What has Australian agronomy contributed to world food security in the last 20 years, and what lies ahead?

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Abstract
Australian agronomy (research and extension on land, water, soil and plant management for field crop and pasture production, performed by agronomists born and/or employed in Australia) contributes to world food security mainly by increasing productivity (yield increases per unit area or input, or per head of livestock). In the last 20 years Australian agronomy has improved world food security by underpinning increased production of field crops and livestock that theoretically could support about 30 million people per year with grain plus enough meat, edible oil and dairy products to add dietary quality and flavour. This assumes that the food is in fact eaten, and not lost post-harvest or used for alternative purposes. The calculated numbers of people who could be fed involve numerous assumptions and are fraught with uncertainty. About one third of the increased production has been achieved in Australia and two thirds in developing countries, mainly in Asia. Internationally, many benefits have come from bilateral projects funded by ACIAR and/or AusAID, involving scientists from Australia and a developing country, often with links to an International Agricultural Research Centre. Australian agronomists have also contributed to food security through training activities and through leadership positions in other countries and international organisations, but these benefits are impossible to quantify. Looking ahead, inertia in the system (technical innovations still to be adopted, and projects currently in progress) suggests that this level of contribution will be maintained for another decade or so; beyond that timeframe the contribution by Australian agronomists is essentially unpredictable.

Concepts, methods and approaches

In "The Hitchhiker's Guide to the Galaxy", Douglas Adams (1979) proposed that the answer to "the ultimate question of life, the universe and everything" was 42. The computer, *Deep Thought* that had been constructed to do the calculations explained that the answer was incomprehensible because the questioners did not understand what they were asking. I approach this topic in a similar spirit of entertainment and adventure. The topic requires some definitions at the outset in order to define the framework for this paper. The answer to the question in the title depends on the definitions and assumptions. If these are changed, the answer will also change; and in the end, the answer is just a first approximation.

Definitions
Here, I will restrict the word "agronomy" to mean the science of land, water, soil and plant management for field crop and pasture production. Modern definitions sometimes include plant improvement but I take a narrower view.

"Australian agronomy" is a mysterious and nebulous concept. Some readers might assume that some aspects of agronomy are peculiarly Australian in nature – particular approaches, applications or concepts. Australian agronomists do have a particular focus on water use efficiency and nutrient management, and with a few exceptions they work mainly in water- and nutrient-limited crop production systems; but agronomy is a global science. Other readers might assume that this talk should be restricted to the contribution of agronomy to the production of crops *in Australia*, or in countries with climates or soils like those in Australia. But "Australian" agronomists have achieved some of their greatest successes in countries that have very different climates, soils and farming systems. Finally, some readers might assume that we are here discussing not Australian *agronomy*, but Australian *agronomists*; but Australia's research organisations employ agronomists who were born and trained in many countries, and whose influence reflects (at least in part) their prior training and professional experience. Here, I have tended to define "Australian agronomy" as research and extension undertaken by agronomists born or employed in Australia. This does not mean that all the agronomic technology or know-how has been developed in Australia.

"World food security" is another flexible and evolving concept, with dozens of definitions. The game has moved on from the supply-side thinking of the 1980s (eg food production/supply and price stability), to include demand-side issues (food access, ability to pay for food, and food preferences). Thus, global food security is now linked to poverty reduction and human health. One definition (FAO 2002) states: "food security [is] a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary and food preferences for an active and healthy life". Such a state is almost impossible to envisage, yet alone measure. There is no single, simple measure of food security. Proxy indicators include average *per capita* availability of staple foods (ie *apparent consumption*; this includes production, imports, exports, non-food uses and wastage, and thus over-estimates food consumption). Here, I have chosen to estimate numbers of people actually fed, using web-available data (mostly from various FAO sources) on production and apparent consumption and using a range of numbers to cover variation in apparent consumption between countries. Food production is still a major factor, but is modified by trade and distribution issues, consumer expenditure patterns (including the extent of poverty), and within-country variability in purchasing power (as measured, for example, by the Gini index). The definition and approach allow (in fact, require) one to include feeding grain to livestock in order to facilitate the shift towards more animal protein in human diets as a contribution to world food security. However, it discounts food security benefits that result from research that leads to more sustainable production, lower food production costs and/or cheaper prices.

Human dietary energy requirements vary tremendously with age, sex, body weight, level of activity etc. According to Wikipedia, the average minimum energy requirement is about 1800 kcal (7530 kJ)/day. This is consistent with the body of data provided by FAO (2004). The *per capita* consumption range I have used for crops such as rice and wheat is 150-500 g/day. Since rice and wheat contain around 350-380 kcal/100g, the upper level theoretically would provide the total daily energy requirements of an "average" person; but relatively few people consume only rice, or only wheat. It seems more meaningful to speak of rice- or wheat-based diets.

The main staple crops that fundamentally underpin world food security are shown in Table 1. Some of these crops are principally fed to livestock, and in these cases it is necessary to convert grain production figures to livestock products using food conversion ratios, dressing percentages and bone-out percentages that are available in the literature, before then estimating the numbers of people supported. To convert grain production to edible meat, I have assumed that grain will be fed to beef cattle at a conversion rate of 7:1 (ie 1 kg of liveweight for every 7 kg of grain), a dressing percentage of 55% (ie 55kg of dressed carcass from 100 kg of liveweight) and a bone-out rate of 70% (ie 70 kg of edible meat from 100 kg of dressed carcass). Other kinds of livestock are usually more efficient than beef cattle in converting feed to liveweight gain. Conversion rates are also influenced by other factors. In general, my conversions are conservative, ie they will *under-estimate* the amount of meat produced from grain-fed livestock.

In the case of meat I have assumed that most people will use it to add flavour and quality to a wheat- or rice-based diet. A rather arbitrary daily intake 25-50 g/person is used – levels that might be appropriate to a developing country (Australians consume about 100 g beef/day, and about 130 g red meat/day). Beef contains 160-300 kcal/100g, so this intake corresponds to 40-150 kcal/capita/day.

Attribution of benefits: Conception versus implementation

In assessing and attributing impact, it is helpful to distinguish between conception (the genesis or origination of an idea or practice) and implementation (the application or execution of a pre-conceived idea or practice, often requiring considerable modification). The differences can be illustrated through two practices that are relevant to this paper: the application of fertiliser to crops, particular near the sown plants, and the use of reduced tillage.

The genesis of the application of nutrients to crops is lost in pre-history. While the use of modern fertilisers originated with the fertilisers themselves in the mid-19th Century, the practice of applying organic nutrients probably originated soon after the domestication of livestock, 6,500-8,500 years BC. During the 20th Century, the placement of nutrients near the favoured plant(s) received much attention. The concept of *micro-dosing* (the placement of small, sub-optimal amounts of fertiliser near the sown plants) probably arose in Kenya during the implementation of an Australian Centre for International Agricultural Research (ACIAR)[1] project in the 1990s (more on this later), although it may have originated earlier. After their conception and early testing, the implementation of all these practices on a scale that is significant in terms of global food security has required endless experimentation and modification and the personal exertion of many people often unconnected to the originator of the idea.

The plough originated about 10,000 years ago; again its origins are lost in pre-history, and it was preceded by simpler forms of ground disturbance to favour crop establishment. Its benefits included the conservation of soil moisture, including by the control of weeds. The development of modern zero-tillage agriculture (Evans 1998) was made possible by the invention of modern herbicides, particularly Paraquat in 1955 (released to commerce in 1961). Zero-tillage research commenced in the USA in the late 1940s, and the practice of zero-tillage commenced on farms (with Paraquat) in 1962 – two years before the first experiments were undertaken in Australia. Thus, the concept is not new, and did not originate in Australia. However, Australia now leads the world in the adoption of zero-tillage, and has contributed a good deal of adaptive research both in Australia and other countries (more on this later).

The point is that it is one thing to come up with an idea; it is another thing to make it work in practice and to scale it up to make a significant difference to world food security. By definition, not many people can be originators, but many can be practitioners. There are not too many new ideas around, but there is endless scope for ingenious adaptation and implementation.

It is also important to recognise that agronomic innovations take time, and the 20-year timeframe of this paper includes innovations that were commenced well before 1992, but which are still being adopted.

A default calculation using bibliometrics

To the extent that innovation depends on scientific progress reported in the scientific literature, a first approximation of the contribution of Australian agronomy to the increase in world food production in the last 20 years can be obtained from a bibliometric analysis. Data specifically for agronomic publications have not been found, but data for broader aggregations that include agronomy are available (eg Archambault 2010; DIISRTE 2011). In terms of total scientific publications, Australia currently provides about 3.2% of the world total (its share has increased steadily in the last 20 years, from 2.2% in 1993), and in the broad field of agricultural science Australia currently provides about 3.8% (Australian science is relatively specialised towards agricultural science). The impact of Australia's agricultural science (as measured by citation indices) is about 30% higher than its share of world publications. Assuming that growth in world food production is solely due to agricultural science and technology (**a most unlikely assumption**), Australian agricultural science may have contributed about 4% of the increase in world food supply in the last 20 years. The world population increased from 5.5 billion in 1992 to 7 billion in 2012, and world food supplies increased more or less in tandem. Australian agricultural science may therefore have generated enough food to support an additional 60 million people. Assuming further that figures for agronomic research are of the same order as those for agricultural science as a whole, and that about half the increase in world food production has been due to improved agronomy, Australian agronomy may have generated enough food to support an additional 30 million people per year. While this analysis is highly speculative and needs more work, the more detailed analysis in this paper suggests it may be quite close to the mark.

The approach taken below has been to analyse the contribution of Australian agronomy to Australian food production, and then to examine the contributions Australian agronomists have made to international agriculture. The emphasis is on food production because most of the agronomic contribution is likely to have been in this area rather than in post-harvest technology and food distribution (trade *etc*).

Contribution of Australian agronomy to Australian food production

Rationale

Australian agronomy can contribute to world food security by underpinning food crop and livestock production in Australia and exporting the surplus. By global standards, Australia is not a major producer of most staple crops (Table 1). Among the 8-10 crops of major significance to world food security (those listed first in the Table) only for wheat, barley and sorghum does Australia's share of world production rise above 1%. More than half of the world's food energy is provided by three grain crops (wheat, rice and maize), and Australia produces less than 1% of the combined global harvest, almost all in the form of wheat. Australia's share of the world production of potatoes – globally the 4th most significant staple crop – is less than one half of one percent. In the Asia-Pacific region, bananas and coconuts are significant staple crops, and Australia produces only 0.3% of the world's bananas and virtually no coconuts. However, for a few crops of lower global significance for food security (oats, lupins, faba beans and canola) Australia produces a significant share of world production. Australia also produces about 5 Mt of the world's sugar from sugarcane – a crop which should really be given greater status as a food security crop.

Table 1. Global and Australian production in 2010 of crops significant for world food security. (Source: FAO on-line database).

Crop	Production (world); Mt	Production (Australia)[1]; Mt	Australia (% of world)
Wheat	651	22.1	3.4
Rice (paddy)	672	0.2	0.03
Maize	844	0.3	0.04
Potatoes	324	1.3	0.4
Cassava	230	-	-
Sweet potatoes	107	0.05	0.05
Bananas	102	0.3	0.3
Coconuts	62	-	-
Barley	123	7.3	5.9
Sorghum	56	1.6	2.9
Rapeseed (canola)	59	2.2	3.7
Soybeans	262	0.06	0.02
Oats	20	1.4	7.0
Lentils	4.58	0.14	0.03
Faba beans	4.3	0.2	4.7
Lupins	0.934	0.629	67.3
Sugarcane[2]	1685	31.5	1.9
Tomatoes	146	0.5	0.3

[1] Production of wheat in Australia in 2010 was above average for the decade, but below the production record of approximately 29 Mt in 2011/12. Australian production of rice was well below the normal level (approximately 1.0 Mt).
[2] The figures are for green cane, not for sugar. Australia currently produces about 5.4 Mt of sugar per year (about 3.5% of the world total), and provides about 9% of the international trade.

Despite its relatively low share of world grain production, Australia produces more grain than it needs to feed its population, and the surplus is exported and can contribute to world food security. Australian livestock products are also exported in considerable quantities. Most of the production data in the following sections come from ABARES (2010).

Wheat

About 75% of Australia's wheat production is exported. About 20% of the global wheat harvest is traded internationally, and Australia provides 15-20% of the global trade (ITS Global 2006). The market is quite segmented and competitive. Australia's major markets are in Asia (Indonesia, South Korea, Japan, Malaysia, China) and the Middle East (Sudan, Yemen, Iraq, Egypt).

Over a period of 100 years Australian wheat yields (grain/hectare) have increased both incrementally and in a stepwise fashion (eg Fischer 2009), with major steps corresponding to the adoption of new management packages (combinations of new agronomic practices and new varieties), including "breakthrough technologies". The most recent step, commencing in the 1980s and masked considerably by the millennium drought, saw average yields rise from levels of about 1.3-1.4 t/ha to about 2.0 t/ha in the last two years (2010/11 and 2011/12). This was a period in which the adoption of conservation tillage was a significant management change, along with greater use of nitrogen fertiliser and break crops. Agronomy underpinned about half this yield advance, and the interaction of management and varieties contributed another part. There was a strong focus on water use efficiency and on the capture of the highly variable rainfall and its storage in the soil. The area sown to wheat also increased by about 15%. Using decadal averages, production increased from levels of about 15 Mt in the 1980s to 20 Mt in the decade to 2009/10. After adjusting for the increased area and for productivity gains due to plant breeding, these figures suggest that Australian agronomy has lifted Australian wheat production by about 1.2 Mt per year above the levels of the 1980s (sufficient to feed 6.6-22.1 million people at 150-500 g/capita/day). However, if one uses current levels of 28-29 Mt and current grain yields of around 2.0 t/ha, the notional contribution rises to 4-5 Mt/year (sufficient to feed 23-91 million people). Whether this level of production is maintained remains to be seen.

Rice

Australia, in "normal" years, produces about 1 Mt of rice (about 0.2% of global production, sufficient to support 5-20 million people at rates of 150-500 g/capita/day in rice-based diets), but consumes only about 10 kg/capita/year (although consumption is rising rapidly). Because only about 5-7% (25-30 Mt) of global rice production is traded internationally and because most of the Australian crop is exported, Australian rice makes up 3-4% of the export trade. The prolonged millennium drought masked any yield increases due to better crop management, so in terms of my food security indicator the contribution of agronomy was negligible, even negative! However, it is worth noting that at the time of the global rice price spike in 2007/08, the failure of the Australian crop was raised as a possible contributing factor (*eg* Bradsher 2008). Although this has since been discounted (*eg* FAO 2011), the debate continues and it could perhaps be argued that Australian agronomy can contribute to world food security by helping to maintain Australia's rice production (already at global best practice in terms of yield and water use efficiency), and thus reducing price fluctuations. This assumes, however, that Australian rice producers in future will be allowed enough water to irrigate their crops.

Sugar

There is a lot of confused thinking and contradictory literature about the importance of sugarcane in food security. It is considered by some to be an "industrial" or "estate" crop, which competes with the production of other food crops (even more so if the crop is used to produce bioethanol), degrades the environment and reduces agro-biodiversity, marginalises women small-farmers and adversely affects human health. On the other hand, the sugarcane industry does provide a saleable food product and employment (but mainly for men?) and thus can increase household income; sugar is a component of many diets - it provides 7-9% of the global dietary intake (eg Evans 1998; Hagelberg 2003; FAO 2012), and in that sense is very much a staple food; and bioethanol enhances energy security, and might reduce the cost of fuel for agriculture. In Australia, a long period of sugarcane yield decline (from about 1970-1990) led to a major agronomic research project that provided a package of improved cropping practices by 2005 (Garside *et al* 2005). Where these are being adopted (current adoption in the central and northern areas is 15-20%; Garside A.L., personal communication), they are lifting sugar yields, and this may in turn contribute to world food security. Meanwhile, green cane trash blanketing (adopted from the mid-1980s onwards) and fertiliser and pesticide management practices emerging from the first Cooperative Research Centre for Sustainable Sugar Production (Lawn 2003) are reducing the environmental impact of sugarcane production in Australia, contributing to the long-term sustainability of the industry and, in that sense, to world food security.

Coarse grains (barley, sorghum, oats, triticale and maize)

Australia is a significant producer and exporter of barley, sorghum and oats (Table 1). Coarse grains are used mainly for livestock feed but they are also all staple grains in the sense that in some parts of the world they are consumed directly in human diets. Some 25-30% of the global barley crop is used in malting/brewing, and the same is true of the Australian crop; as a contribution to world food security this should be discounted and probably disregarded. Globally, the demand for coarse grains is increasing disproportionately as more grain is diverted to produce livestock and biofuel; the same trend can be seen in Australia, where the total area sown to coarse grains has increased by about 35% since the1980s, and where the total production has risen by about 65% (from levels of about 7 Mt in the 1980s to current levels of about 12 Mt) and the percentage exported has declined from about 50% in the 1980s to 40-45% at present.

Barley. About 60% of Australia's barley is exported, and Australia's share of the global barley trade is very high (about 30% of the malting barley trade and 20% of the feed barley trade). Australia exports feed barley to many countries but principally to Saudi Arabia, China and Japan. Australia's barley crop has almost doubled in the last 20 years, from around 3.76 Mt to around 7.38 Mt, mainly due to a 60% increase in the sown area. Quality requirements for brewing constrain yield advances, but yields have increased from around 1.2 t/ha in the 1980s to around 1.7 t/ha at present – a 22% yield gain. Calculating the possible contribution of Australian agronomy in this case requires some juggling of figures. Assume that, without advances in varieties and management, yields both on the land traditionally sown to barley and on the additional land sown to barley would have been the same as in the 1980s, and that the increased production *without* advances would therefore have been 3.76 Mt + 2.26 Mt = 6.02 Mt. If we reduce what remains of the production gain (ie 7.38 – 6.02 = 1.36 Mt) by 30% to remove the malting barley share we are left with 0.95 Mt attributable to advances in technology, and if we then assume that (as for wheat) Australian agronomy was responsible for about half of this, agronomy produced about 476Kt of feed barley – enough to produce 26K t of beef meat, sufficient in turn to provide 25-50 g/person/day to 1.4-2.8 million people. (Of course, in this case, a good deal of the barley is used in other animal industries).

Sorghum. Australia's production of grain sorghum has increased by more than 50% since the 1980s, to current levels of about 2 Mt, and most of this has been achieved through higher yields per hectare. These have increased from average levels of about 2 t/ha in the 1980s to 2.8 t/ha at present – a 40% increase. Most Australian sorghum is now used domestically; only about 20% is exported. If we assume that about half the production gain has been achieved by better agronomy, perhaps an additional 350Kt of sorghum per year – sufficient to produce about 19.25Kt of beef meat - enough to feed 1.1-2.1 million people at daily rates of 25-50g/head – has reflected the efforts of Australia agronomists.

Oats. Oats is a multi-purpose crop in Australia, with a significant percentage of the crop grazed during the vegetative stage and with another share used for high-quality hay which is frequently exported to Japan and Korea. Interpreting production data is therefore difficult. However, the sown area has *fallen* since the 1980s, as has total grain production (from about 1.5 Mt to about 1.3 Mt); and yields per hectare are only 15% higher than in the 1980s. Thus, with this crop, at least in relation to the harvested grain and the indicator being used, the food security contribution by Australian agronomists in the last 20 years has been negligible.

Triticale. While the production of triticale has increased threefold since the 1980s (to about 500Kt/year, occasionally exceeding 800Kt), most of the increase has resulted from an increase in the sown area. Most of the Australian crop is fed to pigs and chickens in Australia (Morris, undated), and most of this meat is consumed domestically. The contribution by Australian agronomists to global food security via this crop has thus been limited.

Oilseeds

Canola. Australian oilseed production is primarily (70-90%) canola, with cottonseed, peanuts, soybean *etc.* making up the rest. Here, the discussion will be restricted to canola.

Canola is a relatively new crop in Australia. During the 1990s production grew rapidly, from 99Kt in 1990/91 to a peak of 2.3 Mt in1999 (Cotton and Potter 1999; Potter *et al*. 2009). In the years since then, annual production has averaged about 1.7 Mt but has recently again reached levels of 2.3-2.4 Mt. Improved varieties have been critical to the development of the industry, but there is clear evidence of the contribution of agronomists. If we assume 36% commercially extractable oil content, and if we use 5-15 kg/capita/year as the consumption of edible oil in developing countries, the oil extracted from 1.7 Mt of Australian canola (about 612 Kt edible oil) would meet current consumption levels of 41-122 million people in developing countries, provided it was all used for food. If agronomy underpinned one third of this, the amount would be sufficient for 14-41 million people.

Grain legumes

Writing in 1987, Hamblin described the dramatic expansion of the Australian grain legume industry, which grew from an area of about 200 Kha in 1980 to 1.3 Mha in 1986. At that time, lupins (774 Kha) and field peas (365 Kha) were the main crops. The area peaked subsequently at about 2.3 Mha in about 2002 (data are hard to find) producing about 2.5 Mt of grain. Since then, the total area has declined to about 1.6 Mha and the relative importance of the five main grain legumes has changed: the lupin area has declined, the lentil and chickpea areas have grown and the field pea and faba bean areas have stayed roughly the same. Production (totalled over all five grains) has averaged about 1.8 Mt/year during the last decade. Ignoring the lupin contribution (which accounted for about half the total, and which is mainly used as livestock feed), the remaining grain (*ca* 823Kt/year) would provide 11-30 kg per year for 27-75 million people (India's current consumption *per capita* is around 13kg/year). If agronomy contributed only one quarter of this, its share of pulse production gains would notionally feed 6.8-18.7 million people. Although the land would probably otherwise have been used for cereal or oilseed production, and although it is almost impossible to separate the contributions of agronomy and plant breeding, it is worth pointing out that pulses are a major staple food in South Asia, where most of the Australian exports are consumed.

Pasture agronomy
There is no doubt that in the last 20 years production of beef, prime lamb and dairy products has increased significantly, but the key issue here is the contribution made by pasture agronomy (crop agronomy has been covered above). The challenge is made more difficult by the lack of good data on areas of sown pasture.

Dairy products. Almost half of Australia's annual milk production (in various milk products) is exported, mainly to countries in East and SE Asia. During the last 20 years the dairying area in Australia declined slightly to about 2.2 Mha, yet milk production rose from 6,262 ML in 1990 to a peak of 11,271 ML in 2001/02; it has since declined to 9,101 ML in 2011 (Dairy Australia 2011; Lubulwa & Shafron 2007). These trends in milk production partly reflected the size of the dairy herd, which rose from about 1.65 million dairy cows in 1990 to almost 2.2 million at the peak, followed by a decline to 1.6 million in 2011. However, the prime driver of the increased productivity was 50% higher productivity per cow (from 3781 litres/cow in 1990 to 5699 litres in 2011). This in turn resulted from a range of factors, including better nutrition. This was partly due to better pastures, which provide about 60% of the Australian dairy feedbase. The application of nitrogen fertiliser to dairy pastures roughly trebled during the 20-year period (Staines and Windsor, quoted by Eckard 2010), and this possibly underpinned a similar trebling of on-farm silage production and consumption. However, during the same period the use of grains and concentrates also doubled; by 2011 the industry was using about 2.5 Mt of grain (Dairy News Australia 2012). Given the complex interactions between feed sources it is difficult to quantify the contribution of pasture agronomy to the increased milk production, but it can be assumed to be high. A more thorough analysis is needed.

Beef and veal. Production of beef and veal increased by about 40% during the last 20 years. A good deal of the extra production (perhaps as much as 80%) came from Queensland. E.F. Henzell (personal communication) has concluded that in the period from the early-mid 1980s to about 2007, annual carcass weight production in Queensland increased by about 515 Kt. During the same period, about 5 Mha of land was sown to pastures (1.35 Mha of legume-based pastures and 3.6 Mha of grass-only pastures) using plant varieties and associated technologies mostly derived from the plant introduction, evaluation and pasture management research of agronomists. These newly sown pastures contributed about 87 Kt of the increased Queensland carcass production, or 60.9 Kt of meat, sufficient to provide 25-50 g/person/day for 3.3-6.7 million people. Small increases in beef cattle productivity also occurred in the Northern Territory and the Kimberleys, and the live cattle trade from northern Australia (averaging about 700,000 head/year from 1996-2010) contributed to food security in SE Asia. In southern Australia, it is less easy to discern a major contribution arising from pasture agronomy.

Mutton and lamb. Production of mutton fell during the last 20 years. However, driven by exports, production of prime lamb rose by about 30-40%. Total sheep meat production therefore changed very little. The live sheep trade declined during the period. In terms of the food security indicator, pasture agronomy therefore contributed little overall, but it very probably contributed to the sustainability of the sheep meat industries and to the profit of individual producers.

Summary
Using the most conservative of these estimates, the analysis suggests that during the last 20 years Australian agronomy underpinned the production of enough *additional* Australian cereal grains, pulses, oilseeds, meat and milk products to feed 6-10 million people a reasonably balanced diet. The assumptions are brave, and whether such numbers of people were actually fed is unknown.

Contribution of Australian agronomy to food production in other countries

Rationale
Australian agronomy contributes to food production in other countries directly through bilateral research activities and indirectly through Australia's involvement with the multilateral system of International Agricultural Research Centres. There are also indirect contributions through the building of research capacity in developing countries and through the contribution of Australians to the global pool of knowledge. Although the impact of training is hard to quantify, it is probably highly effective, as attested by the handful of quantification attempts (eg Gordon and Chadwick 2007).

Australia's bilateral contribution is principally managed by ACIAR, although AusAID also supports a significant Australian contribution, particularly through training.

ACIAR supports research activities in many fields of agricultural science. Since its establishment in 1982, ACIAR has supported more than 200 projects that have had a significant agronomic component. Independent benefit/cost analyses of a sample of these (perhaps biased towards those that have most obviously made a difference) are summarised in Table 2. The data indicate that these projects should deliver benefits of more than $2 billion over a 30-year timeframe. Such financial benefits should deliver food security benefits, but it is not always possible to estimate these from the available data. For the present paper, I have examined a few projects to estimate their contributions in terms of additional food generated (or likely to be generated).

Table 2. Benefit/cost analyses of ACIAR projects in which Australian agronomists were involved, and in which a significant component of the research was agronomic. (Sources: ACIAR Impact Assessment Series, Economic Assessment Series and miscellaneous papers).

Nature of the research	Countries that benefited	Estimated present value of benefits ($m)[1]	Benefit/cost ratio	Reference
Diagnosis of nutritional disorders of grain sorghum	India	9.2[2]	8.4	Menz 1991
Improvement of semi-arid tropical farming systems	Kenya	25.5	3.5	Lubulwa *et al*. 1995
Phosphorus and sulphur nutrition of tropical crops	Australia	2.4	3.4	ACIL Consulting 1998
Pigeonpea improvement	India	48.1	6.5	Ryan 1998
Control of *Phalaris minor* in the Indian rice-wheat belt	India	238	183	Vincent and Quirke 2002
Water and nitrogen management in wheat-maize production on the North China plain	China	216.2[2]	77	Harris 2004
Conservation tillage for dryland cropping	China, Australia	578.6	36.3	Vere 2005
Water management in public irrigation schemes	Vietnam	14.7	9.8	Harris 2006
Capacity-building to overcome production constraints to dryland sorghum	India, Australia	0[3]	-	Longmore, Gordon and Bantilan 2007
Forage legume development	Indonesia	1,308[2]	28	Martin 2010
Total		**2,440.7**		

[1] Dollars are for various years; eg for the first study listed, benefits are expressed in 1990 Australian dollars; for the last study, benefits are expressed in 2011 Australian dollars. 5% discounting was used in most examples. Where more than one b/c analysis has been undertaken, the lower estimates have been used.
[2] Net Present Value.
[3] This project was a mixture of plant improvement and modelling. The project generated prospective benefits of $201.5m (2007 dollars), but these were all for the plant improvement component. The agronomic component (training in APSIM modelling) subsequently led to significant but as yet unquantified benefits in Africa.

Improvement of semi-arid farming systems in Kenya

From 1983-93, an Australian CSIRO team led by Bob McCown, Roger Jones and Jeff Simpson undertook research in Kenya on small-farm crop production (Lubulwa *et al*. 1995). The research demonstrated, in particular, the essentiality of applying N fertiliser if worthwhile crop yields were to be obtained. The nature of the N response curves obtained by Brian Keating suggested that small doses of N (ie much less than the economically optimum and particularly the biologically optimum levels) applied close to young maize plants would provide a low-risk, high-return option for small farmers who were highly risk-averse. The technique later became known as *micro-dosing*, using application rates equivalent to about 17 kgN (50 kg ammonium nitrate)/ha, and has been further researched and advocated by ICRISAT since that time**.** In 2003/04, with support from DFID (the UK Department for International Development) and ECHO (the European Commission Humanitarian Aid Office), micro-dosing was delivered to 160,000 farmers in Zimbabwe, by providing each farmer with 25 kg of ammonium nitrate at no cost (Twomlow *et al*. 2010). Results from more than 1000 trials indicated that yield increases of 30-50% (typically around 500 kg/ha) were to be obtained. However, provision of free fertiliser is non-sustainable. Since 2006, the One Acre Fund (a US-based NGO) has been selling a package of technologies and support activities (including micro-dosing) that is currently being delivered to 145,000 small farmers in Kenya, Rwanda and Burundi and that will be delivered to 225,000 farmers in 2013 (Tony Kalm, personal communication). Excess farm produce (including maize) is being sold, and farm profits are being doubled. Using simple assumptions it seems likely that the current level of scale-up is producing an additional maize harvest of 20-30 Kt/year – sufficient to feed 100,000-500,000 people at consumption rates of 150-500 g/day. Adoption seems likely to increase rapidly.

A key question raised by this project is the attribution of benefits. Do we attribute the benefits to Australian agronomy, to ICRISAT, to the One Acre Fund or to some combination of these and other organisations? And a key message is that without a sustainable adoption pathway, the impact of research is likely to be low and delayed.

Pigeonpea improvement and management in India

From 1982-88 Don Byth (University of Queensland) led two projects that speeded up the development and adoption of short-duration pigeonpeas in India. ICRISAT was a key partner. According to Bob Lawn (personal communication), the key breakthrough was Eoin Wallis' agronomic work which showed that by adjusting agronomy to accommodate photoperiodic effects, high yields could be obtained from short-duration crops. It is quite clear that the work contributed to a significant increase in the area sown to pigeonpeas in India (from about 2.9 Mha in 1981-83 to 4.0 Mha in 1994-96) and favourably influenced the direction of ICRISAT's pigeonpea breeding program (Ryan 1998). However, problems of quantifying the production increase and assigning credit for this make it difficult to assess the contribution to food security made by the Australians.

Conservation tillage research on the Loess Plateau of China

From 1993-2003, Australian researchers led by Jeff Tullberg (University of Queensland) collaborated with Chinese counterparts on research on minimum tillage for wheat and maize on the Loess Plateau in northern China (Vere 2005). The research required in particular the development or modification of new planting equipment, and its wide-scale adoption required the production of thousands of small planters (there were 2 no-till seeder manufacturers in north China in 2001, and 20 by 2004) to suit the small tractors and small farm sizes characteristic of Chinese agriculture. Average wheat yields increased by 17.7%, and average maize yields by 12.3%. There were also significant production cost reductions, but these are ignored here. The estimated ceiling adoption level across 13 north-western Provinces was 17.5%, and at the time of the impact assessment there were 67.9 Mt of wheat and 65.2 Mt of maize produced per year in this region. Projected increased grain production arising from the research was therefore 2.1 Mt of wheat per year at ceiling adoption (sufficient to feed 11-38 million people at 150-500 g/capita/day) and 1.4 Mt of maize per year – sufficient to produce about 77 Kt of beef meat, enough to supply 4-8 million people at daily rates of 25-50 g/capita (perhaps twice this many if it were to be converted to chicken meat). Of course, there are many caveats in these extrapolations; in particular, the research (although effectively the first of its kind in China) would have been undertaken eventually by others, and the impacts were estimated *ex ante*; but the research *was* undertaken by the Australian/Chinese team, and was assumed by the independent assessor to have brought forward adoption by 3 years; and the technology is said to have been adopted on 0.42 Mha by 2005, and on more than 3 Mha by 2009 (He *et al*. 2011), suggesting that the ceiling adoption target was being approached.

Zero tillage and weed control in the Indian rice-wheat belt

From 1997-2000, and again since 2006, ACIAR has supported research in India led by Gurjeet Gill (University of Adelaide). The first project focussed particularly on the control of the annual grass *Phalaris minor* in wheat crops, using zero tillage as one part of a weed control package that included new herbicides. The second project is developing direct drilling technology for rice crops. The impact of the first project has been assessed by Vincent and Quirke (2002). The project provided sustainable and profitable weed control practices that also provided a yield advantage of 150 kg/ha by allowing the crop to be planted a month earlier. These practices have already been adopted on more than 1 Mha in Haryana. This additional wheat production (about 150 Kt/year) would provide food for 0.8-2.7 million people at consumption rates of 150-500 g/day - a *direct* food security benefit. Of course, the main *indirect* benefit in terms of food security is the protection of previously existing wheat yields.

The second project has shown that the yield penalty associated with direct-drilled rice can be eliminated by sowing rice at the same calendar date on which rice is usually sown in nurseries for subsequent transplanting. Better machinery has also been developed, allowing seeding rates to be reduced significantly. It is too early to predict the likely *direct* food security benefits, but the *indirect* benefits in the reduced costs of energy and labour inputs are likely to be very large. In both these projects, as with zero tillage in China, the development and success of a local equipment manufacturing industry has been (and will be) crucial to adoption.

Forage shrub legumes in SE Asia

Since 1984 ACIAR has invested in about 50 projects involving tropical forages. Those concerned with *Stylosanthes* (globally the pre-eminent tropical forage genus) have probably delivered significant benefits, but were mostly concerned with plant improvement and plant protection (ie not agronomy) and their payoff has not yet been quantified. About a dozen projects have been mainly focussed on shrub legumes such as leucaena in SE Asia. All of the shrub legume projects had a strong agronomic component but many have also involved some plant improvement and other research. The current project is led by Max Shelton (University of Queensland), but many Australians (including Shelton) have led or been involved in previous projects. The research has shown consistently that very large gains in livestock (cattle) production could be obtained, and Martin (2010) has estimated that the Net Present Benefits of the research exceed $1 billion (Table 2). However, most of these benefits are still prospective and have been excluded from this paper.

Other bilateral projects involving Australian agronomists

Prior to 5 years of civil war (1970-75), Cambodia was a rice exporting nation. By 1975, rice plantings had been reduced by 77% and rice production by 84% compared with 1970 levels (Nesbitt 2003). By 1979, under the murderous Pol Pot regime that followed the war, a quarter of the population (particularly better-educated people) had perished and Cambodia had an annual rice deficit of 0.2-0.5 Mt. The Cambodia/IRRI/Australia Project (CIAP) was funded by AusAID from 1987-2001. Led by Harry Nesbitt, it included agronomy, plant improvement and capacity-building. By 1995 Cambodia was again self-sufficient; by 2002 it was again an exporter; and since 2007 it has exported about 1.5 Mt/year (the precise amount is difficult to estimate). There is no doubt that this project contributed to the food security of the 15 million people of Cambodia during the last 20 years, and through rice exports probably supports another 8-27 million at consumption rates of 150-500 g/person/day. Perhaps half this contribution might be attributed to Australian agronomists – say 7.5 million Cambodians and 4-13 million others.

The Lao/IRRI Project (1990-2006) was funded by the Swiss aid program, but was led from 1990-2001 by John Schiller, an Australian agronomist employed at IRRI (Barclay and Shrestha 2006). The project led to an increase in rice production in Laos from about 1.5 Mt in 1990 to 2 Mt in 1999 and 2.5 Mt in 2004 – a production gain of about 0.7 Mt at the conclusion of Schiller's leadership. Most of the increase was due to adoption of improved IRRI varieties, but capacity-building was another major factor. If one attributed (say) 10% of the yield increase to agronomy and another 10% to capacity-building, and one third of this to Schiller's leadership and Australian training, one might say that 0.25-0.8 million people may have been supported by "Australian agronomy"; but at this level of inexactitude the exercise is almost futile.

Extrapolation

Using the most conservative of these estimates, this handful of bilateral projects may have underpinned the production of enough additional grain to support about 23 million people through the efforts of Australian agronomy and/or agronomists. They are likely to be among the most beneficial of the complete set of agronomic projects funded by ACIAR or AusAID, but it is also unlikely that the other projects would have delivered no food security benefits at all. However, let us conservatively assume that the Australian agronomists' contribution to world food security through the bilateral program in the last 20 years is in the order of 23 million people. This estimate depends very heavily on the extent to which conservation tillage has been adopted in China, and on the attribution of impacts from the CIAP Project in Cambodia.

Multilateral programs: the International Agricultural Research Centres

The CGIAR system of International Agricultural Research Centres (IARCs) has food security as only one of its 4 goals (the others are reduced poverty, improved nutrition and health, and sustainable management of natural resources). This tension among desired outcomes is reflected in seemingly endless change in its geographical and disciplinary focus and in structural organisation. The most recent reorganisation has led to the establishment of 15 cross-IARC research programs. Agricultural productivity, however, is at the heart of much of its research.

The most recent assessment of the impact of the CGIAR Centres (Renkow and Byerlee 2010) indicates that their plant breeding has made a dramatic contribution to world food security by lifting crop productivity; it contributed almost 30% of the global yield increase in developing countries of ten field crops, including wheat where an impressive 50-60% is claimed. Agronomy is squeezed into natural resources management (NRM), and the impact of the IARCs in this field has been much less dramatic, partly because NRM research deals with systems and its impacts are much more country- or region-specific (rather than global). The authors are reduced (as I have been) to using examples, and they single out zero tillage as an example of significant impact. Numerous Australian agronomists have been involved in the research of the IARCS - as CGIAR employees, as research partners in bilateral projects such as those described above, or in ACIAR's "Special Purpose Grants" which link Australian researchers directly to the IARCs. There seems to have been limited benefit/cost analysis of these grants. A notable Australian contribution to tropical pasture development was made by Bela (Bert) Grof, who was associated with the development of signal grass (*Brachiaria decumbens* cv. Basilisk), first in Australia and then (with CIAT) in South America where it is now sown on tens of millions of hectares. The adoption and impacts extended well into the 20-year review period.

Training and leadership

Australia has invested heavily in training agricultural scientists from developing countries in a wide range of fields, including agronomy. The impact of training is hard to quantify, and there are few data on which to base an assessment of its contribution to world food security. Recently, a new framework for assessing the impact of training has been developed for ACIAR and the Crawford Fund (Gordon and Chadwick 2007). While its widespread application lies in the future, two "rules of thumb" that emerged from the literature review are particularly helpful: (a) improvements in human capital explain about 30% of the increase in total factor productivity; and (b) about half of the increased agricultural productivity can be attributed to interstate or international R&D spillover effects.

Australian agronomists have contributed to food security through leadership positions in other countries and international organisations. Dozens of names could be mentioned. By focussing and managing R&D, they have made contributions to food security that cannot be quantified but are surely significant.

Pulling it together

Based on this analysis the work of Australian agronomists during the last 20 years may have underpinned the production of enough additional grain and livestock products to feed 30 million people. This assumes that the food is eaten, and is not lost post-harvest or used for alternative purposes. About one third of the contribution has been made in Australia and two thirds overseas (principally in Asia). Limited confidence can be placed in the data for the overseas contribution. The data for the contribution in Australia are more robust but are obscured by the millennium drought. In virtually every case, attribution issues are challenging.

Both in Australia and overseas, zero tillage has been a major component of the success of Australian agronomy. While this technology was not conceived or first invented in Australia, Australia has become a global leader in its adaptation and application, and has successfully transferred it to developing countries in Asia.

What lies ahead?

The future is always hard to predict, but in this case almost impossible. The fallback or default answer is:

“More of the same”. There is probably enough inertia in the system (both in terms of projects now under way and technology awaiting further exploitation) to suggest that the current contribution will be maintained for a decade or so.

However, beyond this timeframe the contribution will be affected by decisions of many kinds, both in Australia and overseas, that are outside the control of agronomists and that will affect both inputs and outputs. Profit (not food security) is the primary driver of Australian agriculture, and our future direction will be influenced by the same three pressures that have always been in play: our ability to capture markets and deliver a product; our ability to access and pay for new technology; and our ability to accommodate the environmental expectations of other, mainly city-dwelling Australians. Will Australian farmers continue to produce crops and livestock in about the current mixture, or will cost/price pressures change the mixture away from food-producing crops and livestock towards commodities that have little impact on food security (wool, cotton, grapes, biofuel crops)? Will we have enough Australian agronomists to maintain our share of the global research agenda and the global agronomy publications? The number of scientists working on sown tropical pastures has now fallen from a peak of about 125 during the 1970s to the pre-World War II level of about a dozen (Clements and Henzell 2010); a decline has also occurred for production-focussed crop scientists in the Australian tropics (Lawn 2011). Rebuilding the agronomic base in the tropics (if it is to occur) will be a generational challenge.

Internationally, our contribution will be affected very significantly by where we work. We already know that about 40% of the world’s food is produced on about 250 Mha of irrigated land, and Cassman (1999) has suggested that food security will depend on further intensification of crop production in the 4 major cropping systems that already underpin world food supply: irrigated lowland rice systems in Asia; irrigated rice/wheat systems in north India, Pakistan, Nepal and southern China; temperate non-irrigated maize-based systems on the North American plains; and temperate non-irrigated systems in north-west and central Europe. There is a contrary view that there is more advance to be made per unit of research investment in dryland agriculture, but it seems to me that only climate change will alter the fundamental pattern of agriculturally-endowed regions.

However, the Australian aid program is influenced by other issues, notably poverty reduction, and our aid program is likely to increasingly target the less endowed regions of Africa, west Asia and the Middle East. There are already signs that this is happening (eg the establishment within ACIAR of the Australian International Food Security Centre with its strong African focus, and the involvement of CSIRO’s Sustainable Agriculture Flagship in a number of partnerships and alliances in Africa).   While this will play to our agronomic strengths in dryland cropping, it may reduce the effectiveness of our investment in terms of people fed per agronomic aid dollar spent.

Will we be smart enough to develop better bilateral research collaboration arrangements with China, India and other heavily-populated regions as they “graduate” from the aid program? Without the aid dollar, will private investment and our trivial international scientific cooperation funding be adequate to meet the public food security interest? Will our State-based employing organisations allow their staff to work on international food security issues?

New paradigms will emerge, driven by necessity, scientific discovery and profit. The operating environment for agronomists is changing before our eyes: disinvestment in “public” agricultural science, changing food preferences, genetically modified plants, adaptation to climate change, possible breakthroughs in photosynthesis, reduced energy inputs and opportunities for biofuels, pressure from environmentalists *etc*. What has not changed is the key imperative: people must eat to survive, and more than 80% of the world’s food is derived directly from plants (Evans 1998). As long as that situation continues, agronomists will be needed.

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