Report Two

Opportunities and challenges for continuous cropping systems

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Take Home Messages

- Continuous cropping can be sustained for decades, but requires careful management.
- A larger proportion of N supply as fertiliser will be required over time even when grain legumes are included in crop sequences.
- Herbicide resistance develops faster under continuous cropping. Integrated management to keep key weed populations at very low levels is essential for long-term viability.
- Suitably diverse crop and end-use portfolios and flexible management help build resilience to climate and crop price shocks.

Background

Australian broad-acre farms have intensified crop area. In the two decades from the mid-1980s crop area doubled and sheep numbers halved (Kirkegaard et al., 2011). Many farms, or parts of farms are continuously cropped. The reasons for intensification (e.g. social, financial, logistic, biophysical) vary with individual businesses. In this paper, our aim is not to focus on the "pros and cons" of mixed vs crop-only systems. Rather we seek to highlight the main challenges faced in continuous cropping systems, and provide some recent research outcomes on best-bet management to sustain profitable continuous cropping with current and foreseeable technologies. The major challenges we foresee are (1) maintaining soil fertility (2) managing weeds and diseases and (3) managing economic risk and resilience.

Managing soil fertility

Q1. Are you mining, maintaining or manufacturing soil fertility, and at what cost to your business?

Organic matter, soil structure and fertility

Pasture phases are the most effective way to build stable soil organic matter (humus), N fertility and structure - so maintaining these assets under continuous cropping systems is a challenge (Angus and Peoples 2012). Conservation cropping systems (no-till, stubble retention) can certainly build coarse soil organic matter (i.e. plant residues), maintain cover, protect soil structure and reduce erosion but at best only maintain, rather than build stable soil organic matter. Maintaining adequate levels of humus is essential to ensure the structural stability of soils, and for the provision of nutrients (soil fertility), which will be soil type (texture) specific. Recent studies indicate that the failure to maintain or build humus may be due to a lack of sufficient nutrients (N, P, S) rather than a lack of carbon under continuous cropping systems (Kirkby et al., 2016). For example, to sequester one tonne of soil carbon as humus requires 83 kg/ha N, 20 kg P and 14 kg S. Using this knowledge, the long-term decline in soil carbon was reversed in a continuously cropped (28-year) field by adding supplementary nutrients to incorporated crop residues – because nutrient input, and not carbon input was limiting. Modern farming systems focussed on "nutrient use efficiency" (i.e. kg grain per kg fertiliser applied) may not account for the nutrients required to maintain or build the soil microbes that generate stable organic matter. As the levels of organic fertility declines, the supply of plant-available nutrients such as N from the soil will also decrease over time. Consequently there will be a requirement for progressively more fertiliser to support increases in crop yields.

Nitrogen fertility

Humus is the primary source of mineralised organic N for crops, and organic N in southern Australian soil declines at around 2-3% per year in cropped soils with a "half-life" of 34 to 23 years. In the absence of legume-based pastures, mineral N from native organic matter or pasture residue declines, and must be replaced with other legume or fertiliser N sources. Farm N budgets based on different farming system scenarios can predict the likely increase in the fertiliser needs required (Table 1).

Year	N from mineralisation (kg/ha)	Fertiliser N requirement (kg/ha)
2013	108	80
2033	54	134
2053	17	161

Table 1. Source of N for a typical 4 t/ha wheat crop in southern NSW assuming continuous cropping (Angus and Peoples, 2012).

Soil	Nil N	9 kg/ha	40 kg/ha (9+31)	1-year Pasture then 9 kg/ha N
Swale	-210a	-156c	-61a	-102b
Mid-slope	-102b	-81b	10a	-92b
Dune	-64c	-15b	60a	-21b

Table 2. Calculated N balance for different soil types under different N management during a 5-year cereal phase at Mallee Sustainable Farming Karoonda field site (from McBeath et. al., 2015).

For example in southern NSW, with 4.0 t/ha average wheat yields, a 60:40 crop:pasture ratio can maintain N balance, while continuous cropping will increasingly rely on N inputs, potentially eroding the initial economic advantage (Angus and Peoples, 2012).

The trend towards lower mineral N levels in pre-sowing tests over recent years provides evidence of diminishing organic N levels, as pasture area declines and long crop sequences with low legume frequency are not balanced with equivalent increased fertiliser N. In southern NSW, the number of pre-sowing deep soil mineral-N tests that measured <30kg/ha Min-N doubled between the periods 2008-2010 and 2013-2015, while those >120 kg/ha have halved (Jim Laycock pers. Comm., 2017). This “mining” may make sound economic sense initially, but if yield and quality levels are to be maintained or increased in the medium to long-term, improved nutrient balance must be achieved. The data for a variable soil site at Karoonda in SA Mallee (Table 2) shows how significantly more N than the current district practice of 9 to 20 kg/ha N annually is required to maintain N balance in the cereal phase.

The cost and risk of supplying an increasing proportion of N as fertiliser to support crop yield on N-depleted soils may become prohibitive. Current N prices are relatively low compared with long-term average or peak N prices, and N prices are likely to rise in future as the efficiency of production facilities reaches a peak. There are numerous strategies available to maintain N fertility and profitability under continuous cropping.

Improved efficiencies of fertiliser N use

Good agronomy and following the 4R mantra of IPNI (Right product, Right rate, Right place, Right time) are important for the provision of sufficient quantities of all plant nutrients, including N, in all farming systems - but strategies to improve fertilizer-use efficiency become critical in continuous cropping systems as the original soil organic matter levels and pools of pasture-derived N diminish. The adoption of precision agriculture techniques and variable rate technologies in broad-acre agriculture is increasing steadily in Australia, with typical economic gains estimated of around $40/ha for N-related applications. On variable soils such as in the Mallee, significant improvements in overall productivity, water-use efficiency and profit along with reduced risk can be achieved over traditional flat-rate applications by increasing N rates on sand hills and reducing N rates on flats. An example is found at Karoonda SA, where profitable responsiveness to N fertiliser

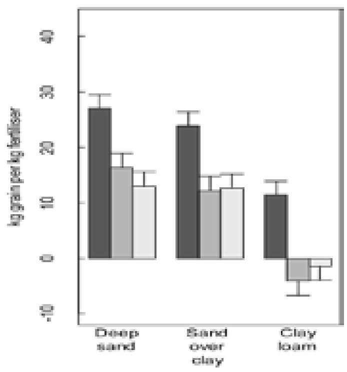


Figure 1. Grain yield responsiveness (kg/ha) per kg/ha N input on the deep sand, sand over clay and clay loam soil types across the 2010 (dark bars), 2011 (medium bars), 2012 (light bars). Data from McBeath et al., (2015) https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/07/Managing-the-profit-and-risk-of-fertiliser-nitrogen-investment-in-sandy-soils

Treatments	Z30			Anthesis			Grain Yield (t/ha)
	t/ha	N%	N-up (kg/ha)	t/ha	N%	N-up (kg/ha)	
Surface	1.4	3.8	51	7.8	1.3	103	4.0
Deep	1.4	4.4*	60	9.2*	1.5*	136*	5.2*

*Table 3. Effect of deep banding vs surface applied N (122 kg N/ha as urea) at Temora in 2016 (starting soil N, 58 kg/ha). The crop captured more N early in the season which increased biomass and yield in a wet season. (Data mean of 3 stubble treatments). *indicates significant differences (P<0.01). (Data source: Kirkegaard et. al., CSIRO Stubble Initiative 2016 CSP00186)*

is reliably achieved on the sandier soils but was profitable only in the extremely wet year of 2010 on the heavier flat soils (Figure 1).

As soil N fertility slowly declines under continuous cropping, more fertiliser may be required at sowing to ensure adequate N to achieve crop yield potential. In stubble-retained systems, surface applied N is more prone to immobilisation and the amount that can be drilled with the seed is limited. Banding N fertiliser below or beside seed rows at sowing can improve the efficiency of N uptake in crops by making more available to the plant, reducing the competition for N with soil microbes (immobilisation), and reduce leaching or denitrification losses prior to plant uptake by slowing the rate of nitrification. In an experiment at Temora in 2016, the amount of applied N captured by wheat crops was improved by deep banding N below seed in the presence or absence of stubble (Table 3).

Greater N-use efficiency of in-crop N applications may also be achieved by top-dressing just prior to rainfall during the peak period of crop demand after stem elongation or by mid-row banding equipment which has been adopted by some farmers and is being evaluated by researchers from Agriculture Victoria and NSW DPI. Banding urea between every second row (mid-row banding) may have advantages over banding under every row because the concentration of ammonium is doubled and the fertiliser remains longer in this form before its conversion to nitrate. Mid-row banded urea is effectively a slow-release fertiliser that prevents excessive vegetative growth. The ammonium it forms in soil is less prone to loss than nitrate (Angus et. al., 2014).

Slow-release fertiliser products (urease inhibitors, nitrification inhibitors and polymer coated urea) to better match N supply to crop demand are also available but currently these products may be too expensive for many broad-acre grain applications (Angus et. al., 2014). As new polymers and products become available they may have specific applications, especially in the higher rainfall zones on soils prone to leaching.

Increasing the efficiency of fertiliser use by improving the synchrony of N supply with crop N demand to reduce unnecessary losses of mineral N (leaching, denitrification, run-off) and converting those to plant uptake makes economic and environmental sense. But paradoxically, pushing for higher N efficiency by avoiding N immobilisation can lead to a heavier reliance on mineralisation to supply crops, and represents an increased net loss of organic N. Ultimately the requirement for N fertiliser will increase at a faster rate assuming crop yields (i.e. N removal) continue to improve. The total N decline can only be slowed if additional "new" sources of N enter the system to balance product removal and losses.

Integrating legumes in the system

In the absence of legume-based pasture phases, other ways to incorporate legumes into the crop system will help to maintain a better organic N balance. Legumes frequently fix around 20 kg/ha N per tonne of shoot biomass grown, but there is enormous variability in fixed and net N inputs of different end-uses, though harvested grain legumes rarely match those achieved by well-managed, legume-based grazed pastures (Table 4).

System	N fixed (kg/ha)	Net N input (kg/ha)
Grain legumes (harvested)	134 (65 to 310)	45 (-40 to 96)
Grain legumes (brown manured)	144 (86 to 246)	144 (86 to 246)
Pastures	174 (102 to 256)	132 (70 to 199)

Table 4: Average and range of N fixed and Net N input for crop legumes (harvested for grain or brown manured) and pasture systems (Data courtesy Mark Peoples, collated from field experiments during 2011-2015 GRDC Crop Sequence Initiative CSP00146)

Incorporating legumes into a farming system also reduces the financial risk associated with large N fertiliser inputs, as no N is applied to the legume, and less is usually required for the following cereal crops. In the experiments reported in Table 3, the amount of extra mineral N available to crops at sowing following legumes compared to cereals is variable (5 to 92 kg/ha; median 33 kg/ha) but some simple rules of thumb can assist in predicting the likely amounts as follows (Peoples 2016);

- 0.13 kg extra Min-N/ha per mm fallow rainfall
- 9 kg extra Min-N/ha per tonne of shoot residue N
- 15 kg extra Min-N/ha per tonne legume grain harvest

The amount of mineral N supplied by legumes tends to be higher in equi-seasonal areas of NSW than in winter dominant and summer dominant rainfall areas, and tended to be higher for faba bean, and lower for lentil and vetch. We estimate that the first wheat crop can recover the equivalent of ~30% of the N in legume stubble and root residues, with <10% being taken up by the second crop grown after a legume. This compares to a 50-60% apparent uptake of top-dressed fertiliser N applied to wheat at Z30.

Higher value grain legumes such as chickpea and lentil can provide a highly profitable option as a regular part of a continuous crop sequence in suitable environments, although net removal of N by high-yielding grain legumes is common. The area sown to these grain legumes is expanding with improved varieties and agronomic packages, however variable prices and marketing issues can increase the economic risks from year to year. Meanwhile the halving in the area of lupins, in the last decade or so means that legume crop area in 2015 was no greater than in the 1990s (htttp://www.pulseaus.com.au/storage/app/media/industry/AU-lentil-area.pdf).

Legumes with lower grain value (e.g. lupin, pea, vetch) can provide a range of other flexible and diverse end-uses in continuous crop sequences such as grazing, hay or brown-manure where the N benefits combine with weed control and water conservation to reduce production risk and input costs, and provide a significant benefit to the overall crop sequence (Table 5). In this example from a fully-phased experiment at Temora (2014-2016), compares a typical C-W-W sequence, with a sequence that includes vetch hay, the major difference in the total costs incurred was the savings in N application to the canola following the vetch hay.

The income from hay combined with highly effective non-chemical weed control (see later) and water conservation, especially preceding higher value and risky crops such as canola, can make this a good option. The N inputs and soil cover are reduced in the hay option compared with brown manuring, and low cover can also be an issue with low biomass grain legumes on erosion-prone areas. Brown manuring of grain legumes (or long fallow) is less economic in more reliable rainfall areas because of the income forgone in the year it is used, but along with hay may be viable in lower rainfall areas (Kirkegaard et al., 2014), or in areas as part of a "double-break" where it precedes a higher value but riskier crop such as canola (see later in Weed section).

Legume intercrops (where more than one crop species are grown together) are common in subsistence and organic agriculture or where labour costs are low (e.g. China), and frequently demonstrate "over-yielding" where the mixture is more productive then the monocrops due to biological synergies (typically by a factor of 1.2). Mixtures of legume and non-legume crops to date have been used less in broad-acre, mechanised agriculture. A recent review by Fletcher et al., (2016) suggests there may be potential for some promising mixtures (e.g. Peaola) with Australian experiments finding productivity increases by a factor of 1.5 compared to monocultures. Commercial peaola crops have been grown in this way for more than 10 years on some Canadian farms where growers have innovated to overcome the main practical issues. An excellent interview

System	Average N costs ($/ha/yr)	Average total costs ($/ha/yr)	EBIT ($/ha/yr)
Aggressive (C-W-W)	**$109**	$515	$508
Sustainable (Vetch-C-W-B)	$70	$464	$520

Table 5. Comparison of N input costs, total inputs costs and profit of two systems in a phased experiment at Temora (2014-2016) demonstrating that a more diverse ('Sustainable') cropping systems including a vetch hay crop can be as profitable with less N input cost. Data courtesy CSIRO and FarmLink Research Stubble Initiative "Sequences for Seeders" Project CSP00174.

with one of the key growers (Colin Rosengren) can be found here https://www.realagriculture.com/2014/07/agronomy-geeks-west-ep-15-ins-outs-intercropping/

Phosphorus

Phosphorus is a significant input cost and crop recoveries are commonly poor so improved efficiencies should always be sought (Peoples et. al., 2014). Though "peak phosphorus" concerns have generally abated, the depletion of subsoil P (mostly in northern regions) where it may be hard to replace, and the stratification of P in long-term no-till soils, where the P becomes concentrated in the surface layers and unavailable to plants when the soil dries remain important issues. Strategic tillage provides a suitable option to deal with stratification, and deeper banding of P can provide another solution. Novel products that are more mobile in soil, techniques for deep placement and novel root P foraging traits are all areas of current research interest.

*Though N and P have been singled out for discussion, continuously cropped soils can clearly be depleted in any of the essential nutrients - but few would threaten any business where regular monitoring of soil and plant fertility is conducted and relevant action taken.

Acidity

Crop production primarily acidifies soil by removal of alkalinity in grain and hay. Leaching of nitrate along with associated cations down the soil profile will also acidify soils, but this has become less common as soil N levels decline and agronomy of crops and pastures improves. It is still an issue on lighter soil types in higher rainfall regions more prone to leaching. Leaching of nitrate may in fact be lower under continuous cropping than in annual legume pastures.

Acid soils remain an issue in many Australian grain-growing areas, but with an estimated 300+ years of available lime reserves and a long history of well-researched and widely available liming strategies, it should theoretically not be an insurmountable problem with best management practices. The main challenge is to deal with acid, or acidifying subsoils, which become difficult to treat due to the immobility of lime in soil. Once again strategic tillage and regular lime application at adequate levels will ensure that the lime moves to depth rather than remain in surface layers. In naturally acid deep sandy soils such as in WA, deep placement of lime using specially designed machinery, or even carefully timed mouldboard ploughing (every 10 years) are approaches that have been used successfully.

The search for genetic tolerance to soil acidity and the aluminium toxicity it induces is ongoing as the mechanisms and the genes responsible for tolerance in wheat have been identified and moved into barley. Research into tolerance in other sensitive crops is underway (Peoples et al., 2014). Genetic tolerance will continue to be of greater importance in low rainfall regions where yield responses to liming are uneconomic.

Weed, disease and pest management

Continuous cropping can lead to greater weed and pest pressures such as herbicide resistance, and increasing weeds that are favoured by modern, no-till cropping systems (e.g. brome grass). Well-managed pasture phases provide excellent opportunities to control most biotic threats to crop production, but a range of integrated weed, pest and disease management approaches are available for application in continuous cropping systems. A diverse cropping sequence (i.e. a sequence of different crop species and end-uses) provides the most cost-effective defence against most of these threats.

Herbicide resistant weeds

A key challenge and a major cost to continuous cropping systems that are primarily reliant on herbicides for weed control is the development of herbicide resistance. Maintaining a diversity of crops, control practices and herbicides is the key to staying ahead of this problem. The number of weed individuals to which a given mode of action is exposed, and how often, determines the speed at which resistance develops. Therefore, development of resistance is slowed by maintaining weed populations at very low levels, and preventing seed set in individuals that have survived chemical control. Keeping weed populations at very low levels by a variety of complimentary practices forms the basis of integrated weed management, which is essential to ensure the sustainability of continuous cropping systems. The large areas sown under continuous cropping has contributed to increasing use of dry seeding which, in the absence of knockdown herbicides, can place increasing reliance on selective herbicides if weed seed banks are not kept low.

Rotate & Mix Herbicides

Maintaining adequate diversity in crops and their end-uses provides the best opportunity to rotate and mix herbicides with different modes of action to slow the development of herbicide resistance.

Under continuous cropping, greater application of herbicides in summer also increases the risk of herbicide residues in soil causing crop damage. The increasing use of more sensitive crops such as pulses in alkaline low rainfall areas on sands with low biological activity adds to these concerns. Herbicide residues from Group B chemistry can commonly limit crop choice but a range of other residues are also being investigated for their potential impact and careful management requirements (https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2016/02/Herbicide-residues-in-soils-are-they-an-issue). Different crop types allow the use of different chemical and non-chemical control measures e.g. crop-topping in legume crops and narrow windrow burning (usually more effective in canola and grain legumes than in cereals). Maintaining low weed levels also provides an opportunity to use cheaper herbicide options where possible to reduce input costs.

Recent experiments in fields with high levels of multiple post-emergent herbicide resistant annual ryegrass (HRARG) have shown that it is difficult to reduce weed seed banks without adequate crop diversity, even with the use of expensive herbicides (Table 6). The experiments show that although high yielding and profitable intensive wheat sequences can be managed in the medium term, considerable weed populations are maintained, which are able to develop resistance to further modes of action as they are exposed to them. Round-up ready (RR) canola followed by wheat with high gross margins provided the highest gross margin, but was less effective at reducing the seed bank than most of the double-break options. Sequences that involved either canola or a spray-topped lupin grain crop in year 1 followed by cereal hay or RR canola in year 2 provided high gross margin with the most effective weed control.

In addition to diverse crop species, including fallow or different end-uses such as hay or brown-manure also provided opportunities to drastically reduce seed set using non-selective herbicides with different modes of action (e.g. glyphosate and paraquat) in tandem ('double knocking'). Brown-manure crops have the disadvantage of providing no income in the year they are grown, so that the residual water, N and weed control benefits must compensate for lost income, and the extent to which this is possible varies for specific circumstances, but have been demonstrated to be economic at farm level https://www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2013/02. In severely infested fields it may take a "double-break" (two years with very high levels of weed control) to reduce weed seed banks to manageable levels.

Competitive Crops

Competition from crop plants can be very effective at reducing weed seed production, and is a vital component of integrated weed management. The aim of crop competition is to reduce the amount of light that gets to weeds in the crop canopy,

Break Type	Crop x Input Year 1 (2013)	Crop x Input Year 2 (2014)	Crop x Input Year 3 (2015)	ARG Seedbank Year 4 (2015) (seeds/m^2)	Average Annual 3yr Gross Margin ($/ha/yr)
Double	Fallow	RR Canola	Wheat (H)	56	$603
Double	Lupin grain	RR Canola	Wheat (H)	63	$790
Double	Lupin BM	RR Canola	Wheat (H)	110	$552
Double	RR Canola	Wheat (Hay)	Wheat (H)	122	$834
Single	Lupin grain	Wheat (H)	Wheat (H)	142	$757
Single	Pea BM	Wheat (H)	Wheat (H)	162	$486
Single	RR Canola	Wheat (H)	Wheat (H)	219	$883
Nil	Wheat (H)	Wheat (H)	Wheat (H)	366	$585
Single	RR Canola	Wheat (L)	Wheat (H)	2387	$845
Single	Pea BM	Wheat (L)	Wheat (H)	3118	$397
Nil	Wheat (L)	Wheat (L)	Wheat (H)	3140	$388

Table 6. Average annual 3-year gross margin and annual ryegrass (ARG) seedbank following 3 years of various crop sequence and input strategies at Eurongilly, NSW (2013 to 2015). Sequences included double- and single breaks of pulses (grain or brown manure - BM), canola, fallow and cereal hay and wheat with high or low (H, L) N and herbicide input costs. Initial ARG seedbank in 2012 was 1815 seeds/m2. (Data source, Swan et al., 2015).

particularly those that emerge after knockdown herbicides have been applied and residual activity from pre-emergent herbicides has ceased. There are four main components to crop competition;

- Row spacing. Crops on narrow rows (<250 mm) cover the ground faster, let less light through the canopy to weeds and reduce seed set (Borger et al. 2016a) and crop yields can be higher on narrow rows, particularly in high yielding environments (Scott et al. 2013). Operational benefits of wider rows (>250 mm) include better stubble handling (including the ability to inter-row sow), lower cost of machinery, lower draught and horsepower requirement, and greater crop safety for pre-emergent herbicides. Row spacing is thus a trade-off between these factors and higher yields and crop competition. The need for vigorous and competitive crop canopies has seen a recent trend back to narrower rows on some continuous cropping farms, particularly those in higher rainfall areas.
- Row orientation. Crop rows that are sown east-west shade the inter-row more effectively than when sown north south. This helps the crop be more competitive with weeds growing in the inter-row, and has been shown to reduce seed set in ryegrass by about 50% (http://ahri.uwa.edu.au/sow-west-young-man/). Paddocks should be set up with east-west seeding runs where it is efficient to do so. Row orientation becomes increasingly critical on wider row spacing.
- Plant density. Crops are able to compete more effectively with weeds when they are planted at higher density, as there are less gaps in the crop and the canopy closes over faster.
- Vigorous crops. Maintaining healthy and vigorous crops assists with crop competition (e.g. early sowing into warmer soils, liming to adequate pH, good nutrition and disease management). Crop species vary in their ability to compete (oats and barley > wheat; canola > pulses) and crop varieties also vary (hybrid canola > OP canola > TT canola). New wheat germplasm has been selected for early vigour, and has levels similar to barley, and these have been shown to have much better weed competitive ability.

Harvest Weed-Seed Control

Numerous methods have been developed and tested in recent years to collect and destroy weeds that have escaped in-crop control (Borger et. al., 2016b). These options include narrow windrow burning, chaff carts, chaff lining, mechanical seed destruction and direct bailing. These tend to be more effective in controlling some weeds (e.g. ryegrass) more than other early shedding weeds (e.g. barley grass). Some form of harvest weed seed control is essential in continuous cropping systems situations, particularly those that do not have hay crops or a high frequency of crops that can be crop-topped in their crop sequence. Together with sustaining new herbicide technology, further increases in the extent of use of weed seed control options is likely to be a key factor in sustaining continuous cropping.

New Developments

Increasingly sophisticated seeding systems including precision row and seed placement are likely to bring further benefits for weed control and crop performance in intensively cropped environments (better establishment in difficult conditions, greater early vigour and targeted disturbance and nutrition to benefit crops over weeds. New forms of novel, non-chemical control are also under development (mechanical, microwave, steam, compressed air) and may provide options to reduce the pressure on herbicide usage if affordable options for broad-acre applications emerge.

Disease and pest control

Maintaining a diversity of crops and practices is also the key to managing pests and diseases in continuous cropping systems. Particular attention must be paid to diseases and pests that:

- Develop resistance to available fungicides or pesticides (e.g. Green Peach Aphid)
- Overcome genetic resistance that was once reliable (e.g. Blackleg in canola)
- Infect a wide host range, so less controlled by diversity (e.g. Rhizoctonia, Pratylenchus, Sclerotinia)
- Are exacerbated by current agronomic practice (e.g. Crown rot, slugs and snails under no-till)
- Are novel or exotic pests not previously encountered (e.g. Russian Wheat Aphid, WSMV)
- Become expanded in severity or range by climate change (e.g. Clubroot in canola)

An assessment of the relative risk posed by these threats within continuous cropping systems is needed to develop the most cost-effective and sustainable way to avoid economic loss. Sensible, flexible and pragmatic approaches to soil and crop management will be necessary in circumstances where diverse crop sequences alone are inadequate to manage pest damage.

System	Mean Yields (t/ha)	3 Yr System Financials				2016* ARG (seeds/m²)
		Input cost ($/ha/yr)	Total cost ($/ha/yr)	EBIT ($/ha/yr)	Profit/Cost ratio	
Aggressive (C-W-W)	2.3, 4.1, 3.9	354	515	508	0.98	442
Conservative (C-W-W)	2.5, 3.6, 3.3	289	439	506	1.14	2772
Sustainable (Vetch-C-W-B)	3.9, 2.4, 4.1, 5.2	254	464	520	1.14	482

Table 7. Comparison of 3 cropping systems in a phased experiment at Temora (2014-2016) demonstrating that a more diverse ('sustainable') cropping systems can be as profitable with less cost and risk while achieving similar control of annual ryegrass as more conventional high input approaches (Note: initial ARG seedbank in March 2014, 1864 pl/m2). In the 'aggressive' system, ARG control is based on hybrid RoundUp Ready® canola followed by Sakura® and Boxer Gold® in subsequent wheat crops. In the 'conservative' system, ARG control is based on open pollinated TT canola, and trifluralin in subsequent wheat crops. In the 'sustainable' system, ARG control is based on hay-cutting and double-knocking in vetch, open pollinated TT canola followed by Sakura in wheat and Boxer Gold plus crop competition in barley.

Economic resilience

Q. Productivity, profitability and peace of mind

The recent, medium-term (3-5 year) farming systems experiments such as those reported here (in Tables 4 and 5) can carefully account for the variable input costs to provide useful information on the likely economic impact of different management strategies. They also support the value of maintaining diversity in species and end-use to not only maintain profitability and the biophysical assets of the farm (N fertility and weed seed burden) but to do so while reducing financial risk, in this case the profit to cost ratio (Table 7).

However, medium-term, small-plot experiments while valuable, cannot adequately account for the broader economic and logistical issues that are encountered at farm-scale. Often these issues can dominate financial planning and relate to labour, equity, debt levels and farm size. These considerations can dictate what is feasible in implementing the advice arising at experimental scales.

Several recent studies of real farm businesses have emphasised the dramatic changes in the economics and risk of grain farming in recent years as cropping intensity has increased. As farm size, cropped area and land values increased, so too have debt levels, machinery costs and total interest so that despite improvements in productivity, farm income to cost ratios have decreased significantly. For the Victorian Mallee farmers in the example below (Figure 2), a net farm income of around $100K involved costs of around $400K in early 2000s, but that has doubled to $800K today.

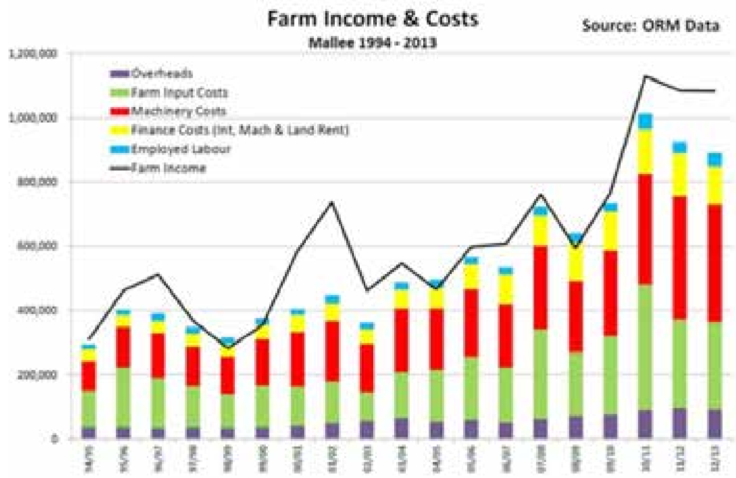
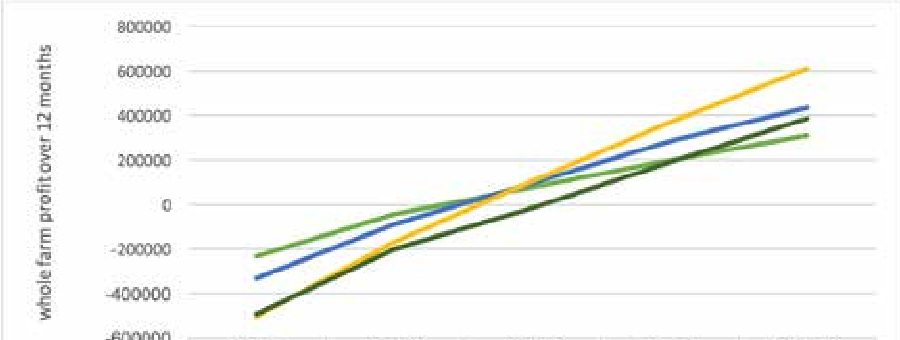


Figure 2. Average annual farm income and costs for 12 Mallee farms 1994 to 2013. As reported in van Rees et al., (2015) and by Ed Hunt (2015). Data source, ORM Pty Ltd.



	Decile 1	Decile 3	Decile 5	Decile 7	Decile 9
50%	-232000	-42000	76000	196000	308000
70%	-331000	-89000	94000	281000	435000
100%	-501000	-171000	102000	366000	608000
100% cereal	-493000	-199000	-17000	190000	384000

Figure 3. Average whole farm profit for typical farms at Karoonda (2,400 ha) assuming 80% equity. The numbers represent whole-farm profit predicted under different seasonal conditions (Decile 1=driest 10% of years, Decile 9 = wettest 10% of years, Decile 5 = Average year) and are graphed for ease of comparison (Data courtesy: Ed Hunt, Michael Moodie and Mallee Sustainable Farming).

Subsequent economic modelling to compare continuous cropping and mixed farms in this and other regions have demonstrated that it is very important to consider economic outcomes on actual yields over a number of years, rather than using long-term averages. Such analyses revealed that while continuously cropped farms (100%) and mixed farms may have similar profitability in average seasons, the continuously cropped farm was able to better capitalise in good seasons but was at greater risk in poor seasons (Fig 3). The study also demonstrated that the less diverse, continuously cropped farm (100% cereal) had the lowest economic performance in all but the very best of seasons, supporting much of the experimental data related to the benefits of diversity.

Though the absolute numbers shown above will change across different locations, the general trends will be consistent and the best strategies will be dependent on physical (soil type, rainfall), economic (equity, debt), and social (labour, skill levels, family circumstances) situations on individual farms. In riskier, low rainfall environments profits in high rainfall seasons are constrained by a (sensible) unwillingness to fertilise to levels required, increasing the need for legume nitrogen sources. As has been demonstrated above, reliance on increasingly expensive herbicide bills to maintain productivity also becomes a problem. In the absence of pasture phases with livestock, other ways to reduce risk must be sought including finding greater off-farm income, maintaining higher levels of equity, more consideration of machinery investments, use of contract services, or value adding.

Studies in other areas of intense cropping using real farm data support these findings. Lawes and Kingwell (2012) conducted a study of the economic resilience of 123 farms in the intensively cropped northern wheat belt of WA during the years 2004 to 2009 which included a period of significant drought. Indicators included business equity, operating profits, return on capital and debt to income ratio. Business equity declined on 60% of farms during the period, but the other indicators varied over time with no trends. The most resilient farms had the following features; (i) cropped more than 50% of the farm, (ii) were prudent with expenditure, (iii) maintained enterprise diversity, and (iv) grew wheat yields that were close to potential. Interestingly there was no impact of farm size which averaged 3200 ha.

In relation to mixed vs continuous cropping, most consultants agree that "it is not what you do, but how well you do it" that defines the success of the farm business, whether a mixed farm or continuously cropped (Kirkegaard et al., 2011). However with the biological and economic buffer of the pasture phase absent, a consistent message in studies of successful intensively cropped farms (in addition to sound financial management) is the importance of more frequent monitoring and measurement to assist in management decisions, and timeliness in implementing them. The fact that the top 25% of grain specialists make double the return on capital (8.8%) as the other 75% (4.5%) (ABARES 2015) emphasises that point.

As researchers and agronomists our challenge is to test and develop innovations that can continue to increase production efficiency, decrease costs and reduce risk in the face of the biological, climatic and economic challenges that we have discussed here.

Conclusion

Based on currently available technologies and price relativities, it is likely that continuous cropping can be sustained over many decades. However, in order for these systems to be sustainable, careful attention to key aspects of the farm is required, particularly control and provision of N and weeds. Under continuous cropping it becomes necessary to provide a greater proportion of crop N supply as fertiliser, and expend greater resources in maintaining low weed populations. As a result, production costs usually rise, and risk of substantial economic loss following price or climate shocks needs to be managed. Maintaining diverse crop species and end-uses forms the foundation of the solution to many of the biophysical as well as economic challenges faced in continuous cropping systems.

Useful Resources

http://www.farmlink.com.au/project/crop-sequencing

https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/09/Farming-Systems-Managing-Profitability-and-Risk-in-SA-Grain-Business

http://www.agronomy2015.com.au/papers/agronomy2015final00274.pdf

https://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Leading-farmers-have-closed-the-yield-gap

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