Chapter 9

Advances in crop residue management

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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).

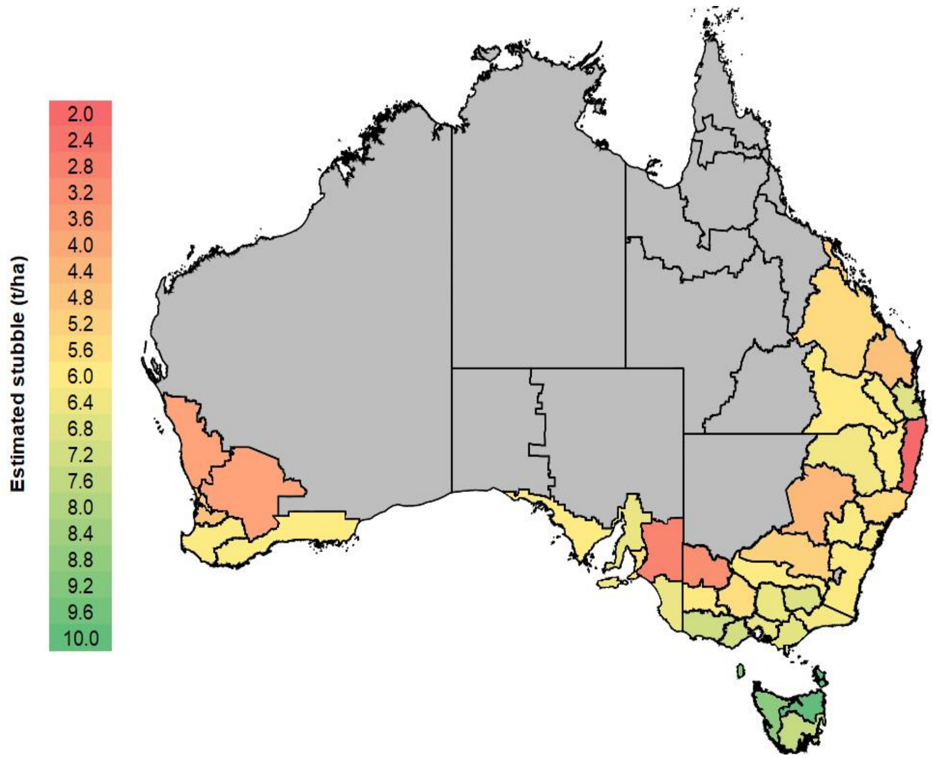

Figure 1. Estimated residue quantity available, based on regional average wheat yields for the period 2012-2017

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).

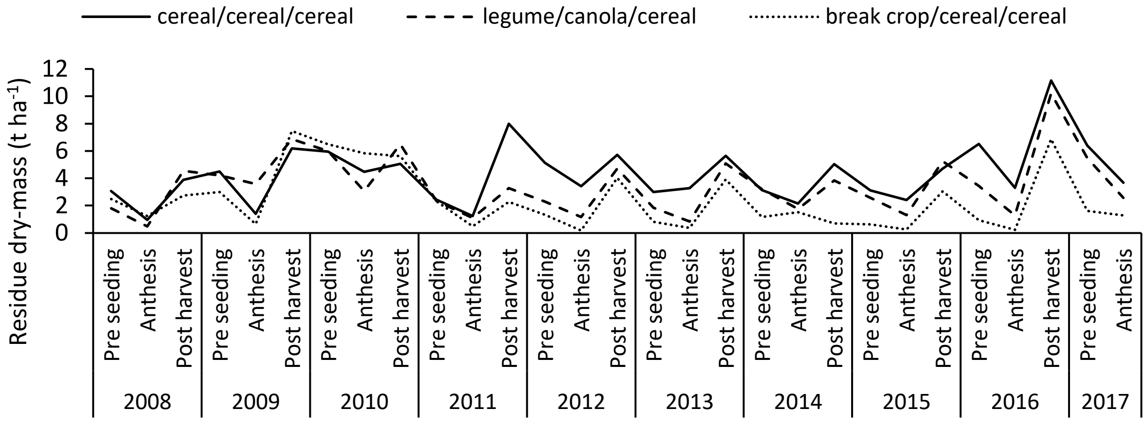

Figure 2. Crop residue dry-mass from 2008 to 2017 in a long-term NT trial at Cunderdin (WA). The legume/canola/cereal rotation started with the legume in 2008, 2011, 2014 and 2017. The break crop/cereal/cereal rotation had legume as the break crop in 2008 and 2011 and fallow in 2014 and 2017 (unpublished 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

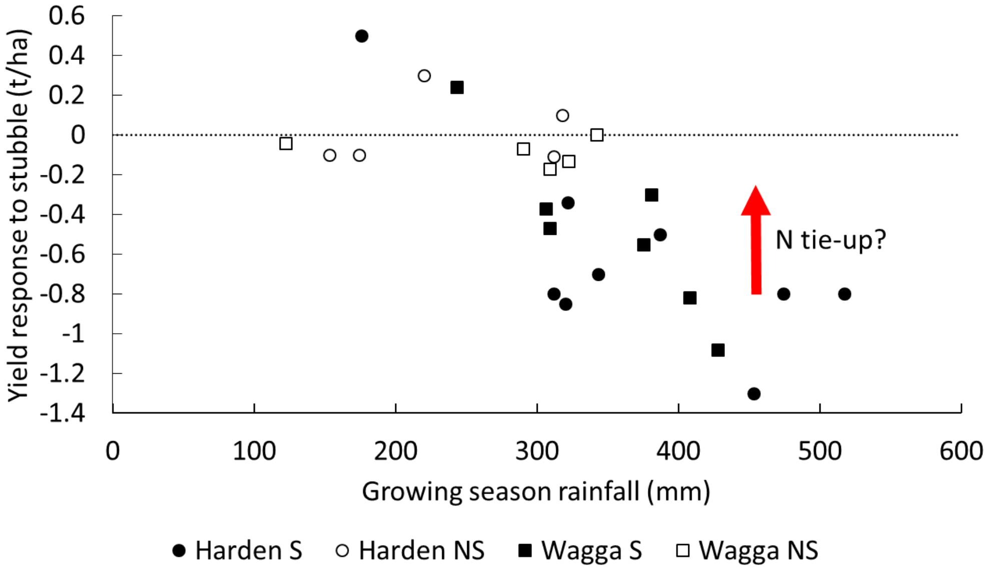

Figure 4. Yield response to crop residue (stubble) with different amounts of growing season rainfall at two sites in southern NSW (after Kirkegaard *et al*. 1994, Heenan *et al*. 1994, Giller *et al*. 2015) Solid circles represent seasons where differences between stubble retained and stubble burnt were 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, bailing, 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	↓ erosion ↑ soil moisture ↑ soil organic matter and nutrient reserves ↑ soil physical and biological quality ↓ prevalence of some weed and disease species.	↓ 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	↑ 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	↑ rates of organic matter decomposition ↓ soil physical and biological quality ↓ soil moisture ↑ erosion
Removal (baling, burning)	↑ ease of seeding operations ↓ prevalence of some disease species. ↑ effectiveness of pre-emergence herbicides	↑ 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 seedings (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. sclerotiotum* 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.

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