured topsoils (Kandosols, Chromosols and Tenosols) in the south-east (Li *et al.* 2019) but is more mobile in sandy topsoils in the west (Whitten *et al.* 2000).

Practices to neutralise subsurface acidification are expensive. The simplest is to apply larger than normal amounts of lime to the surface soil, with or without tillage (Scanlan *et al.* 2017). Other methods are directly injecting lime into subsurface soil through tubes behind rip tynes, or extensive profile modification using a rotary spader to mix surface-applied lime through ~30 cm of soil (see Chapter 8). With enough lime, all of these practices eventually reduce the level of subsurface soil toxins, increase crop access to subsoil water, increase yield potential and hence nutrient demand. The more vigorous the soil disturbance the faster the subsurface acidity will be neutralised. There is evidence that neutralising subsurface and subsoil acidity can unlock indigenous P, as Shierlaw and Alston (1984) found by ameliorating subsoil compaction. Alternatively, there may be a greater requirement for fertilizer as yield potential increases.

Conclusions

The many interactions between plant nutrition and CA have been the subject of research over the past 3 decades. The results have led to changes in management of fertiliser rate, timing and placement appropriate for CA. The optimum rates of N fertilisers for crops are known to vary in response to N immobilisation by retained stubble, N contributions from legume rotation and increases in potential yields through improved water use efficiency. Rates of P and K fertilisers also reflect changes in yield potential and hence nutrient demand, but perhaps a bigger issue for both the less mobile nutrients is placement to ensure good root access.

Two nutritional challenges stand out because of the cost they impose on Australian agriculture and the relatively small amount of research that is underway. One is neutralising the looming acidification of subsurface soil in high and medium-rainfall agricultural regions in the south-east and west. The second is to start restoring the P status of pasture soils in the Brigalow bioregion.

Both challenges apply to large areas of land, about 40 M ha in each case, located in relatively favourable climatic regions. In both cases the land will become more degraded if left untreated, and research is needed to find effective and economic treatments. Neither challenge is directly related to CA, although subsurface acidification is partly due to the reduction in profile mixing of lime applied to topsoils due to reduced cultivation. Given the presence of both constraints in subsoil as well as topsoil layers (the latter in the case of low soil P in the Brigalow bioregion), strict adherence to CA principles represent a limitation to the management strategies that can be deployed. Use of strategic/occasional tillage appear to be part of any future solution. However, the profitability of both systems needs to be increased to cover the cost of additional inputs. New application strategies will be needed to maximise the efficiency of use of these inputs.

The low recovery of applied nutrients by crops and pastures is a large cost to Australian agriculture that will only grow larger as fertilisers provide an increasing proportion of the nutrient supply, although there is currently little evidence that CA has affected nutrient use efficiency. Future research will need to improve fertiliser recovery and use efficiency. Based on this review, the most promising lines of research are the placement of fertilisers and soil ameliorants into layers and bands of the soil that support root growth and supply nutrients in amounts and at times that synchronise with crop demand. This may ultimately require the development of new farm implements.

It will also be important to retain legume-based pastures and pulses as part of CA because these species require no N fertiliser, contribute residual N to following crops and increase potential yield of rotational crops in other ways. Despite their importance, the area of rotational pastures is declining, and pulses make up only 11% of cropped land (ABARES 2018). The greatest contribution of pulses was in the west from the early 1980s to the late 1990s, when the area of lupin crops grew from zero to 20% of the cropped land. At the same time, the trend of wheat yield increased rapidly suggesting that lupins made a major contribution to system productivity. The area of lupins in the west has subsequently decreased but their brief success shows the potential contribution that pulses can make. Support for pulse growing will enhance CA.

Australian dryland farmers make most of their income in relatively few favourable seasons and on their most fertile soils. In winter-rainfall regions tactical management of in-season N fertiliser in these exceptional seasons can help capture high yields. Improved seasonal weather forecasts and variable rate systems could assist farmers with risky decisions about applying N to ‘feed the crop’, while deep placement of P, K and lime ‘feed the soil’ and provide an environment in which N can be managed to achieve the water-limited yield.

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References

- ABARES (2018) Agricultural commodities. ACS2018_PulseTables.v1.2.0.xlsx. (Australian Bureau of Agricultural and Resource Economics: Canberra)
- Abbott LK, Macdonald LM, Wong MTF *et al.* (2018) Potential roles of biological amendments for profitable grain production – A review. *Agriculture, Ecosystems & Environment* **256**, 34-50
- Angus JF (1995) The role of nitrogen in wheat. In (Eds. IG Fenton and PW Orchard) “Making better fertiliser, lime and gypsum recommendations” pp. 68-88 (NSW Agriculture: Wagga Wagga)
- Angus JF, Walker CN, Pedler JF, Norton RN (2010) Optimizing nitrogen for wheat growing on hostile soils. *Better Crops* **94**, 13-15
- Angus JF, Bolger TG, Kirkegaard JA, Peoples MB (2006) Nitrogen mineralisation in relation to previous crops and pastures. *Australian Journal of Soil Research* **44**, 355-365
- Angus JF, Gupta VVSR, Pitson GD, Good AJ (2014) Effects of banded ammonia and urea fertilizer on soil and the growth and yield of wheat. *Crop and Pasture Science* **65**, 337-352
- Angus JF, Kirkegaard JA, Hunt JR *et al.* (2015) Break crops and rotations for wheat. *Crop and Pasture Science* **66**, 523-552
- Angus JF, Grace PR (2017). Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. *Soil Research* **55**, 435-450
- Barr JB, Desbiolles JMA, Fielke JM (2016) Minimising soil disturbance and reaction forces for high speed sowing using bentleg furrow openers. *Biosystems Engineering* **151**, 53-64
- Batten GD, Fettell NA, Mead JA, Khan MA (1999) Effect of sowing date on the uptake and utilisation of phosphorus by wheat (cv. Osprey) grown in central New South Wales. *Australian Journal of Experimental Agriculture* **39**, 161-170
- Beegle DB, Kelling KA, Schmitt MA (2008) Nitrogen from animal manures. In (Eds. JS Schepers, WR Raun) “Nitrogen in agricultural soils” Agronomy Monograph No. 49, pp 823-881 (American Society of Agronomy: Madison, WI)
- Bell MJ, Lester DW, Graham R *et al.* (2016). Phosphorus and potassium nutrition. GRDC Updates Coonabarabran and Goondiwindi www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/phosphorus-and-potassium-nutrition
- Bell MJ, Lester DW, Smith LN, Want PS (2012) Increasing complexity in nutrient management on clay soils in the northern grain belt – nutrient stratification and multiple nutrient limitations. *Proceedings of 16th Australian Agronomy Conference*, UNE Armidale
www.agronomyaustraliaproceedings.org/images/sampled/2012/8045_7_bell.pdf
- Bell MJ, Mallarino AP, Moody PW *et al.* (2017a) Soil characteristics and cultural practices that influence potassium recovery efficiency and placement decisions. In (Eds. Murrell TS, Mikkelsen RL) “Frontiers of Potassium Science” Rome, Italy. pp O277-O288 (International Plant Nutrition Institute: Peachtree Corners, GA, USA)
- Bell MJ, Moody PW, Anderson GC, Strong W (2013a) Soil phosphorus – crop response relationships and criteria for oils, grain legumes and summer cereal crops in Australia. *Crop and Pasture Science* **64**, 499-513
- Bell MJ, Moody PW, Thompson ML *et al.* (2017b). Improving potassium rate recommendations by recognizing soil potassium pools with dissimilar bioavailability. In (Eds. Murrell TS, Mikkelsen RL) “Frontiers of Potassium Science” Rome, Italy, pp O239-O248 (International Plant Nutrition Institute: Peachtree Corners, GA, USA)
- Bell R, Reuter D, Scott B *et al.* (2013c) Soil phosphorus-crop response calibration relationships and criteria for winter cereal crops grown in Australia. *Crop and Pasture Science* **64**, 480-498
- Bell MJ, Sands D, Lester D, Norton R (2015). Response to deep placed P, K and S in central Queensland. *Proceedings of 17th Australian Agronomy Conference*, Hobart www.agronomyaustraliaproceedings.org/
- Bell MJ, Strong W, Elliott D, Walker C (2013b) Soil nitrogen – crop response calibration relationships and criteria for winter cereal crops grown in Australia. *Crop and Pasture Science* **64**, 442-60
- Borrell AK, van Oosterom EJ., Mullet JE *et al.* (2014) Stay-green alleles individually enhance grain yield in sorghum under drought by modifying canopy development and water uptake patterns. *New Phytologist*, **203**, 817-830
- Brennan RF, Bell MJ (2013) Soil potassium- crop response calibration relationships and criteria for field crops grown in Australia. *Crop and Pasture Science* **64**, 514-522
- Bunemann EK, Schwenke G, van Zwieten L (2006) Impact of agricultural inputs on soil organisms – A review. *Australian Journal of Soil Research* **44**, 379-406
- Cade-Menun BJ, He Z, Zhang H *et al.* (2015) Stratification of phosphorus forms from long-term conservation tillage and poultry litter application. *Soil Science Society of America Journal* **79**, 504-516

- Cossani CM, Sadras VO (2019) Increasing co-limitation of water and nitrogen drives genetic yield gain in Australian wheat. *European Journal of Agronomy* (in press).
- Celestina C, Midwood J, Sherriff S *et al.* (2018) Crop yield responses to surface and subsoil applications of poultry litter and inorganic fertiliser in south-eastern Australia. *Crop and Pasture Science* **69**, 303-316
- Colaço AF, Bramley RGV (2018) Do crop sensors promote improved nitrogen management in grain crops? *Field Crops Research* **218**, 126-140
- Cornish PS, Myers LF (1977) Low pasture productivity of a sedimentary soil in relation to phosphate and water supply. *Australian Journal of Experimental Agriculture* **17**, 776-783
- Damon PM, Bowden B, Rose T, Rengel Z (2014) Crop residue contributions to phosphorus pools in agricultural soils: A review. *Soil Biology and Biochemistry* **74**, 127-137
- Dang YP, Balzer A, Crawford M *et al.* (2017) Strategic tillage in conservation agricultural systems of north-eastern Australia: why, where, when and how? *Environmental Science and Pollution Research* www.link.springer.com/article/10.1007/s11356-017-8937-1
- Delroy ND, Bowden JW (1986) Effect of deep ripping, the previous crop, and applied nitrogen on the growth and yield of a wheat crop. *Australian Journal of Experimental Agriculture* **26**, 469-479
- Duncan EG, O'Sullivan CA, Roper MM *et al.* (2018) Influence of co-application of nitrogen with phosphorus, potassium and sulphur on the apparent efficiency of nitrogen fertiliser use, grain yield and protein content of wheat: Review. *Field Crops Research* **226**, 56-65
- Fillery IRP, Khimashia N (2016) Procedure to estimate ammonia loss after N fertiliser application to moist soil. *Soil Research* **54**, 1-10
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018) Winter wheat phenology can stabilise flowering date and maximise grain yield in semi-arid Mediterranean and temperate environments. *Field Crops Research* **223**, 12-25
- Giller KE, Andersson JA, Corbeels M *et al.* (2015) Beyond conservation agriculture. *Frontiers in Plant Science* **6**, 870-884
- GRDC (2017) Farm practices survey report 2016. www.grdc.com.au/resources-and-publications/all-publications/publications/2018/farm-practices-survey-report-2016
- Hunt JR, Lilley JM, Trevaskis B *et al.* (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change* **9**, 244-247
- Hunt JR, Swan AD, Breust PD *et al.* (2016) Sheep grazing on crop residues increase soil mineral N and grain N uptake in subsequent wheat crops. *Proceedings of 2016 International Nitrogen Initiative Conference* www.ini2016.com
- Kautz T, Amelung W, Ewert F *et al.* (2013) Nutrient acquisition from arable subsoils in temperate climates: A review. *Soil Biology and Biochemistry* **57**, 1003-1022
- Kirkegaard J, Angus J, Swan A *et al.* (2008) Ripping yarns: 25 years of variable responses to ripping clay soils in south-eastern Australia. *Proceedings of 14th Australian Agronomy Conference*, Adelaide www.agronomyaustraliaproceedings.org/images/sampled/2008/concurrent/managingsubsoils/5934_kirkegaard
- Krapp A (2015) Plant nitrogen assimilation and its regulation: a complex puzzle with missing pieces. *Current Opinion in Plant Biology* **25**, 115-122
- Lawes, RA, Oliver, YM and Huth, NI (2019) Optimal nitrogen rate can be predicted using average yield and estimates of soil water and leaf nitrogen with infield experimentation. *Agronomy Journal* **111**, 1155-1164
- Lester DW, Bell MJ, Sands DJ, Weaver TB (2017) Cereal and legume crop responses to deep-placed K with and without P in NE Australian Vertosols. In (Eds. Murrell TS, Mikkelsen RL) "Frontiers of Potassium Science" Rome, Italy (International Plant Nutrition Institute: Peachtree Corners, GA, USA) <http://www.ipni.net/ipniweb/conference/kfrontiers.nsf/article/conference-proceedings>
- Li GD, Conyers MK, Helyar KR *et al.* (2019) Long-term surface application of lime ameliorates subsurface soil acidity in the mixed farming zone of south-eastern Australia. *Geoderma* **338**, 236-246
- Li Y, Chen D, Walker CN, Angus JF (2010) Estimating the nitrogen status of crops using a digital camera. *Field Crops Research* **118**, 221-227
- Lobell D B (2007) The cost of uncertainty for nitrogen fertilizer management: A sensitivity analysis. *Field Crops Research* **100**, 210-217.
- Lombi E, McLaughlin MJ, Johnston C *et al.* (2005) Mobility, solubility and lability of fluid and granular forms of P fertiliser in calcareous and non-calcareous soils under laboratory conditions. *Plant and Soil* **269**, 25-34
- Loss S, Applebee M (2006) Agronomic performance and adoption of liquid fertilisers in Western Australia. *Proceedings of 13th Australian Agronomy Conference*, Perth WA www.agronomyaustraliaproceedings.org/images/sampled/2006/poster/adoption/4604_loss.pdf

- Lotfollahi M, Alston AM, McDonald GK (1997) Effect of nitrogen fertiliser placement on grain protein concentration of wheat under different water regimes *Australian Journal of Agricultural Research* **48**, 241-250
- Ma Q, Rengel Z, Siddique KHM (2011) Wheat and white lupin differ in root proliferation and phosphorus use efficiency under heterogeneous soil P supply. *Crop and Pasture Science* **62**, 467-473
- Mason MG (1992) Effect of management of previous cereal stubble on nitrogen fertiliser requirement of wheat. *Australian Journal of Experimental Agriculture* **32**, 355-362
- McBeath TM, McLaughlin MJ, Kirby JK, Armstrong RD (2012) The effect of soil water status on fertiliser, topsoil and subsoil phosphorus utilisation by wheat. *Plant and Soil* **358**, 337-348
- McBeath TM, McLaughlin MJ, Armstrong RD *et al.* (2007) Predicting the responses of wheat (*Triticum aestivum* L.) to liquid and granular phosphorus fertilisers in Australian soils. *Soil Research* **45**, 448-458
- McLaren TI, McBeath TM, Simpson RJ *et al.* (2017) Direct recovery of ³³P-labelled fertiliser phosphorus in subterranean clover (*Trifolium subterraneum*) pastures under field conditions – The role of agronomic management. *Agriculture, Ecosystems & Environment* **246**, 144-156
- McIvor JG, Guppy C, Probert ME (2011) Phosphorus requirements of tropical grazing systems: the northern Australian experience. *Plant and Soil* **349**, 55-67
- McLaughlin MJ, Alston A, Martin J (1988) Phosphorus cycling in wheat pasture rotations. I. The source of phosphorus taken up by wheat. *Soil Research* **26**, 323-331
- McLaughlin MJ, McBeath TM, Smernik RJ *et al.* (2011) The chemical nature of P accumulation in agricultural soils—implications for fertiliser management and design: an Australian perspective. *Plant and Soil* **349**, 69-87
- Monjardino M, McBeath TM, Brennan L, Llewellyn RS (2013) Are farmers in low-rainfall cropping regions under-fertilising with nitrogen? A risk analysis. *Agricultural Systems* **116**, 37-51
- Moody PW (2007) Interpretation of a single point P buffering index for adjusting critical levels of the Colwell soil P test. *Australian Journal of Soil Research* **45**, 55-62
- Moody PW, Bell MJ, Klepper K *et al.* (2010) Implications of minimum till dryland cropping systems for diagnostic P and K soil tests. *Proceedings of 19th World Congress of Soil Science* **5**, 4985-4988
http://soilscienceaustralia.com.au/images/sampled_data/publications_tab/confproceedings/2012Soil%20Symposium/12589%20Papers%20V04.pdf
- Nkebiwe PM, Weinmann M, Bar-Tal A, Muller T (2016) Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. *Field Crops Research* **196**, 389-401
- Noack SR, McBeath TM, McLaughlin MJ (2010) Potential for foliar phosphorus fertilisation of dryland cereal crops: A review. *Crop and Pasture Science* **61**, 659-669
- Norrish, SA (2003) Soil and water interactions controlling wheat crop response to phosphorus fertiliser in north-western New South Wales. PhD Thesis, University of Western Sydney
- Norton RM (2012) Wheat grain nutrient concentrations for south-eastern Australia. *Proceedings of 16th Australian Agronomy Conference*, UNE Armidale NSW
www.regional.org.au/au/asa/2012/nutrition/7984_nortonr
- Norton RM (2016) Nitrogen management to optimise canola production in Australia. *Crop and Pasture Science* **67**, 419-438
- PAMI (2015) Emergence and yield comparison of mid-row and side banding seeding/fertilizer systems. Research Update 768 (Prairie Agricultural Machinery Institute: Humboldt, Saskatchewan, Canada)
www.pami.ca
- Pearce A, McCaskill M, Ludwig I *et al.* (2017) What are the limiting nutrients for crops of high yield potential in the South East of South Australia? *Proceedings of 18th Australian Agronomy Conference*, Ballarat, Victoria
www.agronomyaustraliaproceedings.org/images/sampled_data/2017/86_ASA2017_Pearce_Amanda_Final.pdf
- Peck G, Chudleigh F, Johnson B, Lawrence D (2015) Use of phosphorus fertiliser for increased productivity of legume-based sown pastures in the Brigalow Belt region – a review. Project report. Meat and Livestock Australia www.era.daf.qld.gov.au/id/eprint5039
- Peoples MB, McLennan PD, Brockwell J (2008) Hydrogen emission from nodulated soybeans [*Glycine max* (L.) Merr] and consequences for the productivity of a subsequent maize (*Zea mays*L.) crop. *Plant and Soil* **307**, 67-82
- Potgieter AB, Lobell DB, Hammer GL *et al.* (2016) Yield trends under varying environmental conditions for sorghum and wheat across Australia. *Agriculture and Forest Meteorology* **228**, 276-285
- Robertson MJ, Llewellyn RS, Mandel R *et al.* (2012) Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. *Precision Agriculture* **13**, 181-199

- Rose TJ, Wood RH, Rose MT, van Zwieten, L (2018) A re-evaluation of the agronomic effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor NBPT. *Agriculture Ecosystems and Environment* **252**, 69-73
- Rossolem CA, Mallarino AP, Nogueira AR (2017) Can cycling of potassium from crops and other organic residues be integrated into potassium rate recommendations? In (Eds Murrell TS, Mikkelsen RL) "Frontiers of Potassium Science" Rome, Italy. pp. O158-O165 (International Plant Nutrition Institute: Peachtree Corners, GA, USA)
- Sandral GA, Tavakkoli E, Harris F *et al.* (2017) Improving nitrogen fertiliser use efficiency in wheat using mid-row banding. Proceedings of 18th Australian Agronomy Conference, Ballarat, Victoria
http://agronomyaustraliaproceedings.org/images/sampled/2017/175_ASA2017_Sandral_Graeme_Final.pdf
- Scanlan CA, Bell RW, Brennan RF (2015) Simulating wheat growth response to potassium availability under field conditions in sandy soils. II. Effect of subsurface potassium on grain yield response to potassium fertiliser. *Field Crops Research* **178**, 125-134
- Scanlan CA, Brennan RF, D'Antuono MF, Sarre GS (2017) The interaction between soil pH and phosphorus for wheat yield and the impact of lime-induced changes to soil aluminium and potassium. *Soil Research* **55**, 341-353
- Scanlan CA, Davies SL (2019) Soil mixing and redistribution by strategic deep tillage in a sandy soil. *Soil and Tillage Research* **185**, 139-145
- Schroder P, Curnow B (1977) Fertilizer test strips will help give the answers. *Journal of Agriculture Victoria* **75**, 270-272
- Shierlaw J, Alston AM (1984) Effect of soil compaction on root growth and uptake of phosphorus. *Plant and Soil* **77**, 15-28
- Snyder CS (2017) Enhanced nitrogen fertiliser technologies support the '4R' concept to optimise crop production and minimise environmental losses. *Soil Research* **55**, 463-472
- Speirs SD, Scott BJ, Moody PW, Mason SD (2013) Soil phosphorus tests II: A comparison of soil test-crop response relationships for different soil tests and wheat. *Crop and Pasture Science* **64**, 469-479
- Sprague SJ, Rasmussen IS, Lilley JM *et al.* (2019) Nitrogen relations of dual-purpose crops (in preparation)
- Syme JR, Mackenzie J, Strong WM (1976) Comparison of four wheat cultivars for yield and protein response to nitrogen fertilizer *Australian Journal of Experimental Agriculture and Animal Husbandry* **16**, 407-410
- Thomas GA, Felton WL, Radford BJ (1997) Tillage and crop residue management. In (Eds. AL Clarke, PB Wylie) "Sustainable crop production in the sub-tropics: an Australian perspective" pp 27-34. Information Series QI97035 (Qld Department of Primary Industries: Brisbane)
- van Herwaarden AF, Angus JF, Richards RA, Farquhar GD (1998) 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser. II Carbohydrate and protein dynamics. *Australian Journal of Agricultural Research* **49**, 1083-1093
- Wallace A, Nuttall J, Henry F *et al.* (2016) Mid-row banding nitrogen fertiliser in-season In "Improving nitrogen use efficiency of cropping systems of southern Australia" (Agriculture Victoria: Horsham, Vic)
www.grdc.com.au/resources-and-publications/all-publications/publications/2016/11/mid-row-banding-nitrogen-fertiliser-in-season
- Weaver, D, Wong MF (2011) Scope to improve phosphorus (P) management and balance efficiency of crop and pasture soils with contrasting P status and buffering indices. *Plant and Soil* **349**, 37-54
- Whitten MG, Wong MTF, Rate AW (2000) Amelioration of subsurface acidity in the south-west of Western Australia: downward movement and mass balance of surface incorporated lime after 2-15 years. *Australian Journal of Soil Research* **38**, 711-728
- Wichern F, Eberhardt E, Mayer J *et al.* (2008) Nitrogen rhizodeposition in agricultural crops: Methods, estimates and future prospects. *Soil Biology and Biochemistry* **40**, 30-48

Chapter 15

Harnessing the benefits of soil biology in conservation agriculture

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Soil biology and ecology in conservation agriculture

“Soil, the 1 m skin of the earth, sustains all life forms in the terrestrial ecosystem and is vital to the very existence and substance of human life” (Dick 2018). Soils function as biological entities due to the microbial communities that exist within them. It is estimated that in 1 kg of soil, there are more than 1 billion bacteria and >2 km of fungal hyphae. More than 95% of soil microbial species are non-culturable, but metagenomic analysis of nucleic acids is transforming our ability to understand the breadth and diversity of soil microbial communities and their functional capabilities.

Soil microbial communities are dependent for the most part on food sources, water and oxygen. In Australian soils, which are low in soil organic matter, spatial heterogeneity results in more concentrated communities associated with microsites such as plant roots (rhizosphere) and decomposing residues (detritosphere) which support approximately 60% of all microbial life in surface soils. In the rhizosphere, carbon (C) and other nutrients and water are supplied by rhizodeposition with above- and below-ground crop residues being major sources of C inputs in agricultural soils. Microbial communities in the rhizosphere generally originate from the general soil but spatial isolation and minimal food sources in the soil limit their proliferation and activities. In the rhizosphere, interactions among microorganisms and plants are generally mutualistic. Apart from food and nutrients supplied by plants, microorganisms benefit from interactions with each other and provide benefits to the plant by transforming nutrients to available forms or by competing with or suppressing plant pathogens. This is a somewhat simplistic view of plant-microbial interactions: in reality relationships are more complex (Roper and Gupta 1995). Some aspects of this complexity are addressed in this chapter.

Conservation agriculture (CA), as defined by FAO, and technologies that have expanded from it, has four basic elements that we focus on in this Chapter:

- reduced or no-tillage (no-till);
- retention of plant/crop residues;
- diverse rotations; and
- precision agriculture including controlled traffic.

Each of these elements greatly impacts soil microbial communities, their function and system productivity. We first consider some of these impacts in the context of soil ecology and the soil food web under Australian cropping systems.

Ecological changes associated with conservation agriculture - soil physico-chemical properties

Despite the large numbers of microorganisms in the soil, they often exist in a biological desert. This is due to the small size of microbial (e.g. bacteria) cells in relation to the volume and surface area of soil particles. This can make it difficult for microorganisms to operate as a community as many of them need each other in order to carry out ecosystem services within the soil. For example, many organisms require C as an energy source to transform other nutrients; non-symbiotic nitrogen (N) fixing bacteria may rely on cellulolytic microorganisms for the supply of more available forms of C, and N mineralisation is more rapid with a complete web of soil organisms. Such mutualistic interactions are enabled through co-location on or within soil aggregates and pore networks. Microorganisms frequently contribute directly to soil aggregate formation through the production of polysaccharides that bind soil particles and through fungal hyphal networks that hold multiple aggregates together (Figure 1). However, cultivation, particularly intense disturbance, can disrupt aggregates and soil structure, and

therefore compromise microbial functions that supply nutrients to plants and provide protection from pathogens.

In Australia, adoption of CA has resulted firstly in significant increases in the labile and biologically available pools of soil organic matter. The particulate organic C pool typically accounts for 20-35% of total C especially in the surface (0-5 cm) soil layer. This particulate organic matter forms centres of microbial activities supporting both beneficial and deleterious microorganisms (plant pathogens). Secondly, reduced tillage has increased the gradient of microbial biomass distribution in the soil profile with the majority of microorganisms (50-75%) and soil biological activity concentrated in a thin surface layer to 5 cm depth (Gupta *et al.* 1994, Roper *et al.* 2010). In addition, in rainfed cropping regions, optimum conditions for microbial activity are short and infrequent because surface soils are generally prone to cycles of wet periods separated by long dry periods often under hot conditions. CA alters soil moisture retention properties favourably, albeit for short periods, thereby promoting optimal periods for microbiological functions (Gupta *et al.* 2011).

CA has facilitated the development and maintenance of soil aggregates, particularly larger and more fragile aggregates where organic matter is protected, and microbial processes proliferate (Six *et al.* 2000). Aggregate turnover is reduced under no-till compared with cultivation resulting in the formation of stable microaggregates in which C is stabilised and sequestered in the long term. Soil aggregates support the function of diverse populations of soil microflora by providing a range of conditions such as oxygen gradients, and very specific habitats (*e.g.* non-symbiotic N fixing bacteria which require lowered oxygen for nitrogenase activity). Not only does a well-structured soil promote water infiltration itself, but under reduced tillage or no-till, old root pathways remain intact as conduits for water entry to the soil. This mechanism is especially critical for water infiltration and crop production on water repellent soils which occupy more than 10 million hectares of agricultural land in southern Australia and Western Australia (WA) (Roper *et al.* 2013).

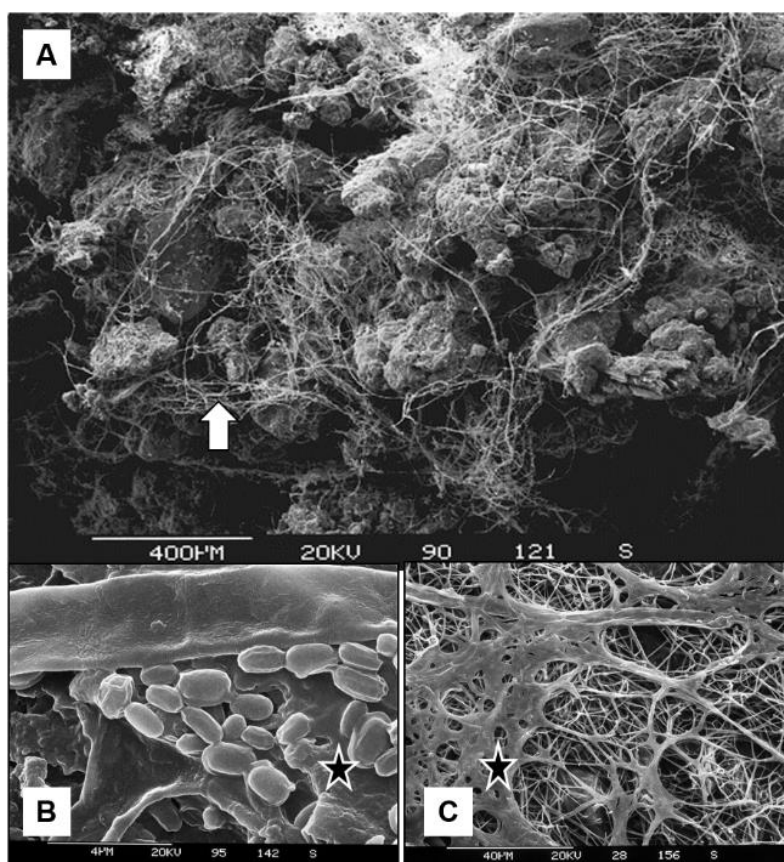


Figure 1. A network of fungal hyphae (arrow) holding soil particles to crop residues as part of soil aggregate formation (A), microbial glues (★) produced by bacteria (B) and fungi (C) help bind soil particles into stable aggregates (Gupta VVSR, CSIRO, unpublished).

The improved soil structure and stability in CA systems facilitates better drainage and water holding capacity, reducing the effects of water logging and water stress. As well, above-ground residues form the focal point for aggregate formation and fungal hyphal networks resulting in reduced wind erosion. Furthermore, crop residues protect soil surfaces and microbial communities from extreme temperatures and act as a surface mulch to reduce water losses under dry conditions (Ward *et al.* 2013). In wet environments, this may contribute to surface water-logging, but this may be offset by improved water infiltration and drainage in well-structured aggregated soils. Biopores, formed by macrofauna (earthworms, termites and ants) and plant roots, are conduits for water, oxygen and nutrients to subsoils, and have been shown to play an important role in the ability of plant roots to access water and nutrients from deeper layers of the soil profile in hostile or compacted soils (White and Kirkegaard 2010). Crop residues feed soil fauna that build these structures which are protected by no-till. The presence of old decomposing roots in close contact with new roots increases the interaction between microorganisms in the rhizosphere and the detritosphere creating a biologically modified environment with implications for both beneficial and deleterious biological functions.

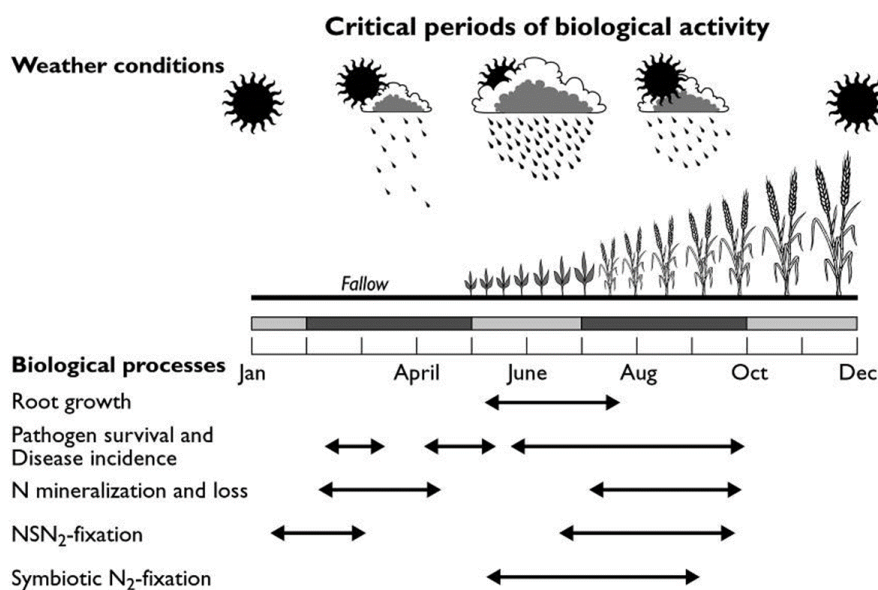


Figure 2. A conceptual model describing the significance of soil biological processes and their impact within the farming system in a Mediterranean-type climate in the southern and Western Australian cropping regions, where winter rainfall predominates (modified from Gupta *et al.* 2011).

Diversity of agro-ecological zones, cropping systems and biologically-optimal periods

Several edaphic and environmental factors contribute to microbial diversity and function in different agro-ecological zones. Winter rainfall predominates in Mediterranean-type environments in southern agro-ecological regions creating biologically optimal periods in terms of microbial activity, nutrient mineralisation and pathogen survival during non-host periods. Hot dry summers in this region severely limit microbial activity (Figure 2).

In northern New South Wales and Queensland, summer dominant rainfall coupled with warm conditions promotes active microbial communities culminating in rapid decomposition of C resources and significant biological activity by co-located microbial communities such as cellulolytic microorganisms and non-symbiotic N fixing bacteria (Roper and Gupta 2016).

Much of the agricultural regions of southern Australia and WA, with winter dominant rainfall patterns, are cereal dominated with wheat being the primary crop grown and other major rotational winter crops

being barley, canola, field pea and lupin. In the subtropical region of northern NSW and Qld, winter crops such as wheat, barley and chickpea as well as summer crops such as sorghum, mungbean and cotton are grown. The third element of conservation agriculture is the use of diverse rotations. However, growers tend to focus on crops that are most profitable, sometimes with increased risk of disease or weed infestation due to limited rotation cycles. For example, in south and WA, repeated cereal/canola crops are common. Considerable benefits in ecosystem function could be achieved through greater plant diversity which has been shown to increase microbial diversity, minimise the proliferation of soil-borne pathogens (Yukicevich *et al.* 2016) and increase biological resilience. Therefore, research on alternative crops suitable for each region is critical for stable and profitable conservation agriculture systems.

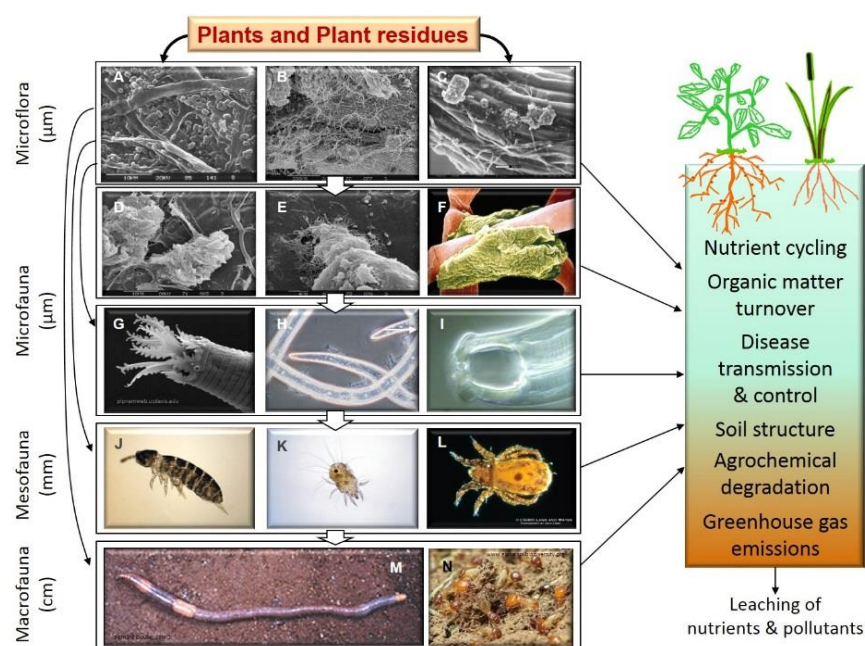


Figure 3. A pictorial representation of the soil detrital food web in agricultural systems: (A) bacteria, (B) fungi, (C) arbuscular-mycorrhizal fungi (AMF), (D) bacterial feeding amoeba, (E) testate amoeba, (F) mycophagous amoeba, (G) bacteriovore nematode, (H) fungivore nematode, (I) predatory nematode, (J) collembola, (K) mesostigmata mite, (L) mite, (M) earthworm, (N) termite.

Microbiology and soil fauna – food web and trophic levels

The soil food web consists of organisms of many different sizes and activities, from earthworms and smaller soil animals to fungi and bacteria (Figure 3). The soil food web ecology with its emphasis on how the biota community is assembled has the potential to act as an integrating concept across conservation biology, community ecology and provision of ecosystem services (Coleman *et al.* 2018).

Soil organic matter, whether derived directly from plants or from animals, drives the soil food web as a basic source of energy. Soil microflora (bacteria, fungi and protozoa) are the principal decomposers of organic matter, whereas the soil fauna, and their interactions with other soil organisms, impact on nutrient (N, phosphorus (P) and sulphur (S)) cycles. While microfauna feed directly on microflora, mesofauna feed on detritus, rich in microflora, and thus are key in microbial turnover (both beneficial and pathogenic) and nutrient cycling. Macrofauna are known as ecosystem engineers and fragment plant residues thereby stimulating microbial activity. They can create biopores and help redistribute organic matter and microorganisms, especially under reduced tillage and crop residue retention.

Under CA, soils are extremely heterogeneous both in terms of food source and habitat suitability for various organisms, resulting in hot spots of activity (*e.g.* detritosphere, rhizosphere, aggregatusphere,

drilosphere and porosphere) all of which support >90% of total soil biological activity (Beare *et al.* 1995). Larger amounts of soil organic matter generally support greater soil food web activity, if other conditions including soil moisture are suitable. Too dry and there will be little activity; too wet and there will be a lack of oxygen, leading to a reduction in activity and a shift towards anaerobic organisms (usually bacteria).

Harnessing benefits from micro-organisms – functional perspectives

Adoption of CA has enhanced soil habitat structures and the availability of food sources (C) from crop residues for food web activities including key functions such as C turnover and sequestration, nutrient cycling, disease suppression, aggregate structure and stability and community resilience (Coleman *et al.* 2018). Evidence exists for changes, following the adoption of CA in microbial and faunal communities (beneficial and pathogenic) in all soil types and from all agro-ecological regions of Australia, both in rainfed and irrigated agricultural systems.

Stubble retention and reduced tillage has shifted microbial communities towards a fungal-dominated food web compared with bacterial dominated communities in systems with cultivation and stubble removal. The time taken for such changes to eventuate varies with soil type, rainfall intensity and annual distribution, and crop residue management. Whilst immediate changes in nutrient cycling and plant pathogen dynamics can occur, development of disease suppression may take 5-7 years (Gupta *et al.* 2011). Effects of CA on the genetic diversity of bacterial and fungal communities may take longer to materialise (Gupta *et al.* 2010) and it can take 20 years or more to realise significant increases in soil organic C (Sanderman *et al.* 2010). Recent evidence suggests that the rate of C sequestration under CA can be accelerated by manipulating the stoichiometry of C inputs (C:N:P:S ratios) which influences the microbial C turnover (*i.e.* microbial assimilation efficiency, see Chapter 16).

Reduced tillage systems also introduce a significant stratification in the abundance, diversity and activities of heterotrophic organisms compared with that in conventional tillage systems. The effects of this stratification on stubble and soil-borne diseases such as *Fusarium* crown rot, rhizoctonia and foliar diseases have been observed in all agricultural regions (see Chapter 11).

The main limitation for microbial functions in soils is a lack of C or food as an energy source for microbial activity. CA provides such a source through stubble retention but often it is inaccessible for many microorganisms and requires decomposition to available forms. Microorganisms responsible for decomposition of organic matter are diverse as described above, and are universal within soil communities. However, their efficiency and community size may be limited due to historically low organic matter inputs. After a few years of stubble retention within CA, however, decomposer microbial communities respond to inputs of organic matter and rates of decomposition increase, although rates of change can vary with quality and quantity of stubbles or if stubbles are left standing or in contact with the soil (Adl 2003).

Crop residues and their decomposition products drive the many microbial functions in soils. In the following sections we focus on the benefits of CA for some aspects of N cycling including N mineralisation and non-symbiotic N fixation, the role of arbuscular-mycorrhizal fungi, disease suppression of necrotrophic fungi, nematodes, earthworms, termites and other soil fauna.

N cycling

Mineralisation / immobilisation Nitrogen mineralised from the decomposition of soil organic matter and crop residues makes a substantial contribution to crop N uptake (Angus and Grace 2017). The mineralisation of organic substrates (soil organic matter and crop residues) and the release of nutrients into soils is regulated by heterotrophic activity within the decomposer microbial community and microbial turnover. Microbial processes such as depolymerisation of SOM, ammonification, nitrification, N fixation and denitrification all control the rate and timing of N mineralisation and subsequently plant available mineral N in soils. Microflora-microfaunal (*e.g.* protozoa and nematodes) interactions modulate microbial turnover in soils and thus the release of mineral N previously immobilised within the microbial biomass.

Following the adoption of CA, increased biologically available C and improved soil structure promote microbial diversity, growth and activity including N cycling. Changes in the short-term flux of labile SOM pools (*e.g.* dissolved OM and particulate organic matter C) due to stubble retention significantly influence biological N cycling and N availability. Soil microbial biomass (MB), the mass of living components of soil organic matter, is both a source and sink of biologically mediated nutrients. Changes in MB due to modified management, seasonal conditions and the rhizosphere significantly impact net N mineralisation and microbial immobilisation. MB-C accounts for 1.5-3.0% of soil organic C and MB-N for 2.0-5.0% of total N. In cereal crops, MB generally increases (by >2-fold) from sowing to the end of flowering after which it reduces depending upon seasonal conditions. Therefore, increased MB and the accompanying N tie-up (immobilisation) associated with stubble retention may reduce N availability to cereals, especially during the early crop growth stages. However, N tie-up is only a temporary constraint as the immobilised N will be released through microbial turnover, generally later in the crop season in spring when rapid crop growth and development occur.

CA can alter the composition and abundances of microbial communities involved in N mineralisation and immobilisation, and also influence fertiliser N use efficiency. Stubble retention and no-till alter enzyme activity, with increasing activity associated with stubble incorporation in the short-term due to associated changes in microbial composition and microbial turnover (Ladd *et al.* 1994, Hoyle and Murphy 2006). Both the rate and timing of N mineralisation regulate plant available N in soils and, therefore, crop growth (Gupta *et al.* 2011). In dryland cropping in Australia, the effects of stubble treatment on gross N mineralisation, nitrification and immobilisation are seasonally dependant. For example, in the stubble retained and no-till systems, N immobilisation exceeds nitrification and N mineralisation in the absence of plant demand, during April to June, provided soil moisture is available. Therefore it is important to consider microbial immobilisation of N when planning the fertiliser N needs of a following crop, particularly for cereals in CA systems.

Crop residue quality influences N supply from decomposition. For example, intensive cropping, especially intensive cereal cropping, instead of mixed farming where crop rotation with legume pastures is common, has generally resulted in a decline in the quality of crop residues and consequently N mineralisation. Cereal crop residues have high C:N ratios (100:1) compared with N-rich legume residues with C:N ratios between 15 and 25. Crop residues with a C:N ratio >22:1 generally result in immobilisation of mineral N within the microbial biomass.

Legume crop residues can make a significant contribution to the N needs of following cereal crops. For example, an apparent recovery of 30±10% of legume residue N by following wheat crops was observed over 20 legume treatments in dryland experiments conducted in eastern Australia (Peoples *et al.* 2017). Cereal stubble is not a major source of N for following cereal crops but should mainly be seen as a source of C for microbial activity. In no-till systems, only 1-6% of the N requirement of cereal crops is derived from the previous year's wheat stubble (Gupta *et al.* 2017). Non-cereal break-crops (*e.g.* legumes and canola) also help cereals to access the soil mineral N pool better, through improved root health and by reducing cereal root diseases (Gupta *et al.* 2011).

Traditionally, the capacity for N mineralisation in soils was estimated as a fraction of SOM-C or total N. However, in CA, where seasonal variations in MB occur, N that can be mineralised from SOM and crop residues and N immobilisation need to be considered to estimate N supply potential at the beginning of a crop season.

Non-symbiotic N fixation Non-symbiotic N fixation (NSNF) by free-living N-fixing bacteria can provide economic and environmental sustainability to N management in Australian agriculture. Non-symbiotic N fixation refers to N fixation by bacteria (autotrophic and heterotrophic) growing independently in soil utilising the products of decomposed plant residues, in termite mounds, or in close association with plant roots without forming nodules (Roper and Gupta 2016). With the increased adoption of intensive cropping and larger areas under consecutive cereal crops (>50%), NSNF has the potential to contribute substantially to the N requirements in cereal crops.

Adoption of CA has made the soil habitat more favourable for NSNF. It increases the number of microsites with available C and the number of aggregates, especially macro-aggregates, which are critical for the development and maintenance of microsites of reduced oxygen tension required for NSNF by free-living bacteria in soils. Any increase in soil disturbance reduces aggregation, reduces soil C and disrupts the soil pore network by which stubble decomposing organisms and N-fixing bacteria interact. As a result, NSNF under reduced tillage is characteristically higher than in cultivated soils (Roper and Gupta 2016). However, biological changes in NSNF in response to adopting CA can take several years to develop.

The availability of C as an energy source is critical for NSNF. Crop residues are 50-70% (dry weight) cellulose and hemicellulose which, after decomposition, can be used for NSNF. As a result, rates of NSNF are proportional to the amount of crop residue and how quickly it is decomposed. In cereal crops under CA, conserved aggregates and microsites promote additional inputs of N by free-living N-fixing bacteria utilising root exudates as C sources, particularly during rapid crop growth in spring when soils are wet and temperatures are favourable for activity.

Genetic profiling (*nifH* gene sequencing analysis) of N-fixing bacteria in soils under cereal crops and under CA in QLD, NSW, South Australia (SA) and WA identified a diverse group of N-fixing bacteria (>110 genera), but these varied according to region, soil type and environment, and cereal crop varieties (Gupta *et al.* 2014). This indicates a significant potential for N inputs from NSNF. Estimates of NSNF in soils from cereal fields, measured by a laboratory-based incubation (¹⁵N isotope) assay, range from 0.2 to 1.5 kg N/ha/day in sands and sandy loam soils in low to medium rainfall regions of southern Australia and WA to 0.5 to 2 kg/ha/day in clays and loamy soils in high rainfall regions (Gupta *et al.* 2014). Amounts of NSNF increase with increasing % clay content and are reduced by extremes of pH (Roper and Gupta 2016). Clays are important in stabilising aggregates and creating micro-aerobic microsites needed for NSNF. Warm and wet soils are most favourable for NSNF and therefore, regions with summer rainfall favour NSNF. Mineral N concentrations above 25 kg N/ha in surface soils can reduce NSNF, but this varies with soil type.

Under CA, populations of soil fauna such as ants (and termites) and earthworms are generally more abundant. Significant amounts of N fixation can occur in the guts of termites and other arthropods, (4-10 kg N/ha/year, Roper and Gupta 2016), but these amounts can differ according to crop rotations, and the quantity and quality of crop residues.

Arbuscular-mycorrhizal fungi – P and other nutrients

Arbuscular-mycorrhizal fungi (AMF, Phylum Glomeromycota) form symbiotic relationships with plants and are important in the health of many crop species functioning in the efficient acquisition of plant nutrients, especially P and zinc (Zn), from the soil. They colonise the root cortex of plant species in 80% of plant families (Gianinazzi *et al.* 2010) including most crop species, with notable exceptions being canola and lupin. AMF are obligately dependent on living plant roots for their nutrition and reproduction. Large spores are produced by AMF on external hyphae in the soil where they survive between annual host crops.

Because of their extensive hyphal networks in soil, the adoption of CA with reduced or no-till has been beneficial for AMF and their activities. However, because AMF live as symbionts of host plants, long periods of plant-free fallow and/or non-host crops, can cause the decline in viable AMF propagules, resulting in poor colonisation of the next crop and plant nutrient deficiencies known as ‘long fallow disorder’ (Thompson 1987). The extent to which a crop suffers from diminished AMF depends on the mycorrhizal dependency of the crop species, where relative mycorrhizal dependency is the % decrease in biomass or seed yield of plants grown without AMF compared with plants grown with AMF. For example, in a field experiment with the highly mycorrhizal dependent crop linseed, the uptake of soil P and Zn was linearly dependent on the level of AMF colonisation of the roots, and plants without AMF produced only 15% of the biomass and 22% of the seed yield of plants with AMF (Thompson *et al.* 2013). Most crop species grown in the northern grain region obtain significant benefit from the AMF symbiosis (Thompson *et al.* 1997).

Traditional methods of deliberate long fallowing were beneficial to subsequent crop growth through increased storage of soil water and mineral N in the soil profile, due to microbial decomposition of soil organic matter, and reduction in the inoculum load of some soil-borne pathogens. However, fallow land in the northern Australian grain region, managed by burning crop stubble soon after harvest, ploughing and then cultivating after every rainfall event to control weeds, was detrimental to survival of AMF. The adoption of CA has been beneficial to survival of AMF. Furthermore, CA has led to greater infiltration of rainfall and storage of soil water with surface mulch keeping the soil at sowing depth wetter for longer; this has provided more sowing opportunities for intensification of cropping and a reduction in the length of fallow periods. Rather than fixed rotations, northern region growers tend to follow opportunity cropping, sowing a crop when soil moisture reaches a threshold. For example, growers on the Darling Downs, Qld, double-crop by sowing chickpea soon after sorghum harvest if rainfall has been substantial. Such a sequence maximises the level of AMF inoculum for the chickpea crop with benefits of early P inflow into the roots aiding N fixation by the *Mesorhizobium* bacteroids in the root nodules. Similar benefits can be obtained by double-cropping mungbean soon after wheat harvest. Because of the variable climate in the northern region it is not always possible to follow optimum rotations. For example, where drought enforces long fallow, growers can utilise knowledge of mycorrhizal dependency of the various winter and summer crops as well as the ability of different crop species to build up AMF spore numbers in the soil when choosing crops and fertilisers (Thompson *et al.* 1997, Owen *et al.* 2010). Practices that promote early colonisation with AMF of the root systems of mycorrhizal-dependent crops will help in early crop biomass production and better weed competition. However, the apparent lack of positive growth response to AMF in wheat and some other winter crops in rotation experiments in the southern grains region was ascribed to low soil temperature (<10°C) in the two months after sowing, resulting in slow crop growth and poor growth of external AMF hyphae in the soil (Ryan and Kirkegaard 2012).

Recent developments in DNA methods to quantify AMF inoculum levels in soil (PREDICTA®B service, Ophel-Keller *et al.* 2008) have allowed a better understanding of the effects of CA including crop rotation, fallowing and tillage practices on AMF and crop growth. For example, it has identified (i) the dominant AMF groups (clades) in different agricultural regions; (ii) effects of non-mycorrhizal crop types (*e.g.* canola) and long fallow in Vertosols of northern region, and (iii) effect of pastures under CA on AMF levels in SA.

Disease suppression

Suppression of diseases caused by necrotrophic fungal pathogens Biological suppression generally refers to the reduction of the incidence or severity of disease even in the presence of a pathogen, host plant and favourable climatic conditions for the disease. Disease suppression can also occur when soils become inhospitable to the pathogen itself, referred to as pathogen suppression (Cook 1982). Adoption of CA has influenced microbial C turnover and developed agronomically useful levels of disease suppression in cropping soils (Roget *et al.* 1999, Gupta *et al.* 2011). High levels of disease suppression, which can result in minimal or no disease constraints to plant growth and productivity, have been reported from a variety of cropping systems worldwide including in farmer fields and experimental sites in Australia (Gupta *et al.* 2011). Suppressive soils can be differentiated into two categories. ‘General suppression’ refers to the inhibition of pathogenic populations, and is related to either the activity of the total microflora or diverse microbial-faunal interactions. In contrast, ‘specific suppression’ refers to the activity of specific groups of microorganisms (antagonists), such as suppression of take-all of wheat (caused by *Gaeumannomyces graminis*) by *Pseudomonas* species, as demonstrated under CA in WA and SA (Cook and Rovira 1976). It is now evident that the level of disease suppressive activity against soil-borne fungal diseases under CA is a function of the population, activity and composition of the microbial community (Gupta *et al.* 2011, Penton *et al.* 2014, Hayden *et al.* 2018). All soils have an inherent level of suppressive activity, but this level can be significantly modified by farm management practices.

It was considered that soils low in fertility in lower rainfall regions of Mediterranean-type climates may not support suppressive microbial communities. However, agronomically effective levels of disease

suppression in such environments have been demonstrated in long-term field experiments in SA (against rhizoctonia bare patch of wheat, caused by *Rhizoctoniasolani* AG8, and take-all) and subsequently in farmer fields in SA and WA (Gupta *et al.* 2011, Huberli *et al.* 2013). Long-term adoption of CA was one of the key factors that has led to the improvement of disease suppression capacity. For example, in field experiments in SA, disease suppression increased over a period of 5-10 years following a change to CA practices (*e.g.* full stubble retention, limited grazing and higher nutrient inputs to meet crop demand) and complete control of the soil-borne diseases rhizoctonia bare patch and take-all was observed within 10 years, under a range of rotations including continuous cereal, cereal-grain legume and cereal-pasture (see review by Gupta *et al.* 2011).

The successful control of many soil-borne plant pathogens involves management of the pathogen at a combination of different microsites (*e.g.* inoculum source and rhizosphere) in soil and at different time periods (pre-season or in the presence of the susceptible plant). Therefore, *in situ* enhancement of natural disease suppression may be more effective than adding inoculants (Cook 2007). Suppressive ability is a continuum and all soils have some potential for disease suppression. Management practices that supply higher levels of biologically-available C over long periods (>5-7 years) and maintain higher levels of microbial C turnover can result in changes to the composition and activity of the soil microbial community and consequently increase suppression. Management and biotic factors that promote disease suppression are:

- monoculture of host crops over a number of years resulting in increased populations of specific biocontrol agents;
- antibiotic producing/antagonistic microflora and non-pathogenic variants;
- modification of physico-chemical properties of soil;
- addition of composts or other organic manures;
- crop rotations involving crop types that promote specific microbial communities;
- crop residue retention and appropriate tillage treatments;
- addition of large amounts of simple substrates; and
- continued addition of C inputs to support higher levels of C turnover over a long period or multiple seasons.

Suppressive ability is not a fixed property of a soil but can be acquired and maintained at a level beneficial to crops (Roget *et al.* 1999, Gupta *et al.* 2011). This means that productivity losses from root diseases under CA can be reduced, and high water use efficiency attained without expensive and variable chemical controls.

Harnessing beneficial functions from soil fauna

Microfauna - Nematode communities

There are about as many nematode species (Phylum Nematoda) in nature as there are insect species, and nematodes can be found in all ecological niches on the planet. Plant parasitic nematodes occur in the soil and invade the roots of plants using lytic enzymes and the thrusting of their stylet (needle-like mouthparts) to breach cell walls. They include ectoparasitic and endoparasitic nematodes. The majority of nematode species in soil are non-plant parasitic, but feed on other soil organisms and are termed free-living. They form different trophic groups which are adapted to feed on various microorganisms, *i.e.* bacterivores, fungivores, predatory nematodes and omnivores, which can be predatory but in the absence of suitable prey can also feed on bacteria and fungi. Free-living nematodes feeding on microflora and protozoans results in the release of excess inorganic nutrients, particularly N, that can be utilised by crops and hence they accelerate nutrient cycling in soils.

In a large survey (450 soil samples from 22 sites in the Australian grain growing regions covering seven soil orders), Linsell *et al.* (2014) found that the most influential factors affecting nematode communities were inorganic fertilisers, soil moisture, organic matter additions and tillage. Among the free-living nematodes, bacterivores are considered to be smaller with short generation times responding quickly to increases in soil bacterial populations following inputs of organic substrates or soil disturbance.

Fungivores are larger with longer generation times responsive to saprophytic fungal populations developed on plant detritus and mycorrhizal hyphae. Predatory and omnivorous nematodes are the largest in body size with long generation times that respond to increases in microbe-feeding nematodes and protozoans but are most sensitive to agronomic disruptions to the soil ecosystem. Under CA, soils receiving greater additions of organic materials are enriched with bacterivores and fungivores. At a southern Australian site, the nematode community under no-till was dominated by fungivores (reflecting residue retention on the soil surface favouring fungal decomposition) and the large omnivorous nematode (*Eudorylaimus*) indicating a more structured community due to little soil disturbance than with conventional tillage which was dominated by bacterivores (probably due to stubble incorporation) (Linsell *et al.* 2014).

Suppression of plant-parasitic nematodes General suppression of plant parasitic nematodes in a soil largely results from organic matter inputs stimulating a range of soil biota that prey on (*e.g.* predatory nematodes) and parasitise (*e.g.* bacteria and fungi) nematodes (Stirling 2014). Among the predators of nematodes are other specialised nematodes such as *Mononchus* spp., and microarthropods such as springtails and mites. Nematophagous fungi kill by colonising the nematode. In addition, zoosporic fungi and oomycetes, and bacteria parasitise nematodes. Most of these organisms are non-specific in the species of nematode that they attack, preying on or parasitising free-living as well as plant parasitic nematodes. Addition of organic matter through stubble retention increases the population sizes of saprophytic nematode-trapping fungi and predators such as microarthropods and mites, and stubble on the soil surface moderates surface soil temperature extremes and reduces evaporation, creating a better environment for organisms that prey on nematodes. A pasture phase can contribute to this process as pasture was found to support more abundant and diverse populations of nematodes, including omnivorous and predatory nematodes than adjacent cropped soil whether managed by direct drilling or conventional cultivation (Yeates and Stirling 2008).

Specific suppression on the other hand is mediated via organisms with a narrower range of nematode hosts, *e.g.* the oomycete *Nematophthora gymnopbila* and the fungus *Pochonia chlamydosporia* that control cereal cyst nematode *Heterodera avenae* (Stirling 2014). Other examples of specific suppressors are the mycelial and endospore-forming bacteria *Pasteuria* spp. where *Pasteuria thornei* infects root-lesion nematodes (*Pratylenchus* spp.), and *Pasteruira penetrans* infects root-knot nematodes (*Meloidogyne* spp, Stirling 2014). Since the propagules of the biocontrol agent are most likely to be associated with the body of the dead nematodes close to old roots under no-till, roots of the new crop would likely follow old root channels where there would be a high concentration of the propagules of the nematode-attacking organisms providing better biocontrol than if these physical relationships were disrupted through soil tillage (Stirling 2014).

In the subtropical grain region of north-eastern Australia the root-lesion nematode *P. thornei* attacks a range of cereal and pulse crops growing on Vertosols (Thompson *et al.* 2008). Under conservation agriculture, nematodes can occur in the soil profile to depth (*e.g.* 60 cm), but sometimes nematode numbers are lower in the topsoil. It has been suggested that this is due to suppression of *P. thornei* in this biologically active layer (0-15 cm, Stirling 2014). An alternative hypothesis is that elevated temperatures in the topsoil over summer and faster desiccation contribute to increased death rates of *P. thornei* in the topsoil. Desiccation and heating of the topsoil are likely to be greater where stubble is burnt leaving the soil exposed to the sun: the soil is then tilled during the fallow period exposing fresh surfaces to heating and drying (Thompson *et al.* 2018).

Mesofauna – Microarthropods

Microarthropods are important intermediary members of the soil foodweb with a key role in the decomposition of crop residues and SOM, and accelerating the mineralisation of plant nutrients (*e.g.* N and P) through consumption of microbes. They can also consume spores and hyphae of pathogenic fungi and AMF, and aid in the dispersal of propagules of AMF. CA can alter the abundance and composition of springtails. For example, studies on the effects on microarthropods of three long-term treatments (*i.e.* conventional tillage/stubble burned, no-till/stubble retained, conventional tillage/stubble incorporated), in wheat cropping systems in two field experiments at Harden and Cowra in southern

NSW, indicated that springtails (33 species identified) and mites (67 species identified) had increased numbers under stubble retention (standing or incorporated) than under stubble burned, and fungal feeding species were also proportionally higher with stubble incorporation. Mites predominated during dry periods and springtails when the soil was wetter (Longstaff *et al.* 1999).

Macrofauna – Earthworms and termites

Earthworms Earthworms (Phylum Annelida) feed largely on decaying plant material (detritivores) on the soil surface and in the soil itself where they also consume microbiota including mycorrhizal fungi and accelerate mineralisation of nutrients such as N into plant available forms. The burrows (biopores) they create in the soil are significant conduits for water percolation into the soil profile. The casts (faecal pellets of ingested soil enriched with organic matter waste) that they leave on the soil surface and in their burrows contribute to better soil structure and nutrient supply. Traditional methods of burning stubble and cultivating the soil have been detrimental to earthworms. In contrast, CA provides stubble as a food base for earthworms, and reduced tillage decreases the mechanical impact on earthworms *per se* and disruption of their burrows. The combination of reduced/no-till with surface retention of stubble has meant that the topsoil remains wetter for longer and is therefore more suitable for earthworm activity.

In the southern temperate grain region, earthworms belonging to the lumbricid species *Aporrectodea caliginosa* were found to be twice as numerous in wheat cropped soil under reduced tillage compared with conventional cultivation in a red-brown earth soil (Rovira *et al.* 1987). In a long-term experiment on a Vertosol in the sub-tropical grain region, earthworms of the species *Aporrectodea trapezoides* were six times more numerous with 21 times the biomass under no-till and stubble retention than under mechanical tillage and stubble burning, 5 months after a wheat crop (Thompson 1992). *A. trapezoides* was also more efficient in recycling N from plant residues and improving wheat growth than *Aporrectodea rosea* in southern Australia (Baker 1996). Under no-till and stubble retention on a Vertosol, the deep burrowing earthworm *Polypheretima elongata* produced many tunnels and an estimated 500 t/ha of casts deposited on the soil surface in 2 years in a field experiment in a sub-tropical environment. Compared with soil, these casts were enriched in nutrients by 62% for nitrate, 29% for extractable P and 27% for organic C (Wildermuth *et al.* 1997).

Soil compaction, resulting from pressure of heavy farm machinery used when soil is wet beyond its plastic limit, can be as detrimental to earthworms as tillage. On a Vertosol in central Qld, compaction once annually reduced mean macrofauna numbers from 70 to 15/m and earthworm numbers from 41 to 2/m. The soil compacted above its plastic limit retained higher shear strength and resistance to a cone penetrometer than the non-compacted treatment for 5 years following the cessation of compaction. However, annual compaction with an axle load of 6 Mg when the soil was drier than the plastic limit in the top 0.08 m had no adverse effects on the soil macrofauna (Radford *et al.* 2001). Insufficient earthworms in the compacted treatments was attributed to the persistence of the compaction effects (Radford *et al.* 2007).

Despite obvious benefits to agriculture from earthworm activities, the greater permeability of the soil due to earthworm burrowing can result in leaching of nitrate (Subler *et al.* 1997) and in some circumstances, where large numbers of earthworms are present under CA extra N fertiliser may be required compared with conventionally cultivated treatments (Thomas *et al.* 2003).

Termites Unlike earthworms, termites do not require moist soil to move and therefore, they are active throughout the year. Ants and termites have similar functional roles to earthworms as ecosystem engineers in drier and hotter regions under low tillage and they may provide valuable ecosystem services in dryland agriculture in the Mediterranean-type and arid climates (Evans *et al.* 2011). In long-term field experiments on Vertosols cropped to sorghum and wheat in semiarid central Qld, four species of subterranean termites occurred regularly in no-till treatments but were absent from cultivated treatments (Holt *et al.* 1993). Termite galleries extended to at least 500 mm below the soil surface with significantly more gallery structures under no-till (~70% of samples), than reduced tillage (~25%) and conventional tillage (0%) (Holt *et al.* 1993). The lack of termites in the tilled treatments was considered to be due to

the physical disruption of the termite feeding galleries. More galleries were noted where stubble was retained than removed, particularly under no-till, indicating that the crop stubble was food for the termites which contributed to its rapid decomposition and release of nutrients. In a 5-year experiment, Robertson *et al.* (1994) measured significantly higher population densities of detritivores and predators in soil under no-till than under conventional cultivation and suggested that no-till increased the sustainability of the ecosystem through increasing fauna responsible for soil amelioration and predation of insect pests. Increased wheat yields with no-till compared with conventional tillage were considered to be due to greater infiltration of water into the soil via biopores created by soil fauna (Radford *et al.* 1995). In the north eastern limits of wheat production in WA, ants and termites increased wheat yield by 36% due to increased soil water infiltration and improved soil nitrogen (Evans *et al.* 2011).

Evidence for value for beneficial functions

Beneficial functions of individual and groups of microorganisms from the adoption of CA in terms of N cycling, AMF benefits to P and Zn uptake, and disease suppression in soils have been articulated above. Improvements in these functions often benefit crop productivity through better plant nutrition, crop health and maintenance of overall soil quality, especially when all the three principles of CA, *i.e.* no-till, stubble retention and crop rotation, are practised (Mezzalama *et al.* 2011, Pittelkow *et al.* 2014). In addition, there is a collective benefit from microbial communities interacting with each other under CA promoted by the combination of:

- enhanced food reserves for microbial activity and potential to increase soil biota diversity, through retention of stubbles and organic matter; and
- enhanced microbial and soil faunal activities from reduced tillage due to preserved soil structures including stable aggregates containing favourable microsites for microbial processes, and biopores created by soil fauna that are critical for the transport of organic matter, nutrients and water to depth in soil profiles.

Biopores and aggregates enable stable coexistence between microbial groups allowing cooperative microbial functions among a broad range of microorganisms responsible for nutrient capture and transformations, and plant protection. The development and maintenance of these structures is dependent on retaining spatial connectivity among soil organisms and between microbially rich microsites, which can be disrupted severely by cultivation, particularly if it is intense or repeated, as shown above for non-symbiotic N-fixation and disease suppression.

It has been demonstrated that CA results in concentration of organic matter at the soil surface in comparison with conventional cultivation. Whilst this is true in the short term, over time, transport of organic matter, nutrients and water by soil fauna down biopores, which they create, has the potential to increase organic matter at depth, creating stable environments for both microbial activity, root development and root-microbe interactions including disease suppression, and nutrient and water supply. The introduction of diverse rotations comprising plants with different root architectures and exudates is also likely to expand this process. Increases in microbial diversity and reduced proliferation of soil-borne pathogens following increases in plant diversity have already been demonstrated (Gupta *et al.* 2011, Yukicevich *et al.* 2016).

Interventions to maximise biological functions in CA

CA has increased soil biota diversity and beneficial functions in the low organic matter Australian agricultural soils that were depleted following decades of excessive cultivation and crop residue removal. Two of the key challenges for the continued use of CA are related to herbicide resistance in weeds and controlling crop diseases. The heavy reliance on herbicides to control weeds has led to herbicide resistant weeds, prompting the development of new measures including various harvest weed seed control (HWSC) strategies (see Chapters 6 and 10). Some growers are introducing occasional (strategic) tillage (Dang *et al.* 2015 and Chapter 7) or using rotations and green manuring to improve weed control. The need to develop novel weed control measures is further driven by observations that microbial processes in soils can be negatively impacted by some herbicides. For example, there is

evidence that mineralisation of N can be reduced by herbicides such as sulfonylureas (Group B) and triazines (Group C) (Rose *et al.* 2015, Gupta and Neate 1997). Motta *et al.* (2018) measured changes in the gut microbiota and increased mortality of honey bees exposed to glyphosate, which is the main knockdown herbicide in no-till systems across Australia and elsewhere and is under increasing scrutiny and risk of banning in some countries. Future multidisciplinary agronomic research could focus on increasing early crop vigour to outcompete weeds through strategic placement of nutrients below the seed at seeding combined with breeding of cultivars that produce natural herbicides and /or contain early vigour traits (see Chapter 17).

Biological disease suppression could help combat the effects of soil-borne diseases for which there are no effective chemical or plant-based control options currently available, but the time required to improve the capacity of resident soil biota for disease suppression through management practices alone makes this a challenge. Although there are no resistant varieties against soil-borne diseases, there is evidence that rhizosphere communities associated with some crop varieties reduce the susceptibility to plant pathogens (Mendes *et al.* 2017). By increasing our understanding of rhizosphere microbiology of cultivars and parents of modern varieties, it may be possible to develop new varieties with ‘designer plant-microbe combinations’ to improve exploitation of microbial diversity, and control diseases (Neate and Gupta 2018).

Microbial communities (microbiome) associated with roots, now considered as an extended phenotype of plants, have been shown to have a major impact on plant health through interactions on growth and development, facilitation of nutrient uptake and the ability to tolerate biotic and abiotic stresses. New molecular (‘omics’) tools are helping to identify the key drivers of diversity and functional potential of the microbiome of the plant, along with an understanding of spatial and temporal factors that operate under field conditions. This new knowledge presents an opportunity to develop designer microbiomes tailored for individual management systems and environments.

Inoculation of known beneficial microorganisms has been used for many years, and inoculation of legumes with *Rhizobium* spp. has been a successful tool for capturing atmospheric N by legumes and enhancing N availability in a range of soil types and regional environments across Australia. In more recent times, inoculants have been developed to promote plant growth and suppress plant disease (Barnett *et al.* 2019) and for P acquisition from soil (Richardson and Simpson 2011). In many instances the success of inoculation for biocontrol in the field environment has been variable due in part to problems associated with survival, in particular with rhizosphere microorganisms. However, inoculants that are endophytes, which reside within the target plant, are protected from competition from natural microflora. Despite this, not all inoculations are successful due to many biotic and abiotic factors including environmental conditions that influence plant-pathogen-microbe interactions. Inoculation into soils without a target plant has generally been less successful. For example, water repellency in sandy soils was reduced by the addition of wax-degrading bacteria under laboratory conditions but not in the field (Roper *et al.* 2015). However, by creating an environment that promoted the growth and activity of naturally-occurring wax-degrading bacteria, through adoption of CA and addition of lime to the soil, significant reductions in soil water repellency have been measured (Roper 2005).

In recent years a ‘biological amendment movement’ has caught the imagination of some farmers, but the success of these approaches has not been well demonstrated. These amendments range from individual and combinations of microorganisms, to biological materials. Often these biological amendments lack robust experimental trials proving their value or otherwise, and this has jaded the trust of growers in such amendments (Farrell *et al.* 2017). However, biological amendments that promote the activities of naturally-occurring microbial communities and their functions may be worth exploring. Precision agriculture may enable carefully targeted applications (*e.g.* to the rhizosphere of the plant) of such amendments to derive most benefit.

Precision agriculture, including controlled traffic, is enabling management of paddocks based on potential productivity of variable soil types and nutrient availability within the paddock. Precision sowing technology and Global Positioning System (GPS) guided seeding are increasingly common and present the opportunity for strategic placement of seed in relation to last season’s crop rows, providing

benefits through water harvesting, increased nutrient availability and reduced weed seed populations. In the lower rainfall regions of southern Australia and WA under CA, surface soils on or near the previous year's row represent a rich detritusphere with enhanced microbial diversity and activity compared with inter-row soils. The down side is that on or near row locations may pose a greater soil-borne disease risk and therefore, there is likely to be a trade-off between beneficial and deleterious microbial communities (Gupta *et al.* 2018). A better understanding of spatial variation in microbiological communities and functions is needed to harness the benefits from the increased microbial diversity in CA systems. Controlled traffic is reducing the areas within paddocks exposed to wheel traffic thereby preserving soil structure and microbial interactions in the soil.

Summary

Adoption of CA in Australian cropping systems has resulted in significant shifts in soil microbial and faunal communities and functions. Much of this is beneficial and relates to the increased biologically available C which drives microbial functions such as: mineralisation of nutrients (N, P and S), including non-symbiotic N fixation; increased disease suppression in the long term; shifts in microbial communities from a bacterial dominated to a fungal dominated food web resulting in improved potential for C sequestration; conserved AMF and soil fauna communities, more stable microbial networks and functions and stable aggregates and biopores that improve soil structure and reduce soil erosion. Precision agriculture is helping to maintain these beneficial changes on more of the field by reducing compaction and conserving soil structure and biological processes on a greater proportion of the cropped area.

The negative impacts of CA in terms of increased soilborne and foliar diseases are crop and variety dependent and can be managed using diverse rotations. Likewise, new practices such as HWSC have emerged to deal with herbicide resistant weeds, thereby reducing the use and potential harm of herbicides to soil biota and functions. The tie-up of N by retained C-rich residues early in the season is short-term and readily alleviated with applied N, and in some cases may protect N from excess leaching. Some benefits are time dependent; for example, the development of microbial communities that suppress diseases may take up to 5 years and increases in C due to sequestration may take many decades. Deliberate selection of beneficial plant microbiomes through either targeted management and/or specific selection of crop genotypes has the potential to enhance the effectiveness of future developments in CA but will require a multidisciplinary systems-based approach to research.

With the current focus on security of food to feed the growing global populations, there is a need to develop innovative cropping systems that are both economically and environmentally sustainable. For example, in Australia there is a large yield gap (>50%) between what is potentially attainable with current technology and what is actually achieved (www.yieldgapaustralia.com.au) and this has been attributed to diseases and poor synchronisation of the availability of nutrients and water with the demands of the crop. Climate variability adds additional uncertainty to the efforts to reduce the yield gap and improve food production. *Harnessing the power of soil biota as part of conservation agriculture should help us reduce the yield gap.*

References

- Adl SM (2003) "The ecology of soil decomposition" (CABI Publishing: Wallingford, UK)
- Angus JF, Grace PR (2017) Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. *Soil Research* **55**, 435-450
- Baker G (1996) The impact of earthworms on cereal yield and grain protein levels in South Eastern Australia. Final Report GRDC Project CSO134. <https://grdc.com.au/research/reports/report?id=865>
- Barnett SJ, Ballard RA, Franco CMM (2019) Field assessment of microbial inoculants to control Rhizoctonia root rot on wheat. *Biological Control* **132**, 152-160
- Beare MH, Coleman DC, Crossley Jr DA *et al.* (1995) A hierarchical approach to evaluating the significance of soil biodiversity to biogeochemical cycling. *Plant and Soil* **170**, 5-22
- Coleman DC, Callaham Jr MC, Crossley Jr DA (2018) "Fundamentals of soil ecology" (Academic Press: UK)
- Cook RJ (1982) Use of pathogen-suppressive soils for disease control. In (Ed. RW Schneider) "Suppressive Soils and Plant Disease" pp 51-65 (American Phytopathological Society: St Paul, Minnesota, USA)

- Cook RJ (2007) Management of resident plant growth-promoting rhizobacteria with the cropping system: a review of experience in the US Pacific Northwest. *European Journal of Plant Pathology* **119**, 255-264
- Cook RJ, Rovira AD (1976) The role of bacteria in the biological control of *Gaeumannomyces graminis* by suppressive soils. *Soil Biology and Biochemistry* **8**, 269-273
- Dang YP, Seymour NP, Walker SR *et al.* (2015) Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: I. Drivers and implementation. *Soil and Tillage Research* **152**, 104-114
- Dick R (2018) Soil health: The theory of everything (Terrestrial) or just another buzzword? *CSA News* November 2018 pp 12-17 doi:10.2134/csa2018.63.1114
- Evans TA, Dawes TZ, Ward PR, Lo N (2011) Ants and termites increase crop yield in a dry climate. *Nature Communications* **2**, 262
- Farrell M, Macdonald LM, Jenkins SN *et al.* (2017) Understanding Biological Farming Inputs. *Final report to the GRDC*, project number CSO00044 38pp
- Gianinazzi S, Gollote A, Binet M-N *et al.* (2010) Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. *Mycorrhiza* **20**, 519-530
- Gupta VVSR, Roper MM, Kirkegaard JA, Angus JF (1994) Changes in microbial biomass and organic matter levels during the first year of modified tillage and stubble management practices on a red earth. *Australian Journal of Soil Research*. **32**, 1339-1354
- Gupta VVSR, Neate SN (1997) Impact of agrochemicals on soil biota and biological processes. *Proceedings of Symposium on Synthetic organic chemicals as pollutants in the environment* (Australian Soil Science Society: South Australian branch) 17-19
- Gupta VVSR, Rovira AD, Roget DK (2011) Principles and management of soil biological factors for sustainable rainfed farming systems. In (Eds. P Tow, I Cooper, I Partridge, C Birch) "Rainfed farming systems" pp 149-184 (Springer Science and Business Media)
- Gupta VVSR, Penton CR, Lardner R, Tiedje J (2010) Catabolic and genetic diversity of microbial communities in Australian soils are influenced by soil type and stubble management. *Proceedings of 19th World Congress of Soil Science* Brisbane, Australia pp. 1-4 (published on DVD) www.iuss.org
- Gupta VVSR, Penton CR, Kroker S *et al.* (2014) Diversity of *nifH*-harbouring bacteria and non-symbiotic N₂ fixation in Australian cropping soils. *Proceedings of 17th Australian Nitrogen Fixation Conference*, 40-41 (Australian Society for Nitrogen Fixation: Adelaide)
- Gupta VVSR, Kirkegaard J, McBeath T *et al.* (2017) The effect of stubble on nitrogen tie-up and supply. GRDC Research, Ballarat, Vic. https://grdc.com.au/data/assets/pdf_file/0019/308044/9664-GRDC-Bendigo-update-proceedings-2018-interactive.pdf
- Gupta VVSR, McBeath T, Kroker, SK *et al.* (2018) How far is too far: Precision sowing drives microbiology trade-offs with soilborne diseases. *Proceedings of 10th ASDS meeting*, Adelaide pp 88-89
- Hayden HL, Savin KW, Wadeson J *et al.* (2018) Comparative metatranscriptomics in disease suppressive and non-suppressive soils for *Rhizoctonia solani* AG8. *Frontiers in Microbiology* **9**, 1-19
- Holt JA, Robertson LN, Radford BJ (1993) Effects of tillage and stubble residue treatments on termite activity in two central Queensland vertosols. *Australian Journal of Soil Research* **31**, 311-317
- Hoyle FC, Murphy DV (2006) Seasonal changes in microbial function and diversity associated with stubble retention versus burning. *Australian Journal of Soil Research* **44**, 407-423
- Hüberli D, Miyan S, Connor M, MacLeod W (2013) Identification and bioassay of disease suppressive soils in Western Australia. *Proceedings of 10th International Congress of Plant Pathology*, Beijing, China, 25-30
- Ladd JN, Amato M, Li-Kai Z, Schultz JE (1994) Differential effects of rotation, plant residue and nitrogen fertilizer on microbial biomass and organic matter in an Australian Alfisol. *Soil Biology and Biochemistry* **26**, 821-831
- Linsell K, Stirling G, Stirling A *et al.* (2014) Free-living nematodes as indicators of biological soil health. GRDC Updates www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2014/07/free-living-nematodes-as-indicators-of-biological-soil-health
- Longstaff BC, Greenslade PJM, Colloff, M *et al.* (1999) Managing soils in agriculture. The impact of soil tillage practices on soil fauna. RIRDC Publication No. 99/18 64 64 pp (RIRDC: Barton, ACT)
- Mendes LW, Raaijmakers JM, de Hollander M *et al.* (2017) Influence of resistance breeding in common bean on rhizosphere microbiome composition and function. *The ISME Journal* **12**, 1-13
- Mezzalama M, Govaerts B, Sayre K, Verhulst N (2011) Conservation agriculture: a solution to soil degradation and soil-borne diseases. *CGIAR SP-IPM Technical Innovation Brief* **14**, 1-2 www.sipm.cgiar.org
- Motta VS, Rayman K, Moran NA (2018) Glyphosate perturbs the gut microbiota of honey bees. *PNAS* **115**, 10305-10310
- Ophel-Keller K, McKay A, Hartley D *et al.* (2008) Development of a routine DNA-based testing service for soilborne diseases in Australia. *Australasian Plant Pathology* **37**, 243-253

- Owen KJ, Clewett TG, Thompson JP (2010) Pre-cropping with canola decreased *Pratylenchus thornei* populations, arbuscular mycorrhizal fungi, and yield of wheat. *Crop and Pasture Science* **61**, 399-410
- Peoples MB, Swan AD *et al.* (2017) Soil mineral nitrogen benefits derived from legumes and comparisons of the apparent recovery of legume or fertiliser nitrogen by wheat. *Soil Research* **55**, 600-615
- Penton CR, Gupta VVSR, Tiedje JM *et al.* (2014) Fungal community structure in disease suppressive soils as assessed by 28S LSU gene sequencing. *PLoS ONE* **9**(4), e93893
- Pittelkow C, Liang X, Linquist BA *et al.* (2014) Productivity limits and potentials of the principles of conservation agriculture. *Nature* **517**, 365-368
- Radford BJ, Key AJ, Robertson LN, Thomas GA (1995) Conservation tillage increases soil water storage, soil animal populations, grain yield, and response to fertiliser in the semi-arid subtropics. *Australian Journal of Experimental Agriculture* **35**, 223-232
- Radford BJ, Wilson-Rummenie AC, Simpson GB *et al.* (2001) Compacted soil affects soil macrofauna populations in a semi-arid environment in central Queensland. *Soil Biology and Biochemistry* **33**, 1869-1872
- Radford BJ, Yule DF, McGarry D, Playford C (2007) Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. *Soil and Tillage Research* **97**, 249-255
- Richardson AE, Simpson RJ (2011) Soil microorganisms mediating phosphorus availability. *Plant Physiology* **156**, 989-996
- Robertson LN, Kettle BA, Simpson GB (1994) The influence of tillage practices on soil macrofauna in a semi-arid agroecosystem in northeastern Australia. *Agriculture, Ecosystems and Environment* **48**, 149-56
- Roget DK, Coppi JA, Herdina, Gupta VVSR (1999) Assessment of suppression to *Rhizoctonia solani* in a range of soils across SE Australia. *Proceedings of the First Australasian Soilborne Diseases Symposium* (BSES, Brisbane, Australia) pp 129-130
- Roper MM (2005) Managing soils to enhance the potential for bioremediation of water repellency. *Australian Journal of Soil Research* **43**, 803-810
- Roper MM, Gupta VVSR (1995) Management practices and soil biota. *Australian Journal of Soil Research* **33**, 321-339
- Roper MM, Gupta VVSR, Murphy D (2010) Tillage practices altered labile soil organic carbon and microbial function without affecting crop yields. *Australian Journal of Soil Research*. **48**, 274-285
- Roper MM, Ward PR, Keulen AF, Hill JR (2013) Under no-tillage and stubble retention, soil water content and crop growth are poorly related to soil water repellency. *Soil & Tillage Research* **126**, 143-150
- Roper MM, Gupta VVSR (2016) Enhancing non-symbiotic N₂ fixation in Agriculture. *The Open Agriculture Journal* **10**, 7-27
- Roper MM, Davies SL, Blackwell PS *et al.* (2015) Management options for water-repellent soils in Australian dryland agriculture. *Soil Research* **53**, 786-806
- Rose MR, Cavignaro TR, Scanlan CA *et al.* (2015) Impact of herbicides on soil biology and function. *Advances in Agronomy* **136**, 133-220
- Rovira AD, RJ Smettem RJ, Lee KE (1987) Effect of rotation and conservation tillage of earthworms in a red-brown earth under wheat. *Australian Journal of Agricultural Research* **38**, 829-834
- Ryan MH, Kirkegaard JA (2012) The agronomic relevance of arbuscular mycorrhizas in the fertility of Australian extensive cropping systems. *Agriculture Ecosystems & Environment* **163**, 37-53
- Sanderman J, Farquharson R, Baldock J (2010) Soil carbon sequestration potential: a review for Australian agriculture. *Report for Department of Climate Change and Energy Efficiency*. 80pp
- Six J, Elliott ET, Paustian K (2000) Soil macroaggregate turnover and microaggregate formation: a mechanisms for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* **32**, 2099-2103
- Stirling GR (2014) "Biological control of plant-parasitic nematodes: soil ecosystem management in sustainable agriculture" 2nd edn (CAB International Wallingford: UK.)
- Subler S, Baranski CM, Edwards CA (1997) Earthworm additions increased short-term nitrogen availability and leaching in two grain-crop agroecosystems. *Soil Biology and Biochemistry* **29**, 413-421
- Thomas GA, Thompson JP, Amos RN (2003) A long-term fallow management experiment on a Vertisol at Hermitage Research Station in southern Queensland, Australia. *Proceedings of 16th Triennial International Soil Tillage Research Conference* pp 1223-1228
- Thompson JP (1987) Decline of vesicular-arbuscular mycorrhizae in long fallow disorder of field crops and its expression in phosphorus deficiency of sunflower. *Australian Journal of Agricultural Research* **38**, 847-867
- Thompson JP (1992) Soil biotic and biochemical factors in a long-term tillage and stubble management experiment on a vertisol. 2. Nitrogen deficiency with zero tillage and stubble retention. *Soil and Tillage Research* **22**, 339-361
- Thompson JP, Bowman R, Seymour NP *et al.* (1997) VAM boosts crop yields. The natural way to healthy crops. QDPI Farming Systems Institute Crop Link Research Focus 8pp (QDPI: Brisbane)

- Thompson JP, Owen KJ, Stirling GR, Bell MJ (2008) Root-lesion nematodes (*Pratylenchus thornei* and *P. neglectus*): a review of recent progress in managing a significant pest of grain crops in northern Australia. *Australasian Plant Pathology* **37**, 235-242
- Thompson JP, Clewett TG, Fiske ML (2013) Field inoculation with arbuscular-mycorrhizal fungi overcomes phosphorus and zinc deficiencies of linseed (*Linum usitatissimum*) in a vertisol subject to long-fallow disorder. *Plant and Soil* **371**, 117-137
- Thompson JP, Rostad HE, Macdonald, B, Whish JPM (2018) Elevated temperature reduces survival of peak populations of root-lesion nematodes (*Pratylenchus thornei*) after wheat growth in a vertisol. *Biology and Fertility of Soil* **54**, 243-257
- Ward PR, Roper MM, Jongepier R, Alonso Fernandez MM (2013) Consistent plant residue removal causes decrease in minimum soil water content in a Mediterranean environment. *Biologia* **68**, 1128-1131
- White RG, Kirkegaard JA (2010) The distribution and abundance of wheat roots in a dense, structured subsoil-implications for water uptake. *Plant, Cell & Environment* **33**, 133-148
- Wildermuth GB, Thompson JP, Robertson LN (1997) Biological change: disease, insects and beneficial organisms. In (Eds. AL Clarke and P Wylie) "Sustainable Crop Production in the Sub-tropics – An Australian Perspective" pp 112-130 (QDPI: Brisbane)
- Yeates GW and Stirling GR (2008) Regional patterns among soil nematode assemblages in Australasian pastures and effects of management practices. *Australasian Plant Pathology* **37**, 298-307
- Yukicevich E, Lowery T, Bowen P *et al.* (2016) Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture. A review. *Agronomy for Sustainable Development* **36**: 48-62

Chapter 16

Soil Organic Matter and Carbon Sequestration

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Introduction

Organic matter is a fundamental component of soil that plays an important role in a wide range of physical, chemical and biological functions. Soil organic matter (SOM) is also central to the storage of carbon (C) in terrestrial ecosystems and is the major contributor to balancing the global C budget. Agricultural practices however, are a major disruptor to this balance and historically have resulted in large losses of SOM, particularly through intensive cultivation of soils. Consequently there is current interest world-wide to improve the management of SOM in agriculture that aim to 'build and retain' C in SOM to develop more sustainable systems that mitigate climate change. Broad-acre cropping systems play a significant role in this regard and conservation agriculture (CA) based on reduced or no-till (NT) systems are purported widely to be an effective management approach to redress this. Interestingly, the role of tillage in management of SOM received very scant attention in the original edition of '*Tillage*' (Cornish and Pratley 1987) and there has since been much conjecture with respect to CA practices and SOM dynamics. Nonetheless it is evident that there is need for better understanding of the influences of crop management and tillage practices on SOM.

Importance of soil organic matter (SOM)

SOM contributes to soil function through a range of processes that are associated with improved soil structure through stabilisation of aggregates, enhanced water holding capacity and/or water infiltration and in supporting higher soil fertility (Figure 1, Petersen and Hoyle 2016). SOM is also the key energy substrate for microorganisms in soil that facilitate various soil biogeochemical processes and via mineralisation, provides nitrogen (N), phosphorus (P) and sulfur (S) to plants (Murphy 2015).

Soils are the most significant store of terrestrial C with an estimated global pool of 2,500 Pg of C, which is predominantly associated (~62%) directly with soil organic C (SOC) and thus SOM (Lal 2004). Collectively, the amount of C associated with SOC is some 3.3 and 4.5 times more than that contained in atmospheric CO₂ and living biomass, respectively. Whilst dependent on many geographical, climatic and pedological factors, soils contain SOC contents that typically range from ~45 to 140 Mg (or tonnes) C/ha (to 1 m depth, with extremes up to 725 Mg C/ha), which equates to 80 to 240 Mg of SOM/ha (Lal 2004). By equivalence, this represents between 0.5% to 1.6% SOM (by soil mass) when averaged to 1 m of soil depth (at soil bulk density of 1.5 g soil/cm³) or ~1.8 to 5.3% SOM when averaged over the top 30 cm.

It is well recognised that anthropological influences (*e.g.* land-use change, deforestation, agricultural production, urbanisation) have caused a major decline in SOM content throughout the world. Some 50 to 75% of the antecedent total SOM content is estimated to have been lost due to agricultural practice with higher rates of loss occurring in recent times (Lal 2007, Sanderman *et al.* 2017). For broad-acre cropping systems in temperate climates this equates to typical losses of between 30 and 60 Mg C/ha. In Australian soils, Chan and McCoy (2010) have estimated that at least 50% of the original C stocks have been lost in intensively managed cropping systems. This is consistent also with reduced levels of organic N in Australian soils (which, as discussed below is closely linked to SOC content), where more than 50% of the organic N that is associated with SOM has been 'mined' from soil (*i.e.* mineralised from resident SOM). Reduced soil N is associated with both more intensive cropping, along with lesser dependence on biological N fixation through reduced legume rotation. Combined, this has led to a higher dependence on mineral-based N fertilisers to support crop growth in current practices (Angus and Grace 2017).

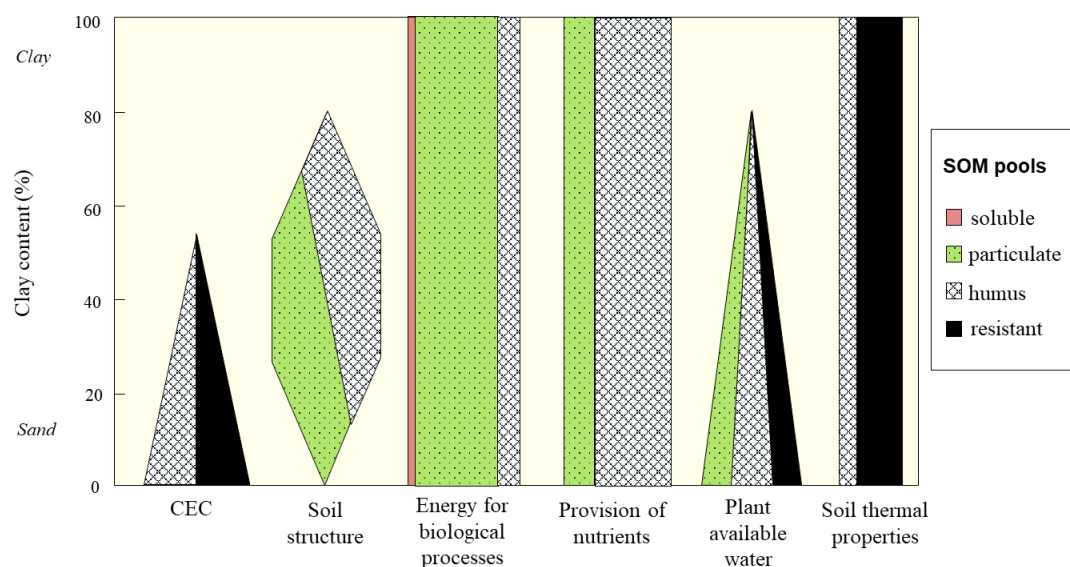


Figure 1. Conceptual role of SOM and pools of soil organic C (soluble, particulate, humus, resistant) on a range of soil functions. Object size indicates relative importance in relation to soil texture (sand to clay) (modified from Hoyle *et al.* 2011, courtesy of J. Baldock).

Rebuilding of ‘lost soil C’ and sequestration of soil C in managed ecosystems is therefore of considerable current interest to agricultural practitioners and environmental policymakers worldwide (Amudson and Biadeau 2018). Strategies proposed to restore soil C include; increased return of crop residues and bio-solids (manures, composts and other wastes) to soil, minimisation of soil disturbance, more continuous ground cover, a strengthening of nutrient recycling and a more positive nutrient balance, enhanced biodiversity and use of more diverse crop rotations, and a reduction in losses of water and nutrients from soils through erosion and leaching. These are associated with key farming principles in CA (Lal 2007, Giller *et al.* 2015) that promote:

- increased use of perennials;
- higher net primary productivity in agricultural systems (*i.e.* through crop choice and nutrient management); and
- greater adoption of NT farming practices with lesser soil disturbance.

Throughout Australia there has been a considerable increase in CA practices in recent decades which have led to increased return of crop residues to soil along with reduced cultivation (see Chapter 2). For example, in 2015 retained standing or surface stubble accounted for 56.8% (35.5% and 21.3%, respectively or 7.7 and 4.7 million ha) of crops, where broad-acre cereals accounted for a total area of 18 million ha (ABARES 2016). Associated with this is a significant reduction in burning of residues as a management tool. Despite this, there is conflicting evidence whether changed practice (*i.e.* increased adoption of NT and reduced burning) has led to an increase in C sequestration, with many studies finding little or no effect even when practised for a decade or longer.

Origins of SOM and pools of soil C

Development of cropping systems to effectively manage SOM requires understanding of SOM composition and the processes that drive the generation and degradation of SOM and the mechanisms associated with either its stabilisation or mineralisation in soils. Plant-derived C through photosynthesis is the primary source of C that contributes to SOM in both natural and agricultural systems. Plants contribute to SOM through rhizodeposition, root growth and return of above ground biomass (fresh organic matter; FOM) as litter, which includes crop residues (Figure 2). A large component of plant materials consumed by herbivores (*i.e.* grazing animals, insects and other macrofauna) is also returned to soil through excreta and death. Based on the annual C balance of a typical Australian wheat crop, ~40% of total annual C is allocated below ground in roots (20% to root growth and structure) and as

rhizodeposits (10% as sloughed cells and root turnover), with ~10% of total photosynthate being released as root exudates. At a grain yield of 2.4 Mg/ha (and a typical harvest index of ~0.4) a wheat crop thus generates ~4.0 Mg/ha of stubble biomass per annum which equates to ~1.6 Mg C/ha (up to 4 Mg C/ha in high yielding crops), even without accounting for the contribution from roots and root exudates. Collectively, across Australia cereal crops thus generate around 16 to 20 million Mg C/year (40 to 50 million tonnes of stubble). In addition to its use for soil conservation purposes in NT systems or as a low-quality feed supplement, this C-rich residue has large potential to contribute to SOM. Similarly worldwide, crop residues, including cereal and rice stubbles and maize stover are a significant C resource.

SOM is the organic fraction of the soil (exclusive of un-decayed plant and animal residues) that is comprised of a continuum of materials in varying states of decay (Lehmann and Kleber 2015) and is comprised of both active and stable pools that collectively contribute to total soil C (or total SOM). Active pools are influenced more by management changes and typically account for up to 40% of SOM, and includes:

- soluble C (~2 to 5% of SOM) that is largely in soil solution and easily extracted in water;
- microbial C (~5 to 10% of SOM) that is the component in living microbial biomass; and
- particulate organic matter (POM; ~25% of SOM) which is derived from the immediate breakdown of residues most recently returned to soil.

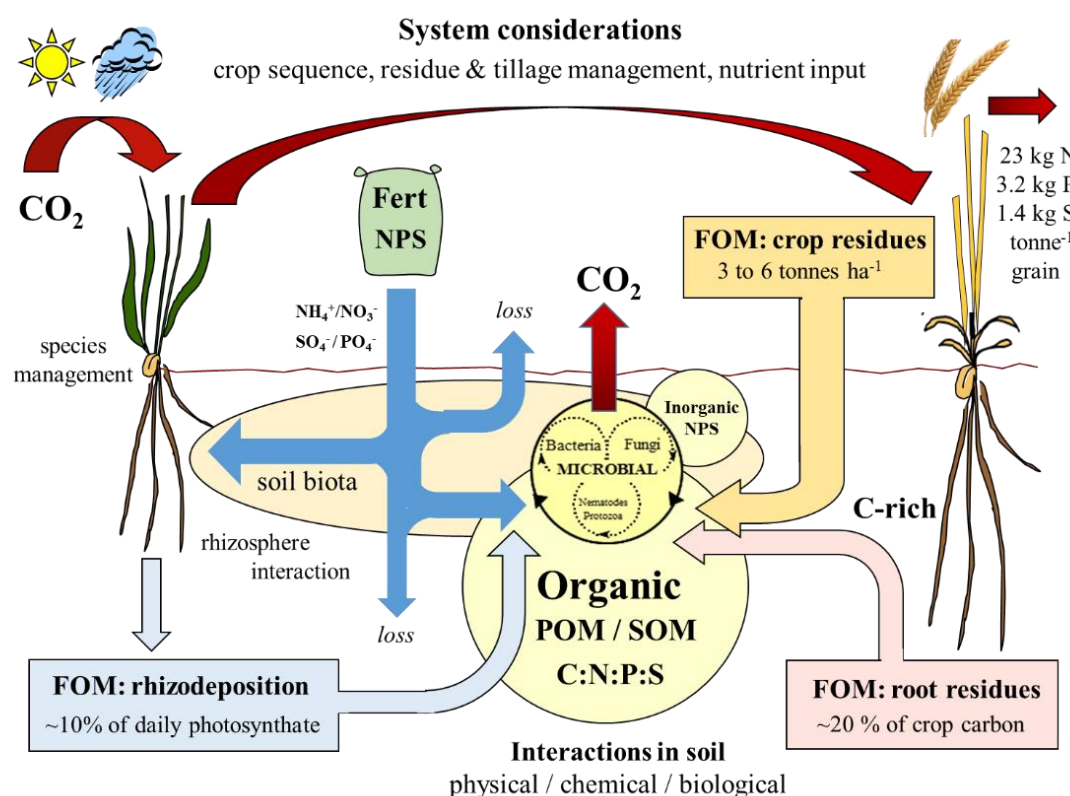


Figure 2. Schematic representation of carbon flow in plant-soil systems highlighting the interaction between inputs generated through net primary productivity and C pools in SOM

The soluble (or dissolved organic C) originates from root and microbial exudates and soluble compounds that are released through cellular degradation. Being predominantly in soil solution, soluble C (or soluble SOM) is readily metabolised by microorganisms or, through higher mobility, may be leached into deeper soil horizons (Strahm *et al.* 2009). Land-use impacts on soluble SOM are subject to seasonal fluctuations, but are enhanced by crop root growth (*e.g.* in spring) that contributes soluble C through exudate and turnover (Haynes 2005). Microbial biomass is the ‘living component’ of SOM and includes microflora (fungi, bacteria, archaea and smaller organisms such as phages) that

collectively constitute ~90% of the biomass, with microfauna (10 to 100 μm , including protists and nematodes) making up the remainder (Glaser *et al.* 2004). Turnover of this pool of SOM is rapid (days to weeks) and is mediated by microbial growth and cell death that is strongly influenced by seasonal conditions; *viz* temperature and moisture (Hagerty *et al.* 2014) and management practices (*e.g.* use of agrochemicals and tillage), that in particular disrupt fungal hyphal networks (Grandy and Robertson 2006). Distribution of C between fungi and bacteria and their relative dominance in different agricultural systems is suggested to be a major mediator in SOM dynamics (Six *et al.* 2006).

Soil POM is formed initially from the breakdown of FOM inputs that included litter and excreta, green manure crops, organic fertilisers (manures and composts) and crop residues. POM is comprised of decomposing residues, fungal hyphae, fine plant roots and other associated biomass and is an intermediate stage between FOM and more stable SOM (Janzen *et al.* 1992). The POM (50 to 2000 μm fraction) and has a short turnover time (1-2 years) and is more readily mineralised in soil following system disturbance and cultivation (Hoyle *et al.* 2011). Thus, management practices that affect either the rate of residue input (*e.g.* fertilisation, crop rotation, crop yield, tillage practice, periods of fallow) or influence the rate of residue decomposition have major influence on changes in the size of the POM pool (Schmidt *et al.* 2011). Cultivated soils and low production systems, for instance, typically have less POM than undisturbed soils under native systems, forests and/or plantations and pastures. The efficiency of conversion of POM to SOM (*i.e.* net humification efficiency) is a key factor to understand the accumulation and stabilisation of soil C, with rates of conversion of FOM-C to SOM-C of between 10 to 30% typically reported (Kirkby *et al.* 2014).

The more stable and predominant fraction of SOM (60 to 80 % in most soils) consists of both humic (fulvic and humic acid fractions) and non-humic substances (including identifiable biopolymers and complex amines) that, compared with POM, are more resistant to degradation. The more stable component of SOM is commonly termed ‘soil humus’ which by definition is associated with the <53 μm soil fraction (Baldock *et al.* 2013, Hoyle *et al.* 2011). Various studies have shown that other fine fractions of soil (<400 μm sieved) are similarly associated with the more stable component of SOM (Kirkby *et al.* 2011, Magid and Kjærgaard 2001). This pool of more stabilised soil C has a slower turnover rate that is typically in the order of 2 to 3% per annum. Stable SOM is largely constituted by microbial detritus and to a lesser extent by lignified material from plant cell walls. As such, it represents a key target for effective sequestration of soil C.

The resistant fraction of SOM also includes charcoal, which depending on soil type and prior history, generally accounts for 0 to 10% of total SOM. Although not inert, charcoal in soil largely resists decomposition even after cultivation and has a half-life measured in centuries (Baldock *et al.* 2013).

Dynamics of SOM and stabilisation in soil

Degradation of FOM and POM involves the physical and biochemical decomposition of organic material followed by repeated processing (mineralisation) by soil microorganisms (Chen *et al.* 2014). During mineralisation, most of the C from the FOM/POM is returned (*i.e.* some 70 to 90%, depending on extent of humification efficiency) to the atmosphere as CO_2 (Stockmann *et al.* 2013). Through decomposition and mineralisation there is a concomitant release of inorganic nutrients (N, P, S) that are either re-utilised by microorganisms, are available for crop growth or undergo further interactions within the soil. This includes fixation reactions for P; adsorption and precipitation, denitrification and leaching for N, and depending on soil type, potential leaching of S and P.

SOM thus originates directly from FOM inputs that are added to soil or through POM that is either recalcitrant to mineralisation or, through microbial processing and generation of organic debris, becomes stabilised in soil. Historically, lignified plant material (which constitutes up to 20% of FOM) has been considered to be a major contributor to stable SOM, whereas more recent evidence indicates that microbial detritus is the more significant component. The processing of FOM and POM by microorganisms generates ‘new’ microbial biomass that when turned-over creates significant amounts of detritus. Accordingly, microbial detritus has been shown to make up to at least 50% of stabilised

SOM (Miltner *et al.* 2012, Ma *et al.* 2018). Comparatively, the microbial detritus contribution to SOM is some 40 times larger than the living microbial biomass. Management practices that provide large inputs of more labile C (*e.g.* application of nutrient-rich manures) that significantly increase microbial biomass in soil have been shown to contribute to increased accumulation of SOM (Engelking *et al.* 2008). Likewise, crop residues with appropriate management (especially through deliberate nutrient enrichment, as discussed below) similarly have potential to contribute to increased levels of SOM.

The concentration (or cumulative stock) of SOC in soil at any one time reflects the balance between FOM supply and SOM loss by decomposition and erosion. This net balance of SOC is the result of complex interactions between environmental factors and land management (Hoyle *et al.* 2011, Orgill *et al.* 2014, 2017a). Climate and soil type in particular explain a considerable proportion of the variability in SOC within a given land use, largely due to direct effects on net productivity (biomass production) and rate of decomposition. Once in the soil, the fate of FOM/SOM is mediated by soil temperature and moisture, the decomposer microbial community (see Chapter 15) and the degree of SOM protection against decomposition.

SOM is stabilised through either resistance to mineralisation or by interaction within the soil matrix and subsequent protection within soil aggregates (Gupta and Germida 2015). Stabilisation involves interaction with soil mineral surfaces, particularly in soils with high clay content (Figure 1), which also reduces accessibility to microorganisms (von Lützow *et al.* 2006, Eldor 2016). Generally, SOC content is greater with increased precipitation and clay content, and decreases with an increase in temperature. Thus, climate largely regulates SOC in the surface layers, while clay content largely determines SOC in deeper soil layers. SOM in deeper soils is also considered to be more protected from mineralisation through its isolation from microorganisms that dominate in the surface layers. Generally, there is also a positive correlation between aggregation and SOM concentrations (Jastrow *et al.* 2007). Tillage is a key process that disrupts macro-aggregates in soil and has been shown to lead to subsequent losses of SOM (Six *et al.* 2004). Accordingly, increased frequency of cultivation increases the rate of loss of SOM, whereas reduced tillage is proposed widely as a means for the protection and subsequent accumulation of SOM.

Nutrient stoichiometry and its importance in SOM dynamics

The interaction of microorganisms in mediating SOM stabilisation in soil and directly contributing to SOM formation is further supported by the similarity in nutrient composition of SOM (*i.e.* stoichiometry of C:N:P:S) within the soil microbial biomass, and from the ¹³C isotope enrichment ‘signature’ of the microbial biomass and that of stabilised SOM (Dijkstra *et al.* 2006, von Lützow *et al.* 2006). The ratio of C:N:P:S in SOM of agricultural soils across the globe is relatively constrained and is tightly linked across soils from both natural and agricultural ecosystems, with relatively little impact from management, soil type or climate (Cleveland and Liptzin 2007). This consistency in nutrient stoichiometry for SOM is even stronger when P is specifically considered in organic forms (Kirkby *et al.* 2011), and is consistent with the fact that most of the N and S in soil (>90%) occurs in organic form that (along with organic P) is intimately associated with SOM.

Importantly, the elemental nutrient ratio that occur in more stable SOM (*i.e.* typically 70:6:1:1 for C:N:P:S) is similar to the ratio that is found in the microbial biomass (60:7:1:1 for C:N:P:S), as compared with the wide range of ratios commonly found in plant residue inputs (263:5:0.5:1 C:N:P:S for wheat residue and 102:2:0.3:1 for canola residue). Likewise, the nutrient ratios in the POM fraction are considerably wider than in stable SOM and are closer to the ratios found in originating plant residues (Cleveland and Liptzin 2007, Kirkby *et al.* 2011, Richardson *et al.* 2014). Collectively, this indicates that the processing of FOM to SOM by microorganisms requires a ‘concentration’ (enrichment) of nutrients (*i.e.* narrowing of CNPS ratios) to reach that which is present in stabilised SOM (Tipping *et al.* 2016). This is particularly important for FOM inputs that have wide nutrient ratios (such as C-rich stubble) and means that the ‘efficiency’ of conversion of stubble to SOM is strongly mediated by the availability of nutrients (van Groenigen *et al.* 2006, Kirkby *et al.* 2014).

Microorganisms in soil primarily utilise C in FOM as an energy source for growth and production of microbial biomass. This growth requires a stoichiometric balance of nutrients (N, P, S) to meet microbial demand. Depending on inherent soil fertility and the quality of FOM (*i.e.* nutrient composition) that is returned to soil, these nutrients are either co-obtained from the decomposed FOM, or are directly acquired from soil or soil solution which, depending on the stage of crop development, may be in direct competition with plant demand. Thus, addition of C-rich crop residues to soil can in many cases ‘induce’ short-term nutrient deficiencies (especially N) that may limit crop growth (*e.g.* each tonne of stubble returned typically ‘ties up’ around 5 kg N/ha).

Alternatively, when deficient, microorganisms are also able to obtain nutrients to support their growth through re-utilisation (mineralisation) from previous generations of microbial biomass (*i.e.* fresh microbial residue) or effectively can directly ‘mine’ pre-existing SOM to obtain N, P or S. The balance of such processes is largely governed by the quality of C inputs and nutrient availability and is commonly referred to as the ‘priming effect’ (Kuzakov 2010). This priming effect may lead to a direct increase in SOC formation (where SOM accumulates; known as a negative priming effect) or, more commonly with C-rich crop residues, results in increased rates of SOM mineralisation, where levels of SOC actually decline via a positive priming effect (Fontaine *et al.* 2004, Kuzakov 2010, Stockmann *et al.* 2013).

The priming effect on SOM dynamics is driven by microbial demand for nutrients when provided with C-rich substrates. This means that retention of crop residues with wide C:N:P:S ratio, for example through conservation farming practices, may not necessarily increase SOM sequestration when nutrients are limiting (Kirkegaard *et al.* 2014, Baker *et al.* 2007). On the contrary, the provision and use of legume residues generally leads to an increase in the net sequestration of SOM as the legume residues have a higher nutrient quality (as compared with cereal stubble), thus providing more nutrients for microbial degradation of the plant residue with lesser dependence on mineralisation of pre-existing SOM (Drinkwater *et al.* 1998).

Recent studies under controlled laboratory conditions have shown that the addition of supplementary nutrients (based on nutrient ratios of stable SOM) alongside C-rich FOM inputs can lead to an increase in SOC accumulation. This increase in SOM was sufficient to overcome the mineralisation of ‘native’ SOM (*i.e.* SOM existing prior to the addition of FOM) arising from a positive priming effect (Kirkby *et al.* 2013, Orgill *et al.* 2017b). For example, in the incubation study by Kirkby *et al.* (2014), ¹³C-labelled wheat straw was added to four contrasting soil types with markedly differing clay contents (8% to 60%). A three-fold increase in the conversion (gross humification efficiency) of stubble-C to SOM-C was observed where the straw was added with supplementary N,P and S. Importantly, it was demonstrated that addition of nutrients with the straw led to both a substantial increase in new SOC formed as well as a reduction in the loss of pre-existing SOC (SOM), resulting in an overall increase in net humification efficiency (*i.e.* from -17 to 10% without nutrients to 15% to 40% with nutrients across the soils). The supply of nutrients (N, P and S) with wheat straw reduced the need for soil microorganisms to mineralise pre-existing SOM to obtain nutrients, and thus can mediate either positive or negative change in SOC (Fontaine *et al.* 2004, Kirkby *et al.* 2014). Orgill *et al.* (2017b) demonstrated a similar concept in pasture soils using an incubation experiment to show that soils with high SOC concentrations were able to continue to accumulate SOC with increasing FOM inputs (*i.e.* C inputs), but only when additional nutrients were supplied. This mechanistic understanding of microbial mediated C dynamics in soil is important to interpret changes in the levels of soil SOM under field conditions (van Groenigen *et al.* 2006) in response to different soil types and crop and pasture management systems, including the adoption of different tillage practices.

Management of SOM and sequestration of C in agricultural systems

There is evidence that management can be adopted to build SOM in agricultural soils through a range of practices (Sanderman *et al.* 2010, Lal 2017, Poulton *et al.* 2018) including:

- crop and pasture sequence (especially through a pasture and/or legume phase);
- use of cover crops;

- amendment of soils with C-based materials (*e.g.* bio-solids, manures);
- nutrient inputs (fertiliser) to promote plant growth and/or the humification of crop residues;
- innovative tillage and residue management.

In particular, these strategies:

- increase the amount of above- and below-ground FOM inputs to soil with facilitation of microbial biomass generation and turnover;
- affect the location of FOM inputs within the soil profile; or
- influence the rate of FOM conversion to more stable forms of SOM.

Pastures and pasture leys in crop rotations

Under comparable pedo-climatic conditions managed grassland and pasture systems (like undisturbed natural systems) can support higher levels of SOM than intensively managed cropping soils. Conversion from cropping to pasture or use of a pasture phase in a cropping sequence can increase SOC content (Table 1). Reduced disturbance of soil under pasture and enhanced soil aggregation leads to increased protection of SOC (Six *et al.* 2004). Generally, there is also higher levels of biomass return in pasture systems via plant deposition and return of animal excreta, with less export of biomass.

In a meta-analysis of the impact of land-use change on SOC concentrations, Guo and Gifford (2002) found that the SOC stocks increased by on average 19% after the transition from crop to pasture, with the length of time since conversion having no clear effect on the amount of C accumulated. The rate of SOC accumulation (sequestration) under pasture depends largely on soil type and climate, as compared with other management factors (Conyers *et al.* 2015, Rabbi *et al.* 2015, Sanderman *et al.* 2010). Nonetheless under long term pastures, SOM sequestration is increased particularly with the inclusion of legumes (with significant inputs of biological N) and with fertilisation (particularly P and S fertiliser in Australian soils) that increase net primary production (Haynes and Williams 1992, Orgill *et al.* 2017b). By contrast selection of grass species, including differences between annual and perennial species and/or introduced grasses versus native pasture plants had lesser impact (Schwenke *et al.* 2013, Conant *et al.* 2017). In the study by Coonan *et al.* (2019) a net difference in C accumulation of 12 Mg C/ha (19 % increase from 61.7 to 73.6 Mg C/ha) was observed over a 20 year period in a soil under a legume-based pasture fertilised with P and S and dependent on N from biological fixation. Whilst largest difference in C concentration was observed in the 0 to 10 cm layer of soil, soil C stocks were significantly increased to a depth of at least 60 cm. This is consistent with other studies that have shown typical annual rates of C accumulation in improved pasture soils under Australian conditions of around ~0.5 Mg C/ha/year (Table 1). Accumulation of SOC has similarly been observed in cropping soils that are either returned to pasture or during the pasture phase of a crop system, particularly when soils with initially low SOC concentrations were converted to pasture both in short or longer term rotations (Table 1).

Conversely, pasture management can have limited or no impact on SOC sequestration in cases where the growth potential of the pasture is limited by inadequate soil nutrition or where the composition of the pasture sward has low legume content (Badgery *et al.* 2014). The impact of management practices and land use change on SOC sequestration is indeed variable and measurements may also be limited by spatial and temporal variability in sampling. This includes, high pre-existing levels of SOM, poor sensitivity in measuring a change in soil C (against a large background), and lack of consideration of soil depth in calculating changes in either the concentration or stocks of SOC (Badgery *et al.* 2014, Robertson *et al.* 2016). Additionally, reported rates of soil C sequestration, such as those summarised in Table 1, are not necessarily linear and are likely to only be maintained for finite duration, being constrained in the longer term by soil characteristics and climatic factors (Conyers *et al.* 2015, Sanderman *et al.* 2010).

Table 1. Rate of soil C sequestration for pasture and the pasture phase of crop-pasture rotations in response to management factors (dns = data not specified).

Land use and location	Mean rate C sequestration (Mg C/ha/yr)	Management factors	Years	Soil depth (cm)	Reference
Permanent pasture					
Global meta-analysis	0.66 0.28 0.57	Legume pasture Grazing management Fertilisation	25 (0.7 to 200)	38 (2 to 800)	Conant <i>et al.</i> 2017
Brazil	0.61	Grazing management and fertilisation	8.8 (4 to 14)	30	Maia <i>et al.</i> 2009
Brazil	1.17 0.66	Legume pasture Non-legume pasture	10	30	Tarré <i>et al.</i> 2001
NSW, Australia	0.50	Annual and perennial pasture	13	30	Chan <i>et al.</i> 2011
ACT, Australia	0.60	Fertilisation and increased stocking rate	20	60	Coonan <i>et al.</i> 2019
Australian meta-analysis	0.1 to 0.3	Fertilisation, legumes and irrigation	dns	30+	Sanderman <i>et al.</i> 2010
Crop to permanent pasture					
Global meta-analysis	0.87	Cultivation to pasture	25 (0.7 to 200)	38 (2 to 800)	Conant <i>et al.</i> 2017
Global meta-analysis	0.33	Conversion from agricultural use to grassland	26 (6 to 81)	29.6 (5 to 300)	Post and Kwon 2000
Europe	0.56	Cropland to grassland	32 (16 to 41)	80	Poeplau and Don 2013
NSW, Australia.	0.48	Crop to perennial pasture	22	10	Young <i>et al.</i> 2009
Martinique	1.50	Cultivated to pasture	5	30	Chevallier <i>et al.</i> 2000
Australian meta-analysis	0.3 to 0.6	Fertilisation, legumes and irrigation	dns	30+	Sanderman <i>et al.</i> 2010
Crop to pasture in rotation (long-term)					
Denmark	2.5 (0.8 to 3.9) ¹	Converted from cereal crop to a 6-year arable pasture (clover) crop rotation	1 -5 years of ley phase	25	Müller-Stover <i>et al.</i> 2012
USA	1.9 (1.2 to 2.7) ²	Wheat with ryegrass/clover leys of different ages	2-6 years of ley phase	23	Johnston <i>et al.</i> 1994
UK	0.7 (g C kg ⁻¹ year ⁻¹) ³	Grassland/clover leys following annual tillage	3 years of ley phase	12	Clement and Williams 1964
Denmark	1.1 (0.3 to 1.9)	Rotation with ley grass phase and barley crop phase	1-6 years of ley phase	20	Christensen <i>et al.</i> 2009
Crop to pasture in rotation (short-term)					
Sweden	0.36 to 0.59	Ley grassland/cereal crop rotation with 3 years of grassland and 1 year of crop	4 year rotation for 35 years	20	Börjesson <i>et al.</i> 2018
USA	0.15	Corn/wheat/clover rotation with fertilizer and manure	3 year rotation for 26 years	100	Buyanovsky and Wagner 1998
NSW, Australia	0.26	No till wheat with pasture (clover) rotation	2 year rotation for 25 years	30	Chan <i>et al.</i> 2011
NSW, Australia	0.23	Pasture in a crop rotation (33% to 67% pasture content)	2-6 year rotation for 18 years	30	Helyar <i>et al.</i> 1997
QLD, Australia	0.65	Cultivated with grass/legume leys	4 year rotation for 10 years	4	Dalal <i>et al.</i> 1995

¹ Sequestration calculated compared with a treatment with 0 years of pasture, determined using a bulk density (BD) of 1.55g soil cm⁻³

² Calculated using a BD of 1.65 g soil cm⁻³; C sequestration was compared with a treatment with 1 year of pasture

³ Reported as an increased in % soil C calculated using appropriate adjustments for variation in soil volume; BD was not reported

Residue and tillage management in continuous crop systems

The trajectory of SOC levels (*i.e.* SOM) in farming systems is determined by the balance of organic materials returned to the soil (especially after harvest, Figure 2) and the amount of C lost by either microbial respiration or physical processes. Management practices that have major influence on this balance in continuous cropping systems are the amount and type (quality) of the residue inputs, tillage practice and level of fertilisation (van Wesemael *et al.* 2010, Sanderman *et al.* 2011).

Inputs Whilst return of C-rich crop residues to soil (inputs) would be expected to contribute to the build-up of SOM compared to removal or burning, the results from many studies are unclear (Table 2). In the meta-analysis conducted by Lehtinen *et al.* (2014), SOC levels tended to increase with residue retention with increasing response from duration of retention, and most notably was evident in soils with clay content >35%, which is consistent with other studies. In a review of various long-term experiments, Powlson *et al.* (2011) concluded that whilst most studies tended to report ‘greater’ SOC accumulation with residue retention, differences were statistically significant in a minority of studies only. In a long term experiment of our own (Harden, NSW, Australia), SOC levels from a NT system have been compared with a conventionally cultivated system (with stubble retained or burnt in both cases) with essentially no difference in SOC levels occurring after 25 years, although there were effects on SOM distribution within the uppermost layers of the soil profile (unpublished data).

By contrast to crop stubble, green manure cover crops or legume rotations consistently increase SOM. In a review from 37 trials, Poeplau and Don (2015a) found that soils under cover crops had significantly higher SOC stocks than associated reference crops, with a mean annual change of 0.32 Mg/ha/yr to a soil depth of at least 20 cm. While cover crops consistently increase SOC levels, their use in many parts of Australia is limited by water availability. Manures, composted recycled organics (RO) and other bio-solids similarly have potential to build SOM in agricultural soils (Gibson *et al.* 2002, Poulton *et al.* 2018). Typical increases in SOC are equivalent to 0.008 to 0.08 Mg C/ha per tonne of RO applied in the top 10 cm, with typical rates of manure application of 5 Mg ha⁻¹ being applied. Whilst there is wide range in humification efficiency of RO products (5 to 50%), it compares favourably with the 4.6% efficiency reported for stubble retention under Australian conditions (Heenan *et al.* 1996), and the 15% average typically reported for plant residues (Lal 1997). The major existing barrier to the widespread use of RO products in the agricultural sector is the prohibitive cost of materials, transport and handling, and logistical factors associated with broad-acre application.

Tillage The effects of soil cultivation practices and intensity of tillage on mineralisation and/or sequestration of SOM has received wide attention, particularly in view of the increased adoption of NT. A predominant finding is that retention of crop residues in NT systems can lead to greater SOM levels in surface soil layers, but due to stratification within the soil profile can lead to lower SOC levels at depth (Baker *et al.* 2007). By contrast, incorporation of residues into soil has been shown to increase SOC deeper in the soil profile (Alcantara 2016).

Several studies support that NT sequesters more SOC compared with CT (*e.g.* Syswerda *et al.* 2011, Varvel and Wilhel 2011). In most cases though, where sampling was >30 cm, increased levels of SOC at the surface in NT systems were generally offset by increased SOC levels at depth under conventional cultivation (Table 2). In addition, it is evident that surface retained SOM was generally less decomposed (*i.e.* higher POM component) and would be more prone to further decomposition, and thus readily lost from the system over time (Wander and Bidart 2000). Furthermore, it has been shown that incorporation of stubble-C into microbial biomass was greatly facilitated by cultivation and soil mixing as compared with surface retention (Helgason *et al.* 2014). SOM at depth in conventionally cultivated systems also appears to be more recalcitrant to mineralisation and is more aligned with stabilised SOM (Alcantara 2016). In our own long-term study (Harden, NSW), there was no difference in SOC levels after 25 years under residue retained systems with either NT or CT when measured to 1.6 m depth. Whilst SOC levels appeared higher in 0-30 cm layer with NT system compared with cultivation, the overall differences in SOC were not significant. Interestingly, even when residues (standing stubble) were burnt, the SOC levels in the (0-30 cm) layer were equal with both CT and NT, and again were not different over the whole soil profile.

In considering the adoption of tillage and management practices to promote C sequestration, it is important to recognise the impact of both the distribution of SOC throughout the profile and the potential of the material to contribute to stabilised SOM. Accordingly, the effectiveness of NT to sequester SOC compared with CT may be greatly reduced, negated or even reversed when the whole profile is considered (Baker *et al.* 2007, Angers and Eriksen-Hamel 2008, Luo *et al.* 2010, Chatterjee 2018, Powlson *et al.* 2014). Additionally, the effects of soil bulk density (BD) need to be considered to convert concentrations of SOC (% or mg C/kg soil) to C-stocks (Mg C/ha). Use of a fixed depth sampling to measure total SOC can introduce bias when compared with SOC stocks in soils that are subject to management induced changes in BD. This is particularly relevant for shallow sampling depths (<30 cm), where higher BDs generally occur under NT systems (Aguilera *et al.* 2013, Don *et al.* 2011, Palm *et al.* 2014). For example, as reviewed by Meurer *et al.* (2018), the positive benefits of NT observed in the 0-30 cm layer of soils from long-term trials were overestimated in more than 50% of cases when BD was not considered. Significant differences in SOC concentration observed between NT and CT were also negated when determined using an equivalent soil mass (Du *et al.* 2017).

The influence of gravel in soil (especially at depth) is of further importance, both for its effect on soil BD and recent findings that have shown that gravel may also contain significant amounts of SOM as a coating (*i.e.* up to 10% of total SOC in deep soil layers, Kirkby *et al.* unpublished), but is routinely excluded from soil analyses. Finally, the methodology used for C determination is important (*i.e.* such as simple oxidation methods) that generally over-estimate the POM fraction of SOM (*i.e.* relative to analytical-based techniques). This generates further bias between C in surface layers and C at depth by underestimating the amount of more stable SOM in surface soils under different tillage systems.

Fertilisation Based on evidence that higher quality nutrient-rich residues are more effective in contributing to SOM and the apparent nutrient requirements of the microbial biomass to process C-rich residues into SOM (*i.e.* stoichiometric interactions as discussed previously), over-fertilisation of crops or direct fertilisation of crop residues (nutrient enrichment) has been proposed as a useful management tool to promote C sequestration. Increased fertilisation has either increased SOC levels or had no effect, despite in most cases having a positive effects on net primary production (Table 2). Direct application of nutrients to crop residues is effective in enhancing the formation of stable SOC through increased humification efficiency under controlled laboratory incubations (Moran *et al.* 2005, Kirkby *et al.* 2013).

Extending this approach to the field, Jacinthe *et al.* (2002) showed that humification efficiency for wheat residue-C to SOC was increased over a 4 year period from 14 to 32% with deliberate application of nutrients to stubble. Kirkby *et al.* (2016) similarly demonstrated this in the field (Harden, NSW), where crop residues (primarily wheat; average input 9 Mg stubble/ha/year) were incorporated over a 5 year period into soil to ~15 cm depth as soon as possible after harvest, with or without supplementary nutrient addition (NPS).

Stocks of SOC were increased across the 5 year period by 5.5 Mg C/ha over 0 to 160 cm in the soil profile where supplementary nutrients were added, as compared with a decrease of 3.2 Mg/ha where wheat straw only was incorporated, with 90% of this loss (relative to initial levels) being in the 0 to 10 cm layer (Kirkby *et al.* 2016). Some 50% of the increase in SOC in response to nutrients occurred below 30 cm and was suggested to be a result of leaching of C from the surface layers as either soluble C, colloidal material including microbial detritus, or as a result of increased root growth at depth (Kirkby *et al.* 2016). The importance of nutrients (especially N) to promote C sequestration from residues has similar been demonstrated in other field-based studies (van Goenigen *et al.* 2006, Poeplau *et al.* 2017). On the other hand, recent ‘on-farm’ trials conducted across 8 sites throughout south-eastern Australia (Van Rees *et al.* 2017) found no clear benefit for SOC sequestration following nutrient supplementation on stubble over 3 years when applied to residues that were incorporated immediately prior to sowing of the subsequent crop. These trials however used relatively low stubble loads and overall there was low sensitivity in C measurements (to 30 cm depth) with no differences either for treatments that had stubble removed.

The opportunity to increase humification efficiency of stubble to increase soil C through stoichiometric balanced microbial processing requires further validation. For example, better understanding of timing

Table 2. Soil C sequestration in crop systems in response to management factors including; residue retention, tillage practice and fertilisation (dns = data not specified).

Management and location	C sequestration (+/=-) change, or % increase)	Management factors	Soil depth (cm)	Reference
Residue inputs				
South Africa	(+) with retention	Various rotations of maize, fallow, soybean and wheat residue retained or removed	10	Gura and Mkeni 2019
Europe	mean 7% SOC increase	47 field trials with crop residue incorporation <i>cf</i> removal. Highest response at >35% clay content	dns	Lehtinen <i>et al.</i> 2014
Italy	mean 6.8% SOC increase	Field experiment <i>cf</i> residue removal or incorporation over 20 years. No further increase after 40 years	30	Poeplau <i>et al.</i> 2017
Europe	(+) with retention	14 field studies with different levels of crop residue <i>cf</i> with complete removal. Response only at > 4 t/ha/yr	30	Searle and Bitnere 2017
Sweden	(+) or (-) with retention	16 long-term trials (average 36 yrs) with retained <i>cf</i> removed stubble. Soils with clay >30% showed consistent response with retention	30	Poeplau <i>et al.</i> 2015b
Tillage practice and residue management				
Belgium	(=)	Reduced till <i>cf</i> conventional till with and without residue retention over 8 years	30	Hiel <i>et al.</i> 2018
USA	(=)	No-till and conventional till <i>cf</i> residue retention and 2 levels of removal (50 and 100%)	60	Guzman 2103
Kenya	(=)	Reduced till <i>cf</i> conventional till with and without residue retention over 11 years	30	Paul <i>et al.</i> 2013
China	(=)	Meta-analysis no-till <i>cf</i> conventional till from 57 sites. SOC with NT > CT in 0-20 cm layer; SOC with NT < CT below 20 cm. Overall NT > CT calculated using fixed depth, but NT=CT on equivalent soil mass	20+	Du <i>et al.</i> 2017
Australia	(=)	Reduced till <i>cf</i> conventional till with/without residue retention over 25 years No difference in SOC to 1 m depth	100	Kirkby <i>et al.</i> (unpublished)
Tillage practice				
Global	(+) upper layers	Conventional till <i>cf</i> to no till in 69 experiments. NT increased SOC by 3.1 t/ha in 0 to 10 cm layer, but decreased SOC by 3.3 t/ha below 20 cm	40	Lou <i>et al.</i> 2010
USA	(-) lower layers (=)	No-till <i>cf</i> chisel till at 3 sites. NT at one site had higher SOC but only in 0-15 cm. No difference in whole profile SOC	90	Chatterjee 2018
USA (mainly)	(+) upper layers	Meta-analysis (24 long-term studies) with no-till <i>cf</i> conventional till. Generally SOC with NT > CT in upper layers (0-10 cm); SOC with NT < CT in layers >15 cm	dns	Angers and Eriksen-Hamel 2008
USA	(-) lower layers			
USA	(+)/(=)	Conventional till <i>cf</i> no-till on sites >12 years. Higher SOC under no-till 0 to 20 cm, no difference to 100 cm	100	Syswerda <i>et al.</i> 2011
USA	(+)	No-till <i>cf</i> with 5 tillage systems over 20 years. SOC in NT greater in 0 to 60 cm, no difference below 60 cm	150	Varvel and Wilhelm 2011
Fertilisation: crop and/or residue				
USA	(+) (=)	Corn rotations with varying N rates. Increased SOC in 0 to 7.6 cm; no difference over depth to 30.5 cm	30.5	Liebig <i>et al.</i> 2002
China	(+)	SOC assessed under different fertiliser regimes. Increase in SOC for NPK ~2 times <i>cf</i> with N alone	dns	Tian <i>et al.</i> 2015
China	(=)	Long-term fertilisation effects (23 years) on SOC. No difference between balanced inorganic fertilisers (NPK) and unfertilised control	100	Song <i>et al.</i> 2015
Australia	(+)	SOC increased by 5.5 t/ha over 5yr when supplementary nutrients were added to stubble prior to incorporation, SOC decreased by 3.2 t/ha with no nutrients added	160	Kirkby <i>et al.</i> 2016
India	(+)	After 9 years under five fertiliser treatments (N, NPK, FYM, FYM+N, FYM+NPK) SOC stocks increased by 2.6, 5.7, 4.1, 6.9 and 9.8 Mg/ha respectively <i>cf</i> unfertilised control	45	Bhattacharyya <i>et al.</i> 2009
USA	(+)	Wheat straw-C conversion to SOC averaged 32% when supplementary N was added to the straw retained in the field but only 14% when no supplementary N was added	10	Jacinto <i>et al.</i> 2002

and form of nutrients applied to stubble and interaction with tillage practice (*e.g.* time of cultivation, tillage system, use of liquid nutrients applied directly to stubble) is needed.

Based on our own experience it is evident that greater opportunity exists with balanced nutrient inputs (N, P, K, S) with high stubble loads (~10 Mg/ha) and in soils with initially low SOC levels (<2%) and high clay content. Moreover, high humification efficiencies appear to require thorough mixing of substrates with soil (be it stubble, manures or other organic amendments) with adequate moisture and temperature to ensure effective microbial processing in order to maximise the contribution to stabilised SOM. On the contrary, surface-retained stubble systems characteristically have slower rates of decomposition that are often constrained by nutrient stratification and sub-optimal conditions for microbial function (Kirkegaard *et al.* 2014). This is consistent with higher predominance of POM in surface soil and a lesser accumulation of stabilised SOM. As previously discussed, POM does not necessarily lead to long term changes in soil physicochemical properties or other benefits associated with SOM sequestration, as the POM is relatively unstable and is more readily lost from the soil (Wander and Bidart 2000, Baker *et al.* 2007).

Practical implications for C sequestration in farming systems

The adoption of any practice to facilitate C sequestration in cropping soils needs to be evaluated against a wide range of economic, environmental and practical criteria. Most important is that any rationale to ‘build’ soil SOC must be considered against other factors that drive the farm enterprise and thus needs to be effectively integrated within the ‘whole of farm’ system. In addition, the ‘opportunity cost’ of better utilising stubble to build SOM must be evaluated against other ecosystem services that surface-retained residues currently provide; for example, as ground cover for erosion control, water retention, weed suppression and low quality animal feeds (see Chapter 2).

Recent economic analysis of cereal crop systems in Western Australia, on sandy soils in rainfall and N limited environments, suggests a value of ~AU\$8 Mg C/ha/year, with the benefit being derived predominantly (75%) from the sequestration value, as compared with 20% and 5%, respectively, for N replacement and productivity improvement (Petersen and Hoyle 2016). Even with extrapolation of this over multiple years, this benefit is somewhat modest relative to the cost of generating additional stored soil C. For instance, the inorganic nutrient requirement to generate SOM from C-rich wheat stubble based on stoichiometric composition has been reported as 73, 17 and 11 kg/ha of N, P and S, respectively (Richardson *et al.* 2014), per tonne of soil C (*i.e.* typical difference in units of nutrient per 1000 units of C for stubble compared with SOM). This represents a significant and real cost in terms of fertiliser equivalence (*i.e.* ~\$150/ha based on current price) for nutrients that, although not lost from the soil system, would not immediately be available for plant growth as compared with fertiliser strategies that directly target crop growth only.

The longer-term availability of nutrients when ‘stored’ in SOM, and whether or not they provide a more synchronised supply to meet plant demands throughout the crop cycle (*i.e.* through more sustained rates of mineralisation as compared with a pulse of nutrient supply that is a common feature in current fertiliser practice) is an important consideration. Likewise, having higher retention of nutrients in crop soils may also increase risks associated with either greater leaching or other potential loss processes such as microbial-driven denitrification (Xia *et al.* 2018). This would in course offset any potential benefits. Nonetheless, it presents a ‘paradigm shift’ in thinking from ‘fertilising the crop’ to ‘fertilising the system’ (Richardson *et al.* 2014) and needs to be considered with regard to longer term trajectories for soil fertility. Indeed consideration of a more systems-based approach with greater emphasis on nutrient management and improved nutrient balance replacement has been proposed as an additional pillar to the basic principles of CA (see Chapter 14) that is currently structured around reduced tillage, permanent soil cover and diverse rotations (Giller *et al.* 2015).

Effective management of crop residues and tillage practice along with diverse rotations, organic amendments and fertiliser inputs remain key levers to manage SOM and its contribution to sustainable production. The objective to increase the sequestration of SOC is likely to require innovations around these practices. For example, strategic tillage (see Chapter 7) is proposed to address some of the

emerging issues in NT systems including stratification of SOM and inorganic nutrients, herbicide resistant weeds and soil compaction, and may thus have an important role also in facilitating SOM dynamics and opportunities to sequester C in soils. This is particularly relevant to the management of deep soil C that has been shown to be a major contributor to whole soil C stocks (Rumpel and Köger-Knabner 2011), yet relative to surface soils, has received less attention especially in its role in contributing to stabilised SOM.

Further consideration of the long-term implications of ‘not restoring’ SOM also needs to be assessed from a range of perspectives including environmental, societal and economic. Key questions that remain to be addressed include:

- whether current levels of SOM or rates of depletion in crop-based systems are sustainable and what are the consequences if further depletion were to occur;
- whether it is practical or economically feasible (or even desirable) to return SOM to levels that existed in soil pre-agriculture, given that land-use change will inevitably have some impact on soils and ecosystem function; and, from that,
- what is the optimal level of SOM in agricultural soils for provision of benefits from SOM and long-term sustainability. Associated with this is understanding of SOM levels, where soils become ‘dysfunctional’ in terms of ecosystem services provided by SOM. These will depend on a range of geo-climatic factors and the production system being considered.

Lastly, the desire or need to increase C in agricultural soils through better utilisation of C-rich residues as a means to address climate change is an issue that lies beyond the responsibility of growers alone and requires commitment to act from wider society. Willingness to act may thus inevitably require implementation of policy directed at mitigation incentives, payment schemes or participation through industry-led C-trading programs.

References

- Amudson R, Biadeau L (2018) Soil carbon sequestration is an elusive climate mitigation tool. *Proceedings National Academy Sciences* **11**, 11652-11656
- Aguilera E, Lassaletta L, Gattingerd A, Gimeno BS (2013) Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. *Agriculture, Ecosystems & Environment* **168**, 25-36
- Alcantara V, Don A, Well R, Nieder R (2016) Deep ploughing increases agricultural soil organic matter stocks. *Global Change Biology* **22**, 2939-2956
- Angers DA, Eriksen-Hamel NS (2008) Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. *Science Society of America Journal* **72**, 1370-1374
- Angus JF, Grace PR (2017) Nitrogen balance in Australia and N-use efficiency on Australian farms. *Soil Research* **55**, 435-450
- Badgery WB, Simmons AT, Murphy BW *et al.* (2014) The influence of land use and management on soil carbon levels for crop-pasture systems in central New South Wales, Australia *Agriculture, Ecosystems & Environment* **196**, 147-157
- Baker JM, Ochsner TE, Ventra RT, Griffis TJ (2007) Tillage and soil carbon sequestration – what do we really know? *Agriculture, Ecosystems and Environment* **118**, 1-5
- Baldock JA, Hawke B, Sanderman J, Macdonald LM (2013) Predicting contents of carbon and its component fractions in Australian soils from diffuse reflectance mid-infrared spectra. *Soil Research* **51**, 577-595
- Bhattacharyya R, Prakash V, Kundu S *et al.* (2009) Effect of fertilisation on carbon sequestration in soybean-wheat rotation under two contrasting soils and management practices in the Indian Himalayas. *Australian Journal of Soil Research* **47**, 592-601
- Börjesson G, Bolinder MA, Kirchmann H, Katterer T (2018) Organic carbon stocks in topsoil and subsoil in long-term ley and cereal monoculture rotations *Biology and Fertility of Soil* **54**, 549-558
- Buyanovsky GA, Wagner GH (1998) Carbon cycling in cultivated land and its global significance. *Global Change Biology* **4**, 131-141
- Chan K, McCoy D (2010) Soil carbon storage potential under perennial pastures in the mid-north coast of New South Wales, Australia. *Tropical Grasslands* **44**, 184-191
- Chan KY, Conyers MK, Li GD *et al.* (2011) Soil carbon dynamics under different cropping and pasture management in temperate Australia: Results of three long-term experiments. *Soil Research* **49**, 320-328

- Chatterjee A (2018) On-farm comparisons of soil organic carbon under no-tillage and chisel-plow systems. *Soil and Plant Science* **68**, 471-476
- Chen R, Senbayram M, Blagodatsky S *et al.* (2014) Soil C and N availability determine the priming effect: microbial N mining and stoichiometric decomposition theories. *Global Change Biology* **20**, 2356-2367
- Chevallier T, Voltz M, Blanchart E *et al.* (2000) Spatial and temporal changes of soil C after establishment of a pasture on a long-term cultivated vertisol. *Geoderma* **94**, 43-58
- Christensen BT, Rasmussen J, Eriksen J, Hansen EM (2009) Soil carbon storage and yields of spring barley following grass leys of different age. *European Journal of Agronomy* **31**, 29-35
- Clement CR, Williams TE (1964) Leys and soil organic matter. I. Accumulation of organic carbon under different leys. *Journal of Agricultural Science* **63**, 377-383
- Cleveland CC, Liptzin D (2007) C:N:P stoichiometry in soil: is there a “Redfield ratio” for the microbial biomass? *Biogeochemistry* **85**, 235-252
- Conant RT, Cerri CEP, Osborne BB, Paustian K (2017) Grassland management impacts on soil carbon stocks: a new synthesis. *Ecological Applications* **27**, 662-668
- Conyers M, Liu DL, Kirkegaard J *et al.* (2015) A review of organic carbon accumulation in soils within the agricultural context of southern New South Wales, Australia. *Field Crops Research* **184**, 177-182
- Coonan EC, Richardson AE, Kirkby CA *et al.* (2019) Soil carbon sequestration to depth in response to long-term phosphorus fertilization of grazed pasture *Geoderma* **338**, 226-235
- Cornish PS, Pratley JE (Eds.) (1987) “Tillage: New Directions in Australian Agriculture”. (Inkata Press:Melbourne)
- Dalal R, Strong W, Weston E *et al.* (1995) Sustaining productivity of a Vertisol at Warra, Queensland, with fertilizers, no-tillage, or legumes. 1. Organic matter status. *Australian Journal of Experimental Agriculture* **35**, 903-913
- Dijkstra P, Ishizu A, Doucet R *et al.* (2006) ¹³C and ¹⁵N natural abundance of the soil microbial biomass. *Soil Biology & Biochemistry* **38**, 3257-3266
- Don A, Schumacher J, Freibauer A (2011) Impact of tropical land-use change on soil organic carbon stocks; a meta-analysis. *Global Change Biology* **17**, 1658-1670
- Drinkwater LE, Wagoner P, Sarrantonio M (1998) Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* **396**, 262-265
- Du Z, Angers DA, Ren T *et al.* (2017) The effect of no-till on organic C storage in Chinese soils should not be overemphasized: A meta-analysis. *Agriculture, Ecosystems & Environment* **236**, 1-11
- Eldor P (2016) The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biology & Biochemistry* **98**, 109-126
- Engelking B, Flessa H, Joergensen RG (2008) Formation and use of microbial residues after adding sugarcane sucrose to a heated soil devoid of soil organic matter. *Soil Biology & Biochemistry* **40**, 97-105
- Fontaine S, Bardoux G, Abbadie L, Mariotti A (2004) Carbon input to soil may decrease soil carbon content *Ecology Letters* **7**, 314-320
- Giller KE, Andersson J, Corbeels M *et al.* (2015) Beyond conservation agriculture. *Frontiers in Plant Science* **6**, 870
- Gibson TS, Chan KY, Sharma G, Shearman R (2002) Soil carbon sequestration utilising recycled organics. A review of the scientific literature. *The Organic Waste Recycling Unit, NSW Agriculture*, 95 pp
- Glaser B, Turrión Ma-B, Alef K (2004) Amino sugars and muramic acid – biomarkers for soil microbial community structure analysis. *Soil Biology & Biochemistry* **36**, 399-407
- Grandy S, Robertson G (2006) Aggregation and organic matter protection following tillage of a previously uncultivated soil. *Soil Science Society of America Journal* **70**, 1398-1406
- Guo L, Gifford R (2002) Soil carbon stocks and land use change: a meta-analysis. *Global Change Biology* **8**, 345-360
- Gupta VVSR, Germida JJ (2015) Soil aggregation: Influence on microbial biomass and implications for biological processes. *Soil Biology & Biochemistry* **80**, A3-A9
- Guzman JG, Al-Kaisi MM (2014) Residue removal and management practices effects on soil environment and carbon budget. *Soil Science Society of America Journal* **78**, 609-623
- Hagerty SB, Van Groenigen KJ, Allison SD *et al.* (2014) Accelerated microbial turnover but constant growth efficiency with warming in soil. *Nature Climate Change* **4**, 903-906
- Haynes RJ, Williams PH (1992) Accumulation of soil organic matter and the forms, mineralization potential and plant-availability of accumulated organic sulphur: Effects of pasture improvement and intensive cultivation. *Soil Biology & Biochemistry* **24**, 209-217
- Haynes RJ (2005) Labile organic matter fractions as central components of the quality of agricultural soils: an overview. *Advances in Agronomy* **85**, 221-268

- Heenan DP, McGhie WJ, Thompson F, Chan KY (1996) Decline in soil organic carbon and total nitrogen in relation to tillage, stubble management and rotation. *Australian Journal of Experimental Agriculture* **35**, 877-884
- Helgason BL, Gregorich EG, Janzen HH *et al.* (2014) Long-term microbial retention of residue C is site-specific and depends on residue placement *Soil Biology & Biochemistry* **68**, 231-240
- Helyar KR, Cullis BR, Furniss K *et al.* (1997) Changes in the acidity and fertility of a red earth soil under wheat-annual pasture rotations. *Australian Journal of Agricultural Research* **48**, 561-586
- Hiel M, Barbieux S, Pierreux J *et al.* (2018) Impact of crop residue management on crop production and soil chemistry after seven years of crop rotation in temperate climate, loamy soils. *Peer J* **6**, e4836
- Hoyle FC, Baldock JA, Murphy DV (2011) Soil organic carbon – role in rainfed farming systems with particular reference to Australian conditions. In (Eds. P Tow, I Cooper, I Partridge) “Rainfed Farming Systems” pp 339-361 (Springer International)
- Jacinthe PA, Lal R, Kimble JM (2002) Effects of wheat residue fertilization on accumulation and biochemical attributes of organic carbon in a Central Ohio Luvisol. *Soil Science* **167**, 750-758
- Janzen HH, Campbell CA, Brandt SA *et al.* (1992) Light-fraction organic matter in soils from long-term crop rotations. *Soil Science Society of America Journal* **56**, 1799-1806
- Jastrow J, Amonette J, Bailey V (2007) Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration. *Climatic Change* **80**, 5-23
- Johnston AE, McEwen J, Lane PW *et al.* (1994) Effect of one to 6 year-old ryegrass clover leys on soil nitrogen and on the subsequent yields and fertilizer nitrogen requirements of the arable sequence winter-wheat, potatoes, winter-wheat, winter beans grown on a sandy loam soil. *Journal of Agricultural Science* **122**, 73-89
- Kirkby CA, Richardson AE, Wade LJ *et al.* (2014) Nutrient availability limits carbon sequestration in arable soils. *Soil Biology & Biochemistry* **68**, 402-409
- Kirkby CA, Kirkegaard JA, Richardson AE *et al.* (2011) Stable soil organic matter: a comparison of C:N:P:S ratios in Australian and other world soils. *Geoderma* **163**, 197-208
- Kirkby CA, Richardson AE, Wade LJ *et al.* (2016) Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. *PLoS ONE* **11**, e0153698
- Kirkby CA, Richardson AE, Wade LJ *et al.* (2013) Carbon-nutrient stoichiometry to increase soil carbon sequestration. *Soil Biology and Biochemistry* **60**, 77-86
- Kirkegaard JA, Conyers MK, Hunt JR *et al.* (2014) Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems & Environment* **187**, 133-145
- Kuzyakov Y (2010) Priming effects: Interactions between living and dead organic matter. *Soil Biology & Biochemistry* **42**, 1363-1371
- Lal R (1997) Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO₂-enrichment. *Soil and Tillage Research* **43**, 81-107
- Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* **304**, 1623-1627
- Lal R (2007) Carbon management in agricultural soils. *Mitigation and Adaptation Strategies for Global Change* **12**, 303-322
- Lehmann J, Kleber M (2015) The contentious nature of soil organic matter. *Nature* **528**, 60-68
- Lehtinen T, Schlatter N, Baumgarten A *et al.* (2014) Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils. *Soil Use and Management* **30**, 524-538
- Liebig M A, Varvel GE, Doran JW, Wienhold BJ (2002) Crop sequence and nitrogen fertilization effects on soil properties in the western corn-belt. *Soil Science Society of America Journal* **66**, 596-601
- Luo ZK, Wang EL, Sun OJ (2010). Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: a review and synthesis. *Geoderma* **155**, 211-223
- Ma T, Zhu S, Wang Z *et al.* (2018) Divergent accumulation of microbial necromass and plant lignin components in grassland soils. *Nature Communications* **9**, 3480
- Magid J, Kjærgaard C (2001) Recovering decomposing plant residues from the particulate soil organic matter fraction: size versus density separation. *Biology and Fertility of Soils* **33**, 252-257
- Maia SMF, Ogle SM, Cerri CEP, Cerri CC (2009) Effect of grassland management on soil carbon sequestration in Rondônia and Mato Grosso states, Brazil. *Geoderma* **149**, 84-91
- Meurer KHE, Haddaway NR, Bolinder MA, Kätterer, T (2018) Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil: A systematic review using an ESM approach. *Earth Sciences Review* **177**, 613-622
- Miltner A, Bombach P, Schmidt-Brücken B, Kästner M (2012) SOM genesis: microbial biomass as a significant source. *Biogeochemistry* **111**, 41-55

- Moran KK, Six J, Horwath WR, van Kessel (2005) Role of mineral-nitrogen in residue decomposition and stable soil organic matter formation. *Soil Science Society of America Journal* **69**, 1730-1736
- Müller-Stover D, Hauggaard-Nielsen H, Eriksen J *et al.* (2012) Microbial biomass, microbial diversity, soil carbon storage, and stability after incubation of soil from grass-clover pastures of different age. *Biology and fertility of soils* **48**, 371-383
- Murphy BW (2015) Impact of soil organic matter on soil properties—a review with emphasis on Australian soils. *Soil Research* **53**, 605-635
- Orgill SE, Condon JR, Conyers MK *et al.* (2014) Sensitivity of soil carbon to management and environmental factors within Australian perennial pasture systems. *Geoderma* **214**, 70-79
- Orgill SE, Condon JR, Conyers MK *et al.* (2017a) Parent material and climate affect soil organic carbon fractions under pastures in south-eastern Australia. *Soil Research* **55**, 799-808
- Orgill SE, Condon JR, Kirkby CA *et al.* (2017b) Soil with high organic carbon concentration continues to sequester carbon with increasing carbon inputs. *Geoderma* **285**, 151-163
- Palm C, Blanco-Canqui H, DeClerck F *et al.* (2014) Conservation agriculture and ecosystem services: an overview. *Agriculture Ecosystems and Environment* **187**, 87-105
- Paul BK, Vanlauwe B, Ayuke F *et al.* (2013) Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity. *Agriculture Ecosystems and Environment* **164**, 14-22
- Petersen EH, Hoyle FC (2016) Estimating the economic value of soil organic carbon for grains cropping systems in Western Australia. *Soil Research* **54**, 383-396
- Poeplau C, Don A (2013) Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. *Geoderma* **192**, 189-201
- Poeplau C, Don A (2015a) Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems and Environment* **200**, 33-41
- Poeplau C, Kätterer T, Bolinder MA *et al.* (2015b) Low stabilization of aboveground crop residue carbon in sandy soils of Swedish long-term experiments. *Geoderma* **237**, 246-255
- Poeplau C, Reiter L, Berti A, Kätterer T (2017) Qualitative and quantitative response of soil organic C to 40 years of crop residue incorporation under contrasting N fertilisation regimes. *Soil Research* **55**, 1-9
- Poulton P, Johnston J, Macdonald A *et al.* (2018) Major limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology* **24**, 2563-2584
- Powlson DS, Glendining MJ, Coleman K, Whitmore AP (2011) Implications for soil properties of removing cereal straw: results from long-term studies. *Agronomy Journal* **103**, 279-287
- Powlson DS, Stirling CM, Jat ML *et al.* (2014) Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* **4**, 678-683
- Rabbi SMF, Tighe M, Delgado-Baquerizo M *et al.* (2015) Climate and soil properties limit the positive effects of land use reversion on carbon storage in Eastern Australia. *Scientific Reports* **5**, 17866
- Richardson AE, Kirkby, CA, Banerjee, S, Kirkegaard, JA (2014) The inorganic nutrient cost of building soil carbon. *Carbon Management* **5**, 265-268
- Robertson F, Crawford D, Partington D *et al.* (2016) Soil organic carbon in cropping and pasture systems of Victoria, Australia. *Soil Research* **54**, 64-77
- Rumpel C, Köger-Knabner I (2011) Deep soil organic matter – a key but poorly understood component of terrestrial C cycle. *Plant and Soil* **338**, 143-158
- Sanderman J, Farquharson R, Baldock J (2010) Soil carbon sequestration potential: a review for Australian agriculture. CSIRO, Adelaide, Australia. 81 pp
- Sanderman J, Hengl T, Fiske GJ (2017) Soil carbon debt of 12,000 years of human land use. *Proceedings National Academy Sciences* **114**, 9575-9580
- Schmidt MWI, Torn MS, Abiven S *et al.* (2011) Persistence of soil organic matter as an ecosystem property. *Nature* **478**, 49-56
- Schwenke GD, McLeod MK, Murphy SR *et al.* (2013) The potential for sown tropical perennial grass pastures to improve soil organic carbon in the North-West Slopes and Plains of New South Wales. *Soil Research* **51**, 726-737
- Searle S, Bitnere K (2017) Review of the impact of crop residue management on soil organic carbon in Europe. International Council on Clean Transportation, Working Paper 2017-15
- Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research* **79**, 7-31
- Six J, Frey S, Thiet R, Batten K (2006) Bacterial and fungal contributions to carbon sequestration in agroecosystems. *Soil Science Society of America Journal* **70**, 555-569

- Song ZW, Zhu P, Gao HJ *et al.* (2015) Effects of long-term fertilization on soil organic carbon content and aggregate composition under continuous maize cropping in Northeast China. *Journal of Agricultural Science* **153**, 236-244
- Stockmann U, Adams MA, Crawford JW *et al.* (2013) The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment* **164**, 80-99
- Strahm BD, Harrison RB, Terry TA *et al.* (2009) Changes in dissolved organic matter with depth suggest the potential for postharvest organic matter retention to increase subsurface soil carbon pools. *Forest Ecology and Management* **258**, 2347-2352
- Syswerda SP, Corbin AT, Mokma DL *et al.* (2011) Agricultural Management and Soil Carbon Storage in Surface vs. Deep Layers. *Soil Science Society of America Journal* **75**, 92-101
- Tarré R, Macedo R, Cantarutti RB *et al.* (2001) The effect of the presence of a forage legume on nitrogen and carbon levels in soils under *Brachiaria* pastures in the Atlantic forest region of the south of Bahia, Brazil. *Plant Soil* **234**, 15-26
- Tian K, Zhao Y, Xu X *et al.* (2015) Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: A meta-analysis. *Agriculture Ecosystems & Environment* **204**, 40-50
- Tipping E, Somerville CJ, Luster J (2016) The C:N:P:S stoichiometry of soil organic matter. *Biogeochemistry* **130**, 117-131
- van Groenigen KJ, Six J, Hungate BA *et al.* (2006) Element interactions limit soil carbon storage. *Proceedings National Academy Sciences* **103**, 6571-6574
- van Rees H, Jackman A, Beveridge M, Baldock J (2017) Can soil organic matter be increased in a continuous cropping system in the low to high rainfall zone? *Southern Farming Systems Trial Results* 134-137
- van Wesemael B, Paustian K, Meersmans J *et al.* (2010) Agricultural management explains historic changes in regional soil carbon stocks. *Proceedings National Academy Sciences USA* **107**, 14926-14930
- Varvel GE, Wilhelm WW (2011) No-tillage increases soil profile carbon and nitrogen under long-term rain-fed cropping systems. *Soil and Tillage Research* **114**, 28-36
- von Lützow, M, Kögel-Knabner I, Ekschmitt K *et al.* (2006) Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions: a review. *European Journal of Soil Science* **57**, 426-445
- Wander MM, Bidart MG (2000) Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. *Biology and Fertility of Soils* **32**, 360-367
- Xia L, Lam SK, Wolf B *et al.* (2018) Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. *Global Change Biology* **24**, 5919-5932
- Young RR, Wilson B, Harden S, Bernardi A (2009) Accumulation of soil carbon under zero tillage cropping and perennial vegetation on the Liverpool Plains, eastern Australia. *Australian Journal of Soil Research* **47**, 273-285

Chapter 17

Breeding Evolution for Conservation Agriculture

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Introduction

It is now over 30 years since Peter Cornish first published his considered thoughts on delivering improved crop and pasture varietal performance for changing farming systems, including then new conservation agriculture (CA) regimes (Cornish 1987). Since this time breeding programs have changed markedly to accommodate the many genetic, phenotypic and statistical tools that enable increased rates of genetic gain and/or reduced cost in varietal development. Most crop and pasture breeding programs have since become privatised, increasing competition to facilitate the uptake and efficient use of new technologies. Returns to breeding companies are captured through seed sales and for some crops through End Point Royalties (EPR) where a levy is returned on seed or hay delivered for sale. Breeding has become less of an ‘art’ and more of a science with an explosion in genome-based understanding and how genes and their expression can be exploited to deliver improvements in selection. Notwithstanding, elements of traditional breeding have been maintained owing to the need for breeders to understand better and exploit those traits contributing to improved disease resistance, quality and adaptation in their gene pools.

The adoption of CA was targeted to improve the environmental and economic sustainability of farming systems. Farming systems evolved as factors limiting performance and profitability became better understood; in particular, how increased water productivity could be achieved by changing sowing date, improved crop sequences and addressing increases in on-farm input costs. The breeding evolution was globally-led and independent of the evolution in farming systems. Yet while genetic gain in wheat prior to 1987 was stable at 0.6% per year (Fischer *et al.* 2014), it has remained so since, even with the improved understanding of the genome and factors affecting adaptation with CA.

The opportunities to improve water use efficiency in rain-fed systems have been highlighted previously (*e.g.* Kirkegaard and Hunt 2010, Flohr *et al.* 2018, see also Chapter 13). Yet the literature does not acknowledge a strong capacity for exploiting genotype \times management interaction in elite breeding lines (*e.g.* Cooper *et al.* 2001) presumably because the breeders’ gene pools are genetically narrow or environmental factors such as rainfall, temperature and soil type dominate genotype ranking in multi-environment studies. That aside, CA-adapted germplasm has been identified when genotype \times tillage studies are broadened to include very diverse overseas germplasm (Trethowan *et al.* 2012). Further, assessment of mapping populations has identified genomic regions with potential to improve adaptation with CA (Trethowan *et al.* 2012).

This chapter focuses on breeding activities targeting genetic improvement in high yield systems and does not address low-input or organic agriculture (see Wolfe *et al.* 2008). We report on recent advances in breeding and on future opportunities to incorporate new genetics to improve performance in CA systems. We also report on how a physiological framework has allowed for an improved understanding of factors limiting the performance of crops, especially wheat under CA, and the targeting of novel genes not present in commercial breeding programs. Finally, we discuss how better understanding of the genetic architecture of key traits has permitted more rapid breeding and delivery of germplasm to commercial breeding programs. Our focus here is on wheat, as it is the dominant crop in rain-fed farming systems in Australia and receives the most breeding investment. However, the principles are also applicable to other major crops.

The evolution in breeding methods

The breeding of crops can be summarised as a continuum of activities commencing with parent identification and crossing, population development and early-generation screening, and extensive testing in multi-environment trials culminating in cultivar release (Robertson *et al.* 2015). The significant effort in managing this complex and integrated series of processes reflects many years of sustained effort and both considerable financial cost and risk to the breeder. The skill of the breeder commences and is limited by the identification of the optimal parents and their crossing as these set the population mean and genetic variance from which genetic gain will be subsequently made. The breeder must then identify and target which tools to employ, and when, to reduce the time and cost between cross and release, and increase the likelihood of delivering a highly competitive variety into the marketplace. Many of the tools developed for improved breeding over the past 30 years are discussed briefly.

Biotechnology

Perhaps the greatest evolutionary change in breeding over the past 30 years has been in the capacity to move beyond selection of a phenotype to selecting directly for a targeted gene. Advances in biotechnology have provided plant breeders with the opportunity to increase the rate of genetic gain when breeding new varieties. Molecular markers have been the main biotechnological tool used in this respect and, through their application, increased understanding of the genetics underlying both simple and complex traits has been attained. The usefulness of molecular markers arises from the ability to detect DNA sequence variation between individuals and through the association of this genotypic variation with phenotypic variation (Langridge *et al.* 2001).

Numerous types of molecular markers have been developed over the past 30 years, including:

- random amplified polymorphic DNAs (RAPDs);
- restriction fragment length polymorphism (RFLP);
- amplified fragment length polymorphisms (AFLPs);
- simple sequence repeats (SSRs, commonly referred to as microsatellites); and
- single nucleotide polymorphisms (SNPs).

In recent years SNPs have become the dominant molecular marker platform, due to their abundance within genomes and the availability of low cost, high-throughput systems for their detection. The most beneficial application for markers in breeding is to select for desirable alleles of a phenotype of interest, in a process termed marker-assisted selection (MAS). In plant breeding, MAS has been used to increase the efficiency of back-crossing, combine (pyramid) genes for traits of interest, and reduce linkage drag (Collard *et al.* 2005, Francia *et al.* 2005). The advantages of MAS, when compared with traditional phenotypic selection, are greatest for traits that show low heritability, are difficult to phenotype, or are not expressed in single plants (Dreisigacker *et al.* 2016). In these instances, increases in genetic gain in breeding programs is achieved by increased selection accuracy and reduced generation time.

MAS had been touted as having the potential to revolutionise plant breeding and lead to the occurrence of another ‘Green Revolution’ (Naylor and Manning 2005). Presently however, MAS is routinely used in plant breeding programs only for selecting alleles with large effects on traits with simple inheritance, such as flowering time, height, and qualitative disease resistance (Zou *et al.* 2017). While these activities provide evidence of the value of MAS, many traits of agricultural importance (such as yield, quality, abiotic stress tolerance, and resistance to certain diseases) are under polygenic control, and successful application of MAS for such polygenic traits is highly desirable. Indeed, Mohler and Singrun (2005) suggest that the incorporation of loci that contribute to variation in quantitative traits (quantitative trait loci, QTL) into breeding programs is the principal task of MAS. MAS for QTL can theoretically be achieved simply by selecting for the presence of specific marker alleles that are tightly linked to, or flank, favourable QTL alleles. However, despite an explosion of reports on the identification of molecular markers linked to QTL for many traits, MAS for quantitative traits is mostly unsuccessful (Bernardo 2008).

Francia *et al.* (2005) have described several reasons why MAS for QTL tracking can fail. These include:

- uncertainty of the QTL position;
- deficiencies in QTL analysis leading to under-estimation or over-estimation of the number and magnitude of effects of QTL;
- an inability to detect a QTL-marker association in divergent backgrounds;
- the possibility of losing target QTL due to recombination between marker and QTL;
- difficulty in evaluating epistatic effects; and
- difficulty in evaluating QTL \times environment interactions.

Marker-assisted recurrent selection (MARS) is extension of MAS for genetically complex, polygenic traits. MARS uses recurrent selection to accumulate multiple markers through selection, crossing and reselection within the same cross before incorporating new alleles in crossing with other parents (Bernardo 2008). It has proven to be an effective low-cost breeding system targeting genetically-complex traits in some crops (*e.g.* improving maize under drought, Bankole *et al.* 2017).

Genomic selection (GS) was devised to overcome the restriction of tracking only a limited set of markers linked to QTL with large effects on traits of interest. By using all molecular markers to predict the performance of an individual, GS seeks to capture the additive genetic effects of all QTL affecting the trait of interest (Meuwissen *et al.* 2001). The implementation of GS requires a training population that has been phenotyped in the target population of environments and densely genotyped (Voss-Fels *et al.* 2019). The genotypic and phenotypic information from the training population is then used to develop models that predict the genetic value of unobserved individuals using their genotypic data alone. The GS models allow plant breeders to select individuals with the highest genomic estimated breeding values (GEBVs) for further evaluation, and to design crossing strategies to accelerate the rates of genetic gain for traits of interest. Simulation and empirical studies have shown that GS outperforms traditional MAS, leading to accelerated genetic gain both by improving selection accuracy and by shortening breeding cycles (Heffner *et al.* 2010, Arruda *et al.* 2015).

Genomics

Genomics linked to improved field and controlled environment phenotyping has been useful in identifying genes associated with improved performance. Transcriptomics enables high-throughput investigation of changes in mRNA expression levels while proteomic and metabolomic profiling has enabled investigation of the effects of post-transcriptional and post-translational gene regulation. Genetic engineering permits the identification and transfer of foreign DNA to a new recipient genome. Resulting ‘Genetically Modified Organisms’ (aka GMOs) provide novel genetic diversity not present within the broader crop gene pool and include varietal resistance to glyphosate herbicide. Genome editing relies on targeting of specific nucleotides monitored and selected following mutagenesis. The generation of mutants is rapid and relatively inexpensive although less precise than for genetic engineering. However, unlike GM, Australian government approval is not required if the DNA-cutting proteins allow the host cell to repair the break naturally and do not use a template containing genetic material to direct the repair process.

Quality phenotyping

Accurate prediction for complex traits is dependent upon high-quality phenotypic data. Emerging reports are supporting additional gains in prediction accuracy for complex traits such as yield, when GS is combined with high-throughput phenotyping (HTPP). Technologies such as LiDAR, thermal imaging, and spectral reflectance are being deployed using manned and un-manned vehicles, generating a wealth of field phenotypic data that was not previously available to breeders (Deery *et al.* 2016, Jimenez-Berni *et al.* 2018, Rodrigues *et al.* 2018). Although several studies have demonstrated that prediction accuracy for grain yield improves when secondary traits captured by HTPP (*e.g.* canopy temperature and normalised difference vegetative index [NDVI]) are used for GS model training (Rutkoski *et al.* 2016, Crain *et al.* 2018), incorporation of HTPP in GS approaches is still in its infancy, requiring further research.

‘Managed Environment Facilities’ (MEFs) have been constructed across Australia to provide a set of nationally coordinated research sites where traits and other pre-breeding outputs can be assessed side-by-side and under the same controlled, managed conditions (Rebetzke *et al.* 2013). Such facilities provide the understanding from which a clear value proposition can be delivered for new traits, methods or technologies relevant to breeding. While originally developed for assessment of putative drought tolerance traits, the careful control within the MEFs can be readily extended to include other constraints (*e.g.* subsoil and nutrient limitations) and capacity to assess different farming systems toward better understanding of genotype \times management interaction (*e.g.* time of sowing).

Considered here as a component of phenotyping, the Australian National Variety Trialling (NVT) program is globally unique in the distribution and testing of advanced commercial breeding lines independent of the breeding companies themselves. The program is funded and coordinated through grower levies by the Grains Research Development Corporation, and aims to provide growers and agronomists with grain yield, quality and agronomic information to aid in the selection of varieties for on-farm use.

Statistical methodology

The large datasets encompassing genetic, pedigree, phenotypic and environmental information are becoming fully integrated as ‘big data’ available for genetic and environmental prediction of breeding line performance. Statistical modelling has moved from least squares based analyses to likelihood based modelling permitting delivery of unbiased estimates of genotype prediction where data are incomplete. Complementing the statistical analysis of data has been an evolution in crop modelling relevant to uptake for use in commercial plant breeding. Improved models have provided understanding of the potential for different traits to contribute to improved adaptation, and trait value toward a value proposition important in prioritising breeding objectives (Robertson *et al.* 2015). The greatest value in crop modelling for breeders has most likely been through the interpretation of large genotype \times environment interaction in breeders’ own and national variety trials. From those trials sampled environments are characterised and the performance of genotypes interpreted relative to performance of known genotypes for an historic set of environments (Chenu *et al.* 2011). The environmental characterisation has largely been defined around timing and amount of soil water but could be extended to other factors including soil constraints and non-optimal temperature regimes (*e.g.* frost and heat, Watson *et al.* 2017).

Other tools

A range of other technologies have been developed to reduce the cost or increase the confidence in commercial breeding. For example, speed-breeding methods aimed at reducing the time from cross to line testing (*e.g.* doubled-haploids and environmental manipulation to hasten the interval between successive generations) and use of off-season nurseries for testing and seed-increase have potential to reduce the time to commercial release of cereal varieties by 3 to 5 years.

An evolution in output trait understanding and delivery

The revolution with CA has relied on the appropriate genetics to complement dramatic changes in the farming system while maintaining the same or improved genetic gains. Coinciding with this revolution has been a gradual change in the climate and its effect on drought and air temperatures to affect productivity (Lobell *et al.* 2015, Hochman *et al.* 2017). The genetic diversity in Australian wheat breeding programs is relatively small following a gradual reduction in genetic variability particularly following the widespread use of CIMMYT germplasm in the 1970s following the Green Revolution (Joukhadar *et al.* 2017).

New genetics and breeding strategies are required to maintain genetic gain given the reduction in effective population size and development of large linkage blocks throughout the genome. Given the emphasis on maintaining high milling quality, disease-resistant gene complexes, targeting new genetics from overseas breeding programs, is key (Joukhadar *et al.* 2017) yet must be relevant to our climate and specifically to our farming systems. One strategy is to source genetics targeting traits aimed at

overcoming current and future agronomic and climate constraints. In some cases the genetics does not reside in Australia and must be sourced elsewhere (*e.g.* increased crop competitiveness for suppressing herbicide-resistant weeds) while in others much of the genetics is already contained in older Australian wheat varieties (*e.g.* awnless wheats for frost risk mitigation and greater coleoptile length for improved establishment).

Table 1. Current and future agronomic challenges confronting growers, and those traits and their capacity for selection and delivery in commercial wheat breeding programs

Breeding target	Trait	Genetic variation?	Genetic complexity	Screening method(s)
Challenges with early growth				
Establishment with deep sowing/stubble retention	Greater coleoptile length	Yes ^B	Complex	Molecular markers/phenotypic screening
Early sowing in warm soils	Greater coleoptile length	Yes ^B	Complex	Molecular markers/phenotypic screening
Dry sowing and false breaks	Reduced seed dormancy	Yes ^B	Unknown	Phenotypic screening
Late-sowing cereals	Rapid early leaf area/biomass	Yes ^B	Complex	Phenotypic screening
Overcoming hard soil constraints	Greater early vigour/thick coleoptile	Yes ^B	Complex	Molecular markers/phenotypic screening
Challenges with reproductive growth				
Optimising flowering date	Development	Yes ^A	Simple	Molecular markers
Frost mitigation	Awnless milling and hay wheats	Yes ^A	Simple	Molecular marker
Challenges with managing stubble				
Reducing stubble loads	Reduced height	Yes ^B	Simple	Molecular markers
Challenges with disease and insect pests				
Stubble-hosted diseases (<i>e.g.</i> yellow leaf spot)	Disease resistance	Yes ^A	Complex	Molecular markers/phenotypic screening
Soil-borne diseases (<i>e.g.</i> crown rot, Rhizoctonia)	Disease resistance	Yes ^A	Complex	Molecular markers/phenotypic screening
Invertebrate pests (<i>e.g.</i> snails, slugs, nematodes)	Pest resistance	For some ^A	Simple/complex	Molecular markers/phenotypic screening
Challenges with weeds				
Herbicide-resistant weeds (<i>e.g.</i> annual ryegrass)	Crop weed competitiveness	Yes ^B	Complex	Phenotypic screening

^A Variation present in commercial breeding programs; ^B Variation not present in breeding programs

The value in using a physiological approach to understanding limits to adaptation with CA was highlighted in Rebetzke *et al.* (2014b). A surprising phenomenon, given the many improvements in the structural and biological properties of soils in CA systems, is the observed reduced early seedling vigour and poor establishment with commercial wheat varieties. Wheat germplasm containing novel high early vigour genes developed leaf area and biomass more rapidly than commercial wheat varieties in hard, undisturbed soils. In modelling the benefits of greater early vigour in wheat, Zhao *et al.* (2019) demonstrated a benefit with greater establishment and seedling vigour throughout the Australian wheat-belt. Table 1 describes those traits aimed at genetically addressing constraints to productivity in Australian cereal-based farming systems. A discussion of some output traits is provided elsewhere (*e.g.* see Chapter 18) while brief descriptions of some selected key traits is provided below.

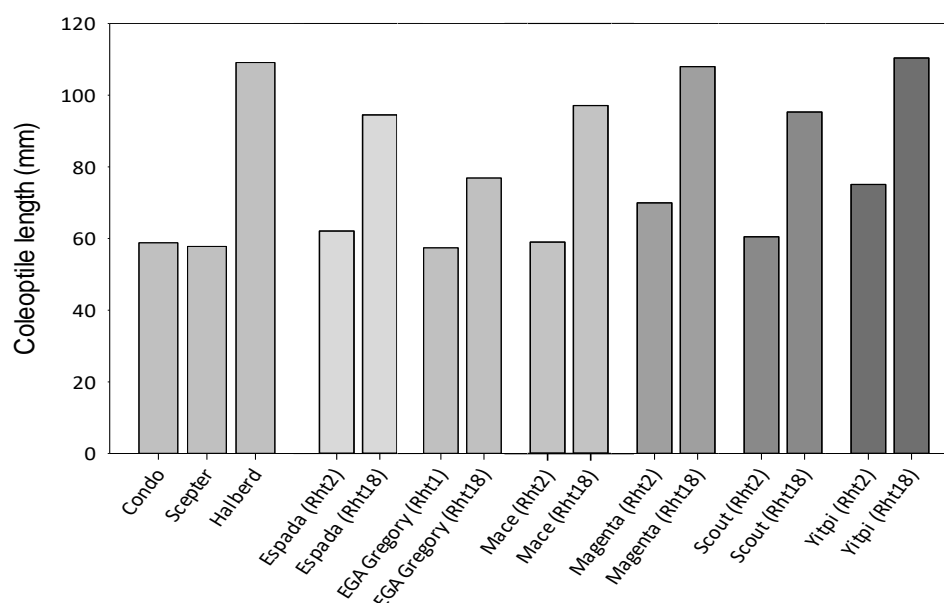


Figure 1. Average coleoptile length for backcross three-derived *Rht2* and *Rht18* dwarf near-isogenic lines in six wheat genetic backgrounds assessed at soil temperatures of 23°C. Semi-dwarf varieties Condo and Scepter, and tall variety Halberd are included for comparison (average LSD for all mean comparisons was 9 mm)

Improving crop establishment

Development of wheat varieties with the capacity to emerge from deep sowing would benefit growers in arid regions (Kirkegaard and Hunt 2010). Often sufficient moisture for germination is available deeper in the soil profile but the shorter coleoptiles of current semi-dwarf wheats prevent successful establishment if sown deep into this moisture (Schillinger *et al.* 1998, Flohr *et al.* 2018). Deeper sowing into stored soil moisture will also allow sowing programs to commence earlier. This will have the impact of increasing yield at both the farm and field scales (see Chapter 18). Deep sowing commonly results in few typically later-emerging seedlings producing small relative growth rates and slower leaf area to reduce seedling biomass (Hadjichristodoulou *et al.* 1977, Rebetzke *et al.* 2007a). In turn, later emerging plants have smaller biomass at anthesis, fewer spikes and lower final biomass and yield (Rebetzke *et al.* 2007a). Other factors contributing to poor establishment include stubble residue on the soil surface (Rebetzke *et al.* 2005, Soane *et al.* 2012), diseases such as crown rot and increasing soil temperatures associated with earlier sowing and/or climate changes. Modern semi-dwarf wheats containing the *Rht1* (syn. *Rht-B1b*) and *Rht2* (syn. *Rht-D1b*) dwarfing genes produce c. 45% shorter coleoptiles at 27 vs 15°C soil temperatures (Rebetzke *et al.* 2016a).

Genetic increases in coleoptile length will improve crop establishment with deep sowing, stubble retention and warmer soil temperatures. Shorter coleoptiles and poor emergence have commonly been associated with presence of the *Rht1* and *Rht2* dwarfing genes (Schillinger *et al.* 1998, Rebetzke *et al.* 2007a, b). Many of the alternative, gibberellin-sensitive dwarfing genes (*e.g.* *Rht4*, 8, 12, 13 and 18) reduce plant height with little or no effect on coleoptile length (Rebetzke *et al.* 2012a) or coleoptile diameter (Rebetzke *et al.* 2004). The increase in coleoptile length in replacing *Rht2* with *Rht18* is shown in Figure 1 where *Rht18* near-isogenic lines (NILs) produced an average 50% longer coleoptile when grown at 23°C soil temperature. The increase in coleoptile length was consistent across six genetic backgrounds with coleoptile length equivalent to that of the long coleoptile tall check variety, Halberd. Three *Rht2* and *Rht18* NIL pairs were separately assessed with deep-sowing at 120 mm at Merredin in 2018.

Figure 2 summarises a 50-90% increase in numbers of emerged seedlings in lines containing the GA-sensitive *Rht18* dwarfing gene. There was no statistical difference in establishment at the shallow (*i.e.* 40 mm) sowing depth (data not shown). Other studies have also demonstrated the potential of the *Rht18* dwarfing gene in the development of semi-dwarf, long coleoptile wheat targeted at sowing depths

exceeding 110 mm (Schillinger *et al.* 1998, Rebetzke *et al.* 2007a) and where stubble loads are high (Rebetzke *et al.* 2005). Together with genomic regions linked to increased coleoptile length (Rebetzke *et al.* 2007b, 2014a), new gibberellin-sensitive dwarfing genes have been delivered in elite genetic backgrounds to Australian wheat breeders for population development.

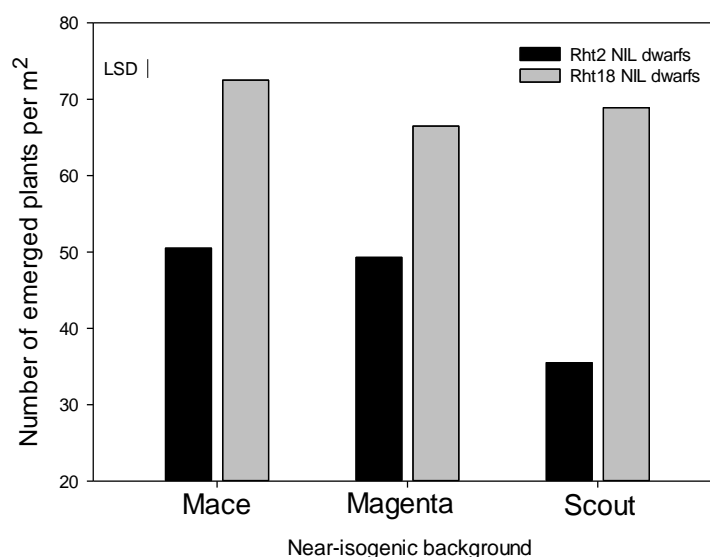


Figure 2. Average numbers of emerged seedlings (per m²) for backcross three-derived *Rht2* and *Rht18* near-isogenic lines in Mace, Magenta and Scout genetic backgrounds when sown at 12 cm sowing depth at Merredin in 2018

Crop weed competitiveness

The uptake of CA systems has prompted greater use of herbicides to place significant pressure on current herbicide modes of action (MOA). In turn, greater reliance on herbicides has increased selection pressure on weeds to evolve widespread herbicide resistance (D’Emden and Llewellyn 2006, Broster *et al.* 2019). In Australia, more than 500 unique cases of herbicide-resistant weeds have been identified showing resistance to 23 of the 26 known MOA (Heap 2019). The ongoing identification of new herbicide resistance emphasises the need to develop and implement alternative, non-herbicide protection strategies. Implementing ‘Integrated Weed Management’ (IWM) tools is a targeted strategy which aims to maintain the longevity of new and existing chemistries (see Chapter 10). Crop competition is one non-herbicide IWM control tool complementing agronomic methods, including changes in sowing density and sowing orientation as competition strategies. There is also evidence that early growth is impeded in no-till systems (Verhulst *et al.* 2011, Rebetzke *et al.* 2014b). Although compensated by more rapid later development, this provides an environment for greater weed growth early in the season. A greater sowing density increases competition by the crop for resources, mirroring the mass-competitor strategy of weeds to the advantage of the crop (Weiner *et al.* 2010). Similarly, optimally orientating the sowing of rows can limit the light available for weeds growing between rows. For example, changing the row orientation to an east-west sowing in wheat and barley in Western Australia decreased weed biomass by 37-51% (Borger *et al.* 2010). A third less-used competition strategy is to modify the crop variety itself to have a competitive advantage. This strategy is easily implemented with other IWM tools and moreover has low cost and low risk, assuming such varieties are commercially available.

Early vigour, defined as more rapid leaf area development through wide leaves and greater biomass at stem elongation, is a common mechanism for plant-to-plant competition in natural plant communities (Aerts 1999). Greater leaf area should shade and thereby suppress the competing weeds early before canopy closure. Wheat varieties with greater early vigour should provide an effective ideotype for crop-competition in managed farming systems as they do in natural plant-plant competition. The challenge globally is that very few competitive crop varieties have been released commercially and very few are wheats with greater early vigour. A reason for the lack of released vigorous competitive varieties might

be the lack of early vigour in wheat germplasm arising from the over reliance of *Rht1* and *Rht2* dwarfing genes following the green revolution (Rebetzke and Richards 1999). To address this, a global survey of over 2000 overseas and Australian wheat genotypes were screened under controlled environment conditions for width of leaves 1 and 2, and early leaf area. The 28 most vigorous genotypes were then selected for intermating in the development of a structured high vigour, recurrent selection population. The resulting 38 F1 progeny were self-pollinated to produce S0 progeny and then 40-50 S0:1 progeny. Seed were sized to a common weight and screened under controlled conditions for leaf 1 and 2 widths. Lines containing the largest mean leaf widths were transplanted and used for subsequent crossing and generation of a new cycle. Several new crosses were performed resulting in 80 new cycle 1 populations. The process was then repeated over multiple cycles (Zhang *et al.* 2015).

Weed competitive genotypes were developed from crosses between vigorous cycle 3 selections and widely adapted Australian cultivars Wyalkatchem and Yitpi (Zerner *et al.* 2016). High vigour-selected lines were assessed for competitiveness under field conditions using cultivated oat, barley, winter ryegrass and/or canola as weed surrogates. In particular, two of the cycle 3-derivatives (W470201 and W640704 – both top-crosses from Australian wheat varieties) stood-out in early leaf area development and biomass while maintaining spring habit and semi-dwarf stature. Both lines suppressed the competitor by up to 97%. Figure 3 shows the difference in suppression of weed-mimic canola between Scout, a commercialised adapted Australian cultivar, and the developed line W470201.

Interestingly, selection for wider leaves one and two has been shown to carry through to enlarged size and area for all leaves. Greater leaf area promotes a denser more shaded canopy that can readily suppress later germinating weeds. Greater early leaf area also reduces soil evaporation and means that a greater proportion of soil water is transpired through plant leaves with a resulting increase in water productivity.

The research and delivery work of developing competitive wheat lines is ongoing with aims to supply growers with another non-herbicide IWM tool for controlling weeds. Current weed-competitive donors include cycle 6 high vigour derivatives with populations derived from modern Australian varieties so as to maintain excellent milling quality and yield. To facilitate rapid delivery to growers, there is strong collaboration with wheat breeders with over 5000 back-cross and top-cross breeding lines now distributed.



Figure 3. Commercial Australian cultivar Scout and developed weed competitive breeding line W470201 sown with (+canola) and without (control) competition from weed-surrogate canola at Condobolin NSW Australia in 2017. Wheat was sown at 160 plants m⁻² in all plots and canola sown at 60 plants/m² in +canola plots. The experiment was designed with three replicated paired plots with the same suppression identified

Soil-borne and leaf diseases

Tillage moves and disturbs the spores and mycelium that cohabit together in the zone of soil disturbance. Tillage also reduces soil water potential to slow the movement of water-mobile pests (*e.g.* *Pythium* spp.), incorporates disease-infected residues (*e.g.* yellow spot and *Fusarium* crown rot), and reduces bulk density to permit greater rates of root elongation away from soil borne pathogens such as *Rhizoctonia solani* and *Pseudomonas* spp. (Simpendorfer *et al.* 2002). Movement to RT or NT must factor these changes and the capacity for varieties to tolerate and preferably resist biotic constraints to growth (see Chapter 11).

Globally, RT and NT have been associated with increased incidence of both soil-borne diseases including take-all (*Gaeumannomyces graminis* (Sacc.) Arx & D. Olivier var. *tritici* J. Walker), pythium seed and root rot (*Pythium* spp.), rhizoctonia root rot (*Rhizoctonia solani* Kuhn), common root rot (*Bipolaris sorokiniana*) and crown rot (*Fusarium pseudograminearum*) (Bockus and Shroyer 1998, Wildermuth *et al.* 1997), and leaf diseases including yellow spot (*Pyrenophora tritici-repentis* (Died.) Drechs), fusarium head blight (*Fusarium graminearum* Schwabe), septoria tritici blotch (*Mycosphaerella graminicola*.) and septoria glume blotch (*Stagonospora nodorum* (Berk.) Castellani & E. G. Germano) (Bockus and Shroyer 1998).

Crop rotation and fungicides are key to control many of these diseases as genetic resistance either does not exist, is partial in its control or is genetically complex. That said, significant breeding efforts for improved resistance to *Septoria tritici* and glume blotch, yellow spot, crown rot and *Pratylenchus thornei* for reduced-tillage systems are delivering wheat varieties with improved tolerance to these key diseases (McIntosh 1997, see Chapter 11).

Shorter stem lengths to reduce stubble loads

Significant amounts of stubble following harvest could previously be burned or grazed. With widespread adoption of CA, growers are less willing to use such techniques to deal with sometimes as much as 10 t/ha of residual leaf and straw. Further, efforts to speed harvest and thereby reduce the cost and duration of harvesting has prompted identification and adoption of innovative technologies such as use of stripper fronts borrowed from other crops. Furthermore, the retention of crop residues is widely regarded to reduce soil evaporation and enhance WUE. The move from tall to semi-dwarf cereals has changed the allocation of assimilates away from straw to grain to reduce crop lodging and increase crop yields. Total biomass has remained largely unchanged with increases in grain number reflecting increases in partitioning (or ‘harvest index’). As indicated, the green revolution GA-insensitive *Rht1* (syn. *Rht-B1b*) and *Rht2* (*Rht-D1b*) dwarfing genes are present in many of the world’s semi-dwarf wheats and so represent the most commonly adopted dwarfing genes in wheat breeding programs globally (Rebetzke *et al.* 2012a).

There is opportunity to reduce height further through the development of doubled- or sesqui-dwarfs: doubled-dwarfs containing combinations of GA-insensitive and -sensitive dwarfing genes (Rebetzke *et al.* 2012b). Figure 4 summarises changes in grain yield with reduction in plant height for a range of different dwarfing gene near-isolines (NILs) evaluated under irrigation at Yanco NSW in 2018. Reductions in plant height were associated with increasing grain yield up to a maximum of c. 65 cm height whereupon further reductions in height were linked to reductions in grain yield. Compared with the tall recurrent parent Halberd, almost all single-dwarf NILs were significantly greater in grain yield (except for the extreme height-reducing, GA-insensitive *Rht3* and *Rht10* NILs). Further reductions in plant height in the weaker sesqui-dwarfs were associated with additional increases in grain yield through greater harvest index (data not shown). By contrast, the extreme height and yield reduction with *Rht1+Rht2* doubled dwarfs reduces their potential. Extreme height reduction in cereals is problematic given their reduced capacity for mechanised harvest and reduced biomass and yield, especially in very dry seasons.

The 10 to 15 cm reduction in stem length (Figure 4) and greater harvest index with sesqui-dwarfs highlights their potential to reduce crop residues. Given the now widespread development of markers linked to these dwarfing genes it should be straight-forward to select and enrich for combinations of key dwarfing genes early before the expensive process of yield and quality testing. Further, the physiology of the GA-sensitive dwarfing genes provides opportunity for use of plant growth regulators to manage crop architecture for different times of sowing and seasonal conditions.

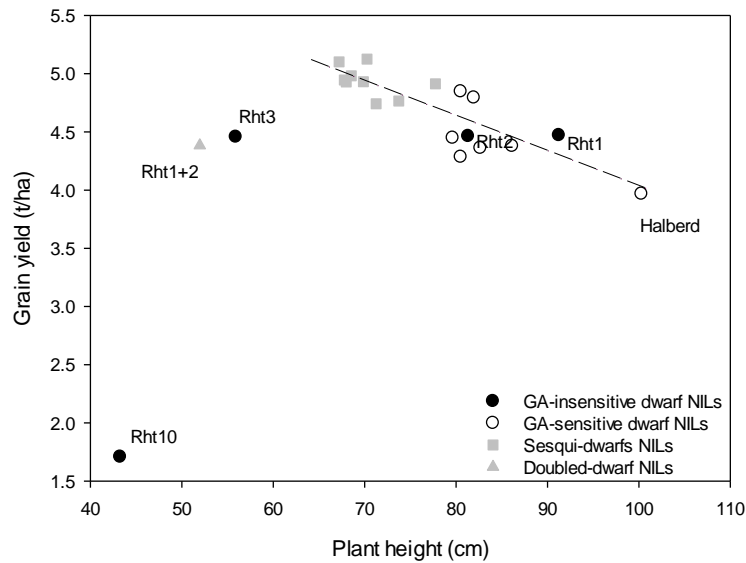


Figure 4. Relationship of plant height and grain yield for gibberellic acid (GA) -insensitive and -sensitive single and doubled dwarfing gene near-isolines (NILs), and original tall parent Halberd when grown with partial irrigation at Yanco Managed Environment Facility in 2018 (Line of best fit is $Y = 7.061 - 0.031.X$, $r^2 = 0.74$, $P < 0.01$)

Awnless cereals for frost-prone regions

Drought- and frost-affected crops have reduced grain yields and quality and, owing to significant on-farm input costs, their incidence later in the season can result in a substantial loss of profitability to growers. Frost costs the Australian grains industry ~\$700M AUD each year in direct costs (An-Vo *et al.* 2018). Affected crops may be fed to livestock but enterprises without animals have little option but to cut and bail for hay that has significantly reduced value. This reduced value reflects the presence of the awns – ‘thread-like appendages extending from the tips of each spikelet’. All Australian wheat varieties lacked awns until delivery in the 1970s of *Rht1* and *Rht2* dwarfing gene wheats from CIMMYT containing awns. Dried awns are sharp and brittle, and can penetrate the gums and cheeks of animals when grazed. Awns have also been linked to increased pre-harvest sprouting and weather damage (King and Richards 1984), greater disease susceptibility in the ear and developing grain, and a predisposition to frosting of the ear itself (R.A. Richards pers. comm.). There is strong grower interest in a return to awnless cereals, and their potential for grazing and baling for hay in main-season sown crops. This interest is particularly strong in regions with a greater risk of frost damage at flowering.

Long awns are considered an important component trait of the high yielding wheat ideotype, particularly for wheat grown under water-limited conditions (Reynolds and Tuberosa 2008). Studies have demonstrated a grain yield advantage for awned wheats of up to 16% and particularly under drier conditions (*e.g.* Motza and Giunta 2002). Yet awns are often the first photosynthetic organ to desiccate under drought, and commonly senesce well before senescence of the upper canopy. In experiments conducted across 23 irrigated and rain-fed environments in Australia and Mexico, grain yields were the same for more than 40 BC₁F₆-derived awned and awnless NILs representing four genetic backgrounds (Rebetzke *et al.* 2016). Awnless wheats produced significantly greater numbers of grain per spike (+5%) reflecting more fertile spikelets and more grain in tertiary florets. The increased grain number was compensated by reductions in grain size (-5%) and an increased frequency of ‘screenings’ to reduce seed-lot quality of awnless NILs. It appears that allocation of assimilate to large and rapidly developing awns decreases spikelet number and floret fertility to reduce grain number particularly in distal florets. Kernel size is subsequently increased to reduce screenings and increase test weight particularly in droughted environments. Despite the average reduction in kernel size, awnless lines were identified in most backgrounds that combined higher grain yield with larger grain size, increased grain protein and reduced screenings.

Is there a place for late-sown cereal varieties?

Australian cereals are bred and managed for typically early-to-late May sowings. A return by breeding programs to the development of longer-season wheats for early sowing demonstrates the capacity to modify the timing of vegetative and reproductive growth to increase water use efficiency and provide valuable feed in mixed farming operations where the likelihood of early rainfall is high (Hunt *et al.* 2019, see also Chapter 18). New cereal varieties with appropriate vernalisation and photoperiod genes have been released with advanced breeding lines from across multiple breeding programs currently in the Australian NVT system (Flohr *et al.* 2018).

In reality, the likelihood of later sowing opportunities is much greater than for early sowing throughout much of the Australian wheat-belt. Yet there are no varietal wheat options for late-sowing (*i.e.* mid-June to mid-July), and late sowing is commonly associated with large reductions in grain yield (Shackley and Anderson 1995). Late-sown cereals have significant potential in:

- maintaining grain yields in regions where rainfall necessary for germination and early growth is late;
- managing herbicide-resistant weeds through double-knock herbicide strategies (see Chapter 10);
- delaying flowering to avoid frost in frost-prone areas; and
- more cost-effective nutrient management to reduce the risk of over/under supply of nitrogen with shorter duration crops.

In a farming systems context, a competitive, high biomass, early flowering cultivar for late-sowing would give farmers additional flexibility to plan and adjust their sowing operations with greater precision. More crop could be sown with an ideal agronomic package, the implication being that farmers could achieve higher average yields across the farm, and make better use of machinery capital, where the effective sowing window for wheat is increased with changing climate. It would also give additional opportunities for the use of double knockdown herbicide strategies in seasons with a late break.

There is potential to further exploit genotype \times management interaction in development of rapid growing wheat varieties with potential for very late sowing. Growers have expressed strong interest in access to higher biomass cereals for late-sowing with 78% of 200 growers surveyed on social media (Twitter®) in 2018 in support of such varieties (G.J. Rebetzke unpub. data). Previously, more vigorous barley and triticale varieties, and wheat varieties like ‘H45’, could be sown mid-to-late July to outcompete late-emerging weeds and produce high grain yields. Commercial breeding programs have released developmentally faster wheat varieties including ‘Zippy’ and ‘Axe’. However, uptake by growers has been poor as, unlike H45, these recent wheat varieties have slow leaf area development resulting in reduced biomass and lower grain yields. Australian wheats are very conservative in their early shoot and root growth (*e.g.* Figure 5). Genetic variation for rapid early growth is available globally, and the CSIRO has been using novel S1 recurrent selection to accumulate rapid growth genes from 28 overseas wheats to increase early leaf area and biomass, and early root growth (Figure 5).

Conclusions

Wheat breeders have been successful in maintaining genetic gains of near 0.6% per year despite the widespread adoption of CA and associated changes in wheat-based, farming systems and increasingly variable climate. This gain has been achieved without compromising grain quality and resistance to key diseases particularly the different rust pathogens. Breeders will continue to release varieties addressing a wide range of farming systems needs but there is the real likelihood of future reduced genetic gains owing to an increasingly narrowing genetic base together with the potential for rapid gene fixation with genomic selection. Further, climate variability will likely increase genotype \times environment interaction in breeders’ nurseries and the National Variety Trials to reduce confidence in selection and the identification of higher-yielding, broadly-adapted genotypes.

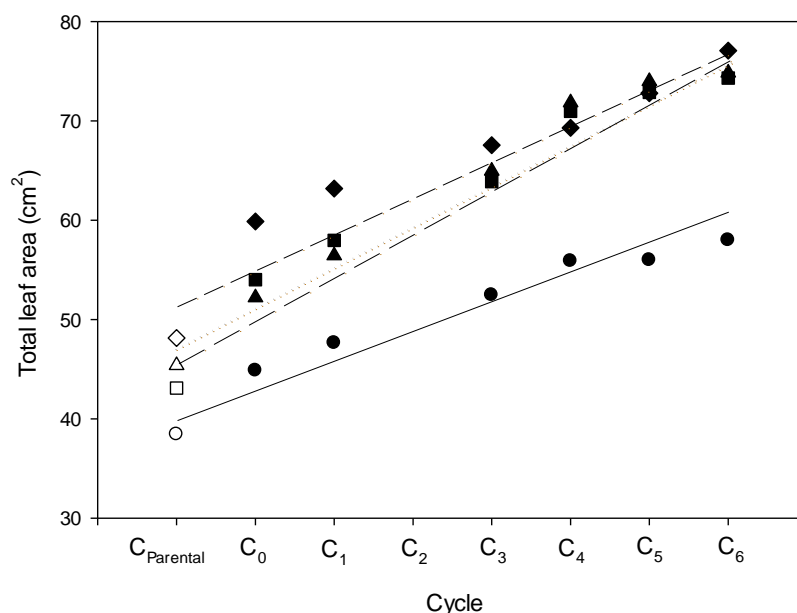


Figure 5. Relationship between cycle number and mean total seedling leaf area measured in four environments: Sow 1 (\circ ; $r^2 = 0.93^{**}$); Sow 2 (\square ; $r^2 = 0.94^{**}$); Sow 3 (\diamond ; $r^2 = 0.93^{**}$); and Sow 4 (Δ ; $r^2 = 0.95^{**}$) (note that cycle 2 lines were accidentally discarded during long-term seed storage) (Zhang *et al.* 2015)

Future crop varieties will require greater skill and attention in their selection around new disease and insect threats, greater weed competitiveness, tolerance of higher air and soil temperatures and drought through grain-filling, and with optimised flowering times to reduce the potential for damage from frost. There will also be changes to crop management that will require genotypes with new traits. Consideration towards a physiological framework in breeding is appealing as it allows for the creation of idealised genotypes targeting improved adaptation to those constraints limiting productivity. Further, such a framework permits the identification of new parental germplasm containing those genetics currently not present or at low frequency for implementation in breeding programs (*e.g.* weed competitiveness, high biomass for late-sowing and greater coleoptile length, modified root architecture). However, uptake of new output traits and genes will require clear and robust value propositions to effect changes in long-standing breeding objectives while their incorporation, selection and delivery in new varieties necessitates open and regular communication between the agronomists, physiologist, molecular biologist and the breeder.

References

- Aerts R (1999) Interspecific competition in natural plant communities: mechanisms, trade-offs and plant-soil feedbacks. *Journal of Experimental Botany* **50**, 29-37
- An-Vo DA, Mushtaq S, Zheng B *et al.* (2018) Direct and indirect costs of frost in the Australian wheatbelt. *Ecological Economics* **150**, 122-136
- Arruda MP, Lipka AE, Brown PJ *et al.* (2015) Comparing genomic selection and marker-assisted selection for Fusarium head blight resistance in wheat (*Triticum aestivum* L.). *Molecular Breeding* **36**, [doi:10.3835/plantgenome2015.01.0003](https://doi.org/10.3835/plantgenome2015.01.0003)
- Bankole F, Menkir A, Olaoye G *et al.* (2017) Genetic gains in yield and yield related traits under drought stress and favorable environments in a maize population improved using marker assisted recurrent selection. *Frontiers in Plant Science* **8** doi.org/10.3389/fpls.2017.00808
- Bernardo R (2008) Molecular markers and selection for complex traits in plants: Learning from the last 20 years. *Crop Science* **48**, 1649-1664
- Bockus WW, Shroyer JP (1998) The impact of reduced tillage on soilborne plant pathogens. *Annual Review of Phytopathology* **36**, 485-500
- Borger CPD, Hashem A, Pathan S (2020) Manipulating crop row orientation to suppress weeds and increase crop yield. *Weed Science* **58**, 174-178
- Broster JC, Pratley JE, Ip RHL *et al.* (2019) Cropping practices influence incidence of herbicide resistance in annual ryegrass in Australia. *Crop and Pasture Science* **70**, 77-84

- Chenu K, Cooper M, Hammer GL *et al.* (2011) Environment characterization as an aid to wheat improvement: interpreting genotype-environment interactions by modelling water-deficit patterns in North-Eastern Australia. *Journal of Experimental Botany* **62**, 1743-1755
- Collard BCY, Jahufer MZZ, Brouwer JB, Pang ECK (2005) An introduction to markers, Quantitative Trait Loci (QTL) mapping and marker-assisted selection for crop improvement: The basic concepts. *Euphytica* **142**, 169-196
- Cooper M, Woodruff DR, Phillips IG *et al.* (2001) Genotype-by-management interactions for grain yield and grain protein concentration of wheat. *Field Crops Research* **69**, 47-67
- Cornish PS (1987) Crop and pasture plant selection for new cultural systems. In (Eds. PS Cornish, JE Pratley) "Tillage: New Directions in Australian Agriculture" pp 355-378 (Inkata: Melbourne)
- Crain J, Mondal S, Rutkoski J *et al.* (2018) Combining high-throughput phenotyping and genomic information to increase prediction and selection accuracy in wheat breeding. *Plant Genome* **11**, doi: 10.3835/plantgenome2017.05.0043
- Deery DM, Rebetzke GJ, Jimenez-Berni JA *et al.* (2016) Methodology for high-throughput field phenotyping of canopy temperature using airborne thermography. *Frontiers in Plant Science* **7**, 1808 doi.org/10.3389/fpls.2016.01808
- Dreisigacker S, Sukumaran S, Guzmán C *et al.* (2016) Molecular Marker-Based Selection Tools in Spring Bread Wheat Improvement: CIMMYT Experience and Prospects. In (Eds. VR Rajpal, SR Rao, SN Raina) "Molecular Breeding for Sustainable Crop Improvement" Volume 2, pp 421-474 (Springer International)
- D'Emden FH, Llewellyn RS (2006) No-tillage adoption decisions in southern Australian cropping and the role of weed management. *Australian Journal of Experimental Agriculture* **46**, 563-569
- Fischer RA, Byerlee D, Edmeades G (2014) "Crop Yields and Global Food Security". pp 8-11 (ACIAR: Canberra, ACT)
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018) Genotype \times management strategies to stabilise the flowering time of wheat in the south-eastern Australian wheatbelt. *Crop and Pasture Science* **69**, 547-560
- Francia E, Tacconi G, Crosatti C *et al.* (2005) Marker-assisted selection in crop plants. *Plant Cell, Tissue and Organ Culture* **82**, 317-342
- Hadjichristodoulou A, Della A, Photiades J (1977) Effect of sowing depth on plant establishment, tillering capacity and other agronomic characters of cereals. *Journal of Agricultural Science* **89**, 161-167
- Heap I (2019) The International Survey of Herbicide Resistant Weeds. www.weedscience.org
- Heffner EL, Lorenz AJ, Jannink J-L, Sorrells ME (2010) Plant breeding with genomic selection: Gain per unit time and cost. *Crop Science* **50**, 1681-1690
- Hochman Z, Gobbett DL, Horan H (2017) Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology* **23**, 2071-2081
- Hunt JR, Lilley JM, Trevaskis B *et al.* (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change* **9**, 244
- Jimenez-Berni JA, Deery DM, Rozas-Larraondo P *et al.* (2018) High throughput determination of plant height, ground cover, and above-ground biomass in wheat with LiDAR. *Frontiers in Plant Science* **9** doi.org/10.3389/fpls.2018.00237
- Joukhadar R, Daetwyler HD, Bansal UK *et al.* (2017) Genetic diversity, population structure and ancestral origin of Australian wheat. *Frontiers in Plant Science* **8**, doi.org/10.3389/fpls.2017.02115
- King RW, Richards RA (1984) Water uptake in relation to pre-harvest sprouting damage in wheat: ear characteristics. *Australian Journal of Agricultural Research* **35**, 327-36
- Kirkegaard, JA, Hunt, JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- Langridge P, Lagudah ES, Holton TA *et al.* (2001) Trends in genetic and genome analyses in wheat: a review. *Australian Journal of Agricultural Research* **52**, 1043-1077
- Lobell DB, Hammer GL, Chenu K *et al.* (2015) The shifting influence of drought and heat stress for crops in northeast Australia. *Global Change Biology* **21**, 4115-4127
- McIntosh RA (1997) Breeding wheat for resistance to biotic stresses. In "Wheat: Prospects for Global Improvement", pp 71-86 (Springer: Dordrecht)
- Meuwissen THE, Hayes BJ, Goddard ME (2001) Prediction of total genetic value using genome-wide dense marker maps. *Genetics* **157**, 1819-1829
- Mohler V, Singrün C (2005) General Considerations: Marker-Assisted Selection. In (Eds. Lörz H, Wenzel G) "Molecular Marker Systems in Plant Breeding and Crop Improvement" pp 305-317 (Berlin, Heidelberg: Springer Berlin Heidelberg)
- Motzo R, Giunta F (2002) Awnedness affects grain yield and kernel weight in near-isogenic lines of durum wheat. *Crop and Pasture Science* **53**, 1285-1293
- Naylor R, Manning R (2005) Unleashing the genius of the genome to feed the developing world. *Proceedings of American Philosophical Society* **149**, 515-529

- Rebetzke GJ, Richards RA (1999) Genetic improvement of early vigour in wheat. *Australian Journal of Agricultural Research* **50**, 291-301
- Rebetzke GJ, Richards RA, Sirault XRR, Morrison AD (2004) Genetic analysis of coleoptile length and diameter of wheat. *Australian Journal of Agricultural Research* **55**, 733-743
- Rebetzke GJ, Bruce S, Kirkegaard JA (2005) Genotypic increases in coleoptile length improves emergence and early vigour with crop residues. *Plant and Soil* **270**, 87-100
- Rebetzke GJ, Richards RA, Fettel NA *et al.* (2007a) Genotypic increases in coleoptile length improves stand establishment, vigour and grain yield of deep-sown wheat. *Field Crops Research* **100**, 10-23
- Rebetzke GJ, Ellis MH, Bonnett DG, Richards RA (2007b) Molecular mapping of genes for coleoptile growth in bread wheat (*Triticum aestivum* L.). *Theoretical and Applied Genetics* **114**, 1173-1183
- Rebetzke GJ, Ellis MH, Bonnett DG *et al.* (2012a) Height reduction and agronomic performance for selected gibberellin-responsive dwarfing genes in bread wheat (*Triticum aestivum* L.). *Field Crops Research* **126**, 87-96
- Rebetzke GJ, Ellis MH, Bonnett DG (2012b) Combining gibberellic acid sensitive and insensitive dwarfing genes in breeding of higher-yielding, sesqui-dwarf wheats. *Field Crops Research* **127**, 17-25
- Rebetzke GJ, Biddulph B, Chenu K *et al.* (2013) Development of a multisite, managed environment facility for targeted trait and germplasm evaluation. *Functional Plant Biology* **40**, 1-13
- Rebetzke GJ, Verbyla A, Verbyla K *et al.* (2014a) Use of a large multiparent wheat mapping population for genomic dissection of coleoptile and seedling growth. *Plant Biotechnology Journal* **12**, 219-230
- Rebetzke GJ, Kirkegaard JA, Watt M, Richards RA (2014b) Genetic vigour helps maintain superior leaf area development for wheat seedlings growing in uncultivated soils. *Plant and Soil* **377**, 127-144
- Rebetzke GJ, Zheng B, Chapman SC (2016a) Do wheat breeders have suitable genetic variation to overcome short coleoptiles and poor establishment in the warmer soils of future climates? *Functional Plant Biology* **43**, 961-972
- Rebetzke GJ, Bonnett DG, Reynolds MR (2016b) Awns reduce grain number to increase grain size and harvestable yield in irrigated and rainfed spring wheat. *Journal of Experimental Botany* **67**, 2573-2586
- Reynolds M, Tuberosa R (2008) Translational research impacting on crop productivity in drought-prone environments. *Current Opinion in Plant Biology* **11**, 171-179
- Robertson MJ, Rebetzke GJ, Norton R (2015) Assessing the place and role of crop simulation modelling in Australia. *Crop and Pasture Science* **66**, 877-893
- Rodrigues FA, Blasch G, Defourny P *et al.* (2018) Multi-temporal and spectral analysis of high-resolution hyperspectral airborne imagery for precision agriculture: Assessment of wheat grain yield and grain protein content. *Remote Sensing* **10**, doi.org/10.3390/rs10060930
- Rutkoski J, Poland J, Mondal S *et al.* (2016) Canopy temperature and vegetation indices from high-throughput phenotyping improve accuracy of pedigree and genomic selection for grain yield in wheat. *G3: Genes, Genomes, Genetics* **6**, 2799-2808
- Schillinger WF, Donaldson E, Allan RE Jones SS (1998) Winter wheat seedling emergence from deep sowing depths. *Agronomy Journal* **90**, 582-586
- Shackley BJ, Anderson WK (1995) Responses of wheat cultivars to time of sowing in the southern wheatbelt of Western Australia. *Australian Journal of Experimental Agriculture* **35**, 579-587
- Simpfendorfer S, Kirkegaard JA, Heenan DP, Wong PTW (2002) Reduced early growth of direct drilled wheat in southern New South Wales-role of root inhibitory pseudomonads. *Australian Journal of Agricultural Research* **53**, 323-331
- Soane BD, Ball BC, Arvidsson J, Basch G *et al.* (2012) No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil and Tillage Research* **118**, 66-87
- Trethowan RM, Mahmood T, Ali Z *et al.* (2012) Genetic control of wheat adaptation to CA. *Field Crops Research* **132**, 76-83
- Verhulst N, Carrillo-García A, Moeller C *et al.* (2011) Conservation agriculture for wheat-based gravity irrigation systems: increasing resilience through improved soil quality. *Plant and Soil* **340**, 467-479
- Voss-Fels KP, Cooper M, Hayes BJ (2019) Accelerating crop genetic gains with genomic selection. *Theoretical and Applied Genetics* **132**, 669-686
- Watson J, Zheng B, Chapman S, Chenu K (2017) Projected impact of future climate on water-stress patterns across the Australian wheatbelt. *Journal of Experimental Botany* **68**, 5907-5921
- Weiner J, Andersen SB, Wille WK-M *et al.* (2010) Evolutionary agroecology: the potential for cooperative, high density, weed-suppressing cereals. *Evolutionary Applications* **3**, 473-479
- Wildermuth GB, Thomas GA, Radford BJ *et al.* (1997) Crown rot and common root rot in wheat grown under different tillage and stubble treatments in southern Queensland, Australia. *Soil and Tillage Research* **44**, 211-224

- Wolfe MS, Baresel JP, Desclaux D *et al.* (2008) Developments in breeding cereals for organic agriculture. *Euphytica* **163**, 323-346
- Zerner RK, Gill GS, Rebetzke GJ (2016) Stability of wheat cultivars in weed competitive ability in differing environments in southern Australia. *Crop and Pasture Science* **67**, 695-702
- Zhang L, Condon AG, Richards RA, Rebetzke GJ (2015) Recurrent selection for wider seedling leaves increases early leaf area development in wheat (*Triticum aestivum* L.). *Journal of Experimental Botany* **66**, 1215-1226
- Zhao Z, Wang E, Rebetzke GJ *et al.* (2019) Modelling impact of early vigour on wheat yield across the Australian wheatbelt. *Journal of Experimental Botany* (in press)
- Zou C, Xie C, Xu Y *et al.* (2017) Enhancing genetic gain in the era of molecular breeding. *Journal of Experimental Botany* **68**, 2641-2666

PART V – MANAGING THE SYSTEM



Farming systems research site, Wagga Wagga NSW (Courtesy: John Kirkegaard and Graeme Sandral)



Establishing the cotton crop (Courtesy: Rose Brodrick)



Furrow irrigation of cotton (Courtesy: Rose Brodrick)

Chapter 18

Evolution of early sowing systems in Southern Australia

Andrew Fletcher, Bonnie Flohr, Felicity Harris

Introduction

Historical advances in water-limited yield in drought-prone environments of southern Australia have been achieved by adapting crop phenology to environment, to ensure that crop establishment occurs following autumn breaking rains (April-May) and flowering occurs in an optimal period in spring after frost risk but before heat stress and terminal drought (Richards 1991). (The autumn break is the first rainfall of sufficient volume to ensure successful germination and establishment and represents the start of the growing season). This historical phenological adaptation included the release of Australia's first adapted spring wheat cultivar 'Federation' by Farrer in 1901, the release of photoperiod insensitive semi-dwarf wheat cultivars in the 1970s, and the adoption of conservation agriculture in the 1980s which supported earlier sowing of wheat and other dominant crops (Fischer 2009).

In the last 20 years, the average farm size has doubled in most cropping zones of Australia (Anderson *et al.* 2016). The widespread adoption of NT, reduced livestock numbers and a wide selection of herbicides have supported a shift towards greater farm size, intensification of cropping programs and associated earlier sowing (D'Emden *et al.* 2008, Fletcher *et al.* 2016). These have been important shifts to achieve economies of scale. Dry sowing is the technique of sowing crops into dry soil before the breaking season rains to enable a larger area of crop to germinate as soon as the germinating rain arrives. To avoid confusion, the term 'early sowing' refers to the date on which physical sowing occurs, either into a dry or moist seed bed. The term 'establishment date' refers to the date on which seed becomes imbibed and germination begins either by planting in a moist seed bed, or the date on which dry sown seed receives germinating rainfall. Early sowing here is also defined as prior to 1 May.

Between 1978 and 2015, national wheat sowing dates have moved earlier by 1 to 1.5 days per year (Figure 1, Stephens and Lyons 1998, Fletcher *et al.* 2016, Flohr *et al.* 2018b), with similar shifts for canola (Kirkegaard *et al.* 2016) and barley also likely. The traditional sowing window of mid-May to June has shifted to a mean sowing date of ~10 May (Figure 1, Flohr *et al.* 2018b). Today, approximately 50% of growers dry sow a proportion of their crop area, which has improved machinery and labour efficiencies (Fletcher *et al.* 2016). While earlier sowing has logistical benefits, advancing mean flowering time closer to the environmental optima has been key to maintaining national yields under seasons characterised by reduced rainfall, warmer springs and more rapid onset of drought (Pook *et al.* 2009, Kirkegaard and Hunt 2010). Canola yield declines 5-12% per week of delay in establishment after mid-April in Australia (Farre *et al.* 2002, Kirkegaard *et al.* 2016) while in wheat, a decline of up to 1-7% yield per week delay past the optimal establishment time has been found in SA, NSW and WA (Kohn and Sorrier 1970, Coventry *et al.* 1993, Sharma *et al.* 2008, Lawes *et al.* 2016). Early crop establishment and longer growth durations achieve greater efficiency in converting rainfall into grain primarily through deeper root growth and access to water (Kirkegaard *et al.* 2015), reduced evaporative losses from the soil (Passioura and Angus 2010) and increased transpiration efficiency (Kemanian *et al.* 2005).

In this chapter we discuss how and why early and dry sowing systems have evolved in Australia, how they have been successfully implemented and the challenges and opportunities that remain. We also use two grower case studies to demonstrate how early sowing is currently implemented on-farm.

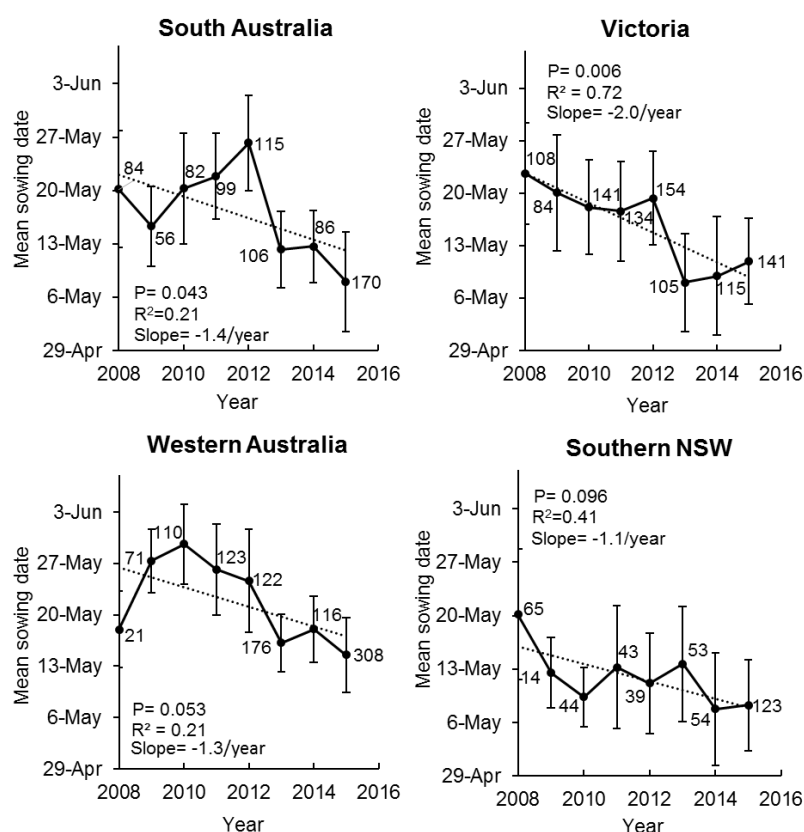


Figure 1. Mean sowing date for different regions from 2008-2015 from the Yield Prophet® data base. The number next to marker is the number of fields included in the mean sowing date for each year. Error bars are the standard deviation around the mean (extracted from Flohr *et al.* 2018b)

Crop type and cultivars for early sowing

In southern Australia, an optimal flowering period (OFP) exists whereby grain yield is maximised, and the combined risk of frost, drought and heat stress are minimised (Farré *et al.* 2004, Flohr *et al.* 2017, Lilley *et al.* 2019). This period is important as grain number in cereals is determined just prior to, and at, flowering (Fischer 1985). The optimum temperature to facilitate pollination and fertilisation in wheat is in the range 18-24°C, with a minimum of 9°C and maximum of 31°C (Porter and Gawith 1999). In canola, grain yield is most sensitive to stress between 100 and 500°C.days (Kirkegaard *et al.* 2018) after the start of flowering, and air temperatures above 29.5°C during flowering can result in floral sterility and grain number reduction (Angadi *et al.* 2000, Morrison and Stewart 2002, Harker *et al.* 2012).

Flohr *et al.* (2017) defined OFPs as the period that minimises the combined effect of frost, heat, water stress and optimises radiation capture for wheat yield for several environments across the south-eastern Australian wheat belt using the Agricultural Production Systems SIMulator (APSIM, Holzworth *et al.* 2014) and historical climate records. Lilley *et al.* (2019) presented a similar study in canola. Both simulation studies found that the OFP varied with environment; the relative importance of seasonal water supply and demand and extremes of temperature varied in the defining windows. Consequently, sowing date recommendations vary for cultivars and crop types with different phenology patterns to optimise these physiological trade-offs under varied climatic conditions, and across growing environments (Matthews *et al.* 2019). By sowing early and growing cultivars with appropriate phenology to match the OFP, Hunt *et al.* (2019) demonstrated that national average wheat yields can be increased by 0.54 t/ha. Availability of a greater range of cultivars that cover a broader range of sowing dates yet flower at the optimum time would increase flexibility and enhance management options available to growers (Fischer 2011).

Wheat cultivars can be broadly classified into two main types distinguished by their response to vernalisation, and their adaptation to different sowing dates; these are referred hereafter as either winter or spring types. Winter types have an obligate vernalisation requirement, meaning they must experience a period of vernalising (cold) temperatures prior to developmental progression from vegetative to reproductive phase (Hunt 2017). Acceleration of development in winter types occurs when exposed to temperatures in the range of -2 to 15°C, with an optimum of 5°C (Ewert *et al.* 2002). In contrast, spring types generally do not require vernalisation to progress developmentally, though can vary in their responses, whereby exposure to vernalising temperatures can hasten their development (facultative vernalisation requirement), or have no effect on development (vernalisation insensitive) (Pugsley 1983, Hunt 2017). Vernalisation and photoperiod (day length) sensitivity interact and as such there is genotypic variation among winter and spring types in their flowering responses across environments (Davidson *et al.* 1985, Eagles *et al.* 2010).

In wheat and barley, yield improvements have been achieved by direct selection for yield based on traditional May sowing dates and an appropriate flowering time, as such cultivars with a spring development pattern dominate southern Australian farming systems (Flohr *et al.* 2017, Porker *et al.* 2017). The early-May sowing dates reported in Figure 2 are optimal for existing mid-fast spring wheat, although if sown too early they may flower outside the OFP, and suffer yield reductions due to frost damage and/or insufficient biomass accumulation. Consequently, winter or slow spring cultivars are required to align better with earlier sowing dates and with the OFP (Figure 2, Porker *et al.* 2017, Flohr *et al.* 2018b).

While dry and early sowing are complementary practices, the dry sowing of slow developing cultivars is not a suitable strategy in all environments, unless seed is sown deep into stored soil moisture to promote establishment at sowing or rainfall is forecast soon after sowing and prior to the recommended sowing date of fast developing cultivars (Asseng *et al.* 2016). This applies particularly to Mediterranean type environments, where average growing seasons tend to be warmer. In these environments vernalisation requirements of winter wheat cultivars are met too late in the season for late emerging crops, which delays flowering and exposes crops to more heat and water stress risk. The yield under these circumstances is less than that of fast developing cultivars sown later.

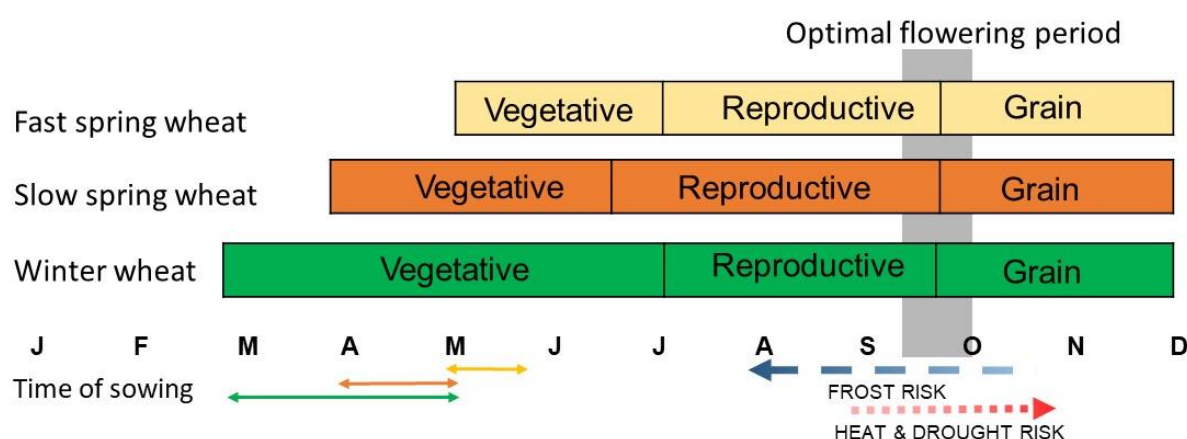


Figure 2. Duration and timing of the different development phases of winter wheat and fast and slow developing spring wheats. Optimal sowing windows are represented by arrows colour coded to the wheat type and the risks of frost and heat/drought are indicated by broken arrows and colour gradients. The grey band represents the OFP which minimises the combined risks from frost and heat/drought (Adapted from Hunt 2017)

Recent trends in earlier sowing, greater areas of dual-purpose cereals, and research highlighting whole-farm benefits of winter cultivars (Hunt *et al.* 2019) has led to an increased demand for adapted winter types (Hunt 2017). Whilst breeders have responded with the release of five new winter wheats in the period 2013-2019 (Porker *et al.* 2019), there has been limited selection within breeding programs for winter barley cultivars. There is currently only one winter barley cultivar suitable for early sowing, cv Urambie, which was released in 2005 (Porker *et al.* 2017). Breeding traits other than phenology have

also been identified as beneficial for early sowing and successful establishment. These include increased coleoptile length and early vigour (Kirkegaard and Hunt 2010, Rebetzke *et al.* 2016, Zhao *et al.* 2019) which could also contribute to increased early biomass available for grazing in dual-purpose systems (Harris *et al.* 2017).

Similar to cereals, earlier sowing of canola can improve productivity and reduce the risks associated with canola production, provided appropriate phenology is used to match the OFP (Kirkegaard *et al.* 2016, Lilley *et al.* 2019). Improved understanding of cultivar phenology (Whish *et al.* 2018, Brill *et al.* 2019) and improved agronomic management has prompted a re-evaluation of sowing date recommendations in canola (Kirkegaard *et al.* 2016, Lilley *et al.* 2019) with sowing windows shifting three weeks earlier than previously recommended. Currently there is a range of spring canola varieties with mid to fast phenology, and very slow phenology winter canola varieties used for grazing in the high rainfall zone, but few commercial varieties with ‘fast winter’ phenology driven by vernalisation (Kirkegaard *et al.* 2016). The potential benefits of these varieties are predicted to be significant for both grain yield and dual-purpose use (Christy *et al.* 2013, Lilley *et al.* 2015) and breeding companies have started to investigate winter-spring crosses and ‘semi-vern’ canola types to fill this phenology gap in Australian canola germplasm.

Crop management with early sowing

Aside from choosing the correct cultivar for early sowing to align with the OFP, there are several other important management considerations in early/dry sowing. In a 2019 survey using Twitter, 41% of growers in south-east and south-west Australia (n=535) rated managing the weed burden as their primary management concern when early and dry sowing (Figure 3). Poor emergence and frost were also important. Few respondents identified suitable cultivar as a limiting factor. Other concerns included false breaks, soil constraints and pre-emergent herbicide performance. These findings are consistent with a regional survey carried out in 2013 in WA (McNee *et al.* 2015).

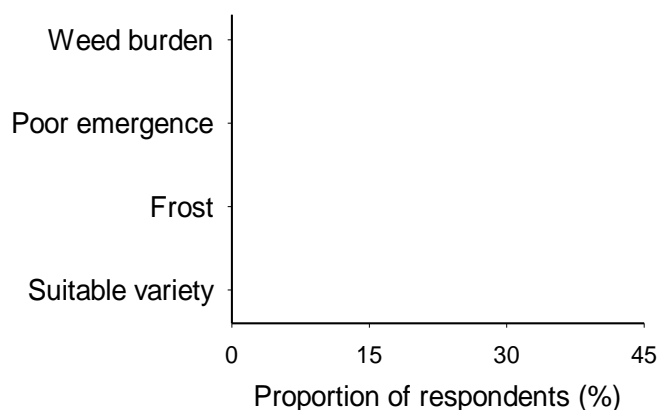


Figure 3. Results of Twitter poll (January 2019) of growers in South-eastern and South-western Australia ranking the most important management risks associated with early and dry sowing (n=535)

Paddock selection and pre-crop management

Paddock selection and pre-crop management are critical for the successful implementation of early sowing. Early sowing increases the reliance on in-season weed management as options for knockdown weed control are limited. Therefore choosing paddocks with low weed pressure is key to success. This can be achieved through various strategies including crop rotation, which minimises the weed seed bank (Seymour *et al.* 2012, Angus *et al.* 2015), and harvest weed seed control (HWSC) in the preceding crop. HWSC can include options such as chaff carts, windrow burning, crop topping and seed destruction (Walsh *et al.* 2013, see also Chapter 10) that minimise the return of weed seeds.

Topography is another important factor when choosing which paddocks to sow early or dry. Paddocks lower in the landscape are at additional risk of frost (Dixit and Chen 2011) and early sowing may exacerbate this further. Fletcher *et al.* (2015) demonstrated that, across a whole farm, dry sowing would give a small increase in the risk of frost particularly at the start of the sowing program. Therefore it is a beneficial strategy to sow winter canola and wheat cultivars first, followed by the paddocks with the least incidence of frost first, and higher risk paddocks last.

Soil type is also an important aspect of paddock choice for early sowing. In water repellent sandy soils, disturbance of dry soil can increase hydrophobicity (Roper *et al.* 2015), adversely affecting the germination and emergence of dry sown crops. Therefore, these soils are not recommended for dry sowing. Lighter sandy soils with lower soil water holding capacity require less rainfall to germinate dry sown crops, and are more suitable for large dry sowing programs (Fletcher *et al.* 2015).

Stored soil moisture is a trigger in the decision to sow early or not. Growers are more confident to dry sow if there is stored soil moisture (McNee *et al.* 2015) because once sufficient rainfall occurs to initiate germination, there is increased likelihood that stored soil water will sustain early crop growth. Long fallow (Oliver *et al.* 2010) and good summer weed control (Hunt and Kirkegaard 2011) can be used to maximise the stored soil moisture at sowing. A simulation study by Flohr *et al.* (2018a) showed that early sowing, deep sowing of long coleoptile wheat cultivars, or long fallow gave smaller increases in wheat yield when applied separately. However, when these three management approaches were combined, mean wheat yields increased by 42%.

In-season weed control

The importance of effective weed control as a management factor for early or dry sowing has been highlighted (Figure. 3, see also Chapter 10). When early sowing, the opportunity to use a double-knock weed-control strategy is foregone (Borger and Hashem 2007). The double knockdown weed control strategy is the sequential application of two different pre-planting herbicides with different modes of action (*e.g.* Glyphosate and paraquat). The double knock strategy is a valuable tool to delay the development of herbicide resistance in weed populations. In early or dry sowings, it is rarely possible to achieve a successful knockdown of grass weeds, as there is often limited soil moisture to stimulate germination of weeds. In populations that have evolved a greater degree of dormancy, weeds will not emerge until later in May. Early sowing systems limit the effectiveness of pre-emergent knockdown herbicides, whilst increasing the reliance on residual pre-emergent herbicides. However, the efficacy of many pre-emergent herbicides is dependent on an interaction with soil moisture, or a significant rain event following application; these conditions may influence efficacy of some residual chemicals at the time of weed germination. For example, Minkey (2017) found that pyroxasulfone applied on 15 April, had an efficacy of 50% after six weeks when applied on dry soil but only 10% when applied on wet soil.

An early sown crop has greater early vigour due to warmer soils, and a higher plant biomass that can shade and compete better with weeds than later sown crops. Preston *et al.* (2017) showed that a similar density of annual ryegrass plants established in wheat sown on 6 May compared with 2 June. However, the number of ryegrass spikes/m² was much lower in the early sown crop when compared in October (Figure 4). On average there was 1 spike/ryegrass plant when wheat was sown 6 May but 1.8 spikes/plant when wheat was sown 2 June. This increased weed competition from early sowing may help reduce the weed seed bank in future seasons especially if combined with new high vigour wheat genotypes (Zerner *et al.* 2016).

Fertiliser management

Early sown crops require different N fertiliser management than those sown in the conventional mid-late May window. In soils with low N, additional fertiliser N is required to maintain protein content and to attain potential yield, and also to manage the long term soil organic N which may decline under early sowing systems (Cossani *et al.* 2019). In high soil N scenarios, excessive N applied to early sown crops may lead to haying off and reduced yield. Identifying the economically appropriate fertiliser N rate is

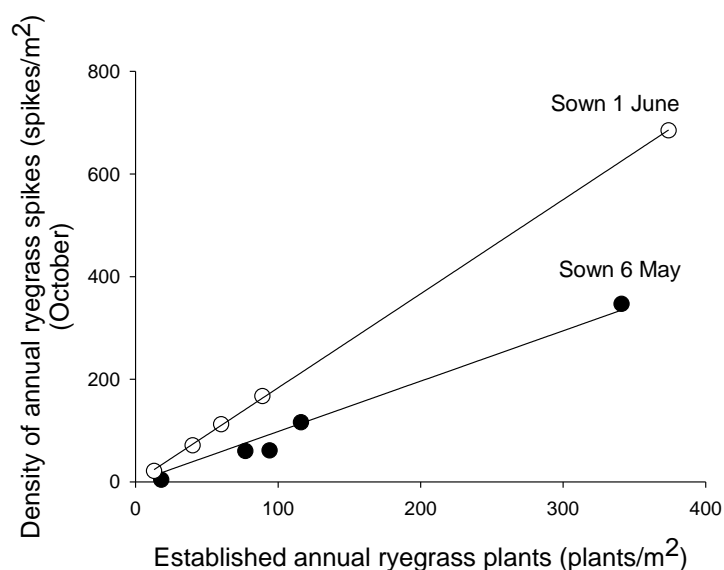


Figure 4. Effect of sowing time on the number of ryegrass spikes in a wheat crop at Roseworthy SA. Ryegrass densities are the result of pre-emergent herbicide use (redrawn from Preston *et al.* 2017)

more challenging in early sown crops, in particular in dry sown situations. When seasonal conditions and yield potential are unknown at the start of the growing season, growers often apply minimal N fertiliser inputs at sowing and rely on top dressing additional fertiliser N when seasonal conditions warrant further application.

Sowing rate and depth

Research has shown no significant yield benefit from altering seed density (50 vs 150 plants/m²) in early-sown wheat crops (Porker *et al.* 2019). However, higher seed rates can increase the competitiveness of the wheat crop with weeds. Frequently growers sow deeper when sowing early to ‘seek’ stored soil moisture and ensure germination. However, higher soil temperatures in early sown crops may limit the depth from which wheat seed can emerge. Rebetzke *et al.* (2016, see also Chapter 17) found that in modern semi-dwarf cultivars the coleoptile length was 43% shorter under soil temperatures of 27 vs 15°C. However, there is genotypic variation in the coleoptile length amongst cultivars, and when sowing early and deep, cultivar choice needs to be adjusted accordingly. Alternative dwarfing genes with longer coleoptiles are currently under development to allow emergence from deeper planting (Rebetzke *et al.* 2007, Kirkegaard and Hunt 2010, Rebetzke *et al.* 2016).

When dry sowing canola there is a greater risk of a small rainfall event that triggers germination but may not be sufficient for continued growth. Due to the risk of poor establishment, sowing densities of early sown canola are often increased (Lilley *et al.* 2018), and seed is sown slightly deeper into wet soil to account for higher evaporation rates. However, deeper sowings lead to decreased germination and emergence (Brill *et al.* 2016) and this trade-off needs to be managed. In contrast, dry sown canola is often sown at a reduced depth to avoid the risk of partial germination (Lilley *et al.* 2018).

Logistical challenges in dry sown crops

There are logistical challenges associated with early sowing crop management. When large areas of a single cultivar have been dry sown, they will emerge at the same time and are at exactly the same growth stage requiring simultaneous in-season management, such as post-emergent herbicide, fungicide, and fertiliser N applications. Fletcher *et al.* (2015) showed that at the whole farm level, dry sowing leads to a more condensed and earlier flowering period compared to farms with no dry sowing. This can be advantageous in seasons ending with heat stress or terminal drought but only minimal increase in frost risk around flowering.

Risks associated with early/dry sowing

Abiotic stresses Early sowing without adjusting cultivar development type results in rapid developmental progression and early flowering, and thus an unacceptable level of frost risk and increased spikelet sterility in frosty seasons and frost-prone environments (Flohr *et al.* 2018b). Cropping programs that begin sowing earlier and sow an appropriate cultivar will have less area of crop at risk of heat stress during grain fill. Growers need to adjust the cultivar development type of both cereals (Flohr *et al.* 2017, 2018b) and canola (Lilley *et al.* 2015, 2019, Kirkegaard *et al.* 2016) to target an optimum flowering window. There are marked differences in frost susceptibility between cereal species, and in many sowing programs barley and oats are sown early in preference to wheat due to reduced sensitivity to frost damage around flowering (DPIRD 2018).

Early sowing can help avoid terminal drought during grain fill by ensuring that grain fill is complete before soil water resources are depleted (Fletcher *et al.* 2015, Flohr *et al.* 2017). However, early sowing can increase the risk of the crop experiencing early soil moisture deficits that may lead to poor emergence, or even seedling death. Fletcher *et al.* (2015) demonstrated that this risk increased dramatically with dry sowing. However, this is rarely a problem, and it may even be beneficial as it will have the effect of seed priming for germination on later germinating rains (Passioura and Angus 2010). In contrast, Wallace (1960) showed that the viability of wheat seed declined when placed in soil that had sufficient moisture for imbibition but not enough to trigger full germination. This loss of viability depended on the soil moisture content and the length of time that the seed was exposed to these conditions (Figure 5). For example, at 15% soil moisture 70% of seed emerged during the initial 18 day period and the remaining 30% of seed was still able to germinate afterwards; but at 9% soil moisture no seed emerged during the initial 18 day period and only 35% of the remaining seed was viable. Growers can use medium term forecasts to dry sow ahead of a forecast rainfall event of sufficient size to ensure germination and emergence (Asseng *et al.* 2016). When sowing in March on heavy clay soils, at least 25 mm of rainfall and stored soil moisture was required for successful wheat establishment, but when sowing on lighter soils in April as little as 10 mm (in furrow irrigation) of water was required (Porker *et al.* 2019).

Early sown canola may be more susceptible to early soil moisture deficits due to its small seed. When sowing early into wet soil the risk of early season drought can be managed by ensuring that sufficient soil moisture for sustained growth is available from rainfall and stored soil moisture. Sharma *et al.* (2013) showed that about 35 mm of plant available soil water was sufficient to sustain plant numbers following initial germination for at least 5 weeks after early April sowing.

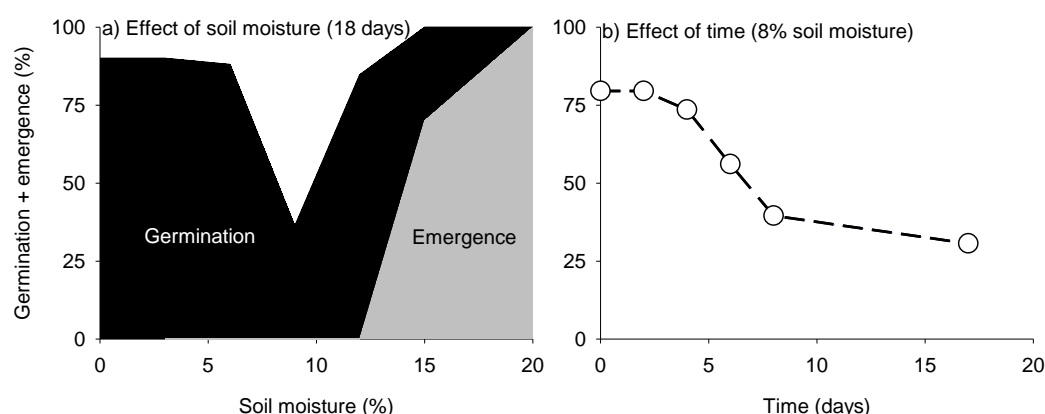


Figure 5. Effect of soil moisture on emergence of wheat seed after 18 days and subsequent germination (a); and number of days at 8% soil moisture on subsequent germination of wheat seed (b). Germination refers to seed that did not germinate and emerge during the 18 day treatment but that was still viable after this period (data from Wallace 1960)

Biotic stress Early established cereals are exposed to a range of new pathogens (Hunt 2017). These include barley yellow dwarf virus, wheat streak mosaic virus, stem and leaf rusts, and *Zymoseptoria tritici* (see Hunt 2017 for a more detailed discussion of the implications of these diseases in early sown cereals). Early

sowing of canola also influence the disease risk of canola. Both black leg (*Leptosphaeria maculans*) and sclerotinia (*Sclerotinia sclerotiorum*) can infect the upper canopy of canola and reduce yield. Sprague *et al.* (2017) demonstrated that early sown canola crops developed greater levels of upper canopy black leg infection compared with delayed sowing. For all crops, disease monitoring and management packages need to be adjusted in early sown crops.

Farming system implications of early sowing practices

Multiple cultivar storage and establishment opportunities

For a given location there is an optimum flowering window for both cereals and canola (Flohr *et al.* 2017, Lilley *et al.* 2019). For a given sowing date, the cultivar needs to be selected to ensure flowering occurs in this period (Figure 1, Hunt 2017, Flohr *et al.* 2018b, Hunt *et al.* 2019, Lilley *et al.* 2019). This means that in environments with variable and unpredictable sowing opportunities, a grower must store multiple cultivars on farm so that the right phenology type can be used for a given sowing opportunity. Yield benefits associated with early sowing of long season cultivars (particularly those in Mediterranean environments) can only occur provided that growers store cultivars with different development speeds on-farm, with no certainty of the area to be planted (or whether sowing opportunities occur at all in a given season) to each until the time when establishment opportunities are known. This varies from season-to season and between environments. For example, by 15 April a wet sowing opportunity has occurred in nearly 50% of seasons at Wagga Wagga NSW, 20% of seasons in Minnipa SA and Mildura Vic but only 13% of seasons in Merredin WA (Figure 6).

In seasons where the break has not occurred it is recommended that winter crop cultivars are not dry sown (Hunt 2017) as the risks of late emergence could mean that this phenology type is inappropriate. One approach is to sow mixtures of early and late cultivars to mitigate the risks of frost and heat (Fletcher *et al.* 2019). However, this approach requires further testing.

The need to store multiple cultivars is a possible barrier to adoption of this system, but given the probable yield increases at the whole farm level demonstrated in Hunt *et al.* (2019), growers will likely see value in adoption. A robust economic analysis of the benefits/risks of storing multiple cultivars on farm is urgently required. It is likely that the outcome of such an analysis will vary between sites depending on the frequency of early sowing opportunities (Figure 6). Innovation in seed sale swaps or multiple cultivar deal options from seed companies might be a way to operationalise and de-risk the need for multiple cultivars.

CA has been a facilitator of earlier sowing as growers no longer require as much or as frequent rainfall in order to sow their crops. However the benefits of early establishment in dryland farming are still ultimately dependent on irregular rainfall or stored soil moisture, and opportunities do not always exist to plant in early/mid-April (Penrose 1993). Field experiments and simulations studies have shown that early sowing systems can achieve yields similar or more than short-cycle cultivars sown later (Coventry *et al.* 1993, Penrose 1993). However the yield advantage expressed by early sown long-cycle cultivars in experiments conducted over decades has been variable (Frischke *et al.* 2015, Peake *et al.* 2018, Hunt *et al.* 2019). Hunt (2017) has speculated that the yield advantage of early sown long-cycle cultivars is only expressed in seasons where the soil profile fills with water during fallow periods, giving the crop greater access to water through longer root growth duration (Lilley and Kirkegaard 2016). Therefore in fine textured soils with high water holding capacity the incidence of establishment opportunities can potentially be increased where long fallowing and early sowing are used as complementary practices (Schillinger and Young 2014). The fallow helps to reduce weeds and disease which can be difficult to control in early sown crops; early sowing with slow developing cultivars allows the crop to have better use of water that is stored at depth in the soil during the fallow (Oliver *et al.* 2010). The breeding of

cultivars with long coleoptiles that can be sown at depth into stored moisture could also enhance early sowing opportunities (Rebetzke *et al.* 1999). Though not experimentally evaluated, the fallow, deep sowing and long coleoptile cultivar synergy may offer a strategy to overcome limited early establishment opportunities of slow developing cultivars, and requires field validation under Australian conditions. The long fallow and winter wheat synergy is widely practised in low rainfall environments of United States Pacific Northwest, where yield increases of up to 1.6 t/ha have been observed relative to continuous spring wheat rotations (Schillinger and Young 2004).

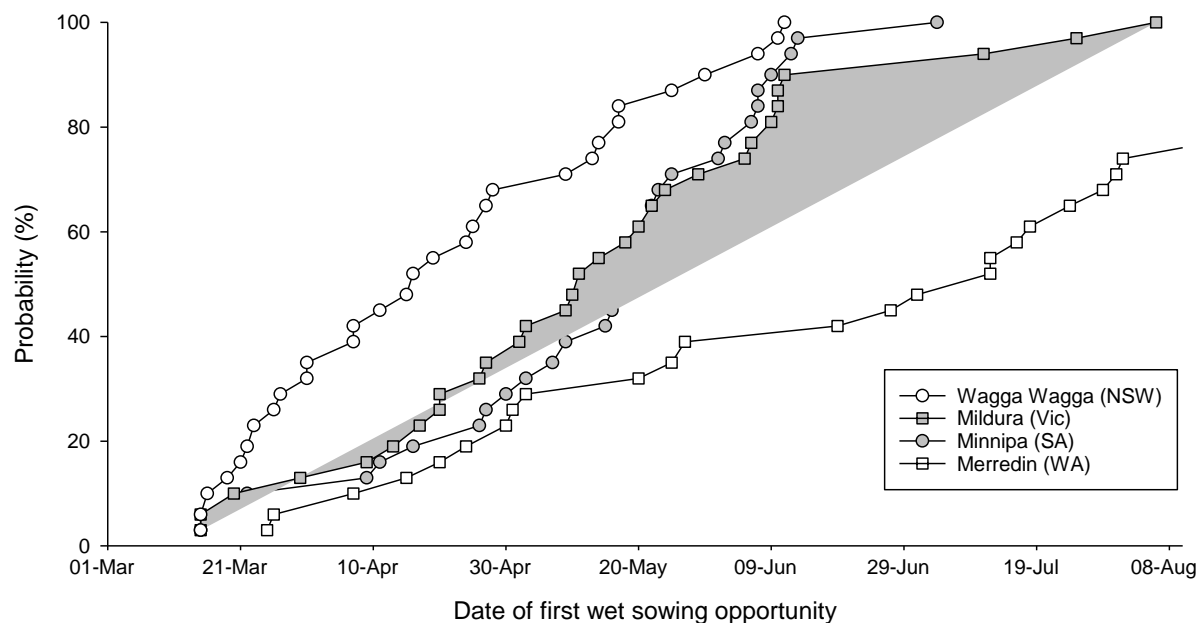


Figure 6. Probability distribution of first sowing opportunity for four representative sites across southern Australia from 1988-2018 using the methods of Unkovich (2010).

The place of early sowing in rotations

Under increasingly warm and variable climates, the efficient use of soil water carried over from the previous crop and of rainfall accumulated during fallow periods is an important element of the farming system (Lilley and Kirkegaard 2007, Hunt and Kirkegaard 2011). One consequence of a deeper root system and a higher yielding crop in one season is that the soil is left in drier state and potentially limits water availability for subsequent crops. A simulation study by Lilley and Kirkegaard (2016) showed that plant available water at sowing of a second crop in sequence was 2-21 mm less following early sowing in the first year compared with a normal sowing time. Historically, crop choice is driven by paddock history in relation to disease and weed break rotation, as well as grain price (Angus *et al.* 2015). As sowing becomes earlier, it is important that soil water availability at the start of the season is considered, and that the crop sequence is managed tactically to optimise the overall system utilisation of water (Lilley and Kirkegaard 2016). It may be preferable to alternate early and normal sowing times within a given paddock. Alternatively, alternating early sown wheat with a long fallow, brown manure, hay or legume crop that helps preserve soil water and N may form a robust crop rotation that also has the benefits of a disease and weed break.

Early sown dual-purpose crops in mixed-enterprises

Utilising early sowing opportunities with dual-purpose crops is a profitable system in mixed farming enterprises. A dual-purpose cereal or canola crop is one that is grazed when vegetative to fill an autumn-winter feed gap. The livestock are removed prior to stem elongation which enables the crop to recover and still produce grain (Virgona *et al.* 2006, Sprague *et al.* 2015). Early sowing combined with slow developing cultivars (Figure 2) results in a longer vegetative stage and greater biomass accumulation to

fill the feed gap (McCormick *et al.* 2012, Bell *et al.* 2015). Early sown, dual-purpose crops have a longer vegetative stage and deeper root growth. They also provide early soil cover which can reduce erosion, evaporation and drainage of early rains (Bell *et al.* 2014).

Grower case studies

Early sowing in practice in southern NSW



John, Michelle, Brendan and Felicity Pattison

- *Location:* Marrar NSW
- *Area:* 1,500 ha
- *Mean annual rainfall:* 520 mm (GSR: 350 mm)
- *Soils:* Red loam, undulating
- *Enterprise mix:* Continuous cropping
canola, wheat, barley, faba beans, lupins
- *Sowing capacity:* 80 ha/day

Sowing across the properties at Marrar commences irrespective of rain in early April, and is ideally completed by mid-May. In most years, crops are sown into moisture with a single disc seeder, which has been afforded by a combination of maintaining full stubble cover (cereals harvested with stripper front) and a rotational weed control strategy. Weed management is a key consideration, which includes an occasional tactical double break in their rotation, and strict summer weed control.

The sowing program commences with canola, progressing to winter wheats, lupins and fababeans, before the remainder of canola is sown prior to the previous benchmark start date of 25 April (Anzac Day). The program then shifts to sowing of longer-season wheat and barley cultivars before finishing with main-season wheat and barley cultivars. In total, sowing consists of 1-2 canola cultivars, 1 lupin and fababean and 2-3 wheat and barley cultivars with the aim to optimise yield and profitability across crops.

The aim is to sow cultivars close to their optimal sowing window, and the order of crops is adjusted as new cultivars are adopted. For example, there has been a clear shift in sowing dates, of up to three weeks in canola, where previously (1990s), they achieved highest yields when sown in early May. The Pattisons have been practising early sowing of cereals since the early 2000s when, as a mixed farming enterprise, they sowed dual-purpose wheats in late March to capture early grazing opportunities.

Early sowing limits pre-season weed control and increases pressure of pests such as mice, slugs and earwigs. However the tactical implementation of the double-break in rotation has reduced the reliance on knock-down herbicides. Pest control is implemented on a seasonal basis if required.

In the future, the Pattisons are interested in commencing sowing earlier, into March, provided that suitable winter cereal cultivars are available that do not need to be managed through grazing. There is also interest in the incorporation of companion cropping into their rotation, as this may offer alternatives to earlier sowing of single species as well as alternative crops, to increase diversity on-farm.

Early sowing in practice in southern WA



Nick and Tryph Gillett

- *Location:* Bencubbin WA
- *Area:* 11,000 ha (10,000 crop and 1,000 fallow)
- *Mean annual rainfall:* 305 mm
GSR: 205 mm average; 165 mm past 10 years
- *Soils:*
Sands, gravel sands, sandy loam, loam to strong clay loams
- *Enterprise mix:* Continuous cropping
wheat (65%), barley (20%), canola (15%)
- *Sowing capacity:* 600 ha/day using 2 units

Seeding at the Gillett's property begins on 10-15 April with the aim of completing seeding by 15 May. Sowing begins irrespective of rainfall and they are happy to plant 100 % of the area dry if necessary. In 2018 they sowed 95% of their crop into dry soil. Sowing takes approximately one month to complete. Barley is normally sown first, followed by canola and then wheat. When possible, canola is sown onto land that was previously in fallow.

The Gilletts have moved to more dry seeding since the 2014 growing season. Severe heat stress in late September 2014 damaged late sown crops at their most vulnerable stage and this highlighted the benefits of sowing early. Previously, they started seeding on 25 April with a view to complete sowing on 10 June. The key drivers for the shift to early and dry sowing have been shorter seasons that highlighted the need to sow early. Also, smaller intensity rainfalls in autumn has meant the focus now aims to utilise small rainfall events rather than sowing into moist soil. Other factors that have made dry sowing possible include: the move to more stubble retention, resulting in a more friable seed bed; and bigger machinery with higher break out pressure tyres.

Nick finds that dry sown crops yield similarly to crops sown on the break of the season. Across his farm he gets more consistent yields using dry sowing as more crop area establishes at the optimal time. Dry sown crops can be less variable than crops sown following light rain. When heavy rain occurs soil crusting can reduce establishment on heavier soil types.

Weed control is the major issue with dry sowing. The weeds and crop emerge at the same time and there is no ability to use a double-knockdown herbicide strategy. Canola can be a useful tool in this respect due to the increased number of herbicide tolerant options. Frost can be an issue with early and dry sowing, although Nick has a geographical spread of crops which helps to mitigate this risk.

Nick does not know whether sowing will get earlier in the future, but he feels he has more to lose from sowing too late compared with sowing too early. Stored summer moisture is an important driver. With stored summer moisture Nick is more confident of sowing early whether into wet or dry soil. An emerging issue with dry sowing is the ability to judge the season and adjust inputs appropriately.

Looking to the future, Nick thinks that wheat cultivars with long coleoptiles that can be sown deep (>100 mm) into stored moisture might be beneficial to his cropping system.

Conclusions and opportunities for future research

In the last 30 years there has been a gradual evolution of sowing dates in southern Australia. Sowing dates have moved earlier by 1 to 1.5 days earlier per year, with a dramatic shift and wide spread adoption of dry sowing in the last 5 years (Fletcher *et al.* 2016, Flohr *et al.* 2018b). The drivers of this revolution have been increased cropping area as farmers seek to improve productivity per labour unit and reduced wet sowing opportunities. The trend towards earlier sowing has been facilitated by no-till and machinery improvements.

Current climate forecasts are limited and are only reliable up to 10 days out. Improved climate forecasting may improve grower confidence and reduce risk when making decisions regarding cultivar choice and utilising sowing opportunities prior to the ‘breaking’ rain (Lilley *et al.* 2019). As our understanding of crop development continues to improve, new cultivars will become available that are better suited to early sowing. Developments in marker assisted selection will aid with the identification of genotypes with the desired suite of traits. Ideally, growers will eventually have access to cultivars that can be sown over a wide range of sowing dates but still flower within the optimum window. Further success with early sowing systems and future yield gains requires continued interaction and collaboration between plant breeders, plant physiologists, agronomists and farmers.

Traits other than flowering time are likely to become increasingly important for early sowing systems. Target traits will include new long coleoptile wheats (Kirkegaard and Hunt 2010, Rebetzke *et al.* 2016, Flohr *et al.* 2018a) with slow development that can be sown early into stored moisture and flower during the OFP. This will also require modification of seeding equipment to enable deeper sowing. Weed control in early and dry sown systems is a key issue to overcome in order to facilitate further success. Therefore high vigour wheat cultivars (Zerner *et al.* 2016, Zhao *et al.* 2019) with weed competitive traits may become a key part of this system. Similarly, crop cultivars and species with new herbicide tolerances have an important role to play. It is unclear whether the competition advantages of early sowing will outweigh the disadvantages of lack of herbicide knockdown options. However, other options to manage the size of the weed seed bank such as crop rotation and harvest weed seed management, will likely become more important.

In the long term, as automation becomes widespread in agriculture the impetus to maximise productivity per labour unit may become relatively less important. For example, if robotic sowing units become available, growers will likely use more smaller units rather than one (or few) large sowing units, because a single operator can remotely control multiple units. In this automated future growers may be able to sow large areas of crop in a relatively short timeframe which would mean that dry sowing becomes less critical. Furthermore, as a new range of sensors are developed, technologies that sense soil moisture and adjust seeding depth automatically so that seed into soil moisture may help to avoid poor establishment. However, recent research has demonstrated that there are large possible yield benefits from early sowing (Flohr *et al.* 2018b, Hunt *et al.* 2019) suggesting that the adoption of early sowing will likely continue to increase.

References

- Anderson WK, Stephens D, Siddique KHM (2016) Dryland agriculture in Australia: Experiences and innovations. In (Eds. M Farooq, KHM Siddique) “Innovations in Dryland Agriculture” pp 299-319 (Springer: Cham)
- Angadi SV, Cutforth HW, Miller PR *et al.* (2000) Response of three Brassica species to high temperature stress during reproductive growth. *Canadian Journal of Plant Science* **80**, 693-701
- Angus JF, Kirkegaard JA, Hunt JR *et al.* (2015) Break crops and rotations for wheat. *Crop and Pasture Science* **66**, 523-552
- Asseng S, McIntosh PC, Thomas G *et al.* (2016) Is a 10-day rainfall forecast of value in dry-land wheat cropping? *Agricultural and Forest Meteorology* **216**, 170-176
- Bell LW, Lilley JM, Hunt JR, Kirkegaard JA (2015) Optimising grain yield and grazing potential of crops across Australia’s high-rainfall zone: a simulation analysis. 1. Wheat. *Crop and Pasture Science* **66**, 332-348
- Bell LW, Moore AD, Kirkegaard JA (2014) Evolution in crop-livestock integration systems that improve farm productivity and environmental performance in Australia. *European Journal of Agronomy* **57**, 10-20

- Borger CP, Hashem A (2007) Evaluating the double knockdown technique: sequence, application interval, and annual ryegrass growth stage. *Australian Journal of Agricultural Research* **58**, 265-271
- Brill R, Xing H, Napier T *et al.* (2019) Canola Agronomy – consistent messages on canola agronomy hold strong in a Decile 1 season. *GRDC Updates*, Wagga Wagga, Australia
- Brill RD, Jenkins ML, Gardner MJ *et al.* (2016) Optimising canola establishment and yield in south-eastern Australia with hybrids and large seed. *Crop and Pasture Science* **67**, 409-418
- Cossani CM, Cozzolino D, Sadras VO (2019) Can N mitigate adverse effects of elevated temperature in wheat? *Proceedings of 19th Australian Agronomy Conference*, Wagga Wagga (in press)
- Coventry DR, Reeves TG, Brooke HD, Cann DK (1993) Influence of genotype, sowing date, and seeding rate on wheat development and yield. *Australian Journal of Experimental Agriculture* **33**, 751-757
- D’Emden FH, Llewellyn RS, Burton MP (2008) Factors influencing adoption of conservation tillage in Australian cropping regions. *Australian Journal of Agricultural Resource Economics* **52**, 169-182
- Davidson JL, Christian KR, Jones DB, Bremner PM (1985) Responses of wheat to vernalisation and photoperiod. *Australian Journal of Agricultural Research* **36**, 347-359
- Dixit PN, Chen D (2011) Effect of topography on farm-scale spatial variation in extreme temperatures in the Southern Mallee of Victoria, Australia. *Theoretical and Applied Climatology* **103**, 533-542
- DPIRD (2018) Managing frost risk. www.agric.wa.gov.au/frost/managing-frost-risk
- Eagles HA, Cane K, Kuchel H *et al.* (2010) Photoperiod and vernalisation gene effects in southern Australian wheat. *Crop and Pasture Science* **61**, 721-730
- Ewert F, Rodriguez D, Jamieson P *et al.* (2002) Effects of elevated CO₂ and drought on wheat: testing crop simulation models for different experimental and climatic conditions. *Agriculture Ecosystems & Environment* **93**, 249-266
- Farré I, Robertson MJ, Asseng S *et al.* (2004) Simulating lupin development, growth, and yield in a Mediterranean environment. *Australian Journal of Agricultural Research* **55**, 863-877
- Farre I, Robertson MJ, Walton G, Asseng S (2002) Simulating phenology and yield response of canola to sowing date in Western Australia using the APSIM model. *Australian Journal of Agricultural Research* **53**, 1155-1164
- Fischer RA (1985) Number of kernels in wheat crops and the influence of solar radiation and temperature. *The Journal of Agricultural Science* **105**, 447-461
- Fischer RA (2009) Farming systems of Australia, exploiting the synergy between genetic improvement and agronomy. In (Eds. V Sadras, D Calderini) “Applied Crop Physiology: Boundaries with Genetic Improvement and Agronomy” pp 23-54 (Elsevier Inc: Amsterdam NL)
- Fischer RA (2011) Wheat physiology: a review of recent developments. *Crop and Pasture Science* **62**, 95-114
- Fletcher A, Lawes R, Weeks C (2016) Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. *Crop and Pasture Science* **67**, 1268-1280
- Fletcher A, Ogden G, Sharma D (2019) Mixing it up – wheat cultivar mixtures can increase yield and buffer the risk of flowering too early or too late. *European Journal of Agronomy* **103**, 90-97
- Fletcher AL, Robertson MJ, Abrecht DG *et al.* (2015) Dry sowing increases farm level wheat yields but not production risks in a Mediterranean environment. *Agricultural Systems* **136**, 114-124
- Flohr BM, Hunt JR, Kirkegaard J, Evans J (2017) Water and temperature stress define the optimal flowering period for wheat in south-eastern Australia. *Field Crops Research* **209**, 108-119
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018a) Genotype × management strategies to stabilise the flowering time of wheat in the south-eastern Australian wheatbelt. *Crop and Pasture Science* **69**, 547-560
- Flohr B, Hunt J, Kirkegaard J *et al.* (2018b) Fast winter wheat phenology can stabilise flowering date and maximise grain yield in semi-arid Mediterranean and temperate environments. *Field Crops Research* **223**, 12-25
- Frischke AJ, Hunt JR, McMillan DK, Browne CJ (2015) Forage and grain yield of grazed or defoliated spring and winter cereals in a winter-dominant, low-rainfall environment. *Crop and Pasture Science* **66**, 308-317
- Harker KN, O’Donovan JT, Turkington TK *et al.* (2012) High-yield no-till canola production on the Canadian prairies. *Canadian Journal of Plant Science* **92**, 221-233
- Harris FAJ, Eagles HA, Virgona JM *et al.* (2017) Effect of *VRN1* and *PPD1* genes on anthesis date and wheat growth. *Crop and Pasture Science* **68**, 195-201
- Hunt JR (2017) Winter wheat cultivars in Australian farming systems: a review. *Crop and Pasture Science* **68**, 501-515
- Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop and Pasture Science* **62**, 915-929
- Hunt JR, Lilley JM, Trevaskis B *et al.* (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change* **9**, 244-247

- Kemanian AR, Stockle CO, Huggins DR (2005) Transpiration-use efficiency of barley. *Agricultural and Forest Meteorology* **130**, 1-11
- Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- Kirkegaard JA, Lilley JM, Brill RD *et al.* (2016) Re-evaluating sowing time of spring canola (*Brassica napus* L.) in south-eastern Australia—how early is too early? *Crop and Pasture Science* **67**, 381-396
- Kirkegaard JA, Lilley JM, Brill RD *et al.* (2018) The critical period for yield and quality determination in canola (*Brassica napus* L.). *Field Crops Research* **222**, 180-188
- Kirkegaard JA, Lilley JM, Hunt JR *et al.* (2015) Effect of defoliation by grazing or shoot removal on the root growth of field-grown wheat (*Triticum aestivum* L.). *Crop and Pasture Science* **66**, 249-259
- Kohn GD, Storrier RR (1970) Time of sowing and wheat production in southern NSW. *Australian Journal of Experimental Agriculture and Animal Husbandry* **10**, 604-609
- Lawes, RA, Huth, ND, Hochman, Z (2016) Commercially available wheat cultivars are broadly adapted to location and time of sowing in Australia's grain zone. *European Journal of Agronomy* **77**, 38-46.
- Lilley JM, Bell LW, Kirkegaard JA (2015) Optimising grain yield and grazing potential of crops across Australia's high-rainfall zone: a simulation analysis. 2. Canola. *Crop and Pasture Science* **66**, 349-364
- Lilley JM, Flohr BM, Whish JPM *et al.* (2019) Defining optimal sowing and flowering periods for canola in Australia. *Field Crops Research* **235**, 118-128
- Lilley JM, Kirkegaard JA (2007) Seasonal variation in the value of subsoil water to wheat: simulation studies in southern New South Wales. *Australian Journal of Agricultural Research* **58**, 1115-1128
- Lilley JM, Kirkegaard JA (2016) Farming system context drives the value of deep wheat roots in semi-arid environments. *Journal of Experimental Botany* **67**, 3665-3681
- Lilley JM, Kirkegaard JA, Brill R, Ware A (2018) Ten tips to early-sown canola. pp7
<https://grdc.com.au/10TipsEarlySownCanola>
- Matthews P, McCaffery D, Jenkins L (2018) Winter Crop Variety Sowing Guide 2019 (NSW Department of Primary Industries: Orange)
www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide
- McCormick JJ, Virgona JM, Kirkegaard JA (2012) Growth, recovery, and yield of dual-purpose canola (*Brassica napus*) in the medium-rainfall zone of south-eastern Australia. *Crop and Pasture Science* **63**, 635-646
- McNee M, Fletcher AL, Minkey D, Celenza L (2015) Extent and attitudes of growers to dry seeding in the agroecological zones of Western Australia. *Proceedings of 17th Australian Agronomy Conference* Hobart, Tas. pp 247-250 www.agronomy2015.com.au
- Minkey D (2017) Decay of pre-emergent herbicides in dry soils. *GRDC Agribusiness Crop Updates*, Burswood WA. www.giwa.org.au/2017researchupdates
- Morrison MJ, Stewart DW (2002) Heat stress during flowering in summer Brassica. *Crop Science* **42**, 797-803
- Oliver YM, Robertson MJ, Weeks C (2010) A new look at an old practice: Benefits from soil water accumulation in long fallows under Mediterranean conditions. *Agricultural Water Management* **98**, 291-300
- Passioura JB, Angus JF (2010) Improving productivity of crops in water-limited environments. *Advances in Agronomy* **106**, 37-75
- Peake AS, Das BT, Bell KL *et al.* (2018) Effect of variable crop duration on grain yield of irrigated spring-wheat when flowering is synchronised. *Field Crops Research* **228**, 183-194
- Penrose L (1993) Yield of early dryland sowing of wheat with winter and spring habit in southern and central New South Wales. *Australian Journal of Experimental Agriculture* **33**, 601-608
- Pook M, Lisson S, Risbey J *et al.* (2009) The autumn break for cropping in southeast Australia: trends, synoptic influences and impacts on wheat yield. *International Journal of Climatology* **29**, 2012-2026
- Porker K, Bruce D, Spriggs B *et al.* (2019) Emerging management tips for early sown winter wheats. GRDC Grains Research Update, Wagga Wagga, Australia
- Porker K, Coventry S, Trevaskis B, Fettell N (2017) Is Vrn-H1 a missed opportunity for southern Australian barley growers? *Proceedings of 18th Australian Society of Agronomy Conference*, Ballarat, Australia,
- Preston C, Kleeman S, Gill G *et al.* (2017) Weed control and its impact on yield.
www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/07/weed-control-and-its-impact-on-yield
- Pugsley AT (1983) The impact of plant physiology on Australian wheat breeding. *Euphytica* **32**, 743-748
- Rebetzke GJ, Richards RA, Fettell NA *et al.* (2007) Genotypic increases in coleoptile length improves stand establishment, vigour and grain yield of deep-sown wheat. *Field Crops Research* **100**, 10-23
- Rebetzke GJ, Richards RA, Fischer VM, Mickelson BJ (1999) Breeding long coleoptile, reduced height wheats. *Euphytica* **106**, 159-168

- Rebetzke GJ, Zheng B, Chapman SC (2016) Do wheat breeders have suitable genetic variation to overcome short coleoptiles and poor establishment in the warmer soils of future climates? *Functional Plant Biology* **43**, 961-972
- Richards RA (1991) Crop improvement for temperate Australia: Future opportunities. *Field Crops Research* **26**, 141-169
- Roper MM, Davies SL, Blackwell PS *et al.* (2015) Management options for water-repellent soils in Australian dryland agriculture. *Soil Research* **53**, 786-806
- Schillinger WF, Young DL (2004) Cropping systems research in the World's driest rainfed wheat region. *Agronomy Journal* **96**, 1182-1187
- Schillinger WF, Young DL (2014) Best management practices for summer fallow in the World's driest rainfed wheat region. *Soil Science Society of America Journal* **78**, 1707-1715
- Seymour M, Kirkegaard JA, Peoples MB *et al.* (2012) Break-crop benefits to wheat in Western Australia – insights from over three decades of research. *Crop and Pasture Science* **63**, 1-16
- Sharma DL, D'Antuono MF, Anderson WK *et al.* (2008) Variability of optimum sowing time for wheat yield in Western Australia. *Australian Journal of Agricultural Research* **59**, 958-970
- Sharma DL, Peek C, Riethmuller G, Abrecht DG (2013) How much moisture is enough to successfully establish April-sown canola. Crop Updates. Perth www.giwa.org.au/2013-crop-updates
- Sprague S, Graham J, Brill RCM (2017) Early flowering canola - what is the blackleg risk? *Proceedings of 18th Australian Agronomy Conference*. Ballarat, Australia
- Sprague SJ, Kirkegaard JA, Dove H *et al.* (2015) Integrating dual-purpose wheat and canola into high-rainfall livestock systems in south-eastern Australia. 1. Crop forage and grain yield. *Crop and Pasture Science* **66**, 365-376
- Stephens DJ, Lyons TJ (1998) Variability and trends in sowing dates across the Australian wheatbelt. *Australian Journal of Agricultural Research* **49**, 1111-1118
- Unkovich MJ (2010) A simple, self adjusting rule for identifying seasonal breaks for crop models. *Proceedings of 15th Australian Agronomy Conference*. Lincoln, New Zealand
www.regional.org.au/au/asa/2010/crop-production/sequence/7129_unkovich.htm
- Virgona JM, Gummer FAJ, Angus JF (2006) Effects of grazing on wheat growth, yield, development, water use, and nitrogen use. *Australian Journal of Agricultural Research* **57**, 1307-1319
- Wallace HAH (1960) Factors affecting subsequent germination of cereal seeds sown in soils of subgermination moisture content. *Canadian Journal of Botany* **38**, 287-306
- Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. *Weed Technology* **27**, 431-436
- Whish J, Lilley J, Cocks B, Bullock M (2018) Predicting canola phenology in warm environments. *AusCanola 2018: Proceedings of 20th Australian Research Assembly on Brassicas*.
- Zerner, C, Rebetzke GJ, Gill GS (2016) Genotypic stability of weed competitive ability for bread wheat (*Triticum aestivum*) genotypes in multiple environments. *Crop and Pasture Science* **67**, 695-70
- Zhao Z, Rebetzke GJ, Zheng B *et al.* (2019) Modelling impact of early vigour on wheat yield in dryland regions. *Journal of Experimental Botany* **70**, 2535-2548

Chapter 19

Diversifying the cropping phase

Marisa Collins and Rob Norton

Introduction

Globally, growing crops in short rotation or in monoculture is common, largely in response to market trends, increasing frequency of climate trends affecting grower risk profiles (*e.g.* droughts, frost, high temperatures), changing global food demands, technological advances, government incentives, and retailer/consumer trends. This phenomenon persists despite the risks associated with monocultures and the known benefits from growing crops after an unrelated ('break') crop species (Kirkegaard *et al.* 2008, Seymour *et al.* 2012, Angus *et al.* 2015, Hegewald *et al.* 2018). In Australia, extensive evidence illustrating the advantages of rotations and break crops exists but continuous monocultures of wheat, or short sequences dominated by wheat, persist (Robertson *et al.* 2010, Seymour *et al.* 2012). Factors that favour the expansion of cereal monoculture include increased availability of inexpensive inputs (fertiliser and herbicides) and persistent perceptions that wheat-intensive sequences are lower risk and more profitable, particularly in association with poor legume performance in many years and low canola yields in dry seasons (Kirkegaard *et al.* 2014). Factors favouring expansion of break crops comprise wide-spread adoption of conservation agriculture (CA) combined with better adapted, lower risk, and higher yielding break crop options as well as attractive market prices for many break crop options. In Australia, wheat-dominant farming systems define break crops as a pulse or oilseed (usually canola), grown instead of cereals.

Diverse crop sequences, along with less tillage and soil cover form the three pillars of CA. Over the last 30 years, the largely wholesale adoption of CA and particularly NT in Australia has been a progressive response to a range of factors challenging the sustainability of our farming systems (Kirkegaard *et al.* 2014). Highly mechanised and intensive approaches to cropping broad-scale areas on soils at high risk to erosion/structural instability, and economic drivers such as increasing fuel costs and labour shortages in regional areas, have led to widespread implementation (> 74%, Umbers *et al.* 2017) of CA practices such as reduced/no-till systems and stubble retention/surface cover (Llewellyn *et al.* 2012, Kirkegaard *et al.* 2014). Break crops play an integral role in the success and sustainability of this system through several mechanisms.

Benefits of break crops include yield improvement for following crops through impacts on:

- disease;
- soil nutrient supply and demand; and
- soil structure and water supply benefits,

and are well documented (Hunt and Kirkegaard 2011, Angus and Peoples 2012, Kirkegaard and Ryan 2014, Angus *et al.* 2015). However, more recently, the application of no-till/reduced tillage practices and associated high levels of herbicide application required for fallow weed management have created the additional benefits of:

- weed control and management of herbicide resistance risk (D'Emden and Llewellyn 2006, Bajwa 2014).

The challenges associated with individual break crops and inclusion of break crops within sequences also include economics, management of grower risk, and optimisation of individual crops and cropping sequences (Goward *et al.* 2017) as well as addressing the agronomic challenges of the poor performance of break crops under soil constraints; pest and disease management; management of weeds including herbicide resistance and residuals; and soil protection under break crops.

Trends in break crop useage in Australia

Area and species

During the 2002-2010 dry period in south-eastern Australia, now known as the ‘millenium drought’, dryland wheat production increased, despite a 12% yield decrease in on-farm yields comparing drought and pre-drought years (van Dijk *et al.* 2013). This occurred as growers increased the intensity and area of wheat production by 22% under a drier, higher risk environment (van Dijk *et al.* 2013). This occurred at the expense of other dryland crops, particularly canola and pulses. The environment risk is an important consideration when deciding where, when and what break crops are grown. For example, in Western Australia (WA) Robertson *et al.* (2010) found the area grown to lupins and canola, decreased in drier regions compared with medium rainfall areas. Even though the area cropped to break crops is smaller (15%) in drier areas / seasons break crops were still an important component of the farming system and the response of whole-farm profit was at or near an optimum of 23-38% (Robertson *et al.* 2010). The difference between grower action and simulation was that modelling did not account for the effect that risk played in grower decisions about planting break crops. Since the end of the millennium drought, total production area planted to both pulses and canola has increased 3-6% overall, while concurrently the area planted to wheat area decreased from 85 to 74% (ABARES 2018). This represents a > 60% increase in the total area planted to both pulses and canola in the period from 2008 to 2017. Most notably, this trend accelerated in 2017-18 with break crop production comprising 9% pulses and 14% canola of total production area (ABARES 2018).

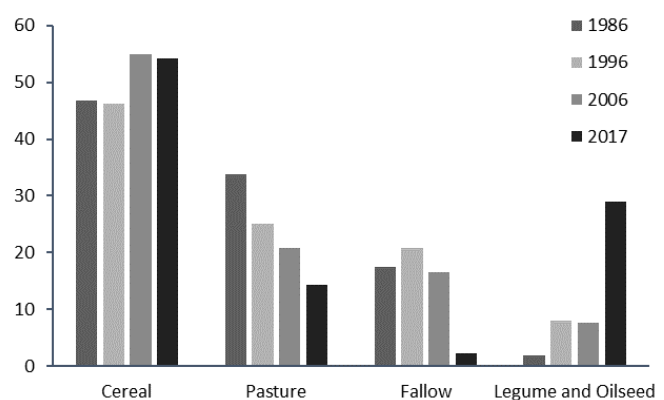


Figure 1. Percentage of paddocks recorded for each land use during the 1986, 1996, 2006 and 2017 Victorian land-use survey (Moodie and Sonogan, unpublished)

The most common break crops in Australian farming systems are canola (14%), chickpeas, lupins, field peas, fababeans, lentils and mungbeans (ABARES 2018). Break crops underpin the continued profitability of cereal (wheat or barley) based cropping sequences (Goward *et al.* 2017) and, since the 1990s, they have increasingly replaced pastures and fallow in our farming systems as shown by Moodie and Sonogan (Figure 1) in a long-term land-use survey of the Victorian Mallee (low rainfall zone in north-east Victoria) across 1986, 2006 and 2017. The proportion of fallow paddocks decreased sharply after the 2006 survey while the percentage of paddocks managed as a regenerating pasture steadily decreased from the 1980s. The management phase with the greatest increase was lentils with 10.6% of paddocks sown to this crop in 2017 compared with just 1.2% of paddocks in 2006 and no paddocks in 1996. Lentils are well suited to both the environment and farming systems in the Mallee region and attractive market prices have made them a profitable break crop choice for many growers. The proportion of field pea, vetch and canola crops has also increased significantly over the past decade. Similar trends in changes of land-use have occurred in other areas of the southern grain region, particularly in NSW, as traditional mixed crop-livestock systems with long-term pastures have changed towards more intensive cropping of cereals and canola (Kirkegaard *et al.* 2011).

Since the early 1990s, canola has become a significant part of cropping systems in medium and higher rainfall areas of southern and western Australia, with little to no production in northern growing regions

above 30°S (Kirkegaard *et al.* 2016). Prior to 1990, only limited canola was grown but, with the development of improved tolerance to blackleg and the incorporation of herbicide tolerance, the production area doubled each year for most of the 1990s and by 2017 there were 2.73 Mha sown producing 3.6 Mt, with just over 50% in WA and large areas in NSW and Vic (ABARES 2018). Much of this increase was a consequence of the release of triazine tolerant (TT) canola types which allowed effective weed control against particular weeds such as wild radish (*Raphanus raphanistrum*).

Table 1. Break crop area and production nationally and by state in 2017 including change in production from 1990 (FAOSTAT 2017, ABARES 2018)

Crop type	Area sown '000 ha	Production kt	Percentage change in production 1990 to 2017	Percentage of production by state				
				NSW	QLD	SA	VIC	WA
Wheat	12,237	21,244	41 %	21	3	19	19	37
Barley	3,878	8,928	117 %	13	1	20	24	41
Canola	2,729	3,669	3629 %	17	0	9	20	54
Chickpeas	1,116	1,148	503 %	35	56	3	5	1
Lupins	518	631	-17 %	12	0	12	6	70
Lentils	353	485	16067 %	6	0	52	41	1
Fababeans	220	330	1874 %	15	2	36	45	1
Field peas	222	289	-9 %	18	0	43	24	15

Since that period, with the addition of alternative herbicide tolerances, improved disease resistance and better adapted cultivars including hybrids, canola has become the third ranked winter crop in area sown and crop value (ABARES 2018). Production areas fluctuate seasonally, principally in the lower rainfall areas where a late autumn break will see growers shift away from canola to barley. Overall, canola is around 13% of the winter crop area. In some of the higher rainfall regions, such as the Lower Eyre Peninsula or parts of Western Australia, canola can be up to 30% of the cropped area and so has become a significant part of the farming system and the crop rotation. Five-year average gross value of production is around \$2b per year (ABARES 2018).

For pulses, rapidly increasing production levels and area planted over the last decade have been planted to winter legumes, including chickpeas, lentils and fababeans (Table 1), and in northern Australia summer legumes such as mungbeans (ABARES 2018). The initial increase in pulses was in response to the demand for protein supplements for intensively housed animals, although more recently high value pulses like chickpea and lentil make their way into the premium human consumption markets. Since 1990, but particularly from 2000 onward this has been somewhat offset by a seasonally dependant but steady decline in both area planted (-10%) and production (9-17%) for both field peas and lupins, particularly in WA (ABARES 2018). Five year average gross value of production for pulses (gross value \$1.6b) consisted of chickpeas 35-40%, lupins 20-25%, lentils (8-17%), field pea (8-13%), fababeans (8-13 %) and mungbeans < 5% (Table 2).

Chickpeas are primarily grown in NSW and Queensland (Table 2) with small levels of production in all other regions (Table 1). Lupins are mostly produced in WA (> 70%) where they grow across a large area of the grain belt in soils that often have low fertility and persistent soil constraints. They are also grown in NSW, Victoria and South Australia in much lower production levels. Lentil production has increased exponentially since 1990 (Table 1) almost exclusively is grown in SA and Victoria. Fababeans are mostly cultivated in Vic (39%), SA (33%) and NSW (24%) with small production in WA and Qld. Field peas are a major pulse crop in the southern cropping zone (S-NSW, Vic, SA) with > 65% production in SA and Victoria, and smaller areas in WA.

Yield benefits to wheat from break crops

Research from Australia and around the world generally find an average yield improvement of 1.1-1.8 (t/ ha) of grain by wheat grown following a legume in the absence of N fertiliser, and an additional 0.8 t/ha if wheat is grown after canola compared with wheat on wheat (Angus *et al.* 2015). While original research suggested that the break crop gave a percentage increase in the subsequent cereal, there are

many studies now that suggest the break crop effect is a fixed amount rather than being proportional to the yield of the cereal crop (Kirkegaard and Ryan 2014, Angus *et al.* 2015, Moodie *et al.* 2017). This effect is persistent across rainfall zones with several studies finding cumulative break crop effects of over of 1 t/ha in subsequent wheat crops against relatively low background yields of continuous cereal treatment ranging from 1.5-3.5 t/ha in the low rainfall zone (LRZ) in the Vic / SA Mallee (McBeath *et al.* 2015, Moodie *et al.* 2017). There can be carryover of the break crop benefit with additional yield in a second wheat crop after a single break crop, ranging from 20% of the effect on a first wheat crop after canola, to 60% after legumes (Angus *et al.* 2015). In WA, Seymour *et al.* (2012) found that significant break-crop benefits from lupins (+0.40 t/ha) persisted to a third wheat crop but effects were inconsistent beyond that point. The persistence of the break crop effect is affected by environmental conditions that can affect the legacy effect of break crops, particularly the amount of N fixed and so the response to additional N (Kirkegaard and Ryan 2014, Angus *et al.* 2015).

Table 2. Pulse production and areas of planting over the five years to 2017 (ABARES 2018).

Crop type	% of pulse crop production	Areas of production
Chickpeas	35 - 40	N-NSW and Qld > 90% production, grows in all regions
Lupins	20 - 25	WA > 70% production, < 12% in NSW, SA and Vic
Lentils	8 - 17	SA and Vic > 90% production, NSW, WA
Fababeans	8 - 13	SA and Vic > 80% production, NSW, Qld, WA
Field peas	8 - 13	SA and Vic > 65% production, NSW and WA
Mungbeans	< 5	N-NSW and Qld > 95% production

Large yield impacts (>0.5 t/ha), both positive and negative, can persist for 3-4 years in semi-arid environments as a result of water, N and disease inoculum legacies of early crop sequence choices (Kirkegaard and Ryan 2014). The impact on weed populations tends to be limited to shorter cycles due to weed seed persistence (Moodie *et al.* 2017). Under medium and high rainfall, the mean yield effect on a third wheat crop is generally negligible (Angus *et al.* 2015). There is also an additive yield benefit to additional successive break crops ('double-break'), with two successive break crops yielding 0.1- 0.3 t greater than after a single break crop (Angus *et al.* 2015). A review by Angus *et al.* (2015) found the observed ranking of break-crop species in terms of mean yield response of the following wheat crop was: oats < canola, mustard and flax < field peas, fababeans, chickpeas, lentils and lupins. This is similar to Seymour *et al.* (2012) in WA finding yield response was fallow (0.30 t/ha) < oats (0.35 t/ha) < canola (0.40 t/ha) < field peas (0.45 t/ha) < lupin (0.60 t/ha). For all break crops, the mean wheat yield increase appears largely independent of the level of wheat yield, representing a step-change rather than a proportional improvement in yield. While the major drivers of yield response are generally known (*e.g.* nitrogen, water, weeds and disease), the trigger points for the drivers of the response are poorly defined for nearly all grain regions. Understanding these trigger points in our farming systems and climates would aid growers in making decisions about the point at which the benefits outweigh the higher risk of these crops and inform the decision to include them within the system.

Crops grown after break crops are consistently higher yielding than continuous wheat (Figure 2) and generally have lower input costs; consequently, cumulative economic returns for sequences that include break crops tend to be greater over a 3-5 year time-frame (McBeath *et al.* 2015, Goward *et al.* 2017). Across a range of rainfall zones Angus *et al.* (2015) collated 180 comparisons of canola-wheat versus wheat-wheat sequences and almost all experiments demonstrated a yield benefit (*i.e.* data points for yield after canola were above the 1:1 dashed line) which represented an average 0.8 t/ha additional grain for wheat grown following canola (Figure 2A). Comparison of legume-wheat and wheat-wheat sequence comparisons (300 experiments) suggested that on average an additional 0.7 to 1.6 t/ha of wheat grain was harvested after a legume crop depending upon the species (Angus *et al.* 2015).

Observed benefits/impacts of break crops depend on seasonal conditions, paddock history, crop inputs and key agronomic constraints within farming systems and rainfall zones (Figure). As a rule of thumb the more limiting the productivity constraint is (*e.g.* disease, nitrogen, weed pressure) and the higher the yield potential (*i.e.* high water availability) the break crops effect can be larger, particularly if inputs

are low or limiting. Achieving a break crop benefit then depends on selecting the best break crop for the grower's planting situation, climate, soil type and farming system. Some of these observed increases in wheat yields after canola or legumes may be derived from the breaking of cereal disease cycles (Kirkegaard *et al.* 1994, Kirkegaard *et al.* 2004): for legumes, effects on soil biology and increased availability of N and other nutrients can also be very important components of the yield benefits (Peoples *et al.* 2009, Angus *et al.* 2015). For many fields, changes in soil structural characteristics that encourage a deeper rooting depth by following crops, or the carry-over of residual soil water (Kirkegaard *et al.* 2008, Kirkegaard and Hunt 2010) influence growth and yield of the following crops. In fields with heavy weed burdens, particularly grassy weeds, break crops can provide an alternative range of weed control options. As discussed previously, in some instances, these benefits can last for several subsequent cereal crops.

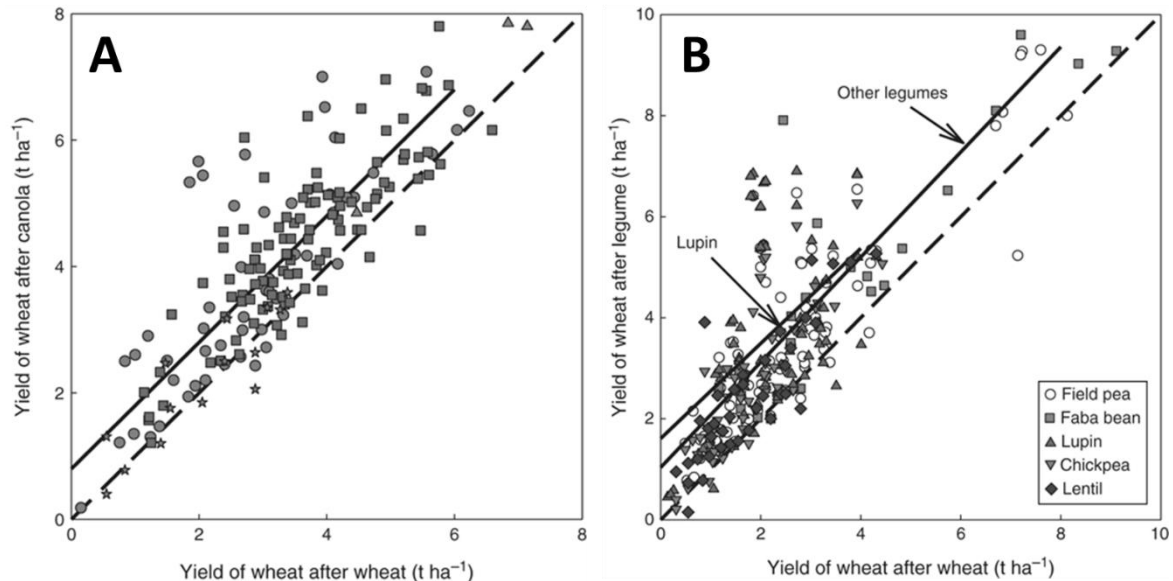


Figure 2. Yield of wheat after (A) canola compared with wheat after wheat growing in the same experiments. Symbols represent experimental locations. Circles, Australia; Squares, Sweden; Triangles, Other Europe; Stars, North America. (B) grain legumes compared with wheat after wheat growing in the same experiments. The dashed lines represent equal yields and the solid lines represent fitted equations. Symbols represent field pea, \circ ; faba bean, \blacksquare ; lupin, \blacktriangle ; chickpea, \blacktriangledown ; lentil, \blacklozenge . The 1:1 dashed line represents equal yield (Angus *et al.* 2015)

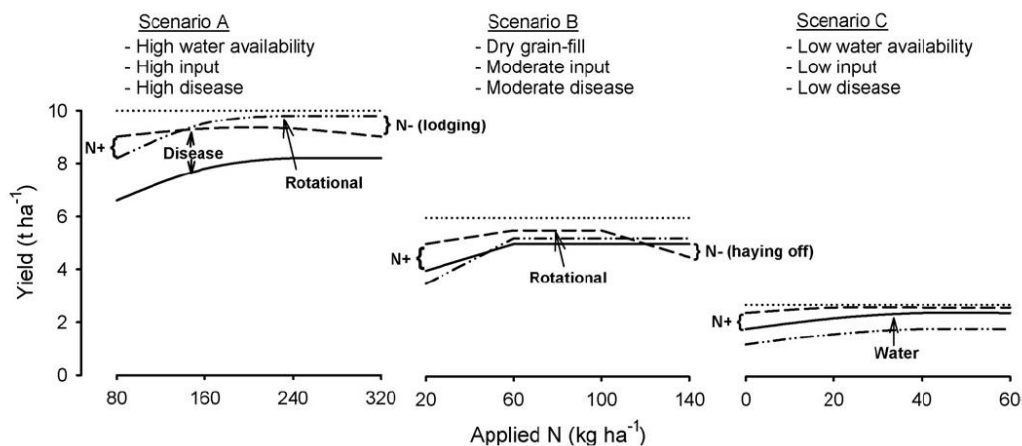


Figure 3. Typical responses of wheat to previous wheat (solid), legume (dashed) and oilseed (dot-dash) break crops under different potential yield scenarios and different N application rates. The dotted line shows the potential yield. The mechanisms causing responses to differ between previous crops are shown (N = nitrogen, \pm denotes yield increase or decrease associated with N (Kirkegaard *et al.* 2008)

Disease breaks

Plant diseases have been estimated to cause an average loss of \$913 M/year or 19.5% of the average annual value of the wheat crop, in the decade from 1998-99 to 2007-08 (Murray and Brennan 2009). Nationally, the three most important pathogens have been *Pyrenophora tritici-repentis* (tan spot), *Puccinia striiformis* (stripe rust) and *Phaeosphaeria nodorum* (septoria nodorum blotch). In addition, if current controls are not used, losses would be far higher for *Heterodera avenae* (cereal cyst nematode) up to an estimated \$2.2b/year. A national survey of plant pathologists found that cultural methods, particularly crop sequences that include break crops, were the only controls used for many key pathogens (Murray and Brennan 2009). Break crops decrease disease pressure on cereals primarily by acting as non-hosts that breaks the life cycle of crop-specific cereal pathogens. There are several other mechanisms through which cereal root disease may be controlled by crop sequences in addition to provision of a non-host crop including microbial antagonism, biofumigation and allelopathy (Angus *et al.* 2015). The value and impact of break crops on yield of the following cereals is influenced by the presence and level of diseases in the cropping system, the host status of the proposed break crop and the availability of other control strategies such as host tolerance, host resistance or chemical control.

For example, in northern grain systems chickpea grown in rotations with wheat can reduce the build-up of pathogens of cereals such as the crown rot fungus *Fusarium pseudograminearum*, improve soil N fertility and facilitate control of grass weeds (Felton *et al.* 1997, Dalal *et al.* 1998). Benefits provided by chickpeas are offset by populations of root-lesion nematode (RLN, *Pratylenchus thornei*) increasing under chickpea, reducing crop yield and the yield of subsequent susceptible crops (Thompson *et al.* 2000). Use of alternate chemical control methods such as nematicide only resulted in small (6%) yield gains (Reen *et al.* 2014). Previous studies have identified that chickpea genotypes vary in their resistance to RLN (Reen *et al.* 2014), but few cultivars have shown sufficient resistance to RLN to maintain densities below threshold levels (Thompson *et al.* 2011, Rodda *et al.* 2016). Similarly mungbean is also susceptible and will build RLN levels (Owen *et al.* 2018) within the northern grain regions (N-NSW, S-Qld and C-Qld).

In general, selection of an appropriate break crop for the climate, farming system and paddock history can effectively reduce the incidence and severity of most root, crown and foliar diseases of following cereal crops (Kirkegaard *et al.* 2004, Evans *et al.* 2010, Lawes *et al.* 2013). The pathogens that cause most of these diseases are fungal, but nematodes and bacteria can also constrain cereal root growth and reduce yield (Murray and Brennan 2009). Including break crops in crop sequences is important because other methods are often relatively ineffective (Murray and Brennan 2009). For example, there is little to no effective host resistance to take-all in wheat (Cook 2006, Kwak and Weller 2013) but good resistance exists to cyst nematodes (Eastwood *et al.* 1994, Ogbonnaya *et al.* 2001) and stripe rust (Chen 2005). Wheat cultivars differ in their tolerance and resistance to RLN (Thompson *et al.* 1999) but, as discussed earlier, some break crops such as chickpeas will increase RLN thereby increasing infestation severity for following wheat crops. Some wheat cultivars have host resistance to crown rot but they do not yield reliably more than susceptible cultivars in the presence of the disease (Kirkegaard *et al.* 2004).

Some diseases such as Rhizoctonia bare patch (*R. solani*), a common soil pathogen in south-east Australian grain regions have a wide host range and cannot be easily controlled by a single break crop. *Brassica* break crops provide partial control (Gupta *et al.* 2010; McBeath *et al.* 2015) but the mechanisms remain unclear. It was recognised early that canola produced sulfur-rich isothiocyanates that inhibit the growth of some cereal pathogens (Angus *et al.* 1994) but subsequent research has proposed that other rhizosphere effects, including stimulation of known cereal disease antagonist *Trichoderma* spp., may be responsible for the suppression of some pathogens (Smith *et al.* 2004, Watt *et al.* 2006). Kirkegaard *et al.* (2004) suggested that *Brassica* break crops led to lower levels of crown rot due and lower levels of crown rot inoculum due to more rapid breakdown of residual wheat stubble under dense canola canopies. Higher soil N status and higher levels of stubble and inoculum carry-over following chickpea increased crown rot severity (Kirkegaard *et al.* 2008). Fababeans on narrow row spacings are also effective at decreasing crown rot with denser canopy creating favourable microclimate for stubble breakdown (Moore *et al.* 2003).

The recent advent of pre-sowing DNA-based soil testing, such as the Predicta®-B tests used in Australia for a range of cereal diseases, can reduce the risk of severe losses and provide a guide to the disease risk and therefore decisions about growing wheat or a break crop (Ophel-Keller *et al.* 2008, see also Chapter 11).

Residual soil nutrients and water

Nitrogen Legumes contribute to total nitrogen (N) content of cropping soils through biological N₂ fixation when the amount of N fixed exceeds the N removed from the paddock in grain (Peoples *et al.* 2009). In legumes, total N accumulation generally increases linearly with dry matter (DM) production (Evans *et al.* 2001) due to the ability of legumes to maintain N content as DM accumulates even when soil mineral N is low. Improvement in grain yields or N uptake by cereal crops grown after legume breaks compared with cereal-after-cereal sequences, when water supply is not limited, has long been observed in many studies (Evans *et al.* 1991, Angus *et al.* 2006, Peoples *et al.* 2009, Seymour *et al.* 2012, Moodie *et al.* 2016). This is usually attributed to elevated availability of soil mineral N and healthier wheat crops recovering more soil N following legumes (Peoples *et al.* 2017). Nitrogen contributed by legumes is an important component of soil mineral-N supply to cereal and oilseed crops in Australia (Heenan *et al.* 1994, Angus *et al.* 2015). Grain pulses often fixed more N than pastures, although legume-dominant pastures provide greater net inputs of fixed N, since a much larger fraction of the total plant N is removed when pulses were harvested for grain than was estimated to be removed or lost from grazed pastures (Table 3, Peoples *et al.* 2001). Additive effects of shoot DM, N-fixation and grain yield explained most ($R^2 = 0.87$) of the variation in net soil N gain across crops.

Table 3. Average nitrogen fixation by crop species across studies

Crop species	kg N fixation (range)	Units	Reference
Annual pasture species	30 to 160	kg N/ha	Peoples <i>et al.</i> 2001
	56 to 97 (167 to 306)	kg N/ha	Unkovich <i>et al.</i> 2010
Lucerne	37 to 128	kg N/ha	Peoples <i>et al.</i> 2001
	83 (2 to 284)	kg N/ha	Unkovich <i>et al.</i> 2010
Grain pulses	14 to 160	kg N/ha	Peoples <i>et al.</i> 2001
	24 to 90 (24 to 227)	kg N/ha	Unkovich <i>et al.</i> 2010
Grain pulses (above + below ground)	30 to 40	kg N/plant	Peoples <i>et al.</i> 2009
Fababean	113 (8 to 271)	kg N/ha	Evans <i>et al.</i> 2001
	90 (1 to 205)	kg N/ha	Unkovich <i>et al.</i> 2010
Lupin	80 (-29 to 247)	kg N/ha	Evans <i>et al.</i> 2001
	136 (26 to 288)	kg N/ha	Unkovich <i>et al.</i> 2010
Field pea	40 (-46 to 181)	kg N/ha	Evans <i>et al.</i> 2001
	84 (8 to 227)	kg N/ha	Unkovich <i>et al.</i> 2010
Chickpea	6 (-67 to 102)	kg N/ha	Evans <i>et al.</i> 2001
	40 (0 to 24)	kg N/ha	Unkovich <i>et al.</i> 2010
Lentil	61 (1 to 111)	kg N/ha	Unkovich <i>et al.</i> 2010

Shoot DM production and maintaining total plant N are not the only factors driving N gain in grain crop legumes. The proportion of N due to N-fixation (%Ndfa) is variable across crop species and the association between legume genotype/rhizobia and N₂ fixation is inhibited in paddocks with high nitrate N availability (Peoples *et al.* 1995). Location and interactions between rainfall/temperature also influence the proportion of N in the plant generated by N₂ fixation (%Ndfa, Peoples *et al.* 2001). In cooler, winter dominant regions in south-eastern Australia legume crop growth is highly driven by fixed N with %Ndfa uniformly high (65-94%). In contrast, summer-dominant rainfall regions of central and northern NSW are greatly influenced by large variations in %Ndfa, 0-81%) caused by yearly fluctuations in growing season (April-October) rainfall, common farmer practices (*e.g.* N fertiliser carryover from previous crops) which results in a build-up of soil mineral-N prior to sowing, and higher summer rainfall often associated with higher N mineralisation over summer (Peoples *et al.* 2001, Peoples *et al.* 2017). These factors can also apply in southern systems, particularly when fallows are kept weed-free and effective capture of summer rainfall occurs (Hunt *et al.* 2013). In general, positive N contributions generally occur when %Ndfa > 42-44% (Evans *et al.* 2001). In these northern summer

rainfall dominant grain regions there was a lower reliance of legumes on N₂ fixation for growth (19-74%) and more variable relationships between N₂ fixation and DM accumulation (9-16 kg shoot N fixed/t legume DM). The relationship between shoot DM and fixed N is often weaker for chickpea and field pea compared with most other crops (Peoples *et al.* 2009). In southern, winter dominant grain regions, where soil N is consistently low, shoot DM can provide a reasonable estimate of N₂-fixation, while in the north the soils, climate and farming systems provide conditions that make N₂ fixation based on crop N or total N singularly at high risk of error.

The growth of legume break crops, and the consequent N fixation and N carryover is affected by a range of factors. These include soil nutrient and water availability, seasonal conditions, selection of suitable legume crops for climate and farming systems, occurrence of frost, drought and high temperatures and various pests and diseases and soil constraints such as acidity and compaction (Peoples *et al.* 2001, Peoples *et al.* 2009). Farming practices that affect the presence and effectiveness of N-fixing rhizobia in soil (no inoculation, poor inoculant quality, hostile soils), increase soil concentrations of nitrate N (excessive tillage, extended fallows, fertiliser N), or enhance competition for soil mineral N (intercropping legumes with cereals) can also affect N-fixation and therefore N availability for the following crop (Peoples *et al.* 2009). Additional nitrate N available to following crops are affected by rainfall and location, crop DM, type of legume grown (grain or taken to brown manure) and the way in which net soil N benefit is expressed (*e.g.* per hectare, rainfall basis, residual shoot DM and % total legume residue: Peoples *et al.* 2017, Armstrong *et al.* 2019, Table 4).

As well as the direct benefit of N carryover to the subsequent crop the following wheat crop may also benefit from reduced N immobilisation due to the lower C:N ratio of legume residues (Angus *et al.* 2015) as well as non-N benefit due to the impact on soil biology of hydrogen emitted from nodules as a by-product of N₂ fixation (Peoples *et al.* 2009).

Table 4. Additional nitrate N available to following crops

Legume N source and location	Additional nitrate N		Reference
Grain legumes – South East Australia	35 to 57	kg N/ha	Angus <i>et al.</i> 2015, Peoples <i>et al.</i> 2017, Evans <i>et al.</i> 2001
Grain legumes – South West Australia	90	kg N/ha	Evans <i>et al.</i> 2001
Brown-manured (BM) legumes	60 ± 16	kg N/ha	Peoples <i>et al.</i> 2017
Grain legumes	35 ± 20	kg N/ha	Peoples <i>et al.</i> 2017
Grain and BM legumes on rainfall basis	0.15 ± 0.09	kg N/ha/mm	Peoples <i>et al.</i> 2017
Grain legumes on residual shoot DM	9 ± 5	kg N/ha/t/ha	Peoples <i>et al.</i> 2017
Total legume residue	28 ± 11	%	Peoples <i>et al.</i> 2017

Non legumes Non-legume break crops may also offer soil N benefits. For example, one puzzle about the yield increase due to the canola break was that a yield benefit occurred even under low disease pressure. Improved N status of wheat following canola compared with wheat following other crops was observed by Kirkegaard *et al.* (1999) even though apparent starting N status was similar. O’Sullivan *et al.* (2016) reported that wheat following canola had a lower fertiliser N requirement than wheat following wheat or pasture, and hypothesised that the presence of canola roots decreased nitrification rate, and so conserved N as NH₄⁺ during the canola season thus leading to increased N immobilisation rates and an elevated organic N pool in the subsequent wheat crop.

Nutrients other than N Another root-based interaction occurs between canola and phosphorus. Compared with barley, canola produces longer roots and more citrate root exudate under low P conditions (Wang *et al.* 2015). This exudate acidifies the rhizosphere and solubilises P, so that P uptake is enhanced. This effect is supported by the lower critical P soil test value for canola relative to wheat (Bell *et al.* 2013). More recently, in the northern grain region mineralisation after canola was found to be higher than after other winter crops, particularly during the summer period, due to rapid decomposition of canola leaves where much of the N is stored (Bell *et al.* 2018). In many crops, mycorrhizae play a role in P acquisition but canola and lupins are both non-hosts for this root dwelling

symbiont. Ryan and Kirkegaard (2012) found little evidence to support consideration of arbuscular mycorrhizal fungi (AMF) in farm management and many agronomic practices that underpin sustainable productivity reduce colonisation. In part, significant problems exist with the methodology of most AMF field studies, leading to questions about benefits. This study concluded that management of AMF by farmers would not be warranted until benefits are demonstrated at the field scale under prescribed agronomic management (Ryan and Graham 2018). For canola, under moderate to higher P status, Ryan *et al.* (2002) reported no difference in colonisation or plant P status for crops grown after canola compared with mycorrhizal host crops. Some legume break crops, including chickpea, pigeon pea and white lupin affect P uptake through mobilising fixed forms of soil P via rhizosphere effects from the secretion of organic acids such as citrate and malate and other compounds from their roots (Hocking 2001). While it is speculated that yield benefits and increased water uptake observed after tap-rooted legume species (*e.g.* lupin) and canola is due to the root penetration of soil hardpans, and the provision of a continuous network of residual root channels and macropores in the subsoil, the evidence for this is conflicting (Cresswell and Kirkegaard 1995). In Mallee alkaline sodic soils differences in wheat yields were shown to be related to the growth and morphology of the previous crop root systems (Nuttall *et al.* 2008).

Residual soil water The amount of water used by different crops and left in the soil profile at harvest varies significantly and can be an additional significant factor in the break crop benefit on yield. For example at seven locations in the northern grain region grain legumes (chickpea, fababean, field pea, mungbean) left more residual soil water at harvest than cereals (Bell *et al.* 2019a). Angus *et al.* (2015) also observed wetter soil profiles after field peas than after wheat, although not as wet as after fallow. The residual soil moisture at harvest can be a combination of both reduced water required by legume crops but also due to rainfall events occurring late in the season when crops are senescing and so cannot utilise additional water. Residual soil water at maturity of a break crop can be used by the following crop provided it is not first lost to soil evaporation and/or utilised by weeds in summer fallow (Hunt *et al.* 2013). Surface soil water is more likely to be lost to evaporation than water retained deeper in the profile. Break-crop stubble can affect retention of soil water as well as fallow efficiency through effects on rainfall infiltration and retention over the fallowing period (Hunt *et al.* 2013) and reductions in evaporation. Kirkegaard and Ryan (2014) found, in semi-arid regions of southern Australia, that high levels of soil-water extraction by the first wheat crop after the break crop may lead to lower soil water and reduced yields in following crops if soil water reserves are depleted and not replenished with sufficient rainfall.

The efficiency with which soil water accumulates during fallows and availability of that soil water for use by crops are key drivers of farming system productivity and profitability. Using short or long fallows to accumulate soil water to buffer subsequent crops against the highly variable climate is critical in all grain regions (Hunt and Kirkegaard 2011, Bell *et al.* 2019b). A range of factors can influence the efficiency of fallows (*i.e.* the proportion of rain that accumulates in the soil profile) including ground cover, seasonal conditions, evaporation, fallow weed control, timing of rainfall events, soil dryness, the length of the fallow and residual water left at the end of the proceeding crop. While grain legumes often leave more residual soil water at harvest than cereals, the difference can diminish over summer due to lower and less resilient stubble cover reducing water infiltration thereby decreasing fallow efficiencies for legume break crops in comparison with wheat (Bell *et al.* 2019a). For example, in chickpea crops there was an extra 41 mm of soil water post-harvest compared with wheat, but this diminished to 10 mm at sowing. Fallow efficiencies generally follow the order winter cereal crops > canola > winter grain legumes.

Weed control and management of herbicide resistance

Herbicide-resistant weed populations are threatening crop-production profitability and sustainability across 20 million ha in Australia (Walsh and Powles 2007). Globally, Australia is currently ranked second behind USA in number of herbicide resistant weeds and the range of modes of herbicide action reported (Heap 2019). Weed management in CA can be more challenging than in conventional

agriculture as there is no tillage to remove weeds, there is limited weed seed burial and frequent infestation of perennial weeds (Chauhan *et al.* 2012, see also Chapter 10).

In almost all grain-growing regions in WA, herbicide-resistant weeds occupy > 20% per cent of the farm area and between 10-20% in most other farming regions, with the exception of Tasmania, Central Qld and N-NSW / SW Qld (Umbers *et al.* 2017). Lower rates of herbicide resistance in the northern grain region (NNSW, Qld) are associated with increased crop diversity involving summer and winter crops. The evolution of glyphosate resistance in a range of weed species has shown that maintaining diversity in weed management strategies are crucial to sustain glyphosate (Powles 2008). Including diversity through break crops in crop sequences and varying mode of actions (MOA) for herbicides are now key tools to prevent increases in herbicide resistances on-farm.

Widespread herbicide resistance has forced changes in agronomic and herbicide practices, particularly in WA where the spread of herbicide resistant weeds has accelerated at a pace faster than most other areas of the world. The use of crop competition (higher seeding rate or narrower row spacing) is practised; 24% of growers nationally sowed crops in a manner that assists with weed competition (Umbers *et al.* 2017). In most regions, over 20% of crop sown is selected to assist with weed competition, with the adoption rates over 30% in CQld, SA/Vic border area, high rainfall areas in Vic central and Mallee, and in WA. Grower practice has largely run ahead of research in this area with agronomists and growers quickly realising that one of the best tools they have for controlling weeds is strategic deployment break crops to reduce selection pressure on particular weeds, facilitate the use of alternate herbicide MOA chemistry (*e.g.* grass herbicides in broad-leaf crops) and provide crop competition. For example, use of broad-leaf break crops such as canola and legumes allows the use of Group A herbicides to control grass weeds in-crop. The competitive ability of crops varies with species and variety: a comparison of several crops in a NT system in NNSW showed wheat > canola and fababean > chickpea for weed competition (Felton *et al.* 2004). More vigorous early growth and plant height are both factors related to a greater shading ability and, consequently, to a better ability to suppress weeds. Recent work in the Victorian Mallee (NVic) found break crops provided large productivity and profitability benefits in low-rainfall zone crop sequences at sites with significant grassy weed burdens (Moodie *et al.* 2017). The work concluded that the inclusion of one or two year break phases within crop sequences was a reliable management option to improve the yield of wheat where agronomic constraints such as grassy weeds impact production in continuous cereal systems.

Choosing the right break crop

Growing break crops for maximum profit requires careful management and consideration of both environmental factors such as rainfall and soil type along with recent paddock fertiliser and herbicide histories. Local knowledge and good agronomic advice is important. Break crop checklists such as that shown in Table 5 provide a starting point. Matching legumes to a well-suited environment is particularly important as individual species are generally less well adapted to the range of environments than canola and the potential break crop benefit could be greater (Angus *et al.* 2015). Recent reviews and results from long-term experiments clearly illustrate that yield benefits from break crops often result from a combination of factors (*e.g.* soil-N and water, disease and water, weed control and soil-N benefits) rather than a single factor. While most common factors driving yield benefits from break crops are covered in this chapter there is evidence that other factors including microbial antagonism, biofumigation, allelopathy, arbuscular mycorrhizal fungi interactions, recovery and loss of N from residues. Synergy with agronomic practices such as tillage, fungicides, inter-row sowing also potentially play an important role in the impacts of break crop (Kirkegaard *et al.* 2008, Angus *et al.* 2015, Peoples *et al.* 2017).

Table 5. Break crop guide checklist (based upon Goward *et al.* 2017). Recommendations based on utilising grain, hay and brown manure break crops. High density legume = high density legume pasture. Key: x = not recommended, light grey = consider selection and seek local advice, dark grey = recommended.

	Rainfall zone			Soil factors			Weeds		Paddock history	Disease risk				
Crop option	High or irrigated	Medium	Low	Mineral N		pH	Grasses	Broad leaf	Herbicide residues	Root		Other		
				High	Low					Take-all	Crown rot	Yellow spot	Blackleg / sclerotinia	Aschochyta
Grain														
Lentil						x								
Fababean														x
Lupin														
Field peas														x
Chickpeas						x								x
Vetch														
Canola													x	
Hay														
Subclover pasture			x											
High density legume			x											
Cereal										x	x	x		
Brown manure														
Field pea														x
Vetch														
High density legume			x											

Challenges and future developments in break crops

Profitability Throughout the 2000s the millennium drought in south-eastern Australia and persistent decreases in rainfall distribution and amount in Western Australia increased the perceived risk of growing grain legumes and oilseeds. The recovery in the area planted to both legumes and particularly to canola since then has been boosted by the development of higher yielding cultivars with varying levels of disease resistance and, in the case of canola, herbicide tolerance, coinciding with competitive markets albeit with variable market prices (in the case of legumes) and a rise in herbicide resistance in associated weeds. The persistent question for many growers is whether a break crop can be as profitable as or more profitable than continuous wheat.

Recent research has extended the previous largely agronomic work demonstrating the benefits of break crops to following crops at paddock scale (*e.g.* Angus *et al.* 2015), to the economic and risk benefits to the overall farm business across the crop sequence (*e.g.* McBeath 2015, Goward 2017, Moodie 2017). This has been done with the aim of increasing diversity on Australian farms. The five year crop sequencing initiative supported by GRDC used field experiments and farmer case studies in high, medium and low rainfall environments to investigate the profitability of break crops when considered over a crop sequence. The inclusion of break phases improved the overall profitability of the crop sequence, providing that at least one of the break phases was profitable (Goward *et al.* 2017). Canola was the most widely adapted break crop and returned higher gross margins than wheat in the majority of experiments across the rainfall zones and years. Lupins grown for grain in low and medium rainfall areas were more profitable than various wheat treatments in several experiments. Fababeans or subterranean clover cut for hay were more profitable options for the medium-high rainfall areas or under irrigation. In LR zones such as the Victorian Mallee where cereal crop yields are impaired by the presence of multiple agronomic constraints (*e.g.* grass weeds, soil borne disease and low soil fertility), profitability of field peas, chickpeas and lentils could match or even exceed that of maintaining a poor performing cereal (Moodie *et al.* 2017). In the presence of a major constraint to wheat production such as a high weed burden, sequences involving ‘double breaks’ can be the most profitable.

Periods of continuous wheat can make sense and be profitable in some circumstances. For example, crop sequence experiments in southern NSW (Kirkegaard *et al.* 2014) found that continuous wheat was the most profitable three year crop sequence, but mostly because it was phased with a grass-free lucerne sward, keeping both disease and weed pressures were low, and residual N was high.

Short-term profitability of grain production of any given crop at a field level is driven by grain price, yield and input costs. When growers choose a canola or legume break crop it is highly desirable that it be as profitable as a cereal in its own right or as part of a profitable crop sequence over several years.

Research priorities The relatively rapid growth and adoption of canola in Australia and the stability of the industry provides insights into the success factors for break crop development. Public policy played a critical role in the adoption of alternative crops through investments in research and extension including grower-led efforts. Policies also provided incentives for market development and risk management strategies. Grower perceptions of risk, the ability to utilise existing resources and knowledge, and access to markets have been important social considerations for crop diversification in Australia and elsewhere (Maaz *et al.* 2018). Most of the current breeding effort and agronomy in pulses remains publically funded in Australia and this appears to be paying off in the growing areas of higher value pulses such as lentils and chickpea as new and better varieties, together with detailed grower guides to manage nutrition, disease and optimal sowing windows for different cultivars become available (*e.g.* GRDC GrowNotes).

Further investment in legume research to understand the yield-limiting factors and to enhance their success within farming system will be required across different regions. The recent successful application of crop simulation models to the agronomy and systems benefits of early-sown wheat and canola is currently not possible for most grain legumes as the pulse modules for APSIM are currently limited. Improved understanding of crop phenology and physiology embedded within crop simulation models will be a powerful tool both for the improved agronomy of individual pulses, and to capture their benefits within the cropping system. More specialist research into ways to overcome constraints that limit the production areas are also needed, as pulses tend to be adapted to specific soil types; for example, development of acid-tolerant rhizobia for legumes aimed at expansion of the range of environments for legume production, including soils acidic in either or both top- and sub-soils, under which legumes and rhizobia currently perform poorly (*e.g.* HRZ in Vic and southern NSW, Ballard *et al.* 2018).

Management of residual herbicides within crop sequences needs to be carefully considered when using break crops, particularly pulses that differ in their sensitivity to residual herbicides. Many pulses are sensitive to commonly used Group B herbicide residues and all are sensitive to Group I pyridine residues. Other considerations include lentils following chickpeas if Group F herbicides have been used. In areas that receive minimal summer-autumn rain and delayed opening rain, residual herbicide effects become far more pressing on rotation choices. Pulses following cereal could then become a higher risk situation than pulse following pulse.

Reduced efficacy potentially has contributed to increased evolution of herbicide resistance in annual ryegrass, wild radish and wild oats (Scott *et al.* 2010). Incidence of herbicide resistance to Group A herbicides used to control weeds in broad-leaf crops also presents a significant threat to the viability of break crops. Resistance to ALS inhibitor herbicides, including ‘fops’, ‘dims’ and ‘dens’ has already been found in broad-acre situations in ryegrass, wild oats, phalaris, brome grass, crab grass, goose grass, canary grass and barley grass, amongst others in Australia (Heap 2019). If early maturing and shedding weeds such as brome grass and barley grass become resistant and widespread, grower’s ability to control weeds in break crops will become severely limited and result in increased reliance on more expensive herbicide chemistries. The demise of lupins in Western Australia was partly due to the increase expense of controlling herbicide resistant grasses (Seymour *et al.* 2012). Evolution of herbicide resistance in broadleaf crops such as wild radish, sow thistle and prickly lettuce amongst others, also adds to the complexity of the challenge for broadleaf weed management issues for pulse and canola crops.

Ongoing fertility decline, especially N, in the absence of pasture phases, will be an increasingly issue for legume break crops as most crop legumes do not leave much N, provide little to no input to SOC and leave soils at erosion risk due to rapid stubble breakdown due to lower DM and C:N ratios (Kumar *et al.* 2019). The challenge is to find new and innovative ways to keep legumes in the system – for example intercropping, cover cropping, grazed cover crops, hay, brown manure. A recent review by Fletcher *et al.* (2018) found that, for over 70% of paddocks planted with ‘peaola’ (canola-field pea

intercrops), there was a 50% productivity increase. In cereal-grain legume intercrops two-thirds showed increases in crop productivity compared with monocultures. Future research is required to assess the genotypic potential within crop species for adaptation to intercropping, the long-term rotational benefits and challenges associated with intercrops and the yield variability and complexity-productivity trade-offs in order to provide more confidence for grower adoption. Farming systems models will be central to many of these investigations but are likely to require significant improvement to capture important processes in intercrops, particularly for legume grain crops which are limited in current models (*e.g.* competition for water, nutrients and light).

In summary, the increase in production area of canola and legumes since the millennium drought illustrates that break crops are providing growers with profitable crop options both individually, due to improved market prices (particularly for pulses) and higher yielding cultivars, but also as a valuable tool in overcoming agronomic constraints (disease, soil-N, water and weed management) as part of a 3-5 year crop sequence. Challenges to production for canola have been largely overcome by investment into research and extension that develops understanding of the constraints and benefits of canola in our farming systems. Ideally, this level of understanding will continue to develop for legumes through on-going investment, particularly around profitable legumes for different rainfall zones and climates, herbicide residues and weed management. Adapting to climate challenges and changes occurring both now and in future will require this depth of understanding for all break crops to remain sustainable and profitable in our farming systems.

References

- ABARES (2018) 7121.0 agricultural commodities 2016-17. (Australian Bureau of Statistics: Canberra)
- Angus JF, Bolger TP, Kirkegaard JA, Peoples MB (2006) Nitrogen mineralisation in relation to previous crops and pastures. *Australian Journal of Soil Research* **44**, 355-365
- Angus JF, Gardner PA, Kirkegaard JA, Desmarchelier, JM (1994) Biofumigation – isothiocyanates released from brassica roots inhibit growth of the take-all fungus. *Plant and Soil* **162**, 107-112
- Angus JF, Kirkegaard JA, Hunt JR *et al.* (2015) Break crops and rotations for wheat. *Crop and Pasture Science* **66**, 523-552
- Angus JF, Peoples MB (2012) Nitrogen from Australian dryland pastures. *Crop & Pasture Science* **63**, 746-758
- Armstrong RD, Perris R, Munn M *et al.* (2019) Effects of long-term rotation and tillage practice on grain yield and protein of wheat and soil fertility on a vertosol in a medium-rainfall temperate environment. *Crop and Pasture Science* **70**, 1-15
- Bajwa AA (2014) Sustainable weed management in conservation agriculture. *Crop Protection* **65**, 105-113
- Ballard R, Farquharson E, Ryder M *et al.* (2018) Pulse rhizobia performance on acid soils. GRDC Updates, Wagga Wagga, NSW
- Bell L, Erbacher A, Lawrence D *et al.* (2019a) Impacts of crops and crop sequences on soil water accumulation and use. GRDC updates. Goondiwindi Qld
- Bell L, Klepper K, Mairs J *et al.* (2018) Farming system impact on nitrogen and water use efficiency, soil-borne disease and profit. GRDC Updates, Goondiwindi Qld
- Bell L, Zull A, Aisthorpe D *et al.* (2019b) Economic performance and system water-use-efficiency of farming systems. GRDC Updates, Goondiwindi Qld
- Bell MJ, Moody PW, Anderson GC, Strong W (2013) Soil phosphorus-crop response calibration relationships and criteria for oilseeds grain legumes and summer cereal crops grown in Australia. *Crop and Pasture Science* **64**, 499-513
- Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture: A review. *Crop Protection* **38**, 57-65
- Chen XM (2005) Epidemiology and control of stripe rust *Puccinia striiformis* f. sp. *tritici* on wheat. *Canadian Journal of Plant Pathology* **27**, 314-337
- Cook RJ (2006) Toward cropping systems that enhance productivity and sustainability. *Proceedings of National Academy of Sciences* **103**, 18389
- Cresswell HP, Kirkegaard JA (1995) Subsoil amelioration by plant-roots – the process and the evidence. *Australian Journal of Soil Research* **33**, 221-239
- D’Emden FH, Llewellyn RS (2006) No-tillage adoption decisions in southern Australian cropping and the role of weed management. *Australian Journal of Experimental Agriculture* **46**, 563-569

- Dalal RC, Strong WM, Weston EJ *et al.* (1998) Sustaining productivity of a vertisol at Warra, Queensland, with fertilisers, no-tillage, or legumes 5. Wheat yields, nitrogen benefits and water-use efficiency of chickpea-wheat rotation. *Australian Journal of Experimental Agriculture* **38**, 489-501
- Eastwood RF, Lagudah ES, Appels R (1994) A directed search for DNA sequences tightly linked to cereal cyst nematode resistance genes in *Triticum tauschii*. *Genome* **37**, 311-319
- Evans J, Fettell NA, Coventry DR *et al.* (1991) Wheat response after temperate crop legumes in south-eastern australia. *Australian Journal of Agricultural Research* **42**, 31-43
- Evans J, McNeill AM, Unkovich MJ *et al.* (2001) Net nitrogen balances for cool-season grain legume crops and contributions to wheat nitrogen uptake: A review. *Australian Journal of Experimental Agriculture* **41**, 347-359
- Evans ML, Hollaway GJ, Dennis JI *et al.* (2010) Crop sequence as a tool for managing populations of *Fusarium pseudograminearum* and *F. culmorum* in south-eastern Australia. *Australasian Plant Pathology* **39**, 376-382
- FAOSTAT (201) Food and agriculture data. Food and Agriculture Organization of the United Nations, Rome, Italy
- Felton WL, Haigh BM, Harden S *et al.* (2004) Comparing weed competition in chickpea, fababean, canola and wheat. *Proceedings of 14th Australian Weeds Conference*, Wagga Wagga, NSW
- Felton, WL, Marcellos, H, Alston, C *et al.* (1997) Chickpea in wheat-based cropping systems of northern New South Wales. I Influence on biomass, grain yield, and crown rot in the following wheat crop. *Australian Journal of Agricultural Research* **49**, 401-408
- Fletcher AL, Kirkegaard JA, Peoples MB *et al.* (2016) Prospects to utilise intercrops and crop variety mixtures in mechanised, rain-fed, temperate cropping systems. *Crop and Pasture Science* **67**, 1252-1267
- Goward, L, Swan, A, Peoples, M (2017) Profitable break crop management guide
www.farmlink.com.au/project/crop-sequencing
- Gupta VVSR, McKay A, Diallo S *et al.* (2010) Temporal dynamics of *Rhizoctonia solani* ag8 inoculum in Australian soils. *Proceedings of 6th Australian Soilborne Diseases Symposium* (Horticulture Australia)
- Heap I (2019) The international survey of herbicide resistant weeds. www.weedscience.com
- Heenan DP, Taylor AC, Cullis BR, Lill WJ (1994) Long-term effects of rotation, tillage and stubble management on wheat production in southern NSW. *Australian Journal of Agricultural Research* **45**, 93-117
- Hegewald H, Wensch-Dorendorf M, Sieling K, Christen O (2018) Impacts of break crops and crop rotations on oilseed rape productivity: A review. *European Journal of Agronomy* **101**, 63-77
- Hocking PJ, Stapper M (2001) Effects of sowing time and nitrogen fertiliser on canola and wheat, and nitrogen fertiliser on Indian mustard. I. Dry matter production, grain yield, and yield components. *Australian Journal of Agricultural Research* **52**, 623-634
- Hunt JR, Browne C, McBeath TM *et al.* (2013) Summer fallow weed control and residue management impacts on winter crop yield through soil water and n accumulation in a winter-dominant, low rainfall region of southern Australia. *Crop and Pasture Science* **64**, 922-934
- Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop and Pasture Science* **62**, 915-929
- Kirkegaard J, Christen O, Krupinsky J, Layzell D (2008) Break crop benefits in temperate wheat production. *Field Crops Research* **107**, 185-195
- Kirkegaard JA, Conyers MK, Hunt JR *et al.* (2014) Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in australian mixed farming systems. *Agriculture Ecosystems & Environment* **187**, 133-145
- Kirkegaard JA, Gardner PA, Angus JF, Koetz E (1994) Effect of brassica break crops on the growth and yield of wheat. *Australian Journal of Agricultural Research* **45**, 529-545
- Kirkegaard JA, Howe GN, Mele PM (1999) Enhanced accumulation of mineral-N following canola. *Australian Journal of Experimental Agriculture* **39**, 587-593
- Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- Kirkegaard JA, Lilley JM, Morrison MJ (2016) Drivers of trends in Australian canola productivity and future prospects. *Crop and Pasture Science* **67**, 9
- Kirkegaard JA, Peoples MB, Angus JF, Unkovich MJ (2011) Diversity and evolution of rainfed farming systems in southern Australia. In (Eds. P Tow, I Cooper, I Partridge, C Birch) "Rainfed Farming Systems" pp 715-754 (Springer Netherlands: Dordrecht)
- Kirkegaard JA, Ryan MH (2014) Magnitude and mechanisms of persistent crop sequence effects on wheat. *Field Crops Research* **164**, 154-165
- Kirkegaard JA, Simpfendorfer S, Holland J *et al.* (2004) Effect of previous crops on crown rot and yield of durum and bread wheat in northern nsw. *Australian Journal of Agricultural Research* **55**, 321-334

- Kumar N, Natha CP, Hazraa KK *et al.* (2019) Impact of zero-till residue management and crop diversification with legumes on soil aggregation and carbon sequestration. *Soil & Tillage Research* **189**, 158-167
- Kwak Y-S, Weller DM (2013) Take-all of wheat and natural disease suppression: A review. *The Plant Pathology Journal* **29**, 125-135
- Lawes RA, Gupta V, Kirkegaard JA, Roget DK (2013) Evaluating the contribution of take-all control to the break-crop effect in wheat. *Crop and Pasture Science* **64**, 563-572
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Maaz T, Wulforst JD, McCracken V *et al.* (2018) Economic, policy, and social trends and challenges of introducing oilseed and pulse crops into dryland wheat cropping systems. *Agriculture Ecosystems & Environment* **253**, 177-194
- McBeath TM, Gupta V, Llewellyn RS *et al.* (2015) Break-crop effects on wheat production across soils and seasons in a semi-arid environment. *Crop and Pasture Science* **66**, 566-579
- Moodie M, Peoples M, Goward L, Wilhelm N (2016) The net contributions of fixed N by crop legumes in low rainfall farming systems. *Proceedings of 7th International Nitrogen Initiative Conference*, Melbourne, Victoria
- Moodie M, Wilhelm N, Telfer P *et al.* (2017) Broadleaf break crops improve the profitability of low rainfall crop sequences. *Proceedings of 18th Australian Society of Agronomy Conference*, Ballarat, Victoria
- Moore K, Backhouse D, Simpfendorfer S, Verrell A (2003) Crop rotation reduces crown rot in wheat. Research Updates Tamworth Agricultural Institute 2002 p 43 (NSW DPI: Tamworth)
- Murray GM, Brennan JP (2009) Estimating disease losses to the Australian wheat industry. *Australasian Plant Pathology* **38**, 558-570
- Nuttall JG, Davies SL, Armstrong RA, Peoples MB (2008) Testing the primer-plant concept: wheat yields can be increased on alkaline sodic soils when an effective primer phase is used. *Australian Journal of Agricultural Research* **59**, 331-338
- O'Sullivan CA, Duncan E, Whisson K *et al.* (2016) Changes in N cycling in the rhizosphere of canola leads to decreased N requirement in a following wheat crop. *Proceedings of International Nitrogen Conference*, Melbourne Australia
- Ogbonnaya FC, Subrahmanyam NC, Moullet O *et al.* (2001) Diagnostic DNA markers for cereal cyst nematode resistance in bread wheat. *Australian Journal of Agricultural Research* **52**, 1367-1374.
- Ophel-Keller, K, McKay, A, Hartley, D, Herdina, Curran, J (2008) Development of a routine DNA-based testing service for soilborne diseases in Australia. *Australasian Plant Pathology* **37**, 243-253
- Owen K, Clewett TG, Bell KL, Thompson JP (2018) Lost opportunity: Mungbeans (*Vigna radiata*) in wheat cropping systems favour *Pratylenchus thornei*. *Journal of Nematology* **50**, 650-650
- Peoples MB, Bowman AM, Gault RR *et al.* (2001) Factors regulating the contributions of fixed nitrogen by pasture and crop legumes to different farming systems of eastern Australia. *Plant and Soil* **228**, 29-41
- Peoples MB, Brockwell J, Herridge DF *et al.* (2009) The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis* **48**, 1-17
- Peoples MB, Ladha JK, Herridge DF (1995) Enhancing legume N₂ fixation through plant and soil-management. *Plant and Soil* **174**, 83-101
- Peoples MB, Swan AD, Goward L *et al.* (2017) Soil mineral nitrogen benefits derived from legumes and comparisons of the apparent recovery of legume or fertiliser nitrogen by wheat. *Soil Research* **55**, 600-615
- Powles SB (2008) Evolved glyphosate-resistant weeds around the world: Lessons to be learnt. *Pest Management Science* **64**, 360-365
- Reen RA, Thompson JP, Clewett TG *et al.* (2014) Yield response in chickpea cultivars and wheat following crop rotations affecting population densities of *Pratylenchus thornei* and arbuscular mycorrhizal fungi. *Crop and Pasture Science* **65**, 428-441
- Robertson MJ, Lawes RA, Bathgate A *et al.* (2010) Determinants of the proportion of break crops on Western Australian broadacre farms. *Crop and Pasture Science* **61**, 203-213
- Rodda MS, Hobson KB, Forknall CR *et al.* (2016) Highly heritable resistance to root-lesion nematode (*Pratylenchus thornei*) in Australian chickpea germplasm observed using an optimised glasshouse method and multi-environment trial analysis. *Australasian Plant Pathology* **45**, 309-319
- Ryan MH, Graham JH (2018) Little evidence that farmers should consider abundance or diversity of arbuscular mycorrhizal fungi when managing crops. *New Phytologist* **220**, 1092-1107
- Ryan MH, Kirkegaard JA (2012) The agronomic relevance of arbuscular mycorrhizas in the fertility of Australian extensive cropping systems. *Agriculture Ecosystems & Environment* **163**, 37-53
- Ryan MH, Norton RM, Kirkegaard JA *et al.* (2002) Increasing mycorrhizal colonisation does not improve growth and nutrition of wheat on vertosols in south-eastern Australia. *Australian Journal of Agricultural Research* **53**, 1173-1181

- Scott BJ, Eberbach PL, Evans J, Wade LJ (2010) Stubble retention in cropping systems in southern Australia: Benefits and challenges. EH Graham Centre Monograph No.1, Charles Sturt University, Wagga Wagga
- Seymour M, Kirkegaard JA, Peoples MB *et al.* (2012) Break-crop benefits to wheat in Western Australia – insights from over three decades of research. *Crop and Pasture Science* **63**, 1-16
- Smith BJ, Kirkegaard JA, Howe GN (2004) Impacts of brassica break-crops on soil biology and yield of following wheat crops. *Australian Journal of Agricultural Research* **55**, 1-11
- Thompson JP, Brennan PS, Clewett TG *et al.* (1999) Progress in breeding wheat for tolerance and resistance to root-lesion nematode (*Pratylenchus thornei*). *Australasian Plant Pathology* **28**, 45-52
- Thompson JP, Greco N, Eastwood R *et al.* (2000) Integrated control of nematodes of cool season food legumes. In (Ed. R Knight) “Linking Research and Marketing Opportunities for Pulses in the 21st Century” Vol. 34 pp 491-506 (Springer: Dordrecht)
- Thompson JP, Reen RA, Clewett TG *et al.* (2011) Hybridisation of Australian chickpea cultivars with wild cicer spp. Increases resistance to root-lesion nematodes (*Pratylenchus thornei* and *P. neglectus*). *Australasian Plant Pathology* **40**, 601-611
- Umbers A, Watson P, Watson D (2017) Farm Practices Survey Report 2016. (GRDC: Kingston, ACT)
- van Dijk A, Beck HE, Crosbie RS *et al.* (2013) The millennium drought in southeast Australia (2001-2009): Natural and human causes and implications for water resources, ecosystems, economy, and society. *Water Resources Research* **49**, 1040-1057
- Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. *Weed Technology* **21**, 332-338
- Wang YL, Almvik M, Clarke N *et al.* (2015) Contrasting responses of root morphology and root-exuded organic acids to low phosphorus availability in three important food crops with divergent root traits. *Aob Plants* **7**, 11
- Watt M, Kirkegaard JA, Passioura JB (2006) Rhizosphere biology and crop productivity – a review. *Australian Journal of Soil Research* **44**, 299-317

Chapter 20

Crop-livestock integration in Australia's mixed farming zone

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Introduction

Mixed crop-livestock systems exist where farms operate a mix of crop and livestock enterprises as part of their farming business. Mixed farming businesses occur across most of Australia's broad-acre cropping zone. This zone covers some 57 M ha including 25 M ha of crops and 23 M ha of pastures and supports over 40% of Australia's livestock equivalents (Bell *et al.* 2014, Healy *et al.* 2013). Due to the nature of reporting of agricultural production and farm data in Australia it is difficult to discern the actual number and area of crop-livestock systems. Based on an analysis of ABS and ABARES data, Healy *et al.* (2013) estimated that in 2010-11 there were 21,300 mixed farming enterprises: 11,600 farms were classified as 'grain-sheep' or 'grain-beef cattle' farms, 5,600 were predominantly grain farms but had at least 250 sheep or 50 cattle, and 4,100 predominantly livestock farms that also undertook crop production. About 83% of all cropping farms were mixed farms. The continued dominance of mixed crop-livestock systems across Australia is a notable distinction from agriculture in other developed countries (*e.g.* Europe, North America), where systems have been increasingly specialised (Russelle *et al.* 2007, Wilkins 2006).

Crop-livestock systems in Australia occur across a diverse range of agro-climatic regions (Figure 1). These span from the sub-tropical semi-arid regions of central and southern Queensland to high rainfall, temperate environments in south-eastern Australia to the Mediterranean climatic zones of south-west Western Australia and southern South Australia. Similarly, the soils that support agriculture across these regions also vary greatly, from high clay content soils with high water holding capacities (*e.g.* southern Queensland and northern NSW) to shallow soils with significant sub-soil constraints (*e.g.* southern Victoria and South Australia) to deep sandy soils with low water holding capacities (*e.g.* northern Western Australia). As the nature of cropping and livestock enterprises equally vary across these diverse agro-ecosystems, the type of practices involving integration of crops and livestock also vary.

While there have been some significant changes crop-livestock farming across Australia over the past 30 years, these systems have evolved, and new technologies have emerged that suggest they will continue to persist into the future. In this chapter, we explore how some of these practices have emerged or changed in different regions and how they offer advantages to mixed crop-livestock farmers.

Drivers of crop-livestock integration

Crop-livestock systems offer a range of benefits and challenges for farmers that drive the adoption or use of these systems (Bell and Moore 2012). First, risk mitigation to climate and price variability is provided through diversification of enterprises, particularly if their annual economic returns are not correlated. In many cases annual farm returns from livestock and crop production are not highly correlated and hence annual variability in farm income is reduced where a combination of both enterprises contributes. Cropping enterprises are often associated with higher potential profitability but higher risks, while livestock enterprises provide a more consistent cash-flow and often provide needed revenue during dry seasonal conditions when crop production is not profitable. Further risk management opportunities exist where there is capacity to tactically adjust activities in response to either climate or price fluctuations. For example, capacity to shift land from crop or livestock uses if current prices are more favourable to one over the other, or if seasonal conditions mean that a crop is no longer profitable (*e.g.* drought or frost damage) using this as a forage source for livestock.

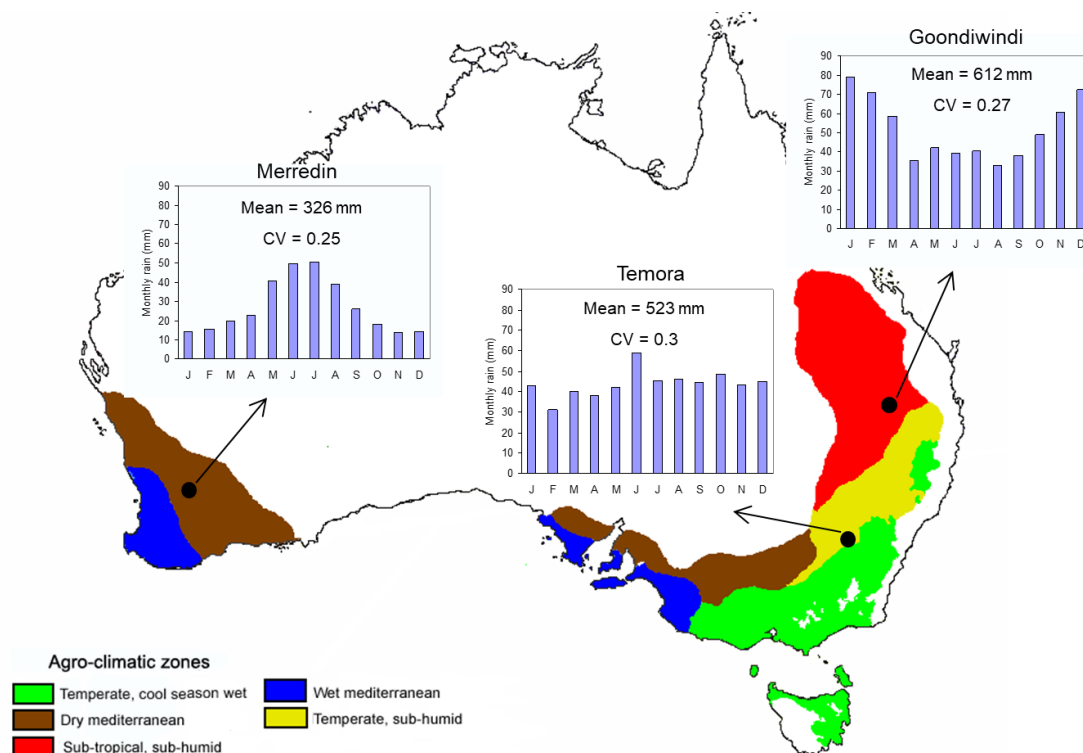


Figure 1. Agro-climatic regions where mixed crop-livestock farming operates in Australia. Agro-climatic zones are defined by Hutchinson *et al.* (2005). Insets demonstrate location differences in rainfall seasonality, amount and variability (co-efficient of variation, CV) in rainfall across regions

Secondly, mixed farm enterprises often emerge where the farm resources (land, labour or machinery) need to be allocated to different activities to maximise farm profitability. This is most obvious where there is variability in land capabilities or soil types, meaning that livestock are favoured on certain land types and cropping on others (Lacoste *et al.* 2016). Where land capability across the farm varies little there is less inclination to operate a diversity of enterprises on the farm. Allocation of farm labour and machinery resources can also influence crop-livestock systems. For example, where farm activities between crops and livestock are complementary this can allow for better use of labour resources available or more stable labour input requirements. On the other hand, competition for these resources can also impede the integration of crops and livestock.

Thirdly, crop-livestock integration can bring about significant production complementarities and resource maintenance benefits. Nutrients can be transferred from livestock to cropping to reduce fertiliser inputs and conversely crops can provide highly valuable forage sources for livestock enterprises. Where these transfers can occur with minimal costs they can be highly beneficial to the farm's efficiency. However, when there are significant costs associated with these resource transfers (*e.g.* transport costs between farms or regions or negative consequences for subsequent crop or livestock production) these benefits diminish and greater care (and analysis) is required to quantify the benefits relative to costs. Integrating livestock with cropping systems, particularly via pasture rotations, can help maintain or rebuild the resilience and function of soils for crop production via increasing soil organic matter and soil fertility, improving soil biological activity, reducing pest and disease populations or depleting weed populations in the soil seed bank. Reduced offsite environmental problems such as dryland salinity, soil erosion and water turbidity can also be achieved, though these benefits are often more associated with specific practices than with crop-livestock systems *per se*.

While many farming businesses may operate a mix of crop and livestock enterprises the degree that these are integrated varies greatly. That is, some farmers may operate both enterprises in their farm in response to different land capabilities and to provide some risk mitigation benefits, but little further

integration occurs. On the other hand, high levels of integration occur where land frequently changes between uses for crop or livestock production or in some cases this is happening simultaneously (*e.g.* grazing dual-purpose crops, pasture cropping). The degree of integration is influenced by the relative importance of each of the drivers of these systems outlined above. Integration of crop-livestock systems also involves greater complexity and higher management focus to capture their benefits. Yet, in many cases farms are operating with lower labour availabilities and greater management attention is required to optimise each of the elements of the farming business. Hence, social and technical capacities to manage these more complex farming systems is a critical aspect that is often underappreciated when addressing the advantages of integration of crops and livestock.

Trends and status of crop-livestock integration in Australia

Over the past 40 years there have been significant trends in farm and crop areas, livestock numbers and labour use on Australian cropping farms. Figure 2 updates the data presented in Bell and Moore (2012).

The unusually high price for wool during the 1980s, due to the reserve price scheme, was an important driver. The total area of cropping farms decreased by about a third during the 1980s, as many mixed farmers shifted their land use to the point where they were no longer classified as “mixed livestock and cropping” farms but were primarily sheep producers. Within the remaining cropping farms, the area under crop decreased by about 3 M ha from 1980 to 1990, the average stocking rate increased by about 5% and the proportion of DSEs present as sheep increased from 75% to 80%. After the end of the reserve price scheme for wool in 1991, prices for wool quickly fell from 700 c/kg to 430 c/kg. Subsequently, the total area of cropping farms recovered rapidly, and the area of land under broadacre crops increased steadily from about 1990 to 2010 (Figure 2). The percent of cropping land on Australian mixed farms has grown from around 28% in 1975-1980 to over 40% since 2010. This change has not been universal across the mixed crop-livestock zone, with very large increases (nearly double) in cropped area observed in southern and Western Australia, while NSW and Queensland have not changed dramatically.

At the national scale, there was a sharp drop in livestock on mixed farms after 2002 (Figure 2b). This reduction in livestock numbers was a result of both substitution of broadacre crop production for livestock production, and a reduction in the number of DSEs per non-cropped hectare from 2.8 DSE/ha in 2002 to 2.1 DSE/ha in 2010. This occurred despite a marked increase in the relative price of lamb meat that was like the wool price spike during the 1980s (Figure 3). It was thought that the ‘Millennium drought’ of 2002-2008 may have been holding back increases in livestock numbers in response to high relative lamb prices (Bell and Moore 2012), but at the national scale this has not yet been observed. Since about 2010, the 20-year trends toward a greater area of cropped land and fewer livestock have both slowed or halted.

One possible explanation is that the productivity of broadacre crop production has improved more rapidly than the productivity of livestock production over this period (Dahl *et al.* 2013). This disparity in relative productivity of the two sectors may be continuing to affect the relative financial attractiveness of cropping and livestock production. However, productivity growth in the sheep and beef industries exceeded that in the grains industry between 2000 and 2010 (Dahl *et al.* 2013), so it may be expected that this may indeed see livestock numbers again increase in the mixed farming zone.

A clear trend in these data is the increase in farm size that has also occurred over the past 40 years, increasing from 1200-1500 ha in 1975-1980 to over 2000 ha since 2010 (Figure 2c). This has also had a corresponding effect on the labour use per ha, so that now a labour unit is managing around 1000 ha on mixed farms in Australia (Figure 2d). This declining labour intensity is likely to be an important driver of crop-livestock systems in the future and may be a factor influencing the persistence of reduced livestock numbers in many mixed farming regions.

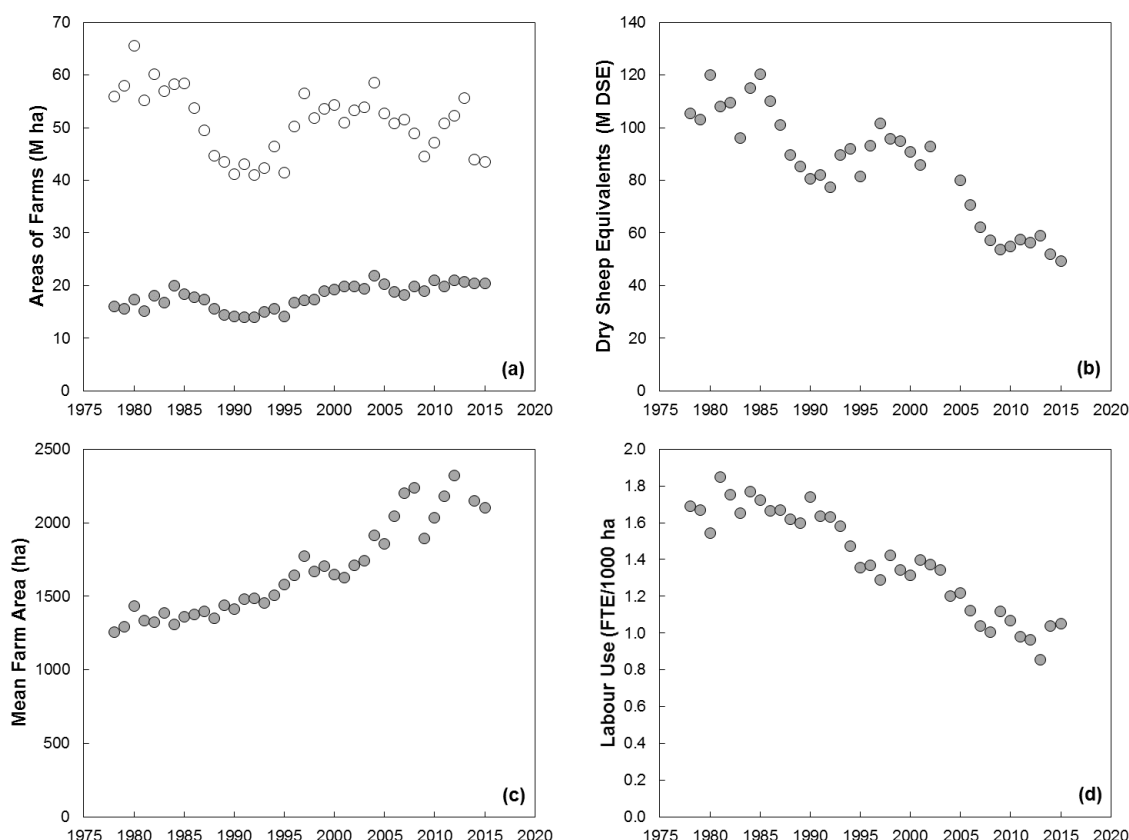


Figure 2. Major trends in Australian cropping farms (*i.e.* those classified in the Australian Agricultural and Grazing Industries Survey as “mixed livestock and cropping” or “wheat and other crops”) over the period 1978-2015. (a) Total area of cropping farms (○); total area under crops in cropping farms (●). (b) Total livestock number, expressed as millions of dry sheep equivalents. (c) Mean area operated per farm. (d) Labour use per unit area; one full-time equivalent (FTE) equals 48 weeks of labour time (for details of calculations, see Bell and Moore 2012)

There are relatively limited quantitative data that provide information on the extent of crop-livestock integration activities on Australian mixed farms. The 2012-2013 ABS survey estimated that a total of 17,600 farms included a pasture phase in crop rotations, compared with 29,200 farms that grew cereal crops. From this it can be deduced that about 1 in every 5 mixed farms completely separates cropping and pastures, and that 4 in 5 practises at least some crop rotation. However, on an area basis, the proportion of pastures in crop rotations appears to be lower. Healy *et al.* (2013) estimated 23.6 M ha total area of pastures on mixed farms, while the 2012-13 ABS estimate of pastures in rotations was only 6.4 M ha. This implies that many – perhaps a majority – of crop-livestock farms have a high proportion of permanent pastures (>70%) and far less is used in crop rotations. Pasture-cropping, growing grain crops into existing pastures, was only reported on 0.2 M ha or <1% of area under broad acre crops (ABS 2013).

According to ABS data (2011-2015) an average of 3.8 M ha of crop stubbles was grazed nationally out of an average total area of broadacre crop residues of 21 M ha. This area of grazed crop residues (18%) is much lower than that reported by Healy *et al.* (2013); their estimate corresponds to 14-15 M ha of residue area grazed by stock on mixed farms. The reason for the discrepancy is not apparent. Healy *et al.* (2013) estimated that 3.2 M ha of grain crops were grazed by livestock, or about 13% of their estimate of the area of crops on mixed farms. The survey did not distinguish between dual-purpose grazing of crops later intended to recover for grain yield and crops sacrificially grazed.

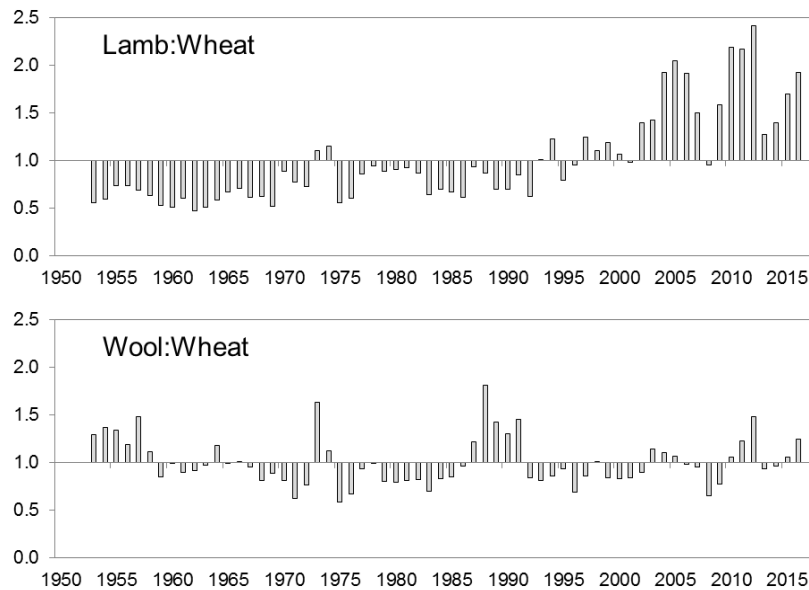


Figure 3. Fluctuations in prices between livestock products (wool and lamb) relative to the price of wheat between 1953 and 2015. Values are ratios of the ABARES index of the price of each commodity, scaled so that for the period examined the long-term average for each equal 1.0

Changing crop-pasture rotations

The intensification of cropping across the mixed farming zones of Australia has been associated with significant changes in the use and role of pastures in crop rotations. Traditional ley farming systems using self-regenerating annual legumes, such as subterranean clover and annual medics, have been in decline (Howieson *et al.* 2000). Cheap nitrogen fertilisers have reduced the importance of inputs from pasture legumes in rotations. A range of profitable break crops (*e.g.* canola, lupins, field peas, lentils, chickpeas and fababeans) have reduced the frequency of pastures in crop rotations, which has greatly reduced the viability of pasture leys regenerating from seed after several years. At the same time, the lower returns from livestock enterprises and extended drought periods during the 2000s resulted in reduced inputs such as phosphorus fertiliser and weed control during the pasture phase. Herbicide residues like sulfonylureas limited pasture legume production particularly nitrogen fixation. These combinations of factors have resulted in pastures moving to phased rotations (1-5 years), where farmers re-sow the pasture/forage (annual or perennial) after each cropping sequence. This has required a change in the plant attributes required but also increased the opportunities for other forage species to be used (especially perennial pastures).

Pastures or forages are now being increasingly deployed in cropping systems because they offer weed management or soil structure and health improvements. Annual ryegrass is one of the most problematic weeds in cropping systems, but a high-quality livestock feed. There are opportunities to utilise annual ryegrass with livestock as well as for conserved fodder for subsequent use in feed gaps and drought to reduce seed set (Piltz *et al.* 2017). Alternatively, grazing preference can allow selective removal or reduction in prevalence of problematic weeds such as annual ryegrass. For example, the annual legume biserrula is less palatable than annual ryegrass and strategic grazing can be used to reduce ryegrass populations (Loi *et al.* 2005). Some studies have shown competitive pastures or fodder crops can greatly reduce annual rye grass populations but other weeds (*e.g.* wild radish) were less effectively managed. Winter cleaning of pastures using selective herbicides to remove grasses has been demonstrated to increase significantly the yield of subsequent crops for up to 3 years (Harris *et al.* 2002). This may provide multiple benefits of improving N supply (Harris *et al.* 2002), and reducing disease carry over, and reducing subsequent weed numbers. Later ‘spray-topping’ does not sufficiently reduce grass weeds and hence results in greater disease presence. In areas where soil structural constraints are a problem, deep-rooted pastures (*e.g.* lucerne) that can penetrate and colonise hostile subsoils are preferred as they

leave root channels that can later be used by other crops to access deep soil water. This has now been shown to have benefits for subsequent crop productivity on these poorly structured soils (McCullum *et al.* 2004). Perennial grass-based pastures have also been shown to improve greatly soil aggregation, and rebuild soil biological activity (Bell and Garrad 2017).

Next-generation annual legumes

The production and persistence of traditional pasture legumes including subterranean clover and annual medics have been challenged in recent decades because of climate change and changing agricultural practices. Increasing frequency of ‘false breaks’ result in germination of large numbers of seedlings of subterranean clover and annual medics that subsequently die. Further, because of relatively shallow root system of these species (Loi *et al.* 2005), moisture stress in spring can result in plant death prior to seed set or significantly reduced seed set. These two factors deplete the soil seedbank over time and lower populations of these species in pastures (Howieson *et al.* 2000, Loi *et al.* 2005). In addition, harvest methods for subterranean clover are costly and can cause increased risk of soil erosion (Loi *et al.* 2005). While the use of lucerne has expanded, particularly in eastern Australia, to fill the gap left by traditional annual legume species, its use is limited by poor tolerance of both the lucerne plant and its symbiont to acidic soil conditions and relatively poor tolerance of waterlogging (Charman *et al.* 2008). Additionally, lucerne requires higher level grazing management for persistence than traditional annual legume species and it is difficult to maintain companion species in lucerne pastures (Wolfe and Dear 2001).

In response, Australian plant breeders and rhizobiologists have developed a range of new legume/symbiont options for mixed farming systems. Many of the species and their associated symbionts have not been previously commercially available for use in Australian or world agriculture. The following characteristics were the focus for these new species:

- High levels of seed production with seed able to be easily harvested using conventional farm machinery;
- Higher levels of hard seed to protect against false breaks and assist in maintenance of a long-term soil seed bank with capacity to survive through a cropping phase and regenerate without the need for resowing;
- Hard seed break down patterns suitable for a range of agroecological regions and farming system uses including use of novel pasture establishment strategies (*e.g.* twin and summer sowing);
- Deeper root systems to facilitate greater survival and production (including seed production) under adverse climatic conditions and to prolong the length of the growing season and feed quality;
- Effective, readily manufacturable rhizobium to facilitate nitrogen fixation in new plant species; and
- Rhizobium with saprophytic competence to ensure persistence through cropping phases in the absence of the host plant.

The developed annual legume species show significant advantages over subterranean clover in many of these attributes (Table 1). In addition, some new annual legume species and their symbionts have improved tolerance to acid soil conditions (*e.g.* biserrula and serradella), waterlogging (*e.g.* gland clover) and resistance to common pasture pests including red-legged earth mite (*e.g.* gland clover). Research has shown these species to be well adapted to many agroecological regions where their production (herbage and seed) has generally been comparable with traditional species and sometimes superior under adverse seasonal conditions (Hackney *et al.* 2015, Loi *et al.* 2005, Loi *et al.* 2012). In addition, new legume species can enable alternative pasture establishment methods (see below) which can further enhance their productivity and resilience (Hackney *et al.* 2015, Loi *et al.* 2008)

Following first year seed set and because of their relatively high hard seed levels, many of the new generation annual legumes can be used as ‘on-demand’ pasture breaks in cropping rotations (Hackney *et al.* 2015). That is, the annual legume can regenerate from soil seedbank reserves without the need for resowing because of their high levels of hard seed. The duration of the cropping phase applied over

such legumes is dependent on the hard seed content of the legume species (and the variety within species) and the rate of hard seed break down.

Table 1. The hard seed content (%), rooting depth (m), herbage mass (t DM/ha), seed yield (kg/ha) and harvestability index of a range of annual legume species from field trials in Western Australia and/or New South Wales

Species	Hard seed (%)	Root depth (m)	Herbage mass (t DM/ha)	Seed yield (t/ha)	Harvestability index ¹
Arrowleaf clover	40-60	0.8-1.5	4.0-11.0	0.3-0.8	
French serradella	0-55	1.0-1.8	4.0-10.0	0.2-2.0	92
Gland clover	40-60	0.8	3.0-8.0	0.2-0.8	67
Bladder clover	40-60	0.8-1.3	2.5-10	0.5-2.0	74
Biserrula	70-90	1.2-2.0	2.5-10	0.2-1.6 ^{1,2}	70
Subterranean clover	10-50	0.6-1.2	1.5-6.7	0.05-0.6 ^{1,2}	0

¹ Harvestability index is the percentage of seed harvested via use of a conventional header relative to the total seed produced by the pasture species (from Loi *et al.* 2005)

Pasture establishment techniques

The establishment of lucerne and subterranean clover pastures within the mixed farming zone has predominantly been achieved by undersowing with the last crop of the rotation (commonly wheat or barley). It is widely documented that establishing pastures via undersowing commonly leads to poorer pastures and increases the risk of complete pasture failure; this is particularly important in perennials that can't build up numbers over time. Despite this, surveys have indicated that the majority of farmers continue to establish pastures via undersowing (Swan *et al.* 2014). Maintaining cash flow from the cover-crop in the year of establishment appears to be a key driver, particularly where short pasture phases are unlikely to compensate for the lost grain income (McCormick *et al.* 2012). If livestock production once again become more important in the system, then this may see this practice change.

During the 1990s the uptake of direct drilling as the primary method of crop establishment increased dramatically, involving the use of knife points on tynes followed by press wheel which left the seed bed ridged. Common row spacing for crops also widened during this period to enable the machines to handle stubble. What this meant for pasture establishment was that small seeded pastures were being sown into rough seed beds where there might be little seed to soil contact. Pastures sown in conjunction with crops or with machines with limited ground-following capacity were also often sown deeper than ideal for pasture seeds. The introduction of canola in many regions has improved farmers' ability to sow small seeds, but commonly seeds sown with a cereal are still being sown too deep.

Traditionally, establishment of shallow-rooted temperate annual legume-based pastures has occurred once the danger of a false break has passed. The requirement for good moisture conditions mean that sowing may not occur until late autumn and in some cases early winter. Subsequently, growth is slow and poor first year herbage production and seed set may be observed. With the development and commercialisation of a range of aerial seeding annual legumes capable of being harvested on farm with a conventional header, new pasture establishment options have been developed concurrently. On-farm harvesting results in minimal seed scarification and therefore the hard seed content remains high (generally over 90%, Loi *et al.* 2005). Two methods of pasture establishment, summer sowing and twin sowing have been developed to exploit the availability of a cheap on-farm seed source and the hard seed breakdown patterns of various species and cultivars within species.

Summer sowing involves sowing unscarified seed (or in the case of serradella, in-pod seed) over the summer before the break of season. The high summer temperatures break down the hard seed and plants can establish on opening autumn rainfall. This method of establishment ensures pastures can emerge and establish while soil and air temperatures remain high. This can facilitate more rapid pasture establishment, higher first year herbage production and increased seed production compared with conventional late autumn scarified seed sowing (Hackney *et al.* 2015, Loi *et al.* 2012). Selection of species and cultivar within species is critical to ensure hard seed content and break down is compatible

with local conditions. Use of a suitable form of symbiont delivery with capacity to survive high summer-low soil moisture conditions is essential to the success of this method of establishment. This method of establishment also results in temporal separation of labour demands for pasture and crop sowing which may be beneficial in many systems.

Twin sowing uses unscarified or in-pod seed sown with the final crop in the cropping phase. The seed (or pod) has very low germination with very few plants emerging in the final crop year. Unlike conventional undersowing, this method of pasture establishment does not require the crop seeding rate to be reduced and there is no competition between the pasture legume and the crop for resources. The final crop year allows a seed softening year for the legume seed which then emerges the following autumn. Choice of species and variety within species is again vital to success of this method of pasture establishment with hard-seeded French serradella cultivars and bladder clover being the most successful to date (Hackney *et al.* 2013, Loi *et al.* 2012).

Both summer and twin sowing require use of higher seeding rates (12-15 kg bare unscarified seed/ha or 20-30 kg in-pod seed/ha) compared with conventional pasture establishment. Many farmers have established seed increase blocks on-farm from which seed is harvested and subsequently used to sow other areas on the farm. As with any pasture sowing operation, appropriate weed control in the years leading up to pasture establishment is critical and herbicide plant-back requirements should be carefully observed to minimise risk of residual damage.

Perennial grasses in ley pastures

One further opportunity afforded by the change from annual ley pastures to pasture phases has been the potential to integrate perennial grasses into pastures used in crop rotations. Temperate grasses such as phalaris (*Phalaris aquatic*) and cocksfoot (*Dactylis glomerata*) are grown mainly in permanent pastures in the higher rainfall zone. However, improved drought tolerance of phalaris, tall fescue (*Festuca arundinacea*) and cocksfoot with the development of more summer dormant varieties (Clark *et al.* 2015) have shown they can successfully persist for several years in the mixed farming zone with rainfall around 450 mm (Culvenor *et al.* 2016, Harris *et al.* 2008). Potential benefits from temperate perennial grasses in the system include increased winter forage production compared with lucerne, increased growing season compared with annuals, reduced animal health risks associated with pure legume stands and increased ground cover, particularly over summer. Hayes *et al.* (2018) demonstrated that perennial grasses increased forage production over annual pastures, phalaris maintained ground cover above 70% and perennial grasses reduced the incursion of annual grass weeds. The addition of lucerne at low plant density within the perennial grass also increased annual biomass. This work has shown there is potential for wider application of temperate perennial grasses in pasture phases on mixed farms, yet the adoption remains low. Inability to control problem grass weeds (*e.g.* ryegrass, barley grass) during the pasture phase, the limited supply of seed for suitable cultivars (*e.g.* summer dormant cocksfoot) for the mixed farming zone, difficulties in establishment and lack of awareness of farmers appear to be major impediments.

Improved tropical grasses have long been used in sown pastures throughout the mixed farming zone of southern and central Queensland. Often, they are used in this region to repair soils where cropping has become unviable (Bell and Garrad 2017). However, these species have applications in temperate and Mediterranean environments across the mixed farming zone. These species are now being widely used throughout northern and central NSW, where they complement other forage sources in the farming system (Boschma *et al.* 2017). In Western Australia, subtropical grasses are being used to protect soils prone to erosion or where crop productivity is low to provide forage during summer. In some cases, they are being used in intercropping systems with grain crops (Lawes *et al.* 2014) or are mixed with winter growing annual legumes. Similarly, they have shown potential in low rainfall regions of South Australia and Victoria. A major challenge with tropical grasses is their feed quality which can deteriorate rapidly during active period of development. Further, in the southern extremities of the mixed farming zone, tropical grasses offer little in terms of forage productivity or feed quality during the colder months of the growing season.

Dual-purpose crops

Dual-purpose crops are used for a period of grazing during their vegetative growth stage and are then allowed to regrow to produce grain later in the season. Dual-purpose crops have long been utilised in mixed farming systems, but the release of wheat varieties with a vernalisation requirement and high grain quality in the 1990s resulted in a resurgence of interest in the role they could play in crop-livestock systems (Dove and Kirkegaard 2014). When sown earlier than traditional spring wheat (*e.g.* March) they provide a long grazing window before their vernalisation requirement has been satisfied and they proceed with reproductive development. These crops can provide over 2000 DSE grazing days/ha supporting 300-400 kg of lamb production/ha without reducing grain yields. Meta-analysis of experiments suggests that grazing crops can reliably increase returns by more than 25-75% (Bell *et al.* 2014). Typically, dual-purpose crops have been used in regions of south-eastern Australia with long growing seasons using winter-type cereals (wheat, barley, oats, triticale). However, there has been growing interest in their application in other higher rainfall regions and in other crop types (*e.g.* canola) (Bell *et al.* 2015, Kirkegaard *et al.* 2008).

In canola, a range of canola germplasm has been evaluated (Christy *et al.* 2013, Kirkegaard *et al.* 2008, Sprague *et al.* 2015) with both winter and spring canolas useful for dual-purpose use in the high and medium rainfall zones (McCormick *et al.* 2015, Sprague *et al.* 2015). Some long-season, winter type 'dual-purpose varieties' are now available commercially (*e.g.* cvs Taurus, Edimax, Hyola 971CL). Dual-purpose canola complements long-season cereals by providing a break crop option to manage root diseases in high rainfall farming systems. These winter canolas have also provided the opportunity for spring-sowing, in order to provide an extended period of grazing over summer and autumn (like forage brassicas) as well as allowing grain production (Paridaen and Kirkegaard 2015). However, this concept has received limited testing, only in southern Victoria, so the wider application is yet to be determined.

Dual-purpose grazing of grain crops is now restricted not only to long-season winter cereals varieties. Recent work has demonstrated that grazing can be obtained also from spring cereal varieties with little reduction in yield (Latta 2015, Seymour *et al.* 2015). This creates wider opportunity for grazing of dual-purpose crops in different environments, including where long-season winter cereals are not suitable, such as in low and medium rainfall and subtropical environments (Bell *et al.* 2015, Lilley *et al.* 2015). However, as earlier sowing is also required to maximise the grazing potential of dual-purpose crops, different phenology types may be required in different environments to ensure flowering still occurs in the optimal window. Experimental and modelling analyses show shorter winter-types (*e.g.* cv Wedgetail) could provide a robust option across a wider range of sowing dates in lower and medium rainfall environments. However, few varieties with this phenology type are currently available.

Livestock productivity benefits from dual-purpose crops

Dual-purpose crops can fill winter feed gaps and provide high quality forage which can be used to achieve very high animal growth rates (250-300 g/d from lambs or up to 2.0 kg LW/d from weaner steers) when grazed during vegetative periods (Dove and McMullen 2009, Dove *et al.* 2016). During the vegetative phase, the energy content of dual-purpose crops is consistently measured at greater than 12 MJ ME/kg DM or 80% digestibility, and protein content >25% (Masters and Thompson 2016). Despite high livestock growth potential, actual growth rates have been highly variable and frequently below those expected. The high potassium to sodium ratio in wheat (and triticale) has been shown to impede Mg absorption and induce subclinical Mg deficiency (grass tetany) in grazing ruminants (Dove *et al.* 2016). The provision of sodium and/or magnesium can address this risk and has been shown to increase herbage intake and increase the weight gain of growing lambs and cattle (25-50%) to a level comparable with predicted growth rates (Dove and McMullen 2009, Dove *et al.* 2016). While the mineral responses have been well established in growing animals there is interest in using dual-purpose crops for gestating ewes, but calcium deficiency has been shown to occur more frequently for ewes grazing cereal crops than those grazing pastures (Masters and Thompson 2016). An experiment (McGrath *et al.* 2015a) and survey (McGrath *et al.* 2013) in southern NSW found little evidence of a high animal health risk for well managed reproducing ewes when grazing wheat, although issues have been sporadically reported.

Dual-purpose crops can provide significant grazing opportunities and livestock production (800-2500 DSE days/ha, 200-650 kg LW/ha) but this varies with the season, grazing management, sowing time and crop type. Early sowing of long-season varieties provides a greater opportunity for grazing than later sowing, with the potential grazing declining by 200 DSE days per week as sowing is delayed after early March (Bell *et al.* 2015). Winter varieties requiring vernalisation to initiate reproductive development provide long grazing windows (up to 100 days) and hence more grazing potential, compared to shorter season spring varieties. Winter canola can provide 800-2600 DSE days/ha and spring canola up to 700 DSE days/ha with similar potential livestock growth rates to cereals, although a period of low growth immediately after introduction to canola often occurs. Across the high rainfall zone of south-eastern Australia dual-purpose crops can provide up to 2500 DSE days/ha but due to their later season break grazing potential is much lower in Mediterranean environments in south-western and southern Australia (Bell *et al.* 2015, Lilley *et al.* 2015, Sprague *et al.* 2015).

While there is potential for grazing crop biomass during winter to fill gaps in feed supply, it is widely acknowledged that there are considerable benefits in integrating dual-purpose crops into the farm feedbase (Dove *et al.* 2015, McGrath and Friend 2015, Squib and Kingwell 2015). In a field study near Canberra, Dove *et al.* (2015) found that pasture spelling during the grazing crop period increased the grazing days on pasture by >40% after crop grazing. Further, this study showed that combinations of dual-purpose wheat and canola crops have complementary impact, further increasing the pasture grazing benefit by providing a longer deferment period (Dove *et al.* 2015). When these benefits were extrapolated, whole-farm stocking rate could be increased by 10-15%, and farm profitability by \$150/ha through the incorporation of 10-15% of the farm to dual-purpose crops (Bell *et al.* 2015). The pasture deferment benefit is much less when short season spring cereals are grazed, and the benefits are likely to come from increased early-season feed (Thomas *et al.* 2015).

The potential to alter the livestock enterprise to capitalise on this additional forage resource has been examined through modelling analyses. These have suggested there may be potential to shift lambing from spring to autumn and employ higher stocking rates to bring about significant increases in farm gross margin. McGrath *et al.* (2014) showed that lambs could be finished earlier, with a greater proportion reaching market specifications through lambing in April rather than in June or August (Table 2).

Table 2. Effect of varying lambing month and stocking rate on lamb production, grain supplements fed and gross margin from incorporating dual-purpose crops into the farm feedbase (adapted from McGrath *et al.* 2014).

Lambing month	Stocking rate (ewes/ha)	% change in GM (\$/ha)	Change in supplement grain fed (kg/ha)	Change in days to lamb sale	Change in lamb production (kg/ha)	Change in % of years lambs reach > 39 kg at sale
April	6	15	-66	+1	+18	+5
	8	67	-140	-1	+40	+15
	10	257	-186	+21	+82	+30
June	6	21	-104	+1	+9	+5
	8	42	-209	-5	+17	+12
	10	95	-384	-15	+20	+8
August	6	8	-84	+1	+5	0
	8	21	-172	+3	+12	0
	10	56	-285	+2	+17	+5

Managing crop grazing to avoid yield penalties

The risk that grazing will reduce grain yield and/or quality is a major concern for growers and is the major impediment to wider adoption of dual-purpose crop grazing. Harrison *et al.* (2011) reviewed previous research on cereals and showed that grain yield can be reduced by crop defoliation by up to 35% or increased by 75%, with a median reduction of 7% in grain yield. However, if grazing is managed correctly, the grazed crop can produce similar grain yields to an ungrazed crop. Grazing after elongation of reproductive stem greatly increased risks of grain yield reductions from grazing in both cereals and

canola (Harrison *et al.* 2011). This effect is complex and involves combinations of reducing tiller numbers and reducing time to recover enough biomass (and resources) to maximise yields. Yield increases due to grazing/defoliation can occur by slowing crop water use and delaying water extraction until it can be used more effectively during grain filling, but this effect is subtle and has not been conclusively proven experimentally. It appears that the economic optimum was reached where crops were grazed to a level incurring a yield penalty of 10-20% compared with an ungrazed crop.

It is now understood that both residual biomass and the time grazing is stopped are both critical factors to be managed to avoid grain yield penalties (Bell *et al.* 2014, Sprague *et al.* 2015). Allowing the crop enough time to regrow and acquire the critical anthesis biomass required to achieve the yield potential in that season. Hence, by removing biomass in higher yielding years larger yield penalties are likely, while in seasons with lower yield potential the required biomass at anthesis to achieve maximum grain yield is often lower. In these situations, where excess biomass is not effectively converted to grain yield, this can be used for grazing without reducing the grain yield in that year. The challenge is in predicting these situations and clearly some environments are more prone to this scenario than others.

Grazing crop residues

Crop stubbles have long been an important forage source for sheep in mixed farming areas, and particularly in the low-medium rainfall zone where the growing season is shorter, and the proportion of land sown to crops is high. However, with the widespread uptake of no-till, stubble retention and controlled traffic farming systems have engendered growing concerns about livestock compacting soil, removing stubble cover and hence impacting on subsequent crops. Recent studies have shown no negative impact of stubble grazing by sheep on subsequent crop yield providing summer weeds are controlled and at least 50-70% of stubble cover (2-3 t DM/ha) is maintained (Bell *et al.* 2012, Hunt *et al.* 2016). However, grazing stubbles was shown to induce small increases in soil bulk density, soil strength and reduced infiltration rate, but this did not result in lower soil water at sowing or reductions in grain yield. Risks of compaction are lower when grazing during summer fallows when soils are drier and more resistant to compaction. Compaction by sheep is generally shallow (5-10 cm) while cattle can induce deeper soil compaction (10-15 cm) particularly on wet soils (Bell *et al.* 2012). However, these shallow compaction events were found to be transient and are alleviated by natural wetting and drying cycles along with sowing operations. Reductions in water infiltration and yield following grazing are due to removal of ground cover rather than compaction (Bell *et al.* 2012, Hunt *et al.* 2016b); that is, 'sheep do more damage with their mouths than their hooves'.

Compared with ungrazed stubbles, stubble grazing was found to increase grain yield and protein in some seasons due to increased N availability to subsequent crops (Hunt *et al.* 2016). This is thought to be driven by more rapid mineralisation of N from livestock excreta and possibly due to lower immobilisation of N by stubble due to reduced inputs of high C:N stubbles. However, further research is required to understand these processes more fully.

The amount of feed available in stubbles depends of the amount and quality of spilt grain, leaf and stem from the dry crop residue and its accessibility. The leaf and stem components, while variable due to crop type and seasonal conditions, is generally very low quality (< 58% digestibility). With increasing efficiency of modern harvesters, less grain is spilt on the ground. Despite this, recent grazing studies show that wheat stubbles, even where modern harvesting machinery is used, are a valuable source of feed. Fresh wheat stubbles provide adult ewes with between 60 and 100 sheep grazing days/ha before the sheep begin losing weight (Thomas *et al.* 2010). Generally, sheep show very rapid growth rates during the first 1-2 weeks, decreasing thereafter as a consequence of declining grain and leaf availability. A significant challenge for managing stubble grazing is identifying when feeding value has declined to a point such that animals should be removed. Knowing this would reduce the risks of overgrazing stubbles and enable farmers to gain the best value from crop residues.

Germinating weeds during fallows can provide high quality feed for short periods – but research shows that this has significant trade-offs for subsequent crops. Controlling weeds during summer fallows is important to increase soil water available for subsequent crops, with large benefits for system

productivity (Hunt and Kirkegaard 2011). Grazing fallow weeds can also increase risks of increasing weed seed spread. A common practice now for farmers is to spray weeds and then graze so that losses of water and nitrogen are minimised, but the weeds still provide some feed for livestock.

Future of crop-livestock integration

There is a significant and renewed desire amongst landholders in the mixed farming zone to increase their investment in livestock production enterprises. Despite this, a survey of 175 farming businesses in central and southern NSW found that the current feedbase was only fulfilling the livestock production goals of producers 50% of the time (Hackney *et al.* 2019). This suggests there are inadequacies in the current feedbase to meet livestock production requirements, poor matching of the feedbase to livestock needs or inadequate management of the feedbase leading to sub-optimal performance in terms of production and/or feedbase quality. Producers cited assistance with fundamental issues including pasture species and selection, pasture establishment, interpretation and manipulation of soil fertility as key requirements to improve their feedbase management. Many farm consultants used by producers have a stronger crop production credentials than pasture expertise. It is important therefore that upskilling occurs in fundamental and advanced concepts of feedbase management and manipulation. Improved skills in crop-livestock systems is needed to minimise financial risks as well as prevent unwanted environmental consequences (*e.g.* overgrazing, poor ground cover, soil loss) and animal production issues (*e.g.* reproductive mortality) that may arise because of inadequate knowledge in these areas.

Several technological and environmental changes may also bring about further disruption to crop-livestock systems over the coming years (Bell *et al.* 2014). Firstly, technologies (*e.g.* virtual fencing, GPS collars to manage livestock instead of fences) have the potential to reduce the labour and infrastructure required for farmers to reintegrate livestock into their cropping enterprises. Such technologies could enable spatial management of grazing to soil type, avoid grazing areas that fall below ground cover limits and use crop grazing to manipulate crops more precisely. The increasing need to employ non-herbicide practices for weed management to slow the build-up of herbicide resistance is also relevant. Decline in soil fertility and resilience under continuous cropping is also likely to need solutions involving longer term pasture-crop rotations. However, greater quantification of the broad range of benefits from such systems are required before farmers will adopt them. Further, increasing climate variability occurring across much of Australia's mixed farming zone is likely to require crop-livestock systems that offer flexibility and resilience to maintain viability of mixed farming enterprises over the long term.

References

- Bell LW, Dove H, McDonald SE, Kirkegaard JA. (2015) Integrating canola and wheat into high-rainfall livestock systems in south-east Australia. 3. An extrapolation to whole-farm grazing potential and productivity. *Crop and Pasture Science* **66**, 390-398
- Bell LW, Garrad R (2017) Perennial pasture leys enhance soil health compared to continuous cropping. *Proceedings of 18th Australian Agronomy Conference*, Ballarat, Australia
- Bell LW, Hayes RC, Pembleton KG, Waters CM (2014) Opportunities and challenges in Australian grasslands: pathways to achieve future sustainability and productivity imperatives. *Crop and Pasture Science* **65**, 489-507
- Bell LW, Kirkegaard JA, Swan A *et al.* (2011) Impacts of soil damage by grazing livestock on crop productivity. *Soil & Tillage Research* **113**, 19-29
- Bell LW, Kirkegaard JA, Moore AD. (2014) Evolving crop-livestock integration systems that improve farm productivity and environmental performance in Australia. *European Journal of Agronomy* **57**, 10-20
- Bell LW, Lilley JM, Hunt JR, Kirkegaard JA (2015) Optimising grain yield and grazing potential of crops across Australia's high rainfall zone: A simulation analysis. 1. Wheat. *Crop and Pasture Science* **66**, 332-348
- Bell LW, Moore AD (2012). Integrated crop-livestock systems in Australian agriculture: Trends, drivers and implications. *Agricultural Systems* **111**, 1-12
- Boschma SP, Murphy SR, Harden S (2017) Growth rate and nutritive value of sown tropical perennial grasses in a variable summer-dominant rainfall environment, Australia. *Grass and Forage Science* **72**, 234-247

- Charman N, Ballard RA, Humphries AW, Auricht GC (2008) Improving lucerne nodulation at low pH: contribution of rhizobial and plant genotype to the nodulation of lucerne seedlings growing in solution culture at pH 5. *Australian Journal of Experimental Agriculture* **48**, 512-517
- Christy B, O'Leary G, Riffkin P *et al.* (2013) Long-season canola (*Brassica napus* L.) cultivars offer potential to substantially increase grain yield production in south-eastern Australia compared with current spring cultivars. *Crop and Pasture Science* **64**, 901-913
- Clark SG, Nie ZN, Culvenor RA *et al.* (2015) Field evaluation of cocksfoot, tall fescue and phalaris for dry marginal environments of south-eastern Australia. 1. Establishment and herbage production. *Journal of Agronomy and Crop Science* **202**, 96-114
- Culvenor RA, Clark SG, Harris CA *et al.* (2016). Field evaluation of cocksfoot, tall fescue and phalaris for dry marginal environments of south-eastern Australia. 2. Persistence. *Journal of Agronomy and Crop Science* **202**, 355-371
- Dahl A, Leith R, Gray E (2013) Productivity in the broadacre and dairy industries. *Agricultural Commodities* **3**, 200-220
- Dove H, Kirkegaard JA, Kelman WM *et al.* (2015) Integrating dual-purpose wheat and canola into high-rainfall livestock systems in south-eastern Australia. 2. Pasture and livestock production. *Crop and Pasture Science* **66**, 377-389
- Dove H, Kirkegaard JA (2014) Using dual-purpose crops in sheep-grazing systems. *Journal of the Science of Food and Agriculture* **94**, 1276-1283
- Dove H, Masters DG, Thompson AN (2016) New perspectives on the mineral nutrition of livestock grazing cereal and canola crops. *Animal Production Science* **56**, 1350-1360
- Dove H, McMullen KG (2009) Diet selection, herbage intake and liveweight gain in young sheep grazing dual-purpose wheats and sheep responses to mineral supplements. *Animal Production Science* **49**, 749-758
- Hackney B, Nutt B, Loi A *et al.* (2015) "On-demand" hardseeded pasture legumes – a paradigm shift in crop-pasture rotations for southern Australian mixed farming systems. *Proceedings of 17th Australian Agronomy Conference*, Hobart, Australia
- Hackney BF, Jenkins J, Powells J *et al.* (2019) Increased emphasis on soil management for improved legume productivity. *Crop and Pasture Science* (in press)
- Hackney B, Piltz J, Rodham C (2013a) Using bladder clover to increase crop and livestock production www.mla.com.au/CustomControls/PaymentGateway/ViewFile.aspx?HXA6lXXUQPvfd2veYljZC0aM Mrgcl4yNPCUoX9RpS3KwVCIPa9RLWs7tTUNdvlvM3EYMKKAFsht7d1Tnt3BqiA
- Hackney B, Piltz J, Rodham C (2013b) Using French serradella to increase crop and livestock production. www.mla.com.au/CustomControls/PaymentGateway/ViewFile.aspx?HXA6lXXUQPvfd2veYljZC0aM Mrgcl4yNPCUoX9RpS3KwVCIPa9RLWs7tTUNdvlvM3EYMKKAFsht7d1Tnt3BqiA
- Harris CA, Clark SG, Reed KFM *et al.* (2008) Novel *Festuca arundinacea* Shreb. and *Dactylis glomerata* L. germplasm to improve adaptation for marginal environments. *Australian Journal of Experimental Agriculture* **48**, 436-448
- Harris RH, Scammell GJ, Muller WJ, Angus JF (2002) Crop productivity in relation to species of previous crops and management of previous pasture. *Australian Journal of Agricultural Research* **53**, 1271-1283
- Harrison MT, Evans JR, Dove H, Moore AD (2011) Dual-purpose cereals: can the relative influences of management and environment on crop recovery and grain yield be dissected? *Crop and Pasture Science* **62**, 930-946
- Hayes RC, Li G, Norton MR, Culvenor RA (2018) Effects of contrasting seasonal growth patterns on composition and persistence of mixed grass-legume pastures over 5 years in a semi-arid Australian cropping environment. *Journal of Agronomy and Crop Science* **204**, 228-242
- Healy D, Gilmour P, Campbell J (2013) Grain and Graze 2 Impact Report. A report for Grains Research and Development Corporation (Roberts Evaluation: Melbourne).
- Howieson JG, O'Hara GW, Carr SJ (2000) Changing roles for legumes in Mediterranean agriculture: developments from an Australian perspective. *Field Crops Research* **65**, 107-122
- Hunt JR, Swan AD, Fettell NA *et al.* (2016) Sheep grazing on crop residues do not reduce crop yields in no-till, controlled traffic farming systems in an equi-seasonal rainfall environment. *Field Crops Research* **196**, 22-32
- Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop and Pasture Science* **62**, 915-929
- Hutchinson MF, McIntyre S, Hobbs RJ *et al.* (2005) Integrating a global agro-climatic classification with bioregional boundaries in Australia. *Global Ecology and Biogeography* **14**, 197-212
- Kingwell R, Squibb L (2015) The role and value of combining dual-purpose crops and lucerne in a mixed-enterprise farming system. *Crop and Pasture Science* **66**, 399-409
- Kirkegaard JA, Sprague SJ, Dove H *et al.* (2008) Dual-purpose canola—a new opportunity in mixed farming systems. *Australian Journal of Agricultural Research* **59**, 291-302

- Lacoste M, Lawes R, Ducourtieux O, Flower K (2016) Comparative agriculture methods capture distinct production practices across a broadacre Australian landscape. *Agriculture, Ecosystems and Environment* **233**, 381-395
- Lawes RA, Ward PR, Ferris D (2014) Pasture cropping with C4 grasses in a barley-lupin rotation can increase production. *Crop and Pasture Science* **65**, 1002-1015
- Lilley JM, Bell LW, Kirkegaard JA (2015) Optimising grain yield and grazing potential of crops across Australia's high rainfall zone: A simulation analysis. 2. Canola. *Crop and Pasture Science* **66**, 349-364
- Loi A, Nutt BJ, Yates R, D'Antuono M (2012) Summer sowing: a new alternative technique to introduce annual pasture legumes into mixed farming systems. *Proceedings of 16th Australian Agronomy Conference*, Armidale www.agronomyaustraliaproceedings.org/images/sampled/2012/7982_7_loi.pdf
- Loi A, Nutt BJ, Revell CK and Flower K (2008). Twin Sowing: a new technique to reduce the costs of pasture establishment. *Proceedings of 14th Australian Agronomy Conference*, Adelaide South Australia www.agronomyaustraliaproceedings.org/images/sampled/2008/concurrent/new-pastures-forage-options/5580_loia.pdf
- Loi A, Howieson JG, Nutt BJ, Carr, SJ (2005) A second generation of annual pasture legumes and their potential for inclusion in Mediterranean-type farming systems. *Australian Journal of Experimental Agriculture* **45**, 289-299
- Masters DG, Thompson AN (2016) Grazing crops: implications for reproducing sheep. *Animal Production Science* **56**, 655-668
- McCallum MH, Kirkegaard JA, Green TW *et al.* (2004) Improved subsoil macroporosity following perennial pastures. *Australian Journal of Experimental Agriculture* **44**, 299-307
- McCormick JI, Virgona JM, Kirkegaard JA (2012) Growth, recovery and yield of dual-purpose canola (*Brassica napus*) in the medium-rainfall zone of south-eastern Australia. *Crop and Pasture Science* **63**, 635-646
- McCormick JI, Hayes RC, Li GD, Norton MR (2014) A review of pasture establishment by under-sowing with special reference to the mixed farming zone of south-eastern Australia. *Crop and Pasture Science* **65**, 956-972
- McGrath SR, Lievaart JJ, Friend MA (2013) Extent of utilisation of dual-purpose wheat for grazing by late-pregnant and lambing ewes and producer reported incidence of health issues in southern NSW. *Australian Veterinary Journal* **91**, 432-436
- McGrath SR, Virgona JM, Friend MA (2014). Modelling the effect on stocking rate and lamb production of allowing ewes to graze a dual-purpose wheat crop in southern NSW. *Animal Production Science* **54**, 1625-1630
- McGrath SR, Bhanugopan, Dove H *et al.* (2015) Mineral supplementation of lambing ewes grazing dual-purpose wheat. *Animal Production Science* **55**, 526-534
- Piltz JW, Stanton RA, Wu H (2017) Effect of ensiling and *in sacco* digestion on the viability of seeds of selected weed species. *Weed Research* **57**, 382-389
- Russelle MP, Entz MH, Franzluebbers AJ (2007) Reconsidering integrated crop-livestock systems in North America. *Agronomy Journal* **99**, 325-334
- Seymour M, England JH, Malik R *et al.* (2015) Effect of timing and height of defoliation on the grain yield of barley, wheat, oats and canola in Western Australia. *Crop and Pasture Science* **66**, 287-300
- Sprague SJ, Kirkegaard JA, Graham J *et al.* (2015) Forage and grain yield of diverse canola (*Brassica napus*) maturity types in the high-rainfall zone of Australia. *Crop and Pasture Science* **66**, 260-274
- Swan AD, Peoples MB, Hayes RC *et al.* (2014) Farmer experience with perennial pastures in the mixed farming areas of southern New South Wales: on-farm participatory research investigating pasture establishment with cover-cropping. *Crop and Pasture Science* **65**, 973-987
- Paridaen A, Kirkegaard JA (2015) Forage canola (*Brassica napus*): spring-sown winter canola for biennial dual-purpose use in the high-rainfall zone of southern Australia. *Crop and Pasture Science* **66**, 275-286
- Thomas DT, Finlayson J, Moore AD, Robertson MJ (2010) Profitability of grazing crop stubbles may be over-estimated by using the metabolisable energy intake from the stubble. *Animal Production Science* **50**, 699-704
- Thomas DT, Moore AD, Norman HC, Revell CK (2015) Small effects of deferment of annual pastures through grazing spring wheat crops in Western Australia can benefit livestock productivity. *Crop and Pasture Science* **66**, 410-417
- Wilkins RJ (2008) Eco-efficient approaches to land management: a case for increased integration of crop and animal production systems. *Philosophical Transactions of the Royal Society B* **363**, 517-525
- Wolfe EC, Dear BS (2001) The population dynamics of pastures with particular reference to southern Australia. In (Eds. PG Tow, A Lazenby) "Competition and Succession in Pastures" pp119-148 (CAB International)

Chapter 21

Impact of simulation and decision support systems on sustainable agriculture

Zvi Hochman and Julianne Lilley

A brief history of the development of simulation capability in Australia

In 1987 when *Tillage* was published, few Australian agricultural researchers were working on simulation. They focused on developing and testing simulation models rather than to advise on sustainable agriculture. The models under development in Australia, such as AUSIM (McCown and Williams 1989) and PERFECT (Littleboy *et al.* 1989) were inspired by US crop models such as the CERES models (Jones and Kiniry 1986) and the EPIC soil and land management model (Williams *et al.* 1989) as well as by the Wheat model (van Keulen and Seligman 1987) and the crop nitrogen response model PAPRAN (Seligman 1981) of the ‘Wageningen School’ in The Netherlands. Crop modellers saw the potential to generate data that were difficult to obtain by other means, to extend the results of short-term field experiments, long enough to capture the variable climate of a region. Crop simulation analysed the effects of different management in environments where both water and N availability were major determinants of yield (Seligman 1981). Soil and land management modellers (*e.g.* EPIC, PERFECT) studied effects of crop management and climate on soil loss and land degradation processes.

Some embryonic applications of models to agricultural issues were underway in Australia but these were limited by the capability of the available models. A prescient example was the use of a crop model and long-term rainfall records to identify the likelihood of expansion of wheat cropping and the impacts of climatic change and climate forcing factors on future yields. Hammer *et al.* (1987) concluded that a better understanding of the action of the climate forcing factors was required before the likely impacts of climatic change on the reliability of cropping could be determined.

The modelling and simulation *status quo* was disrupted in 1990 when the CSIRO Division of Tropical Crops and Pastures and the Queensland Department of Primary Industries established the Agricultural Production Systems Research Unit (APSRU). APSRU brought together the groups which had developed PERFECT, to simulate the effects of soil management on erosion and the productivity of soils, and AUSIM, developed for research on the impact of management with respect to rotations and intercropping of coarse grains and legumes. The result of this collaboration was APSIM, (Agricultural Production System sIMulator), a farming systems model developed to:

- assist the search for better farming strategies;
- aid better production decision making under uncertain rainfall; and
- improve environmental stewardship where fertility depletion and/or soil erosion threatened the economic future of crop production (McCown *et al.* 1995).

Since the formation of APSRU (now rebranded as the APSIM Initiative) there has been ongoing investment in an integrated farming systems simulation platform for use as a research tool in Australia and worldwide. Progressive developments of APSIM were best described in three key papers (McCown *et al.* 1996, Keating *et al.* 2003, Holzworth *et al.* 2014). These described cycles of continuous improvements, testing and further developments in response to the APSIM , user community’s research needs and to opportunities driven by new technologies.

Before a model can be used to conduct virtual (*in silico*) experiments it must first be validated against relevant data for the conditions and variables of interest. Much of the overall modelling effort focused on this validation process. Thus, papers about model development and model validation dominate the literature rather than papers on their applications (Keating and Thorburn 2018). Many of the papers cited here describe a validation process or reference previous validation efforts. We do not dwell on

this important aspect of the work. Instead, we focus on the applications of simulation using APSIM, and on simulation-based decision support systems to advance sustainable agricultural productivity of rainfed cropping systems in Australia.

Impact of decision support systems on sustainable agriculture

Decision support systems (DSS) may be regarded as any method by which information can be transmitted, shared or structured to help people make a decision. Decision trees, heuristics, rules of thumb, old wives' tales and proverbs are all forms of decision support. Here we are concerned with computer-based tools that seek to inform users of the likely consequences of crop management actions that are stipulated by the user (Stone and Hochman 2004). The late 1980s were a time of great optimism for computerised DSS for agriculture in Australia, and a proliferation in the development of local DSS. Proponents believed that "Farmers need all the help they can get. They need the best information available, and they need to have it delivered quickly, reliably and efficiently. Computer-based systems offer the ability to deliver the goods" (Hamilton *et al.* 1991). At the time, a lack of farm computers was seen to be the major constraint to the greater adoption of DSS. However, by 2002 despite over 75% of grain growers owning and using computers and the ready availability of hundreds of DSS, their use in farm management had not grown (Hayman and Easdown 2002, McCown *et al.* 2002).

An important response to this realisation was the FARMSCAPE project which aimed to ascertain under what circumstances, if any, farmers could find value in the simulations for decision making. The FARMSCAPE team employed a Participatory Action Research approach (Zuber-Skenitt 1993) to work directly with small groups of farmers and their advisers on individual farmers' properties in the northern-cropping region. APSIM was used to aid discussions between researchers, farmers and their advisers or planning tactical and strategic management of their farms. Researchers found the ability to demonstrate the credibility of the simulator and their commitment to solving problems perceived by farmers made them keen to explore a wide range of management issues. An extensive evaluation program showed that farmers often attributed significant insights into their production system and changes to their management (and in some cases significant financial reward) to involvement in these sessions. (Carberry *et al.* 2002).

Researchers then turned their attention to the challenge of delivering FARMSCAPE tools and techniques in a cost effective and commercially sustainable manner and to explore the market for DSS in other Australian cropping regions. The FARMSCAPE team developed a close collaboration with the Birchip Cropping Group (BCG); a farmer driven organisation with a membership of 450 family farms in the Victorian Wimmera and Mallee. The collaboration started in 2001 with sensibility and field testing of APSIM and by conducting a series of simulation aided 'what-if' sessions. In 2002, with a degree of credibility achieved, "The Yield Prophet", a monthly fax service to all BCG members, provided updated forecasts of yield probabilities for 5 'locally representative' field sites. From the first issue on May 15 there were clear and increasingly more definite signals that 2002 would be a very low yielding season. As it happened 2002 was the worst cropping season in the collective memory of BCG farmers. But few farmers had enough faith in the simulator to influence their practice. That season, 2002, created a great deal of interest and qualified credibility for APSIM and Yield Prophet®. By 2004, the Yield Prophet® Fax service had evolved into a web-based service to reduce farmer uncertainty about yield prospects and to explore the potential effects of alternative management practices on crop production and income. Key components of Yield Prophet® included access to soil characterisation, pre-season measurement of initial soil water and soil N, access to daily and historical weather data, ability to specify critical management options and real time internet enabled access to APSIM, (Figure 1). Compared with conventional DSS, Yield Prophet offered flexibility in problem definition and allowed farmers to realistically specify the problems in their fields. Uniquely, Yield Prophet® also provided a means for virtual monitoring of the progress of a crop throughout the season. This is particularly important for in-season decision support and for frequent reviewing in real time of the consequences of past decisions and past events on likely future outcomes (Hochman *et al.* 2009).

The implementation of Yield Prophet® through participation of researchers, grower groups, agronomic advisers and farmers was a social process, involving co-learning and thinking (Jakku and Thorburn

2010). This was clearly illustrated by the proliferation of the concepts of PAW at sowing and PAWC of soils in these communities of practice and in the continuing widespread use of hydraulic soil coring equipment to facilitate their measurement. After a period of joint research and development, BCG assumed the management of Yield Prophet® as an income generating subscription-based service which was still active in 2019. By 2018, 1,686 growers supported by 377 advisers had subscribed 4,949 unique paddocks distributed throughout the grain zone (Figure 2). While the number of growers directly involved was a relatively small proportion of Australian grain producers, they tended to be the leading growers who communicated learnings well beyond their farms.



Figure 1. Schematic representation of inputs into Yield Prophet



Figure 2. Location of weather stations used for Yield Prophet paddocks in 2014

Ten years after the completion of the FARMSCAPE project, these largely-intuitive farmers were still highly enthusiastic about the analytic approach that integrated soil water data with simulation of management options. Yield forecasting and tactical decision making, had served farmers as ‘management gaming’ simulations to aid formulating action rules for such conditions, thus reducing the need for an on-going decision-aid service (McCown *et al.* 2012). This preference for intuitive rather than analytic decision-making helps explain why, while some growers continue to use Yield Prophet® as a decision tool for many years, most growers use it for one or two years only.

The experiences of the developers of Yield Prophet® and of other Australian agricultural DSS were harnessed to assess the lessons learned from developing and implementing DSS tools (Hochman and Carberry 2011). The key propositions relating to best practice, listed according to the strength of the participants’ support, were:

- It is essential to have a plan for delivery of the DSS beyond the initial funding period;
- DSS need to be embedded in a support network of farmers, consultants and researchers;
- DSS development requires the commitment of a critical mass of appropriately skilled people;
- A DSS should educate farmers’ intuition rather than replace it;
- A DSS should enable users to experiment with options that satisfy their needs rather than attempt to present ‘optimised’ solutions;
- DSS tools stand on the quality and authority of their underlying science and require ongoing improvement, testing and validation; and
- DSS development should not commence unless it is backed by marketing information.

DSS stakeholders supported the proposition to have a delivery plan beyond the funding period, but resisted the notion of DSS development being market-driven or commercially delivered. Hochman and Carberry (2002) argued that since public funding to deliver DSS for farmers’ management of climate risk is highly unlikely, DSS stakeholders need to change their perception of the commercial delivery

model or find alternative funds to deliver DSS beyond the R&D phase. Yield Prophet[®] remains one of the few examples of an impactful DSS (Robertson *et al.* 2015, Keating and Thorburn 2018). This is an important observation given the current flurry of activity around digital agriculture and the commensurate development of ‘Apps’ (see Chapter 24) driven by the seductive lure of new technology-enabled possibilities.

Table 1 summarises several studies where the combination of simulation studies and experimental research has led to significant impact in Australian cropping systems. In the following sections we describe the insights gained from these studies.

Managing crops in a variable and changing climate

Australia’s farmers face an extremely variable climate that diminishes their capacity to plan for any given season. Simulation provides insights into both fixed strategies and tactical adaptations to help growers adjust their crop management to this variable climate. Analysis of simulation results using long-term weather at a wide range of locations showed that some adaptations are successful regardless of climate forecasts. These include location or soil-specific choices regarding genotype maturities, sowing time and nitrogen application rate. Examples of such adaptations include wheat variety choice (Zheng *et al.* 2018) and a ‘rule of thumb’ about the minimum starting plant available soil water (PAW) for chickpeas in the northern grain zone (Whish *et al.* 2007). However, long-term simulation analyses do not always yield simple solutions. A simulation study to determine the value of different skip row sorghum configurations (leaving every second or third row unsown) showed that the decision required consideration of the starting soil water, the soil’s plant-available water capacity (PAWC), and the farmer’s risk preference (Whish *et al.* 2005). The realisation of the importance of PAW led to the measurement of field-determined drained upper limit and crop lower limit, as well as other chemical properties and soil organic matter which culminated in APSOil (www.apsim.info/Products/APSOil), a national database containing the simulation ready characterisation of over 1000 soils distributed throughout the Australian grain zone (Dalglish *et al.* 2009).

While fixed strategies offer ‘no regrets’ management options for the majority of seasons, seasonal climate forecasts offer the possibility of additional tactical responses to tailor better crop management decisions to the current season. Such adaptations require reliable seasonal forecasts and the ability to carry out *in silico* experiments to determine the impact of management options on crop yields and other outcomes of interest such as soil erosion risk. APSIM’s simulation capability and its facility to flexibly specify management options were one part of this equation. Another was the availability of the Southern Oscillation Index (SOI phase system, Stone *et al.* 1996) as a readily applied forecasting system using analogue years from the past 100 seasons. Since the ‘millennium drought’, and possibly due to the impacts of climate change on the El Niño Southern Oscillation (ENSO), the validity of the statistically based SOI phase system predictions have been called into question (Rodriguez *et al.* 2018) and the future of seasonal forecasting appears to be linked to global circulation models (GCMs). The downscaled daily outputs from POAMA (the Australian GCM) were input into the APSIM wheat model to translate forecast seasonal conditions, from hindcast data, into yield outcomes. Comparison of these outcomes to those from actual climate records for the same seasons showed that POAMA-derived forecasts exhibited more skill than may be gained by a probabilistic analysis of the previous 30 years of climate data but this advantage only applied from June or later in the season (Brown *et al.* 2018). Significant improvements in the skill of seasonal forecasts is prescribed representative concentration pathways (RCPs where RCP 2.6 represents an ambitious mitigation pathway while RCP 8.5 represents continued high emissions throughout the 21st century) as published in the IPCC fifth assessment report (IPCC 2014).

Outputs from GCMs under various RCPs are downscaled to modify local historical climate observations of key determinants of yield potential such as rain, temperature and atmospheric CO₂ concentration. The impact of these variables on crop growth and development processes are captured in cropping systems simulation models such as APSIM. By considering genetic, environment and management interactions, crop models provide a framework to capture impacts of future climates and offer an avenue to identify possible adaptations to offset the impact of climatic change on yields.

Simulation studies of impact assessment have resulted in contradictory results: some show large negative impacts while others show small or positive impacts. Examples of large negative impacts include a study of 80 CC scenarios in South Australia for 2080 with the most likely projected wheat yield changes being decreases across all locations of 13.5 to 32 % (Luo *et al.* 2005). Related studies in South Australia showed a range of negative and positive impacts on grain N contents and the influence of soil type on these impacts (Luo *et al.* 2005b) with yield declines of 10-15 % under non-limiting N supply conditions (Luo *et al.* 2009). In a study of sites in NSW, Victoria and WA, the negative consequences for crop yields were not uniform across crops and locations. Of the crops studied (wheat, barley, lupin, canola and field pea), field pea was the most sensitive to the projected future CCs, and the ensemble median decreases in field pea yields ranged from 12 to 45 % depending on location (Anwar *et al.* 2015). Contrasting results were observed in several other CC impact studies. A study of the impacts of CO₂ concentrations, temperature increases and changes in rainfall amount and intensity for Wagga Wagga in New South Wales showed small differences (+1 and -6 %) for scenarios to 2050 and 2070 (Wang *et al.* 2009). A 40-year simulation study of production of a range of forage crops and lucerne grown at three locations in southeast Australia found increases in dry matter yield of up to 93% depending on species, location and climate change scenario (Pembleton *et al.* 2016).

There has been no formal attempt to reconcile the differences in the predictions arising from these studies. Their small number and lack of uniformity of location, species and methodology rule out resolving the issue with meta-analysis. One important difference in methodologies is that rather than using downscaled GCM projections, some studies used factorial combinations of incremental change in temperature, atmospheric CO₂ concentrations and rainfall. Such combinations may miss the linkages between these non-independent parameters which drive the larger impacts shown by simulation of future climates derived from downscaled GCMs. Also, using different crop growth models produces different results and Martre *et al.* (2015) to recommend using GCM and crop model ensembles. Impacts also depend on the nature of the projected CC and the current climate conditions. A study of sorghum and wheat systems in northeast Australia with simulations spanning representative locations, soil types, management systems, and 33 climate projections found small to positive impacts of projected CC, even after the impacts of extreme heat were added to the simulations. This was attributed to a reduced frequency of drought periods for most climate projections for both sorghum and wheat in the region of study (Lobell *et al.* 2015). Less appreciated is the impact of using different downscaling methods to generate daily climate data. A study of wheat cropping systems showed that different downscaling methods generated different CC impact assessments (Liu *et al.* 2017).

Improved functions to describe the effects of severe weather events such as frosts and extreme heat are required to better represent the impacts of, and adaptations to, future CC (Chenu *et al.* 2017). Functions to estimate the effects of frost stress and heat stress on yield were developed for APSIM-Wheat (Bell *et al.* 2015) and APSIM-Canola (Lilley *et al.* 2015). These functions improved the accuracy of simulations of canola (Kirkegaard *et al.* 2016) and were applied in more recent studies to investigate a wide range of sites and sowing dates (Flohr *et al.* 2017, Hunt *et al.* 2019, Lilley *et al.* 2019).

The impact of CC on regions suited to future wheat production was investigated by combining a species distribution model together with APSIM simulations under future climate scenarios and cropping adaptation measures. This study showed an overall tendency for a decrease in the area suitable for growing wheat and a decline in the yield of the northeast Australian wheat belt while future CC may benefit South Australia and Victoria (Wang *et al.* 2018).

Examples of adaptation studies include those considering various combinations of sowing date, and cultivars with genetic differences in early vigour and flowering time; these have been conducted in a range of Australian cropping regions (Luo *et al.* 2018, Ludwig and Asseng 2010, Lobell *et al.* 2015). Different locations will require different strategies to manage the negative impacts or take advantage of future CC. Breeding of cultivars that are less sensitive to phenophase reduction in response to a warming climate or more heat and drought tolerant has also been proposed (Hunt *et al.* 2018).

Table 1. Selected examples of simulation studies which combined with field agronomy have resulted in significant impact on Australian dryland cropping systems

Description of simulation study	Impact	References
<i>Managing crops in a variable and changing climate</i>		
Importance of stored soil water	Industry acceptance of importance of stored soil water and ‘rules of thumb’ about the minimum starting plant available soil water (PAW) for different crops in the northern grain zone. Creation of APSOIL - a national database containing characterisation of > 1000 soils.	Carberry <i>et al.</i> 2002; Whish <i>et al.</i> 2007; Lilley and Kirkegaard 2007; Dalgliesh <i>et al.</i> 2009
Management of summer fallow	Explained the observed limited benefits from fallow residue management and focussed attention on fallow weed management. Role of cover crops and of legumes in cover crop mixtures. Awareness of N limitation after cover crops.	Hunt <i>et al.</i> 2013; Verburg <i>et al.</i> 2004, 2012; Wunsch <i>et al.</i> 2017
Timely sowing & identification of optimum flowering periods	Simulation studies highlighted that grower sowing times with current cultivars of wheat and canola were later than optimal. Field experiments and extension effort followed (GRDC Water-Use Efficiency, GRDC Early Sowing, GRDC Canola Agronomy projects). Flohr <i>et al.</i> 2018a reported a 10-day shift in median sowing date of wheat from 20 May in 2008 to 10 May in 2015. Estimated to have added an additional 2.3 Mt per year to the Australian wheat crop worth \$540 million annually.	Hochman <i>et al.</i> 2009a; Zheng 2015; Hunt 2016; Flohr <i>et al.</i> 2017, 2018a; Hochman <i>et al.</i> 2019; Lilley <i>et al.</i> 2019
Dry sowing	Demonstrated whole-farm benefits of dry sowing across the WA wheat belt. Showed that benefits in timeliness of seeding outweighed any risks. In 2018 up to 80% of WA crops were sown dry.	Fletcher <i>et al.</i> 2015; Fletcher <i>et al.</i> 2016; https://ab.co/2WP5IY4
Strategic application of N fertiliser in response to soil characteristics and seasonal conditions	Split application of N allows season specific N management decisions to be delayed until seasonal conditions and forecasts provide more knowledge about crop yield prospects. Soil-specific management of nitrogen is more widely adopted in environments with varying soil N supply and demand. Better N management decisions lead to increased profit and reduced risk.	Asseng <i>et al.</i> 1998; Carberry <i>et al.</i> 2013; Hochman <i>et al.</i> 2009, 2013; Huth <i>et al.</i> 2010; Nash <i>et al.</i> 2013; Monjardino <i>et al.</i> 2013; 2015
FARMSCAPE	Farmers gained significant insights into their production system and changed their management.	Carberry <i>et al.</i> 2002
Yield Prophet®	From 2008 to 2018 the total number of subscribed paddock-years was 8,931 (= 4,949 unique paddocks). Used by 1,686 growers supported by 377 advisers throughout the grain zone.	Hochman <i>et al.</i> 2009a
Insights from developing agricultural DSS	Lessons learned by DSS developers is internationally recognised as best practice for successful DSS development and for deciding when not to develop DSS.	Hochman and Carberry 2011; McCown <i>et al.</i> 2002, 2012; Stone and Hochman 2004
<i>Crop genotype improvement and trait value propositions</i>		
Value of deep roots	Stimulated further agronomic and genetic research on capturing deep water and projects seeking genotypic variation in wheat roots. Led to early sowing systems and subsoil amelioration work	Manschadi <i>et al.</i> 2006; Lilley and Kirkegaard 2007, 2011, 2016
Identifying optimum flowering periods	Flowering in the optimal window maximises yield by reducing frost and heat damage and water stress. Growers now maximise yields by matching sowing date and cultivar to achieve optimum flowering time. This work has inspired new research to develop gene-based phenology models.	Chen <i>et al.</i> 2016, 2017; Flohr <i>et al.</i> 2017; Lilley <i>et al.</i> 2019; Zheng <i>et al.</i> 2012, 2013, 2016, 2018
Value of early sowing with slow developing cultivars	Pre-experimental simulation revealed the potential to increase yield by using slow developing cultivars sown earlier than currently practiced. Field experiments and simulation studies demonstrated national value. This research convinced breeding companies to develop winter wheat germplasm for early sowing. At the time of writing these cultivars were in early stages of adoption by growers.	Flohr <i>et al.</i> 2018a,b; Hochman and Horan 2018; Hunt <i>et al.</i> 2012, 2019; Lilley <i>et al.</i> 2019; Moore 2009; Peake <i>et al.</i> 2018; Van Rees <i>et al.</i> 2014

Table 1 cont.

Industry-scale predictions - quantifying and diagnosing wheat yield gaps		
Quantifying and diagnosing Yield Gaps	Further research seeking to identify causes, and methods of closing yield gaps. Funding agencies identified closing the yield gap as a key objective and performance indicator.	Gobbett <i>et al.</i> 2017; Hochman <i>et al.</i> 2012, 2016; van Rees <i>et al.</i> 2014
Scaling up to crop sequences		
Crop sequence and rotations	Advisors are matching crop intensity and break crop frequency to balance risk and return in different production environments.	Hochman <i>et al.</i> 2014; Whish <i>et al.</i> 2019
Value of dual-purpose crops	Dual-purpose canola and wheat adopted in all southern states.	Bell <i>et al.</i> 2015; Lilley <i>et al.</i> 2015
Management of summer fallows	Simulation informed experimental design, extended evaluation of experimental results and understanding of mechanisms of yield response. Whole mixed farm simulation showed no trade-offs between crop and animal production. Complete summer weed control has become best-management practice across the cropping zone.	Hunt and Kirkegaard 2011; Hunt <i>et al.</i> 2013; Kirkegaard <i>et al.</i> 2014; Moore and Hunt 2012; Verburg <i>et al.</i> 2012
Balancing production and environmental imperatives		
Soil erosion and tillage research	Simulation and mapping of soil erosion and its effects on crop yields in Queensland inspired no-till farming and retaining stubble cover. Arrested soil erosion and improved yields.	Littleboy <i>et al.</i> 1992
Lucerne phase farming	Influenced national dryland salinity policy development and stimulated new thinking around duration of lucerne phases.	Verburg <i>et al.</i> 2007a,b
Effect of grazing on soil compaction and crop yields	Simulation demonstrated that compaction due to animals grazing stubbles during the summer fallow or dual-purpose crops in autumn were unlikely to impact soil compaction or yields. This was verified experimentally and helped reduce growers' concerns about livestock grazing cropping lands.	Allan <i>et al.</i> 2016; Bell <i>et al.</i> 2011; Hunt <i>et al.</i> 2016

Climate change is not only about the future. Historical climate records in Australia show clear trends in CO₂, temperature and rainfall patterns since the 1970s. An alternative approach to impact assessment is to quantify the impacts of these recent climate trends on potential yields by using historic daily weather records. This approach avoids the uncertainty associated with both the factorial modification and the synthetic downscaled GCM climate data. In such a study, based on simulation of 50 representative sites throughout the Australian grain zone, water-limited yield potential declined by 27% over a 26-year period from 1990 to 2015. This decline was attributed primarily to reduced rainfall (83%) but also to rising temperatures (17%) while the positive effect of elevated atmospheric CO₂ concentrations prevented a further 4% loss relative to 1990 yields (Hochman *et al.* 2017). This impact assessment is consistent with the upper range of impacts predicted by using downscaled GCM climate data for a comparable future forecast period.

Insights into adaptation to CC can be gained by examining adaptation that have already occurred over the past 30 years or so. The concept of an optimal flowering window (the flowering period which was associated with a mean yield of $\geq 95\%$ of maximum yield) was proposed to identify suitable genotype x sowing date combinations to maximise yield in different locations for recent and predicted regional climate shifts including the decline in autumn rainfall (Flohr *et al.* 2017). A similar concept of the optimal start of the flowering period was developed for canola (Lilley *et al.* 2019). An early sowing system combined with slower-developing wheat genotypes was proposed in response to observed reduced rainfall and increasing temperatures attributed to CC. Crop simulations revealed that such a system could exploit a longer growing season. Near-isogenic lines were developed and used to test this hypothesis in experiments across the grain belt of Australia, and the results were extended using whole-farm simulations (Hunt *et al.* 2019). The authors of this study calculated that the proposed early sowing system can increase national yields by 0.54 t/ha representing an additional 7.1 Mt annually under reduced rainfall and increasing temperature regimes. This adaptation could facilitate increasing yields across Australia under CC.

Adaptation to climate change is an important stop gap measure until amelioration can contain greenhouse gas emissions to prevent the occurrence of more catastrophic global warming. Sequestering soil organic carbon (SOC) is one measure in which crop production can contribute to reducing net emissions. Another is to reduce nitrous oxide (N₂O) emissions. In a simulation study of Australian dryland cropping soils under common farmer management practices and future climate conditions, SOC was predicted to increase by 0.66 Mg C/ha (ranging from -5.79 to 8.38 Mg C/ha) during the 62-year period from 2009 to 2070. Across the regions, ΔSOC, simulated at the resolution of 1 km, exhibited great spatial variability ranging from -108.8 to 9.89 Mg C/ha showing significant negative correlation with baseline SOC level, temperature and rainfall, and positive correlation with pasture frequency and nitrogen application rate (Luo *et al.* 2019). However, the influence of nutrient availability other than N (*i.e.* P and S, see Chapter 14) on the accuracy of such estimates is unknown.

In a simulation study of the net on-farm GHG abatement and gross margins for a range of management scenarios on two grain farms from the western (Dalwallinu) and southern (Wimmera) grain growing regions of Australia (Meier *et al.* 2017), increased cropping intensity consistently provided emissions reductions across site-soil combinations. The practice of replacing uncropped or unmanaged pasture fallows with a winter legume crop was the only one of nine management scenarios to decrease GHG emissions and increase gross margins relative to baseline practice at both locations over a 100-year simulation period. Annual N₂O emissions were an order of magnitude lower from sandy-well-drained soils at the Western Australian location than at the Wimmera site with a clay soil, highlighting the importance of interactions between climate and soil properties in determining appropriate GHG abatement practices.

Crop genotype improvement and trait value propositions

Crop models have the potential to predict plant phenotype based on its genotype, especially for complex adaptive traits. This requires existing crop models to be enhanced with sufficient physiological rigour for complex phenotypic responses to the environment to be predicted by the model dynamics. The approach quantifies capture and use of radiation, water, and nitrogen within a framework that predicts the realised growth of major organs based on their potential and whether the supply of carbohydrate and nitrogen can satisfy that potential (Hammer *et al.* 2010). Current and prospective enhancements to crop models are designed to enable them to better:

- characterise the environment that crops experience;
- assess the value of physiological and genetic traits in targeted environments;
- de-convolute G × E interactions in statistical models; and
- utilise high-throughput phenotyping to identify ‘hidden’ traits of interest (Chenu *et al.* 2017).

Examples of this approach include the use of an enhanced APSIM sorghum model to investigate the value of genetic effects associated with crop height. Genotypes differing in height differed in biomass partitioning among organs; a tall hybrid had significantly increased radiation use efficiency - a novel finding in sorghum. The enhanced model also predicted differences in green leaf area retention during grain filling via effects associated with nitrogen dynamics (Hammer *et al.* 2010).

Simulation can be used to characterise drought-related environmental stresses, thereby enabling breeders to analyse their experimental trials with regard to the broad population of environments that they target. Simulations based on more than 100 years of historical climate data were conducted for representative locations, soils, and management systems for a check cultivar (Chenu *et al.* 2011). Three main environment types with different patterns of simulated water stress around flowering and during grain-filling were identified and opportunities to improve breeding and germplasm-testing strategies of 18 representative genotypes were investigated. Other studies similarly have used simulation to characterise the environments and estimate genotype by environment variance in sorghum (Chapman *et al.* 2002) and genotype by environment by management (GxExM) in barley (Ibrahim *et al.* 2019) and to demonstrate the need to match crop design to specific sites and seasons (Clarke *et al.* 2019). Simulations also demonstrated the value of a proposed crop ideotype compared to commercial genotypes in a wide range of environments throughout the Australian grain zone (Kaloki *et al.* 2019).

A case study for improved wheat root systems

This case study explores use of simulation to assess the impact of a hypothetical change in wheat roots systems. The experimental study of Kirkegaard *et al.* (2007) showed that in terminal drought, water extracted from deep in the soil (below 1.2 m) was extremely valuable because it was not lost to evaporation, and became available later in the crop growth during flowering and grain-filling, a period when yield development is particularly sensitive to water stress (Fischer 1979). The experiment reported a marginal water use efficiency of 59 kg grain/ha/mm for the subsoil water, around 3 times more efficient than overall crop water use efficiency of 20-24 kg grain/ha/mm for crops in southern Australia (French and Schultz 1984, Sadras and Angus 2006, Sadras and Lawson 2013). Subsequent simulation studies were used to place these results in the context of the climate record and different soil types, and investigated;

- How valuable would subsoil water be in other seasons in that region, and for other regions or on soils with different water holding capacities (Lilley and Kirkegaard 2007)?
- Would a wheat variety bred to be better at extracting water from deep in the soil be valuable? Where, and under what circumstances would this occur (Lilley and Kirkegaard 2011)?
- What would the legacy of crops with improved water uptake be on subsequent crops in the sequence and how would soil type and crop management interact with these new varieties (Lilley and Kirkegaard 2016)?

Seasonal variation in the value of subsoil water The first simulation study (Lilley and Kirkegaard 2007) was conducted at three locations in the Riverina region of NSW (Cootamundra, Junee and Ardlethan), which varied in average annual rainfall by 140 mm. Soil parameters were initialised on 15 December (representing harvest date of a previous crop) as either (1) at the wilting point in all layers to a depth of 1.8 m, or (2) at the wilting point from the surface to 1.2 m and at field capacity from 1.2 to 1.8 m depth. The soil profile then filled according to seasonal conditions before a crop was sown in the typical sowing window (between 15 May and 15 June of the following year) according to a rainfall rule. On average, the value of the stored deep water was 35 kg/ha/mm, less than the 59 kg/ha/mm in the experiment, but could vary from 0 to 100 kg/ha/mm. Counterintuitively, the study revealed that the value of stored subsoil water was much greater in higher rainfall environments and seasons, due to its more frequent occurrence (the profile was sufficiently wet to allow roots to penetrate to deeper layers). Farm management strategies that increased the likelihood of full-profile wetting such as summer weed control, stubble retention and no-till increased the benefit to subsequent crops in drier environments and seasons.

Benefits of modified root traits for crop water uptake The second simulation study (Lilley and Kirkegaard 2011) investigated the benefits of modifying roots to increase soil exploration and water extraction. The study included the locations of the previous study where rainfall distribution was equi-seasonal, and two additional environments; Wongan Hills, WA, with a deep sandy soil and winter-dominant rainfall, and Dalby, Qld with a deep clay soil and a summer dominant rainfall. In that study, similar initial soil profiles to the above study were set on 15 December and appropriate cultivars and sowing windows were set for each region. Model parameters were modified to create hypothetical cultivars with more rapid downward root growth, and/or more rapid water uptake from all soil layers below 0.5 or 0.8 m (location-dependant). The study predicted that maximum root depth varied with location and season. In wetter seasons and where initial soil profiles were wetter, rooting depth increased, while the inability of roots to penetrate dry soil restricted rooting depth in dry seasons. Later sowing also restricted rooting depth due to inadequate time to reach deep soil layers before the start of grain filling when downward root growth ceased. Depending on the location, faster roots increased maximum water extraction by 3-11 mm, more efficient roots by 12-28 mm, and for the combination of faster and more efficient roots by 14-40 mm. The simulation suggested that wheat varieties with faster and more efficient roots would provide significant long-term average yield benefits of 0.3-0.4 t/ha at all locations tested, and that such traits would rarely result in a yield reduction. A subsequent study showed that greater benefits were achieved by early sowing of long-season cultivars, than by more rapid root growth of spring wheat (Lilley and Kirkegaard 2016).

Farming system context drives the value of deep wheat roots The third simulation study in this series (Lilley and Kirkegaard 2016) accounted for the legacy of greater water extraction by a crop on productivity of subsequent crops. In this study, simulations were set to run continuously without soil resetting, so that soil water extraction of a crop had a direct impact on the availability of soil water to the following crop. In essence, the study investigated the long-term benefit of sowing cultivars with more effective root systems in every year. The study was expanded to include 3 additional locations (Esperance WA, Paskeville, SA and Birchip, Vic) with shallow soils (0.7-1.0 m). Increased water extraction was simulated in two ways, firstly by emulating roots with a faster rate of descent and more efficient extraction rate, and secondly using a cultivar with a greater duration of soil exploration and water extraction by sowing a longer-season cultivar around 3 weeks earlier (similar flowering and maturity dates, Figure 3). The study demonstrated that at sites with shallower soils (depth 1 m or less), which make up a significant area of the Australian cropping zone, the benefits of more extensive root systems were negligible. On deeper soils, more extensive root systems were clearly valuable to acquire resources to increase crop yield, but created a legacy of a drier soil for subsequent crops which reduced the average benefit at some locations and created a negative response in some years. In Dalby, Qld, where crops are grown on stored water (due to the summer dominant rainfall), increasing soil water extraction left the soil in a drier state for subsequent crops and long-term average yield decreased (Figure 3). On all soil types in Australia's southern cropping zone, earlier sowing of slower-maturing crops increased water uptake and average yield.

This series of simulations shows that interactions between root traits and the seasonal rainfall distribution, soil type and crop management at specific sites influence their impact on yield. In a cropping sequence, increasing the proportion of crops which dry the subsoil extensively has implications for the longer-term productivity of the farming system. The crop sequence can be managed tactically by considering stored soil water at sowing, seasonal rainfall and use of fallows, legumes or other crops which extract less water to optimise overall system benefits across the full range of seasons.

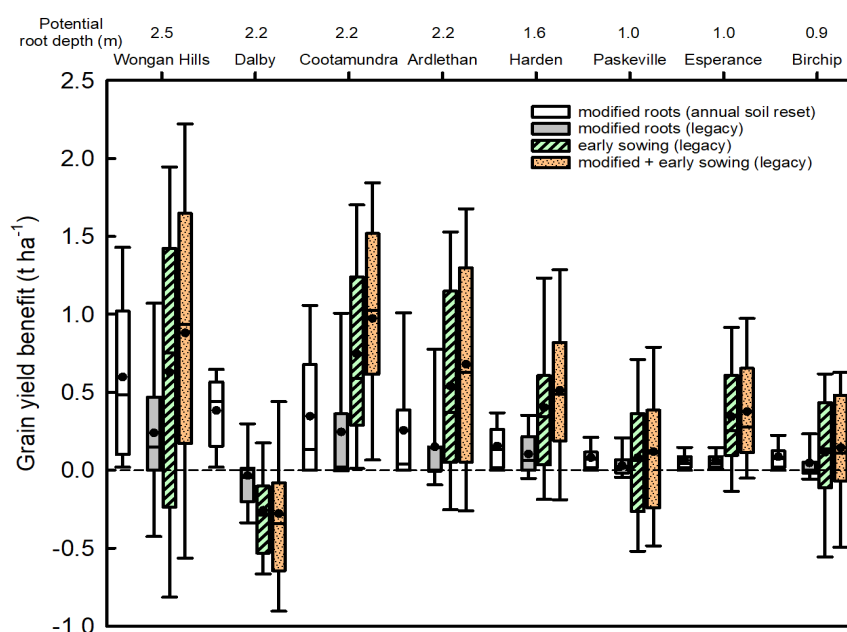


Figure 3. Box plots of simulated yield benefit of cultivars with either modified root systems and/or were sown early relative to the standard cultivar sown in the conventional window at eight sites varying in climate and soil type. Simulations were either reset annually (white) or run continuously (shaded) so that the legacy of crop history affected soil water content. Median (black line), mean (circle), 25th and 75th percentile (box), 10th and 90th percentile (whisker) are presented for 100 years of simulation (redrawn from Lilley and Kirkegaard 2016).

Industry-scale predictions – quantifying and diagnosing wheat yield gaps

Crop yields must increase substantially over the coming decades to keep pace with global food demand driven by population and income growth. This is also an imperative for Australian grain producers who are pressed to increase yields to combat a sustained cost-price squeeze. Quantifying food production capacity on every hectare of current farmland is needed to inform decisions on policy, research, development and investment into future crop yield and land use, and to inform on-ground action by local farmers and their knowledge networks. For rainfed crops, production capacity can be evaluated by estimating water-limited yield (Y_w). Yield gaps (Y_g) are defined as the differences between this theoretical yield level and actual farmer yields (Y_a) such that

$$Y_g = Y_w - Y_a$$

It is also meaningful to express the yield gap in terms of relative yield ($Y\% = 100 \times Y_a/Y_w$) where a low relative yield denotes a relatively high yield gap. To determine yield gaps it is necessary to have good estimates of both Y_a and Y_w . While census-based empirical methods have been used to estimate both Y_a and Y_w , the use of locally validated simulation models, coded to reflect best agronomic practice, results in more robust estimates of Y_w and hence of yield gaps (Van Ittersum *et al.* 2013).

In Australia Y_a values are best determined from ABARES and ABS surveys of individual farmers for which data are aggregated at statistical units that are roughly equivalent to shire boundaries (SA2). The availability of a thoroughly validated crop model, detailed soil maps, and over 3,900 weather stations in the Australian cropping zone, enabled the calculation a highly detailed map of Y_w . Surprisingly these analyses revealed that the average wheat yield gap in Australia is about 50% of Y_w (Figure 4; (Hochman *et al.* 2012, 2016). Yields and yield gaps vary considerably from shire to shire and at regional and subregional levels. They also vary between neighbouring wheat producers. To enable growers, consultants and policy makers to determine how these yield gaps impact them, an interactive series of maps was produced and are publicly available via www.yieldgapaustralia.com.au. Yield gaps for wheat, barley, canola, sorghum and the major pulse crops can be interrogated at multiple scales including a ‘compare my farm’ feature. The website was launched in 2015 and by April 2019 there were 16,517 sessions from 10,163 users, of which 69% were from Australia.

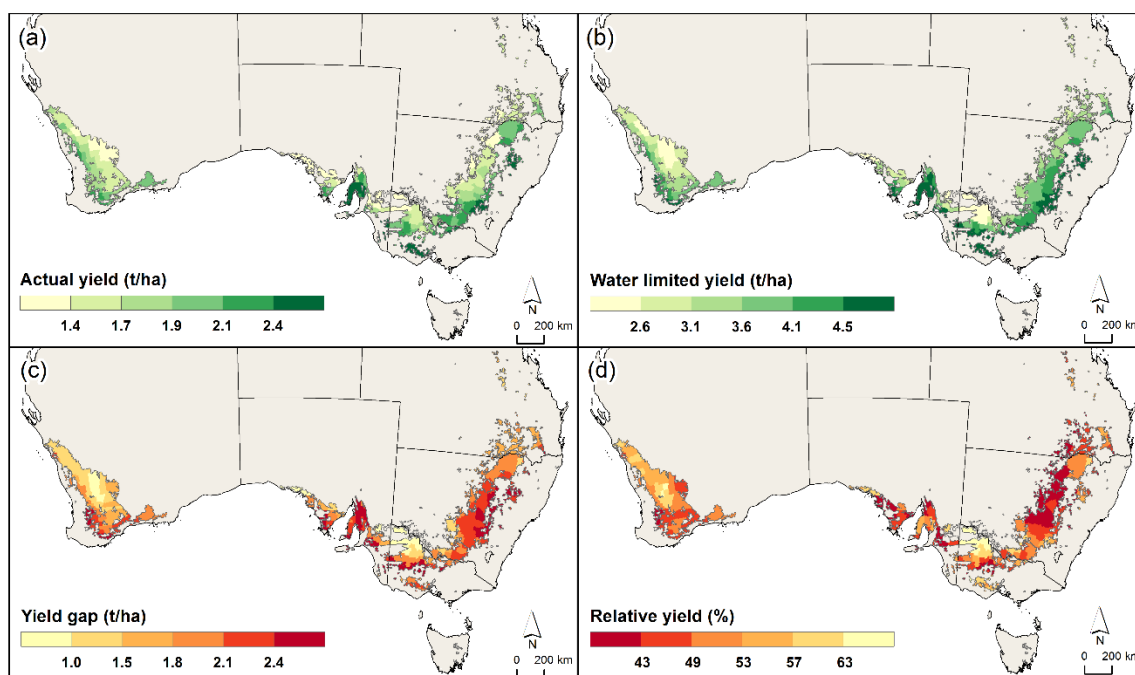


Figure 4. Long-term (1996-2010) average yield maps of (a) actual yields, (b) simulated water limited yields, (c) yield gaps and (d) relative yields ($Y\% = 100 \times Y_a/Y_w$) mapped at SLA resolution and masked to a boundary indicating the winter cereals area of 2005 (source: Hochman *et al.* 2016)

Why then do Australian grain growers achieve only half the yield potential of their crops? The answer to this question has multiple dimensions: biophysical, economic and social. These dimensions were explored in a series of investigations.

Biophysical causes of wheat yield gaps

To ascertain the impact of a range of suboptimal practices on grain yield compared to ‘best management practice’ rules that achieved benchmark water-limited yields simulations were conducted over 15 years at 50 weather stations. Average national losses per suboptimal practice (Treatments 2-8) relative to Yw (Treatment 1) are presented in Table 2. The combined impact of frost and heat stress accounted for yield losses of 16 to 26% depending on the stress function used (Treatments 9, 10). The key message from this analysis was that current levels of N fertiliser application (45 kg N/ha/year) are by far the most limiting biophysical factor and this holds back the national yield by 40%. Treatments 2-8 were not only lower yielding than the Yw treatment - they also had higher CV values indicating greater yield instability. Other research suggests that additional biophysical factors contribute to the yield gap. These include biotic stresses such as plant diseases, insects and other pests, in-crop weeds and extreme weather events (*e.g.* floods, strong winds and hail) other than frost and heat stress (Hochman and Horan 2018).

The large impact of average N fertiliser rates on the yield gap in the above study is in contrast with results of several earlier studies ((Hochman *et al.* 2009, Carberry *et al.* 2013, Hochman *et al.* 2014). The explanation for the difference is that the earlier studies involved farmers, such as Yield Prophet® subscribers, who were well connected to knowledge networks, whereas the more recent study is based on average N usage including all growers.

Table 2. Impacts of sub-optimal management factors, as well as of frost and heat stress, on water-limited yield (Yw) at a national scale

Treatment Number	Treatment	Mean (t/ha)	St Dev (t/ha)	CV (%)	Y% (%)
1	Yw (water-limited yield)	4.28	0.91	21	100
2	Seedling density (50 plants/m ²)	3.78	1.10	29	88
3	Late sowing (2 week delay)	3.97	1.04	26	93
4	Summer weeds	3.18	1.17	37	74
5	Tillage	2.86	1.08	38	67
6	N fertiliser (45 kgN/ha)	2.57	0.78	30	60
7	N fertiliser (90 kgN/ha)	3.30	0.96	29	77
8	Combined N fertiliser (45 kgN/ha) & Summer weeds	2.55	0.92	36	60
9	Frost and heat	3.15	1.00	32	74
10	Frost and heat 2 (moderate impact)	3.60	0.95	26	84

Profit-risk-utility dimension of wheat yield gaps

Large yield gaps may be attributable to (rational) sub profit-maximising input levels in response to risk and risk aversion. To investigate the proposition that risk aversion drives yield gaps, a novel Profit-Risk-Utility Framework that incorporates crop simulation, probability theory, finance techniques, and risk aversion analysis was implemented at fourteen case-study sites in 7 different sub regions across the Australian grain zone. The study demonstrated how farmers might select practices that manage the trade-off between maximising economic net return and exposure to risk across sites ranging from low to high yield potential. Risk-adjusted profit (the difference between the expected mean net return and a risk premium) varied with risk preference and yield potential. Risk aversion had a strong influence on the choice of practice in low yield potential sites, which helps explain yield gaps in those agro-climatic zones. However, in medium to high yielding areas, applying the management inputs required to achieve water-limited yield is the most economical choice even for highly risk averse growers (Monjardino *et al.* 2019).

Socio-psychological dimension of wheat yield gaps

To gain some insight into the socio-psychological drivers of farm level yield gaps, computer assisted telephone interviews were conducted with 232 wheat producers from the same 14 contrasting local areas as the economic risk analysis study described above. The interview data, together with the simulation-based estimates of each farm's wheat yield potential (Y_w), were used to develop a comprehensive framework to understand the causes of wheat yield gaps in 2016. Results revealed significant differences in farming management as well as in farm and grower characteristics between farms with smaller versus larger yield gaps. Farms with smaller holdings, growing less wheat on more favourable soil types were more likely to have smaller yield gaps. Growers with smaller yield gaps were more likely to apply more N fertiliser, to have a greater crop diversity and to be less likely to grow a wheat crop directly after either another cereal crop or a pasture. In addition, they were more likely to soil-test a greater proportion of their fields and to adopt new technologies but were less likely to have problems with herbicide resistant weeds. They were also more likely to use and trust a fee-for-service agronomist and to have a university education (Zhang *et al.* 2019).

Scaling up to crop sequences

The production-environment trade-offs are best evaluated in a whole farm context rather than for individual crops. The APSIM architecture was uniquely designed to enable simulation of crop rotations and cropping sequences. The centrality of soils in multi-seasonal simulations distinguished APSIM as a farming systems simulator rather than as a series of crop models: "*Crops come and go, each finding the soil in a particular state and leaving it in an altered state*" (McCown *et al.* 1995). A simulated chickpea-wheat rotation was an early example that demonstrated how a model may be useful for addressing aspects of cropping system performance (yield as well as loss of organic matter and soil N) in terms of both productivity and sustainability issues (Probert *et al.* 1998).

Analysis of whole systems over multiple seasons is particularly important in cropping regions such as Australia's northern grain zone, where farmers have the option of growing a variety of winter and summer crops and where fallowing is required to store water to safeguard yields of following crops. The agronomic efficiency of cropping sequences compared to individual crops was investigated in a simulation study and longitudinal survey of 94 cropping sequences over 3.5 years. While the income from 36% of the individual crops in the study was found to be more than 80% of their attainable yield (based on N inputs), only 29% of whole cropping sequences achieved this benchmark. Similar results were achieved when crops and crop sequences were evaluated in terms of their metabolisable energy and crude protein yields. In order to increase the agronomic efficiency of crop production in Australia's northern grain zone, attention should be focussed on the intensity and configuration of cropping sequences and on the management of fallows in addition to the management of individual crops (Hochman *et al.* 2014).

Balancing production and environmental imperatives

World population growth, changing diets and limited opportunities to expand agricultural lands will drive agricultural intensification in the decades ahead. Concerns about the reliance of past agricultural intensification on non-renewable resources, about its negative impacts on natural resources, both on and off farm, and on greenhouse gas emissions, provide an imperative for future agricultural intensification to become ecologically efficient. The challenge is to produce more food per unit resource use while minimising the impact of food production on the environment. Ecological efficiencies can be achieved by improved matching of the supply of nutrients to crop requirements both temporally and spatially, and thus minimise the opportunities for excessive nutrients to impact on soil health and water quality (Hochman *et al.* 2013).

Management of soil erosion

From 1950 to 1990 soil erosion in Australia was found to be nearly five times greater under cropping than under uncultivated pasture and forest lands (Koch *et al.* 2015). This difference was attributed to a

greater susceptibility to water and wind erosion due to soil disturbance by tillage and to lack of groundcover. Soil loss can have implications for soil fertility, soil organic matter, soil surface structure and soil acidification. It is generally accepted that soil erosion results in a loss of productivity, but information was sparse on the degree to which erosion reduces yields and was difficult to obtain experimentally because erosion was slow and sporadic, and its effects were often masked by climatic variability and advances in technology.

The PERFECT model was used to estimate the impact of soil erosion on yield through loss of soil depth, plant available water capacity (PAWC) and nitrogen. For a shallow soil on the eastern Darling Downs, erosion caused yield declines that increased rapidly after 25-35 years due to loss of both PAWC and nitrogen. For deeper soils, yield decline was less than 10% for up to 100 years. Yield reduction was variable from year to year, depending on seasonal conditions. In favourable seasons, yield reduction was related to reduced PAWC and less nitrogen, while in drier years yield was determined by growing season water supply rather than soil properties (Freebairn *et al.* 1996).

To examine the spatial distribution of erosion and its effect on production, multiple simulations using the PERFECT model combined information on soil type, slope and rainfall. Fallow management strategy did not affect the area experiencing soil erosion in the highest category (>100 t/ha/y), however, large differences due to fallow management were evident for the lower erosion categories. For NT, only 0.3% of the total area was included in the 50-100 t/ha/y category and approximately 85 % of the study area had less than 10 t/ha/yr of erosion. For stubble burnt management 7.7% of the land area was in the 50-100 t/ha/y category and only 42% had less than 10 t/ha/yr of erosion (Littleboy *et al.* 1992).

The rapid adoption of NT cropping practices in Australia since the 1980s (Llewellyn *et al.* 2012) has had a marked effect on soil erosion in the cropping zone. This is illustrated by a reversal of the soil erosion trend across regions in south eastern Australia where net soil redistribution switched from a loss of 9.7 t/ha/year in 1954-1990 to a gain of 3.9 t/ha/year in 1990-2010 (Chappell *et al.* 2012). Simulation of a mixed farming enterprise in the Murrumbidgee region of NSW showed that seasonal conditions were the dominant effect on the mean farm cover, rather than crop and stock management practices and that retention of wheat stubble increased long-term mean cover by 1-4% (Lilley and Moore 2009). A simulation-based assessment of NT practices showed that the effect of stubble cover on conservation of soil water during the fallow and the earlier sowing opportunities that arise, has increased the national average water-limited yield by 1.4 t/ha (Hunt and Kirkegaard 2011, Hunt *et al.* 2013, Hochman and Horan 2018). Reducing soil erosion by adoption of NT cropping and retaining stubble to improve groundcover appears to be a win-win for the environment and productivity. However, the growing problem of herbicide-resistant weeds will need to be managed carefully to avoid the need to revert to conventional tillage practices.

Management of deep drainage

The replacement of perennial natural vegetation with annual crops in Australia's grain zone has accelerated the rate of leaching of salts beyond the rooting zone. The consequent concentration of these salts elsewhere in the landscape results in dryland salinity (Dunin *et al.* 1999) which is, in turn, a major soil constraint to crop yields (Orton *et al.* 2018). Simulations including a perennial lucerne phase in rotation with crops (phase-farming) showed a reduction in long-term drainage and initially local retreat of water tables by 0.3 m/y (Dunin *et al.* 1999). The temporal variability in transpiration, soil evaporation, runoff and drainage was explored for selected locations in the Murry-Darling Basin over the 1957-1998 climate record. Water excess (*i.e.* runoff plus drainage) was shown to be strongly episodic (60% simulated to occur in 25% of years) and was highest for the annual wheat farming system and lowest for perennial lucerne pasture (Keating *et al.* 2002). While phase farming including 2 or 3 years of lucerne reduced average annual deep drainage significantly, it was achieved at the cost of lower average annual gross margins (Verburg *et al.* 2007).

Nitrogen management for production and environmental protection

Nitrogen fertiliser is a significant source of N for crops on mixed farms in Australia. It is produced from natural gas, a non-renewable resource and is subject to energy-market related fluctuations in supply and price. Efficient use of N by crops results in higher yields, increased protein in grain and increased return of stubble cover and maintenance of soil organic matter. Conversely, inefficient use of N by crops and pastures can result in increased emissions of potent greenhouse gases including nitrous oxide (N₂O) and in loss of N from the root zone. These losses lead to subsequent acidification of soils and to nitrate contamination of water resources. Inefficient use of N fertiliser is clearly inconsistent with concepts of agricultural sustainability and ecological efficiency.

Scenarios embracing a range of cropping rotations, N fertilisers and leguminous crops were evaluated using APSIM with long term data from the Brigalow Catchment in Queensland. Analyses of alternative management systems demonstrated that the use of legumes within cereal rotations was not always as effective in reducing N₂O emissions as improved fertiliser practice. For example, replacing wheat with chickpea did not reduce N₂O emissions relative to fertilised systems and did not assist in increasing soil C due to impacts on stubble cover over the summer months (Huth *et al.* 2010).

Two studies counter-intuitively identified N fertiliser application strategies in which increased N application led to increased yield, water and N uptake, thereby reducing long-term leaching of NO₃. At a deep sand site in the 500 mm rainfall zone west of Moora, Western Australia there was a 50% probability that 141 mm of winter rainfall and 53 kg N/ha could be leached below 150 cm under wheat following a lupin crop. Application of N fertiliser at sowing increased both grain yield and NO₃ leaching. Splitting the N application between the time of sowing and 40 days after sowing decreased NO₃ leaching, increased N uptake by wheat and increased grain yield (Asseng *et al.* 1998). In the high rainfall zone of south eastern Australia, flexible topdressing of N after minimum N application at sowing, maximised crop potential and also economic and environmental performance (Nash *et al.* 2013).

This study of 849 commercial wheat crops in southern and western Australia (2004-2011, Yield Prophet database, Hochman *et al.* 2009) found that only 22% of these crops could expect >20% higher yields from an increased investment in N fertiliser, while 50% of the farmers would realise no benefit from additional fertiliser application. Across all of the crops, regions, and conditions studied, 13% of cases simulations predicted no release of N₂O, and 95% of crop emissions had a global warming potential intensity <200 kg CO₂e/Mg grain, an environmental threshold deemed reasonable for crop production (Grassini and Cassman 2012). Nitrate leaching was predicted in only 17% of cases, with average and maximum leaching losses estimated at 0.7 and 75 kg N/Mg grain. These farmers operate close to eco-efficient frontiers with regard to N (Carberry *et al.* 2013). In the northern grains region, simulation and a survey of 68 fields indicated 50% received more N than required to achieve their yield potential while 71% received more N than required to achieve 80% of their yield potential, with low N use efficiency causing susceptibility to NO₃ leaching (Hochman *et al.* 2014).

Conclusions

The ongoing development and improvement of the cropping systems simulation model APSIM has had considerable impact on Australian cropping systems. We have described three pathways in which this impact has been achieved. The first pathway explored was the direct engagement of researchers with farmers and their advisers in the development and use of decision support systems. The impacts that can be achieved with this approach were illustrated through the FARMSCAPE and Yield Prophet® experiences. Recapping the lessons learned from these experiences is recommended as a guide to current and future efforts inspired by new advances in digital agriculture and App technologies. The case studies on use of models for genotype improvement and on quantifying and diagnosing wheat yield gaps provide a deeper dive into recent coordinated simulation-enabled efforts to improve the productivity of cropping systems. Both efforts are having an impact on farmer practice and an influence on the direction of agronomy research.

The second was through simulation extrapolating experimental results in space and time. This has enabled results, typically obtained from three years of research at two or three sites, to be extrapolated temporally to cover the full range of climate variability and extrapolated geographically to cover the region/s of interest including the whole cropping zone. This pathway is exemplified here by the sections on managing crops in a variable climate, on balancing production and environmental imperatives and in investigation of crop rotations and sequences.

The third pathway explored was applying a model into situations that have not yet been experienced or cannot be readily measured. This was illustrated by investigations into the impacts of, and adaptations to, possible future climate pathways, and by simulations to quantify, over a wide range of environments, the yield improvements that might be gained by potentially desired, but thus far only imagined, crop genotype manipulations.

References

- Allan CJ, Jones B *et al.* (2016) Light grazing of crop residues by sheep in a Mediterranean-type environment has little impact on following no-tillage crops. *European Journal of Agronomy* **77**, 70-80
- Anwar MR, Liu DL, Farquharson R *et al.* (2015) Climate change impacts on phenology and yields of five broadacre crops at four climatologically distinct locations in Australia. *Agricultural Systems* **132**, 133-144
- Asseng S, Fillery IRP, Anderson GC *et al.* (1998) Use of the APSIM wheat model to predict yield, drainage, and NO₃⁻ leaching for a deep sand. *Australian Journal of Agricultural Research* **49**, 363-377
- Bell LW, Kirkegaard JA, Swan A *et al.* (2011) Impacts of soil damage by grazing livestock on crop productivity. *Soil and Tillage Research*, **113**, 19-29
- Bell LW, Lilley JM, Hunt JR, Kirkegaard JA (2015) Optimising grain yield and grazing potential of crops across Australia's high-rainfall zone: a simulation analysis. 1. Wheat. *Crop and Pasture Science* **66**, 332-348
- Brown JN, Hochman Z, Holzworth D, Horan H (2018) Seasonal climate forecasts provide more definitive and accurate crop yield predictions. *Agricultural and Forest Meteorology* **260-261**, 247-254
- Carberry PS, Hochman Z, McCown RL *et al.* (2002) *Agricultural Systems* **74**, 141-177
- Carberry PS, Liang W-L, Twomlow S *et al.* (2013) Scope for improved eco-efficiency varies among diverse cropping systems. *Proceedings of National Academy of Sciences* **110**, 8381-8386
- Chapman SC, Cooper M, Hammer GL (2002) Using crop simulation to generate genotype by environment interaction effects for sorghum in water-limited environments. *Australian Journal of Agricultural Research* **53**, 379-389
- Chappell A, Sanderman J, Thomas M *et al.* (2012) The dynamics of soil redistribution and the implications for soil organic carbon accounting in agricultural south-eastern Australia. *Global Change Biology* **18**, 2081-2088
- Chenu K, Cooper M, Hammer GL *et al.* (2011) Environment characterization as an aid to wheat improvement: interpreting genotype-environment interactions by modelling water-deficit patterns in North-Eastern Australia. *Journal of Experimental Botany* **62**, 1743-1755
- Chenu K, Porter JR, Martre P *et al.* (2017) Contribution of Crop Models to Adaptation in Wheat. *Trends in Plant Science* **22**, 472-490
- Clarke SJ, McLean J, George-Jaeggli B *et al.* (2019) Understanding the diversity in yield potential and stability among commercial sorghum hybrids can inform crop designs. *Field Crops Research* **230**, 84-97
- Dalglish NP, Foale MA, McCown RL (2009) Re-inventing model-based decision support with Australian dryland farmers. 2. Pragmatic provision of soil information for paddock-specific simulation and farmer decision making. *Crop and Pasture Science* **60**, 1031-1043
- Dunin FX, Williams J, Verburg K, Keating BA (1999) Can agricultural management emulate natural ecosystems in recharge control in south eastern Australia? *Agroforestry Systems* **45**, 343-364
- Fischer RA (1979) Growth and water limitation to dryland wheat yield in Australia : a physiological framework. *Journal of Australian Institute Agricultural Science* **45**, 83-94
- Flohr BM, Hunt JR, Kirkegaard JA, Evans JR (2017) Water and temperature stress define the optimal flowering period for wheat in south-eastern Australia. *Field Crops Research* **209**, 108-119
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018a) Fast winter wheat phenology can stabilise flowering date and maximise grain yield in semi-arid Mediterranean and temperate environments. *Field Crops Research* **223**, 12-25
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018b) Genotype × management strategies to stabilise the flowering time of wheat in the south-eastern Australian wheatbelt. *Crop and Pasture Science* **69**, 547-560

- Freebairn DM, Loch RJ, Silburn DM (1996) Soil erosion and soil conservation for vertisols. *Developments in Soil Science* **24**, 303-362
- French R, Schultz J (1984) Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. *Australian Journal of Agricultural Research* **35**, 743-764
- Gobbett DL, Hochman Z, Horan H *et al.* (2017) Yield gap analysis of rainfed wheat demonstrates local to global relevance. *Journal of Agricultural Science* **155**, 289-299
- Grassini P, Cassman KG (2012) High-yield maize with large net energy yield and small global warming intensity. *Proceedings of National Academy of Sciences* **109**, 1074-1079
- Hamilton WD, Woodruff DR, Jamieson AM (1991) Role of computer-based decision aids in farm decision making and in agricultural Extension. Climatic risk in crop production: models and management for the semiarid tropics and subtropics. *Proceedings of an international symposium* pp 411-423 (Wallingford, Oxon, UK: CAB International)
- Hammer GL, van Oosterom E, McLean G *et al.* (2010) Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops. *Journal of Experimental Botany* **61**, 2185-2202
- Hammer GL, Woodruff DR, Robinson JB (1987) Effects of climatic variability and possible climatic change on reliability of wheat cropping—A modelling approach. *Agricultural and Forest Meteorology* **41**, 123-142
- Hayman PT, Easdown WJ (2002) An ecology of a DSS: reflections on managing wheat crops in the northeastern Australian grains region with WHEATMAN. *Agricultural Systems* **74**, 57-77
- Hochman Z, Carberry PS (2011) Emerging consensus on desirable characteristics of tools to support farmers' management of climate risk in Australia. *Agricultural Systems* **104**, 441-50
- Hochman Z, Carberry PS, Robertson MJ *et al.* (2013) Prospects for ecological intensification of Australian agriculture. *European Journal of Agronomy* **44**, 109-123
- Hochman Z, Gobbett D, Holzworth D *et al.* (2012) Quantifying yield gaps in rainfed cropping systems: A case study of wheat in Australia. *Field Crops Research* **136**, 85-96
- Hochman Z, Gobbett DL, Horan H (2017) Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology* **23**, 2071-2081
- Hochman Z, Gobbett D, Horan H, Navarro Garcia J (2016) Data rich yield gap analysis of wheat in Australia. *Field Crops Research* **197**, 97-106
- Hochman Z, Holzworth D, Hunt JR (2009a) Potential to improve on-farm wheat yield and WUE in Australia. *Crop and Pasture Science* **60**, 708-716
- Hochman Z, Horan H (2018) Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. *Field Crops Research* **228**, 20-30
- Hochman Z, Prestwidge D, Carberry PS (2014) Crop sequences in Australia's northern grain zone are less agronomically efficient than implied by the sum of their parts. *Agricultural Systems* **129**, 124-132
- Hochman Z, Van Rees H, Carberry PS *et al.* (2009b) Re-inventing model-based decision support with Australian dryland farmers. 4. Yield Prophet® helps farmers monitor and manage crops in a variable climate. *Crop and Pasture Science* **60**, 1057-1070
- Holzworth DP, Huth NI, deVoil PG *et al.* (2014) APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling and Software* **62**, 327-350
- Hunt JR (2016) Final Technical Report for Project CSP00178 – Increasing yield and reducing risk through early sowing. (GRDC: Barton, ACT)
- Hunt JR, Browne C, McBeath TM *et al.* (2013) Summer fallow weed control and residue management impacts on winter crop yield though soil water and N accumulation in a winter-dominant, low rainfall region of southern Australia. *Crop and Pasture Science* **64**, 922-934
- Hunt JR, Fittell NA, Midwood J *et al.* (2012) Optimising flowering time, phase duration, HI and yield of milling wheat in different rainfall zones of southern Australia. *Proceedings of 16th Australian Agronomy Conference* Armidale, Australia
- Hunt JR, Hayman PT, Richards RA, Passioura JB (2018) Opportunities to reduce heat damage in rain-fed wheat crops based on plant breeding and agronomic management. *Field Crops Research* **224**, 126-138
- Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop and Pasture Science* **62**, 915-929
- Hunt JR, Lilley JM, Trevaskis B *et al.* (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change* **9**, 244-247
- Hunt JR, Swan AD, Fittell NA *et al.* (2016) Sheep grazing on crop residues do not reduce crop yields in no-till, controlled traffic farming systems in an equi-seasonal rainfall environment. *Field Crops Research* **196**, 22-32
- Huth NI, Thorburn PJ, Radford BJ, Thornton CM (2010) Impacts of fertilisers and legumes on N₂O and CO₂ emissions from soils in subtropical agricultural systems: a simulation study. *Agriculture, Ecosystems & Environment* **136**, 351-357

- Ibrahim A, Harrison MT, Meinke H, Zhou M (2019) Examining the yield potential of barley near-isogenic lines using a genotype by environment by management analysis. *European Journal of Agronomy* **105**, 41-51
- IPCC (Intergovernmental Panel on Climate Change) (2014) "Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" (Eds. Edenhofer, O., R. Pichs-Madruga, Y. Sokona *et al.*) p 1465 (Cambridge University Press: Cambridge, United Kingdom) ISBN: 9781107654815 www.ipcc.ch/report/ar5/wg3/
- Jakku E, Thorburn PJ (2010) A conceptual framework for guiding the participatory development of agricultural decision support systems. *Agricultural Systems* **103**, 675-682
- Jones CA, Kiniry JR (1986) "CERES-Maize : a simulation model of maize growth and development" (Texas A & M University Press)
- Kaloki P, Luo Q, Trethowan R, Tan DKY (2019) Can the development of drought tolerant ideotype sustain Australian chickpea yield? *International Journal of Biometeorology* **63**, 393-403
- Keating BA, Carberry PS, Hammer GL *et al.* (2003) An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* **18**, 267-288
- Keating B., Gaydon D, Huth N *et al.* (2002) Use of modelling to explore the water balance of dryland farming systems in the Murray-Darling Basin, Australia. *European Journal of Agronomy* **18**, 159-169
- Keating BA, Thorburn PJ (2018) Modelling crops and cropping systems—Evolving purpose, practice and prospects. *European Journal of Agronomy* **100**, 163-176
- van Keulen H, Seligman NG (1987) "Simulation of water use, nitrogen nutrition and growth of a spring wheat crop" (Wageningen : Pudoc)
- Kirkegaard JA, Hunt JR, McBeath TM *et al.* (2014) Improving water productivity in the Australian Grains industry – a nationally coordinated approach. *Crop and Pasture Science* **65**, 583-601
- Kirkegaard JA, Lilley JM (2007) Root penetration rate – a benchmark to identify soil and plant limitations to rooting depth in wheat. *Australian Journal of Experimental Agriculture* **47**, 590-602
- Kirkegaard JA, Lilley JM, Brill RD *et al.* (2016) Re-evaluating sowing time of spring canola (*Brassica napus* L.) in south-eastern Australia—how early is too early? *Crop and Pasture Science* **67**, 381-396
- Kirkegaard JA, Lilley JM, Howe GN, Graham JM (2007) Impact of subsoil water use on wheat yield. *Australian Journal of Agricultural Research* **58**, 303-315
- Koch A, Chappell A, Eyres M *et al.* (2015) Monitor soil degradation or triage for soil security? An Australian challenge. *Sustainability* **7**, 4870-4892
- Lilley JM, Bell LW, Kirkegaard JA (2015) Optimising grain yield and grazing potential of crops across Australia's high-rainfall zone: a simulation analysis. 2. Canola. *Crop and Pasture Science* **66**, 349-364
- Lilley JM, Flohr BM, Whish JPM *et al.* (2019) Defining optimal sowing and flowering periods for canola in Australia. *Field Crops Research* **235**, 118-128
- Lilley JM, Kirkegaard JA (2007) Seasonal variation in the value of subsoil water to wheat: simulation studies in southern New South Wales. *Australian Journal of Agricultural Research* **58**, 1115-1128
- Lilley JM, Kirkegaard JA (2011) Benefits of increased soil exploration by wheat roots. *Field Crops Research* **122**, 118-130
- Lilley JM, Kirkegaard JA (2016) Farming system context drives the value of deep wheat roots in semi-arid environments. *Journal of Experimental Botany* **67**, 3665-3681
- Lilley JM, Moore AD (2009) Trade-offs between productivity and ground cover in mixed farming systems in the Murrumbidgee catchment of New South Wales. *Animal Production Science* **49**, 837-851
- Littleboy M, Silburn DM, Freebairn DM *et al.* (1989) PERFECT-A computer Simulation model of Productivity Erosion Runoff Functions to Evaluate Conservation Techniques, Queensland Department of Primary Industries Bulletin, QB89005
- Littleboy M, Grundy MJ, Bryant MJ *et al.* (1992) Using spatial land resource data and computer simulation modelling to evaluate sustainability of wheat cropping for a portion of the eastern Darling Downs, Queensland. *Mathematics and Computers in Simulation* **33**, 463-468
- Liu DL, O'Leary GJ, Christy B *et al.* (2017) Effects of different climate downscaling methods on the assessment of climate change impacts on wheat cropping systems. *Climatic Change* **144**, 687-701
- Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Lobell DB, Hammer GL, Chenu K *et al.* (2015) The shifting influence of drought and heat stress for crops in northeast Australia. *Global Change Biology* **21**, 4115-4127
- Ludwig F, Asseng S (2010) Potential benefits of early vigor and changes in phenology in wheat to adapt to warmer and drier climates. *Agricultural Systems* **103**, 127-136
- Luo Q, Bellotti W, Williams M, Bryan B (2005) Potential impact of climate change on wheat yield in South Australia. *Agricultural and Forest Meteorology* **132**, 273-285

- Luo Q, Bellotti W, Williams M, Wang E (2009) Adaptation to climate change of wheat growing in South Australia: Analysis of management and breeding strategies. *Agriculture, Ecosystems & Environment* **129**, 261-267
- Luo Q, Bryan B, Bellotti W, Williams M (2005) Spatial analysis of environmental change impacts on wheat production in mid-lower north, South Australia. *Climatic Change* **72**, 213-228
- Luo Q, O'Leary G, Cleverly J, Eamus D (2018) Effectiveness of time of sowing and cultivar choice for managing climate change: wheat crop phenology and water use efficiency. *International Journal of Biometeorology* **62**, 1049-1061
- Luo Z, Eady S, Sharma B, Grant T *et al.* (2019). Mapping future soil carbon change and its uncertainty in croplands using simple surrogates of a complex farming system model. *Geoderma* **337**, 311-321
- Martre P, Wallach D, Asseng S *et al.* (2015) Multimodel ensembles of wheat growth: many models are better than one. *Global Change Biology* **21**, 911-925
- McCown RL, Carberry PS, Dalgliesh NP *et al.* (2012) Farmers use intuition to reinvent analytic decision support for managing seasonal climatic variability. *Agricultural Systems* **106**, 33-45
- McCown RL, Hammer GL, Hargreaves JNG *et al.* (1996) APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems* **50**, 255-271
- McCown RL, Hammer GL, Hargreaves JNG *et al.* (1995) APSIM: an agricultural production system simulation model for operational research. *Mathematics and Computers in Simulation* **39**, 225-231
- McCown RL, Hochman Z, Carberry PS (2002) Probing the enigma of the decision support system for farmers: Learning from experience and from theory. *Agricultural Systems* **74**, 1-10
- McCown RL, Williams J (1989) AUSIM: A cropping systems model for operational research, Proceedings of SSA IMACS Biennial Conference on Modelling and Simulation (ANU:Canberra)
- Meier EA, Thorburn PJ, Kragt ME *et al.* (2017) Greenhouse gas abatement on southern Australian grains farms: Biophysical potential and financial impacts. *Agricultural Systems* **155**, 147-157
- Monjardino M, Hochman Z, Horan H (2019) Profit-risk-utility trade-offs in the quest to close wheat yield gaps: insights from Australia. (in review)
- Monjardino M, McBeath TM, Brennan L, Llewellyn RS (2013) Are farmers in low-rainfall cropping regions under-fertilising with nitrogen? A risk analysis. *Agricultural Systems* **116**, 37-51
- Monjardino M, McBeath T, Ouzman J *et al.* (2015) Farmer risk-aversion limits closure of yield and profit gaps: A study of nitrogen management in the southern Australian wheatbelt. *Agricultural Systems* **137**, 108-118
- Moore AD (2009) Opportunities and trade-offs in dual-purpose cereals across the southern Australian mixed-farming zone: a modelling study. *Animal Production Science* **49**, 759-768
- Moore AD, Hunt JR (2012) Does control of summer fallow weeds improve whole-farm productivity in both Mediterranean and temperate environments? *Proceedings of 16th Australian Agronomy Conference* <http://www.agronomyaustraliaproceedings.org/index.php/2012-conf-proc-homepage>
- Nash D, Riffkin P, Harris R *et al.* (2013) Modelling gross margins and potential N exports from cropland in south-eastern Australia. *European Journal of Agronomy* **47**, 23-32
- Orton TG, Mallawaarachchi T, Pringle MJ *et al.* (2018) Quantifying the economic impact of soil constraints on Australian agriculture: A case-study of wheat. *Land Degradation & Development* **29**, 3866-3875
- Peake AS, Das BT, Bell KL *et al.* (2018) Effect of variable crop duration on grain yield of irrigated spring-wheat when flowering is synchronised. *Field Crops Research* **228**, 183-194
- Pembleton KG, Cullen BR, Rawnsley RP *et al.* (2016) Modelling the resilience of forage crop production to future climate change in the dairy regions of Southeastern Australia using APSIM. *The Journal of Agricultural Science* **154**, 1131-1152
- Probert ME, Carberry PS, McCown RL, Turpin JE (1998) Simulation of legume-cereal systems using APSIM. *Australian Journal of Agricultural Research* **49**, 317-328
- Robertson MJ, Rebetzke GJ, Norton RM (2015) Assessing the place and role of crop simulation modelling in Australia. *Crop and Pasture Science* **66**, 877-893
- Rodriguez D, de Voil P, Hudson D *et al.* (2018) Predicting optimum crop designs using crop models and seasonal climate forecasts. *Scientific Reports* **8**, 2231
- Sadras VO, Angus JF (2006) Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research* **57**, 847-856
- Sadras VO, Lawson C (2013) Nitrogen and water-use efficiency of Australian wheat varieties released between 1958 and 2007. *European Journal of Agronomy* **46**, 34-41
- Seligman NG (1981) Papran a simulation model of annual pasture production limited by rainfall and nitrogen. In (Eds. MJ Frissel, JA van Veen) "Simulation of nitrogen behaviour of soil-plant systems" 192-221
- Stone RC, Hammer GL, Marcussen T (1996) Prediction of global rainfall probabilities using phases of the Southern Oscillation Index. *Nature* **384**, 252-255

- Stone P, Hochman Z (2004) If interactive decision support systems are the answer, have we been asking the right questions. *Proceedings of 4th International Crop Science Congress*, Brisbane
[www.cropscience.org.au/icsc2004/pdf/1680_stonepj.pdf](http://www.cropsscience.org.au/icsc2004/pdf/1680_stonepj.pdf)
- van Ittersum MK, Cassman KG, Grassini P, Wolf J, Titttonell P, Hochman Z (2013) Yield gap analysis with local to global relevance-A review. *Field Crops Research* **143**, 4-17
- van Rees H, McClelland T, Hochman Z, Carberry PS, Hunt JR, Huth N, Holzworth D (2014) Leading farmers in South East Australia have closed the exploitable wheat yield gap: Prospects for further improvement. *Field Crops Research*, **164**, 1-11.
- Verburg K, Bond WJ, Brennan LE, Robertson MJ (2007a) An evaluation of the tactical use of lucerne phase farming to reduce deep drainage. *Australian Journal of Agricultural Research* **58**, 1142-1158
- Verburg K, Bond WJ, Hirth JR, Ridley AM (2007b) Lucerne in crop rotations on the Riverine Plains. 3. Model evaluation and simulation analyses. *Australian Journal of Agricultural Research* **58**, 1129-1141
- Verburg K, Bond WJ, Hunt JR (2012) Fallow management in dryland agriculture: Explaining soil water accumulation using a pulse paradigm. *Field Crops Research* **130**, 68-79
- Verburg K, Bond WJ, Smith CJ (2004) Fallow management affects the risk of deep water loss. *Proceedings of 4th International Crop Science Congress, Brisbane, Australia*
[www.cropscience.org.au/icsc2004/symposia/6/2/1187_verburgk.htm](http://www.cropsscience.org.au/icsc2004/symposia/6/2/1187_verburgk.htm)
- Wang B, Liu DL, O'Leary GJ *et al.* (2018) Australian wheat production expected to decrease by the late 21st century. *Global Change Biology* **24**, 2403-2415
- Wang J, Wang E, Luo Q, Kirby M (2009) Modelling the sensitivity of wheat growth and water balance to climate change in Southeast Australia. *Climatic Change* **96**, 79-96
- Whish J, Butler G, Castor M *et al.* (2005) Modelling the effects of row configuration on sorghum yield reliability in north-eastern Australia. *Australian Journal of Agricultural Research* **56**, 11-23
- Whish JPM, Castor P, Carberry PS (2007) Managing production constraints to the reliability of chickpea (*Cicer arietinum* L.) within marginal areas of the northern grains region of Australia. *Australian Journal of Agricultural Research* **58**, 396-405
- Whish JPM, Bell LW, DeVoi P *et al.* (2019) Simulating the efficiency and resilience of diverse crop sequences in Australia's subtropical cropping zone. *Proceedings of 19th Australian Agronomy Conference*, Wagga Wagga, Australia
- Williams JR, Jones CA, Kiniry JR, Spanel DA (1989) The EPIC Crop Growth Model. *Transactions of the ASAE* **32**, 497-511
- Wunsch EM, Bell LW, Bell MJ (2017) Can legumes provide greater benefits than, millet as a spring cover crop in southern Queensland farming systems? *Crop and Pasture Science* **68**, 746-759
- Zhang A, Hochman Z, Horan H *et al.* (2019) Socio-psychological and management drivers explain farm level wheat yield gaps in Australia. *Agronomy for Sustainable Development* **39**, 10-23
- Zheng B, Chapman S, Chenu K (2018) The value of tactical adaptation to El Niño-Southern Oscillation for east Australian wheat. *Climate* **6**, 77
- Zuber-Skerritt O (1993) Improving learning and teaching through action learning and action research. *Higher Education Research & Development* **12**, 45-58

Chapter 22

High input irrigated crops

Rose Brodrick and Michael Bange

Introduction

Irrigated production in Australia constitutes a small proportion (4% of the land area) of broadacre cropping area in Australia but contributes 21% of the gross value of broadacre production to the Australian economy (ABS 2019). The three major irrigated broadacre crops grown in Australia are cotton, sugarcane and rice. Cotton is the largest of these crops grown under irrigation; both cotton and sugarcane are also grown under rainfed production (Table 1).

Table 1. Value, area and irrigation water applied in cotton, sugarcane and rice in Australia 2016-17 (source: Australian Bureau of Statistics 2019)

	Value of agricultural commodity produced \$M	Area under crop ha '000	Area watered ha '000	Volume applied ML '000	Application rate ML/ha
Cotton	1681	519	328	2 566	7.8
Sugar cane	1621	453	212	974	4.6
Rice	252	82	82	940	11.4

Since 1987 there have been several agronomic changes and improvements in crop production that are not unique to irrigated production systems and are transferable across industries. Many of these are covered in more detail in other chapters. In many cases however, irrigated producers have been early adopters of precision agriculture, controlled traffic and automation. For all three crops, key production changes have included use of rotation crops for productivity gains, breeding of locally adapted cultivars with a dual focus on yield and quality, unique agronomic, policy or technological changes that have influenced production methods, and a shift in focus to integrated approaches to crop management (including an emphasis on protecting natural resources).

A very significant challenge in broadacre irrigated production has been the increasingly drier climate in cotton and rice growing regions and shrinking water resources (Jones 2010) caused by Australia's variable and changing climate (Humphreys *et al.* 2006, Bange *et al.* 2016). Indirectly, production is significantly affected by government regulation of water to mitigate these effects. In the case of sugarcane, arguably the impact of run-off into sensitive marine systems, and the associated impact of these pollutants on the Great Barrier Reef (GBR), has been the most significant challenge for that industry, and is yet to be overcome (Hamman and Deane 2018).

Regulations that require reduced environmental impact or resource use for these three crops have impacted on production methods and led to a focus on best management practices and improved water use efficiency. These challenges have been accompanied by reductions in land availability, rising costs of production, environmental concerns, and potentially a decline in trade as a result of competition from other commodities (*e.g.* such as man-made fibres for cotton, or increasing production from other overseas markets in the case of rice and sugar).

This chapter outlines briefly some unique changes in rice and sugar production and explores cotton as the main case study in greater detail to exemplify crop management, genetics, and agronomic improvements over the past 30 years. Modern agronomic management of rice is covered in detail by Bajwa and Chauhan (2017) so we do not attempt to repeat the details in their summary here. Irrigated cotton production in Australia is a high cost and capital-intensive industry which has necessitated innovation to remain viable. Due to challenges with insect pesticide resistance and concerns with the

environmental impacts of pesticide use, in the 1990s the Australian cotton industry was the first to utilise genetically modified (GM) cultivars. The introduction of GM cultivars transformed the industry and enabled a strong focus on broad production improvements over the past 30 years. Using the Australian cotton industry as an example we endeavour to give a broad overview of practice change and strategies to address some current challenges facing irrigated broadacre production in Australia now and into the future.

Rice

Rice production and management in Australia is unique compared with other rice producing countries. Australian rice farmers produce high quality rice, attain the highest yields per unit area and grow the most water-use efficient rice in the world (Humphreys *et al.* 2006, Bajwa and Chauhan 2017). This is a significant achievement given the environmental challenges involved. Over the past 30 years, the rice production system in Australia has achieved substantial increases in yield through improved agronomy coupled with locally adapted cultivars; this makes the Australian rice industry an excellent example of agronomic innovation and adoption during this period (Bajwa and Chauhan 2017).

Key challenges faced by Australian rice growers include reduction in water availability, low temperature damage and continued environmental pressures (Humphreys *et al.* 2006). Reduced water availability has been due to both prolonged droughts and changes in legislation to reserve water for environmental flows.

A novel agronomic innovation that led to increased rice yields was flooding of the crop for the duration of the growing season, in order to provide protection from cold temperature stress, which can cause floret sterility during the reproductive period (Williams and Angus 1994). This practice has been adjusted as water availability has declined; under water-limited conditions, flooding is delayed in order to align better with the cold-sensitive early pollen microspore stage. Nitrogen management in particular has been adjusted to keep in step with changes in water management and yield improvements. In the past twenty years, average water productivity of the Australian rice crop has almost doubled (Humphreys *et al.* 2006), primarily due to yield improvement associated with the introduction of semi-dwarf cultivars and improved water management.

Rice production is now limited to suitable soil types of low permeability, in order to reduce drainage past the root zone. This produces better water use efficiency, keeps water tables at depth, and reduces incidence of soil salinity. Growers require approval from the local irrigation management corporation to grow rice on particular fields (Thompson *et al.* 2002) which are deemed suitable using electromagnetic induction soil surveys to assess the permeability of the soil (Beecher *et al.* 2002).

Rice production area in Australia has declined over the past 30 years; the major challenge facing the industry in the future is water availability and the competition from other crops with lower water consumption or higher value. There are limited soils and climates suitable for growing rice in Australia. For the industry to be sustainable, continued varietal improvement particularly for both heat and cold tolerance will be required, together with diversification of rotations and further improvements in water productivity (Thompson *et al.* 2002, Humphreys *et al.* 2006, Bajwa and Chauhan 2017).

Sugarcane

Sugarcane production over the past 30 years has shifted increasingly from a focus on production and practice changes that improve productivity or profitability to practices that reduce its environmental footprint. Prior to this, the combination of monoculture, intensive tillage and burning for harvesting had degraded the soil resource to the extent that the associated yield decline of the 1980s and 1990s threatened the viability of the industry (Garside and Bell 2011).

The continuing yield decline was reversed in recent times using a coordinated approach to address this decline (Bell and Garside 2014). The benefits of legume rotations were demonstrated in the 1990s with yield improvements of 15-25% due to improved soil fertility and structure (Garside and Bell 2011). Industry adoption of green cane harvesting, after about half a century of cane burning, delivered

considerable agronomic benefits, including greater soil water retention, improved weed control, reduced erosion, improved soil structure and reduced tillage. As with many other crops, soil compaction due to heavy harvesters became an issue for the industry but was alleviated by controlled traffic farming (Braunack and McGarry 2006).

In the last thirty years, the sugar industry has faced numerous challenges including increased competition from other sugar producing countries, industry deregulation, rising costs of production, pests and diseases, increasing climate variability and cyclonic events, and prolonged periods of falling sugar prices. The industry has also been under increased social pressure regarding its environmental responsibilities (*i.e.* its social licence) due to the close proximity of particular cane growing regions to the GBR (Hamman and Deane 2018). Current strategies and practices are considered unlikely to provide sufficient protection to the GBR (Kroon *et al.* 2016).

Future sustainability of the sugar industry will rely on solutions to minimise sediments, nutrients and pesticides entering the GBR catchment; this has become the primary concern for policy-makers and industry alike (Thorburn and Wilkinson 2013, Hamman and Deane 2018). While the sugar industry faces many of the same challenges agronomically as other broad acre crops, it is an imperative that the industry reduces its environmental footprint to maintain its social licence to farm. Innovative approaches to monitor nitrogen use using remote sensing, and modelling to provide application recommendations are being explored (Thorburn *et al.* 2018, Bramley *et al.* 2019).

Cotton

In comparison with the rest of the world Australian broadacre irrigated cotton systems are characterised as high yielding, high quality and high input systems. For the past 25 years the Australian industry has been growing cultivars that contain transgenic traits, providing significant protection to the industry from insect pests and weeds which in the past had challenged industry viability. Overcoming these pest challenges has enabled the industry to refine its crop management substantially in other parts of the system, embracing new technologies; it is one of the most successful cotton industries worldwide (Constable and Bange 2015). The cotton industry has expanded and is now grown in areas much further south than 30 years ago (Figure 1). Current and future challenges in Australian irrigated cotton systems are presented and the current management principles and new research initiatives are discussed.

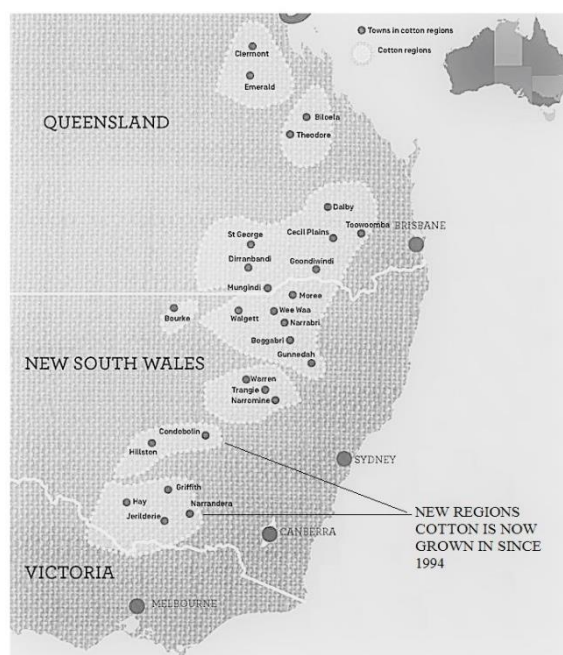


Figure 1. Map of eastern Australia showing cotton growing regions in 2019 (adapted from Cotton Australia 2019)

Historically the most significant challenge to cotton production was yield loss due to a range of insect and mite pests. To control these pests, Australian cropping systems relied on intervention with chemical pesticides, which were a significant component of the cost of production (Fitt and Wilson 2000). In addition, chemical use gave rise to pesticide resistance in key pests, and environmental concerns about pesticide movement off-farm (Fitt 2000, Wilson *et al.* 2004). Circa 1995 transgenic cotton, with *Bacillus thuringiensis* (Bt) genes, was made available to the world's cotton growers. The germplasm containing these genes offered significant potential to reduce pesticide use for the control of major Lepidopteran pests (particularly *Helicoverpa* spp.). However, as the system was changing, pests formerly suppressed by this GM control are emerging as new challenges (Wilson *et al.* 2013).

Agronomic changes were required along with the improved genetics for insect control, as retention of squares (flower buds) and young bolls were higher in these crops in some regions, resulting in a higher and earlier carbohydrate and nitrogen demand by the fruit. Yields can be reduced if management does not meet these internal assimilate demands and, as a consequence, agronomic practice needed to be more precise. Thus, management practices such as planting time (Bange *et al.* 2008), crop nutrition (Rochester and Bange 2016) and irrigation have been re-evaluated (Yeates *et al.* 2010).

Cotton pest management

Cotton growers also employ transgenic cotton that allows over-the-top application of herbicides for weed control, enabling a rapid response to weed infestations. However, this can predispose the system to herbicide resistance if not practised with integrated weed management which includes soil residual herbicides, farm hygiene and tillage. At greatest risk for developing weed resistance is the use of glyphosate in cotton systems (Werth *et al.* 2011). For both insect pest and weed control now and into the foreseeable future, there will be continued reliance on transgenic technologies to assist an integrated pest and weed management program that includes:

- Continued crop improvement to create insect, disease and herbicide tolerant cultivars through both conventional plant breeding and genetic modification; Morphological (*e.g.* leaf hairiness) and biochemical traits (*e.g.* gossypol) are being considered for selection for host plant resistance (Trapero *et al.* 2016).
- Implementation of effective integrated insect, weed and disease management practices that encompass all farm management techniques both 'in-season' and 'off-season' (Wilson *et al.* 2018).
- Effective crop monitoring and use of predictive models to improve timing of pest management interventions. For insect management in cotton there are numerous monitoring techniques to manage specific insects pests within a cropping cycle (Wilson *et al.* 2004), and many are coupled with decision support systems linked to climate (Hearn and Bange 2002).
- Effective industry and on-farm hygiene and bio-security; this has been especially important to curb the spread of Fusarium wilt (*Fusarium oxysporum*), a plant and soil borne disease that reduces cotton yield significantly (Kochman 1995).
- Landscape-scale management involving groups of growers cooperating to reduce communal threats (Hoque *et al.* 2000); this includes consideration of habitat type, and spatial and temporal distribution of habitats to suppress economically important pests (Schellhorn *et al.* 2014).
- Implementation of industry-wide strategies to prevent build-up of weed and insect resistance to pesticides; *e.g.* growers using transgenic cultivars to protect against insects are required to grow a susceptible refuge crop to dilute any potential resistant moth population (Carrière *et al.* 2019).

Water and irrigation management

There have been significant improvements in agronomic water use efficiency in the Australian cotton industry over time. Tennakoon and Milroy (2003) and Roth *et al.* (2013), in their reviews of cotton water use efficiencies, highlighted significant opportunities to improve water use efficiency at all levels (from whole farm to agronomic). Their analyses showed that irrigated cotton farms incurred significant losses through conveyance, storage and application of water, or improper scheduling.

Cotton production in many regions can be rain-fed, partially or fully irrigated. The main irrigation practice is furrow-flood irrigation and practices being developed to improve water use efficiency include:

- Implementing systems that monitor and assess whole farm water use efficiency to identify inefficient parts of the system; growers consistently adopt practices that improve water storage and furrow irrigation efficiencies, and reduce transmission and application losses.
- Use of alternative irrigation systems such as lateral moves, centre pivot, or drip irrigation systems; especially on soils of lighter soil texture. The agronomic crop water use efficiencies of these systems are comparable to furrow irrigation when used on heavier soils, however transmission losses are reduced. Bankless systems, which use gates instead of siphons are used in some regions to reduce the labour needs for irrigation practice. Automated gated systems that monitor water flow down furrows and shut off water at the optimum time can also reduce labour requirements (Uddin *et al.* 2018).
- Better scheduling of irrigation utilising technologies that continuously monitor weather (automatic weather stations), crop soil water use (capacitance probes, neutron moisture meters) and plant stress (canopy temperatures, stem diameter), but allow for differences in soil types, demands of the crop (crop stage) and climatic conditions (*e.g.* temperature and evaporative demand). Most commonly soil water is monitored, with capacitance probes. Some growers also use weather-based systems that provides estimates of current and predicted crop water use from potential evapotranspiration and crop coefficients (IrrisAT, Montgomery *et al.* 2015) Recent research is also demonstrating the value of continuous canopy temperature sensors utilising the Biologically Identified Optimal Temperature Interactive Console (BIOTIC) platform (Upchurch *et al.* 1996). These add extra insights to quantify the level of stress from the plant's perspective. Potential use of the BIOTIC in furrow-flood irrigation systems for cotton is supported by Conaty *et al.* (2012) showing that cotton canopy temperatures exceeding 28°C for 4.45 hours per day can lead to a significant reduction in yield.
- Changes in sowing time to shift periods of maximum water use into periods of lower temperatures or vapour pressure deficits (Braunack *et al.* 2012).
- Using reactive strategies to respond to weather forecasts at both daily and seasonal time steps. Decisions relating to irrigation management can be based on soil moisture storage, seasonal average rainfall, short- and long-term forecasts of weather and climate (rainfall and/or crop evaporative demand) as well as financial and commodity forecasts on a single field or whole farm basis (Power and Cacho 2014). *At the field level*, Brodrick *et al.* (2012) reported opportunities to vary timing of irrigation utilising short term (3 to 4 d) forecasts of evaporative demand. When the soil-water deficit for irrigation is reached and when the forecast for evaporative demand is low, they found irrigation could be delayed without affecting yield or fibre quality. In many instances, it also increased the time for the crop to capture rainfall, reducing the need to deliver irrigation water to the crop. *At the farm level*, water management is improved when water allocations are known well before planting, as this allows for planning cropping areas and level of inputs. This could be improved with improved seasonal forecasts (Ritchie *et al.* 2004).
- Using crop simulation Bange *et al.* (1999) showed that a relationship exists between forecasted wetter seasons and lower yield performance when compared with the average. Currently Nunn *et al.* (2019) are investigating the value of sub-season forecasts for decisions that affect early season crop management. Concurrently it will also be important to access information on business level impacts by downscaling weather and climate predictions to the farm level. Tools and extension networks will be needed to enable farmers to access these climate data, and interpretation provided through a sustainable means of delivery (Brown *et al.* 2019).
- Reducing the risk of crop failure by reducing the area of cotton grown to increase water delivery (ML per ha) from irrigation suppliers before the season begins. Determining the area to plant is a decision that considers crop yield, and therefore the water needed (accounting for climatic risk and system irrigation efficiencies) to break even (Hearn 1992). HydroLOGIC (Richards *et al.* 2008) which incorporates the Australian cotton crop simulation model OZCOT (Hearn

1994) can be used to help plan planting area by comparing yield estimates from simulations with different water allocations and climatic impacts (including rainfall variability). Recent advances in field irrigation management have included the development of a framework ‘VARIwise’ that develops and simulates site-specific irrigation control strategies for in-field management of water (McCarthy *et al.* 2010). VARIwise divides fields into spatial subunits based on databases for weather, soil, and plant parameters to account better for field variability. The OZCOT model is used to simulate the performance of the control strategies and identify the irrigation application maximises yield or water productivity.

- Improvements in practices to capture and retain soil moisture in crop fallows. Extending the fallow period can allow more stored moisture from rainfall. Reduced tillage and stubble retention are now standard practice for moisture conservation. Where there is flexibility in planting time using rainfall to establish crops, rather than pre-irrigation or ‘watering-up’ is used.
- Utilising supplemental irrigation strategies or modified row configurations (*e.g.* skip rows) to enhance crop access to soil moisture. These practices are not necessarily the most water use efficient but offer significant risk mitigation in years where rainfall is limited (Montgomery and O’Halloran 2008). In general, the strategy in limited water situations is to keep irrigating until irrigation water runs out and minimising stress where possible during flowering. Skip-row configurations can also offer significant insurance against losses in both yield and quality and can reduce input costs. Current recommendations are to move from a solid configuration to a skip configuration when yield potential of the available budgeted water falls below 2.2 bales/ha in a solid row configuration (Bange *et al.* 2005).
- Irrigation requirements can be reduced by shortening the time to crop maturity. However, this consideration needs to be balanced against a reduced lint yield due to shorter periods of reproductive growth and maturity (Bange and Milroy 2004). Roberts and Constable (2003) and Bange *et al.* (2006) have shown that after cultivar choice, the main factor driving differences in crop maturity is fruit retention. Transgenic cultivars, which can withstand early pest damage from *Lepidopteron* spp. maintain more fruit, can achieve similar yields to non-transgenic cultivars, and use less water by maturing earlier.
- Investigating the use of degradable polymer films as mulches to conserve water in both rain-fed and irrigated cotton systems, such as those described in Braunack *et al.* (2015). Thin plastic films have been used to increase soil temperature, conserve soil water and to improve crop establishment for cotton. Plastic film mulch is not ideal as it does not degrade and ends up as land-fill. However there are new formulations which degrade to water and carbon dioxide (oxodegradable films). It may also be possible to harvest and concentrate rain water from the film covered areas although consideration would need to be given to field layout for runoff and erosion potential due to slope.
- Reducing yield losses caused by risk of waterlogging through appropriate field design to ensure adequate drainage and runoff, by growing cotton on well-formed hills, and by avoiding irrigation before significant rainfall events using weather forecasts. Yield reductions may be avoided by the application of nitrogen and iron foliar fertilisers prior to waterlogging may (Hodgson and Macleod 1987). Application of the growth regulator aminoethoxyvinylglycine (AVG) prior to waterlogging may have beneficial effects by maintaining photosynthesis, improving node production and reducing fruit abscission (Najeeb *et al.* 2015).
- Choosing a cultivar with inherently longer fibre length can help avoid economic fibre discounts in situations where there is chance of stress around flowering and concern that fibre quality could be severely impaired.

Soil management, including crop rotations and cover crops

Tillage Tillage remains an important practice in irrigated cotton systems for stubble management, and for managing pest (weed and insect) resistance. In the last 30 years there has been a move away from burning cotton stubble to incorporation of mulched stubble in the surface soil. Stubble is generally incorporated at the time when the soil is tilled to reduce the number of over-wintering *Helicoverpa* spp. pupae. This practice, ‘pupae busting’, is a mandatory requirement of utilising transgenic cultivars with insect pest

resistance. Therefore, unlike other broadacre cropping systems there is generally no irrigated cotton system that relies on a 'single pass' tillage operation. A reduction in tillage operations has led to increased crop yields (Hulugalle *et al.* 2005) although it is generally accepted that cover crops or rotations with high residue crops have better potential to increase the productivity of cotton systems.

Rotation The use of wheat and maize in rotation with cotton were shown to raise cotton yields due to improvements in soil physical structure (Hulugalle *et al.* 2007) and reductions in disease but only influenced soil organic C concentrations of the surface soil (Hulugalle *et al.* 2013). Crop rotation sequences with legumes on a different soil type with less sodicity, had higher levels of C in both the top and sub-soil and were associated with higher cotton yields (Rochester and Bange 2016). Rochester (2011b) demonstrated that soil C could be maintained over time with different crop sequences with some minimal incorporation of crop residues associated with crops producing large amounts of biomass in both the cotton and rotation phases.

Soil fertility Cotton production relies on a high levels of nutrition (especially N) to maximise yield. Monitoring soil fertility and crop nutrient uptake are important because growers realise the importance of avoiding nutrient deficiency, and the expense and environmental concerns (including greenhouse gas emissions) associated with excess fertiliser use. Excess N fertiliser can also reduce water use efficiency or yield by encouraging excessive vegetative growth and delayed maturity. Decision support systems (Rochester *et al.* 2001) are used by growers to determine the appropriate rates for N fertiliser use and the need for other nutrients, based on crop stage (utilising climate information) and performance. Current estimates of N requirements of high yielding crops in Australia are in the range of 240-270 kg N/ha crop uptake (Rochester and Constable 2015). A survey of Australian cotton fields by Rochester (2011a) and Macdonald *et al.* (2018) highlighted that a significant proportion of growers had low N use efficiency (kg lint/kg N uptake) because of excessive N fertiliser application increasing the chances of N being lost from the system and contributing to greenhouse gases.

One approach for crop N nutrition is to supplement or even replace entirely the use of artificial N fertiliser with nitrogen fixed by legumes which also improve soil structure. Cotton crops can be grown with N able to supply high yielding provided entirely by legumes (Rochester and Bange 2016), with vetch (*Vicia villosa*) and fababean especially crops.

Crop husbandry

Cultivar choice Cultivar choice is a strong component of realising both target yield and fibre quality levels on farm. At a whole farm level, a key strategy is to select cultivars that have different adaptive traits to spread risk to variable climate and accommodate changes in management. Consideration should be given to cultivars that minimise impacts of water stress, disease (*e.g.* fusarium wilt), or crop maturity when season length is ill-defined.

Yeates *et al.* (2010) found that more early vegetative growth was necessary to support high yielding irrigated cotton systems in transgenic cotton cultivars with high and early fruit loads. In a recent analysis, Constable and Bange (2015) reaffirmed the need to have continued vegetative growth during early boll set, to allow crops to mature later to achieve higher yields. They suggested using a management strategy that regulated vegetative and reproductive growth using water, fertiliser, and growth regulators.

Planting Time Research by Bange *et al.* (2008) in Australia showed that crops with higher fruit retention (such as those generated with transgenic cultivars) can maintain yield and improve fibre length and micronaire for delayed planting dates in warmer and longer seasons. In these studies, yield was maintained for plantings up to 20 d later than the normal planting date, as early growth was more rapid when crops were planted into warmer temperatures. The improved fibre quality (length and micronaire) was associated with the cooler conditions during the early boll filling stages of the crops. Planting crops into warmer conditions also had the benefit of avoiding low temperatures at emergence, which can reduce cotton seedling vigour and lead to poor establishment, poor early growth, and increase the risk of seedling diseases. Braunack *et al.* (2012) also showed that, in longer season cotton growing regions in Australia, water use efficiency could be improved with later planting.

Plant growth regulators (PGRs) Plant growth regulators are commonly used in cotton production systems to control and manipulate growth, which is mainly regulated by endogenous plant hormones. PGRs are an important management tool to ensure optimal and sustainable yields.

While maintaining vigorous vegetative growth before flowering is important to support reproductive growth, there are some situations where vegetative growth can be excessive and reduce light and air circulation in the canopy. This can then increase physiological shedding of fruit and sometimes reduce yield. The main plant growth regulator used to restrict vegetative growth in Australia during the season is Mepiquat Chloride (an anti-gibberellin, Williams *et al.* 2018). Later in the season Mepiquat Chloride is also credited for a range of responses including inducing cut-out, achieving earliness, reducing attractiveness to late season pests and improving crop uniformity.

Strategies to improving Australian cotton production and sustainability

Key approaches to increase yields and fibre quality, and improve resource use efficiencies, are:

- to develop, refine and apply new technologies (*e.g.* precision agriculture, cultivars with both yield and fibre quality improvements, novel plant growth regulators);
- improve agronomic practices (*e.g.* sowing time, plant population, crop nutrition); and
- implement management systems (*e.g.* integrated pest, disease and weed management) that enable cotton to grow healthier or be more tolerant of both abiotic and biotic stresses.

To achieve this, detailed integrative systems research (see Chapter 23) over a greater range of environments and stresses are needed to assess impacts and adaptation options for yield and quality improvements. In a recent review by Hatfield and Walthall (2015), an emphasis was placed on leveraging opportunities by adopting a Genetic x Environment x Management (G x E x M) interaction as a foundational approach to meet global agriculture needs and realising potential of cropping systems in current and future climates. There are few studies in cotton that have demonstrated the value of G x E x M to improve cotton productivity, although analyses by Liu *et al.* (2013), using their advanced line trials containing cultivars grown over a 30-year period from 1982 to 2009, demonstrated that yield gain in the Australian cotton industry resulted from improvement in cultivars (G; 50% improvement), in crop management (M; 26% improvement), and from the interaction between improved cultivars and improved management (G x M; 24% improvement). This approach, termed incremental transformation by Kirkegaard (2019) and ‘Transformational Agronomy’ by Hunt and co-authors (Chapter 23) has essentially underpinned cotton research in the past, but will certainly be needed to continue to meet the challenges for cotton production in the future. The challenge remains on how to exploit the G x E x M interaction in research and commercial production to deliver the benefits of improved yield and quality to cotton growers. Noting these challenges and opportunities, we consider below aspects of Australian cotton production relevant to an enduring profitable and sustainable cotton industry.

Climate change

There is no doubt that one of the most significant challenges facing irrigated industries is climate change. It is a multifaceted and complex challenge for industries and it will affect the sustainability of farms, ecosystems and the wider community. The impacts of climate change on modern cotton systems has been extensively reviewed by Bange *et al.* (2016). Fortunately, many potential adaptation responses available have immediate production efficiency benefits making them attractive options regardless of the rate and nature of future climate change.

Genetic improvement

For Australian cotton breeders, delivering high yielding cultivars to cotton growers is essential to maintain economic viability. Along with traditional approaches to breeding, future breeding efforts will need to rely on both improved genotyping and phenotyping approaches for trait selection (see Chapter 17). Opportunities to improve yield remain possible (Constable and Bange (2015). Options for longer season and more indeterminate growth habit are required with relatively slow crop setting, but with greater final fruit numbers. A challenge for molecular biology is to increase photosynthetic capacity

and translate this into improved canopy radiation use efficiency (RUE) (Wu *et al.* 2016). Such research is still in its infancy and there are many obstacles to overcome, but there may be long-term benefits in increasing rates of photosynthesis. When resources are not limited, it was determined that nutrient uptake and distribution would limit potential yield. Therefore, research in crop management is also required to understand improved nutrient use efficiency through better nutrient uptake and better redistribution to fruit.

Specific tolerances for heat (Constable *et al.* 2001, Cottee *et al.* 2010) and water stress in rain-fed environments (Stiller *et al.* 2005) have been recorded despite no specific selection pressure on these stresses. Recently, genetic variability of transpiration rates to vapour pressure deficits (VPD) has been found in cotton genotypes (Devi and Reddy 2018). Selecting for genotypes that have limited transpiration rates at high VPD could conserve water in the soil.

Current research efforts are attempting to break the negative association between yield and fibre quality in cotton using early generation selection strategies that employ a yarn quality index to integrate the fibre properties of length, strength and fineness together with yield (Clement *et al.* 2015).

Genetic engineering may assist to improve quality or generating novel fibre traits (*e.g.* elongation and moisture absorption). There are also opportunities to improve the value of cotton as a food and fibre crop by improving the quality of cotton seed oil by removing toxic gossypol (Palle *et al.* 2013) and altering the fatty acid composition (Liu *et al.* 2002).

Soil management

It is now widely recognised that microbial processes play central role in the nutrient cycling and hence are key determinants of nutrient availability and nitrogen use efficiency in arable fields (see Chapter 15). However, understanding mechanisms and magnitude of nutrient cycling response in Australian cotton production is an emerging area of research.

Cover crops can also be grown to reduce long fallow periods in a cropping cycle specifically to protect the soil from erosion and reduce nutrient loss through erosion or leaching. Incorporating cover crops as part of cotton rotations are difficult in highly capitalised, mechanised systems (Rochester and Peoples 2005). A better understanding is needed of soil and cotton yield improvements; water requirements and cost of cover crops; and the impact on nutrition uptake by cotton crops

An emerging concern related to modern Australian cotton production systems is soil compaction, caused by machine cotton pickers that have on-board module-building capabilities. These pickers have the potential to increase compaction in the sub-soil limiting efficiencies in both water and nutrition (Braunack and Johnston 2014). Growers using these pickers will need to consider strategies to: ameliorate compaction using crop rotations that dry the soil profile; further implement controlled traffic systems; and seek to reduce moisture in the profile at picking. A review of compaction issues in cotton systems by Antille *et al.* (2016) noted the need for machinery manufactures to customise their systems to allow a fully controlled traffic system to be employed.

Crop management

Strategies to mitigate damage incurred when encountering episodes of extreme environmental stress (through tolerance or avoidance) will need to be developed, building adaptive capacity and resilience. While formulating these strategies, they must take into account all aspects of the production system from planting through to harvest (and potentially post-harvest) and consider all the possible tools available (precision technologies and new genetics, for example).

To help build resilient and productive systems a knowledge of yield potential or ‘yield gap’ in different cotton systems across regions will be important. This will identify the major limiting factors in systems and provide insights into overcoming them. Importantly these limitations will require reassessment with future climate change predictions so that changes to the systems are not short-lived or maladaptive in the future. In many cases, the reduction in the ‘yield gap’ between farm averages and yield potential will be achieved more likely by removing yield constraints of the poorest fields and systems (Constable

and Bange 2015). For rain-fed wheat systems, Hochman *et al.* (2012) measured farmers yield and compared that with the regional yields predicted using simulation models of an adapted crop without limitations, but under water-limited conditions. They also assessed yield potential using crop competition results. For irrigated crop comparisons, it will be important that knowledge of the amount of water available for irrigation across farms is considered specifically because it can vary considerably, thereby strongly affecting yield and fibre quality.

One of the most significant challenges for cotton management into the future will be diminished access to water through reductions in sources of irrigation (surface or groundwater), less rainfall or increases in evapotranspiration through temperature increases. Much existing research has been undertaken in well-watered conditions, and much less research has considered the implications of cotton growth, yield and fibre quality with less water availability. Australian cotton systems will require closer examination of the response to various water deficits and drought recovery cycles. These effects will also need to be considered in light of other management options suggested in this chapter that relate to water use: the development of cotton systems that are earlier maturing, that use less water and allow more crops to be grown in rotation; and improved management options in limited water situations utilising changes in planting time, alternative irrigation systems, row configurations, irrigation scheduling strategies, all with the intent to maximise yield, water use efficiency and fibre quality.

Given the importance of high fibre quality to maintain Australian cotton's share in the international marketplace it is imperative that the industry retains its focus on fully realising the benefits of improving fibre quality. The task for cotton growers/advisers and the industry is to optimise fibre quality in all steps from strategic farm plans, cultivar choice, crop management, harvesting and ginning. Bange *et al.* (2018) have termed this 'Integrated Fibre Management' to emphasise the importance of a balanced approach to managing fibre quality, to be analogous with approaches such as Integrated Pest Management).

Policy and industry considerations

Sustainability of the Australian cotton industry will need adaptation approaches that also reflect changing social, political, and economic drivers at scales that move from the field, to the farm, across varied agriculture industries, and with national and international influences. As an example, there is a need to invest in field-based research on production, but concurrently research is needed that assists in government policy setting. Without these types of considerations, the marginal return on investment into adaptation options can be severely diminished. Key considerations that capture some of these issues from an Australian cotton production perspective include:

- An assessment of the likely impacts of changes in worldwide cotton production. Understanding these impacts is necessary for ensuring the cotton supply chain to maintain market share security against synthetic textile production. Strengthening information-sharing networks on impacts and adaptations to change will be vital in this process.
- Identifying opportunities for the expansion of cotton production in existing and new agricultural production regions (*e.g.* southern and northern Australia). Region-specific impacts will be needed so that cotton growers have the capacity to assess likely impacts into their business.
- Identifying competition and synergies for use of resources (*e.g.* land, water, labour) with other agriculture enterprises.
- Integrating production research outcomes that are optimal in delivering sustainable cotton systems in light of triple bottom line (environmental, economic, and social) concerns.
- Development of multi-peril crop insurance schemes to assist growers deal with extreme climate events.

Conclusion

High-input irrigated crops face many of the same future challenges as other broad acre crops. A combined integrated approach to solve these production challenges across commodities will accelerate Australian agriculture's ability to adapt and sustain production in the future. For irrigated crops, future water availability and irrigation management capabilities play a major role in enabling producers to maintain economically viable operations in variable climates. However, water use for irrigation will continue to compete with industrial and municipal use due to dwindling ground and surface water supplies in many areas. Policy makers will need to decide how this limited resource will be best divided amongst the various stake holders: a major challenge in light of future climate change predictions. Current and future crop management practices will continue to evolve from those, which were developed assuming reasonable access to water, to those that need to operate under constrained water availability.

To meet these challenges there will be a greater need to incorporate other aspects of production efficiencies into the analysis of modern irrigated cropping systems (*e.g.* fuel/energy use or carbon emissions per unit of lint produced) in addition to existing production use efficiencies (*e.g.* water and N). 'Trade-offs' will be needed to minimise economic, social and environmental harm, while maximising new opportunities. One example that highlights this tension is the need for continued improvement in water use efficiency – this has led to demand for more sophisticated irrigation systems that are likely more energy intensive. Importantly to assist in making valid and fair comparisons within the irrigated production system and beyond (*e.g.* with other cropping systems or industries), it will be necessary to present these efficiencies on an economic basis (*e.g.* \$ generated/ML, unit of GHG emitted, kg N applied). A better understanding of the integrated effects (higher atmospheric [CO₂], increased temperatures and atmospheric vapour pressure deficits) of future climate on the physiology, growth and management of crops, including future water use is required.

Ultimately, sustainable and low environmental impact irrigated cropping systems (whether it be sugar, rice or cotton) are required to maintain the 'licence to farm'. Research into the development of new technology and tools that integrate knowledge at many scales, whilst understanding the linkages of on-farm production with the off-farm impacts, will be needed to harness opportunities reliably for ongoing investment in these industries.

References

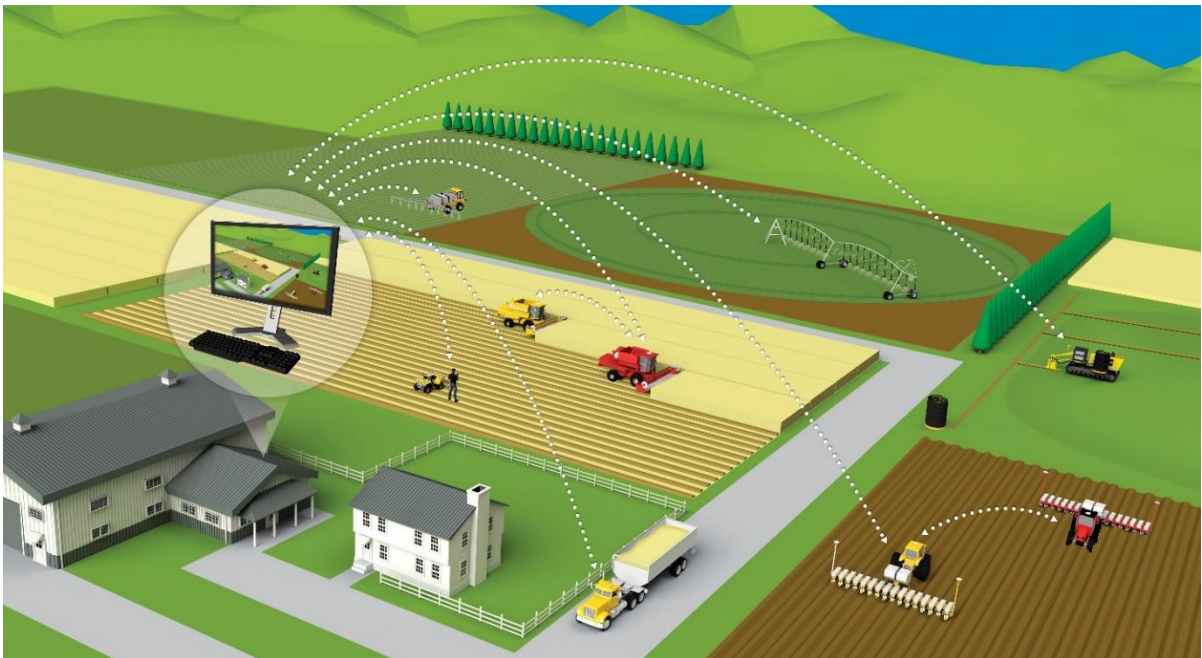
- Australian Bureau of Statistics (2019) <http://www.abs.gov.au/>
- Antille DL, Bennett JM, Jensen TA (2016) Soil compaction and controlled traffic considerations in Australian cotton-farming systems. *Crop and Pasture Science* **67**, 1-28
- Bajwa A, Chauhan B (2017) Rice Production in Australia. In (Eds. BS Chauhan, K Jabran, G Mahajan) "Rice Production Worldwide" pp 169-184 (Springer International:USA)
- Bange M, Carberry P, Hammer G (1999) Seasonal climate forecasting for cotton management. *The Australian Cottongrower* **20**, 36-42
- Bange M, Milroy S, Roberts G (2006) Factors influencing crop maturity. *Proceedings of Beltwide Cotton Conference*. San Antonio, Texas, 1809-1817
- Bange MP, Baker JT, Bauer PJ *et al.* (2016) "Climate Change and Cotton Production in Modern Farming Systems" (CABI: UK)
- Bange MP, Carberry PS, Marshall J, Milroy SP (2005) Row configuration as a tool for managing rain-fed cotton systems: review and simulation analysis. *Australian Journal Of Experimental Agriculture* **45**, 65-77
- Bange MP, Caton SJ, Milroy SP (2008) Managing yields of high fruit retention in transgenic cotton (*Gossypium hirsutum* L.) using sowing date. *Australian Journal of Agricultural Research* **59**, 733-741
- Bange MP, Milroy SP (2004) Growth and dry matter partitioning of diverse cotton genotypes. *Field Crops Research* **87**, 73-87
- Bange MP, van der Sluijs MHJ, Constable GA *et al.* (2018) FIBREpak – A Guide to Improving Australian Cotton Fibre Quality. www.cottoninfo.com.au/publications/fibrepack
- Beecher HG, Hume IH, Dunn BW (2002) Improved method for assessing rice soil suitability to restrict recharge. *Australian Journal of Experimental Agriculture* **42**, 297-307

- Bell MJ, Garside AL (2014) Growth and yield responses to amending the sugarcane monoculture: interactions between break history and nitrogen fertiliser. *Crop and Pasture Science* **65**, 287-299
- Bramley RGV, Ouzman J, Gobbett DL (2019) Regional scale application of the precision agriculture thought process to promote improved fertilizer management in the Australian sugar industry. *Precision Agriculture* **20**, 362-378
- Braunack MV, Bange MP, Johnston DB (2012) Can planting date and cultivar selection improve resource use efficiency of cotton systems? *Field Crops Research* **137**, 1-11
- Braunack MV, Johnston DB (2014) Changes in soil cone resistance due to cotton picker traffic during harvest on Australian cotton soils. *Soil and Tillage Research* **140**, 29-39
- Braunack MV, Johnston DB, Price J, Gauthier E (2015) Soil temperature and soil water potential under thin oxodegradable plastic film impact on cotton crop establishment and yield. *Field Crops Research* **184**, 91-103
- Braunack MV, McGarry D (2006) Traffic control and tillage strategies for harvesting and planting of sugarcane (*Saccharum officinarum*) in Australia. *Soil & Tillage Research* **89**, 86-102
- Brodrick R, Neilsen J, Bange M *et al.* (2012) Dynamic deficits for irrigated cotton – matching the soil water to plant requirements. *Proceedings of 16th Australian Agronomy Conference*. Armidale, NSW
www.regional.org.au/au/asa/2012/soil-water-management/8066_brodrickr.htm
- Brown JC, Schepen A, Roberston D *et al.* (2019) Weather together – Building the weather forecasts farmers want. *Proceedings of 19th Australian Agronomy Conference*. Wagga Wagga, Australia
www.agronomyaustralia.org/
- Carrière Y, Brown ZS, Downes SJ *et al.* (2019) Governing evolution: A socioecological comparison of resistance management for insecticidal transgenic Bt crops among four countries. *Ambio*
doi.org/10.1007/s13280-019-01167-0
- Clement JD, Constable GA, Stiller WN, Liu SM (2015) Early generation selection strategies for breeding better combinations of cotton yield and fibre quality. *Field Crops Research* **172**, 145-152
- Conaty WC, Burke JJ, Mahan JR *et al.* (2012) Determining the optimum plant temperature of cotton physiology and yield to improve plant-based irrigation scheduling. *Crop Science* **52**, 1828-1836
- Constable GA, Bange MP (2015) The yield potential of cotton (*Gossypium hirsutum* L.). *Field Crops Research* **182**, 98-106
- Constable GA, Reid PE, Thomson NJ (2001) “Approaches Utilized in Breeding and Development of Cotton Cultivars in Australia” (Eds. JN Jenkins, S Saha) (Science Publishers Inc: Enfield)
- Cottee NS, Tan DKY, Bange MP *et al.* (2010) Multi-level determination of heat tolerance in cotton (*Gossypium hirsutum* L.) under field conditions. *Crop Science* **50**, 2553-2564
- Cotton Australia (2019) Where is it grown? <https://cottonaustralia.com.au/australian-cotton/basics/where-is-it-grown>.
- Devi MJ, Reddy VR (2018) Transpiration response of cotton to vapor pressure deficit and its relationship with stomatal traits. *Frontiers in Plant Science* **9**, 1572
- Fitt GP (2000) An Australian approach to IPM in cotton: integrating new technologies to minimise insecticide dependence. *Crop Protection* **19**, 793-800
- Fitt GP, Wilson LJ (2000) Genetic engineering in IPM: Bt cotton. In (Eds. GG Kennedy, TB Sutton.) “Emerging Technologies in Integrated Pest Management: Concepts, Research and Implementation” pp 108-125 (APS Press: St. Paul)
- Garside AL, Bell MJ (2011) Growth and yield responses to amendments to the sugarcane monoculture: effects of crop, pasture and bare fallow breaks and soil fumigation on plant and ratoon crops. *Crop and Pasture Science* **62**, 396-412
- Hamman E, Deane F (2018) The control of nutrient run-off from Agricultural areas: Insights into governance from Australia’s sugarcane industry and the Great Barrier Reef. *Transnational Environmental Law* **7**, 451-468
- Hatfield JL, Walthall CL (2015) Meeting global food needs: Realizing the potential via genetics × environment × management interactions. *Agronomy Journal* **107**, 1215-1226
- Hearn AB (1992) Risk and reduced water allocations. *The Australian Cottongrower* **13**, 50-55
- Hearn AB (1994) OZCOT: A simulation model for cotton crop management. *Agricultural Systems* **44**, 257-299
- Hearn AB, Bange MP (2002) SIRATAC and CottonLOGIC: persevering with DSSs in the Australian cotton industry. *Agricultural Systems* **74**, 27-56
- Hochman Z, Gobbett D, Holzworth D *et al.* (2012) Quantifying yield gaps in rainfed cropping systems: A case study of wheat in Australia. *Field Crops Research* **136**, 85-96
- Hodgson AS, Macleod DA (1987) Effects of foliar applied nitrogen fertilizer on cotton waterlogged in a cracking grey clay. *Australian Journal of Agricultural Research* **38**, 681-688
- Hoque Z, Farquharson B, Dillon M, Kauter G (2000) Soft options can reduce costs and increase cotton profits. *The Australian Cottongrower* **21**, 33-37

- Hulugalle NR, Weaver TB, Finlay LA *et al.* (2007) Soil properties and crop yields in a dryland Vertisol sown with cotton-based crop rotations. *Soil and Tillage Research* **93**, 356-369
- Hulugalle NR, Weaver TB, Finlay LA, Heimoana V (2013) Soil organic carbon concentrations and storage in irrigated cotton cropping systems sown on permanent beds in a Vertisol with restricted subsoil drainage. *Crop and Pasture Science* **64**, 799-805
- Hulugalle NR, Weaver TB, Scott F (2005) Continuous cotton and cotton-wheat rotation effects on soil properties and profitability in an irrigated vertisol. *Journal of Sustainable Agriculture* **27**, 5-24
- Humphreys E, Lewin LG, Khan S *et al.* (2006) Integration of approaches to increasing water use efficiency in rice-based systems in southeast Australia. *Field Crops Research* **97**, 19-33
- Jones RN (2010) Water Resources. In (Eds. C Stokes, M Howden) "Adapting Agriculture to Climate Change: Preparing Australian Agriculture, Forestry and Fisheries for the Future" pp1-2 (CSIRO Publishing: Melbourne, Australia)
- Kochman JK (1995) Fusarium wilt in cotton – a new record in Australia. *Australasian Plant Pathology* **24**, 74
- Kroon FJ, Thorburn P, Schaffelke B, Whitten S (2016) Towards protecting the Great Barrier Reef from land-based pollution. *Global Change Biology* **22**, 1985-2002
- Liu Q, Singh SP, Green AG (2002) High-stearic and high-oleic cottonseed oils produced by hairpin RNA-mediated post-transcriptional gene silencing. *Plant Physiology* **129**, 1732-1743
- Liu SM, Constable GA, Reid PE *et al.* (2013) The interaction between breeding and crop management in improved cotton yield. *Field Crops Research* **148**, 49-60
- Macdonald BCT, Latimer JO, Schwenke GD *et al.* (2018) The current status of nitrogen fertiliser use efficiency and future research directions for the Australian cotton industry. *Journal of Cotton Research* **1**, 15
- McCarthy AC, Hancock NH, Raine SR (2010) VARIwise: A general-purpose adaptive control simulation framework for spatially and temporally varied irrigation at sub-field scale. *Computers and Electronics in Agriculture* **70**, 117-128
- Montgomery J, Hornbuckle J, Hume I, Vleeshouwer J (2015) IrriSAT – weather based scheduling and benchmarking technology. *Proceedings of 17th Australian Agronomy Conference* Hobart, Australia www.agronomyaustraliaproceedings.org/images/sampled/2015_Conference/pdf/agronomy2015final00449.pdf
- Montgomery J, O'Halloran J (2008) A comparison of water use between solid plant and one-in-out skip. *The Australian Cottongrower* **29**, 21-25
- Najeeb U, Atwell B, Bange M, Tan DY (2015) Aminoethoxyvinylglycine (AVG) ameliorates waterlogging-induced damage in cotton by inhibiting ethylene synthesis and sustaining photosynthetic capacity. *Plant Growth Regulation* **76**, 83-98
- Nunn C, Brown JC, McIntosh PC *et al.* (2019) Use of seasonal forecasts for guiding early season decisions in Australian cotton systems. *Proceedings of 19th Australian Agronomy Conference*. Wagga Wagga, Australia www.agronomyaustralia.org/
- Palle SR, Campbell LM, Pandeya D *et al.* (2013) RNAi-mediated ultra-low gossypol cottonseed trait: performance of transgenic lines under field conditions. *Plant Biotechnology Journal* **11**, 296-304
- Power B, Cacho OJ (2014) Identifying risk-efficient strategies using stochastic frontier analysis and simulation: An application to irrigated cropping in Australia. *Agricultural Systems* **125**, 23-32
- Ritchie JW, Abawi GY, Dutta SC *et al.* (2004) Risk management strategies using seasonal climate forecasting in irrigated cotton production: a tale of stochastic dominance. *Australian Journal of Agricultural and Resource Economics* **48**, 65-93
- Richards D, Bange MP, Johnston SB (2008) HydroLOGICL An irrigation management system for Australian cotton. *Agricultural Systems* **98**, 40-29
- Roberts GN, Constable GA (2003) Impact of crop management on cotton crop maturity and yield. *Proceedings of 11th Australian Agronomy Conference*. Geelong, Victoria www.regional.org.au/au/asa/2003/p/4/roberts.htm
- Rochester IJ (2011a) Assessing internal crop nitrogen use efficiency in high-yielding irrigated cotton. *Nutrient Cycling Agroecosystems* **90**, 147-156
- Rochester, IJ (2011b) Sequestering carbon in minimum-tilled clay soils used for irrigated cotton and grain production. *Soil and Tillage Research* **112**, 1-7
- Rochester IJ, Bange M (2016) Nitrogen fertiliser requirements of high-yielding irrigated transgenic cotton. *Crop and Pasture Science* **67**, 641-648
- Rochester IJ, Constable GA (2015) Improvements in nutrient uptake and nutrient use-efficiency in cotton cultivars released between 1973 and 2006. *Field Crops Research* **173**, 14-21
- Rochester IJ, Peoples MB (2005) Growing vetches (*Vicia villosa* Roth) in irrigated cotton systems: inputs of fixed N, N fertiliser savings and cotton productivity. *Plant and Soil* **271**, 251-264

- Rochester IJ, Peoples MB, Constable GA (2001) Estimation of the fertiliser requirement of cotton grown after legume crops. *Field Crops Research* **70**, 43-53
- Roth G, Harris G, Gillies M *et al.* (2013) Water-use efficiency and productivity trends in Australian irrigated cotton: a review. *Crop and Pasture Science* **64**, 1033-1048
- Schellhorn NA, Bianchi FJ, Hsu CL (2014) Movement of entomophagous arthropods in agricultural landscapes: links to pest suppression. *Annual Review Entomology* **59**, 559-81
- Stiller WN, Read JJ, Constable GA, Reid PE (2005) Selection for water use efficiency traits in a cotton breeding program: Cultivar differences. *Crop Science* **45**, 1107-1113
- Tennakoon SB, Milroy SP (2003) Crop water use and water use efficiency on irrigated cotton farms in Australia. *Agricultural Water Management* **61**, 179-194
- Thompson JA, Bouman B, Hengsdijk H *et al.* (Eds.) (2002) Water management of rice in southern New South Wales, Australia. *International Workshop on Waterwise Rice Production*, International Rice Research Institute, Los Banos
- Thorburn PJ, Boote KJ, Nendel C *et al.* (2018) Recent advances in crop modelling to support sustainable agricultural production and food security under global change. *European Journal of Agronomy* **100**, 1-3
- Thorburn PJ, Wilkinson SN (2013) Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments. *Agriculture Ecosystems & Environment* **180**, 192-209
- Trapero C, Wilson IW, Stiller WN, Wilson LJ (2016) Enhancing Integrated Pest Management in GM cotton systems using host plant resistance. *Frontiers in Plant Science* **7**, 500
- Uddin J, Smith RJ, Gillies MH *et al.* (2018) Smart automated furrow irrigation of cotton. *Journal of Irrigation and Drainage Engineering* **144**
- Upchurch DF, Wanjura D, Burke JR, Mahan, J (1996) Biologically Identified Optimal Temperature Interactive Console (BIOTIC) for Managing Irrigation. United States of America
- Werth J, Thornby D, Walker S (2011) Assessing weeds at risk of evolving glyphosate resistance in Australian sub-tropical glyphosate-resistant cotton systems. *Crop and Pasture Science* **62**, 1002-1009
- Williams RL, Angus JF (1994) Deep floodwater protects high-nitrogen rice crops from low-temperature damage. *Australian Journal of Experimental Agriculture* **34**, 927-932
- Williams S, Bange M, Constable G (2018) Managing crop growth. In (Eds. A Twine, R Redfern) "The Australian Cotton Production Manual 2018" pp 102-106 (The Cotton Research and Development Corporation: Narrabri, Australia)
- Wilson L, Downes S, Khan M *et al.* (2013) IPM in the transgenic era: a review of the challenges from emerging pests in Australian cotton systems. *Crop and Pasture Science* **64**, 737-749
- Wilson LJ, Mensah RK, Fitt GP (2004) Implementing integrated pest management in Australian cotton. In (Eds. A Rami Horowitz, I Ishaaya) "Novel Approaches to Insect Pest Management in Field and Protected Crops" pp 97-118 (Springer-Verlag: Berlin)
- Wilson LJ, Whitehouse MEA, Herron GA (2018) The management of insect pests in Australian cotton: An evolving story. *Annual Review of Entomology* **63**, 215-237
- Wu A, Song Y, van Oosterom EJ, Hammer GL (2016) Connecting biochemical photosynthesis models with crop models to support crop improvement. *Frontiers in Plant Science* **7**, 1518
- Yeates SJ, Richards D, Roberts J (2010) High insect protection of GM Bt cotton changes crop morphology and response to water compared to non Bt cotton. *Proceedings of 15th Agronomy Conference*, Lincoln, New Zealand www.agronomyaustraliaproceedings.org/index.php/2012-conf-proc-homepage

PART VI – TO THE FUTURE



Connected farm: increasing connectivity allows data and local information to be shared instantaneously between sensors, equipment and people (Courtesy: Trimble Connected Farm)



Swarmlbot: Equipment automation is replacing large farm equipment with ‘swarms’ of smaller, lighter robotic units capable of a diverse range of tasks
(Courtesy: SwarmFarm Pty Ltd)



The DOT autonomous platform driving a fertilizer spreader (left) and boom spray (right) on display at Ag-in-Motion field day in Saskatoon Canada July 2019.
(Courtesy: John Kirkegaard)

Chapter 23

Transformational Agronomy: restoring the role of agronomy in modern agricultural research

James Hunt, John Kirkegaard, Corinne Celestina, Kenton Porker

Introduction

The global food security challenge has prompted many to propose the need for ‘transformational change’ in food production systems through technological ‘breakthroughs’. These transformative technologies are often distinguished from the ‘incremental’ advances generated by agronomy and breeding which are dismissed as business as usual, and inadequate to achieve the productivity improvements sought. Since the prequel to this book was published in 1987, the reduction in yield gap achieved by the Australian grains industry has been formidable. In the 10 years prior to 1987, Australian wheat growers averaged 34% of water limited potential yield. In the 10 years prior to 2017, they averaged 52%, a 35% gain relative to the most recent period, or 1.2% per annum (Hochman *et al.* 2017). When viewed over the 30-year period this change is truly transformational, but the transformation has come through incremental gains (Kirkegaard 2019).

It may seem curmudgeonly to be critical of aspirations to achieve transformational breakthroughs, but in a world of diminishing expenditure in agricultural research it will be important to target dwindling funds well. Proposed transformational changes often focus on one component of a system championed by largely disconnected research disciplines. In reality, and throughout history, few individual technologies have been singularly transformational either in the scale or the speed with which they have influenced productivity (Evans 1998). Rather, step changes in productivity have come only when combinations of technologies, often a mix of old and new, synergise within a system. In the context of Australian wheat production, the productivity gains of the last 30 years have been due to many disparate technologies combining to form a coherent system. The advent of glyphosate and grass selective herbicides drove the rapid adoption of no-till (Llewellyn *et al.* 2012) which improved soil water conservation and allowed earlier sowing (Stephens and Lyons 1998). Wheat was increasingly grown in rotation with broadleaf break crops (canola and pulses – industries initiated through substantial public investment) rather than other cereals or weedy pastures which reduced yield losses due to root disease. Meanwhile breeders consistently achieved genetic yield progress of 0.5% per annum (Siddique *et al.* 1990, Sadras and Lawson 2011, Fischer *et al.* 2014, Kitonyo *et al.* 2017) and overcame significant biotic and abiotic constraints to production which interact with management (cereal cyst nematode, stripe rust, acidity, boron). Early sown, disease-free crops responded profitably to N fertiliser, applications of which tripled over the 30-year period (Angus and Grace 2017).

To fulfil the goals of sustainable intensification, Fischer and Connor (2018) estimate that similar gains (1.1-1.2% per annum) are required over the next two decades to keep pace with increased global demand for food. Whilst it is an oft cited cliché that agricultural productivity must increase to feed a growing global population enjoying an increasing quality of life, the challenge is real. It lies not so much in producing enough food to feed the world, but in producing enough food to keep prices sufficiently low that the poorest citizens of the globe can reasonably afford it. The second challenge is then keeping growers in business whilst they grow food that remains affordable to the world’s poor. Australian growers need these increases to remain competitive in the global market. There is evidence that the 0.5% genetic yield progress historically achieved by breeders may be slowing in at least some breeding programs (Fischer *et al.* 2014, Flohr *et al.* 2018b). The obvious question arises – where will future yield increases come from, and what role will the profession of agronomy play to deliver them? We argue that to meet these challenges, the role of agronomy should be restored and the frameworks in which agricultural research in this country is conducted reviewed.

Defining agronomy

Agronomy is generally defined as the science and practice of understanding how agricultural systems work in order to improve production, profitability and/or sustainability (Manley *et al.* 2019). It is an integrative profession – requiring an understanding of many scientific disciplines related to agricultural systems, including plant and animal science (ecology, physiology, nutrition, genetics and pathology), soil science (soil physics, chemistry and biology), meteorology, economics, sociology, geomatics, statistics and data science. This makes agronomists unique in the field of science – most other scientists specialise deeply within these disciplines. Many individual scientists devote their entire careers to researching and improving understanding of a small component of these fields.

Agronomists are generalists by definition. This is perhaps where agronomists can be underestimated in academic and scientific circles. Whilst their knowledge must be broad, it can only ever be relatively shallow, and findings (though extremely useful and impactful) are rarely universal but instead highly context dependent. In many ways their activities are more akin to engineering than science, and the chances of conducting research that truly advances human understanding and is deemed worthy of publication in high impact journals such as *Science* and *Nature* is consequently low. In addition to broad (if shallow) science knowledge, agronomists must have good working knowledge of the farming systems that they study. Whilst this knowledge is often informed or underpinned by science, many times it also requires an appreciation of on-farm logistics, economic realities and social and cultural norms.

There is also an important distinction that needs to be made within the field of agronomy. Many that term themselves agronomists work in commercial roles advising farmers on management practices, particularly regarding inputs of fertilisers and biocides. Here we refer to these as *commercial agronomists*. Other agronomists (typically employed by government agencies, grower groups and universities but also including private businesses) discharge research roles, conducting experiments to improve understanding and improve management. These we refer to as *research agronomists* and they are the focus when we use the term ‘agronomist’ in this chapter.

Restoring agronomy

In recent times the integrative and generalist view of agronomy has been lost. Agronomy has been increasingly viewed as the ‘left-over bits’ of agricultural research once plant breeding, crop nutrition, crop protection and farming systems are moved into their respective silos. Whilst there has been an increasing effort to understand the interactions between genetics (G), environment (E), and management (M) in crop production systems, unfortunately agronomy has become synonymous with the ‘M’ in the term ‘G x E x M’ (Messina *et al.* 2009). This is reflected in the management structures of numerous research organisations and funding bodies both within Australia and beyond. This has had the effect of relegating agronomic studies to hypothesis-free empirical dabbling involving the management factors that remain within control of the farmer, including time of sowing, seeding rate, row spacing and the like. Except for time of sowing, yield effects of these factors are uniformly small and variable and rarely interact meaningfully with other aspects of management. Whilst growers often appreciate hearing results of these experiments (largely to confirm that they are doing the right thing), they are unlikely to lead to the transformational change growers require to stay profitable, or the world needs to feed itself. They are frequently revisited, often when a new piece of technology is made available *e.g.* precision seeding. This view of agronomy we refer to as *reactive agronomy*.

If the required yield increases are to be achieved, this is not the role that agronomy must play. Agronomists instead must act as directors and integrators of multidisciplinary research teams that are formed specifically to address significant constraints to production. They must oversee and optimise the G x E x M system, and not be concerned only and lastly with ‘M’. The argument for this is compelling – agronomists understand farming systems context and have a better appreciation of the factors that are limiting production (sometimes more than the growers themselves). They have the generalist science knowledge to understand which specific disciplines of research can be brought to bear on a challenge or opportunity, and how different disciplines must interact with each other to exploit synergies and avoid trade-offs to form tractable solutions. They also have familiarity and credibility

with growers and commercial agronomists that is required to test research findings in the right context to ensure adoption and impact. Agronomists must be the leaders, the translators and the communicators, accessing the best discipline-based knowledge and expertise where relevant to deliver transformational change.

In this chapter we define a framework that allows multi-disciplinary teams led by (or at least involving) agronomists to identify and quantify constraints to production, profitability and sustainability, propose and test solutions, and work with farmers and advisors to integrate them into farming systems. We refer to this process as *transformational agronomy*. It builds on the concept of *systems agronomy* (Giller *et al.* 2015), which emphasises that agronomy must not merely focus on production or environment but consider social and economic factors and interactions and trade-offs in context. As systems agronomy argues that ‘principle’ based approaches (*e.g.* maintenance of permanent soil organic cover as a principle, regardless of negative impacts on yield in some contexts) are unlikely to lead to sustainable intensification, we further this to argue that ‘discipline’ based approaches are equally unlikely to be transformational. This is simply because substantial constraints to production are complex and involve trade-offs in a broad range of factors beyond the scope of any one discipline. Multiple disciplines working in balanced unison with integrating leadership are required.

Transformational agronomy also borrows from participatory research (Pretty 1995) or collective inquiry in recognising the importance of participation of end-users (*i.e.* farmers and their advisors) from the outset. This is essential not only for appropriate framing of research questions and conduct of experiments, but to ensure successful adoption of proven interventions.

The context and examples that we use here to describe transformational agronomy are from dryland crop production in southern Australia, but we argue that the same framework could equally be applied to any agricultural system in the world.

The role of agronomists: closing yield gaps vs increasing potential yield

The concept of potential yield (PY) and yield gaps is crucial for the following discussion and we follow the nomenclature of Fischer (2015). The most important definition for dryland crop production in Australia is water limited potential yield (PY_w), defined as the yield of the best cultivar under optimum management with no manageable constraints (*e.g.* nutrient deficiency, weeds, disease) except for water supply. Farm yield (FY) is yield achieved by farmers in their fields. The difference between FY and PY_w is termed the yield gap. Economic yield (EY) is the yield attained by farmers when economically optimal practices and levels of inputs have been adopted while facing all the vagaries of weather. Economic yield is typically 75-85% of PY_w (van Ittersum *et al.* 2013). The difference between EY and FY is the exploitable yield gap.

Hochman *et al.* (2017) estimate that Australian wheat producers are currently achieving 55% of PY_w . However, van Rees *et al.* (2014) demonstrated that leading farmers have closed the exploitable yield gap and are achieving 75-85% of PY_w . This implies a split (or a continuum) among Australian wheat farmers between those that are regularly achieving EY, and those with a substantial exploitable yield gap. This split raises a question about what level of limited agronomic research resources should be spent closing yield gaps by assisting farmers to implement better management, and what level should be spent overcoming current constraints to PY_w . We argue that as optimal management practices are usually in the public domain, it is predominantly the role of commercial agronomists to work with farmers to close yield gaps. It should be the focus of research agronomists to look for ways to increase PY_w . Some exceptions to this general distinction are discussed later.

Transformational agronomy

Our proposed framework for transformational agronomy is described below, and schematically represented in Figure 1. Our restoration of the definition of agronomy is indicated by the grey box.

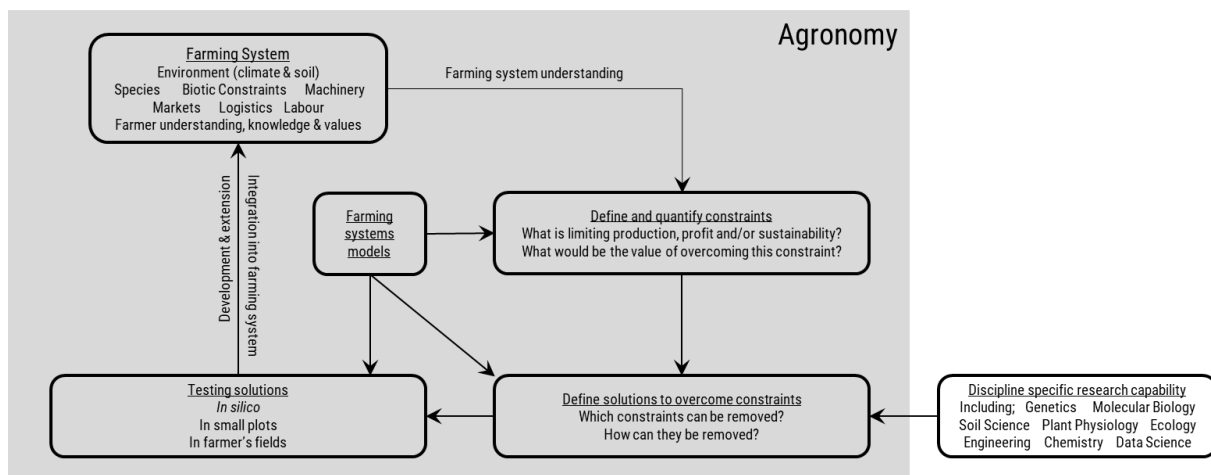


Figure 1. A framework for achieving transformational agronomy. Agronomists must understand farming systems sufficiently to define constraints to production. The value of overcoming these constraints must then be quantified. Expertise from discipline-specific researchers forming multidisciplinary teams coordinated by agronomists must be accessed to form tractable solutions which are then tested and re-integrated back into the farming systems context from which the constraint derived.

Definition and quantification of constraints to production

The critical first step to develop research programs that can transform farming systems is accurate definition of a constraint to production, and/or an opportunity to overcome such a constraint. As we discuss later, this can be harder than it seems. Agronomists are often best placed to identify constraints, as they are grounded in real farming systems, but also have knowledge of what discipline-based science and technology may have to offer in the way of solutions.

Often experiments are necessary to accurately define and quantify a constraint to production before the value of a solution is known. This is where the science training of agronomists is critical. The importance of accurately identifying and quantifying genuine constraints to production cannot be overstated. The history of agricultural research is littered with examples of research addressing assumptions which were subsequently revealed to be poorly founded or erroneous. Often this has been caused by proponents of principle- or discipline-based research pushing what they considered to be a constraint to production, with only weak prior quantification. Ryan *et al.* (2019) use the case of arbuscular mycorrhizal fungi (AMF) to demonstrate how readily discipline specialists sabotage the real needs of sustainable intensification (or even common sense) to promote their own narrow disciplinary interests as central (Ryan and Graham 2018). Mycorrhizal specialists propose that food security can be served best by moving towards AMF-sufficient farming systems that mimic natural systems (Rillig *et al.* 2018). A systems agronomy approach instead considers sustainable intensification against defensible physiological benchmarks, and then diagnoses the constraints in such a way that AMF, if important, would become part of the solution (Ryan *et al.* 2018).

Such behaviour is not uncommon and is completely rational in a research environment where funding is scarce, and funding bodies are increasingly seeking short- to medium-term impact over novelty. It is easier for researchers to adopt a narrative that places their discipline as central to deliver transformational change than it is to work with other disciplines and generalists to solve properly defined and quantified constraints. There is no greater evidence of this than the vast pile of plant molecular biology papers (many working on model species) that commence their introduction with rhetorical outline of the need to increase crop production to feed a growing world population. Whilst this narrative has helped capture an astounding level of resources and prestige, it has done very little to change what happens in farmers' fields anywhere in the world (Porter *et al.* 2018). In many ways this situation is merely the result of the deeply human adage 'when all you have is a hammer, all you see is a nail.

For instance, the notion that crop yields in the high rainfall zones of SE Australia were limited by the predominance of sodic sub-soils was first raised by Gardner *et al.* (1992) and repeated by many others (*e.g.* Zhang *et al.* 2006, Adcock *et al.* 2007, MacEwan *et al.* 2010). None of these studies reported empirical evidence that sodic sub-soils actually reduce root growth and crop yield. On the contrary, Gardner *et al.* (1992) cite a study by Whitfield *et al.* (1992) that measured roots of canola and wheat down to 1.0 m and water extraction beyond this depth. Similarly, Zhang *et al.* (2006) cite the study of Lorimer and Douglas (2001) that observed wheat roots growing into dense sodic clay subsoils. The substantial negative effects of sodic soils on crop yields appear to be overstated and based largely on assumptions. The ripple effect of these assertions has been millions of dollars on research attempting to ameliorate sodic sub-soils with gypsum and organic amendments. Many of these experiments injected high rates of manure into the sub-soils, and erroneously claimed substantial yield responses due to amelioration of subsoil constraints (Gill *et al.* 2008, Gill *et al.* 2012, Sale *et al.* 2019). The likely explanation for the (at times physiologically implausible) yield increase was provision of nutrients in manure in a nutrient-limited environment (Celestina *et al.* 2018, Celestina *et al.* 2019). Measured changes in soil physical properties are explained more parsimoniously by improved root growth in response to alleviation of nutrient deficiency.

This situation could have been avoided if researchers had more accurately defined and quantified the constraints that were limiting yields prior to embarking on sub-soil amelioration treatments, instead of simply assuming sodic sub-soils were the major problem to be addressed. To do this would have required characterising soil physiochemical properties and plant available water capacity to confirm that soil water extraction by plant roots was indeed restricted (Celestina *et al.* 2019) – a potentially costly and time-consuming, but necessary undertaking. Even without the identification of genuine constraints to production, the inclusion of proper control treatments and use of appropriate sampling protocols in these experiments would have allowed nutrient- and non-nutrient effects on crop yield to be separated (Celestina *et al.* 2019), thereby revealing nutrient deficiency – not sodic sub-soils – as the critical constraint to crop production in the high rainfall zone of SE Australia. Until clearer attribution is provided, yield benefits attributed to deep placement of organic amendments beyond nutritional impacts will remain contentious.

Since Gardner *et al.* (1992) was published, yields in the high rainfall zone of SE Australia have increased dramatically without any broad scale amelioration of sodic subsoils (Robertson *et al.* 2016). This has been achieved by installation of raised beds to alleviate waterlogging, better crop rotation reducing root disease and weed burden, timely sowing of high yielding cultivars either specifically bred or imported for the region, and a dramatic shift in the levels of fertiliser (particularly N) applied to crops. It was root disease, seasonal timing of crop development, foliar disease and nutrition that was limiting yields, not sodic soils. The direct cost to the Australian grains industry and taxpayer is many millions of dollars. An unaccounted cost is the opportunity cost of what research could have been funded with this money. This example highlights how critical it is to define and quantify constraints to production accurately prior to conducting research to avoid potentially costly mistakes.

Defining solutions to overcome constraints

Defining solutions requires discipline-specific knowledge. Frequently constraints have more than one viable solution, and some solutions interact either positively (synergies) or negatively (trade-offs). Agronomists need to have enough cursory knowledge of associated disciplines to be able to seek input from experts at this point. At the same time, the agronomist must act as an independent evaluator of solutions and choose those most likely to succeed. They must also be prepared to collaborate with disciplinary specialists with whom they may not normally interact to engage fundamental scientists to develop applied solutions.

Testing solutions

Testing solutions in silico

Once constraints have been accurately defined and quantified, plausible solutions need to be tested. Some constraints and solutions can be well represented by crop simulation models such as APSIM (Holzworth *et al.* 2014) and, in these instances, it is extremely cost-effective to initially test solutions *in silico*. The benefits of using models for testing are that they allow solutions to be evaluated over a very large number of sites and seasons at very little cost. Environmental and farming systems interactions can be properly investigated, and outputs of variables that can be expensive or difficult to measure in the field can be cheaply obtained.

This process is often termed *pre-experimental modelling*, and there are many examples in Australian dryland crop production of simulation studies that have quantified constraints to production or evaluated solutions to constraints. This includes potential for summer weed control to improve capture of summer fallow rain; this was tested *in silico* (Kirkegaard and Hunt 2010, Hunt and Kirkegaard 2011) as part of the Grains Research and Development Corporation (GRDC) ‘water use efficiency’ initiative (Kirkegaard *et al.* 2014). Responses were promising and were subsequently tested in field experiments (Haskins and McMaster 2012, Hunt *et al.* 2013, Kirkegaard *et al.* 2014). Likewise, simulation studies identified that slow-developing cultivars of wheat sown early could achieve higher yields than the current practice of fast cultivars sown later (Moore 2009, van Rees *et al.* 2014). This was tested experimentally and found to be the case (Flohr *et al.* 2018c, Peake *et al.* 2018, Hunt *et al.* 2019). Simulation studies on canola have shown that the principles extend beyond wheat (Christy *et al.* 2013) and are currently being experimentally tested (Brill *et al.* 2019).

There are other situations that do not lend themselves to modelling. This is particularly the case when constraints are biotic. Simulation models, particularly APSIM, do not incorporate well-validated modules that can simulate the dynamics of biotic constraints such as weeds, invertebrate pests or disease, or their effect on crop growth and yield. Whilst there have been efforts to incorporate these or build new tools with dynamic modules (*e.g.* DYMEX, Whish *et al.* 2015), this stands as a significant gap in the utility of crop simulation. Whilst many biotic constraints are manageable, this relates less to the improvement of PY_w and more to the closure of yield gaps, but there are notable exceptions. A recent example is the refinement necessary in defining optimal sowing and flowering times for canola (Lilley *et al.* 2019) due to increased risk of upper canopy blackleg (*Leptosphaeria maculans*); this would have gone unrecognised had the agronomists and physiologists involved not been working closely with pathologists as the new early sowing systems were developed (Sprague *et al.* 2018).

Testing solutions in experimental plots

Promising solutions identified by first-principles or simulation must be experimentally tested to determine their efficacy in overcoming the intended constraints. Small plot experiments are still the most cost-effective way to achieve this, particularly if many factors are involved. Testing solutions effectively in plots requires good science training and critical thinking to ensure appropriate experimental designs and conduct, and that valid controls are used (see Celestina *et al.* 2019). Input from the discipline of statistics is critical at this point.

Because agronomy is so context dependent, it is crucial that experiments have the same context as the farming systems they are intending to emulate. This is yet another reason why it is of value to seek the involvement of leading growers and commercial agronomists in research from the outset. They are invaluable to provide feedback on the relevance of research, particularly experimental context.

The skill and level of dedication required to conduct plot experiments successfully cannot be overstated. Skilled operators are needed to ensure that factors other than those explicitly under evaluation in experiments do not dictate results. For instance, Peake *et al.* (2018) point out that many published field experiments that have sought to compare long and short duration wheat crops (McDonald *et al.* 1983, Ortiz-Monasterio R *et al.* 1994, Gomez-Macpherson and Richards 1995) have done so under nitrogen limitation, meaning that any inherent yield differences were unlikely to have been expressed.

Testing solutions in farmers' fields

As adoption rates of controlled traffic farming increase (Umbers 2017) – and with it, the precision and ease with which solutions can be tested at large scales – the potential to use swathes in farmers' fields as statistical units in field experiments is increasing. This has tremendous power from both a statistical and adoption perspective and can be a positive aspect of collective inquiry. However, the types and number of interventions that can be tested via these means are limited. Conduct of these sorts of experiments will always slow down agricultural operations, increases expense to the grower and likely reduces yield and profitability. These experiments require extremely dedicated, benevolent or well compensated co-operators to be successful. Even if experiments in farmers' fields testing interventions against controls are not possible, proposed interventions need implementation on farm if they are to achieve their intended aim. It is thus critical for research agronomists to work closely with growers and commercial agronomists on farm.

In many cases the interventions being tested by research agronomists emerge from techniques already practised by leading growers. Often there is overlap between the adoption phase, and the research and development phase. An illustration of this is the case of summer fallow weed control in southern Australia. Leading commercial agronomists and growers had identified the effect that controlling summer weeds had on crop yield (van Rees and Smallwood 2000) well before the constraint was properly quantified by research agronomists, or the mechanisms fully understood. The constraints were subsequently quantified by experimentation and simulation and the mechanisms clarified (Hunt and Kirkegaard 2011, Hunt *et al.* 2013). Scientific quantification of the constraint then helped drive further adoption of summer weed control as growers and commercial agronomists in southern Australia could attach a robust monetary value and risk level to the practice (Kirkegaard *et al.* 2014).

Integration into farming systems

Until solutions to constraints that have been tested by research agronomists are adopted in farmers' fields, this investment in RD&E has not generated any return. Integration of solutions to complex constraints into farming systems is far from easy but, despite this, the returns from agricultural research are generally high (Alston *et al.* 2009). Barriers to adoption are many and diverse. There are always production trade-offs with proposed solutions and often costs or changes in risk profile. There are also social and economic barriers that are frequently insurmountable. Tools such as ADOPT (Kuehne *et al.* 2017) can provide valuable insight for researchers as to the likelihood of adoption of solutions and what potential barriers might be, although ideally such analysis would take place in early stages of research. Adoption will always be greatest if research is conducted in close collaboration with growers and their advisors.

Sometimes trade-offs are perceived rather than real. In the case of summer fallow weed control, a frequently cited reason for letting fallow weeds grow has been the provision of feed for livestock at a time of year when supplementary feeding was often needed. Such assumptions need to be challenged with data. Whole farm modelling demonstrated that the small reduction in supplementary feeding due to uncontrolled growth of summer weeds could not compensate for the associated reduction in crop yields (Moore and Hunt 2012). Similar perceptions that sheep trampling causes lasting damage to no-till soils and reduces crop yields were also overturned with careful testing and measurement (Hunt *et al.* 2016).

Modelling also has a role to play in this step of the process as it can scale-up findings from small plots to the level of the whole farm. This we refer to as *post-experimental modelling*. The impact of some interventions on yield can be magnified at the level of the whole farm, whilst others can be diminished. For instance, a modest yield increase (0-10%) from slow developing cultivars sown early could scale up to a 20% increase in whole farm yield (Hunt *et al.* 2019). Conversely, numerous crop sequencing experiments have demonstrated the superior economic performance of break crops in comparison to long fallow. However, model-based scale-up to continuous cropping at the whole farm level diluted the impact due to operational and logistical considerations (Cann *et al.* 2019).

The role of impact evaluation

A difficult question to answer for the Australian grains industry is what level of resources should be invested to evaluate the adoption or other impacts from research. In contrast to the USA, where centralised management records for most grain crops are kept as a requirement for state subsidised insurance, there are very little standardised or comprehensive data available on management practices used by Australian growers. Organisations that have sought to acquire these data have had to do so through the use of surveys (Umbers 2017), which are deeply limited in terms of their sample size and the qualitative information that they tend to obtain. Some records are available through databases from commercial services accessed by growers (*e.g.* both Anderson *et al.* (2016) and Flohr *et al.* (2018c) used the Yield Prophet® database to evaluate temporal changes in growers' sowing time), but these are also limited in size and often skewed towards progressive growers.

There are emerging technologies that could be extremely helpful to solve this problem. Remote sensing could be used to detect many practices, such as summer fallow weed control, sowing time and crop species, but there are few published examples. Quality of historic satellite images has previously been a barrier (Gobbet and Hunt 2017) which may be removed with improved satellite systems. The power of this would be the incredibly large sample sizes and veracity of information (what actually happened as opposed to what the grower said happened, as is obtained in a survey).

Much is made of the potential for online storage of farm management data and subsequent analysis using advanced data science techniques (*e.g.* machine learning). These analyses are only as good as the data that go into them; with little financial incentive for detailed record keeping, growers generally are currently poor at maintaining accurate records. This may change with shifting societal expectations of provenance and traceability of food commodities, or if the data analytics provide more utility in decision making. Some funding organisations such as GRDC in Australia invest in their own assessments of impact. Interestingly a recent assessment found the work on early sowing systems described here as an example of transformational agronomy had an estimated internal rate of investment of 152%, more than double the nearest project area (snail and slug management), and well above a series of other high-profile projects on rust control, weed control and legume N fixation (11 to 64%, GRDC 2019).

In summary, we think it vital to demonstrate impact of research through rigorous evaluation of changes in management practices, but currently available techniques are expensive, and the methods flawed; it seems prudent not to spend too much growers' money finding out what they are doing. This will hopefully change as the technology and expectations outlined above change.

Novel transformational agronomy

Below are three constraints that we believe could be overcome with the multi-disciplinary research that is embodied in transformational agronomy. Indeed, if these could be achieved we believe it would lead to transformational changes in production and profit for Australian growers. These are complex problems and will not be overcome cheaply or easily, but the pay-off from doing so would justify the investment.

Removal of N limitation

Nitrogen deficiency remains the single biggest factor contributing to the sizeable exploitable yield gap in Australian wheat production (Hochman and Horan 2018) and likely other non-legume crops (barley, oats, canola) as well. It is true even of elite growers in favourable seasons (van Rees *et al.* 2015). At first this appears somewhat paradoxical; nitrogen management in grain crops is extremely simple – crop requirement is well related to yield as described by the simple rule of thumb taught to all budding agronomists: 40 kg/ha N per tonne of anticipated wheat yield. Sources of N are also readily quantified – mineral N in the soil prior to sowing can be cheaply and easily measured from intact soil cores. Mineralisation is more difficult to estimate but it is possible and is self-correcting (spring rain leads to higher yield potential but also more mineralisation). The complexity comes in reliably estimating anticipated yields. This requires no less capability than the accurate prediction of weather several months in advance! The difficulty arises from Australia's extremely variable rainfall. For instance, in

southern NSW when growers need to make decisions regarding N inputs (July-August) in seasons with no stored soil water prior to sowing, possible yields range from 0 to 7 t/ha, all dependent on September and October rainfall. In addition, over-fertilisation with N can reduce both yield and grain quality through haying-off (van Herwaarden *et al.* 1998). N fertiliser is also a costly input and, mindful of perhaps exaggerated environmental losses (Turner *et al.* 2012, Schwenke *et al.* 2014), growers tend to err on the conservative side in their applications.

There have been consistent attempts to improve prediction of yields to make N management more precise. This has included the use of forecast systems (Asseng *et al.* 2012) and decision support systems that integrate soil resources and management variables and present likely response to N inputs in probabilistic terms (Hochman *et al.* 2009). Whilst seasonal forecasts are likely to improve in their skill as computing power increases, they will never be perfect. Given the substantial nature of the problem a fresh approach is required. One such solution that may work in environments with low N losses (*e.g.* low rainfall areas with high soil water holding capacity) is the use of N fertiliser to maintain a base level of soil fertility ('N bank') sufficient to achieve water limited potential yields in the majority of growing seasons (as is currently done for phosphorus). Implementation of this strategy would need to consider the amount of mineral N in the soil profile to adjust inputs for carry-over of previously applied N fertiliser not used by the crop. If applied appropriately at the time of rapid crop uptake, environmental losses from the 'N bank' would be low in stubble retained farming systems where the majority of applied N is either taken up by the crop or immobilised into organic forms. Losses could be further reduced through use of higher efficiency N application strategies (*e.g.* deep and mid-row banding). Once the N banks are built, the cost of N fertiliser for growers is deferred into the season following (rather than the season of) high yields; this could have substantial economic value through improved cash flow and tax benefits. It would also reverse the mining of soil N that has occurred under Australian crop production since the decline in area of legume-based pastures (Angus and Grace 2017).

Whilst this solution represents a closing of the yield gap rather than an increase in potential yield and therefore defies the general statement about the role of research agronomists made above, the complexity of the constraint and gaps in knowledge are such that research is required. A multidisciplinary team is also essential to test this solution effectively. It requires accurate measurement of N losses and N cycling within the soil, and this requires discipline-specific expertise from within the field of soil science. Economic assessment would also be critical, and it also requires investigation of management techniques to minimise possible negative effects on yield and quality from high levels of soil mineral N. Pre- and post-experimental simulation would be essential first to test assumptions, identify locations and treatments that would be promising to test in the field, and then extend field results over multiple sites and seasons. If found to be successful, GIS tools (yield and protein mapping) would allow even greater efficiencies through spatial mapping of N removal in grain.

Crop establishment in the absence of autumn rainfall

From the time of Farrer, much of the agricultural research conducted in Australia has aimed to coincide critical periods of yield determination in crop species with climatically optimal conditions for growth. The cool, wet winters during which crops are grown in southern and Western Australia transition rapidly into hot, dry summers at which time temperatures become supra-optimal and water highly limiting. When combined with spring frosts, this creates a reasonably narrow period during which crops must undergo their critical development phases in order for yields to be maximised (usually associated with flowering, Dreccer *et al.* 2018). Whilst the concept of such optima has long been known (Anderson *et al.* 1996), it has been the advent of computer simulation that has allowed them to be quantified for multiple locations across many seasons, firstly for wheat (Flohr *et al.* 2017) and then canola (Lilley *et al.* 2019) with other crops likely to follow. Shifting crop development closer toward optimal flowering periods has been the major mechanism behind many of the transformational changes in Australian crop production. This includes such iconic advances as the release of Federation wheat with its faster development pattern (Pugsley 1983), the rise of no-till which allowed much earlier sowing (Stephens and Lyons 1998), and more recent shifts to dry and early sowing (Fletcher *et al.* 2016, Hunt *et al.* 2019).

Recent quantification of optimal flowering periods (Flohr *et al.* 2017, Lilley *et al.* 2019) has revealed that leading growers are now coinciding critical periods with seasonal optima for the first time in history (Flohr *et al.* 2018c). The only times they do not achieve timely flowering is when they have been unable to do so due to dry autumns providing insufficient soil moisture to allow seeds to germinate and emerge. Somewhat ironically, this new period of enlightenment regarding optimal sowing times of major crops has coincided with declining autumn rainfall (Pook *et al.* 2009, Cai *et al.* 2012) making it harder than ever for growers to achieve optimal flowering periods. This defines our second opportunity to overcome a major constraint to crop production – achieving crop establishment in the absence of breaking autumn rain. Once again, an integrated solution to this constraint demands multidisciplinary expertise led by a generalist with appreciation of G x E x M context. Input is required from disciplines of agricultural engineering, plant physiology, genetics and soil physics.

Our knowledge of the regulation of seed germination has developed greatly in recent times yet understanding of the basis of variation of seed establishment in the field remains limited. This is probably because most seed biology experiments are performed in laboratories on Petri dishes or under optimal conditions, whereas seeds in the field are subject to a complicated soil matrix where they experience a variety of different stresses (Finch-Savage and Bassel 2015). Domestication and breeding have provided incremental improvements in the ability of crops to germinate and emerge under sub-optimal conditions, but here we discuss ways in which agronomically directed research could be applied to transform seed performance when surface soil is dry.

Soil water potential is a major factor in determining germination and establishment. Many species can germinate at soil water potentials well below those that maximise plant growth (Wuest and Lutcher 2013). Distinguishing between adequate and marginal water to enable germination can be difficult for growers – there are no well-defined criteria for determining if a soil contains a high enough water content to germinate different crop species. At water potentials above -1.1 MPa, germination rates are rapid (Wuest and Lutcher 2013). Further decreases in water potential slow the speed of germination; below -1.6 MPa, germination ceases. Pawloski and Shaykewich (1972) showed that these effects were similar between soils, even when soils differ in hydraulic conductivity. Crop establishment could be enhanced by the ability of seeds to germinate at lower water potentials. This could be achieved by genetic or other means. Singh *et al.* (2013) examined differences between wheat cultivars as a function of water potential and found significant variation in the ability to germinate at low water potentials. Genetic variation for rates of seed water uptake (which initiates germination and is the first stage in the malting process) exists in barley, and it has been suggested that this could be exploited by breeders for the benefit of the malting and brewing industries (Cu *et al.* 2016). The same principles and expertise could be applied to field germination at lower water potential. An obvious trade-off that may arise with the genetic ability to germinate at low water potentials is susceptibility to pre-harvest sprouting (Rodríguez *et al.* 2015). Expertise from plant physiologists concerned with the regulation of dormancy would be essential to harness this opportunity.

Beyond genetic means, strategies for manipulating germination processes used in horticulture crops and rice could be evaluated. Seed priming techniques limit the availability of water to the seed so there is sufficient to progress metabolism, but insufficient for completion of germination (Halmer 2004). Seed priming has potential to reduce the lag time between imbibition and emergence and synchronise seedling emergence. Seed priming has been shown to improve emergence of wheat under low temperatures (Farooq *et al.* 2008), but not necessarily under low water potentials (Giri and Schillinger 2003). The inclusion of plant growth regulators, hormones or micronutrients during priming can also improve germination and emergence (Jisha *et al.* 2013, Ali *et al.* 2018). It is clear from the literature there are many potential solutions that could improve seed germination and establishment at low water potentials. Extensive field appraisal of these techniques is required.

Inadequate moisture at ideal sowing depth has led to growers sowing deeper to ‘moisture-seek’ (placing seed into moist soil below a layer of dry soil) to make use of residual moisture stored from summer rains or the previous growing season. Their ability to do this is currently restricted by the availability of sowing equipment capable of placing seeds into moist soil at depth, and the ability of plants to emerge from depth. Coleoptile length is an important trait determining the success of emergence from depth

(see Chapter 20) but there are also other genetic factors involved (Mohan *et al.* 2013). Modern Australian semi-dwarf wheat and barley cultivars show poor emergence when sown deep (greater than 8 cm) due to shortened coleoptiles (Rebetzke *et al.* 2007). Warmer soils in future may further exacerbate poor establishment and with deeper sowing.

Pre-experimental modelling indicates substantial benefits for crop yield in southern Australia if machinery and genotypes could be developed that allowed placement and emergence of seed at depth (Kirkegaard and Hunt 2010, Flohr *et al.* 2018a). Establishment of crops in this way is routine in the drylands of the Pacific North West USA, where seeds of winter wheat and now other crops are sown deep using deep furrow drills into moisture remaining from 13-month fallows and can emerge with 10-15 cm of soil covering them (Schillinger and Papendick 2008). Rebetzke *et al.* (2016) have argued the case for Australian breeders to use novel dwarfing genes that do not suppress coleoptile length. Larger seed size is also known to improve deep-sown crop establishment. Large-seeded canola improved the timeliness of establishment and subsequent grain yield of canola when rainfall for crop establishment was marginal but there was moisture available deeper in the seedbed (Brill *et al.* 2016).

Frost, drought and heat

Whilst optimisation of flowering times has allowed the combined stresses of drought, frost and heat to be minimised, these abiotic stresses still take a large toll on crops every year. They would continue to do so even if establishment in the absence of autumn rain (see above) could be achieved. With all avenues for avoidance of frost, drought and heat explored, the only means remaining to increase yields in the face of these cardinal abiotic stresses is through crop tolerance. It is our opinion that this will most likely be achieved via genetic solutions, but that these must be considered in an appropriate G x E x M context.

Frost, drought and heat are inextricably linked. Frost risk declines as flowering moves later into the spring, but risk of drought and heat increases. This means that tolerances to all three stresses are not necessary to improve yields. If tolerance can be found to either frost on the one hand, or drought and heat on the other, then optimal flowering will shift accordingly to reduce the likelihood of occurrence of opposing stress. That is, if we can solve frost stress then we have solved drought and heat stress, and vice versa. The value of this approach has been demonstrated by economic analyses of potential frost tolerance. The benefit of shifting flowering time to avoid drought and heat has also been quantified (An-Vo *et al.* 2018). Therefore, the important question is which of these stresses will be cheapest and easiest to solve?

Drought and heat are perhaps easier targets compared with frost in that it is reasonably easy to screen for tolerance in different genotypes. For various reasons, frost tolerance is extremely tricky to phenotypically screen for, and frost itself is virtually impossible to recreate under controlled conditions. Thus, we believe it likely that the breakthrough will come through combined drought and heat tolerance rather than frost tolerance. The trick with heat and drought is that they interact. Studies that have attempted to identify sources of heat tolerance in the absence of drought have found tolerance is associated with stomatal opening and rapid water-use that depresses canopy temperatures relative to the atmosphere (Reynolds *et al.* 1994). For heat tolerance to be useful in the Australian context, it must be effective under limited water supply (Hunt *et al.* 2018).

Whilst there may be some promise in selecting morphological traits known to confer both heat and drought tolerance (Hunt *et al.* 2018), the greatest and most cost-effective progress may be made by breeders selecting for high yield at late flowering times where crops would be routinely exposed to concurrent drought and heat stress. However, this is where wider crop physiology and management context becomes important – it would be crucial that late flowering be achieved with slow developing cultivars that could be sown early and thus exploit a full growing season rather than by late sowing of faster developing cultivars where yield potential would be limited by shallow rooting depth and low biomass accumulation (Kirkegaard *et al.* 2015, Lilley and Kirkegaard 2016).

Barriers to transformational agronomy

In this chapter we have outlined some of the factors that have diminished the role of agronomists in the research process and, though we recognise individual responsibility for change, various barriers for young agronomists can be identified (Table 1). Broader thinking in assessing opportunities to increase water limited potential yield or close yield gaps, foreseeing interactions and developing field experiments and simulations to test them must be encouraged – as opposed to narrow disciplinary and single factor experiments. Such a change must commence with training, which has already been mentioned as a deficiency in recent years (see Chapter 3). This will inevitably lead to better collaborations and partnerships; institutional arrangements should encourage and support rather than dictate or obstruct such interactions. Siloed research and funding organisations discourage these interactions as do overly aggressive intellectual property (IP) and legal arrangements, yet active encouragement and facilitation is required to initiate and maintain them.

Table 1. A range of barriers to transformational agronomy and behaviours that can minimise them.

Barrier	Description	Improvement
Conceptual	How we think about things	Think more broadly about interactions (G x E x M)
Statistical	How we design/analyse	Embrace systems designs and experiments
Cultural	How we approach research	Partnerships and collaboration
Structural	How we organise teams	Reward integrators as specialists
Institutional	How we are rewarded	Reward impact, not just impact factors
Training	How we are taught	Elevate agronomy in university courses

Structural and institutional arrangements must encourage and reward those working in, and leading teams that deliver real impact through increased adoption of practices that improve yield or reduce input costs, risk or environmental damage rather than simply rewarding individual researchers based on publication metrics and impact factor. Unfortunately, there is evidence that success in funding proposals is negatively correlated with multi-disciplinary teams, suggesting the problem is entrenched (Bromham *et al.* 2016). Career progression is generally slowed in science ranks for those who are not seen to specialise, and in technical ranks for those working in field-based agronomy – yet these staff are crucial to the quality, relevance and rigour in on-farm experimental research.

Achieving these changes must start with the training of the next generation of transformational agronomists, who are motivated by the prospect of a rewarding career of high-quality research delivering real impact in future food security.

References

- Adcock D, McNeill AM, McDonald GK, Armstrong RD (2007) Subsoil constraints to crop production on neutral and alkaline soils in Southern Australia: a review of current knowledge and management strategies. *Australian Journal of Experimental Agriculture* **47**, 1245-1261
- Ali N, Farooq M, Hassan MA, Arshad MS *et al.* (2018) Micronutrient seed priming improves stand establishment, grain yield and biofortification of bread wheat. *Crop and Pasture Science* **69**, 479-487
- Alston JM, Pardey PG, James JS, Andersen MA (2009) The Economics of Agricultural R&D. *Annual Review of Resource Economics* **1**, 537-566
- An-Vo D-A, Mushtaq S, Zheng B *et al.* (2018) Direct and indirect costs of frost in the Australian wheatbelt. *Ecological Economics* **150**, 122-136
- Anderson WK, Heinrich A, Abbotts R (1996) Long-season wheats extend sowing opportunities in the central wheat belt of Western Australia. *Australian Journal of Experimental Agriculture* **36**, 203-208
- Anderson WK, Stephens D, Siddique KHM (2016) Dryland agriculture in Australia: Experiences and innovations. In (Eds. M Farooq, KHM Siddique) “Innovations in Dryland Agriculture” pp 299-319 (Springer International Publishing: Cham)
- Angus JF, Grace PR (2017) Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. *Soil Research* **55**, 435-450
- Asseng S, McIntosh PC, Wang G, Khimashia N (2012) Optimal N fertiliser management based on a seasonal forecast. *European Journal of Agronomy* **38**, 66-73

- Brill R, Xing H, Napier T *et al.* (2019) Canola agronomy – consistent messages on canola agronomy hold strong in a Decile 1 season. *Grains Research Update* Wagga Wagga (GRDC: Barton, ACT) <https://bit.ly/2KpV4BX>
- Brill RD, Jenkins ML, Gardner MJ *et al.* (2016) Optimising canola establishment and yield in south-eastern Australia with hybrids and large seed. *Crop and Pasture Science* **67**, 409-418
- Bromham L, Dinnage R, Hua X (2016) Interdisciplinary research has consistently lower funding success. *Nature* **534**, 684
- Cai W, Cowan T, Thatcher M (2012) Rainfall reductions over Southern Hemisphere semi-arid regions: the role of subtropical dry zone expansion. *Scientific Reports* **2**, 702
- Cann DJ, Hunt JR, Malcolm B (2019) Long fallows can maintain whole-farm profit margins and reduce risk in semi-arid south-eastern Australia. *Agricultural Systems* (in press)
- Celestina C, Hunt JR, Sale PWG, Franks AE (2019) Attribution of crop yield responses to application of organic amendments: A critical review. *Soil and Tillage Research* **186**, 135-145
- Celestina C, Midwood J, Sherriff S *et al.* (2018) Crop yield responses to surface and subsoil applications of poultry litter and inorganic fertiliser in south-eastern Australia. *Crop and Pasture Science* **69**, 303-316
- Christy B, O'Leary G, Riffkin P *et al.* (2013) Long-season canola (*Brassica napus* L.) cultivars offer potential to substantially increase grain yield production in south-eastern Australia compared with current spring cultivars. *Crop and Pasture Science* **64**, 901-913
- Cu S, Collins HM, Betts NS *et al.* (2016) Water uptake in barley grain: Physiology; genetics and industrial applications. *Plant Science* **242**, 260-269
- Dreccer MF, Fainges J, Whish J *et al.* (2018) Comparison of sensitive stages of wheat, barley, canola, chickpea and field pea to temperature and water stress across Australia. *Agricultural and Forest Meteorology* **248**, 275-294
- Evans LT (1998) "Feeding the Ten Billion" (Cambridge University Press: Cambridge UK)
- Farooq, M, Basra, SMA, Rehman, H, Saleem, BA (2008) Seed priming enhances the performance of late sown wheat (*Triticum aestivum* L.) by improving chilling tolerance. *Journal of Agronomy and Crop Science* **194**, 55-60
- Finch-Savage WE, Bassel GW (2016) Seed vigour and crop establishment: extending performance beyond adaptation. *Journal of Experimental Botany* **67**, 567-591
- Fischer RA (2015) Definitions and determination of crop yield, yield gaps, and of rates of change. *Field Crops Research* **182**, 9-18
- Fischer RA, Byerlee D, Edmeades GO (2014) "Crop yields and global food security: will yield increase continue to feed the world?" ACIAR Monograph No. 158 (Australian Centre for International Agricultural Research: Canberra ACT)
- Fischer RA, Connor DJ (2018) Issues for cropping and agricultural science in the next 20 years. *Field Crops Research* **222**, 121-142
- Fletcher A, Lawes R, Weeks C (2016) Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. *Crop and Pasture Science* **67**, 1268-1280
- Flohr BM, Hunt JR, Kirkegaard JA, Evans JR (2017) Water and temperature stress define the optimal flowering period for wheat in south-eastern Australia. *Field Crops Research* **209**, 108-119
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018a) Genotype × management strategies to stabilise the flowering time of wheat in the south-eastern Australian wheatbelt. *Crop and Pasture Science* **69**, 547-560
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018b) Genetic gains in NSW wheat cultivars from 1901 to 2014 as revealed from synchronous flowering during the optimum period. *European Journal of Agronomy* **98**, 1-13
- Flohr BM, Hunt JR, Kirkegaard JA *et al.* (2018c) Fast winter wheat phenology can stabilise flowering date and maximise grain yield in semi-arid Mediterranean and temperate environments. *Field Crops Research* **223**, 12-25
- Gardner W, Fawcett R, Steed G *et al.* (1992) Crop production on duplex soils in south-eastern Australia. *Australian Journal of Experimental Agriculture* **32**, 915-927
- Gill JS, Clark GJ, Sale PW *et al.* (2012) Deep placement of organic amendments in dense sodic subsoil increases summer fallow efficiency and the use of deep soil water by crops. *Plant and Soil* **359**, 57-69
- Gill JS, Sale PWG, Tang C (2008) Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. *Field Crops Research* **107**, 265-275
- Giller KE, Andersson JA, Corbeels M *et al.* (2015) Beyond conservation agriculture. *Frontiers in Plant Science* **6**, 870
- Giri GS, Schillinger WF (2003) Seed priming winter wheat for germination, emergence, and yield. *Crop Science* **43**, 2135-2141

- Gobbet D, Hunt JR (2017) Detecting trends in cereal crop sowing dates using Landsat. In (Eds. X Deng, C Pettit, S Zarpelon Leao, J Doig) “Research@Locate17” Sydney, NSW
www.ceur-ws.org/Vol-1913/RL17_paper_4.pdf
- Gomez-Macpherson H, Richards RA (1995) Effect of sowing time on yield and agronomic characteristics of wheat in south-eastern Australia. *Australian Journal of Agricultural Research* **46**, 1381-1399
- GRDC (2019) GRDC Performance 2017-2018: Report to growers. *GRDC Groundcover* Issue **138**, 18-19
- Halmer P (2004) Methods to improve seed performance in the field. In (Eds. RL Benech-Arnold, RA Sánchez) “Seed Physiology: Applications to Agriculture” (Food Products Press: Binghamton, NY)
- Haskins B, McMaster C (2012) Summer fallow management in 2010 across central west NSW. *Proceedings of 16th Australian Agronomy Conference*. Armidale, NSW
www.regional.org.au/au/asa/2012/soil-water-management/8114_haskinsbj.htm
- Hochman Z, Gobbett DL, Horan H (2017) Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology* **23**, 2071-2081
- Hochman Z, Horan H (2018) Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. *Field Crops Research* **228**, 20-30
- Hochman Z, Van Rees H, Carberry PS *et al.* (2009) Re-inventing model-based decision support with Australian dryland farmers: 4. Yield Prophet® helps farmers monitor and manage crops in a variable climate. *Crop and Pasture Science* **60**, 1057-1070
- Holzworth DP, Huth NI, deVoil PG *et al.* (2014) APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* **62**, 327-350
- Hunt JR, Browne C, McBeath T *et al.* (2013) Summer fallow weed control and residue management impacts on winter crop yield through soil water and N accumulation in a winter-dominant, low rainfall region of southern Australia. *Crop and Pasture Science* **64**, 922-934
- Hunt JR, Hayman, PT, Richards, RA, Passioura, JB (2018) Opportunities to reduce heat damage in rain-fed wheat crops based on plant breeding and agronomic management. *Field Crops Research* **224**, 126-138
- Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. *Crop and Pasture Science* **62**, 915-929
- Hunt JR, Lilley JM, Trevaskis B *et al.* (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. *Nature Climate Change* **9**, 244-247
- Hunt JR, Swan AD, Fittell NA *et al.* (2016) Sheep grazing on crop residues do not reduce crop yields in no-till, controlled traffic farming systems in an equi-seasonal rainfall environment. *Field Crops Research* **196**, 22-32
- Jisha KC, Vijayakumari K, Puthur JT (2013) Seed priming for abiotic stress tolerance: an overview. **35**, *Acta Physiologiae Plantarum* **35**, 1381-1396
- Kirkegaard JA (2019) Incremental transformation: success from farming systems synergy. *Outlook on Agriculture* **48**, 105-112
- Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- Kirkegaard JA, Hunt JR, McBeath TM *et al.* (2014) Improving water productivity in the Australian grains industry – a nationally coordinated approach. *Crop and Pasture Science* **65**, 583-601
- Kirkegaard JA, Lilley JM, Hunt JR *et al.* (2015) Effect of defoliation by grazing or shoot removal on the root growth of field-grown wheat (*Triticum aestivum* L.). *Crop and Pasture Science* **66**, 249-259
- Kitonyo OM, Sadras VO, Zhou Y, Denton MD (2017) Evaluation of historic Australian wheat varieties reveals increased grain yield and changes in senescence patterns but limited adaptation to tillage systems. *Field Crops Research* **206**, 65-73
- Kuehne G, Llewellyn R, Pannell DJ *et al.* (2017) Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy. *Agricultural Systems* **156**, 115-125
- Lilley JM, Flohr BM, Whish JPM, Farre I, Kirkegaard JA (2019) Defining optimal sowing and flowering periods for canola in Australia. *Field Crops Research* **235**, 118-128
- Lilley JM, Kirkegaard JA (2016) Farming system context drives the value of deep wheat roots in semi-arid environments. *Journal of Experimental Botany* **67**, 3665-3681
- Llewellyn RS, D’Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204-212
- Lorimer MS, Douglas, LA (2001) Effects of management practice on properties of a Victorian red-brown earth. 2. Wheat root distribution and grain yield. *Australian Journal of Soil Research* **39**, 307-315
- Manley W, Foot K, Davis A (2019) “A Dictionary of Agriculture and Land Management” (Oxford University Press: Oxford UK).

- MacEwan RJ, Crawford DM, Newton PJ, Clune TS (2010) High clay contents, dense soils, and spatial variability are the principal subsoil constraints to cropping the higher rainfall land in south-eastern Australia. *Soil Research* **48**, 150-166
- McDonald G, Sutton B, Ellison F (1983) The effect of time of sowing on the grain yield of irrigated wheat in the Namoi Valley, New South Wales, *Australian Journal of Agricultural Research* **34**, 229-240
- Messina C, Hammer GL, Dong ZS *et al.* (2009) Modelling crop improvement in a G×E×M framework via genotype-phenotype relationships. In (Eds. VO Sadras, D Calderini) "Crop Physiology: Applications for Genetic Improvement and Agronomy" pp 235-265 (Academic Press: Burlington, MA)
- Mohan A, Schillinger WF, Gill KS (2013) Wheat seedling emergence from deep planting depths and its relationship with coleoptile length. *PLoS ONE* **8**, e73314
- Moore AD (2009) Opportunities and trade-offs in dual-purpose cereals across the southern Australian mixed-farming zone: a modelling study. *Animal Production Science* **49**, 759-768
- Moore AD, Hunt JR (2012) Does control of summer fallow weeds improve whole-farm productivity in both Mediterranean and temperate environments? *Proceedings of 16th Australian Agronomy Conference*. Armidale, Australia www.agronomyaustraliaproceedings.org/
- Ortiz-Monasterio JI, Dhillon SS, Fischer RA (1994) Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. *Field Crops Research* **37**, 169-184
- Pawloski MC, Shaykewich CF (1972) Germination of wheat as affected by soil water stress. *Canadian Journal of Plant Science* **52**, 619-623
- Peake AS, Das BT, Bell KL *et al.* (2018) Effect of variable crop duration on grain yield of irrigated spring-wheat when flowering is synchronised. *Field Crops Research* **228**, 183-194
- Pook M, Lisson S, Risbey J *et al.* (2009) The autumn break for cropping in southeast Australia: trends, synoptic influences and impacts on wheat yield. *International Journal of Climatology* **29**, 2012-2026
- Porter JR, Wollenweber B, Jamieson PD, Fischer T (2018) From genes to networks to what-works. *Nature Plants* **4**, 234-234
- Pretty, JN (1995) Participatory learning for sustainable agriculture. *World Development* **23**, 1247-1263
- Pugsley AT (1983) The impact of plant physiology on Australian wheat breeding. *Euphytica* **32**, 743-748
- Rebetzke GJ, Richards RA, Fittell NA *et al.* (2007) Genotypic increases in coleoptile length improves stand establishment, vigour and grain yield of deep-sown wheat. *Field Crops Research* **100**, 10-23
- Rebetzke GJ, Zheng B, Chapman SC (2016) Do wheat breeders have suitable genetic variation to overcome short coleoptiles and poor establishment in the warmer soils of future climates? *Functional Plant Biology* **43**, 961-972
- Reynolds M, Balota M, Delgado M *et al.* (1994) Physiological and morphological traits associated with spring wheat yield under hot, irrigated conditions. *Functional Plant Biology* **21**, 717-730
- Rillig MC, Aguilar-Trigueros CA, Camenzind T *et al.* (2018) Why farmers should manage the arbuscular mycorrhizal symbiosis. A response to Ryan & Graham (2019). *New Phytologist* **222**, 1171-1175
- Robertson M, Kirkegaard J, Peake A *et al.* (2016) Trends in grain production and yield gaps in the high-rainfall zone of southern Australia. *Crop and Pasture Science* **67**, 921-937
- Rodríguez MV, Barrero JM, Corbineau F *et al.* (2015) Dormancy in cereals (not too much, not so little): about the mechanisms behind this trait. *Seed Science Research* **25**, 99-119
- Ryan MH, Graham JH (2018) Little evidence that farmers should consider abundance or diversity of arbuscular mycorrhizal fungi when managing crops. *New Phytologist* **220**, 1092-1107
- Ryan MH, Graham JH, Morton JB, Kirkegaard JA (2019) Research must use a systems agronomy approach if management of the arbuscular mycorrhizal symbiosis is to contribute to sustainable intensification. *New Phytologist* **222**, 1176-1178
- Sadras VO, Lawson C (2011) Genetic gain in yield and associated changes in phenotype, trait plasticity and competitive ability of South Australian wheat varieties released between 1958 and 2007. *Crop and Pasture Science* **62**, 533-549
- Sale PW, Gill JS, Peries RR, Tang C (2019) Crop responses to subsoil manuring. I. Results in south western Victoria from 2009 to 2012. *Crop and Pasture Science* **70**, 44-54
- Schillinger WF, Papendick RI (2008) Then and now: 125 years of dryland wheat farming in the inland Pacific northwest. *Agronomy Journal* **100**, S-166-S-182
- Schwenke GD, Manning W, Haigh BM (2014) Ammonia volatilisation from nitrogen fertilisers surface-applied to bare fallows, wheat crops and perennial-grass-based pastures on Vertosols. *Soil Research* **52**, 805-821
- Siddique KHM, Tennant D, Perry MW, Belford RK (1990) Water-use and water-use efficiency of old and modern wheat cultivars in a Mediterranean-type environment. *Australian Journal of Agricultural Research* **41**, 431-447
- Singh P, Ibrahim HM, Flury M *et al.* (2013) Critical water potentials for germination of wheat cultivars in the dryland Northwest USA. *Seed Science Research* **23**, 189-198

- Sprague SJ, Marcroft SJ, Lindbeck KD *et al.* (2018) Detection, prevalence and severity of upper canopy infection on mature *Brassica napus* plants caused by *Leptosphaeria maculans* in Australia. *Crop and Pasture Science* **69**, 65-78
- Stephens DJ, Lyons TJ (1998) Variability and trends in sowing dates across the Australian wheatbelt. *Australian Journal of Agricultural Research* **49**, 1111-1118
- Turner DA, Edis RE, Chen D *et al.* (2012) Ammonia volatilization from nitrogen fertilizers applied to cereals in two cropping areas of southern Australia. *Nutrient Cycling in Agroecosystems* **93**, 113-126
- Umbers, A (2017) "Farm Practices Survey Report 2016" (GRDC: Barton, ACT)
www.grdc.com.au/resources-and-publications/all-publications/publications/2018/farm-practices-survey-report-2016
- van Herwaarden AF, Farquhar GD, Angus JF *et al.* (1998) 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser. I. Biomass, grain yield, and water use. *Australian Journal of Agricultural Research* **49**, 1067-1082
- van Ittersum MK, Cassman KG, Grassini P *et al.* (2013) Yield gap analysis with local to global relevance—A review. *Field Crops Research* **143**, 4-17
- van Rees H, McClelland T, Hochman Z (2015) Leading farmers have closed the yield gap – what are the implications for productivity growth? *GRDC Research Update for Advisors*. Ballarat, Australia.
www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/02/leading-farmers-have-closed-the-yield-gap
- van Rees H, McClelland T, Hochman Z *et al.* (2014) Leading farmers in South East Australia have closed the exploitable wheat yield gap: Prospects for further improvement. *Field Crops Research* **164**, 1-11
- van Rees H, Smallwood BD, Kaminskas S, Rawlings (Eds) (2000) Summer weed control options. *Proceedings of the Victorian Cropping Systems Update 2000*. Longerenong College. (John Lamb Communications: SA)
- Whish, JPM, Herrmann, NI, White, NA *et al.* (2015) Integrating pest population models with biophysical crop models to better represent the farming system. *Environmental Modelling & Software* **72**, 418-425
- Whitfield D, Newton P, Mantell A (1992) Comparative water use of dryland crop and pasture species. *Proceedings of 6th Australian Agronomy Conference*, Armidale, NSW
www.agronomyaustraliaproceedings.org/images/sampled/1992/concurrent/cropping-systems/p-09.pdf
- Wuest SB, Lutchter LK (2013) Soil water potential requirement for germination of winter wheat. *Soil Science Society of America Journal* **77**, 279-283
- Zhang H, Turner NC, Poole ML, Simpson N (2006) Crop production in the high rainfall zones of southern Australia – potential, constraints and opportunities. *Australian Journal of Experimental Agriculture* **46**, 1035-1049

Chapter 24

Digital agriculture

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Introduction

Since about 2010 there has been an explosion in the interest and expectations for data-driven agriculture, often dubbed ‘digital agriculture’. Digital agriculture is often used interchangeably with the term ‘smart farming’, which refers to the use of data to inform farm decisions and then automation and actuation to execute those decisions. Several technological drivers have converged to bring about this interest (Koch 2017):

- advances in, and availability of, cheaper sensor networks and the Internet of Things (IoT, Atzori *et al.* 2010);
- big data analysis (Wolfert *et al.* 2017);
- availability of connectivity at a decreasing cost per bit; and
- inter-operability of devices.

Effectively, farmers are becoming enabled to make use of farm business data that was previously impossible or impractical to collect and analyse. For the purposes of this chapter we restrict our attention to the use of data to inform farm decision making, including the broader definition of smart farming that includes the idea of taking data beyond the farm gate to inform decisions by regulators, financial institutions, agribusiness and governments. Digital agriculture is broader than ‘precision agriculture’, which is traditionally defined as matching farm operations to variable conditions, especially with the use of spatially-aware technologies and data (Robertson *et al.* 2012).

The advent of global navigation satellite systems (GNSS), including the widely known United States (US) global positioning systems (GPS), and yield monitors heralded the beginnings of precision agriculture. The core idea of precision agriculture was that collection and analysis of spatial information would allow more efficient production. More recently there has been heightened interest and associated hype around digital agriculture. This is being driven by a range of forces and was initially centred in the US. The primary opportunities have arisen by the confluence of several factors:

- First, the cost of collecting data is declining as new technology and sensors become available. Machinery is increasingly ‘smart’, is sensorised and able to communicate digitally;
- Second, the computing platforms and services such as the cloud are becoming ubiquitous, providing natural platforms with both the required storage and computational power to deliver digital agriculture services;
- Third, existing agricultural companies are going digital to ensure their future relevance and to open new data streams to exploit in the development of new products and services; and
- Fourth, there is a range of successful digital business models being imported into the agriculture space. For example, Google has shown that access to data about users can provide information to sell to advertisers, as well as information to tailor the experience to individual users. Some digital agriculture companies are trying to replicate this model. Other companies in agriculture are proceeding to implement decision-support techniques which are well developed in business analytics (*e.g.* dashboards) to provide situational awareness to managers.

These factors combine with the relative lack of maturity of the industry to produce a complex range of products in the market that seek to provide new sensor technology mounted on drones, services to support information cloud-based platforms, integrate information to support more refined decision

making, more complex business models that link producers and suppliers. Some do a mixture of all of these. There is also a variety of start-ups in this space that will pivot their business models to attempt to find a profitable configuration. Some products are only regionally specific and lack transferability, and others are focussed on specific farm management tasks without consideration of how they impact on other parts of the farm system, if at all.

As digital applications are developed for the agricultural industry, there will be a spectrum for the use of these data-intensive technologies and the degree to which the collection and actuation of farm tasks are automated. As the number of steps increases between data acquisition and task execution, this increases the complicated nature of the task. For example, in the simplest case, GNSS-guided farm machinery has only three steps between the use of the data-generating technology and the action: a GNSS-enabled vehicle is geo-located; this in turn guides auto steer, which results in a controlled driving pattern. Such cases are typified by embodied technologies that can directly increase efficiency or productivity as soon as they are used and require little or no human control or oversight. By way of contrast, a more complicated case of the application of fertiliser nitrogen to various sub-field zones in a cereal crop involves collection of spatial information, definition of management zones, selection of nitrogen fertiliser rates, encoding the variable rate controller to apply the prescribed rates, and application of the prescribed rates. Various biophysical and economic variables, with their own inherent uncertainty, need to be accounted for along the way. In these cases the digital technologies are not embodied in the technology being applied and require some kind of decision support tool to convert information to knowledge in a more complicated and challenging adoption scenario.

This chapter focuses on those digital agriculture applications where data are used to support farm decisions, through the use of decision support tools. We discuss the role of decision support tools, their state in Australian agriculture and data requirements. We consider the rise of ‘platforms’ and what a desirable future for decision tools might look like. We finish by considering the future requirements for digital agriculture from a farmer perspective.

The role of decision support tools

Decision support is the process of improving decision-making by providing some combination of information and analytics to a decision-maker. Most sources of rural data need to be mediated through some form of decision support if they are to benefit managers. In order to make the information or knowledge available, a decision support tool requires some kind of user interface; the interface is commonly implemented using information and communication technologies (ICT), but this is not a necessary feature. Figure 1 illustrates a typical agricultural decision support workflow, using the Yield Prophet® tool as an example.

Monitoring and diagnosis

Some decision support tools are designed to provide new information about the current state of plants, animals, land, water and infrastructure; the integration of this information into a decision-making process is left to the user. These tools provide value to a decision-maker by improved understanding of current conditions, often by deriving a diagnostic system parameter that would otherwise be inaccessible and/or relatively costly to the decision-maker. Tools provided with many spatial sensing products (e.g. yield monitor maps, mapping of canopy temperature or cover from unmanned aerial vehicle [UAV] data) are in this category.

An emerging opportunity in this category is the imperative to produce safe, quality, sustainable and ethical products embodied in volunteer traceability systems. Such systems speak of each participant in a commodity supply chain being able to provide information on ‘one step forward, one step back’ along the chain as a minimum requirement. For producers, this ‘one step back’ component could include inputs, management regimes, and environmental metrics.

Rural decision support software can have a range of different purposes. The following list is expanded from that provided by McCown (2002b):

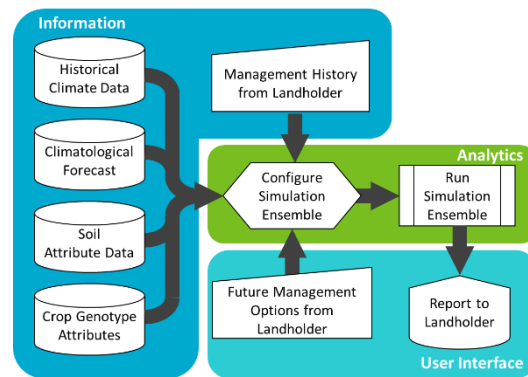


Figure 1. Information flows in the Yield Prophet® tool, showing the key components: information, analytics and a user interface.

Analysis of options in highly structured tasks

Tools with this purpose are the most widespread agricultural applications. They contribute value to the decision-making process by using powerful analytics to estimate the future outcomes of alternative actions, often in conjunction with a monitoring step, and they typically focus on a small number of variables that are relevant to the task. The intended user is typically a producer or an advisor, but can also be regulators. Perhaps the best-known example of this ‘decision calculus’ tool in Australian agriculture is Yield Prophet® (Birchip Cropping Group; Hochman *et al.* 2009), in which the user can explore the likely consequences of several specific crop management decisions such as cultivar choice or nitrogen fertiliser rates, based on probabilistic estimates of their consequences for crop yield (see Chapter 23).

Provision of prescriptions

Tools with this purpose share the same underlying rationale and logic as those in the previous category, but differ in that they select a single recommended action. A simple example of a prescription tool (control decisions for silverleaf whitefly in cotton) is shown in Figure 2. Some prescription tools, such as the FieldView™ tool delivered by the Climate Corporation in the US, are designed to produce ‘packages’ of prescriptions that cover multiple decisions – and the interactions between them – simultaneously. Local climate information is used to calculate a day-degree sum; this is combined with in-field sampling to derive a single recommendation for action.

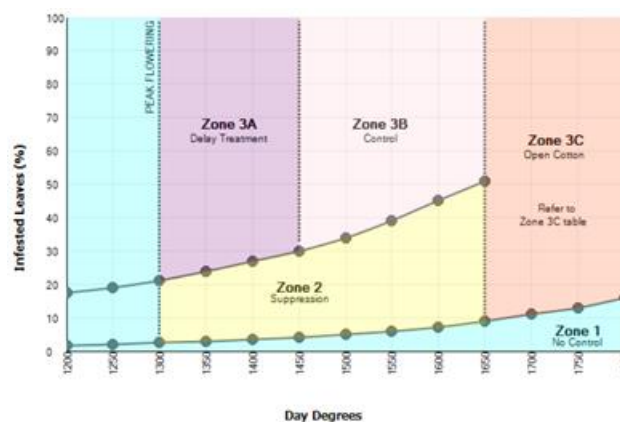


Figure 2. A simple prescription tool: silverleaf whitefly control recommendations from CSIRO’s CottAssist tool (Cotton Research and Development Corporation and CSIRO, 2015)

Use in consulting

These tools are based on ‘versatile simulators’ (McCown 2002b), *i.e.* complex simulation models designed to mimic system function and performance, cost-effectively. A problem is defined by the ultimate user (a producer, policy maker, or some other actor). An advisor then applies the simulator to the problem and its particular circumstances. The analysis process differs from other tools in that the task is typically not well-structured, so that the set of possible decision options emerges from an iterative process of asking ‘what-if’ questions; the consultant acts as the interface between a ‘hard systems’ and a ‘soft systems’ approach. These tools are generally designed to provide information about a wide range of potentially-relevant variables. The GrassGro® decision support tool for grazing systems (Moore *et al.* 1997) was explicitly re-designed to operate in this mode (Herrmann and Zurcher 2011).

Meeting external regulatory demands

In situations where standards for environmental conservation and safety are sought, decision support systems can be used in two ways. Documented compliance by farmers with the recommendations from a tool that embodies the current understanding of best management practice can demonstrate effective self-regulation (the CottAssist® tools are used in this way by the cotton industry). Alternatively, regulatory bodies can use decision support tools to evaluate whether proposed rural activities are acceptable, such as the widespread use of the OVERSEER™ nutrient budgeting tool (Wheeler *et al.* 2006) by regional planning authorities in New Zealand (Freeman *et al.* 2016).

The current state of decision support in Australian agriculture

A great many decision support products have been developed for Australian rural industries, dating back to the SIRATAC® system in the 1970s (Hearn *et al.* 2002). The 2007 Australian Farm Software Directory produced by the Queensland Department of Primary Industries identified ~75 distinct decision support tools, excluding software primarily designed for information recording. This variety is also seen in other countries (*e.g.* Rose *et al.* 2016 located 395 tools in the UK); it reflects the diversity of rural industries and the continuing development of new data streams and technologies. Some tools started as management information systems to which analytics have been added; some have been developed by machinery providers to add value to monitoring information; some are extensions of research models, often resulting from projects funded by rural R&D corporations (RDCs); yet others (*e.g.* the MLA Feed Demand Calculator® and the recently-released AskBill™ product for the sheep industries) were initiated by RDCs or Cooperative Research Centres (CRCs) in response to a perceived industry need.

While apps have proliferated it has been more difficult to identify documented cases where impact in the use of decision tools has occurred with end users. Robertson *et al.* (2015) recorded 11 cases where crop simulation models played a pivotal role in research, development or extension activity, and led to a demonstrable impact with decision makers (farmers, advisors, breeders). Many of the examples originated from the northern, subtropical grains region (see Chapter 23). This is a cropping region with high climate variability and a diverse farming system where growers have a wide range of crop and fallow options. It is also the historical base for the group that developed the Agricultural Production Systems sIMulator (APSIM, Holzworth *et al.* 2014). The unifying theme of all 11 examples is that models were used to integrate and quantify the effects of climate, soil and management in evaluating a new option for a farmer or plant breeder. Models were used to extrapolate field results beyond site and season specificity and, in doing so, built confidence for the decision maker in the reliability of the option.

Diverse analytic techniques

As a result of their diverse purposes and origins, a wide range of analytic techniques are embedded within the currently-available decision support tools. Because of the uncertain nature of the Australian climate, decision support tools that forecast outcomes tend to rely on biophysical simulations of varying levels of complexity, *e.g.* Yield Prophet®, hydroLOGIC® for cotton (Richards *et al.* 2008) or

AskBill®. At its simplest, however, the analytic process can involve the computation and presentation of a summary statistic (*e.g.* degree-day counts, as in the federally-funded CliMate™ app, or the normalized difference vegetation index). Other tools are based on straightforward algebraic calculations based on user-input data and/or tables of generic data; many examples of this type have an explicitly financial focus, such as the VegTool® gross margin comparator for vegetable production. There are also tools that rely on predictive equations generated from statistical analysis of experimental or other field data, *e.g.* the LambAlive® tool (Donnelly *et al.* 1997).

More recently, machine learning techniques are being employed to develop predictive equations for use in agricultural decision support. The most widely-publicised example is the work of Climate Corporation in North America, where predictive analytics are used to provide cropping prescriptions to grain growers using local climate, soil, yield and other information. Machine learning approaches rely on the collation of large, consistent datasets of outcomes (*e.g.* crop yields) that can be related to other large, consistent datasets of potential predictors. The dearth and relative inaccessibility of such predictors in Australia must therefore be resolved if they are to find widespread application in Australian agricultural production. As well as offering the potential for improved prediction of outcomes in task-analysis tools, however, machine learning offers the prospect of analytics that can update themselves as farming practices shift, through the ongoing (and automated) collection of data and re-estimation of predictive equations. The emergence of IoT sensors that provide highly-time-resolved data (*e.g.* microclimate/soils sensors) and new algorithmic approaches is challenging the notion of the minimum data required to train an artificial intelligence (AI) system. The requirement is smaller than intuitively assumed – especially when data are shared into the AI platform from multiple sources, such as sensors deployed across a landscape that experience a multitude of dynamic ranges and integrated with spatial remote sensed information from mobile, aerial and/or satellite systems.

Dissemination channels in transition

The earliest agricultural decision support tools in Australia were delivered by models linked to main-frame computers (Hearn *et al.* 2002) but nearly all tools developed during the 1980s and 1990s were designed for use on a stand-alone personal computer. Spreadsheet implementations have historically been common; for many tool producers, the quality-assurance drawbacks of a spreadsheet have been outweighed by the familiarity to users of the spreadsheet interface.

In recent years, however, migration of agricultural decision support to the Internet has taken place. At its simplest, existing tools have been hosted on their providers' websites, to improve their findability and accessibility. Yield Prophet® was an early Australian example of server-based computation delivered via a Web page; the attraction of this technical approach is the ubiquity of the Web browser as a channel. In parallel, some long-established tools (*e.g.* GrazFeed®, Freer *et al.* 1997) have been re-implemented as apps for use on portable devices.

Given the advantages for developers and the widespread uptake of the necessary devices, it might be expected that this shift toward app-based or web-based delivery of decision support will soon be complete. Over the medium term, however, automation of agricultural husbandry may well result in a need to decentralise the analytics for small-scale, tactical decisions onto the machinery that is carrying out the tasks; examples might include determining whether a weed is worth killing, or the automatic drafting of livestock into different paddocks. What this will mean for the overall process of decision-making, and the extent to which automation can work with copies of centrally-maintained algorithms versus the extent to which local machine learning will need to take place, is as yet unknown.

Technical challenges to successful adoption of decision support in Australia

Historically, gaining widespread adoption of decision support tools has been a difficult task. This phenomenon – the 'problem of implementation' – is not limited to Australia (Rose *et al.* 2016) nor to agriculture (McCown 2002b). As a result, successful decision support systems in Australia have generated significant industry benefit through relatively small user bases, often by leveraging the networks of influential actors such as agricultural advisors. For example, Yield Prophet® has been

applied to just under 1000 paddocks across the country since 2002. A notable exception is the CottAssist suite of tools, which by 2019 appears to have generated almost 100% uptake over a 10-year period.

Technical challenges for decision support developers include:

- High fixed costs of development caused by diverse populations of potential users – especially with respect to their objectives in farming, the difficulties in accessing and re-using publically-held data, and the lack of consistent interfaces to on-farm data records;
- Limited context-specificity despite this being critical to landholders, caused by the coarse spatial resolution of public environmental data (especially soils and weather) compared with other OECD countries and, once again, the lack of ready links to on-farm data;
- High climatic variability compared with most other developed countries, resulting in a need to communicate probabilistic information in many contexts; and
- Need for high-quality user interfaces because potential users are time-poor and because much of the useful information that decision support can provide is complicated. Digital literacy and confidence amongst would be users is also a challenge that needs to be met (at least in some way) by developers. Surveys by Zhang *et al.* (2017) and Dufty and Jackson (2018) reported approximately one-third of farmers identified a lack of skills as a constraint on their uptake of new ICT tools.

Decision support in ag-tech: the rise of ‘platforms’

The perception of commercial opportunities in digital agriculture has resulted in an explosion of platforms on the market. Rather than starting from computer models and interfaces designed by agricultural scientists and targeted at particular decisions, these new platforms are based on ideas and models that have been successful in other digital industries.

Despite all being marketed as platforms, new software tools are actually highly diverse, reflecting different views of where the opportunities (both real and perceived) lie in the rural sector. At least four broad types of platform are emerging in the North American, and to a lesser extent in the Australian, rural industries:

- Aggregated views of information: these tools are similar in purpose to traditional monitoring/diagnosis tools, but present a decision-maker with multiple data streams (*e.g.* presenting current weather and forecasts, soil moisture and commodity prices side-by-side). These applications provide situational awareness and are analogous to the use of ‘dashboards’ to provide synthesised management information in government and industry. The weakness of these products is their inability to integrate information in an analytical sense.
- Mobile apps: are based on simple, easy-to-use interfaces and are targeted at very particular problems (*i.e.* they are a new way of delivering analysis of options for highly structured tasks). They are often linked with other technology such as drone-mounted or in-field sensors. Examples include the NSW Drought Feed Calculator® and the The Yield™ app for irrigation in horticulture. These tools exploit the ubiquity of smartphones and the well-developed ecosystem to market and deploy apps. The major impediment to using them in Australia is broadband coverage. A 2016-17 ABARES survey of 2,200 Australian broadacre, dairy and vegetable farmers confirmed that the overwhelming majority (96%) owned and used ICT assets as part of their farm business, ostensibly in support of decision making, and 95% were connected to the internet (Dufty and Jackson 2018). This is consistent with the survey conducted by Zhang *et al.* (2017) that identified 94% of 1000 producers surveyed had an internet connection for their business with the largest proportion (55%) relying upon the mobile phone network, and 30% of respondents rely upon landline, ostensibly ADSL/ADSL2+ for internet connectivity. The ubiquity of smart phones and tablets has likewise seen a veritable explosion in the number of decision supporting ‘apps’ available to producers; with listings for producers provided by numerous peak bodies and advisory groups (*e.g.* Roberts 2012; Ag Excellence Alliance 2014). Roberts (2012) provides a listing of 88 ‘useful’ apps and 2 years later The South Australian Ag Excellence Alliance

(www.agex.org.au) released the second edition of “Smart Phone Apps for Smart Farmers” which describes 414 apps.

- Federated analysis platforms: are based on gaining access to data from multiple enterprises and using it to learn to predict, or to benchmark, commercially important quantities such as prices of inputs, commodities, or yields. The resulting analytics can, in principle, be used for any of the purposes described above. These applications mimic the classic ‘big data’ model where the flow of data permits continuous improvement of the analytics. In Europe and the US, their success is critically dependent on the availability of publicly-curated soils and weather information. Variants of such platforms can also provide privileged access to suppliers and markets; in these cases, the platform can mimic the CostCo™ business model in which membership provides access to improved buying power.
- ‘Pure’ platforms: these are platforms in the narrow sense; their purpose is to provide software infrastructure through which multiple third parties can transact business, exchange data and access digital and professional services. They typically include cloud-based storage, standard data formats and access control; access is on a subscription basis. Platforms are powerful tools and if successful can become dominant players. There are preliminary indications that major software companies are developing pure platforms for agriculture often translated from application in a different sector.

We note that some applications contain elements from more than one pattern, and that a given company’s business model may evolve from one mode to another. For example, the Climate Corporation’s FieldView product is a federated analysis platform, but Climate appears to be evolving toward delivering a pure platform.

What might a desirable future for decision support look like?

Analytics and automation reinforce one another We envisage a future where small decisions are automated, freeing decision-makers to focus on the bigger picture. Platforms like UAVs and terrestrial robots can both monitor and act in response to threats to a production system. Like self-steering vehicles in which the controlling software lies within the GNSS-enabled agriculture vehicle, the algorithms that classify disease and pest risks and take corrective actions can reside on the device – a device that can communicate and interact to enable automatic responses.

Value extracted from the full diversity of analytics One element of a desirable future is that the new machine-learning techniques find their full expression; another is the improvement of predictions made with more-traditional simulation approaches through the use of model-data fusion techniques. In both cases, effective means are required to collate information about on-farm activities and outcomes. Barriers to market entry of new analytic approaches – in particular barriers to accessing training data – should be as low as possible, to encourage participation by firms that are new to Australia or to agriculture.

Fixed costs of decision support development and deployment are lowered From the point of view of decision support developers – regardless of the ways their work is deployed – a desirable future includes a range of FAIR cross-sectoral data that are available on acceptable terms (The FAIR principles – Findable, Accessible, Interoperable, Reusable – are described in Wilkinson *et al.* (2016)).

In addition, it will be essential that certain widely-usable computations be available on a FAIR basis as well: examples include ‘harness’ software for carrying out model-data fusion to estimate current conditions on a piece of land, and methods to estimate and present the uncertainties in a prediction of future outcomes on that piece of land.

Sustained, targeted investment in analytic capabilities for Australian agriculture is an essential requirement to deliver the value of cross-sectoral data. For example, updating (model-independent) information about the changing plant and animal genotypes used here is likely to be necessary: the North American business model, where the genetics and the analytics are owned by the same

commercial entities, is unlikely to emerge in Australia in the medium term. A commitment to FAIR principles on the part of analytics providers should be a minimum pre-condition for public investment.

To exploit FAIR agricultural data and analytics at least cost, we envisage that they will need to be made available as services that are accessed across the Internet (the ‘everything as a service’ approach). This will require investment by custodians to devise and implement interfaces to the necessary services; this process is already well advanced in the soil information space, and to some extent for remote-sensing data.

In a service-oriented environment, the process of acquiring the pieces of a software tool becomes much simpler, but assuring the quality of the software package becomes more complex. In our desirable future there will be one or more “staging services” available to tool developers; these services will simplify handling the technical aspects of trust, especially access control (*i.e.* who can use this information or computation?) and provenance (*i.e.* where did these numbers come from?).

Better and different analytics reach decision-makers If the current limitations to data access and re-use can be overcome, we see a wide range of opportunities to improve (or supersede) existing decision support software. Table 1 provides examples of these possibilities.

Table 1. Some possible future decision support software in a world with improved management of rural data and analytics

	IMPROVEMENTS TO EXISTING TOOLS	NEW KINDS OF TOOLS
Monitoring and diagnosis	<ul style="list-style-type: none"> Higher resolution, more-frequent, maps of crop/forage/tree using metrics that are better suited to diagnosing specific problems and opportunities 	<ul style="list-style-type: none"> Production/financial benchmarking services that are based on wider panels of properties, take local context into account and are available closer to real time Simple crop development monitoring for diverse horticultural crops that includes medium-term forecasts Product traceability systems that integrate with on-farm management activities/data
Analysis of options in highly structured tasks	<ul style="list-style-type: none"> Forecast-based husbandry decision support (<i>e.g.</i> <i>Yield Prophet</i> or <i>AskBill</i>) predict with reduced uncertainties, resulting in increased confidence in decisions, powered by reduced need for manual inputs by users 	<ul style="list-style-type: none"> Variable-rate planning for fertiliser and water inputs that balances farmer objectives and constraints against conditions sensed at small scales ‘Intelligent assistants’ for one-off decisions that are based on textual knowledge-bases as well as numeric data
Provision of prescriptions	<ul style="list-style-type: none"> Automatic feeding of livestock based on their day’s intake as well as currently-monitored attributes such as yield potential 	<ul style="list-style-type: none"> Entry of North American ‘prescription agriculture’ providers to Australia not limited by data supply
Use in consulting		<ul style="list-style-type: none"> Annual land use allocation decisions on cropping and mixed farms supported by provision of multiple information streams
Regulatory compliance		<ul style="list-style-type: none"> Access to EU markets or to price premiums supported through monitoring and interpretation of farm-scale environmental conditions

In addition, we believe that as the fixed costs of developing decision tools fall, landholders themselves will be able to take advantage of the services we describe above to develop their own analytics tools. Examples might include being able to send crop-monitor data to a consultant without a second thought; building specific data streams or analytic modules into business-specific dashboards; using public weather and soil data when analysing on-farm experiments; or reducing the costs of carrying out on-farm experiments as part of a local collective.

Data requirements for digital agriculture

Soil information Unlike the US and some European countries (where publically available sub-farm scale soil maps have been produced), Australia has not had a long-term and detailed soil survey program. Some broad-scale and consistent mapping is available in some jurisdictions and soil information (and streams of soil data) is now available from farm and agribusiness based on proximal and remote sensing technologies. A major step forward was achieved in 2015 with the release of the Soil and Landscape Grid of Australia (Grundy *et al.* 2015).

Changes in the structure of private actors in the agricultural advisory system, increased soil-information capacity in agribusiness and increased capacity on-farm to collect and monitor soil status is now providing new opportunities in soil-information supply and demand in the private sector. For example, there is potential for locally based soil data marketplaces; especially if the data streams available from farm machinery, soil sensors and appropriately interpreted proximal and remote sensing are included. Here we envisage local and intense soil information available on-farm or across farm communities being used by a wide range of actors.

Weather and climate The official and co-operative weather observation networks of the Bureau of Meteorology (herein the Bureau) provide a wide range of real-time data feeds from across Australia, contributing to more than one billion observations processed by the Bureau forecast models every day. The network has varying levels of quality and maintenance regimes, tailored for various purposes, which are captured in the metadata for every record. Beyond the official Bureau network of weather stations there are many private weather stations and networks collecting data. Techniques are now being designed to add these third-party networks to the Bureau suite to both improve the national modelled observations and to take existing weather forecasts and records and calibrate them to the paddock of interest where sufficient weather records are available.

Gridded products of historical weather have been developed to study climate trends throughout Australia. To obtain a grid of historical weather information, point observations are used and then varying techniques such as interpolations or dynamic models can be used to ‘fill in the gaps’.

Any forecast product is generated by considering the relationships between known observations over time, and uses physics to project those relationships into the future. Operational weather forecasting is provided by the Bureau, which also enables third parties to develop and maintain forecast services. To create its official forecasts, the Bureau combines runs from a suite of models, weighted according to recent and historical performance, to create a consensus forecast twice per day.

For many operational decisions, including crop choice and input management, forecasts are needed for the next six months at a local scale. One way to do this is to generate statistical outlook models using past climate records. Analogue years are chosen from the past according to larger climate states such as El Nino Southern Oscillation (ENSO). In recent years dynamical seasonal climate models are becoming skilful enough to be used in agricultural decision making (Rodriguez *et al.* 2018). These models are run at a lower spatial resolution and provide predictions for up to nine months ahead (see Chapter 25). Unlike weather forecasts, however, they provide a probabilistic picture of the future that must be interpreted accordingly. We are now at a cross roads in the statistical vs dynamical model approaches for climate forecasting in agriculture. Both methods have their advantages and are increasingly being combined to provide indications of the unfolding seasonal climate.

Remote sensing The primary uses of remote sensing (RS) imagery in agriculture have been in the detection and mapping of classes of land cover of interest (and their changes over time) and the

measurement of ‘greenness’ – with accompanying estimates of foliage cover and Leaf Area Index. To date, this information has been at a coarse spatial resolution, typically using indices such as the normalised difference vegetation index (the ratio between near infrared and red reflectance). Landsat is the oldest Earth observing mission and has an extensive history of use in agriculture. It started in the 1970s, but came into widespread use around 1982, and is still operating. Landsat has been the imagery of choice because of its application at paddock and sub-paddock scales, the historical record dating from the early 1980s, and its 16-day frequency. Blending activities are becoming more common where Landsat is being combined with Sentinel-2 and the temporal detail of MODIS (two overpasses per day).

New and increasing numbers of RS sensors and platforms are becoming available, most importantly those from the national space agencies (government), the private sector, particularly the miniaturised satellites and sensors (mounted on aeroplanes, drones or UAVs). This new-generation of satellite sensors is providing both high spatial resolution and high repeat frequencies, making it feasible to detect changes in time at paddock and sub-paddock-scales. Many useful applications in agriculture of hyperspectral or radar imagery have been demonstrated, but the low repeat frequencies, coarse spatial resolutions, and/or limited geographical coverage have historically limited their use. This is changing; *e.g.* the European Sentinel-1 satellite includes a synthetic aperture radar sensor and has a revisit time and coverage useful for agriculture and particularly suitable for regions with high cloud cover. Such spatial resolution and revisit frequency does not on its own resolve the issue of local specificity of many of the derived data products, and the need for broad scale transferability remains.

The trend towards increasing numbers of sensors and platforms with higher spatial, temporal and spectral resolutions will result in increasing data volumes. This will pose challenges for the flow, storage and processing of massive volumes of spatial data, in order for it to be useful and timely for farm operations. Several initiatives are providing users with large amounts of remotely sensed imagery ready to be used in analyses. Private providers are changing from business models where they sell imagery to one, to where they provide access to a cloud platform where the user can apply standard processing algorithms or even develop their own. The future will involve an increase in bespoke satellite missions that have specific foci, using constellations of micro-satellites that are cheap, and provide full and rapid coverage for a narrow and specific set of observations.

Farm management data Data on farm operations, crop yields, soil tests, and machinery and staff performance and workflows are collected directly by farmers in a diverse array of manual, semi-automated and automated means. Data reside in a variety of analogue and digital formats, thus limiting analytics and use in decision support tools. Contemporary farm management software has a focus on land use planning, task scheduling, allocating and monitoring, and basic performance recording. Rarely is dynamic information such as weather, soil moisture, machinery performance or crop development stage integrated, and even if it is, the associated analytics are rudimentary.

Being able to link such on-farm dynamic information with relevant public data sources (*e.g.* soils, climate, and remote sensing imagery) will enable more sophisticated analytics and notifications for tactical intervention. At a more strategic level, the ability for farmers to conduct ‘natural experiments’ using machine learning on historical farm information to arrive at optimised management regimes for each paddock and season based on *their* data rather than an abstraction of such in a decision tool is an exciting prospect.

In a response to big agribusiness developing ‘pure’ platforms in the US (see above) there is the emergence of the notion of data aggregation by groups of farmers to maintain control of farmer-derived data, while unlocking greater analytical power. There is also the prospect of creating a data asset that could be monetised, although this has yet to be widely validated in the market.

Telecommunications

Discussion of digital agriculture with the farming community inevitably involves the issue of telecommunications, both on- and off-farm. This includes the dimensions of connectivity from the farm gate to the outside world, but also connectivity within the boundaries; namely from sensors and

technologies deployed across the farm land to a point where it can be taken to the outside world. A survey of farms and farmers by Lamb *et al.* (2017) revealed that farms vary widely in terms of meeting the needs of its deployed data generating technologies, its physical communications environment (topography and land systems, access to external connectivity), the requirements for on- or off-farm data analysis, the particular management platform that the data are interacting with, and the ways the information is provided back to the farm management team for decision making and how it is used. Historically (> 5 years ago) this could have been attributable to a lack of widespread, well understood, 'standard solutions' in the market place. This has changed with the emergence of experienced providers of 'end-to-end' telecommunications solutions for farmers and on-farm devices and link technologies conforming to accepted, established industry standards.

The role of telecommunications in supporting a digital agriculture future is not necessarily technology constrained; if a farm has access to the mobile network somewhere on the farm, or National Broadband Network into the farm house then there is technology available to beam it to where it is needed. Entirely new, innovative, methods of extending connectivity over remote regions are in the R&D pipeline. Others have been around for some time and overlooked. At the same time there has been a significant increase in the development of end-to-end telecommunications technologies and services offered to producers. So-called 'second-tier' telecommunications providers offer their own transmission backhaul capability and in some cases associated cloud-based services. Second-tier providers will help extend the value and potential of existing telecommunication networks.

There are several possible communications pathways to and from remotely connectible devices on farm and these are largely dictated by the volume of data to be communicated, the speed it is to be transmitted, and also whether it is necessary to transmit the data live or whether some form of latency is acceptable. This applies equally to whether data are being sent to a remote device (*e.g.* for the purposes of actioning a command such as releasing a gate or door latch in a shed, switching on heaters, lights or pumps and panning and zooming a remote camera) or whether data are being sent back from a device such as a weather station, remote camera, or a plethora of other plant, soil, water, environmental, animal or asset sensors.

In summary, while limited and patchy telecommunications coverage is a 'hot button' issue for farmers with respect to digital agriculture, many innovations are becoming available that can be matched to the range of 'use cases' on farm. This will continue to evolve at the same time as the public telecommunications network improves coverage.

Farmer-centric imperatives to maximise the value from digital agriculture systems

Here we posit eight imperatives we believe should be borne in mind by those designing and marketing digital agriculture solutions for farmers. These imperatives are informed by theories of technology adoption in agriculture (*e.g.* Rogers 2003) and reinforced by our many interactions with farmers who are implementing digital systems on their farms.

1. Make it easy for me to collect the data

Digital agriculture solutions are based on collecting data. Farmers are time poor and juggle competing demands. They prioritise the most important tasks and will not go to great lengths to collect data unless highly valuable. If information can be automated or collected while conducting another (routine) task then this increases the likelihood of use by farmers. One example is collecting crop yield maps while harvesting, made easy by yield monitors being factory-fitted to harvesters.

2. Too much information can confuse and does not clarify

Digital systems have enormous power to generate high volumes of data. This comes at the risk of overwhelming the decision maker with too much information. Hayman (2004) noted that relationship between more information and improved decision making is not proportional; there is a critical amount of information which is helpful, after which more information can become unnecessary or confusing.

3. I do not need high frequency precise data for every decision

The attraction of digital technologies is that they provide the opportunity to collect information at high spatial resolution and high frequency. For example, many commercially available soil water sensors can log soil water status in intervals of minutes; grain monitors and satellites can record yield and plant biomass to tens of square metres; and GNSS collars on livestock can locate individuals to within a few metres. High frequency/precision information is useful to farmers if it matches the decision time frame or can be aggregated to a scale matching the decision requirement and if management levers can be deployed to similar level of precision. Where information is too frequent and does not match the management decision, it is likely to be under-utilised or at worst, confuse the decision-making.

4. Minimise the steps between data collection and providing me with some knowledge I can use

The fewer the steps in processing between data collection and decision-making the more adoptable will be the digital technology. As the number of steps increases between data acquisition and task execution the complicated nature of the task increases. The number of ancillary variables required to make a confident decision also increases, particularly when converting information to knowledge. Uncertainty increases as the influence of climate, market, logistical or regulatory conditions increase. The corollary is that adoption will be limited in more complicated cases, or where the enabling technology is difficult to access, learn, operate or extract information from. Many of the digital solutions currently in the marketplace require multiple steps between data collection and actionable knowledge.

5. An extrapolation or a forecast helps me more than just a sensor measurement.

A follow-on imperative to 4. is that it is tempting to assume that output from sensors and subsequent analytics provides all that a decision-maker needs. However, most sensor output, no matter how elegantly summarised, needs extrapolation or a forecast that goes beyond the bounds of the data. One of the most useful ways to turn sensed data streams into actionable information is through extrapolation and forecasting. Data collected at sparse points in time or space may require interpolation to fill the gaps, or extrapolation to completely different circumstances such as a soil type, season or management regime. In the face of uncertain climate or market conditions, a forecast of possible scenarios can help evaluate the consequences of various courses of action based on current information. An example is the value added to a soil water measurement by using a weather forecast with a soil water balance model to predict how long that water will last before the next anticipated rain/irrigation, and the associated consequences for plant growth.

6. Help me test and improve my own heuristics, not replace them

Farmers apply deep knowledge formed through experience in the form of heuristics (or rules) to decisions. Farmers use their experience to build a mental construct that allows them to predict what might happen next and react accordingly. The most effective learning-based approaches to improve farmer practice are based on innovative and participatory adult learning methods that build on farmers' heuristics. These involve guided practical field-based investigations through which land users learn for themselves how to address challenges through observation, testing and monitoring of different treatments. Digital technology can assist this learning process by reducing the costs to farmers of knowing what is going on in their fields. Through timely updates of the system status they can adapt to uncertain conditions in a flexible manner.

Because farmers have their own mental constructs of how they think their system 'works', the 'objective' information coming from various sensors is often filtered through a range of subjective factors. These sit within a wider set of socio-cultural influences, including family and rural values, local industry norms and expectations and the behaviour of neighbours.

7. Sensors and analytics are unlikely to tell me everything I need to make a decision

The promotion of the benefits of digital agriculture often comes from an industrial perspective, informed by process control thinking. In industrial settings, the role of a system manager's intuition, beliefs, risk attitude and valuation of competing benefits is less prominent than on a farm. One mistake made by vendors of digital solutions for farmers is the stereotyping of the farmer as a technician, and the farming community as a market for technical-based recommendations. Rather, as McCown (2001) has pointed out, the farm is a socio-ecological system where there is complex interplay between a

‘management’ system and a ‘production’ system with psychosocial and cultural factors at play. An emerging opportunity is to capitalise on the growing use of social media by farmers to canvas views and seek input from fellow farmers on decisions and issues. Such content, when analysed and meshed with ‘hard’ data from decision tools, internet searches and the like could provide a powerful source of farmer-validated information to support decisions.

8. *Connectivity is important, but not for every decision*

A major barrier cited for the widespread use of digital technologies on farms is the lack of broadband connectivity in the field. Voice connectivity is rated as the highest reason for farmers wanting farm-wide connectivity. The second most cited is ‘watch and respond’ whereby farmers can monitor (say from the house, tractor or livestock yards) in order to respond in a timely and appropriate way. The need for comprehensive connectivity needs to be critiqued in terms of the likely use cases for digital systems in the field. For example, connectivity will be important if data need to be processed, analysed and provided in an executable format for tactical decisions ‘on the spot’. However, there are many applications where data can be captured and then processed, analysed and modelled later, when there is a reliable connection to the internet. The advent of cheap and low powered communications systems that provide broad coverage, such as LoRaWAN™ are seen by many farmers as an acceptable communications solution for sensor networks.

Conclusion – looking ahead

Farming will be increasingly data-driven. This will be fuelled by advances in weather and climate forecasts, more dynamic and timely information on the state of soils and crops, and linkages with farm management software to improve operational efficiency, safety and transparency. Large volumes of data will be able to be generated by cheap, ubiquitous sensors. This raises concerns about whether the quality of such data will be out-weighted by the sheer volume of data being generated.

Biggest strides will be made in the short term by improving the quality and accessibility of foundational datasets such as weather and climate, soils and topography, and remote sensed imagery. Further into the future, coupling these data with a growing stream of private data, much of it farmer-derived, will stimulate services from a wider range of providers, and maybe even ‘DIY analytics’. Routine tasks will be automated, and data and analytics bought to bear on more complex decisions.

Greater ubiquity, automation and accessibility of decision tools means they are likely to reach a far greater audience. Digital tools will touch a wider range of actors who interact with, and service, farmers – agronomists, farm consultants, banks, insurers, marketers, input suppliers, bulk handlers, and consumers. Data will have multiple applications and potentially multiplied value when aggregated with others’ data. We envisage digital systems enabling farmers to respond to increasing pressures and opportunities for regulatory compliance, product provenance and best management practice.

Digital agriculture is in the middle of a heightened ‘hype’ phase. Lessons need to be heeded in the history of adoption/dis-adoption of decision support tools. Home-grown rather than imported solutions are likely to succeed in the market due to Australia’s unique farming environment and socio-cultural context. Farmers will insist on being enabled to learn and refine the management of their farms using their data, rather than being presented with prescriptions generated by closed loop data-technology systems.

References

- Ag Excellence Alliance (2014) “Smart Phone Apps for Smart Farmers V2”. (Ag Excellence Alliance Incorporated). <https://data.environment.sa.gov.au/Content/Publications/Smartphone-Apps-for-Smart-Farmers.pdf> . 229 pages. Accessed 11 Dec 2018
- Atzori I, Iera A, Morabito G (2010) The Internet of Things: a survey. *Computer Networks* **54**, 2787-2805
- Cotton Research and Development Corporation and CSIRO (2015). CottAssist – decision tools for cotton management. <https://www.cottassist.com.au>

- Donnelly JR, Moore AD, Freer M (1997) GRAZPLAN: decision support systems for Australian grazing enterprises. I. Overview of the GRAZPLAN project, and a description of the MetAccess and LambAlive DSS. *Agricultural Systems* **54**, 57-76
- Duffy, N, Jackson, T (2018) "Information and communication technology use in Australian agriculture", ABARES research report 18.15, Canberra, November.
<http://www.agriculture.gov.au/SiteCollectionDocuments/abares/ict-use-australian-agriculture.pdf>. Accessed 11 December 2018
- Freer M, AD Moore, JR Donnelly (1997) GRAZPLAN: Decision support systems for Australian grazing enterprises – II. The animal biology model for feed intake, production and reproduction and the GrazFeed DSS. *Agricultural Systems* **54**, 77-126
- Freeman M, Robson M, Lilburne L *et al.* (2016) Using OVERSEER in regulation – technical resources and guidance for the appropriate and consistent use of OVERSEER by regional councils, August 2016. Report prepared by Freeman Environmental Ltd for the OVERSEER Guidance Project Board. Available at: www.overseer.org.nz
- Grundy MJ, Viscarra Rossel RA, Searle RD *et al.* (2015) Soil and landscape grid of Australia. *Soil Research* **53**, 835-844
- Hayman P (2004) Decision support systems in Australian dryland farming: A promising past, a disappointing present and uncertain future. *Proceedings 4th International Crop Science Congress*, Brisbane, Australia, 2004 – crops.cscience.org.au
- Hearn AB, Bange MP (2002) SIRATAC and CottonLOGIC: persevering with DSSs in the Australian cotton industry. *Agricultural Systems* **74**, 27-56
- Herrmann NI, Zurcher EJ (2011) Designing decision support systems for factorial analyses. *Proceedings 19th International Congress on Modelling and Simulation*. Perth, Australia, 12-16 December 2011. (Eds F Chan, D Marinova, RS Anderssen) pp. 1209-1215
- Hochman Z, van Rees H, Carberry PS *et al.* (2009) Re-inventing model-based decision support with Australian dryland farmers. 4. Yield Prophet® helps farmers monitor and manage crops in a variable climate. *Crop and Pasture Science* **60**, 1057-1070
- Holzworth DP, Huth NI, deVoil PG *et al.* (2014) APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* **62**: 327-350
- Koch A (2017) IoT in agriculture – how it is evolving and which policy areas need addressing to facilitate its uptake. *Farm Institute Insights* **14** 1(1), February 2017
- Lamb D (2017) 'Accelerating precision agriculture to decision agriculture: the needs and drivers for the present and future of digital agriculture in Australia. A review of on-farm telecommunication challenges and opportunities in supporting a digital agriculture future for Australia'. Report for the Rural R&D for Profit 'Precision to Decision' (P2D) project
- McCown R L (2001) Learning to bridge the gap between science-based decision support and the practice of farming: Evolution in paradigms of model-based research and intervention from design to dialogue. *Australian Journal of Agricultural Research* **52**, 549-571
- McCown RL (2002b) Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. *Agricultural Systems* **74**, 179-220
- Moore AD, Donnelly JR, Freer M (1997) GRAZPLAN: decision support systems for Australian grazing enterprises. III. Pasture growth and soil moisture submodels, and the GrassGro DSS. *Agricultural Systems* **55**, 535-582
- Richards QD, Bange MP, Johnston SB (2008) HydroLOGIC: An irrigation management system for Australian cotton. *Agricultural Systems* **98**, 40-49
- Roberts, K. (2012). "Useful apps for Australian agriculture – iPhone and iPad" (NSW Department of Primary Industries/Department of Trade and Investment, Regional Infrastructure and Services)
<https://murrumbidgeelandcare.org.au/files/Useful%20apps%20for%20Australian%20agriculture-%20iPhone%20and%20iPad.pdf>. Accessed 12 Dec 2018
- Robertson MJ, Llewellyn RS, Mandel R *et al.* (2012) Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. *Precision Agriculture* **13**, 181-199
- Robertson MJ, Rebetzke GJ, Norton RM (2015) Assessing the place and role of crop simulation modelling in Australia. *Crop and Pasture Science* **66**, 877-893
- Rodriguez D, de Voil P, Hudson D *et al.* (2018) Predicting optimum crop designs using crop models and seasonal climate forecasts. *Scientific Reports* **8**, Article number: 2231
- Rogers E (2003) 'Diffusion of Innovations', 5th edn (Free Press, New York, NY)
- Rose DC, Sutherland WJ, Parker C *et al.* (2016) Decision support tools for agriculture: towards effective design and delivery. *Agricultural Systems* **149**, 165-174

- Wheeler DM, Ledgard SF, Monaghan RM *et al.* (2006) Overseer® nutrient budget model — what it is, what it does. In ‘Implementing sustainable nutrient management strategies in agriculture.’ Fertilizer and Lime Research Centre Occasional Report no. 19 (Eds. LD Currie, JA Hanly) pp 231-36 (Massey University: Palmerston North)
- Wilkinson MD, Dumontier M, Aalbersberg G *et al.* (2016) The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data* volume 3, Article number: 160018, DOI: 10.1038/sdata.2016.18
- Wolfert S, Ge L, Verdouw C, Bogaardt MJ (2017). Big data in smart farming – a review. *Agricultural Systems* **153**, 69-80
- Zhang A, Baker I, Jakku E, Llewellyn R (2017) ‘Accelerating precision agriculture to decision agriculture: the needs and drivers for the present and future of digital agriculture in Australia. A cross-industry producer survey for the Rural R&D for Profit ‘Precision to Decision’ (P2D) project’. (CSIRO: Brisbane)

Chapter 25

Australian Agronomy in the Anthropocene: the challenges of climate

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Introduction

Climate has always been challenging to Australian agriculture; the low and erratic rainfall across much of the country combined with frost, heat events and untimely rainfall makes Australian farming risky and frames the work of agronomists conducting research and providing advice. Australia is the driest inhabited continent with one of the highest year-to-year variability in rainfall (CSIRO and BoM 2015). Australian farmers face a higher degree of production volatility than farmers in any other OECD country and most of this is due to climate (Kimura and Anton 2011). Compared with other OECD countries they have equal highest price volatility and relatively low levels of direct and indirect income support from government (Kimura and Anton 2011). Within Australia, agriculture is more than 2.5 times more volatile than the average of all industries and significantly more volatile than the next ranking industries of insurance and construction, which were 1.5 times the average of all industries (Keogh *et al.* 2011). As pointed out by Malcolm (1994) and Mudge (2009), this variability in climate presents both opportunity and risk. Much of the success of Australian agronomy has been to manage the variability through finding ways to capture more out of seasonal rainfall and use all available water more efficiently (Kirkegaard and Hunt 2010).

Given the importance of climate to Australian agriculture, Connor (1992) expressed surprise that there was no Australian university department or CSIRO division of agrometeorology or agroclimatology. The widespread drought of 1982 coincided with an El Nino event yet there was very little recognition of this link in the agricultural research community. Much of the early applications of modern climate science to farming systems was undertaken by Queensland agricultural researchers in the mid to late 1980s. This work was presented and summarised at a symposium on Climatic Risk in Crop Production held in Brisbane in 1990 (Muchow and Bellamy 1991). CSIRO and the then Queensland Department of Primary Industries formed the Agricultural Production Systems Research Unit in 1991, which had a specific mandate to develop approaches and tools for better climate risk management. Other state departments of agriculture also formed small climate applications groups through the 1990s. Ongoing links between climate science and agricultural science were strengthened and coordinated by the ‘Managing Climate Variability Program’ which started in 1992 and continues. Hammer *et al.* (2000) provide a good summary of the work during the 1990s. An important legacy of this work has been the strong demand pull for information from agronomy, which contrasts with a supply push from climate science in some other parts of the world.

The invitation to contribute this chapter is an example of the increasing emphasis on climate over the last 30 years. The term climate is not listed in the index or any chapter titles in Cornish and Pratley (1987). This was not so much because climate was overlooked or ignored; rather it played a role that was implicit not explicit. Climate-driven processes of erosion and water productivity underpin many of the developments in tillage in Australia, including concepts adapted from other dryland regions, especially the USA (Pratley and Rowell 1987, Fischer 1987). Problems such as excessive tillage during fallows or dust mulching were attempts to deal with erratic and low rainfall. The benefits of stubble retention were largely due to the more efficient storage and use of water and hence ways to manage climate variability (Felton *et al.* 1987, Fisher 1987). Another implicit use of climate was the distinction in tillage practices for crop production between regions with winter and summer rainfall.

In this chapter we argue that over the last three decades, the notion of climate for Australian agronomy has dealt with three broad concepts:

- climate as a static description of a farming region (*e.g.* Mediterranean, subtropical);
- climate variability associated with climate drivers at different time scales such as El Nino Southern Oscillation (ENSO, interannual) and the Madden Julian Oscillation (MJO; intraseasonal); and finally,
- human induced climate change.

These concepts or phases are overlapping and build on each other. The last phase of human induced climate change leads to a range of new challenges for agronomists such as gaining appropriate confidence in climate trends and projections, researching the impacts of changes to temperature, rainfall and carbon dioxide on agricultural systems and identifying the challenges and opportunities to reduce greenhouse gas emissions and sequester carbon. Beyond these practical challenges there is the sobering realisation of the scale and pace that human activity (including agriculture) has had on the planet. In short, agronomists, along with society at large, must come to terms with operating in the Anthropocene.

Agronomists in the Anthropocene

The notion of the Anthropocene is not without controversy. Some geologists see it as a buzzword and remain unconvinced that there has been sufficient evidence of a change in rock strata. Other commentators argue the term is too broad because it covers humanity across time and space when much of the impact and benefit relates to a restricted group of OECD countries since 1950 (Hamilton 2015, Finney and Edwards 2016). A common transition from the Holocene to Anthropocene coincides with the invention of the steam engine in 1784 (Crutzen and Stefan 2003) and the consequent burning of fossil fuels. Others point to the emergence of agriculture 10,000 years ago, which enabled the growth in populations and civilisations (see Lewis and Maslin 2015 for review). A further link between agriculture and the Anthropocene is the hypothesis that carbon dioxide released from clearing forests 8000 years ago and methane from rice irrigation 5000 years ago prevented the next ice age (Ruddiman 2003). A recent example of the Anthropocene is the deposition in New Zealand glaciers of dust from Australian farming (Marx *et al.* 2014).

Fundamental to the concept of the Anthropocene is the ‘Great Acceleration’ since 1950 associated with an exponential increase in population, global prosperity, resource use and changes in natural processes (Stephan *et al.* 2015). Hamilton (2015) argues that using starting points other than 1950 tends to distract from the time and scale of human impact. He cites Stephan *et al.* 2015 “...*Only beyond the mid-20th century is there clear evidence for fundamental shifts in the state and functioning of the Earth System that are beyond the range of the Holocene and driven by human activities*”. This recent time frame is relevant to modern Australian agronomy. The three decades considered by this book (1990 to present) have seen accelerating change which has coincided with causes for both optimism and pessimism about human progress (Pinker 2018 as example of optimism, and Goldin 2018 for review). Modern agronomy is part of the ‘Great Acceleration’ and benefited through advances in germplasm, herbicides, fertilisers, crop protection, satellites, computers and machinery. The productivity gains from agriculture have been a fundamental, if under-recognised, driving force for the Great Acceleration by freeing up resources for other fields of technology and wealth generation (Harari 2011, Meinke *et al.* 2017).

Demand for food and fibre from a growing and more prosperous population requires enormous improvements in production with headwinds of a more hostile climate and other stresses on the earth system (*e.g.* disturbed hydrology, pollution, loss of biodiversity: Rockstrom and Karlberg 2010, Fischer and Connor 2018). Accepting that we are in the Anthropocene is important to this chapter because it distinguishes between the comfortable and accepted notion of climate variability and the less comfortable notion of human induced climate change. While this gives agency to agricultural practitioners, it also assigns responsibility for their actions to the sector. This fundamentally changes the way we view the cause and effect relationships between climate and agricultural production. Clarity on the cause of climate change not only provides confidence in the underlying trends but also points to the challenge for agriculture to reduce emissions and seek opportunities to sequester carbon.

Agronomists may have an advantage in coming to terms with the Anthropocene and human agency when compared with related disciplines such as plant biology, genetics, ecology, geology and

meteorology. These natural science disciplines tend to emphasise a distinction between the natural and human world which has been blurred by the Anthropocene (Cook and Rickards 2017). This human-nature divide has always been blurred by agronomy. Agronomists start with the treatment of agriculture as a human activity and approach landscapes as managed ecosystems. In recent decades agronomists have been encouraged to think more about agriculture as a human activity with increased emphasis on the social and psychological aspects of technology and decision making. The three overlapping concepts of climate addressed below can be seen as increasing levels of human agency. If climate is treated as static, the primary role of humans is to adjust and learn to live with it. Climate variability came with an emphasis on management that identified ways that some Australian farmers worked with the variability to their advantage. The third phase of climate change comes with human agency in adapting to local impacts and mitigating global climate change. Incorporating historical climate information, seasonal climate forecasts and climate change projections into risk assessment and risk management all serve to further, and appropriately, blur the divide between humans and nature.

Climate as a static characteristic of a region

The notion of climate as a static characteristic of a region is captured in Connor's (1992) keynote address to the 1st Australian National Conference on Agro-meteorology where he argued that climate might be of interest to agriculture (averages that characterised a location) but not very relevant to farmers who were mostly interested in weather (deviations from the average that persisted for days or weeks). This argument is valid and backed by farmer interest in weather apps and forecasts. However, this distinction attributes temporal variability and change to weather and restricts climate to spatial variability between regions ignoring year to year and decade to decade temporal variability.

Characterising and comparing average climates is a sensible first step. An early example was Nix (1975) who divided arable land in Australia into five major agroecosystems:

- humid tropics and subtropics (along the Queensland coast);
- semi-arid tropics and subtropics with summer rainfall (far northern Australia), arid (interior);
- subtropical with summer and winter rainfall (Queensland and northern NSW grains belt); and
- temperate with winter dominant rainfall (grains belt of southern NSW, Victoria, Tasmania, South Australia and Western Australia).

More recent classifications include agro-climatic zones (Williams *et al.* 2002, Hutchinson *et al.* 2005) or agro-ecoregions (Padbury *et al.* 2002).

These agro-climatic zones are useful to distinguish farming systems, identify appropriate agronomy and guide the boundaries of cropping activity. Summer rainfall in Queensland and northern NSW allow for both winter and summer cropping whereas the temperate zone is mainly restricted to winter cropping. At most points in the Australian grains belt there is also a transect running from a high rainfall zone bound by topography through medium to low rainfall. The inner edge of the Australian grains belt is a transition zone between cropping and extensive grazing. This margin has attracted a high level of interest, especially in South Australia where, during a severe drought in 1863-1866, the then Surveyor-General George Goyder established a line marking areas of reliable and unreliable annual rainfall. This line became to be understood as the line beyond which cropping was too risky (Meinig 1961, Sheldrake 2005, Nidumolu *et al.* 2011).

Australia is fortunate to have excellent spatial and temporal coverage of climate records, especially rainfall. Yet, in 1863 Goyder had limited rainfall records (the SA colony was only formed 27 years earlier, in 1836). As pointed out by McCown *et al.* (2002), it is a gross underutilisation of the rich data set to take just the average and describe a region as a 400 mm or 600 mm annual rainfall. Maunder (1989) maintained that, although the emphasis on 'average' climate and treating climate as constant was at odds with experience, it was convenient for planning. He argued it was the Sahel drought of the 1970s that prompted the use of the climate archive for planning and risk assessment. The failure of zonation schemes to account for inter-annual variability was noted by Parry and Carter (1988). Similarly, Hutchinson *et al.* (1992) acknowledged that their classification system using pattern analysis

based on long-term mean monthly data could be misleading as locations with similar plant growth response patterns based on long-term mean data can have very different probabilities of cropping success.

This static view of climate was not only held by agriculture. Until relatively recently, meteorological services around the world viewed climate as average weather or ‘meteorological book-keeping’. McGregor (2006) maintained that a system’s view of the earth’s climate, backed up by more ready access to computing power, enabled climate to develop as a scientific study of the dynamics of water and energy fluxes and, in doing so, shift away from classification and regional descriptions of weather. Viewing the climate as a system acts to reverse the idea of climate as ‘average weather’ and sees weather as a sampling process of the envelope provided by climate (McGregor 2006).

Parry and Carter’s (1988) critique of agro-climate zonation systems was deeper than the fact that they ignored variability. They were also critical of the many climate impact studies that dominated the literature until the mid-1970s that treated agriculture as a passive exposure unit. They called for a systems approach, which emphasised the ability of agriculture to interact with, and adapt to, a variable climate. In Australia the early discussion on variability and its management was focussed on drought. Perhaps as an overstatement, Anderson (1979) despaired that “...*the majority of Australian farmers seem to subscribe to the view that rainfall variability, in particular rainfall deficiency, is merely an unfortunate occasional abnormality of the environment; and that, when drought does occur, government assistance will aid survival*”. There are some that still hold that view.

The 1990s National Drought Policy entailed a major re-evaluation of how Australians perceive climate variability and the respective roles of farmers, governments and providers of RD&E in dealing with climate variability. In essence, government shed the responsibility for managing climate variability and handed it to farmers who were expected to be more self-reliant. Government funded providers of RD&E assisted the exchange of responsibility by improving farmers’ risk management through better access to historical climate data, climate forecasting, and the development of decision tools (Kerrin and Botterill 2006). The transfer of risk from government to farmers has been patchy and generated ongoing arguments (Hughes *et al.* 2017). Meinke *et al.* (2019) provide a succinct review of the Australian experience of managing drought, including some of the key risk management tools such as seasonal climate forecasts and agricultural simulation models. They also provide an historical context on how policies have evolved and were developed that shaped the self-reliance of Australian rural businesses.

Managing climate variability

Notwithstanding the complex history of drought policy, Australian agriculture prides itself on an ability to deal with the variable climate. European farming in Australia had to cope with what must have seemed extreme variability. (London and Sydney have approximately the same annual average rainfall; the difference is the variability). As pointed out by Nicholls (1994), the settlement was greeted by an El Nino drought three years after settlement. Captain Arthur Phillip reported in 1791 that “...*so little rain has fallen that most of the runs of water in the different parts of the harbour have been dried up for several months and the run which supplies this settlement is greatly reduced. I do not think it is probable that so dry a season often occurs*”. Nicholls has traced drought as a recurring theme through history. He points out that the late 1800s, in both America and Australia, was a time of rural optimism based partly on the belief that rain followed the plough. In 1881, the official yearbook attributed the run of good seasons to the settlement of the interior stating with confidence that “...*droughts are no longer the terror they used to be*”.

This optimism was ill-founded. In 1888, as the centennial celebrations commenced, the worst drought yet seen in the Colonies began. Henry Lawson wrote in the Bulletin of December 1888 “...*Beaten back in sad dejection/After years of weary toil/On the burning hot selection/where the drought has gorged his spoil*”. In December 1888, H.C. Russell, the New South Wales Astronomer, predicted that drought would break in January 1889. This prediction was based on his observation that previous droughts broke in late summer. He was right. There were widespread floods in the early part of 1889. In his “History of Australia”, Manning Clark commented on the breaking of the 1888 drought that “...*another dry year*”.

was over; there was to be another green year in Australia. Men were to again believe they would find profit from all their labour under the sun". Again the optimism was short-lived. A few years later a drought commenced that did not reach the intensity of the 1888 drought – but it lasted a decade. Despite the steady reduction in the relative importance of agriculture during the 20th century, droughts continue to receive extensive media coverage. Two centuries later, in 1994, an El Niño event again led to grain imports. In 2003, following the 2002 El Niño, grain was shipped from Britain to Brisbane and in 2018 it was only biosecurity considerations that stopped grain imports (Heard 2018).

High variability makes farming difficult, but what is the impact for agronomy? Apart from the obvious point that the wellbeing of farmers and those servicing farmers are linked, climate variability presents a particular suite of challenges for agronomists. Core activities of interpreting field experiments and providing advice for farmers are tasks that would be easier, or at least significantly different, if the climate was less erratic. Making sense from field trials in a variable climate is made even more difficult by the shift over recent decades away from longer term experiments at research stations toward various forms of short term, on-farm research. Although there are many advantages in developing relevant science with end users, one of the trade-offs that has not received as much discussion has been between a higher degree of spatial representation and a lower degree of temporal representation. The difficulty of separating out signal from noise in a variable climate is well documented in agricultural science in Australia. Some examples are as follows:

- Wockner and Freebairn (1991) measured runoff and erosion for 14 years (1976-1990) on the eastern Darling Downs. They found that 70% of the 556 t/ha of soil loss from a bare fallow wheat-system occurred in only six storms.
- Clewett *et al.* (1995) used the simulation model GRASSMAN to show decadal shifts in optimum stocking rates in central Queensland ranging from 10 to 30 head of cattle per 100 ha, concluding that such variation made learning from graziers' own, or even their parents' experience, problematic.
- McCaskill and Blair (1988) noted the bias of the 1950s, 60s and 70s in experimental work, extension programs and data for models on superphosphate and stocking rates in the northern tablelands of NSW. Across most of eastern Australia this was a wetter period. They recommended the climatic conditions prevalent between 1900 and 1949 should be taken into account when assessing management options.
- Chapman (2007) used crop simulation modelling combined with long-term rainfall records to index the climatic environment at a particular location. This allowed the construction of datasets that adequately quantify gene by trait by environment interaction in terms of their key statistical attributes (*e.g.* means, variances and correlations). This approach reduced the 'biological and experimental noise' and allowed for cultivar selection based on an assessment of the upcoming season. It also adds value to traditional plant breeding trials by reducing the environmental noise previously regarded as an inevitable consequence of location-based trials.
- Hochman *et al.* (2017) analysed trends between 1990 and 2015 at 50 sites across the Australian grains belt in: rainfall decline, maximum temperature (0.04 degrees/year) and water limited simulated yield. As noted by other authors (Hunt and Kirkegaard 2010, Fischer *et al.* 2014) this decline can be explained by the Millennium Drought (2002-2009). This last study raises important questions about disentangling drought from drying or drought from an increase in aridity.

Forecasting the climate

Cornish and Pratley (1987, p420) referred to wind erosion from the 1982-3 drought followed by water erosion in 1984. Like almost all agricultural scientists at the time, they made no reference to the fact that 1982 was a strong El Nino and 1984 a La Nina. The three decades being considered by this chapter have seen a growing understanding within the agricultural community that droughts and floods are not just random but influenced by climate drivers such as El Nino and Southern Oscillation (Meinke and Stone 2005, Risbey *et al.* 2006). Subsequent studies have shown that most of the major land degradation events in eastern Australia can be attributed to ENSO cycles (McKeon *et al.* 2004).

Official seasonal climate forecasts, based largely on the ENSO cycle were first available to Australian farmers in the late 1980s. This was a long wait; Charles Todd, a contemporary of Goyder in the colony of South Australia observed in 1893 “...the importance to the farmer, the horticulturalist, and pastoralist of knowing beforehand the probabilities of dry or wet seasons, and whether the rains will be early or late, or both, has naturally led to a desire for seasonal forecasts, they have them it is said in India, why not Australia.” About a century later the eminent agronomist Reg French (1987) urged the study of the variability of weather patterns “...One of the biggest deficiencies in agricultural research is the inability to both predict the probability of rainfall during the growing season and to estimate the yield and economic returns of different crops”.

Climate varies on all timescales and at each timescale the variability can be partitioned into:

- a predictable portion;
- a portion that is likely to be predictable in the near future; and
- a residual, irreducible uncertainty.

Up until 2013, seasonal outlooks in Australia were based on statistical relationships between sea surface temperatures or the southern oscillation index. Since 2013 the Bureau of Meteorology has used dynamic models which are similar to numeric weather models but run at a coarser spatial scale with a daily rather than hourly time step. Another important distinction from statistical models is that dynamic models include adjustments to the radiative properties of the atmosphere from the enhanced greenhouse effect (Baume *et al.* 2015).

Climate change

In 1987, the same year that *Tillage* was published, the Greenhouse 87 conference was held. The first set of climate change projections for Australia were released (high confidence in warming, lower confidence in rainfall, but concerns about winter rainfall in southern part of the continent). Since that time projections have been released by CSIRO in 1990, 1991, 1992, 1996 and 2001, 2007 and 2015 (Whetton *et al.* 2016). Attention to climate change was limited until the Millennium drought 2002-2009 ending with extensive bushfires in February 2009. This coincided with international and national debate on human induced climate change (Hansen 2010).

Current projections for Australia are available at the Climate Change in Australia website (www.climatechangeinaustralia.gov.au/en/). The Australian Climate Futures web tool sorts the projections for a region from all available climate models by two variables; annual mean temperature and rainfall. This provides a matrix of climate futures such as ‘warmer and wetter’ or ‘hotter and much drier’ and the number of models in different futures. The user can change the representative emission pathway and time period to see how this changes. It is envisaged that future emission runs will be able to repopulate the matrix. This allows adaptation planning to proceed with different climate futures rather than always waiting for the publication of the next set of climate model runs (CSIRO and BoM 2015).

There is a higher level of confidence from climate science in the trends and projections in temperature than rainfall. Table 1 lists six aspects of climate change and summarises the confidence from climate science in the projections and the confidence in agricultural science on the impacts. For example the confidence in the rainfall projections is low but the impacts on agricultural systems of any changes to rainfall are well understood. The interaction between these 6 aspects of climate change is important but uncertain. For example elevated carbon dioxide is likely to partially offset some of the impacts of a decline in rainfall, but it is less clear how a drier but carbon dioxide enriched future will respond to a heat wave.

Table 1. Six aspects of climate change showing; confidence in trends and projections from climate science, confidence from agricultural science on impacts and a summary of management options.

1. Elevated levels of carbon dioxide	
Confidence from climate science	Very High for next 10 years; future emissions depend on policy and technology.
Confidence on impacts from agricultural science	High for growth and yield of crops but lower for longer term cropping systems (soil C and N) and grain quality components <i>e.g.</i> protein and its various end use requirements. The growth rate of weeds, pests and disease will also change with elevated CO ₂ .
Management options	In the future there is likely to be deliberate selection of species (C3 vs C4) and varieties that respond more positively to elevated CO ₂ . Monitoring of changes to pests, weeds and disease and revising nutrition will be essential.
2. Increased mean temperature	
Confidence from climate science	Very high Inland regions are expected to warm faster than coastal regions due to less water and hence an increase in sensible heat. The greatest trends in warming across most of the grains belt have been in spring, this may be due to the decrease in spring rainfall associated with the Millennium drought (2002-2009).
Confidence on Impacts from agricultural science	High confidence that rate of crop development will increase. Growth rates will increase in cooler months and regions (<i>e.g.</i> winter in Tasmania). Increased evaporation and more challenging conditions for emergence.
Management options	Understanding of crop phenology can be used to grow slower maturing varieties. Opportunities for expansion of irrigated summer crops <i>e.g.</i> cotton. Stubble retention to reduce evaporation. Long coleoptile wheat varieties.
3. Increased extreme hot temperatures	
Confidence from climate science	High confidence that in a warmer world the weather patterns that bring heat to the grains belt will result in more intense heat waves. Lower confidence in how the weather patterns that set up the hot spells will change.
Confidence on Impacts from agricultural science	Moderate understanding of the impact of heat on different phenological stages and thresholds for different field. Impacts are modified by soil moisture and or irrigation. Relatively poorly represented in simulation models despite recent advances.
Management options	Optimising flowering time for winter crops. Selecting crops and varieties that can tolerate high heat loads through genetic selection.
4. Changes to frost frequency and intensity	
Confidence from climate science	Low – a perceived paradox that, despite warming, the frequency and intensity of frost has increased in some regions. This may be simply due to dry springs or other drivers related to synoptic patterns.
Confidence on impact from agricultural science	Moderate to low – although impact of extreme frost at critical times can be obvious, the exact link between minimum temperature recorded in the Stevenson screen and damage to crops is noisy. Frost damage is poorly represented in simulation models.
Management options	Using the variation between winter crops minor variation in wheat varieties. The use of hay production and switching to livestock in
5. Changes in seasonal rainfall	
Confidence from climate science	Moderate confidence in drying in southern winter growing season. Lower confidence for other seasons and the rest of the Australian grains belt.
Confidence on impacts from agricultural science	Very high – there are extensive studies that provide a good basis for understanding water productivity of major crops and pasture.
Management options	More effective storage of water prior to the growing season, then using the water efficiently by matching sowing time and cultivar to the environment. The impact of dry autumns can be partially offset by sowing part of the cropping program into dry soil.
6. Changes in the intensity of rainfall	
Confidence from climate science	High – a warmer atmosphere contains more energy and will hold more water. This leads to intensification of the hydrological cycle, increasing variability further. Lower confidence in changes to weather systems that bring high or low intensity of rainfall.
Confidence on impacts	High for changes to daily intensity. In regions of numerous low intensity falls, an increase in intensity will improve efficiency of soil water gains. Most contemporary simulation models are not set up to handle sub-daily changes in intensity
Management options	Stubble retention and other erosion management especially on sloping sites.

Perhaps the clearest indication that agronomists are working in the Anthropocene is the need to consider the change in carbon dioxide concentration. The effects of elevated CO₂ depend on the interactions between all other climate variables (*e.g.* temperature, humidity, rainfall, solar radiation). New experimental work at Horsham since 2007 ('Free-Air Carbon dioxide Enrichment', FACE) has shown positive and negative effects of elevated atmospheric CO₂ concentrations on field crops (wheat, field pea, lentil, canola and barley). In these experiments the ambient CO₂ concentrations was elevated from approximately present-day levels of 400 $\mu\text{mol/mol}$ to 550 $\mu\text{mol/mol}$, the level expected by 2050 (Figure 1, Mollah *et al.* 2009).

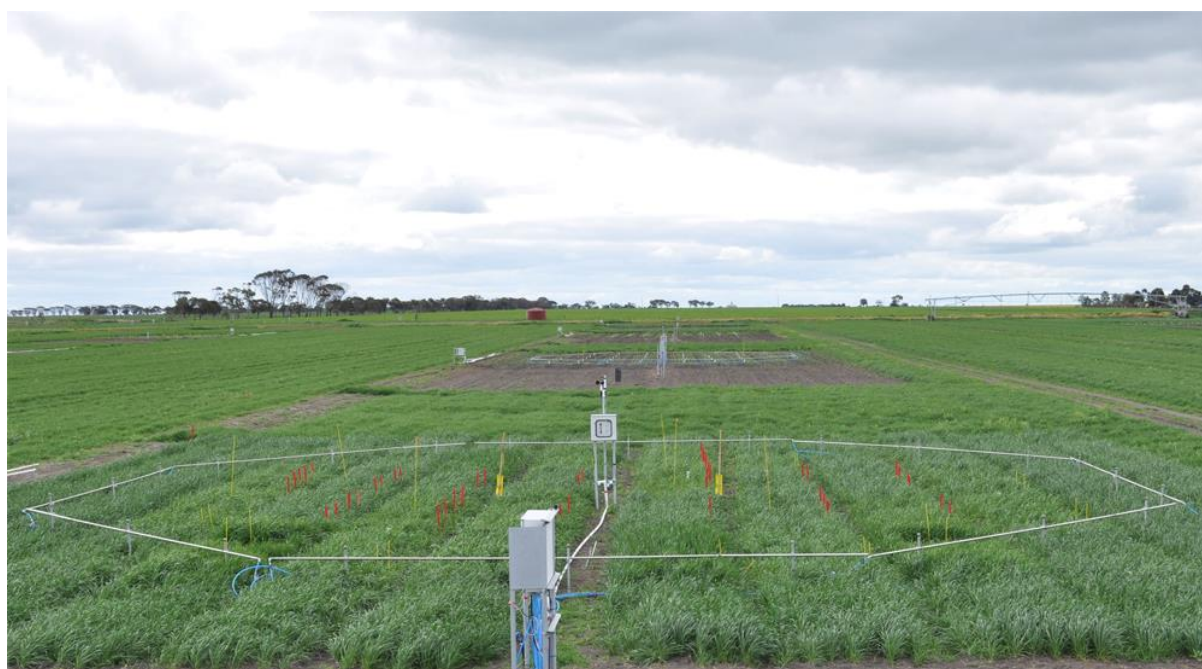


Figure 1. Ambient CO₂ concentrations was elevated in the field from approximately present-day levels of 400 $\mu\text{mol/mol}$ to 550 $\mu\text{mol/mol}$ by 'Free-Air Carbon dioxide Enrichment' (FACE) technology in octagonal rings where CO₂ gas was emitted upwind and computer controlled by atmospheric and wind sensors (Mollah *et al.* 2009, photo courtesy of Rob Norton)

On the positive side, crop biomass, leaf area and yield of many winter crops (wheat, canola, field pea and lentil) all increased about 10-25% from elevated CO₂. Seasonal water use was not greatly affected – crops are nearly always short of water at Horsham resulting in greater water use efficiency. Surprisingly, the quality (protein and baking parameters) of wheat grain was uncontrollably reduced (~6%) by elevated CO₂. More fertiliser does not help and we need more research to find adapted germplasm and management to maintain and increase quality parameters (Fernando *et al.* 2014, Panozzo *et al.* 2014, Walker *et al.* 2017).

The Horsham FACE experiment, however, does not reflect the nominal climate in 2050 because it did not raise the temperature or apply drought in line with 2050 climate projections. It did however, sow some crops late in the first 3 years of the experiments to emulate a hotter environment during maturity. This provided some explanatory account of the interacting effects of elevated CO₂ but not entirely with some large unexplained responses under unstressed conditions (O'Leary *et al.* 2015, Fitzgerald *et al.* 2016). Models that account for known effects of CO₂, temperature and water supplies show more subdued response to elevated CO₂ nationally, but there is optimism that adaptation towards more thermally tolerant crops that do not greatly accelerate development with heating will reduce the potential negative impacts that threaten yields, particularly in southern Australia (Figure 2, Wang *et al.* 2018).

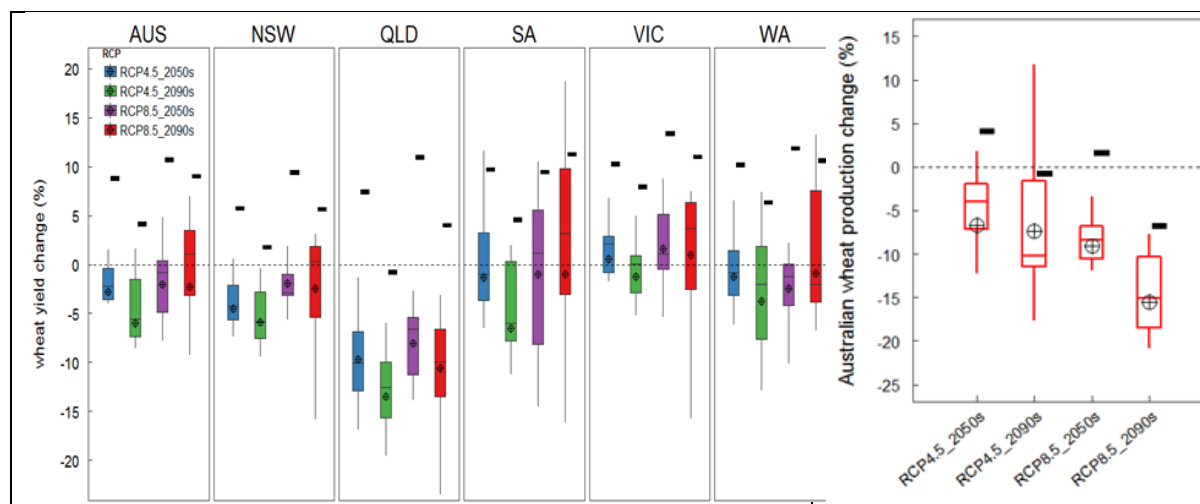


Figure 2. Simulated expected change in wheat yield under various RCP climate change scenarios for each Australian State from Wang *et al.* (2018). An adaptive strategy of increasing heat tolerance without accelerating phenological development raises optimism for increased mean yields for most production regions (black rectangle, -)

As the climate changes, pests and disease can be expected to change in our agroecosystems. In the Horsham FACE experiment barley yellow dwarf virus was increased (over 10%) by elevated temperature (Nancarrow *et al.* 2014) and elevated CO₂ (Trębicki *et al.* 2015). This was brought about by changes in the aphid vector, the bird-cherry oat aphid (*Rhopalosiphum padi*).

The dominating control of climate and weather of our agricultural systems requires more than the classic systems approach – it can be done with a collaborative multi-disciplinary approach “...*provided everybody and every organization support a stronger scientific approach by collaboration beyond our traditional partners and borders*” (O’Leary *et al.* 2018). This is a challenge for the future generations to adapt to a new environment. We know more than earlier generations, so we should put that know-how to good work for everyone’s benefit. Agronomists have the advantage of systems knowledge and will play a key role in such integrated approaches to solve the almost intractable problem.

The role of the agronomist to assess and manage climate risk

Managing risk is an essential part of modern agronomy. In both agronomy research and advisory work there is an increasing request to be more than just cognisant of risk, or acknowledging that things do not always go as planned. An emphasis on business management involves explicitly addressing the trade-offs between risk and reward. Climate is a major source of production risk and agronomists are in a strong position to provide context for the advances in climate science.

The concepts of assessing and managing risk are closely linked to human agency. Bernstein (1996) notes that risk comes from the Italian ‘risicare’, to dare, and emphasises choice, opportunity and gain as much as fate and loss. He maintained risk was one of the key revolutionary ideas that defined the boundary between modernity and the past. The future is more than a whim of the gods, and rewards and risk for different ventures can be weighed, compared and factored into decision making.

Historical climate records underpin the management of climate risk and ready access to patched data sets of daily climate data has underpinned simulation modelling (Jeffries *et al.* 2001). Recent work has increased confidence with interpolation between data points (Bracho-Mujica *et al.* 2018). Tools providing easy access to rainfall records on personal computers such as Rainman (Clewett *et al.* 1995) and on mobile devices CliMate (Freebairn and McClymont 2013) have been used by agronomists in planning and to place the current season in historical context.

Initiating stakeholder engagement between agriculture and climate science is relatively easy because farmers like talking about the weather. It has proven more difficult to develop the conversation and foster links between local farmer knowledge, which is tacit, informal and context specific, and climate

science, which is quantitative, formalised and often expressed as probabilities (Hayman *et al.* 2007, Bruno Soares *et al.* 2018).

Risk assessment can be defined as a quantification of uncertainty. This distinction made by Knight (1921) defines a toss of a fair coin as risk, whereas a biased coin involves uncertainty. After experimenting with the biased coin, the uncertainty could be quantified as risk. As assumptions emerge of stationarity in climate, farmers and agronomists have to reassess whether simple assumptions of the past are the best guide for the future (Quiggen 2001, Howden *et al.* 2014). Similar arguments have been mounted for water managers who based their risk modelling on stationary time series (Milly *et al.* 2008). Cook *et al.* (2015), referring to geographers, indicated “...the Anthropocene presents a disconcerting possibility that, with humans ascending to the scale/scope of geologic forces, their knowledge base and methodologies will become obsolete or less applicable for prediction into some human shaped epoch”.

Concluding remarks

The Anthropocene not only has implications for the human-nature divide. It also accelerates changes in the science-society divide. As agronomists working on the interface between science (agricultural and climate) and farmers, there are new challenges and opportunities. Incomplete knowledge about the future represents opportunities for wider engagement; understanding the interactions of carbon dioxide is an example (O’Leary *et al.* 2018). This fits an increasing emphasis in climate risk on participatory and more equitable approaches (Bruno Soares 2018). Meinke (2019) differentiates between forecasting the *outcome* of management interventions and *foreseeing the likelihood and severity of opportunities and consequences* that might arise from a combination of climate, soil, plant, animal and human interactions. Predicting an outcome transfers all power to the person making the prediction (usually a scientist), while foreseeing likelihoods and consequences empowers actors to choose and actively create the desirable future they envision, while avoiding undesirable outcomes. Foresighting requires all stakeholders working together, using a common tool-kit. This gives agency to the managers, enabling them to draw in tacit as well as scientific knowledge as the basis for their deliberate decisions. This builds trust and a common understanding of what the future holds.

References

- Anderson JR (1979) Impacts of climatic variability in Australian agriculture: A review. *Review of Marketing and Agricultural Economics* **47**, 147-177
- Bauer P, Thorpe A, Brunet G (2015) The quiet revolution of numerical weather prediction. *Nature* **525** (7567), 47-55
- Bernstein PL (1996) “Against the Gods, The remarkable story of risk.” (John Wiley, New York)
- Bruno Soares M, Daly M, Dessai S (2018) Assessing the value of seasonal climate forecasts for decision-making. (Wiley Interdisciplinary Reviews) *Climate Change* **9** (4), e523
- Chapman SC (2007) Use of crop models to understand genotype by environment interactions for drought in real-world and simulated plant breeding trials. *Euphytica* **161**, 195-208
- Clewett JF, Kininmonth W, White BJ (1995) A framework for improving management of climatic risks and opportunities. “Sustaining the agricultural resource base” *12th meeting of Prime Minister’s Science and Engineering Council*, Canberra
- Connor DJ (1992) Climate and agriculture: Weather and farming. *Australian Conference on Agricultural Meteorology*. Melbourne, XV-XXII
- Cook BR, Rickards LA, Rutherford I (2015) Geographies of the Anthropocene. *Geographical Research* **53**, 231-243
- Cornish PS, Pratley JE (Eds.) (1987) “Tillage: New Directions in Australian Agriculture” (Inkata Press: Melbourne)
- Crutzen PJ, Steffen W (2003) How long have we been in the Anthropocene era? *Climatic Change* **61**(3), 251-257
- CSIRO and BoM (2015). “Climate Change in Australia Information for Australia’s Natural Resource Management Regions”. Technical Report. (CSIRO and Bureau of Meteorology: Australia)
- Felton W, Freebairn D, Fettell N, Thomas J (1987) Crop residue management. In (Eds. PS Cornish, JE Pratley) “Tillage: New Directions in Australian Agriculture” pp 171-193 (Inkata Press: Melbourne)
- Fernando N, Panozzo J, Tausz M *et al.* S (2014) Elevated CO₂ alters grain quality of two bread wheat cultivars grown under different environmental conditions. *Agriculture, Ecosystems and Environment* **185**, 24-33

- Finney SC, Edwards LE (2016) The “Anthropocene” epoch: Scientific decision or political statement? *GSA Today* **26**, 4-10
- Fischer R (1987) Responses of soil and crop water relations to tillage. In (Eds. PS Cornish, JE Pratley) “Tillage: new Directions in Australian Agriculture” pp 194-221 (Inkata Press: Melbourne)
- Fischer R, Connor D (2018) Issues for cropping and agricultural science in the next 20 years. *Field Crops Research* **222**, 121-142
- Fitzgerald GJ, Tausz M, O’Leary G *et al.* (2016) Elevated atmospheric [CO₂] can dramatically increase wheat yields in semi-arid environments and buffer against heat waves. *Global Change Biology* **22**, 2269-2284
- Freebairn D and McClymont D (2013) CliMate: A Smart phone app for farmers. www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2013/03/climate-a-smart-phone-app-for-farmers
- French RJ (1987) Adaptation and adjustments in drought prone areas: An overview South Australian study. In (Ed. DA Wilhite *et al.*) “Planning for Drought, Toward a Reduction of Societal Vulnerability” (Westview Press: Boulder Colorado)
- Goldin I (2018) The limitations of Steven Pinker’s optimism. *Nature* **554**, 420-422
- Hamilton C (2015) Getting the Anthropocene so wrong. *The Anthropocene Review* **2**, 102-107
- Hammer GL, Nicholls N, Mitchell CD (2000) “Applications of seasonal climate forecasting in agricultural and natural ecosystems. The Australian experience” (Springer: Netherlands)
- Hansen, J (2010) Obama’s second chance on the predominant moral issue of this century. The Huffington Post, 5 April www.huffingtonpost.com/dr-james-hansen/obamas-second-chance-on-c_b_525567.html
- Harari YN (2011) Histroy’s greatest fraud. In “Sapiens: A brief history of humankind” Chapter 5 (Random House: London)
- Hayman, PT, Crean J, Parton KA, Mullen JM (2007) How do seasonal climate forecasts compare to other innovations that farmers are encouraged to adopt *Australian Journal of Agricultural Research* **58**, 975-984
- Hochman, Z, Gobbett DL, Horan H (2017) Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology* **23**, 2071-2081
- Howden, M, Schroeter, SCrimp S, Hanigan I (2014) The changing roles of science in managing Australian droughts: An agricultural perspective. *Weather and Climate Extremes* **3**, 80-89
- Hughes, N Lawson K (2017) Climate adjusted productivity on Australian cropping farms. In (Eds. T Ancey, MA Samad Azad, F Hernandez-Sancho) “New Directions in Productivity Measurement and Efficiency Analysis: Counting the Environment and Natural Resources” p173 (Elgar:UK)
- Hutchinson MF, Nix HA, McMahon JP (1992) Climate constraints on cropping systems. In (Ed. CJ Pearson) “Field Crop Ecosystems” pp 37-58 (Elsevier: Amsterdam)
- Hutchinson MF, McIntyre S, Hobbs RJ *et al.* (2005) Integrating a global agro-climatic classification with bioregional boundaries in Australia. *Global Ecology and Biogeography* **14**, 197-212
- Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software* **16**, 309-330
- Keogh M, Granger R, Middleton S (2011) “Drought Pilot Review Panel: a review of the pilot of drought reform measures in Western Australia” (Commonwealth of Australia: Canberra)
- Kerrin J, Botterill LC (2013) Institutionalising the science-policy interface in Australia. In (Eds. LC Botterill, G Cockfield) “Drought, Risk Management, and Policy: Decision-Making Under Uncertainty” Chapter 5 (CRC Press:UK)
- Kimura S, Antón J (2011) “Risk Management in Agriculture in Australia” *OECD Food, Agriculture and Fisheries Working Papers, No. 39* (OECD Publishing) www.dx.doi.org/10.1787/5kgj0d8bj3d1-en
- Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- Knight FH (1921) “Risk, Uncertainty and Profit” (University of Chicago Press: Chicago)
- Lewis SL, Maslin MA (2015) “Defining the anthropocene.” *Nature* **519** (7542), 171
- Malcolm LR (1994). Managing farm risk: There may be less to it than is made of it. *Proceedings of Conference on Risk Management in Australian Agriculture* University of New England, Armidale
- Marx SK, McGowan HA, Kamber BS *et al.* (2014) Unprecedented wind erosion and perturbation of surface geochemistry marks the Anthropocene in Australia. *Journal of Geophysical Research: Earth Surface* **119**, 45-61
- Maunder WJ (1989) “The human impact of climate uncertainty: weather information, economic planning, and business management” (Routledge:UK)
- McCaskill MR, Blair G (1988) Medium-term climatic variation of the northern tablelands of N.S.W. *Mathematics and Computers in Simulation* **5**, 159-164
- McCown RL (2002) Changing systems for supporting farmers’ decisions: problems, paradigms, and prospects. *Agricultural Systems* **74**, 179-220

- McGregor GR (2006) Climatology: its scientific nature and scope. *International Journal of Climatology* **26**, 1-5
- McKeon GM, Hall WB, Henry BH *et al.* (2004) "Pasture degradation and recovery in Australia's rangelands. Learning from history" (Queensland Department of Natural Resources, Mines and Energy: Brisbane)
- Meinig DW (1961) Goyder's line of rainfall: The role of a geographic concept in South Australian land policy and agricultural settlement. *Agricultural History* **35**, 207-214
- Meinke H, Stone RC (2005) Seasonal and inter-annual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. *Climatic change* **70**, 221-253
- Meinke H, Bonney L, Evans K, Miles M (2017) Tasmania's Bioeconomy: Employing the Seven Capitals to Sustain Innovative and Entrepreneurial Agrifood Value Chains. In (Eds. S Dabbert, A Pyka, J Weiss, I Lewandowski) "Knowledge-Driven_Developments in the Bioeconomy" pp 117-139 (Springer: Switzerland)
- Meinke H, Rodriguez D, Salinger J, Nelson R (2019) Learnings from managing high climate variability: The Australian experience. *Proceedings of OECD Conference on Risk Valuation and Risk Management in the Agri-Food Sector*, Bratislava, Slovak Republic, 17 and 18 October 2018, in press
- Milly PCD, Betancourt J, Falkenmark M *et al.* (2008) Climate change: Stationarity is dead: Whither water management? *Science* **319**(5863), 573-574
- Mollah M, Norton R, Huzzey J (2009) Australian grains free-air carbon dioxide enrichment (AGFACE) facility: design and performance. *Crop and Pasture Science* **60**, 697-707
- Muchow RC, Bellamy JA (1991) "Climatic risk in crop production: models and management for the semiarid tropics and subtropics" (CAB international)
- Mudge B (2009) Managing risk in an uncertain climate. *Proceedings of 14th Australian Society of Agronomy Conference*, Adelaide www.agronomyaustraliaproceedings.org/images/sampled/2008/plenary/farming-uncertain-climate/6313_mudgeb.pdf
- Nancarrow N, Finlay K, Freeman A *et al.* (2014) The effect of elevated temperature on the titre of Barley yellow dwarf virus PAV in wheat cv. Yitpi. *Virus Research*, 166, 97-1-3
- Nicholls N. (2005) Climatic Outlooks: from revolutionary science to orthodoxy. In (Eds. T Sherratt, T Griffiths, L Robin) "A Change in the Weather" pp 18-29 (National Museum of Australia Press: Canberra)
- Nidumolu UB, Hayman PT, Howden SM, Alexander BM (2012) Re-evaluating the margin of the South Australian grain belt in a changing climate. *Climate Research* **51**, 249-260
- Nix H (1975) Australian climate and its effects on grain yield and quality. In (Eds. Lazenby A, Matheson, E) *Australian Field Crops* (Angus and Robertson: Sydney)
- O'Leary GJ, Aggarwal PK, Calderini DF *et al.* (2018) Challenges and responses to ongoing and projected climate change for dryland cereal production systems throughout the world. *Agronomy* **8**, 1-22
- O'Leary GJ, Christy B, Nuttall J *et al.* (2015) Response of wheat growth, grain yield and water use to elevated CO₂ under a Free Air CO₂ Enrichment (FACE) experiment and modelling in a semi-arid environment. *Global Change Biology* **21**, 2670-2686
- Padbury G, Waltman S, Caprio J *et al.* (2002) Agroecosystems and land resources of the northern Great Plains. *Agronomy Journal* **94**, 251-261
- Panozzo JF, Walker CK, Partington DL *et al.* GJ (2014) Elevated carbon dioxide changes grain protein concentration and composition and compromises baking quality. A FACE study. *Journal of Cereal Science* **60**, 461-470
- Parry ML, Carter TR (1988) The assessment of climatic variations on agriculture: A summary of results from studies in semi-arid regions. In (Eds. ML Parry, TR Carter, TJ Konijn) "The Impact of Climatic Variations on Agriculture" Volume 2: Assessments in Semi-arid Regions, pp9-60 (Kluwer: Dordrecht)
- Pinker S, (2018) "Enlightenment Now: The Case for Reason, Science, Humanism, and Progress" p47 (Viking)
- Pratley JE, Rowell DL (1987) From the First Fleet--evolution of Australian farming systems. In (Eds. PS Cornish, JE Pratley) "Tillage: New_Directions in Australian Agriculture" pp2-23 (Inkata: Melbourne).
- Quiggin J, Horowitz J (2001) "Costs of Adjustment to Climate Change" *Working Papers in Economics and Econometrics* No 415 (ANU; Canberra)
- Risbey JS, Pook MJ, McIntosh PC *et al.* (2009) On the remote drivers of rainfall variability in Australia. *Monthly Weather Review* **137**, 3233-3253
- Rockström J, Karlberg L (2010) The quadruple squeeze: Defining the safe operating space for freshwater use to achieve a triply green revolution in the Anthropocene. *Ambio* **39**, 257-265
- Ruddiman WF (2013) The anthropocene. *Annual Review of Earth and Planetary Sciences* **41**, 45-68
- Steffen W, Broadgate W, Deutsch L *et al.* (2015) The trajectory of the Anthropocene: the great acceleration. *The Anthropocene Review* **2**, 81-98
- Trebicki P, Nancarrow N, Cole E *et al.* (2015) Virus disease in wheat predicted to increase with a changing climate. *Global Change Biology* **21**, 3511-3519

- Walker C, Armstrong R, Panozzo J *et al.* (2017). Can nitrogen fertiliser maintain wheat (*Triticum aestivum*) grain protein concentration in an elevated CO₂ environment? *Soil Research* **55**, 518-523
- Wang B, Liu D.L, O’Leary GJ *et al.* (2018) Australian wheat production expected to decrease by the late 21st century. *Global Change Biology* **24**, 3403-2415
- Wheeler MC, Hendon HH, Cleland S *et al.* (2009) Impacts of the Madden-Julian oscillation on Australian rainfall and circulation. *Journal of Climate* **22**, 1482-1498
- Whetton PH, Grose MR, Hennessy KJ (2016) A short history of the future: Australian climate projections 1987-2015. *Climate Services* **2**, 1-14
- Williams J, Hook RA, Hamblin A (2002) “Agro-ecological regions of Australia: methodologies for their derivation and key issues in resource management” (CSIRO Land and Water:Canberra)
- Wockner G, Freebairn D (1991) Water balance and erosion study on the eastern Darling Downs-an update. *Australian Journal of Soil and Water Conservation* **4**, 41-47

Chapter 26

From conservation to automation in the search for sustainability

Jim Pratley and John Kirkegaard

Introduction

Barr and Cary (1992), in their book “Greening a Brown Land”, describe Australian agriculture as a “...200-year search for sustainable land use”. The problem with that notion, as they point out, is that sustainability is not fixed but evolves with time as community attitudes change – the goal posts are forever moving. This means that there is a constant need to innovate in order to meet emerging challenges and grasp opportunities – and this need never abates. However, unlike the Green Revolution of the 1960s and 1970s, when the focus was to bring know-how together for mass food production, the current paradigm has food production as the aim, but with a range of caveats such as minimising greenhouse gas emissions, protecting the environment, improving human health and meeting market demands such as low pesticide residues, acceptable breeding methods and traceability. At the same time there needs to be efficient, profitable and resilient farm businesses to provide continuity to the market and to ensure quality of life for farm families and employees. Sustainability thus has several components including financial (including productivity), environmental and social.

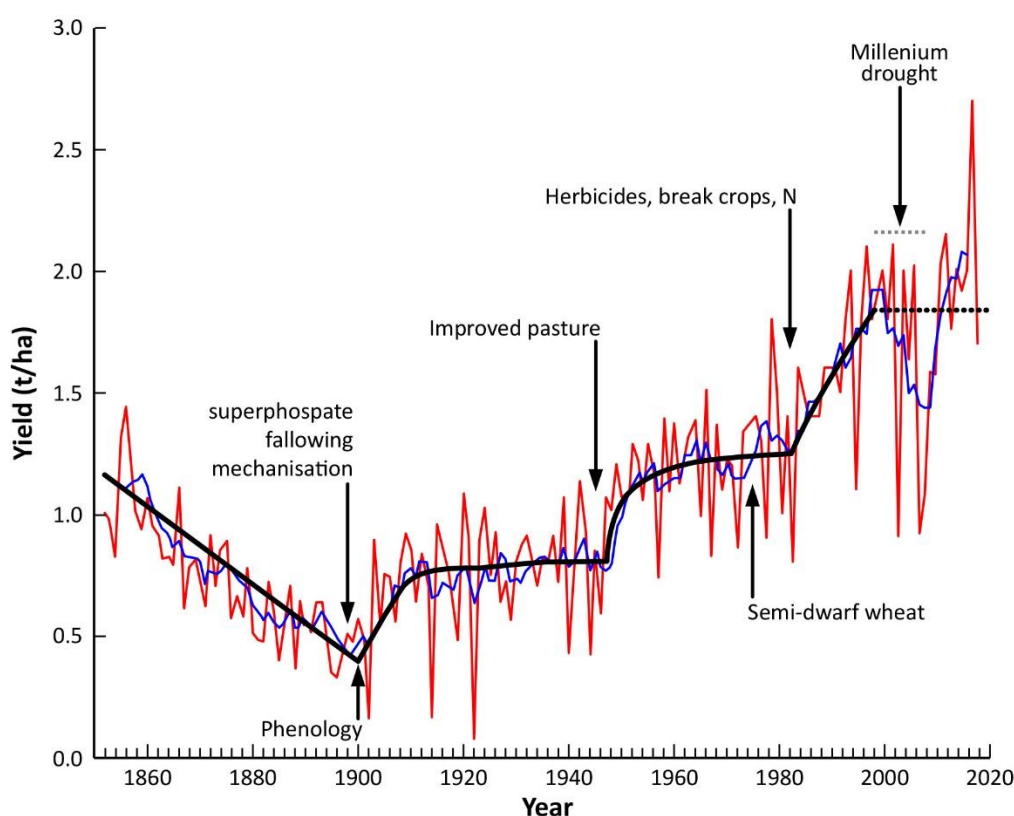


Figure 1. Growth in Australian wheat yields and technologies driving changes (updated from previous versions by Donald 1965, Angus 2001, Kirkegaard and Hunt 2010). Annual yield (red), 5-year running mean (blue), decadal trend (black)

This notion in respect of *productivity* is expressed in the oft-quoted, and here updated, Figure 1 describing the long-term trend in national wheat yields in Australia showing the key innovations and subsequent impact on productivity. The substantial increase from the 1990s largely represents the period

of innovation reported in this monograph and should be cause for some sense of achievement for Australian growers and agronomists. But the experience of the last 15-year period, where yields have seemingly plateaued against significant climate-induced volatility (Hochman *et al.* 2017), emphasises the need for ongoing innovation to close the existing exploitable yield gaps. There is optimism among agronomists and other agricultural scientists working with wheat that technological innovation will continue to close the gap. Such optimism is cautiously warranted (*e.g.* Fischer *et al.* 2014, Robertson *et al.* 2016) given the unprecedented challenges that have been addressed along the wheat yield trajectory in Figure 1 in the past (*i.e.* fertility decline, erosion, droughts, salinity). Notable in the broader diversification of agriculture beyond wheat has been the major developments and progress in other crops such as canola and cotton production over the past 30 years, underpinned by effective research and development. This monograph catalogues the substantial research effort in agronomy that has been undertaken over the past 30 years and emerging innovations, presented as a snapshot in Box 1.

Box 1 A snapshot of some of the current and future innovations and trends highlighted in this monograph

Technologies to deliver benefits through:

- virtual fencing, GPS collars for livestock to enable precise, spatial grazing management
- automation to enable operator to control smaller, multiple units reducing operation time and maximum flexibility
- communication between implements, tractor, human operator
- sensors identifying soil moisture with seeding depth adjustment, crop nitrogen status, precision fertiliser placement matched to crop demand, weed presence for precision removal

Farming increasingly data driven with gains made by:

- improved weather forecasting, remote sensing imagery, automated routine operations, digital management of compliance

Improved IPM outcomes through:

- non-chemical technologies, competitive crops and new herbicides for weed control
- ‘smart’ trapping, predictive modelling, in-field molecular diagnostics, improved varieties for insect control
- pre-plant testing, tolerant varieties, improved fungicide efficacy, perhaps microwave radiation for disease control

Agronomy increasingly privatised through;

- agronomic advice
- technical services such as IT, data analysis, technologies, decision support (DSS)
- greater emphasis on innovation rather than research *per se*

Management capability critical;

- to build flexibility and resilience into the farm business
- to address climate change uncertainties including minimising emissions
- to identify best combinations of GxExM
- to benefit from increasing digital agriculture; digital systems will enable producers to respond better to pressures of compliance, provenance and best management practice

In some cases, productivity improvement has been the result of refinement in the application of innovations occurring in much earlier decades. However, the sense of achievement, as Barr and Cary (1992) indicate, needs to be moderated as new challenges, both agronomic and non-agronomic, impact on the capability of crop producers to manage sustainable farm businesses. We have learnt that, as one challenge is met, others emerge and that is evident in the contributions in this publication.

Significant advances have been achieved in that time in our knowledge of the systems needed to be productive and environmentally sensitive in the Australian landscape. There has been a concurrent

revolution in machinery capability and technology that will provide opportunities for substantial benefits if employed appropriately. Such advances are largely within the control of the producer. But there are many influences, not in the scope of management, which add to the risk of agronomic practice and which should not be overlooked as sometimes they can assume substantial influence. We complete this monograph by reflecting on the some of the risks as we perceive them in the search for a sustainable agronomic future.

Risk and sustainability

Sustainable productivity and profitability

A moment of reflection on the productivity big picture is timely. Keogh (2012) considered the trend estimates of various sectors and industries in the Australian economy for the period 1975 to 2011 in terms of the variability in output (which he calls volatility). The data show agriculture to be the most volatile sector and around 2½ times that of the average of all sectors. Figure 1 suggests that in the years since then, volatility has increased, at least for our major crop wheat.

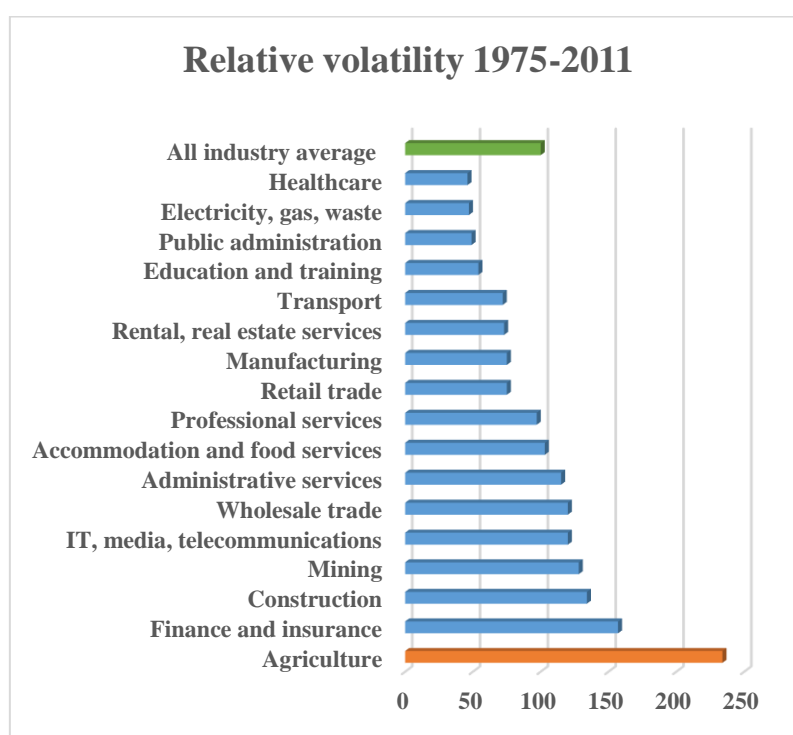


Figure 2. The relative volatility of annual Australian output for 17 sectors of the Australian economy from 1975 to 2011. A trend estimate of volatility was determined by a third order polynomial trend line, using least squares. The standard deviation of the percentage variation between trend and actual output was calculated and then indexed around the average, with average for all components set at an index value of 100 (Keogh 2012)

A closer analysis of agriculture's performance is shown in Figure 3 which demonstrates that volatility itself has varied significantly. It unsurprisingly points to rainfall incidence as a likely major influencer of variability – the period 1985-94 was a relatively wet period and coincided with the focus on water use efficiency as a measure of agronomic performance (French and Schulz 1984a, b, Cornish and Murray 1989). The other periods have had serious drought years and so production was compromised substantially on large parts of the cropping zone. The trend to more specialised cropping-only farms is also likely to have caused an increase in the volatility. What is clear from these data is that, overall, agronomy R&D and improved production on-farm have not made a discernible impact on the risk involved in growing grains, oilseeds and fibres. Climate change imposes another layer of complexity on the already complex operations of agronomy.

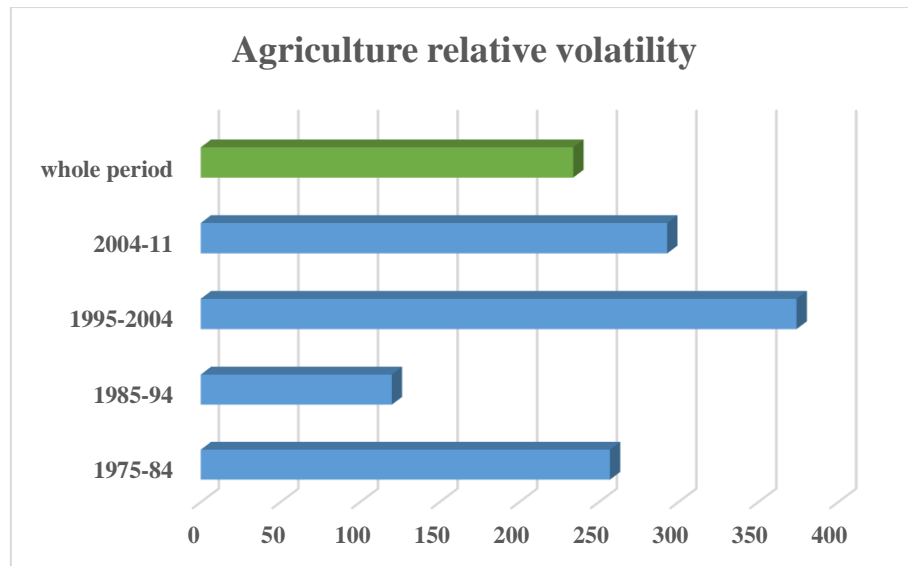


Figure 3. The relative volatility of annual Australian output of agriculture over the period 1975-2004, considered in 4 component periods. Overall average for all sectors is 100.

Another measure for context is the estimate of volatility for Australian crop farmers compared with those from other producing nations (Figure 4). Among 15 countries over a 38-year period, the Australian index for crop production was shown to be much higher than that for any other nation, was 24% greater than the next highest country, and more than double the average of all other countries considered.

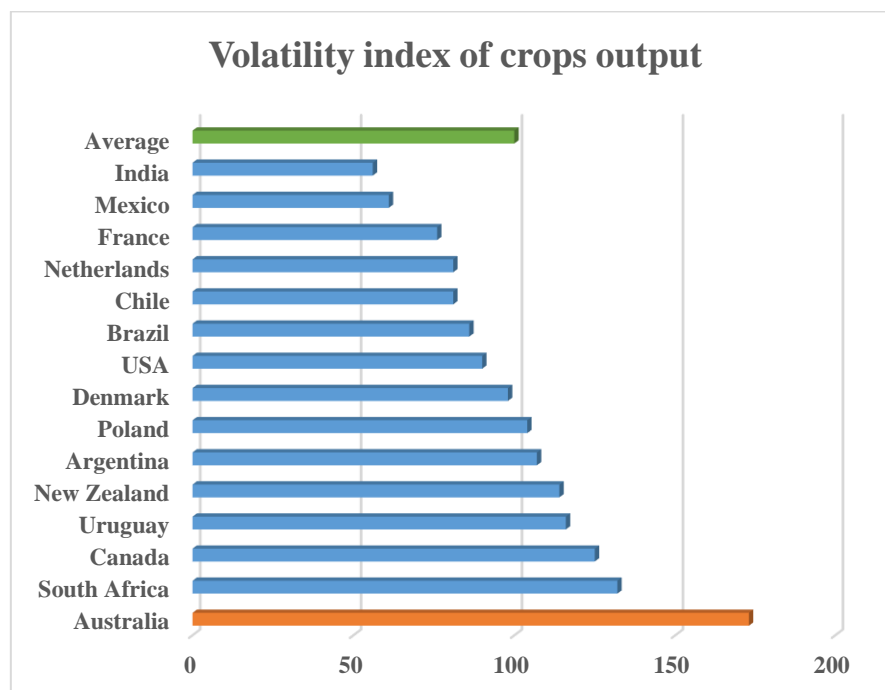


Figure 4. The volatility index of crops output for 15 nations across the period 1961 to 2009. Average volatility is 100 for the nations combined). Volatility estimates are determined as described in Figure 2 (Keogh 2012)

These data explain, as described by Keogh (2012), that Australian farmers, and particularly crop producers, operate in a more volatile business environment than farmers of other nations and other sectors in Australia. While the variability in output, in some cases, could be due to wise decisions not to plant in some seasons, other data suggest this is not a significant factor. Risk management would

seem to be a major priority for farm businesses and, accordingly, for the R&D that supports those businesses. There are many examples in the preceding chapters of research that addresses aspects of risk but clearly there is still much to do, especially given the climate predictions for more variability and extreme events. The moves towards sensor technology for improved spatial and temporal monitoring of soils, plants and weather, advances in plant biotechnology to deliver crops with resilient characters, and more reliable seasonal forecasts for better planning will help, as will better spatial data capability and insights from big data analytics.

Environmental sustainability

Much has also been achieved in the last 30 years in environmental management. As a continent which has the oldest soils and is the driest of the inhabited continents, Australia has had a shared but regrettable history (*i.e.* the first 150 years post-settlement) of soil erosion and soil degradation. The combination of poor soils, bare fallowing and excessive cultivation resulted in the dust bowls of the 1930s and again in the 1970s and early 1980s. Environmentalists rightly complained that agriculture was silting up waterways and was responsible for their eutrophication. The evolution of CA in its various forms has been a response to those challenges and has succeeded in reducing the incidence and severity of erosion events and, thereby, the siltation and eutrophication of the waterways. In the process much has been learnt about managing irrigation and dryland salinity, soil acidity and other environmental challenges.

The adoption of NT farming systems has enabled greater economic resilience in farm businesses. However, NT, as currently practised, is highly dependent on the input of synthetic chemicals which itself has brought new challenges both in agronomic and non-agronomic domains.

Social acceptability and political reality

Although agriculture has been an essential component of Australia's identity and provided quality food and fibre along with quality of life, the sector has been the target from time to time of activists undermining the confidence of communities that food is safe, the environment is well managed and animal welfare is protected (Lockie 2015). In some cases, this has compromised the financial prosperity of farm businesses and threatened the livelihoods of farm families and their communities. In some situations, the right to farm for individuals has been challenged, and the social licence for industries has been brought into question. In extreme cases recently, activists have entered properties and businesses, resulting in families feeling threatened and biosecurity of operations being placed at risk. There has been government response in legislation outlawing such action and imposing high penalties, although the impact of these responses is unclear and the movement remains active. Emerging trends in the perceptions and beliefs about food by the urban majority, often largely disconnected from an informed scientific debate about its production and safety, are unlikely to diminish. Defending sustainable practices and engaging more with customers in 'paddock to plate' or 'farm to fork' engagements will be crucial.

At another level there have been campaigns with the potential to derail critical aspects of conservation agriculture. Two are particularly relevant to agronomy, *viz.* the ongoing anti-GM movement and the more recent anti-glyphosate saga. Although there is a lack of scientific evidence to support either campaign, the use of social media, picked up by mainstream media, has created enough fear and distrust in the community that governments have responded in some cases by restricting the practice or use of these products. Some Australian States imposed moratoria for a time against the growing of GM crops and some international markets do not accept GM products. Likewise, some Australian local councils have stopped employees from using glyphosate, some countries have banned its use and others do not accept produce where glyphosate has been used in its production. Both campaigns, if successful, will have a devastating impact on the practice of CA. In some cases, 'alternative' modes of production arise and take advantage of the uncertainty that has been created by such fear campaigns. The market then determines their viability. There may be opportunities to bring elements of some alternative options into mainstream production systems and diffuse the conflict by improving consumer acceptance.

Geopolitical risk is everpresent. Locally, Lockie (2017) comments that the polarised politics of climate change for example has not served Australian agriculture well in preparing for more uncertain environments. This tends to result in reactive policies of increased drought assistance rather than the development of policy instruments that improve the adoption of risk management strategies by farm businesses. Internationally, political instabilities compromise free trade agreements and often result in re-imposition of tariffs or other trade restrictions. In reality such instability can result in either a threat or an opportunity depending on the issue and the countries involved.

Government interventions alter the risk profile for farmers. Such contributions can be imposing price floors, providing subsidies for crop insurance, direct payments and marketing loans (*e.g.* as in the USA, Maaz *et al.* 2018) and for ecosystem services. Australia and New Zealand receive the lowest level of government intervention and so farms must address their risks strategically rather than depend on governments to do it for them. Chapter 3 canvassed some of the business responses such as increasing farm sizes for economies of scale and the move to a more corporate style of management even for farm families.

Impact of technology on sustainability

It is worth reflecting that when CA commenced its rapid expansion in the late 1980s, there were no mobile phones or laptops. Computers were generally mainframe and PCs were in their infancy. Faxes had become the technology of hard copy communication. Sensor technology was rudimentary at best and the internet did not arrive until around 1993. The CA research agenda described here-in was undertaken alongside the growth and maturity of these technologies which are now taken for granted. In 2020, computer technology has capability not imagined in the 1980s and is embedded in machinery, robots and other aspects of production as an integral part of operations. We have arrived at a point where sensor technology provides the capability, but the applications are not realised as yet. Mobile phones have sophistication now (*i.e.* the ‘smartphone’ since 2007) that provides much capability, particularly with photography, messaging and ‘apps’ opportunities. The current challenge remains how best to use the capability to improve farm business decisions and performance.

The report, “Australia’s Agricultural Future” (Daly *et al.* 2015), highlighted that “...*integrating deep agricultural knowledge with cutting-edge technologies (including sensor networks, robotics, autonomous systems, innovative mathematical and statistical models for big data sets and ICT) will be central to the next agricultural revolution. Agri-intelligence research is a springboard for agriculture into the second machine age, in which computer systems augment human perception and decision making in complex situations.*” Much of this however depends on high band-width internet access for farmers in rural Australia – this represents a shortfall in capability as much of the production areas have little to no access to high speed internet. Success in agriculture will depend on ready access to market and weather information, to supply chains and to the service sector. Agriculture will continue to be the generator of ‘big data’ but its ability to prosper from such rich data will be determined by its connectivity capability, which is a current limitation. Modern farm machinery includes precision technologies that collect data on the machine or crop. Data collection and transfer capability is required to utilise that data both for machinery performance and for farm decisions: large areas of rural Australia lack mobile coverage and/or have very low access speeds (Keogh and Henry 2016).

Connectivity is the single most important enabler for digital innovation in agriculture. Where connectivity is not provided (*e.g.* by the National Broadband Network, NBN), some farms address their own connectivity needs – through LPWAN (low powered wide area network) for small packets of data, to Satellite Iot in remote locations, to on-farm WiFi networks for more complex data sets (KPMG 2019). Transformative technologies that replace labour needs, however, are likely to reduce employment opportunities and increase isolation in agriculture and depopulation of rural areas (Lockie 2018). Alternatively, they may create new jobs in the technological support area although some of these can be undertaken remotely.

Plant breeding technologies have also delivered immense value to Australian, and global, agriculture for some crops. Significant breakthroughs in the last 25 years, most notably ‘genetically modified’

(GM) crop varieties, have transformed cotton production (from 1995) and to a lesser extent canola in Australia, largely in terms of insect and herbicide tolerances. However there has been little improvement so far in potential yield *per se* or in drought tolerance (Fischer *et al.* 2014, Dalal *et al.* 2017) though there is potential to deliver more in terms of adaptability, resilience and functional foods. The breeding technologies have reduced the time taken to produce new varieties by traditional means.

The Future of R&D – the ‘Innovation’ era

A study of innovation in Australia (Innovation and Science Australia 2017) commented that Australia became world record holders in 2017 for 26 years of sustained economic growth. Credit was given to agriculture and mining for this outcome through their “extraordinary innovation, risk-taking and export success”. The Report indicated that innovation was needed to maintain a strong economy through better international competitiveness. To achieve that competitiveness would require:

- Scale-up of high growth industries and companies;
- Commercialising more high-value products and services;
- Fostering great talent; and
- Daring to tackle global challenges.

These represent a challenge to agricultural R&D. Interestingly no mention was made of traditional R&D in the innovation context.

Although there are fears that automation and the digital economy will result in job losses, such jobs are likely to be in routine, manual tasks. However technology is likely to create new, different jobs with emphasis on digital systems and ‘21st Century skills’ such as entrepreneurialism, inter-personal skills and problem solving (Innovation and Science Australia 2017). The Report goes on to say “...rather than fearing that digitalisation and automation will erode jobs or opportunity, we should recognise that these changes will be positive for the economy, and are essential to fill the workforce gap left by demographic change, to lift productivity and contribute to GDP growth”.

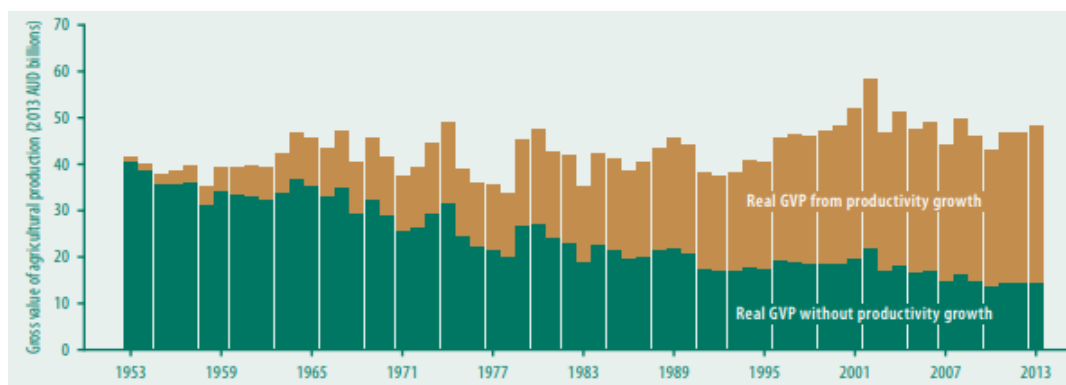


Figure 5. The value of productivity growth to Australian agriculture (From Daly *et al.* 2015)

Australia is positioned as a generator of high quality, clean and green food, and it is important that the contribution of R&D be acknowledged in that achievement. Figure 5 shows the contribution made from productivity growth to the gross value of agricultural production in Australia (Daly *et al.* 2015). While some of this progress is through application of R&D undertaken internationally, Australian researchers, including producers, can be well satisfied with their contribution. The R&D effort by Australian agricultural researchers has been undertaken in large part in isolation from the rest of the national innovation system. Lip service has been given to the National research priorities while addressing what have been the perceived priorities or opportunities for agriculture. While the major research investors, particularly the research and development corporations (RDCs) in conjunction with the Federal Government, have their investment plans, several reviews of the agricultural R&D system (*e.g.* Howard Partners 2018, Ernst & Young 2019) have noted that there is no over-arching shared vision of what agricultural R&D is or should be. There is a strong case for agricultural R&D to be more closely aligned

with the national innovation system as it is likely that transformational developments will come from other sectors such as medicine, engineering or computing. Further, no country will be able to afford all the research needed in agriculture (or other disciplines for that matter) so increasing global collaboration will be paramount.

Our capacity to meet the challenges

Agronomy research performance How then does this fit with Australian agronomy research? A difficulty in evaluation is having reliable metrics for determination. The Australian Council of Deans of Agriculture (ACDA) commissioned a study of performance based on research publications over a 20 year period from 1996 to 2015. Its veracity is subject to researchers actually publishing in recognised journals and adequately describing their research in agronomic terms. It also suffers from the lackadaisical attitude of research funders towards scientific publications. Nevertheless the numbers are insightful enough to ascertain trends relative to global performance of other players operating with similar caveats.

Figure 6 shows the annual publication numbers for papers in agronomy by Australian authors. Over the 20-year period, those numbers increased from 408 in 1996 to 683 in 2015, an improvement of 67%. However, if the share of global publications is considered then there has been a decline in share of 30% over the same period. Other countries have increased their publications more than Australia has.

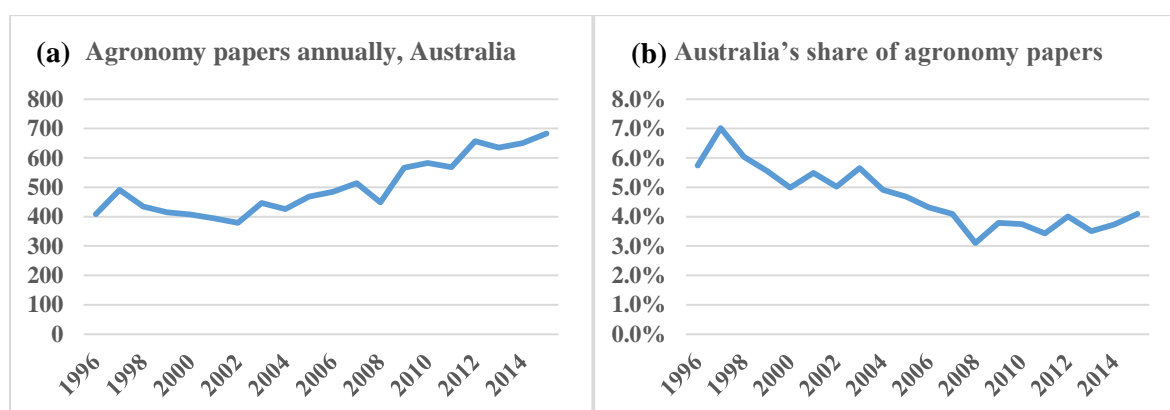


Figure 6. (a) Number of papers in agronomy published annually by Australian authors and **(b)** Australia's global share of agronomy papers annually for the period 1996-2015 (ACDA unpublished)

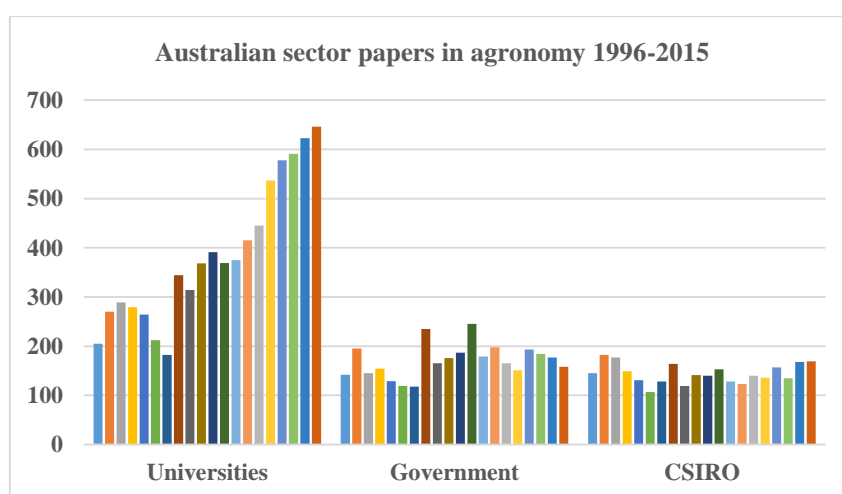


Figure 7. The source of agronomy papers from Australian research organisations annually for the period 1996-2015 (ACDA unpublished)

There is also a long-term trend regarding who provides the research publications in Australia (Figure 7). Over the 20-year period, CSIRO and government agencies have been relatively stable in publication numbers produced but universities have had a 215% increase over that 20-year period. Universities have had publication numbers as a metric for individual promotion and for institutional research grant quantum and so the trend is not surprising, although the extent may be since universities are represented in over 70% of the publications. Government numbers are also misleading as there are big discrepancies between the number trends of different state agencies (data not presented).

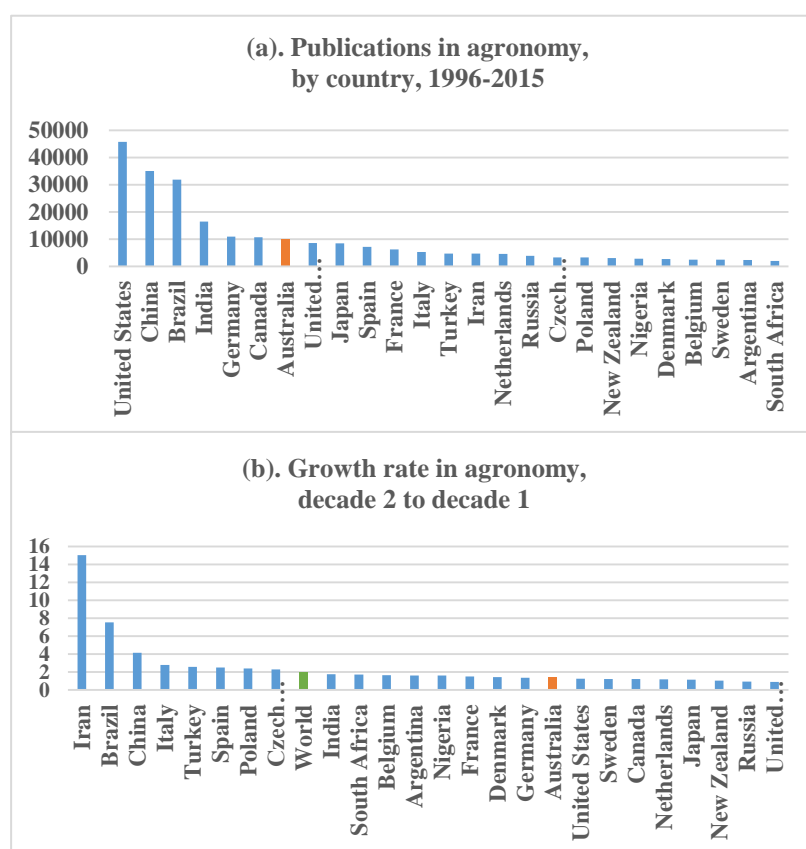


Figure 8. (a) Publication numbers in agronomy by country and (b) growth rate in publications by country from decade 1 to decade 2, for the period 1996-2005 (ACDA unpublished)

Over the 2-decade period Australian agronomic research has performed well, ranking 7th in publication number (Figure 8a), but an analysis of the growth in performance in the second decade relative to the first decade shows that there is a clear drop off in performance relative to several other countries (Figure 8b). It is recognised that some countries, *e.g.* Iran, perform well in this scenario from a low base but, regardless, the data suggest that the international competition is expanding and challenging Australia's standing.

The value of the publications can be inferred from the number of citations the publications received. In this case the measure is relative citations, with the global average citation index being set to 1.0. The data (Figure 9) suggest that for Australian agronomy, research is considered above average over the period of the study with a consistently higher performance in the second decade. This may reflect more ready access due to the internet for citing authors, although all papers, globally are now readily accessible. More specifically, CSIRO compares more than favourably with noted international institutions such as INRA, USDA, UC Davis, Agriculture and AgriFood Canada and Wageningen and has a high proportion in the top 1% of cited papers.

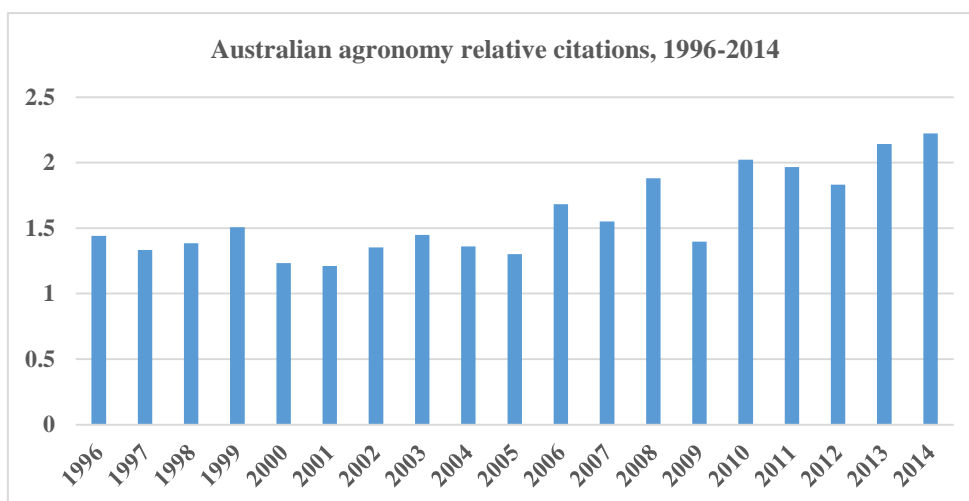


Figure 9. Relative citations (top) annually for Australian agronomy publications for the period 1996-2014, the world average being 1.0 (ACDA unpublished)

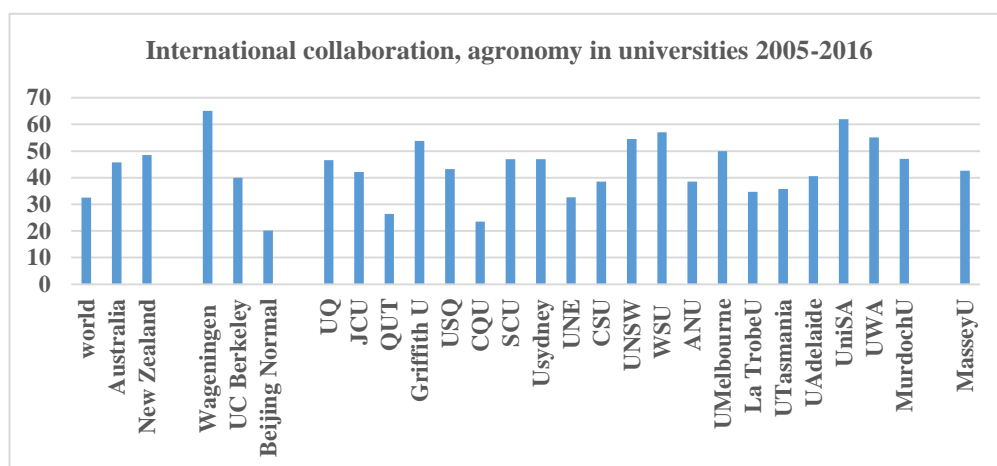


Figure 10. Proportion of Australian agronomy papers with international co-authors for publications in the period 2005-2016 (ACDA unpublished)

An increasingly used metric is international collaboration in research, and this is expected to increase. Figure 10 shows the extent of such collaboration for Australian universities as measured by joint authorship of papers. In general terms, for the period 2005-2016, 45% of Australian-authored papers have an international co-author, a proportion which is well above world average at 32%. International benchmark universities (*i.e.* Wageningen, UC Berkeley and Beijing Normal) have been included in the comparison showing Australia better than UC Berkeley and Beijing Normal but behind Wageningen University. Of the 20 Australian universities included in the study only two were lower than world average for citations over the period of study.

Research funding By all accounts above, Australian agronomy research has been performing well and in advance of many nations. But there are now many new international players in the game expending more on R&D than Australia. Data suggest that Australian government investment continues to decline in real terms and that seems unlikely to change. The major contribution by the Federal Government is the co-investment with industry levies as shown in Figure 11. The data show a steady increase in levy collections since the scheme began in 1990 and the increase matched in actual dollar terms by government until about 2006 when the co-investment flat-lined.

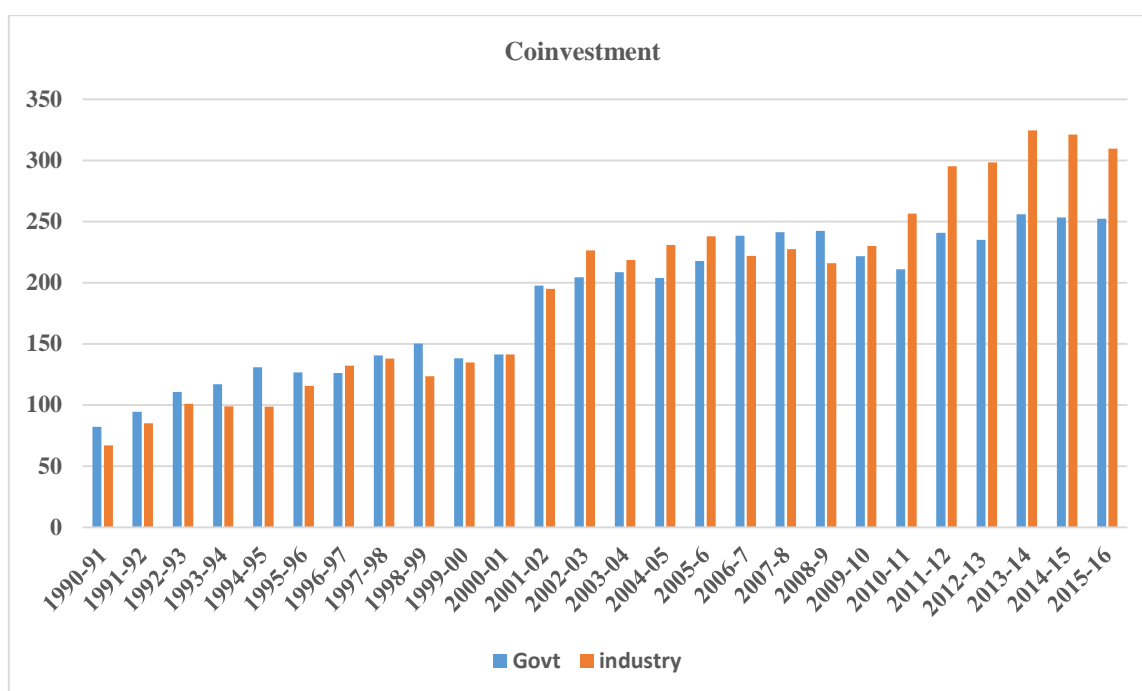


Figure 11. Annual industry levy collection and the ‘matching’ co-investment by the Australian government

The national government also funds other short-term schemes from time to time and its total commitment to R&D since 2005-06 has increased by around \$150 million or nearly 20% to 2014-15. The main component of the growth now counted is to the private sector through R&D taxation incentives (Millist *et al.* 2017). At the same time State governments, who traditionally have been long-term investors in agricultural research, have reduced their commitments by around \$100 million over the same period (see Figure 12). Universities coincidentally have increased their investment by around the same amount and now fund rural R&D to a greater extent than the State agencies.

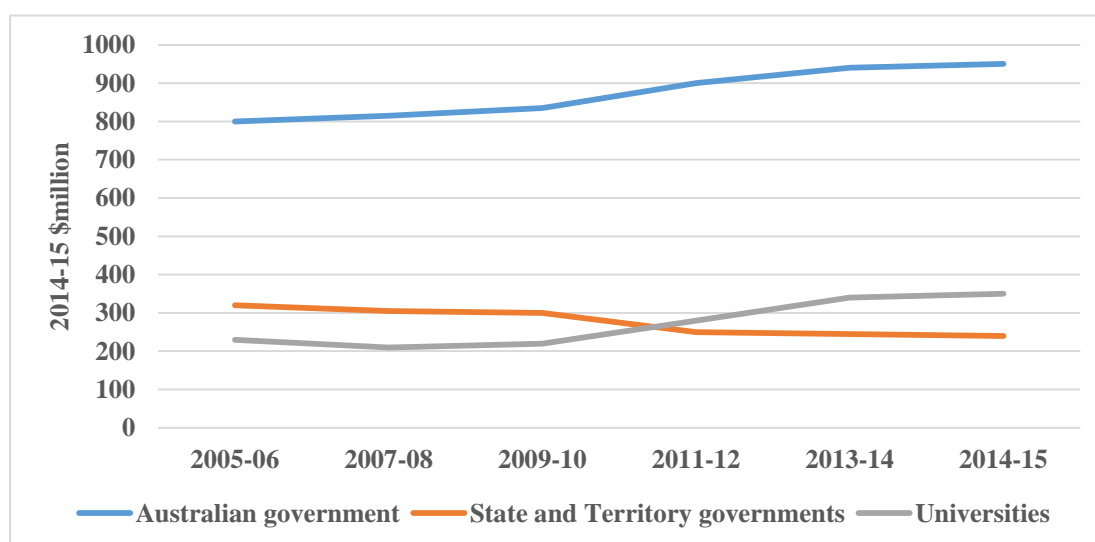


Figure 12. Public funding of agriculture R&D for the period 2005-06 to 2014-15 (adapted from Millist *et al.* 2017)

The public investment in agricultural R&D overall in Australia was considered by Sheng *et al.* (2011) and showed the flat-lining since the 1970s but a reduction in research intensity (*i.e.* the contribution in real terms after allowing for currency value decline, Figure 13).

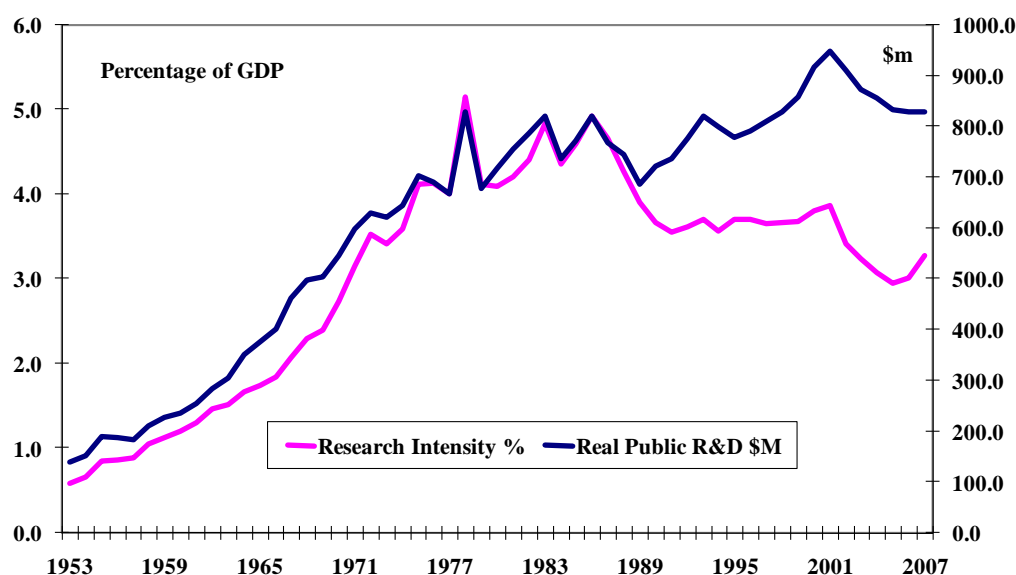


Figure 13. Real public investment and research intensity in Australian agricultural R&D (Sheng *et al.* 2011)

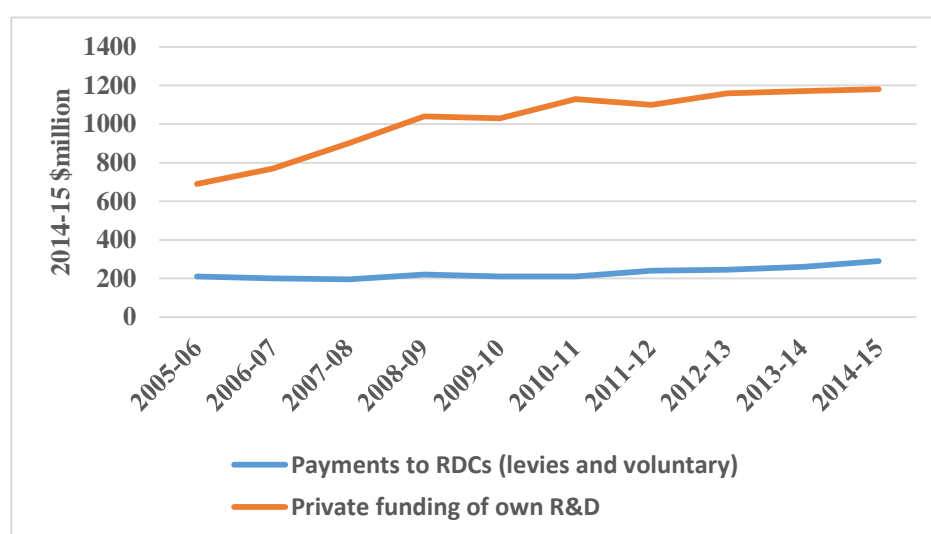


Figure 14. Payments by Government to research and development corporations associated with levies and private sector R&D investment against which taxation deductions are claimed (adapted from Millist *et al.* 2017)

The study by Millist *et al.* (2017) now allows the Government to claim, legitimately, that it is increasing its funding to R&D, thereby offsetting to some degree the issue of research intensity. Closer inspection of the increase suggests that the increase is in privately performed R&D rather than private investment in public R&D. This separation is starkly presented in Figure 14 and perhaps is a signal for future trends.

Research training The scientist pipeline traditionally comprised the training of higher degree research students (HDRs) through PhDs. Such HDRs undertake, under supervision, much of the transformative or ‘blue sky’ research that emanates from universities. That process has delivered high quality scientists into research organisations and industry over a long time. It is expected that research is an attractive

career pathway, but over the last few decades that has not been the case. There are three major impediments to the supply of scientists in agriculture, including agronomy. These are:

- The failure to entice leading graduates into a research training pathway. This is in large part due to the discrepancy between financial conditions imposed on the HDR relative to those in industry. Currently the standard stipend for an HDR is *less than half the salary* of a graduate going straight from undergraduate studies into industry employment. There is no annual increment and no superannuation entitlement – nor is the taxation-free status of much value, particularly given that the scholars will be accumulating a fees debt to be repaid through taxation after graduation.
- The failure of the system to hold onto the HDRs until PhD completion due largely to the buoyant employment market and stipend inadequacy. This is shown in Figure 15 as strong completion rates for international students but a wastage rate of about one-third of domestic HDRs.
- The failure of industry, research organisations and research investors, including RDCs, to provide other than short term contracts to new scientists.

These scientist training conditions and the post-doctoral employment prospects are therefore clearly counter-productive to attracting the keenest minds into agricultural R&D.

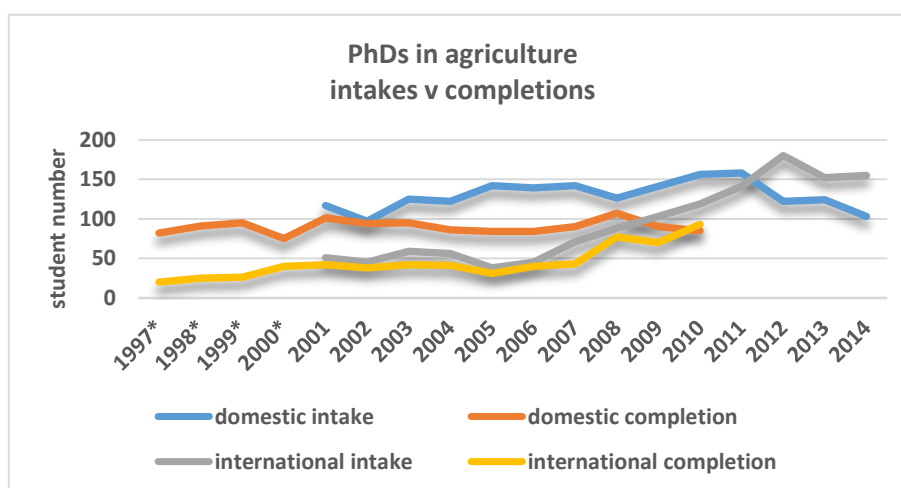


Figure 15. Comparison of intakes and completions of related cohorts of higher degree research scholars. Completions are offset by 4 years to link completions with intakes (Australian Academy of Science 2017)

The program of training PhDs in all disciplines has received much attention in recent years. Such specialised degrees are recognised for their strong scientific skills but are criticised by industry for their lack of business and inter-personal skills. Increasingly, the idea that HDRs should spend some time in industry is suggested to be of benefit to the innovation system and to the individual business and scholar (McGagh *et al.* 2016). It would also improve industry/university collaboration in Australia which currently resides towards the bottom of OECD comparators. This is applicable across the national innovation system and its application in agriculture would be restricted more likely to the secondary industry component than to the primary sector – yet the R&D undertaken is largely directed at the primary sector. The pressure for business experience takes time off those projects involving ‘blue-sky studies’ which may be compromised as a result. Cunninham *et al.* (2016) indicated that there is a disconnect between industry and universities. They record that “...Industry needs to start to understand that blue sky research is not a bad thing and universities need to start rewarding behaviour that industry finds valuable, instead of basing promotion only on publishing academic research”.

While universities remain the awarding institutions for Master and Doctorate research awards, it is important to note that key agricultural research institutions, notably CSIRO and some state agencies, host a significant proportion of Australia’s research scholars in their laboratories and field stations under

co-supervision arrangements with a university. In some cases, scholars undertake their research in private company facilities in conjunction with the university. CSIRO in combination with Universities and Industry endeavours to bridge this gap with an Industry PhD scheme involving a period of industry placement (www.csiro.au/en/Careers/Studentships/Industry-PhD). Such collaborative arrangements provide for a more extended post-graduate experience and exemplify the industry/university model being proposed.

Future of agriculture R&D

R&D in agriculture in Australia has had several phases as described by Howard Partners (2018): mechanisation in the agrarian revolution of the 1700s; emergence of agricultural and associated sciences; and recently the impact of digital applications, data and analytics leading to ‘disruption’ of the industry and business models with support for AgTech and GeneTech start-ups through greater availability of risk capital. Ernst & Young (2019) indicate that Australian agriculture faces unprecedented change including:

- Changing global markets;
- Increasing international competition
- Technological disruption;
- Transforming industry structures;
- Climate variability and change;
- Water scarcity; and
- Increasing threats from pests and diseases.

While the Rural Research and Development Corporations (RDCs) are likely to continue their present functions, the push by the Federal Government towards innovation provides a perturbation that previously has not been experienced. Greater emphasis seems to be placed on entrepreneurship, risk-taking and cross-sectoral collaboration, characters that have previously been anathema to the operation of the RDCs. Greater focus will be on value-adding and will link increasingly with global connections (‘connected innovation’) and associated value chains: more priority will be given to innovation along the length of the supply chain. The ‘buzz words’ include agility, flexibility and responsiveness – their application will be a challenge to the existing R&D system. ‘Start-ups’ are the new currency as there is an expectation that strong commercialisation methodologies will be utilised to attract investment for their support. CSIRO provides such a scheme called “ON: accelerating innovation” to “get ideas out of the lab and into the world” (www.oninnovation.com.au). Hypothesis-based research, which has served the industry and science well, is under threat from the ‘slick’ technologies and the thrust towards innovation.

Howard Partners (2018) describe research as extending the knowledge base while innovation is about application of that knowledge to address problems or create opportunities within a business, environmental or social context. Much of the rhetoric in this space is silent on the first part – that of increasing the knowledge base, the ‘blue-sky’ activity, which has been struggling even in the existing system. The innovation paradigm is perhaps overdue, but it will impact on how things are done by changing the funding base, the culture of research and the attractiveness or otherwise of careers in this space. Unless care is taken it may run out of ideas to commercialise unless there is an underpinning of new knowledge discoveries.

Given then that agriculture is now part of the overall innovation thrust of government, it is worth contemplating just what that might mean. Innovation and Science Australia (2017) identified five urgent imperatives that needed to be addressed for the emerging innovation system (Figure 17) as:

- Education;
- Industry;
- Government;
- Research and Development; and
- Culture and Ambition.

None appear too onerous. **Education** in agriculture has been through a regeneration phase and most institutions are exploring the new digital age and what that involves. At the vocational education and training level new skills in digital technologies and robotics, for example, need to be fostered.

Industry perhaps is a challenge because of the ‘disconnect’ between production and some of the technologies; capabilities in some technical areas are lacking and internet limitations exist for a total embrace of data capture and utilisation.

Government will be applicable to agriculture as to other sectors but regulation hindrance, access to information and appropriate infrastructure seem to be blockages.

Research and Development has been previously canvassed but the lack of attractive support in research training and the uncertainty in research career prospects is of concern. Attracting sufficient investor support for the innovation agenda remains an unknown.

Culture and Ambition relate to ‘national missions’ and is perhaps the most challenging. Previously discussed is the lack of an overall strategy for agricultural research together with a culture of isolation and silo operation. It therefore appears that agriculture, and hence agronomy, could engage with the national innovation agenda as long as the incentives for doing so are clear.

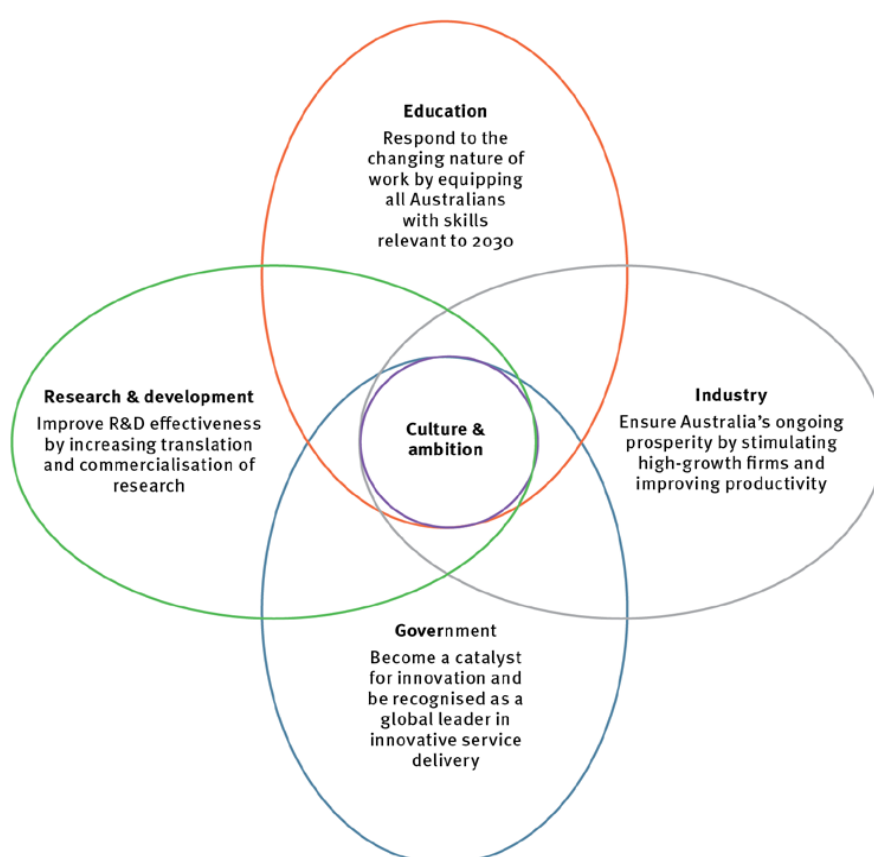


Figure 16. Five imperatives for the Australian innovation, science and research system (Innovation and Science Australia 2017)

The future agronomist

International research (Cunningham *et al.* 2016) suggests that technology (*e.g.* machines, sensors, computers, robots) is displacing the lower skilled, repetitive and manual jobs in society. This has been happening over a long period of time in agriculture. However some jobs require “a high level of perception and manipulation where people can see and respond to circumstances in ways that computers and robots cannot” (Cunningham *et al.* 2016). The Decadal Plan for Agricultural Science (Australian Academy of Science 2017) defines agricultural science, not as a core discipline in its own right, but a

confluence of many different scientific disciplines and endeavours – it is the integrator of advances in enabling sciences (Figure 18). That definition applies aptly to agronomists as discussed previously in Chapter 23. The range of disciplines is increasing rapidly with advances from informatics, big data, the Internet of Things, robotics, molecular biology and others described in this monograph. It is noted that farmers alone cannot be the font of all wisdom because of the complexity involved. In other industries companies have teams of personnel to address such complexity but farmers will need to outsource aspects of the business from time to time. The agronomist will be one of the experts sourced. Agronomists have played a leading role in creating the crop and pasture production systems of today, either through research findings or as a mentor to producers. The departmental extension agronomist played a significant part in implementation on farm until the 2000s but most cropping farmers now employ a private agronomic consultant, suggesting they perform a valuable role which is likely to continue. Both farmer and agronomist will need ‘digital literacy’ in order to be able to take advantage of technology, to engage with machinery and other suppliers and to source information. Agronomists, in turn, will need to engage with particular specialists as circumstances arise.

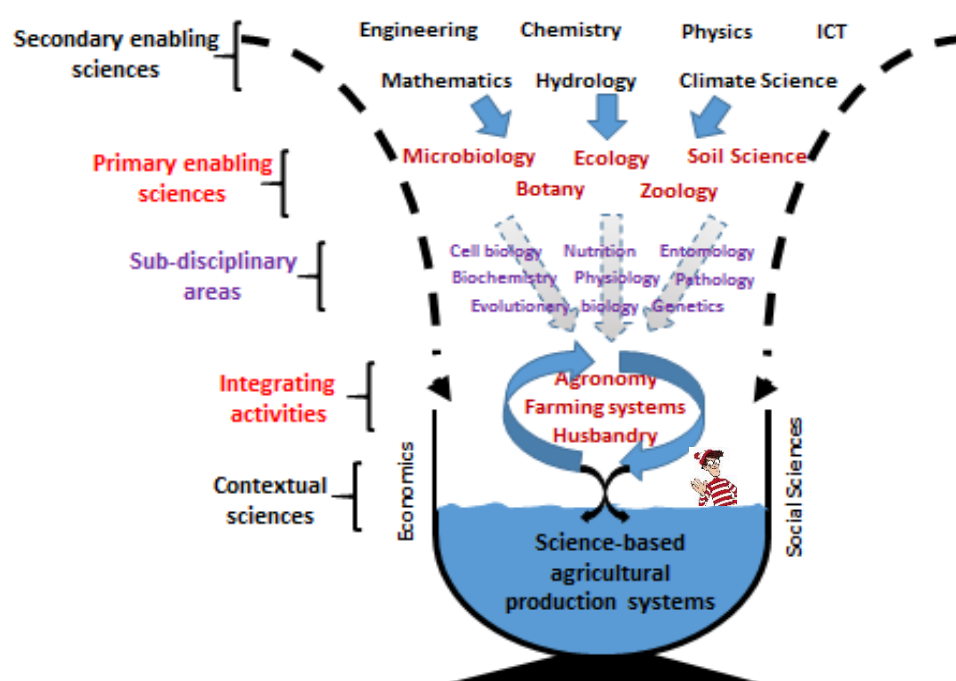


Figure 17. Inputs of disciplines and sub-disciplines for integration by agronomists towards sustainable agricultural production systems (Australian Academy of Science 2017)

This monograph provides strong evidence that the range of agronomists (*i.e.* research, academic, advisory, service) are needed for the tasks ahead. Clearly there is much research to do and the digitising of agronomy on farm and along the supply chains will need agronomic expertise. As integrators, agronomists have a leading role to play (see Chapter 23). The human dimension to agronomy is and will remain important and will not be easily automated because it is intuitive (Chapter 25). Automation will be very helpful in undertaking the tasks, but ‘designers’, *i.e.* the agronomists, will still be needed to determine what, when and how the tasks will be done.

It is also likely that the role of the agronomist will be further extended. The imperatives of minimising greenhouse gas emissions, ensuring land management meets community standards and satisfying increasingly stringent market requirements emphasise a role with greater environmental as well as production credentials. The digital and spatial capabilities of technology will provide increasing scrutiny on farm practices and environmental outcomes and this capability may assist in measuring the role of farmers in respect of ecosystem services, such as carbon capture. In that event, agronomists will play a pivotal role in ensuring that farmers capitalise on these opportunities, and thereby play a bigger role in mitigating risk in crop production.

References

- Angus JF (2001) Nitrogen supply and demand in Australian agriculture. *Australian Journal of Experimental Agriculture* **41**, 277-288
- ATSE (2015) Submission to House of Representatives Standing Committee on Agriculture and Industry Inquiry into Agricultural Innovation (ATSE: Melbourne)
- Australian Academy of Science (2017) Grow. Make. Prosper. The decadal plan for Australian Agricultural Sciences. (National Committee for Agriculture, Fisheries and Food, Australian Academy of Science: Canberra)
- Barlow S, Kingwell R, Pratley J, Keating B (2016) Innovation in Australia's Agrifood systems: are Australia's universities ready for the next challenge? *Farm Policy Journal* **13** (1), 15-23
- Barr N, Cary J (1992) "Greening a Brown Land" (MacMillan Education Australia: Melbourne)
- Cornish PS, Murray GM (1989) Low rainfall rarely limits wheat yields in southern New South Wales. *Australian Journal of Experimental Agriculture* **29**, 77-83
- Cunningham S, Theilacker M, Gahan P *et al.* (2016) "Skills and capabilities for Australian enterprise innovation" (Australian Council of Learned Academies: Canberra) www.acola.org.au
- Daly J, Anderson K, Ankeny R *et al.* (2015) "Australia's Agricultural Future" Report for the Australian Council of Learned Academies, Melbourne www.acola.org.au
- Ernst & Young (2019) "Agricultural Innovation – a national approach to grow Australia's future" Report to Minister for Agriculture and Water Resources, Canberra
- Dalal A, Attia Z, Moshelion M (2017) To produce or to survive: How plastic is your crop stress physiology? *Frontiers in Plant Science* **8** www.frontiersin.org/articles/10.3389/fpls.2017.02067/full
- Donald CM (1965) The progress in Australian agriculture and the role of pastures in environmental change. *Australian Journal of Science* **27**, 187-198
- Fischer RA, Byerlee D, Edmeades GO (2014) "Crop yields and global food security: will yield increase continue to feed the world?" Monograph No. 158. (Australian Centre of International Agricultural Research: Canberra) www.aciar.gov.au/publication/mn158
- French RJ, Schulz JE (1984a) Water use efficiency of wheat in a Mediterranean type environment I. The relationship between yield, water use and climate. *Australian Journal of Agricultural Research* **35**, 734-764
- French RJ, Schulz JE (1984b) Water use efficiency of wheat in a Mediterranean type environment II. Some limitations to efficiency. *Australian Journal of Agricultural Research* **35**, 765-775
- Innovation and Science Australia (2017) "Australia 2030: prosperity through innovation", (Australian Government: Canberra)
- Hochman Z, Gobbett DL, Horan H (2017) Climate trends account for stalled wheat yields in Australia since 1990. *Global Change Biology* **23**, 2071-2081
- Howard Partners (2018) Australia's Rural Innovation System www.howardpartners.com.au/assets/performance-review-of-the-rural-innovation-system-24-august-2018-.pdf
- Keogh M (2012) Including risk in enterprise decisions in Australia's riskiest businesses. *Farm Policy Journal* **9** (1), 11-21
- Keogh M, Henry M (2016) "The Implications of Digital Agriculture and Big Data for Australian Agriculture" Research Report (Australian Farm Institute: Sydney) www.farminstitute.org.au
- Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* **61**, 4129-4143
- KPMG (2019) Agri 4.0 – Connectivity at our fingertips (KPMG: Melbourne) www.KPMG.com.au
- Lockie S (2015) "Australia's agricultural future: the social and political context" Report to SAF07 – Australia's Agricultural Future Project, Australian Council of Learned Academies, Melbourne www.acola.org/wp-content/uploads/2018/08/agriculture-socio-political-context.pdf
- Maaz T, Wulffhorst JD, McCracken V *et al.* (2018) Economic, policy, and social trends and challenges of introducing oilseed and pulse crops in dryland wheat cropping systems. *Agriculture, Ecosystems and Environment* **253**, 177-194
- McGagh J, Marsh H, Western M *et al.* (2016) "Review of Australia's Research Training System". (Australian Council of Learned Academies: Canberra) www.acola.org.au
- Millist N, Chancellor W, Jackson T (2017) Rural research, development and extension investment in Australia. Research Report 17.11 (ABARES: Canberra) www.agriculture.gov.au/abares/publications
- Robertson M, Kirkegaard J, Rebetzke G *et al.* (2016) Prospects for yield improvement in the Australian wheat industry: a perspective. *Food and Energy Security* **5**(2), 107-122
- Sheng Y, Mullen JD, Zhao S (2011) A turning point in agricultural productivity: consideration of the causes. ABARES Research Report 11.4 for GRDC (ABARES: Canberra)

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