Chapter 19

Diversifying the cropping phase

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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).

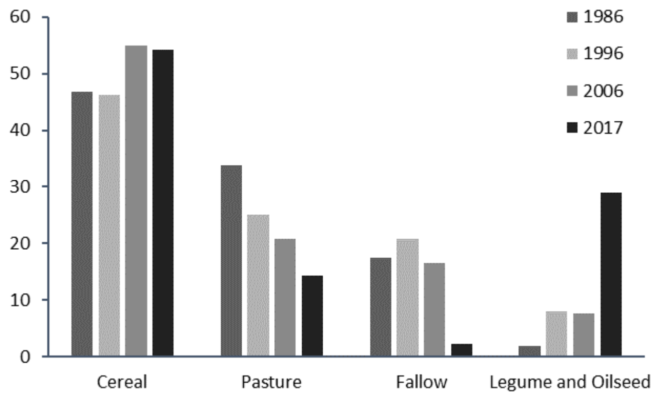

Figure 1. Percentage of paddocks recorded for each land use during the 1986, 1996, 2006 and 2017 Victorian land-use survey (Moodie and Sonogan, unpublished)

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 20*17) 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 30ºS (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 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.

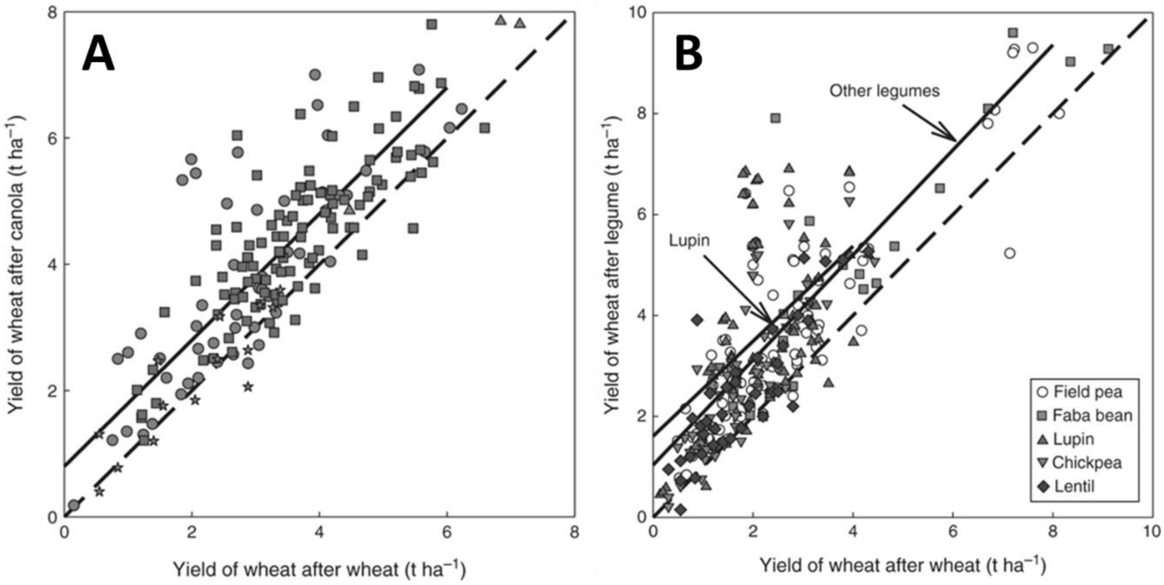

Figure 2. Yield of wheat after (A) canola compared with wheat after wheat growing in the same experiments. Symbols represent experimental locations. Circles, Australia; Squares, Sweden; Triangles, Other Europe; Stars, North America. (B) grain legumes compared with wheat after wheat growing in the same experiments. The dashed lines represent equal yields and the solid lines represent fitted equations. Symbols represent field pea, ○; fababean, ■; lupin, ▲; chickpea, ▼; lentil, ♦. The 1:1 dashed line represents equal yield (Angus *et al.* 2015)

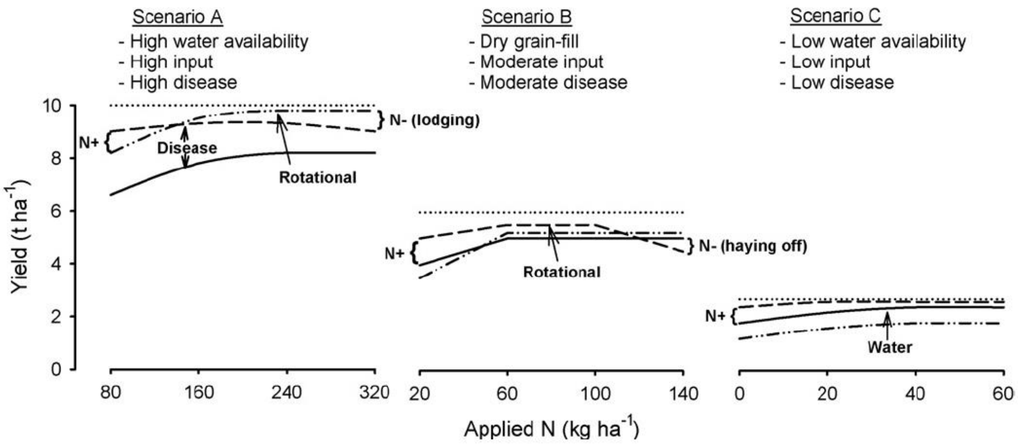

Figure 3. Typical responses of wheat to previous wheat (solid), legume (dashed) and oilseed (dot-dash) break crops under different potential yield scenarios and different N application rates. The dotted line shows the potential yield. The mechanisms causing responses to differ between previous crops are shown (N = nitrogen, ± 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 struformis* (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 N_2 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 *et al*. 2001
	56 to 97 (167 to 306)	kg N/ha	Unkovich *et al*. 2010
Lucerne	37 to 128	kg N/ha	Peoples *et al*. 2001
	83 (2 to 284)	kg N/ha	Unkovich *et al*. 2010
Grain pulses	14 to 160	kg N/ha	Peoples *et al*. 2001
	24 to 90 (24 to 227)	kg N/ha	Unkovich *et al*. 2010
Grain pulses (above + below ground)	30 to 40	kg N/plant	Peoples *et al*. 2009
Fababean	113 (8 to 271)	kg N/ha	Evans *et al*. 2001
	90 (1 to 205)	kg N/ha	Unkovich *et al*. 2010
Lupin	80 (-29 to 247)	kg N/ha	Evans *et al*. 2001
	136 (26 to 288)	kg N/ha	Unkovich *et al*. 2010
Field pea	40 (-46 to 181)	kg N/ha	Evans *et al*. 2001
	84 (8 to 227)	kg N/ha	Unkovich *et al*. 2010
Chickpea	6 (-67 to 102)	kg N/ha	Evans *et al*. 2001
	40 (0 to 24)	kg N/ha	Unkovich *et al*. 2010
Lentil	61 (1 to 111)	kg N/ha	Unkovich *et al*. 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 N_2 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 N_2 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 %Nfda > 42-44% (Evans *et al*. 2001). In these northern summer rainfall dominant grain regions there was a lower reliance of legumes on N_2 fixation for growth (19-74%) and more variable relationships between N_2 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 N_2-fixation, while in the north the soils, climate and farming systems provide conditions that make N_2 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 N_2 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 *et al.* 2015, Peoples *et al.* 2017, Evans *et al.* 2001
Grain legumes – South West Australia	90	kg N/ha	Evans *et al.* 2001
Brown-manured (BM) legumes	60 ± 16	kg N/ha	Peoples *et al*. 2017
Grain legumes	35 ± 20	kg N/ha	Peoples *et al*. 2017
Grain and BM legumes on rainfall basis	0.15 ± 0.09	kg N/ha/mm	Peoples *et al*. 2017
Grain legumes on residual shoot DM	9 ± 5	kg N/ha/t/ha	Peoples *et al*. 2017
Total legume residue	28 ± 11	%	Peoples *et al*. 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 NH_4^+ 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				
				Mineral N		pH				Root		Other		
Crop option	*High or irrigated*	*Medium*	*Low*	*High*	*Low*		*Grasses*	*Broad leaf*	*Herbicide residues*	*Take-all*	*Crown rot*	*Yellow spot*	*Blackleg / schlerotinia*	*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 desirous 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.

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