Chapter 20

Crop-livestock integration in Australia’s mixed farming zone

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Introduction

Mixed crop-livestock systems exist where farms operate a mix of crop and livestock enterprises as part of their farming business. Mixed farming businesses occur across most of Australia’s broad-acre cropping zone. This zone covers some 57 M ha including 25 M ha of crops and 23 M ha of pastures and supports over 40% of Australia’s livestock equivalents (Bell *et al.* 2014, Healy *et al.* 2013). Due to the nature of reporting of agricultural production and farm data in Australia it is difficult to discern the actual number and area of crop-livestock systems. Based on an analysis of ABS and ABARES data, Healy *et al.* (2013) estimated that in 2010-11 there were 21,300 mixed farming enterprises: 11,600 farms were classified as ‘grain-sheep’ or ‘grain-beef cattle’ farms, 5,600 were predominantly grain farms but had at least 250 sheep or 50 cattle, and 4,100 predominantly livestock farms that also undertook crop production. About 83% of all cropping farms were mixed farms. The continued dominance of mixed crop-livestock systems across Australia is a notable distinction from agriculture in other developed countries (*e.g.* Europe, North America), where systems have been increasingly specialised (Russelle *et al.* 2007, Wilkins 2006).

Crop-livestock systems in Australia occur across a diverse range of agro-climatic regions (Figure 1). These span from the sub-tropical semi-arid regions of central and southern Queensland to high rainfall, temperate environments in south-eastern Australia to the Mediterranean climatic zones of south-west Western Australia and southern South Australia. Similarly, the soils that support agriculture across these regions also vary greatly, from high clay content soils with high water holding capacities (*e.g.* southern Queensland and northern NSW) to shallow soils with significant sub-soil constraints (*e.g.* southern Victoria and South Australia) to deep sandy soils with low water holding capacities (*e.g.* northern Western Australia). As the nature of cropping and livestock enterprises equally vary across these diverse agro-ecosystems, the type of practices involving integration of crops and livestock also vary.

While there have been some significant changes crop-livestock farming across Australia over the past 30 years, these systems have evolved, and new technologies have emerged that suggest they will continue to persist into the future. In this chapter, we explore how some of these practices have emerged or changed in different regions and how they offer advantages to mixed crop-livestock farmers.

Drivers of crop-livestock integration

Crop-livestock systems offer a range of benefits and challenges for farmers that drive the adoption or use of these systems (Bell and Moore 2012). First, risk mitigation to climate and price variability is provided through diversification of enterprises, particularly if their annual economic returns are not correlated. In many cases annual farm returns from livestock and crop production are not highly correlated and hence annual variability in farm income is reduced where a combination of both enterprises contributes. Cropping enterprises are often associated with higher potential profitability but higher risks, while livestock enterprises provide a more consistent cash-flow and often provide needed revenue during dry seasonal conditions when crop production is not profitable. Further risk management opportunities exist where there is capacity to tactically adjust activities in response to either climate or price fluctuations. For example, capacity to shift land from crop or livestock uses if current prices are more favourable to one over the other, or if seasonal conditions mean that a crop is no longer profitable (*e.g.* drought or frost damage) using this as a forage source for livestock.

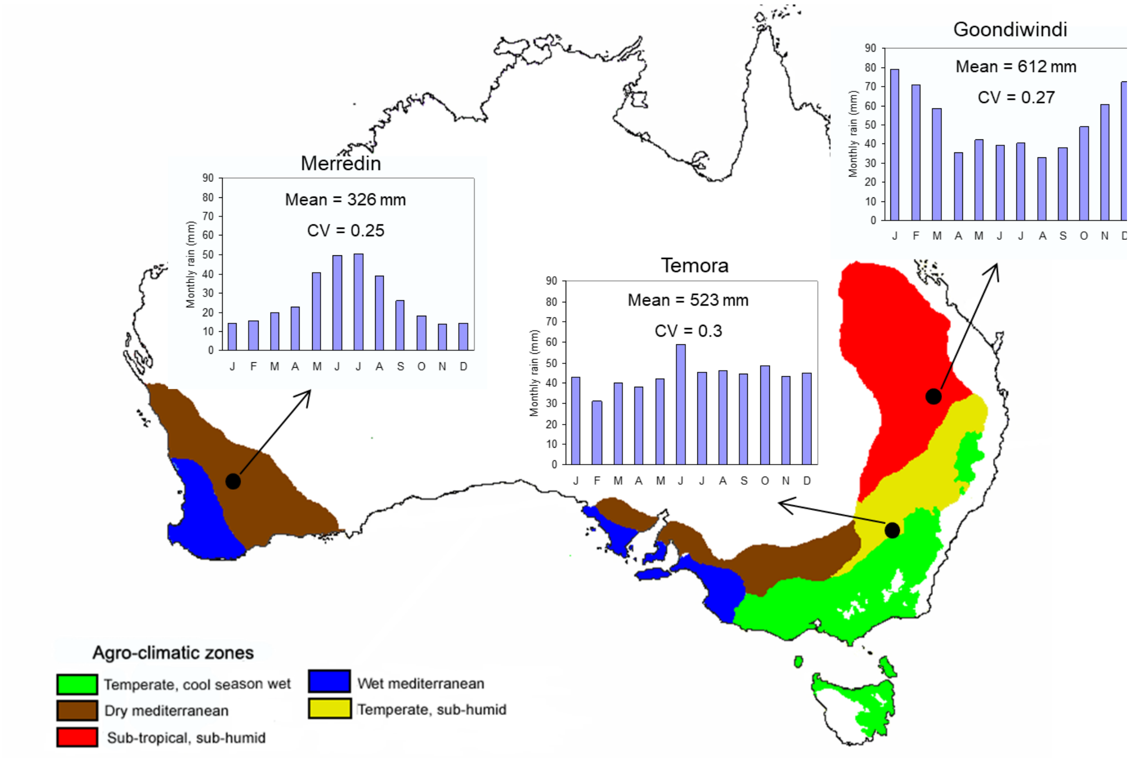

Figure 1. Agro-climatic regions where mixed crop-livestock farming operates in Australia. Agro-climatic zones are defined by Hutchinson *et al.* (2005). Insets demonstrate location differences in rainfall seasonality, amount and variability (co-efficient of variation, CV) in rainfall across regions

Secondly, mixed farm enterprises often emerge where the farm resources (land, labour or machinery) need to be allocated to different activities to maximise farm profitability. This is most obvious where there is variability in land capabilities or soil types, meaning that livestock are favoured on certain land types and cropping on others (Lacoste *et al*. 2016). Where land capability across the farm varies little there is less inclination to operate a diversity of enterprises on the farm. Allocation of farm labour and machinery resources can also influence crop-livestock systems. For example, where farm activities between crops and livestock are complementary this can allow for better use of labour resources available or more stable labour input requirements. On the other hand, competition for these resources can also impede the integration of crops and livestock.

Thirdly, crop-livestock integration can bring about significant production complementarities and resource maintenance benefits. Nutrients can be transferred from livestock to cropping to reduce fertiliser inputs and conversely crops can provide highly valuable forage sources for livestock enterprises. Where these transfers can occur with minimal costs they can be highly beneficial to the farm's efficiency. However, when there are significant costs associated with these resource transfers (*e.g*. transport costs between farms or regions or negative consequences for subsequent crop or livestock production) these benefits diminish and greater care (and analysis) is required to quantify the benefits relative to costs. Integrating livestock with cropping systems, particularly via pasture rotations, can help maintain or rebuild the resilience and function of soils for crop production via increasing soil organic matter and soil fertility, improving soil biological activity, reducing pest and disease populations or depleting weed populations in the soil seed bank. Reduced offsite environmental problems such as dryland salinity, soil erosion and water turbidity can also be achieved, though these benefits are often more associated with specific practices than with crop-livestock systems *per se*.

While many farming businesses may operate a mix of crop and livestock enterprises the degree that these are integrated varies greatly. That is, some farmers may operate both enterprises in their farm in response to different land capabilities and to provide some risk mitigation benefits, but little further integration occurs. On the other hand, high levels of integration occur where land frequently changes between uses for crop or livestock production or in some cases this is happening simultaneously (*e.g.* grazing dual-purpose crops, pasture cropping). The degree of integration is influenced by the relative importance of each of the drivers of these systems outlined above. Integration of crop-livestock systems also involves greater complexity and higher management focus to capture their benefits. Yet, in many cases farms are operating with lower labour availabilities and greater management attention is required to optimise each of the elements of the farming business. Hence, social and technical capacities to manage these more complex farming systems is a critical aspect that is often underappreciated when addressing the advantages of integration of crops and livestock.

Trends and status of crop-livestock integration in Australia

Over the past 40 years there have been significant trends in farm and crop areas, livestock numbers and labour use on Australian cropping farms. Figure 2 updates the data presented in Bell and Moore (2012).

The unusually high price for wool during the 1980s, due to the reserve price scheme, was an important driver. The total area of cropping farms decreased by about a third during the 1980s, as many mixed farmers shifted their land use to the point where they were no longer classified as "mixed livestock and cropping" farms but were primarily sheep producers. Within the remaining cropping farms, the area under crop decreased by about 3 M ha from 1980 to 1990, the average stocking rate increased by about 5% and the proportion of DSEs present as sheep increased from 75% to 80%. After the end of the reserve price scheme for wool in 1991, prices for wool quickly fell from 700 c/kg to 430 c/kg. Subsequently, the total area of cropping farms recovered rapidly, and the area of land under broadacre crops increased steadily from about 1990 to 2010 (Figure 2). The percent of cropping land on Australian mixed farms has grown from around 28% in 1975-1980 to over 40% since 2010. This change has not been universal across the mixed crop-livestock zone, with very large increases (nearly double) in cropped area observed in southern and Western Australia, while NSW and Queensland have not changed dramatically.

At the national scale, there was a sharp drop in livestock on mixed farms after 2002 (Figure 2b). This reduction in livestock numbers was a result of both substitution of broadacre crop production for livestock production, and a reduction in the number of DSEs per non-cropped hectare from 2.8 DSE/ha in 2002 to 2.1 DSE/ha in 2010. This occurred despite a marked increase in the relative price of lamb meat that was like the wool price spike during the 1980s (Figure 3). It was thought that the 'Millennium drought' of 2002-2008 may have been holding back increases in livestock numbers in response to high relative lamb prices (Bell and Moore 2012), but at the national scale this has not yet been observed. Since about 2010, the 20-year trends toward a greater area of cropped land and fewer livestock have both slowed or halted.

One possible explanation is that the productivity of broadacre crop production has improved more rapidly than the productivity of livestock production over this period (Dahl *et al.* 2013). This disparity in relative productivity of the two sectors may be continuing to affect the relative financial attractiveness of cropping and livestock production. However, productivity growth in the sheep and beef industries exceeded that in the grains industry between 2000 and 2010 (Dahl *et al.* 2013), so it may be expected that this may indeed see livestock numbers again increase in the mixed farming zone.

A clear trend in these data is the increase in farm size that has also occurred over the past 40 years, increasing from 1200-1500 ha in 1975-1980 to over 2000 ha since 2010 (Figure 2c). This has also had a corresponding effect on the labour use per ha, so that now a labour unit is managing around 1000 ha on mixed farms in Australia (Figure 2d). This declining labour intensity is likely to be an important driver of crop-livestock systems in the future and may be a factor influencing the persistence of reduced livestock numbers in many mixed farming regions.

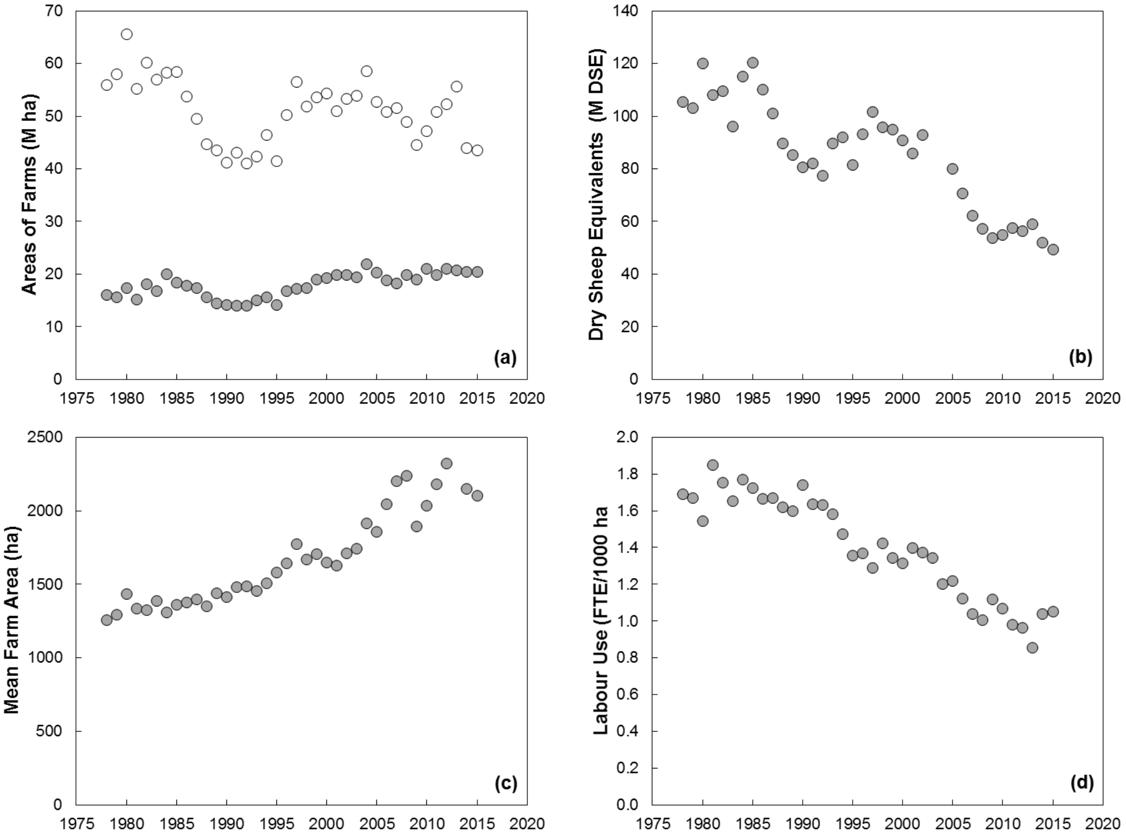

Figure 2. Major trends in Australian cropping farms (*i.e.* those classified in the Australian Agricultural and Grazing Industries Survey as "mixed livestock and cropping" or "wheat and other crops") over the period 1978-2015. (a) Total area of cropping farms (○); total area under crops in cropping farms (●). (b) Total livestock number, expressed as millions of dry sheep equivalents. (c) Mean area operated per farm. (d) Labour use per unit area; one full-time equivalent (FTE) equals 48 weeks of labour time (for details of calculations, see Bell and Moore 2012)

There are relatively limited quantitative data that provide information on the extent of crop-livestock integration activities on Australian mixed farms. The 2012-2013 ABS survey estimated that a total of 17,600 farms included a pasture phase in crop rotations, compared with 29,200 farms that grew cereal crops. From this it can be deduced that about 1 in every 5 mixed farms completely separates cropping and pastures, and that 4 in 5 practises at least some crop rotation. However, on an area basis, the proportion of pastures in crop rotations appears to be lower. Healy *et al.* (2013) estimated 23.6 M ha total area of pastures on mixed farms, while the 2012-13 ABS estimate of pastures in rotations was only 6.4 M ha. This implies that many – perhaps a majority – of crop-livestock farms have a high proportion of permanent pastures (>70%) and far less is used in crop rotations. Pasture-cropping, growing grain crops into existing pastures, was only reported on 0.2 M ha or <1% of area under broad acre crops (ABS 2013).

According to ABS data (2011-2015) an average of 3.8 M ha of crop stubbles was grazed nationally out of an average total area of broadacre crop residues of 21 M ha. This area of grazed crop residues (18%) is much lower than that reported by Healy *et al.* (2013); their estimate corresponds to 14-15 M ha of residue area grazed by stock on mixed farms. The reason for the discrepancy is not apparent. Healy *et al.* (2013) estimated that 3.2 M ha of grain crops were grazed by livestock, or about 13% of their estimate of the area of crops on mixed farms. The survey did not distinguish between dual-purpose grazing of crops later intended to recover for grain yield and crops sacrificially grazed.

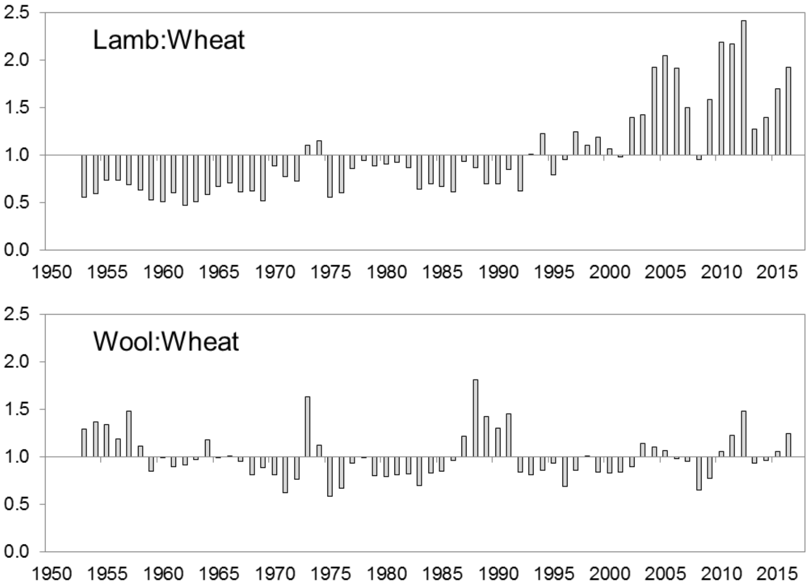

Figure 3. Fluctuations in prices between livestock products (wool and lamb) relative to the price of wheat between 1953 and 2015. Values are ratios of the ABARES index of the price of each commodity, scaled so that for the period examined the long-term average for each equal 1.0

Changing crop-pasture rotations

The intensification of cropping across the mixed farming zones of Australia has been associated with significant changes in the use and role of pastures in crop rotations. Traditional ley farming systems using self-regenerating annual legumes, such as subterranean clover and annual medics, have been in decline (Howieson *et al.* 2000). Cheap nitrogen fertilisers have reduced the importance of inputs from pasture legumes in rotations. A range of profitable break crops (*e.g.* canola, lupins, field peas, lentils, chickpeas and fababeans) have reduced the frequency of pastures in crop rotations, which has greatly reduced the viability of pasture leys regenerating from seed after several years. At the same time, the lower returns from livestock enterprises and extended drought periods during the 2000s resulted in reduced inputs such as phosphorus fertiliser and weed control during the pasture phase. Herbicide residues like sulfonylureas limited pasture legume production particularly nitrogen fixation. These combinations of factors have resulted in pastures moving to phased rotations (1-5 years), where farmers re-sow the pasture/forage (annual or perennial) after each cropping sequence. This has required a change in the plant attributes required but also increased the opportunities for other forage species to be used (especially perennial pastures).

Pastures or forages are now being increasingly deployed in cropping systems because they offer weed management or soil structure and health improvements. Annual ryegrass is one of the most problematic weeds in cropping systems, but a high-quality livestock feed. There are opportunities to utilise annual ryegrass with livestock as well as for conserved fodder for subsequent use in feed gaps and drought to reduce seed set (Piltz *et al.* 2017). Alternatively, grazing preference can allow selective removal or reduction in prevalence of problematic weeds such as annual ryegrass. For example, the annual legume biserrula is less palatable than annual ryegrass and strategic grazing can be used to reduce ryegrass populations (Loi *et al.* 2005). Some studies have shown competitive pastures or fodder crops can greatly reduce annual rye grass populations but other weeds (*e.g.* wild radish) were less effectively managed. Winter cleaning of pastures using selective herbicides to remove grasses has been demonstrated to increase significantly the yield of subsequent crops for up to 3 years (Harris *et al.* 2002). This may provide multiple benefits of improving N supply (Harris *et al.* 2002), and reducing disease carry over, and reducing subsequent weed numbers. Later ‘spray-topping’ does not sufficiently reduce grass weeds and hence results in greater disease presence. In areas where soil structural constraints are a problem, deep-rooted pastures (*e.g.* lucerne) that can penetrate and colonise hostile subsoils are preferred as they leave root channels that can later be used by other crops to access deep soil water. This has now been shown to have benefits for subsequent crop productivity on these poorly structured soils (McCullum *et al*. 2004). Perennial grass-based pastures have also been shown to improve greatly soil aggregation, and rebuild soil biological activity (Bell and Garrad 2017).

Next-generation annual legumes

The production and persistence of traditional pasture legumes including subterranean clover and annual medics have been challenged in recent decades because of climate change and changing agricultural practices. Increasing frequency of 'false breaks' result in germination of large numbers of seedlings of subterranean clover and annual medics that subsequently die. Further, because of relatively shallow root system of these species (Loi *et al.* 2005), moisture stress in spring can result in plant death prior to seed set or significantly reduced seed set. These two factors deplete the soil seedbank over time and lower populations of these species in pastures (Howieson *et al.* 2000, Loi *et al.* 2005). In addition, harvest methods for subterranean clover are costly and can cause increased risk of soil erosion (Loi *et al.* 2005). While the use of lucerne has expanded, particularly in eastern Australia, to fill the gap left by traditional annual legume species, its use is limited by poor tolerance of both the lucerne plant and its symbiont to acidic soil conditions and relatively poor tolerance of waterlogging (Charman *et al.* 2008). Additionally, lucerne requires higher level grazing management for persistence than traditional annual legume species and it is difficult to maintain companion species in lucerne pastures (Wolfe and Dear 2001).

In response, Australian plant breeders and rhizobiologists have developed a range of new legume/symbiont options for mixed farming systems. Many of the species and their associated symbionts have not been previously commercially available for use in Australian or world agriculture. The following characteristics were the focus for these new species:

- High levels of seed production with seed able to be easily harvested using conventional farm machinery;
- Higher levels of hard seed to protect against false breaks and assist in maintenance of a long-term soil seed bank with capacity to survive through a cropping phase and regenerate without the need for resowing;
- Hard seed break down patterns suitable for a range of agroecological regions and farming system uses including use of novel pasture establishment strategies (*e.g.* twin and summer sowing;
- Deeper root systems to facilitate greater survival and production (including seed production) under adverse climatic conditions and to prolong the length of the growing season and feed quality;
- Effective, readily manufacturable rhizobium to facilitate nitrogen fixation in new plant species; and
- Rhizobium with saprophytic competence to ensure persistence through cropping phases in the absence of the host plant.

The developed annual legume species show significant advantages over subterranean clover in many of these attributes (Table 1). In addition, some new annual legume species and their symbionts have improved tolerance to acid soil conditions (*e.g.* biserrula and serradella), waterlogging (*e.g.* gland clover) and resistance to common pasture pests including red-legged earth mite (*e.g.* gland clover). Research has shown these species to be well adapted to many agroecological regions where their production (herbage and seed) has generally been comparable with traditional species and sometimes superior under adverse seasonal conditions (Hackney *et al.* 2015, Loi *et al.* 2005, Loi *et al.* 2012). In addition, new legume species can enable alternative pasture establishment methods (see below) which can further enhance their productivity and resilience (Hackney *et al.* 2015, Loi *et al.* 2008)

Following first year seed set and because of their relatively high hard seed levels, many of the new generation annual legumes can be used as 'on-demand' pasture breaks in cropping rotations (Hackney *et al.* 2015). That is, the annual legume can regenerate from soil seedbank reserves without the need for resowing because of their high levels of hard seed. The duration of the cropping phase applied over such legumes is dependent on the hard seed content of the legume species (and the variety within species) and the rate of hard seed break down.

Table 1. The hard seed content (%), rooting depth (m), herbage mass (t DM/ha), seed yield (kg/ha) and harvestability index of a range of annual legume species from field trials in Western Australia and/or New South Wales

Species	Hard seed (%)	Root depth (m)	Herbage mass (t DM/ha)	Seed yield (t/ha)	Harvestability index[1]
Arrowleaf clover	40-60	0.8-1.5	4.0-11.0	0.3-0.8	
French serradella	0-55	1.0-1.8	4.0-10.0	0.2-2.0	92
Gland clover	40-60	0.8	3.0-8.0	0.2-0.8	67
Bladder clover	40-60	0.8-1.3	2.5-10	0.5-2.0	74
Biserrula	70-90	1.2-2.0	2.5-10	0.2-1.6 [1,2]	70
Subterranean clover	10-50	0.6-1.2	1.5-6.7	0.05-0.6 [1,2]	0

[1] Harvestability index is the percentage of seed harvested via use of a conventional header relative to the total seed produced by the pasture species (from Loi *et al.* 2005)

Pasture establishment techniques

The establishment of lucerne and subterranean clover pastures within the mixed farming zone has predominantly been achieved by undersowing with the last crop of the rotation (commonly wheat or barley). It is widely documented that establishing pastures via undersowing commonly leads to poorer pastures and increases the risk of complete pasture failure; this is particularly important in perennials that can't build up numbers over time. Despite this, surveys have indicated that the majority of farmers continue to establish pastures via undersowing (Swan *et al.* 2014). Maintaining cash flow from the cover-crop in the year of establishment appears to be a key driver, particularly where short pasture phases are unlikely to compensate for the lost grain income (McCormick *et al.* 2012). If livestock production once again become more important in the system, then this may see this practice change.

During the 1990s the uptake of direct drilling as the primary method of crop establishment increased dramatically, involving the use of knife points on tynes followed by press wheel which left the seed bed ridged. Common row spacing for crops also widened during this period to enable the machines to handle stubble. What this meant for pasture establishment was that small seeded pastures were being sown into rough seed beds where there might be little seed to soil contact. Pastures sown in conjunction with crops or with machines with limited ground-following capacity were also often sown deeper than ideal for pasture seeds. The introduction of canola in many regions has improved farmers' ability to sow small seeds, but commonly seeds sown with a cereal are still being sown too deep.

Traditionally, establishment of shallow-rooted temperate annual legume-based pastures has occurred once the danger of a false break has passed. The requirement for good moisture conditions mean that sowing may not occur until late autumn and in some cases early winter. Subsequently, growth is slow and poor first year herbage production and seed set may be observed. With the development and commercialisation of a range of aerial seeding annual legumes capable of being harvested on farm with a conventional header, new pasture establishment options have been developed concurrently. On-farm harvesting results in minimal seed scarification and therefore the hard seed content remains high (generally over 90%, Loi *et al.* 2005). Two methods of pasture establishment, summer sowing and twin sowing have been developed to exploit the availability of a cheap on-farm seed source and the hard seed breakdown patterns of various species and cultivars within species.

Summer sowing involves sowing unscarified seed (or in the case of serradella, in-pod seed) over the summer before the break of season. The high summer temperatures break down the hard seed and plants can establish on opening autumn rainfall. This method of establishment ensures pastures can emerge and establish while soil and air temperatures remain high. This can facilitate more rapid pasture establishment, higher first year herbage production and increased seed production compared with conventional late autumn scarified seed sowing (Hackney *et al.* 2015, Loi *et al.* 2012). Selection of species and cultivar within species is critical to ensure hard seed content and break down is compatible with local conditions. Use of a suitable form of symbiont delivery with capacity to survive high summer-low soil moisture conditions is essential to the success of this method of establishment. This method of establishment also results in temporal separation of labour demands for pasture and crop sowing which may be beneficial in many systems.

Twin sowing uses unscarified or in-pod seed sown with the final crop in the cropping phase. The seed (or pod) has very low germination with very few plants emerging in the final crop year. Unlike conventional undersowing, this method of pasture establishment does not require the crop seeding rate to be reduced and there is no competition between the pasture legume and the crop for resources. The final crop year allows a seed softening year for the legume seed which then emerges the following autumn. Choice of species and variety within species is again vital to success of this method of pasture establishment with hard-seeded French serradella cultivars and bladder clover being the most successful to date (Hackney *et al.* 2013, Loi *et al.* 2012).

Both summer and twin sowing require use of higher seeding rates (12-15 kg bare unscarified seed/ha or 20-30 kg in-pod seed/ha) compared with conventional pasture establishment. Many farmers have established seed increase blocks on-farm from which seed is harvested and subsequently used to sow other areas on the farm. As with any pasture sowing operation, appropriate weed control in the years leading up to pasture establishment is critical and herbicide plant-back requirements should be carefully observed to minimise risk of residual damage.

Perennial grasses in ley pastures

One further opportunity afforded by the change from annual ley pastures to pasture phases has been the potential to integrate perennial grasses into pastures used in crop rotations. Temperate grasses such as phalaris (*Phalaris aquatic*) and cocksfoot (*Dactylis glomerata*) are grown mainly in permanent pastures in the higher rainfall zone. However, improved drought tolerance of phalaris, tall fescue (*Festuca arundinacea*) and cocksfoot with the development of more summer dormant varieties (Clark *et al.* 2015) have shown they can successfully persist for several years in the mixed farming zone with rainfall around 450 mm (Culvenor *et al.* 2016, Harris *et al.* 2008). Potential benefits from temperate perennial grasses in the system include increased winter forage production compared with lucerne, increased growing season compared with annuals, reduced animal health risks associated with pure legume stands and increased ground cover, particularly over summer. Hayes *et al.* (2018) demonstrated that perennial grasses increased forage production over annual pastures, phalaris maintained ground cover above 70% and perennial grasses reduced the incursion of annual grass weeds. The addition of lucerne at low plant density within the perennial grass also increased annual biomass. This work has shown there is potential for wider application of temperate perennial grasses in pasture phases on mixed farms, yet the adoption remains low. Inability to control problem grass weeds (*e.g.* ryegrass, barley grass) during the pasture phase, the limited supply of seed for suitable cultivars (*e.g.* summer dormant cocksfoot) for the mixed farming zone, difficulties in establishment and lack of awareness of farmers appear to be major impediments.

Improved tropical grasses have long been used in sown pastures throughout the mixed farming zone of southern and central Queensland. Often, they are used in this region to repair soils where cropping has become unviable (Bell and Garrad 2017). However, these species have applications in temperate and Mediterranean environments across the mixed farming zone. These species are now being widely used thoughout northern and central NSW, where they complement other forage sources in the farming system (Boschma *et al.* 2017). In Western Australia, subtropical grasses are being used to protect soils prone to erosion or where crop productivity is low to provide forage during summer. In some cases, they are being used in intercropping systems with grain crops (Lawes *et al.* 2014) or are mixed with winter growing annual legumes. Similarly, they have shown potential in low rainfall regions of South Australia and Victoria. A major challenge with tropical grasses is their feed quality which can deteriorate rapidly during active period of development. Further, in the southern extremities of the mixed farming zone, tropical grasses offer little in terms of forage productivity or feed quality during the colder months of the growing season.

Dual-purpose crops

Dual-purpose crops are used for a period of grazing during their vegetative growth stage and are then allowed to regrow to produce grain later in the season. Dual-purpose crops have long been utilised in mixed farming systems, but the release of wheat varieties with a vernalisation requirement and high grain quality in the 1990s resulted in a resurgence of interest in the role they could play in crop-livestock systems (Dove and Kirkegaard 2014). When sown earlier than traditional spring wheat (*e.g.* March) they provide a long grazing window before their vernalisation requirement has been satisfied and they proceed with reproductive development. These crops can provide over 2000 DSE grazing days/ha supporting 300-400 kg of lamb production/ha without reducing grain yields. Meta-analysis of experiments suggests that grazing crops can reliably increase returns by more than 25-75% (Bell *et al.* 2014). Typically, dual-purpose crops have been used in regions of south-eastern Australia with long growing seasons using winter-type cereals (wheat, barley, oats, triticale). However, there has been growing interest in their application in other higher rainfall regions and in other crop types (*e.g.* canola) (Bell *et al.* 2015, Kirkegaard *et al.* 2008).

In canola, a range of canola germplasm has been evaluated (Christy *et al.* 2013, Kirkegaard *et al.* 2008, Sprague *et al.* 2015) with both winter and spring canolas useful for dual-purpose use in the high and medium rainfall zones (McCormick *et al.* 2015, Sprague *et al.* 2015). Some long-season, winter type 'dual-purpose varieties' are now available commercially (*e.g.* cvs Taurus, Edimax, Hyola 971CL). Dual-purpose canola complements long-season cereals by providing a break crop option to manage root diseases in high rainfall farming systems. These winter canolas have also provided the opportunity for spring-sowing, in order to provide an extended period of grazing over summer and autumn (like forage brassicas) as well as allowing grain production (Paridaen and Kirkegaard 2015). However, this concept has received limited testing, only in southern Victoria, so the wider application is yet to be determined.

Dual-purpose grazing of grain crops is now restricted not only to long-season winter cereals varieties. Recent work has demonstrated that grazing can be obtained also from spring cereal varieties with little reduction in yield (Latta 2015, Seymour *et al.* 2015). This creates wider opportunity for grazing of dual-purpose crops in different environments, including where long-season winter cereals are not suitable, such as in low and medium rainfall and subtropical environments (Bell *et al.* 2015, Lilley *et al.* 2015). However, as earlier sowing is also required to maximise the grazing potential of dual-purpose crops, different phenology types may be required in different environments to ensure flowering still occurs in the optimal window. Experimental and modelling analyses show shorter winter-types (*e.g. cv* Wedgetail) could provide a robust option across a wider range of sowing dates in lower and medium rainfall environments. However, few varieties with this phenology type are currently available.

Livestock productivity benefits from dual-purpose crops

Dual-purpose crops can fill winter feed gaps and provide high quality forage which can be used to achieve very high animal growth rates (250-300 g/d from lambs or up to 2.0 kg LW/d from weaner steers) when grazed during vegetative periods (Dove and McMullen 2009, Dove *et al*. 2016). During the vegetative phase, the energy content of dual-purpose crops is consistently measured at greater than 12 MJ ME/kg DM or 80% digestibility, and protein content >25% (Masters and Thompson 2016). Despite high livestock growth potential, actual growth rates have been highly variable and frequently below those expected. The high potassium to sodium ratio in wheat (and triticale) has been shown to impede Mg absorption and induce subclinical Mg deficiency (grass tetany) in grazing ruminants (Dove *et al.* 2016). The provision of sodium and/or magnesium can address this risk and has been shown to increase herbage intake and increase the weight gain of growing lambs and cattle (25-50%) to a level comparable with predicted growth rates (Dove and McMullen 2009, Dove *et al.* 2016). While the mineral responses have been well established in growing animals there is interest in using dual-purpose crops for gestating ewes, but calcium deficiency has been shown to occur more frequently for ewes grazing cereal crops than those grazing pastures (Masters and Thompson 2016). An experiment (McGrath *et al.* 2015a) and survey (McGrath *et al.* 2013) in southern NSW found little evidence of a high animal health risk for well managed reproducing ewes when grazing wheat, although issues have been sporadically reported.

Dual-purpose crops can provide significant grazing opportunities and livestock production (800-2500 DSE days/ha, 200-650 kg LW/ha) but this varies with the season, grazing management, sowing time and crop type. Early sowing of long-season varieties provides a greater opportunity for grazing than later sowing, with the potential grazing declining by 200 DSE days per week as sowing is delayed after early March (Bell *et al.* 2015). Winter varieties requiring vernalisation to initiate reproductive development provide long grazing windows (up to 100 days) and hence more grazing potential, compared to shorter season spring varieties. Winter canola can provide 800-2600 DSE days/ha and spring canola up to 700 DSE days/ha with similar potential livestock growth rates to cereals, although a period of low growth immediately after introduction to canola often occurs. Across the high rainfall zone of south-eastern Australia dual-purpose crops can provide up to 2500 DSE days/ha but due to their later season break grazing potential is much lower in Mediterranean environments in south-western and southern Australia (Bell *et al.* 2015, Lilley *et al.* 2015, Sprague *et al.* 2015).

While there is potential for grazing crop biomass during winter to fill gaps in feed supply, it is widely acknowledged that there are considerable benefits in integrating dual-purpose crops into the farm feedbase (Dove *et al.* 2015, McGrath and Friend 2015, Squib and Kingwell 2015). In a field study near Canberra, Dove *et al.* (2015) found that pasture spelling during the grazing crop period increased the grazing days on pasture by >40% after crop grazing. Further, this study showed that combinations of dual-purpose wheat and canola crops have complementary impact, further increasing the pasture grazing benefit by providing a longer deferment period (Dove *et al.* 2015). When these benefits were extrapolated, whole-farm stocking rate could be increased by 10-15%, and farm profitability by $150/ha through the incorporation of 10-15% of the farm to dual-purpose crops (Bell *et al.* 2015). The pasture deferment benefit is much less when short season spring cereals are grazed, and the benefits are likely to come from increased early-season feed (Thomas *et al.* 2015).

The potential to alter the livestock enterprise to capitalise on this additional forage resource has been examined through modelling analyses. These have suggested there may be potential to shift lambing from spring to autumn and employ higher stocking rates to bring about significant increases in farm gross margin. McGrath *et al.* (2014) showed that lambs could be finished earlier, with a greater proportion reaching market specifications through lambing in April rather than in June or August (Table 2).

Table 2. Effect of varying lambing month and stocking rate on lamb production, grain supplements fed and gross margin from incorporating dual-purpose crops into the farm feedbase (adapted from McGrath *et al*. 2014).

Lambing month	Stocking rate (ewes/ha)	% change in GM ($/ha)	Change in supplement grain fed (kg/ha)	Change in days to lamb sale	Change in lamb production (kg/ha)	Change in % of years lambs reach > 39 kg at sale
April	6	15	-66	+1	+18	+5
	8	67	-140	-1	+40	+15
	10	257	-186	+21	+82	+30
June	6	21	-104	+1	+9	+5
	8	42	-209	-5	+17	+12
	10	95	-384	-15	+20	+8
August	6	8	-84	+1	+5	0
	8	21	-172	+3	+12	0
	10	56	-285	+2	+17	+5

Managing crop grazing to avoid yield penalties

The risk that grazing will reduce grain yield and/or quality is a major concern for growers and is the major impediment to wider adoption of dual-purpose crop grazing. Harrison *et al.* (2011) reviewed previous research on cereals and showed that grain yield can be reduced by crop defoliation by up to 35% or increased by 75%, with a median reduction of 7% in grain yield. However, if grazing is managed correctly, the grazed crop can produce similar grain yields to an ungrazed crop. Grazing after elongation of reproductive stem greatly increased risks of grain yield reductions from grazing in both cereals and canola (Harrison *et al.* 2011). This effect is complex and involves combinations of reducing tiller numbers and reducing time to recover enough biomass (and resources) to maximise yields. Yield increases due to grazing/defoliation can occur by slowing crop water use and delaying water extraction until it can be used more effectively during grain filling, but this effect is subtle and has not been conclusively proven experimentally. It appears that the economic optimum was reached where crops were grazed to a level incurring a yield penalty of 10-20% compared with an ungrazed crop.

It is now understood that both residual biomass and the time grazing is stopped are both critical factors to be managed to avoid grain yield penalties (Bell *et al.* 2014, Sprague *et al.* 2015). Allowing the crop enough time to regrow and acquire the critical anthesis biomass required to achieve the yield potential in that season. Hence, by removing biomass in higher yielding years larger yield penalties are likely, while in seasons with lower yield potential the required biomass at anthesis to achieve maximum grain yield is often lower. In these situations, where excess biomass is not effectively converted to grain yield, this can be used for grazing without reducing the grain yield in that year. The challenge is in predicting these situations and clearly some environments are more prone to this scenario than others.

Grazing crop residues

Crop stubbles have long been an important forage source for sheep in mixed farming areas, and particularly in the low-medium rainfall zone where the growing season is shorter, and the proportion of land sown to crops is high. However, with the widespread uptake of no-till, stubble retention and controlled traffic farming systems have engendered growing concerns about livestock compacting soil, removing stubble cover and hence impacting on subsequent crops. Recent studies have shown no negative impact of stubble grazing by sheep on subsequent crop yield providing summer weeds are controlled and at least 50-70% of stubble cover (2-3 t DM/ha) is maintained (Bell *et al.* 2012, Hunt *et al.* 2016). However, grazing stubbles was shown to induce small increases in soil bulk density, soil strength and reduced infiltration rate, but this did not result in lower soil water at sowing or reductions in grain yield. Risks of compaction are lower when grazing during summer fallows when soils are drier and more resistant to compaction. Compaction by sheep is generally shallow (5-10 cm) while cattle can induce deeper soil compaction (10-15 cm) particularly on wet soils (Bell *et al.* 2012). However, these shallow compaction events were found to be transient and are alleviated by natural wetting and drying cycles along with sowing operations. Reductions in water infiltration and yield following grazing are due to removal of ground cover rather than compaction (Bell *et al.* 2012, Hunt *et al.* 2016b); that is, ‘sheep do more damage with their mouths than their hooves’.

Compared with ungrazed stubbles, stubble grazing was found to increase grain yield and protein in some seasons due to increased N availability to subsequent crops (Hunt *et al.* 2016). This is thought to be driven by more rapid mineralisation of N from livestock excreta and possibly due to lower immobilisation of N by stubble due to reduced inputs of high C:N stubbles. However, further research is required to understand these processes more fully.

The amount of feed available in stubbles depends of the amount and quality of spilt grain, leaf and stem from the dry crop residue and its accessibility. The leaf and stem components, while variable due to crop type and seasonal conditions, is generally very low quality (< 58% digestibility). With increasing efficiency of modern harvesters, less grain is spilt on the ground. Despite this, recent grazing studies show that wheat stubbles, even where modern harvesting machinery is used, are a valuable source of feed. Fresh wheat stubbles provide adult ewes with between 60 and 100 sheep grazing days/ha before the sheep begin losing weight (Thomas *et al.* 2010). Generally, sheep show very rapid growth rates during the first 1-2 weeks, decreasing thereafter as a consequence of declining grain and leaf availability. A significant challenge for managing stubble grazing is identifying when feeding value has declined to a point such that animals should be removed. Knowing this would reduce the risks of overgrazing stubbles and enable farmers to gain the best value from crop residues.

Germinating weeds during fallows can provide high quality feed for short periods – but research shows that this has significant trade-offs for subsequent crops. Controlling weeds during summer fallows is important to increase soil water available for subsequent crops, with large benefits for system productivity (Hunt and Kirkegaard 2011). Grazing fallow weeds can also increase risks of increasing weed seed spread. A common practice now for farmers is to spray weeds and then graze so that losses of water and nitrogen are minimised, but the weeds still provide some feed for livestock.

Future of crop-livestock integration

There is a significant and renewed desire amongst landholders in the mixed farming zone to increase their investment in livestock production enterprises. Despite this, a survey of 175 farming businesses in central and southern NSW found that the current feedbase was only fulfilling the livestock production goals of producers 50% of the time (Hackney *et al.* 2019). This suggests there are inadequacies in the current feedbase to meet livestock production requirements, poor matching of the feedbase to livestock needs or inadequate management of the feedbase leading to sub-optimal performance in terms of production and/or feedbase quality. Producers cited assistance with fundamental issues including pasture species and selection, pasture establishment, interpretation and manipulation of soil fertility as key requirements to improve their feedbase management. Many farm consultants used by producers have a stronger crop production credentials than pasture expertise. It is important therefore that upskilling occurs in fundamental and advanced concepts of feedbase management and manipulation. Improved skills in crop-livestock systems is needed to minimise financial risks as well as prevent unwanted environmental consequences (*e.g.* overgrazing, poor ground cover, soil loss) and animal production issues (*e.g.* reproductive mortality) that may arise because of inadequate knowledge in these areas.

Several technological and environmental changes may also bring about further disruption to crop-livestock systems over the coming years (Bell *et al.* 2014). Firstly, technologies (*e.g.* virtual fencing, GPS collars to manage livestock instead of fences) have the potential to reduce the labour and infrastructure required for farmers to reintegrate livestock into their cropping enterprises. Such technologies could enable spatial management of grazing to soil type, avoid grazing areas that fall below ground cover limits and use crop grazing to manipulate crops more precisely. The increasing need to employ non-herbicide practices for weed management to slow the build-up of herbicide resistance is also relevant. Decline in soil fertility and resilience under continuous cropping is also likely to need solutions involving longer term pasture-crop rotations. However, greater quantification of the broad range of benefits from such systems are required before farmers will adopt them. Further, increasing climate variability occurring across much of Australia's mixed farming zone is likely to require crop-livestock systems that offer flexibility and resilience to maintain viability of mixed farming enterprises over the long term.

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