WALGETT
NEW SOUTH WALES
THURSDAY 15TH
AUGUST 2019

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

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Welcome to the 2019 GRDC Grains Research Updates

Growers, advisers and industry stakeholders are constantly faced with challenges to farm profitability and productivity, which makes staying informed about the latest research and development outcomes a critical part of being in business.

Keeping growers and advisers informed is the key role of the annual Grains Research and Development Corporation (GRDC) Grains Research Updates, which are premiere events on the northern grains industry calendar and bring together some of Australia's leading grain research scientists and expert consultants.

For more than 25 years the GRDC has been driving grains research capability and capacity with the understanding that the continued viability of the industry hinges on rigorous, innovative research that delivers genuine profit gains. GRDC's purpose is to invest in research, development, and extension (RD&E) to create enduring profitability for Australian grain growers.

Despite the tough seasonal conditions currently being experienced across much of the Queensland and New South Wales grainbelts, the industry remains confident about the future and committed to learning more about innovation and technology and embracing practice change that has the potential to make a tangible difference to on-farm profits.

In response, this year's GRDC Grains Research Updates offer regionally relevant, credible and new science-based information covering priority issues like climate and environmental variability, new technology and market conditions to ensure growers and their advisers have up-to-date knowledge to make informed decisions on-farm.

So, I hope you enjoy the 2019 Updates and that the events provide an invaluable opportunity for learning, knowledge sharing and networking.

Luke Gaynor,

GRDC Senior Manager Extension and Communication

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GRDC Grains Research Update
WALGETT

Thursday 15 August 2019, Walgett Sporting Club

Registration: 8:30am for a 9am start, finish 3:05pm

AGENDA		
Time	**Topic**	**Speaker(s)**
9:00AM	**GRDC welcome**	
9:10AM	**Current and predicted climate change impacts on northern farming systems.**	Steven Crimp (ANU)
9:45AM	**New frontiers in cereal breeding for a changing climate.**	Greg Rebetzke (CSIRO)
10:15AM	**Targeted tillage:** modified trashworker with individual tynes activated by WEEDit® technology to selectively dig out weed survivors.	Mike Walsh (University of Sydney)
10:35AM	**Morning tea**	
11:05AM	**5 years of nitrogen research:** do we have the system right? o N movement, use efficiency, application timing & impact on uptake - do we fertilise the system or the crop? o N in pulse crops? o N impacts on screenings	Richard Daniel (Northern Grower Alliance)
11:35AM	**Cover crops for fallow efficiency:** research observations on soil water, health, nutrition and crop performance.	Andrew Erbacher (DAF Qld)
12:05PM	**Lunch**	
1:05PM	**Farming systems research on GM and $ return/mm water:** learnings that translate to Walgett.	Andrew Erbacher (DAF Qld) and Jon Baird (NSW DPI)
1:45PM	**Decision making after a prolonged drought:** setting the business up for rational decisions to get margins back.	Simon Fritsch (Agripath)
2:20PM	**Recovery after the drought:** strategies and decisions for getting back to productivity, discussion forum led by Greg Rummery (Greg Rummery Consulting), Brad Coleman (Coleman Agriculture) and Sandy Stump (Eurambeen Farming Co)	
3:05PM	**Close**	

Contents

Compiled by Independent Consultants Australia Network (ICAN) Pty Ltd.
PO Box 718, Hornsby NSW 1630
Ph: (02) 9482 4930, Fx: (02) 9482 4931, E-mail: northernupdates@icanrural.com.au
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Predicted climate change impacts on northern NSW farming systems

Steven Crimp, Mona Mahani and Mark Howden, ANU

Key words

climate projections, production impacts, adaptation options, farming system

Take home messages

An increasing body of scientific evidence regarding the impact of human activity on the earth's climate has shifted the debate from "*Is climate change real*?" to "*What can we do about it*?" Adapting current management activities must include considerations of both climate variability and change. Advisers have a vital role in helping to develop information-rich farming systems that will improve responses to current climate variability and that can enhance adaptation to climate changes.

Historical changes in climate?

Globally averaged air temperatures have warmed by over 1°C since records began in 1850, and each of the last four decades has been warmer than the previous one (IPCC 2018). This warming is driven by increasing concentrations of all the major long-lived greenhouse gases in the atmosphere, with carbon dioxide (CO_2) concentrations rising above 400 ppm and the CO_2 equivalent (CO_2-e) of all gases reaching 500 ppm for the first time in at least 800,000 years (Foster *et al*., 2017).

In Australia, warming in average temperatures since 1910 has exceeded 1°C (BoM and CSIRO 2018). The frequency of both day-time and night-time temperature extremes have also changed. High monthly maximum temperatures that occurred around 2% of the time in the past (1951–1980) now occur around 12% of the time (2003–2017) (BoM and CSIRO 2018). Similarly, the frequency of very warm monthly minimum, or night-time, temperatures has changed from 2 to 12% more recently. This shift in the distributions towards hotter temperatures and more extreme high temperature conditions has occurred across all seasons, with the largest change being in spring (BoM and CSIRO 2018).

In Walgett, over the period 1950 to 2018, warming has occurred in maximum temperatures of approximately 1.22°C. A declining trend in annual rainfall has also been observed, with around 23% less annual rainfall now than in 1950. Evaporation rates have also risen, driven by warmer maximum temperatures with an additional 240 mm occurring now than in 1950. When comparing the proportion of evaporation to rainfall, the local warming has resulted 29% higher water deficit than in 1950.

We can compare the distribution of annual mean maximum and minimum temperatures for the period 1950 to 1984 and 1985 to 2019 (Figure 1 and Table 1). The analysis reveals that the warming that has occurred has increased the frequency of annual mean maximum temperatures of 29°C from 6% to 20% (Figure 1 and Table 1). The distributional changes in annual mean minimum temperatures are more complex, with a decline in the frequency of warmer temperatures i.e. above 14°C but an increase in the frequency of temperatures between 13 and 14°C.

A similar examination of maximum and minimum temperature extremes (Figure 2 and Table 1) shows that despite some warming in mean minimum temperatures, the frequency of cold extremes has increased i.e. minimum temperatures of -4°C have increased in frequency for 2% to 13% (Figure 2).

The increase in extreme hot days has clearly increased with temperatures of 48 to 50°C now twice as frequent as in the earlier record (Figure 2)

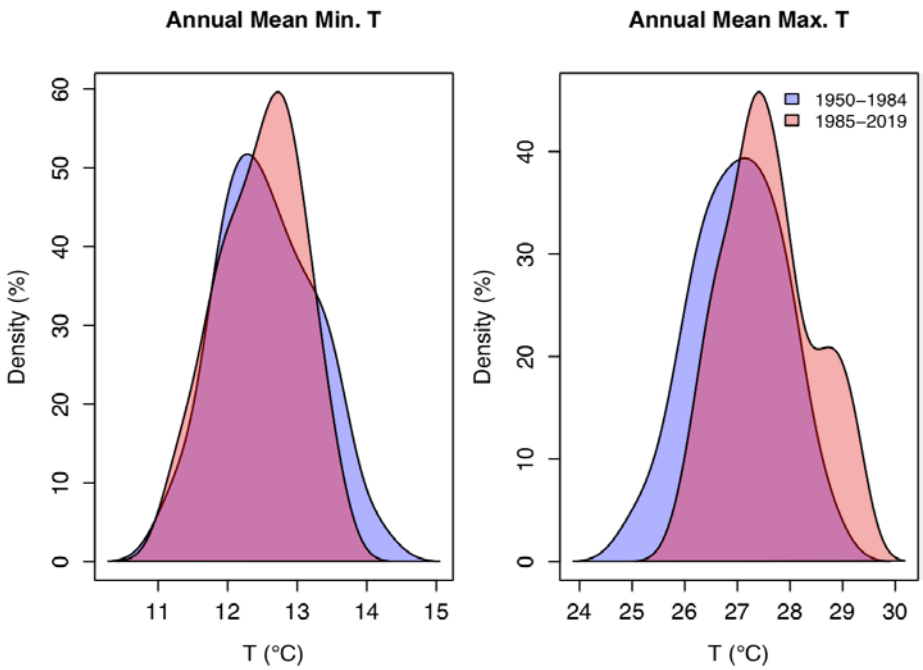

Figure 1. Probability distributions of mean annual minimum temperature (left) and mean annual maximum temperatures (right) for Walgett for two periods, 1950 to 1984 and 1985 to 2019.

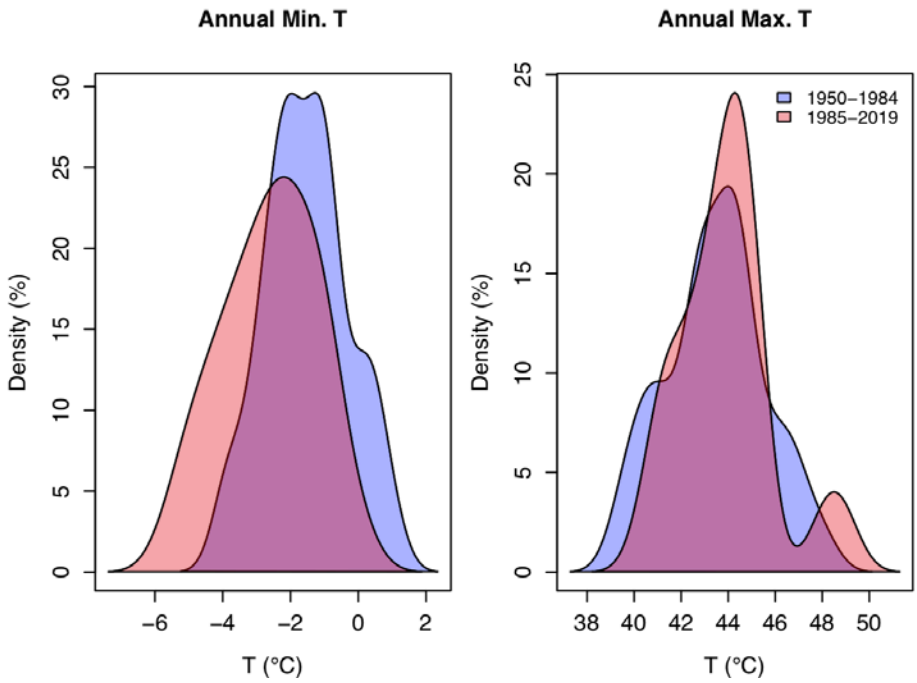

Figure 2. Probability distributions of annual minimum temperature (left) and annual maximum temperature (right) extremes for Walgett for two periods, 1950 to 1984 and 1985 to 2019.

Since 1950 Walgett has experienced historical declines in winter and spring rainfall, with slight increases in summer rainfall. The distribution of annual rainfall for the period 1985 to 2019 shows a higher frequency of amounts between 100mm and 200mm and lower frequency of amounts greater than 700mm (Figure 3 and Table 1). Reduction in rainfall over the observed record has resulted in later season breaks (now +/- 14 days later) and longer dry spell lengths (JJA and SON).

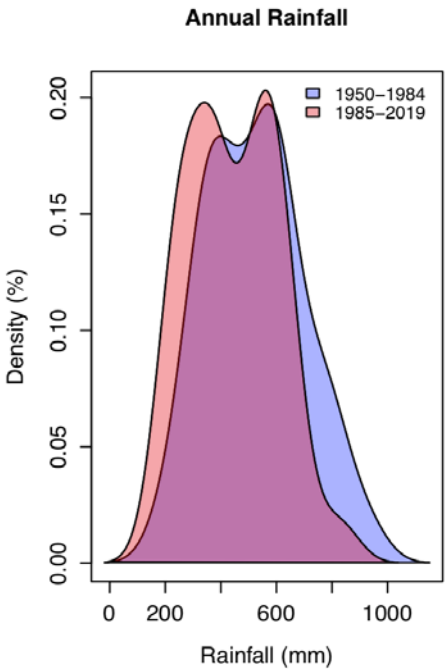

Figure 3. Probability distributions of annual rainfall for Walgett for two periods, 1950 to 1984 and 1985 to 2019.

Table 1. Observed changes in maximum, minimum temperature and rainfall for the period 1950 to 1984 and 1985 to 2019. Data is sourced from the Australian Bureau of Meteorology.

	1950-1984			**1985-2019**		
	Min. T (°C)	Max. T (°C)	Rainfall (mm)	Min. T (°C)	Max. T (°C)	Rainfall (mm)
Minimum	-3.9 (1952)	39.4 (1959)		-5.5 (2002)	40.5 (2010)	
Maximum	1.0 (1973)	48.0 (1973)		0.0 (1988)	49.0 (2014)	
Annual mean minimum	11.2 (1959)	25.0 (1956)	209.9 (1965)	11.2 (2012)	26.0 (2010)	203.7 (2007)
Annual mean maximum	14.1 (1973)	28.7 (1957)	922.4 (1950)	13.5 (1988)	29.2 (2018)	826.8 (2010)

The current acceleration of global warming is expected to continue based on future greenhouse gas (GHG) emissions trajectories. Previous studies have examined how the rates of record-breaking have changed in the US (Anderson & Kostinski 2011), the UK (Kendon, 2014), and Australia (Lewis & King, 2015). These studies have found increased rates of hot temperature records and decreased record setting for cold temperatures in recent decades (King *et al*., 2015; King, 2017). Lewis and King (2015) found that from 2000 to 2014 there were 12 times as many hot record-breaking temperatures as cold records in Australia and attributed this to anthropogenic climate change. Across the world, there were about five times more record-breaking monthly temperatures than would be expected without human induced climate change (Coumou *et al*., 2013) over the early 21st century.

Climate change has been found to not only increase the likelihood of breaking high temperature records (e.g. Lewis and Karoly, 2013), but record-breaking hot summers and years over previous decades are also attributable to anthropogenic climate change (King *et al*., 2016). More recent research by Mann *et al*. (2018) has shown that the synoptic features (large scale weather systems) responsible for prolonged heatwaves are on average 50% more prevalent by 2050 under a business-as-usual GHG emissions trajectory.

In addition to record breaking temperatures, changes in rainfall patterns, sea levels, rates of glacial retreat and biological responses have also been detected consistent with expected climate change projections. This mounting evidence has led to scientific consensus that:

Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that affect the climate system and these changes and resultant trends will continue for the foreseeable future; and

There is at least 95% confidence that humans are the main cause of global warming since 1950, and most likely responsible for 100% of that temperature rise (IPCC, 2013) with a less than 1 in 100 000 chance that human activities are not responsible for the observed increase in global temperatures (Kokic *et al.* 2014).

These changes are already likely to have negatively impacted on Australian agriculture, acting as a major drag on yield growth (Hughes *et al*., 2017) with similar impacts on yield growth globally for the major crops (Porter *et al*., 2014).

A major issue in understanding historical and future climate change is how much are the various human-induced climate forcings (greenhouse gas emissions, stratospheric ozone depletion, Asian aerosols, and landcover change) interact with components of natural variability (Watkins 2005, McKeon 2006). Thus, it is important for successful climate adaptation that agricultural decision-makers keep informed of the evolving climate science and updated climate change scenarios. As scientific understanding improves and there is more confidence in emission scenarios, current and future uncertainties can be rapidly assessed in terms of decision making.

What is expected to happen in the future?

In response to the continued growth in atmospheric GHG concentrations, scientists estimate that global average temperatures could increase by up to 4.8°C by the end of the present century, dependent on global population growth, technological advancement and economic growth (IPCC, 2013). To put this in context, the difference between our historical temperatures and those of the last ice age was only about 5°C. So even though 4.8°C does not sound like much, it signals a huge change in how the climate-ocean-land systems of the earth function and hence how agriculture will operate.

In Australia, national projections suggest up to 1.3°C of additional warming could be experienced by 2030 and up to 5.1°C of warming could be experienced by 2090, with the greatest warming being in inland Australia and the lesser warming along the southern coast and Tasmania (CSIRO, 2015). Global studies indicate that a rule of thumb is that global potential crop production drops by 6% per degree warming (Porter *et al.,* 2014).

Whilst changes in rainfall are more uncertain, projections suggest drier conditions in the southern half of Australia, particularly in the south-west and during the cool season months of May to October, with as much as 20% less by 2030 and up to 50% less rainfall by 2090 (CSIRO, 2015).

At a regional scale projected change in climate for the Far Western region (Walgett represents an eastern town in this study region) are summarised in Table 2. Estimates of median annual warming for 2030 are 0.7°C and for 2070 are 2.1°C (Table 2). Projected changes in annual rainfall for 2030 are small (i.e. +1%) due to projected increases in autumn and summer (i.e. +14% and +3% respectively) and decreases in winter (-7%) and spring (-10%). By 2070 projected median increases in annual

rainfall are +8%, driven by projected mean increases in all seasons except spring (Table 2). Due to continued warming, evaporation rates are likely to increase. The annual potential evaporation (1986-2005) for the region is 2121 mm. By 2030 the median value of annual potential evaporation is projected to increase by 8% and by 2070 by 17%.

Table 2. Projected changes in temperature and rainfall for the Far West region (Walgett is on found on the eastern part of this region). Present average temperatures and rainfall are calculated for the period 1986 to 2005. The data contained in this table represents information compiled from the Queensland Department of Environment and Science, SILO database and NARCliM databases.

Variable	Season	Historical mean (1986 to 2005)	2030	2070
Mean temperature change (°C change)	Annual	19.9°C	+0.7°C	+2.1°C
	Summer	27.3°C	+0.9°C	+2.5°C
	Autumn	20.1°C	+0.6°C	+2.1°C
	Winter	12.1°C	+0.4°C	+1.6 C
	Spring	20.3°C	+0.8°C	+2.3°C
Mean rainfall change (% change)	Annual	443mm	+1	+8
	Summer	144mm	+3	+12
	Autumn	112mm	+14	+13
	Winter	89mm	-7	+4
	Spring	102mm	-10	-5

To contextualise the projected changes discussed above, we can identify locations in Australia where its current climate is similar to the projected climate for Walgett in 2030. These locations are sometimes referred to as climate analogues and include Dirranbandi, Roma, Bourke, Augathella, Brewarrina, Tambo, Collarenebri, Cunnamulla, Mitchell, Charleville, St George and Lightning Ridge (Figure 4).

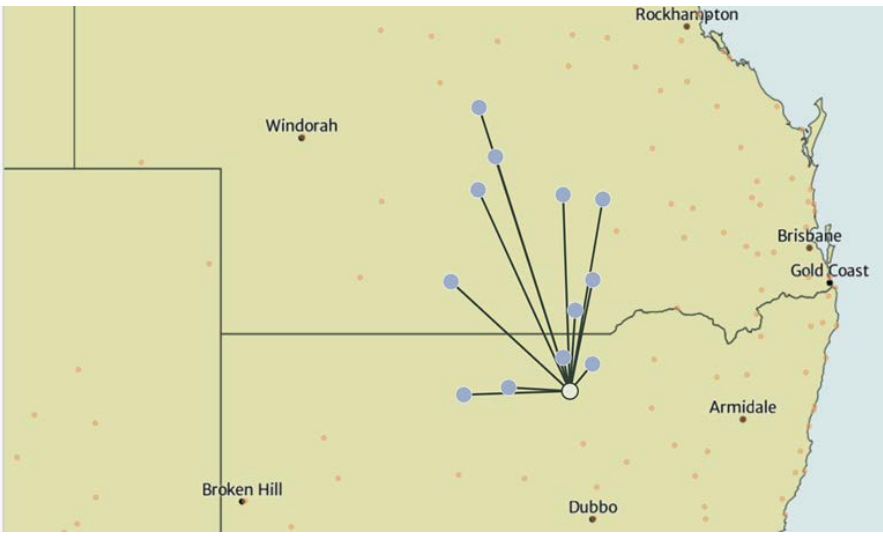

Figure 4. Present day geographical analogues that reflect what Walgett's climate could be like in 2030. Data sourced from https://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-analogues/analogues-explorer/

The impacts of climate change on wheat production for Walgett have been simulated using the Agricultural Production Simulator (APSIM). The simulations are based on a continuous wheat rotation with a Sunvale wheat variety, grown on a grey vertosol soil. The simulations were run using daily climate data for the period 1990 to 2018, with future scenarios for 2030 and 2070 produced by

scaling daily temperature and rainfall from the historical baseline period by the mean annual values found in table 2.

If the 1990 to 2018 climate were to change, with a mean increase in temperature of 0.7°C and slight increase of 1% in annual rainfall (i.e. the median 2030 projection), small improvements (approximately 80 to 200 kg per hectare) might be possible for 5th and 25th percentile yields (Figure 5). The 75th percentile yields are likely to decline by 200 kg per hectare, with little change in the 95th percentile yields (Figure 5).

If temperatures were to increase by 2.1°C and annual rainfall where to increase by 8% from the 1990 to 2018 base period, further improvements in the 5th and 25th percentile yields are possible (i.e. 500 kg per hectare) (Figure 5).

This simple example highlights the sensitivity of wheat production at Walgett to temperature increases and modest changes in annual rainfall, but does not take into consideration the compounding effects pest and disease. This simulation exercise does begin to make a case for adaptation at a range of spatial scales including farm-level and regional scales as well as changes to strategic planning and polices at the state and national level.

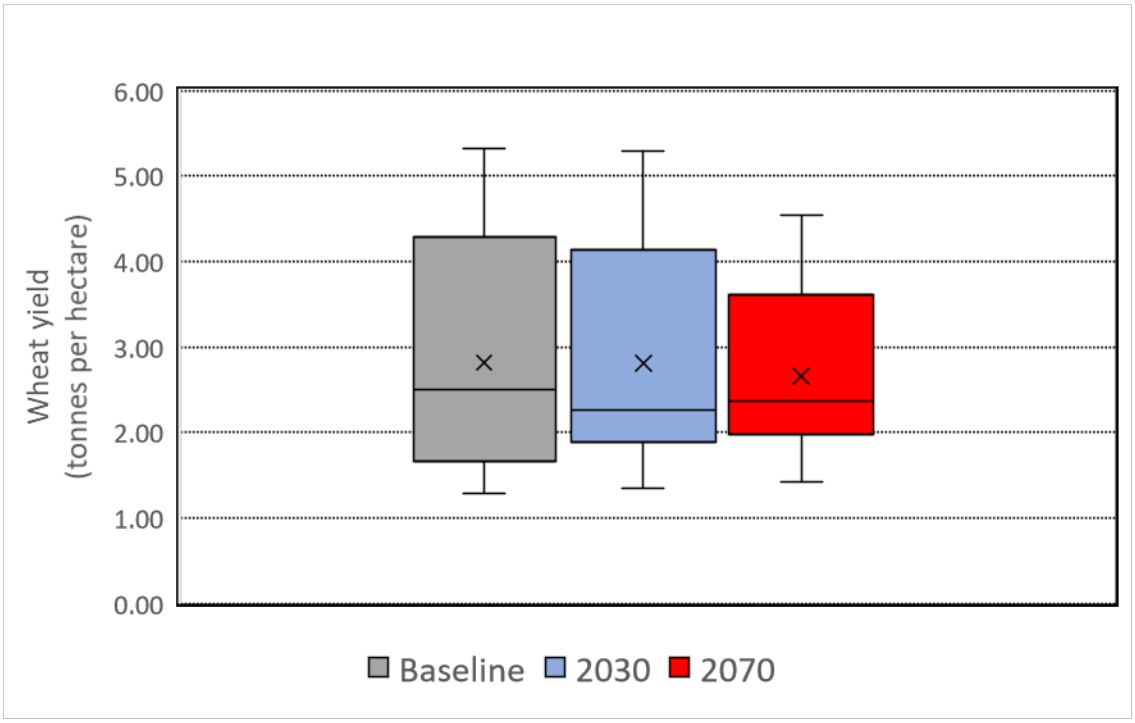

Figure 5. Boxplots of wheat yield for Walgett for the period 1990 to 2018 (baseline), for a 28 year period centred on 2030 and 2070. Simulations were undertaken using APSIM based on a continuous wheat rotation with the Sunvale wheat variety on a grey vertosol soil. Yields are expressed in kilograms per hectare. The horizontal line indicates the average yield, the top and bottom of the 'box' indicates the 25th and 75th percentiles (i.e. the yields exceeded in $\frac{3}{4}$ and $\frac{1}{4}$ of years) and the tops and bottoms of the 'whiskers' indicate the 95th percentile and bottom 5th percentile values). Climate scenarios for the 2030, 2050 and 2070 simulations are based on the mean annual projections of change in temperature and rainfall found in Table 1.

Adapting to projected climate changes

Climate change is likely to pose a significant challenge for Australian agriculture. Of greatest concern are likely to be changes in water availability, and the change in frequency of climatic extremes (e.g. heatwaves, drought and floods).

Many of the actions required for adapting to climate change are extensions of those currently used for managing climate variability. For this reason, efforts to improve current levels of adaptation to climate variability will have positive benefits in addressing likely climate change impacts.

Examples of likely farm level adaptation options include:

- Enhancing the current implementation of zero tillage and other minimum disturbance techniques, retaining crop residues, extending fallows, changing row spacing, changing planting density, staggering planting times, traffic and erosion controls
- Alter planting decisions to be more opportunistic – more effectively considering environmental condition (e.g. soil moisture), climate (e.g. seasonal climate forecasting) and market conditions
- Expand routine record keeping of weather, production, degradation, pest and diseases, weed invasion
- Incorporating seasonal climate forecasts and climate change into farm enterprise plans
- Improve efficiency of water distribution systems (to reduce leakage and evaporation), irrigation practices and moisture monitoring
- Learning from farmers in currently more marginal areas
- Selection of varieties with appropriate thermal time and vernalisation requirements, heat shock resistance, drought tolerance, high protein levels, resistance to new pests and diseases and perhaps that set flowers in hot/windy conditions
- Enhance current consideration of decision support tools/training to access/interpret climate data and analyse alternative management options (e.g. APSIM, EverCrop).

There are also longer-term decisions at a family farm level - to sell up, to buy more land, where to invest. These are especially pertinent for farmers in low rainfall regions and it will increasingly be more difficult to find no-regret decisions if climate change progresses as anticipated (Hayman 2005). These decisions, along with industry infrastructure (silos etc.) and industry support (drought policy), are hard decisions requiring full understanding of the likely future risks (Hayman 2005).

The value of adaptation

There is a growing international body of research examining the benefits of adaptation to climate variability and change, showing a number of adaptation options are available to reduce the possible impacts of climate change.

In Australia studies have examined the economic benefits of adaptation in the wheat industry at both national and regional scales under a range of likely future climate conditions. Hochman *et al.* (2017) highlighted that the adoption of new technology and management systems has held actual yields fairly steady: without these advances, water-limited yield would have dropped by 27%. It was estimated that rainfall declines should have accounted for about three-quarters of the fall in simulated yield potential, whilst observed warming should have accounted for about a quarter of fall in yield potential.

Continued adaptation to climate change has been estimated to add an additional AU$500M per annum to Australia's annual income from wheat exports (Howden and Crimp 2011) via the introduction of improved water-use efficiency options and may mitigate potential yield losses by up to 18% through broader scale adaptation (Ghahramani *et al.* 2015).

The results suggest a number of adaptation options exist to manage increased future downside risk, however the effectiveness of adaptation is driven by the extent of future change. Under conditions of large climate change, tactical adaptation will only have limited effectiveness. More extensive adaptation options, often defined as transformation adaptation, may be required.

Advisers have a key role to play in changing the nature of the climate change dialogue. In the space of about five years, many grain growers and their advisers have moved from asking "What is climate

change?" or "Is it real?" to "How do we manage for climate change?" and "What will the impact be on the grains industry?"

Advisers have a vital role to play in this dialogue, not only in assisting grain growers in reducing greenhouse gas emissions from on-farm activities, but also in developing information systems that growers can tap into in order to build farming systems that can cope with current climate variability and can adjust to ongoing climate changes.

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Acknowledgements

The authors would also like to acknowledge that this research was made possible via financial support from the New South Wales Department of Environment and Heritage. We would like to acknowledge the Australian Bureau of Meteorology (BoM) for provision of its Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) data and the Science Division of the Queensland Department of Environment and Science (DES) for provision of it SILO

climate data. The authors would also like to acknowledge the projection data sets sourced from NARCliM and the climate analogue data from the CSIRO climate projections website.

Contact details

Dr. Steve Crimp
Climate Change Institute
Australian National University
Fenner School of Environment and Society
Building 141, Linnaeus Way, Action, ACT 2601
Ph: 02 6125 7265
Email: Steven.Crimp@anu.edu.au

New genetics to improve wheat establishment and weed competitiveness

Greg Rebetzke[1], C. Ingvordsen[1], W. Spielmeyer[1], B. French[2], C. Zaicou-Kunesch[3] and N. Fettell[4]

[1] CSIRO Agriculture and Food
[2] DPIRD, Merredin
[3] DPIRD, Geraldton
[4] Central West Farming Systems, Condobolin

Key words

wheat, breeding, genetics, dwarfing genes, coleoptile length, establishment

GRDC code

CSP00182, CSP00199, CSP00200

Take home messages

- Current Australian wheat cultivars contain dwarfing genes that reduce coleoptile length by 40%. New dwarfing genes are available that reduce plant height but don't reduce coleoptile length
- A gene increasing coleoptile length was identified and tagged with DNA markers. Breeding lines and DNA markers for new dwarfing and coleoptile length genes have been delivered to Australian breeders for efficient selection of improved crop establishment
- Deep-sowing studies in WA and NSW Managed Environment Facilities show benefit with new dwarfing and coleoptile length promoting genes in increasing emergence at sowing depths of up to 120mm but without changing plant height
- Moisture-seeking points coupled with new genetics should reliably allow seed placement and emergence from sowing depths of 100mm or greater, and/or with warmer soils
- Genetic variability exists with potential to suppress weeds through greater shoot and/or root competitiveness.

Background

In rainfed environments typical of the eastern and southern wheatbelts, crops are typically sown on the first breaking rains but sometimes moisture accumulated through summer is too deep for sowing with conventional variety × drilling systems. Key to good leaf area development for tillering, growth and weed competitiveness is good crop establishment. An ability to establish wheat crops from seed placed 80mm or deeper in the soil would be useful in situations where the subsoil is moist but the surface dry. Seeding onto moisture at depth can assist to extend the opportunities for a greater portion of the cropping program to be sown in the traditional sowing months of May and June or earlier in April following summer rain. A separate but concerning issue is the influence of increasingly warmer soil temperatures on reductions in coleoptile (the shoot that grows from the seed and allows seedling emergence through the soil) length. Earlier sowing into warmer soils will reduce coleoptile length by as much as 60% so that a variety such as Mace with a 75mm coleoptile at 15°C will likely have a 40mm coleoptile at 25°C soil temperature. Some seed dressings and pre-emergent herbicides can further reduce this coleoptile length and affect establishment.

The green revolution *Rht-B1b (syn. Rht1)* and *Rht-D1b (syn. Rht2)* dwarfing genes reduced plant heights to reduce lodging and increase grain yields and so are present in most wheat varieties worldwide. Their presence also reduces the length of the coleoptile by as much as 40%. This reduces

crop emergence when sown at depths greater than 50mm, tiller number and leaf size to reduce water-use efficiency and weed competitiveness.

New dwarfing genes

A range of alternative dwarfing genes have been identified in overseas wheats with potential to reduce plant height and increase yields, while maintaining longer coleoptiles and greater early vigour. Some of these genes (e.g. *Rht8* and *Rht18*) have been used commercially overseas but have not been assessed for use here in Australia. We reduced the larger global set of alternative dwarfing genes to *Rht4, Rht5, Rht8, Rht12, Rht13* and *Rht18*, and then developed linked DNA-markers to assist with breeding of these genes in a commercial breeding program. Separately, we then bred these genes using conventional and DNA-based methods into the old, tall wheat variety Halberd for testing and disseminating to Australian wheat breeders.

Genes that promote coleoptile growth

While switching to new dwarfing genes will remove the growth inhibition on early growth, there is a need to promote coleoptile growth, particularly in the presence of conventional dwarfing genes. A gene with major effect on coleoptile length was identified in current wheat cultivars. Through a GRDC funded project, we demonstrated that the gene not only increased coleoptile length but also emergence with deep sowing in field trials conducted over three years at Yanco NSW (Figure 1). The gene was tagged with molecular markers and tested in a wide range of Australian wheat germplasm. We estimated that only 10% of recently released cultivars carry the coleoptile growth promoting gene. The markers were distributed to Australian breeding companies to assist with the selection and the expected increase of gene frequency in future cultivars. Additional genetic variation for coleoptile length and early growth exists in elite germplasm. For breeders to take full advantage of this variation, additional genes controlling this trait need to be identified and tagged with markers for efficient selection and combining growth promoting genes for even better performance.

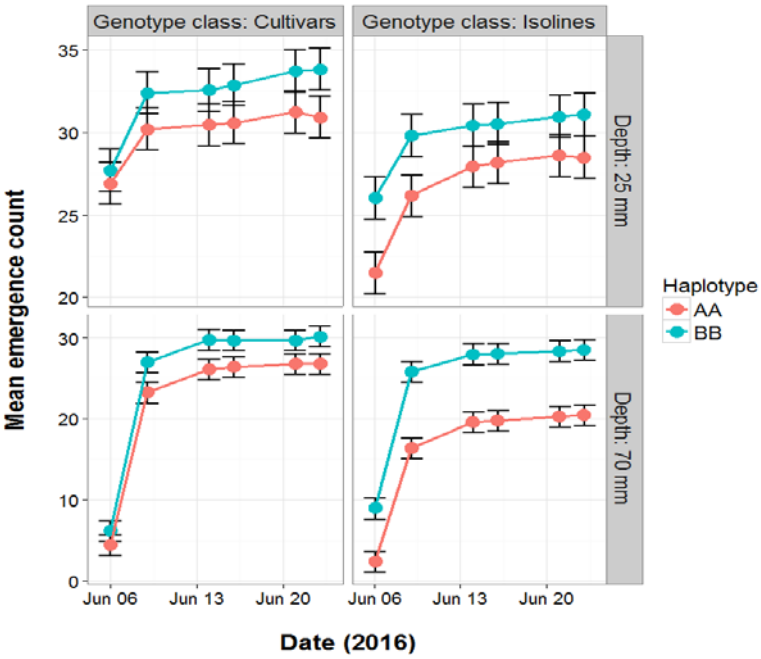

Figure 1. Emergence of wheat commercial cultivars carrying conventional dwarfing genes and tall isolines in Young background in the NSW MEF at Yanco in 2016. Sowing depth treatments were 25 mm and 70 mm depth. 12 cultivars and 12 isolines were grouped according to the presence of the coleoptile length promoting gene (BB, long coleoptiles) and the lack of the gene (AA short coleoptiles).

Preliminary sowing depth field studies

Field studies have commenced on the Halberd-based dwarfing gene lines and show that lines containing these new dwarfing genes produced coleoptiles of equivalent length to Halberd (up to 135mm in length; Figure 2) and established well when sown at 100mm depth in deep sowing experiments conducted at Mullewa and Merredin in 2016 (Figure. 3). Grain yields of lines containing the new dwarfing genes were equivalent to the yields of lines containing the commonly used *Rht-B1b* and *Rht-D1b* dwarfing genes while previous studies have shown the new dwarfing genes were linked to greater grain yields when sown deep, owing to greater plant number with improved establishment.

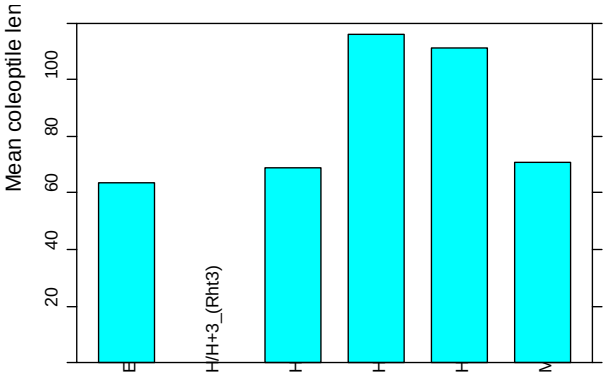

Figure 2. Coleoptile lengths of a tall wheat genotype (Halberd) and genotypes with dwarfing genes *Rht-B1b (syn. Rht1)* and *Rht8* emerging in the field in a Halberd background. Emu Rock⊕ and Mace⊕ are current commercial cultivars with *Rht-B1b* and *Rht-D1b*, respectively.

The most likely useful new dwarfing genes, *Rht13* and *Rht18*, have been bred into a range of current commercial wheats (Figures 4 and 5). Long coleoptile wheat breeding lines in Mace⊕, Scout⊕, Espada⊕, EGA Gregory⊕ and Magenta⊕ have been delivered to Australian breeders for testing and use in breeding. If there are no problems with these new dwarfing genes, we may see the first of the long coleoptile wheat varieties in 3-4 years in NVT testing!

Agronomic opportunities

Although there is real promise in the new genetics, there is significant opportunity in coupling new genetics with new existing seeding technologies. Deep sowing is an issue overseas and in the eastern Australian states. The availability of moisture-seeking points commonly used elsewhere should allow the reliable placement of seed at depths of 100mm or greater. These points produce a slot deep into the soil at the base of which a seed is sown at 10-50mm depth. That said, further research is required aimed at tools and methods assessing across different moisture-seeking points to optimise seed placement at depth across a wide range of soil types.

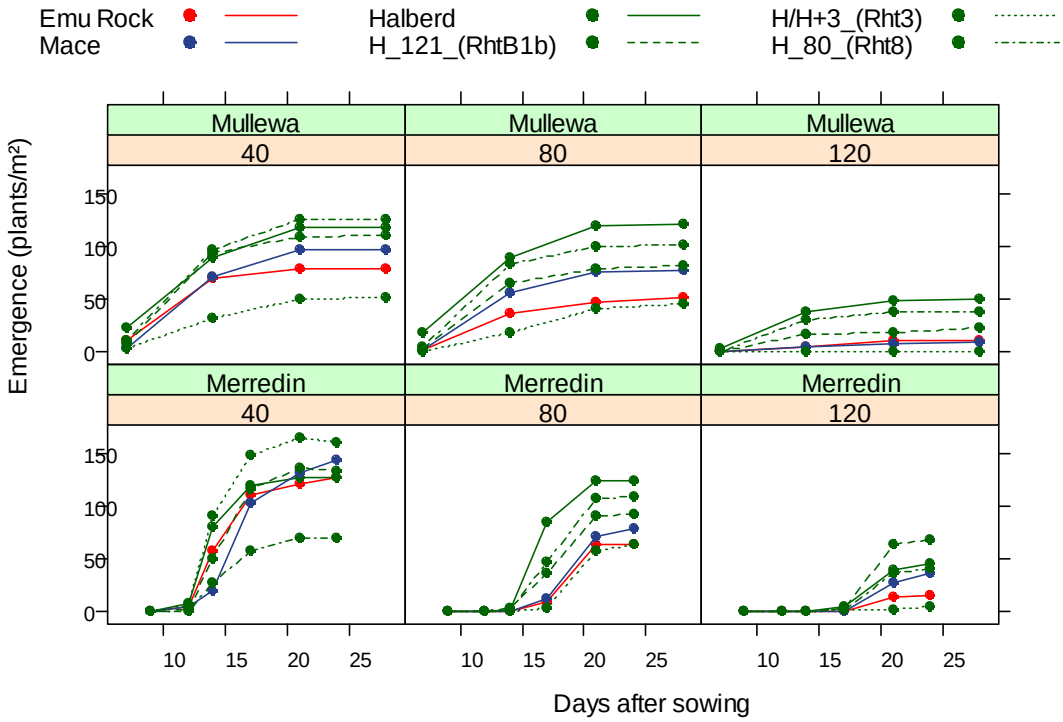

Figure 3. Patterns of emergence of wheat genotypes with different dwarfing genes sown at target depths of 40, 80, or 120 mm at Mullewa and Merredin in 2016 (after French *et al.* 2017).

Weed competitiveness

Weeds cost Australian grain growers an estimated $4B annually through lost production, reductions in crop quality, and herbicide use. These costs are unlikely to reduce with pressure on new actives in the widespread development of herbicide resistance in multiple weed species. Observed differences across cereal species and wheat varietal differences in crop competitiveness with weeds, provides impetus to use breeding and genetic improvement to aid in-crop weed control. In wheat, comparisons across a historic 100-year set of varieties highlighted that older varieties were more competitive with weeds. Presumably, this reflects selection for improved performance in the absence of in-crop herbicides. Overseas studies have demonstrated a reduction in herbicide use of up to 50% when using weed-competitive wheats, while a broader benefit is in integrating competitive varieties with cultural management (e.g. weed seed harvest and tillage) to slow herbicide resistance and reduce herbicide use.

Competitiveness can be thought of as the partial to complete suppression of competing weeds to increase crop yield, or the ability of a variety to tolerate a competitor to maintain higher yields. Selection for greater tolerance is a breeding strategy for many crop insects and diseases but is of less value in weed management as low numbers of weed survivors replenish the seed bank for the next season. In turn, breeding of competitive crops has focussed on selection of genotypes that can better access light, water and nutrients to suppress the growth of weeds. Greater early vigour, as rapid leaf area development and biomass at stem elongation and altered root architecture are mechanisms that contribute to the ability to out compete weeds. Root exudates used in plant defence (allelopathy) may also slow the growth of neighbouring competitors.

In cereals, greater leaf size and rapid early leaf area development are associated with larger seed embryos, higher leaf area, and new dwarfing genes for reducing stem height. Unfortunately, commercial wheat varieties selected for increased yield potential often exhibit poor early growth. A global survey identified 30 wide-leafed, wheat donors which were subsequently used in a CSIRO long-term breeding activity to accumulate favourable genes to increase early vigour. High vigour

lines derived from this program have been used to develop wheats with capacity to suppress the growth of ryegrass by up to 50% (Zerner et al. 2016). Field comparisons between current semi-dwarf wheat varieties and weed-competitive wheat breeding lines indicate wheat yield loss and weed suppression is greater in the weed-competitive lines (Figure 4).

Breeding companies are limited in their ability to develop and deliver new traits. The identification of new opportunities that will deliver greater grower profitability together with development of a clear value proposition will allow for pre-breeders to identify those traits and their underlying genetics and methods in selection for uptake by commercial breeders. In the case of weed competitiveness, the genes for weed suppression have come from outside existing breeding programs and include old Australian varieties and overseas landraces. Parental germplasm has been developed over many years and intercrossed into modern Australian varieties. Together with high-throughput selection methods, these populations have been delivered to Australian breeders for use in their commercial breeding efforts toward new weed competitive wheat varieties.

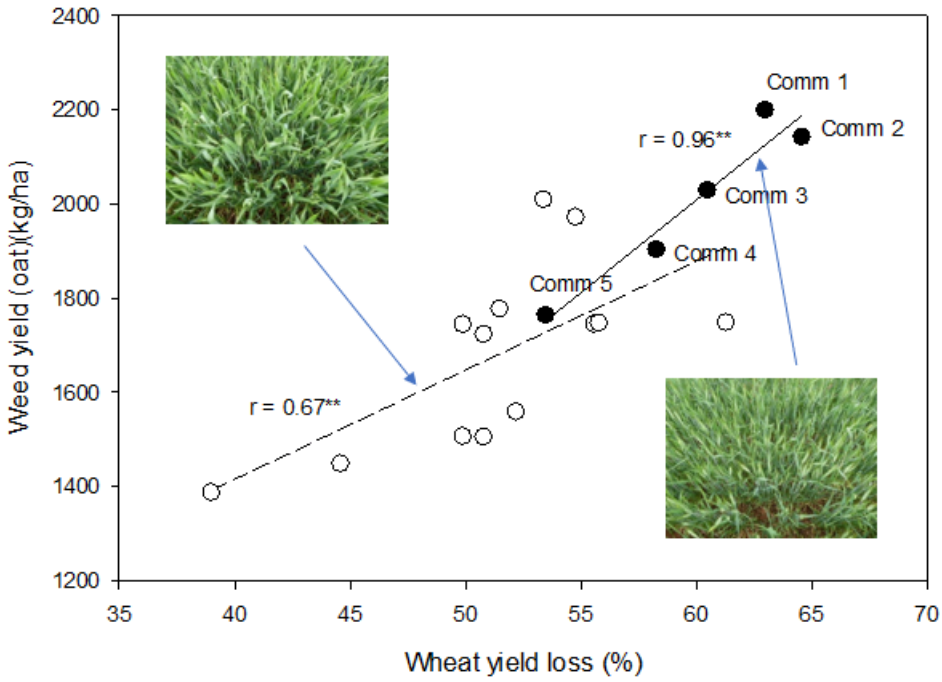

Figure 4. Relationship for yield loss in wheat and growth (as yield) of a weed mimic (oats) for breeding lines (○) and commercial wheat varieties (●) in field plots.

Summary

Wheat breeders now have the new dwarfing genes to breed longer coleoptile wheat varieties. Genes that increase coleoptile length have also been identified and tagged with markers. These genes are expected to play an important role in improving emergence from depth in the presence of conventional dwarfing genes. Matching new genetics with appropriate agronomy and technologies should ensure the emergence and establishment of deep-sown wheats, particularly when sown early to make use of summer rains sitting deep in the soil profile or to increase sowing opportunities in the traditional months of May and June.

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Acknowledgements

We would like to acknowledge the support of the GRDC in funding much of the research reported herein. We'd also like to acknowledge the support of the managers of the GRDC's Managed Environment Facilities for their assistance.

Contact details

Greg Rebetzke
CSIRO
Mb: 0429 994 226
Email: G.Rebetzke@csiro.au

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Figure 4. Wheat variety Mace (left) side-by-side with long coleoptile, Mace containing the *Rht18* dwarfing gene (right) at Condobolin in 2017.

Figure 5. Wheat variety EGA Gregory (left) side-by-side with long coleoptile, EGA Gregory containing the *Rht18* dwarfing gene (right) at Condobolin in 2017.

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Current and future site-specific weed control options

Andrew Guzzomi[1], Carlo Peressini[1], Michael Widderick[2], Adam McKiernan[2], Bhagirath Chauhan[3] and Michael Walsh[4]

[1] University of Western Australia
[2] Queensland Department of Agriculture and Fisheries
[3] University of Queensland
[4] University of Sydney

Key words

Targeted tillage, site-specific weed control, SSWC, rapid response tyne, energy requirements

GRDC codes

UWA 00171, US00084

Take home messages

- "Weed Chipper" is a targeted tillage system developed for site-specific fallow weed control based on a rapid response tyne
- Site specific weed control (SSWC) creates the opportunity to use alternative physical weed control technologies.

Background

The reliance on herbicidal weed control in northern region fallows has led to widespread herbicide resistance evolution in major weed species. As glyphosate is the most widely used herbicide for fallow weed control resistance to this herbicide is increasing at an alarming rate. There is also increasing frequency of resistance to selective herbicides that are being introduced to try and manage glyphosate resistant populations. Alternate non-chemical weed control techniques are desperately needed that are suited to routine use in northern region cropping systems.

Physical and thermal weed control techniques were in use well before herbicides were introduced and the development of new options has continued throughout the herbicide era. However, most of these technologies have not been adopted, primarily due to cost, speed of operation and fit with new farming systems. The introduction of weed detection and actuation technologies creates the opportunity to target individual weeds i.e. site-specific weed control (SSWC). This greatly increases the potential cost-effectiveness of many directional physical weed control techniques in conservation cropping systems.

Aims

1. To develop a rapid response tyne based on a hydraulic break-out tyne
2. Use energy required for effective weed control to compare the efficiency of alternate weed control techniques

Method

Development of a rapid response tyne

A rapid response tyne system has been developed with the operational specifications of being able to specifically cultivate targeted weeds when present in a field at densities of up to 1.0 plant/10 m^2 at an operation speed of 10 km/h. To permit timely development, the rapid response tyne concept

was based on the retrofit of a Shearer Trashworker tyne with a hydraulic breakout system. The Shearer Trashworker was chosen due to its robust build, reputation and prevalence across Australian cropping systems. Its hydraulic breakout system is typical of many other manufacturers thus permitting a design approach which could be adapted to accommodate other arrangements. Although hydraulic systems are not traditionally used in such dynamic environments, to aid timely adoption and acceptance by farmers it seemed sensible to not deviate too far from current accepted and widely adopted agricultural principles.

Whilst focusing on the development of the rapid response tyne around a conventional cultivator, achieving the outcome efficiently and elegantly was not straightforward. As traditional cultivator bars are designed for continuous tillage and full-time tool-soil interaction, the new application required detailed engineering to modify the hydraulic system, mechanism functionality and optimise performance all whilst being highly constrained by the existing geometry.

The initial proof-of-concept design focussed the engineering on minimising the number of additional components and keeping the design simple whilst achieving the chipping action similar to a conventional hoe in well under half a second. A modular approach to the design was taken so as to permit the system to be scaled readily as confidence in system performance was achieved. The Shenton Park rig provided the initial proof-of-concept and the other rigs were used for weed kill testing (Figure 1A to C).

Weed control efficacy

Field testing using the two prototype rigs at the two northern region locations (QDAF and Narrabri) was conducted on a range of fallow weed species. The targeted tillage system was evaluated in a series of field trials for efficacy on weeds of winter fallows (annual ryegrass, wild oats, sowthistle and wild turnip) and summer fallows (barnyard grass, feathertop Rhodes grass, fleabane and sowthistle). At Narrabri, summer and winter field trials investigated the efficacy of the response tyne on the targeted weeds species established at eight growth stages (Table 1).

As the initial mandate for the project was to develop the mechanical response tyne and not the sensor system, the evaluation experiments used a simple photo detector arrangement to trigger the response tyne. A reflector was aligned next to each plant in the plot trial and together with the known travel speed, the system was calibrated to trigger the rapid response tyne when the light beam aligned with the reflector and hence with the weed.

Comparison of weed control technologies

The direct energy requirements for the control of two-leaf weed seedlings were estimated from published reports on the weed control efficacy of a comprehensive range of physical weed control techniques (Table 3). To determine the energy requirement per unit area, a weed density of 5.0 plants/m^2 was chosen to represent a typical weed density in Australian grain fields, based on results from a recent survey of Australian grain growers (Llewellyn *et al.* 2016).

Results

Development of a rapid response tyne

Significant engineering research, development and testing were conducted predominantly around the Shenton Park test rig at UWA (Figure 1A). As with any engineering design, the process involved iterative improvements to the design layout. Once the system was able to achieve a chipping cycle time of less than 400 ms from actuation to return to standby position and the design had been simplified and deemed reliable, the pre-commercial rig was designed and built. Detailed explanation of the engineering process and results will be presented in forthcoming publications.

Figure 1. Initial proof-of-concept rig (Shenton Park) (A), Narrabri trailer mounted self-powered rig (B) and QDAF 3-point-linkage rig (C) and Pre-commercial rig – the 'Weed Chipper' (D) used in the testing and validation of targeted tillage fallow weed control.

Weed kill field testing demonstrated very high efficacy on all targeted summer and winter annual weeds regardless of growth stage (Tables 1 and 2). The survival of any weeds during testing was due to cultivator sweeps not being suitable for targeted tillage. Weed control was 100% effective when the weed was targeted by the point of the sweep, however there was high weed survival when the weed was hit by sweep side. There was also reduced efficacy when weeds were excessively large. When feathertop Rhodes grass was >50cm diameter there was only poor control (Table 2). The system is highly effective on both broadleaf and grass weeds with potentially little resulting soil disturbance (Figure 2).

Table 1. Response tyne efficacy following direct or partial sweep impact on four winter and three summer weed species at eight growth stages, Narrabri NSW 2017 and 2018

Planting date	Wild oats (% control)		Turnip weed (% control)		Sowthistle (% control)		Annual ryegrass (% control)		Feathertop Rhodes grass		Barnyard grass		Fleabane	
	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact
2 leaf	100	0	100	100	100		100	0	100	-	100	-	100	-
4 leaf	100	-	100	0	100	-	100	0	100	-	100	-	100	-
6 leaf	100	-	100	100	100	-	100	0	100	-	100	-	100	-
8 leaf	100	0	100	-	100		100	0	100	-	100	-	100	-
10 leaf	100	0	100	-	100	-	100	0	100	-	100	-	100	-
Bolting/tillering	100	0	100	-	100	-	100	0	100	-	100	-	100	-
Early flowering/heading	100	0	100	-	100		100	0	100	-	100	-	100	-
Flowering	100	-	100	-	100	-	100	0	100	-	100	-	100	0

- indicates no treatments where there was partial contact of the tyne with the weed.

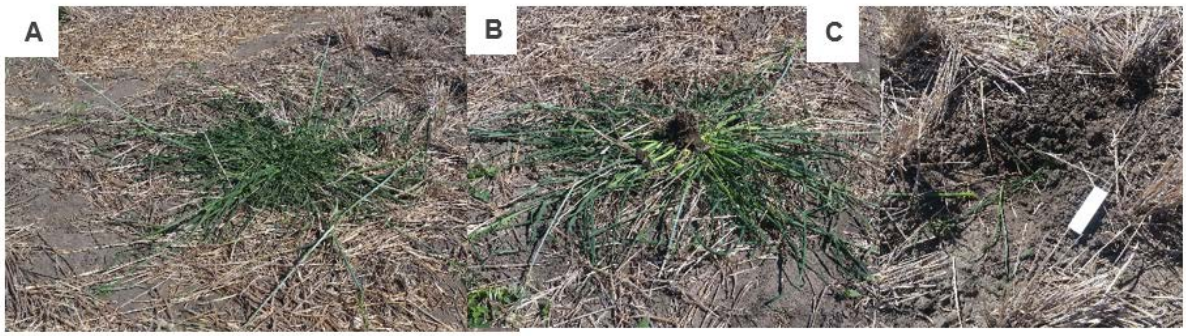

Figure 2. Wild oats pre- targeted tillage (A), post-targeted tillage (B) and the resulting "divot" (C)

Table 2. Weed control efficacy of the rapid response tyne on four weed species at three growth stages combined results from Warwick and Gatton 2018

Weed species	Growth stage	Control (%)
Barnyard grass	Small (<30cm)	100a
	Medium (30-50cm)	97.8ab
	Large (>50cm)	95.6ab
Feathertop Rhodes grass	Small (<30cm)	97.4ab
	Medium (30-50cm)	92ab
	Large (>50cm)	86.1bc
Wild oats	Small (<30cm)	99.1a
	Medium (30-50cm)	98.7a
	Large (>50cm)	98.1ab
Sowthistle	Small (<30cm)	89.9b
	Medium (30-50cm)	79.4c
	Large (>50cm)	73.8c
LSD P=0.05		8.2

Inclusion of weed detection technologies

The efficacy of targeted tillage for weed control is entirely reliant on accurate weed detection. Given that the initial use of targeted tillage will be in fallow, then it is appropriate that current available real-time detection technologies be incorporated in preparation for commercial use. Current boom spray mounted detection systems (WeedSeeker® and WEEDit®) are coupled to spray nozzles that can be rapidly triggered. Preliminary tests using the WEEDit sensing system to trigger the hydraulics on the Shenton Park rig demonstrated its high suitability to the fallow application. The WEEDit system was chosen as being more suitable system for targeted tillage and has now been incorporated into the pre-commercial Weed Chipper rig. Trials using the system coupled with the 6m pre-commercial Weed Chipper, Figure 1D, are currently underway.

There are a group of thermal weed control technologies (flaming, hot water foaming, steaming, etc.) using chemical or electrical energy that may be used for broadcast weed control (Table 3). In comparison to tillage and herbicide-based options, these approaches are considerably more energy

expensive. With 100 to 1000-fold higher energy requirements, it is not surprising that these technologies have not been widely adopted for use in large scale cropping systems, although in more intensive operations, flaming is used to some extent.

Table 3. Total energy requirement estimates for alternative weed control options applied as broadcast treatments. Estimates are based on the control of two-leaf weeds present at five plants/m^2.

Weed control method	Energy consumption (MJ/ha)
Flex tine harrow	4
Sweep cultivator	11
Rotary hoe	13
Organic mulching	16
Rod weeding	18
Spring tooth harrow	22
Basket weeder	29
Roller harrow	29
Disc mower	31
Tandem disk harrow	36
Flail mower	57
Offset disk harrow	64
UV	1701
Flaming	3002
Infrared	3002
Hot water	5519
Hot foam	8339
Steam	8734
Freezing	9020
Hot air	16902
Microwaves	42001
Plastic mulching	211003

Site-specific weed control (SSWC)

The opportunity for substantial cost savings and the introduction of novel tactics are driving the future of weed control towards SSWC. This approach is made possible by the accurate identification of weeds in cropping systems using machine vision typically incorporating artificial intelligence. Once identified, these weeds can be controlled through the strategic application of weed control

treatments. This precision approach to weed control creates the potential for substantial cost savings (up to 90%) and the reduction in environmental and off-target impacts (Keller et al. 2014). More importantly for weed control sustainability, SSWC creates the opportunity to use alternative physical weed control options that currently are not suited for whole paddock use.

Accurate weed detection allows physical weed control treatments to be applied specifically to the targeted weed. As weed identification processes develop to include weed species, size and growth stage, there exists the potential for some approaches (such as electrical weeding, microwaving and lasers) to be applied at a prescribed lethal dose. This dramatically reduces the amount of energy required for effective weed control (Table 3). For example, microwaving, as one of the most energy expensive weed control treatments as a broadcast treatment (42,001 MJ/ha), requires substantially less energy when applied directly to the weed targets (17.8 MJ/ha). Therefore, even though the same number of weeds are being controlled (five plants/m^2), the specific targeting of these weeds results in a 99% reduction in energy requirements.

The accurate identification of weeds allows the use of alternative weed control technologies that are not practically suited for use as whole paddock treatments. For example, lasers are typically a narrow beam of light focused on a point target. In a SSWC approach with highly accurate weed identification and actuation, lasers can be focused precisely on the growing points of targeted weeds, concentrating thermal damage. By reducing the treated area of the weed, off-target losses are further reduced allowing additional energy savings.

Table 4. Total energy requirement estimates for alternative weed control options when applied as site-specific treatment. Estimates are based on the control of two-leaf weeds present at five plants/m^2.

Weed control method	Energy consumption (MJ/ha)
Concentrated solar radiation	14.4
Precise cutting	14.4
Pulling	14.4
Electrocution: spark discharge	14.5
Nd:YAG IR laser pyrolysis	15.1
Herbicides	14.8
Hoeing	15.7
Water jet cutting	15.8
Stamping	16.5
Nd:YAG IR laser pyrolysis	16.9
Microwaves	17.8
Abrasive grit	24.5
Thulium laser pyrolysis	25.9
CO_2 laser cutting	54.8
Targeted flaming	59.9
Electrocution: continuous contact	60.9
Nd:YAG laser pyrolysis	84.4
CO_2 laser pyrolysis	92.3
Nd:YAG UV laser cutting	129.4
Hot foam	131.3
Dioide laser pyrolysis	133.1
Nd:YAG IR laser cutting	204.4
Targeted hot water	517.6

Conclusion

The response tyne's mechanical nature enables it to control weeds with greater flexibility around environmental conditions such as wind, humidity and heat. Its ability to handle a vast range of plant stages of weeds will likely reduce the number of passes required to manage fallow weeds compared to current herbicide practice and help mitigate the current slower travel speed and narrower coverage. The periodic tilling action required for low-density weed populations will also permit the

Weed Chipper to be coupled to low horsepower tractors. With no direct need for chemical use for this system there are likely to be significant cost savings to growers using the Weed Chipper system.

Targeting treatments on individual plants such as in SSWC, results in significant energy savings and makes previously impractical options on a broadcast basis available for use on a site-specific basis. The focus for SSWC research is now dually focussed on the development of weed recognition systems and the evaluation of alternate weed control technologies such as lasers and electrical weeding.

Acknowledgments

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the authors would like to thank them for their continued support. The authors are grateful to Allan Spurling and Karl Teune from David Nowland Hydraulics (Bunbury, Western Australia) for developing the physical hydraulic circuit. The willing advice from Ray Harrington, Geoff Glenn and Mic Fels is also gratefully acknowledged.

Further reading

Site-specific weed control – GRDC Grains Research Update paper, July 2018 (https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/site-specific-physical-weed-control)

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Contact details

Michael Walsh
University of Sydney
12656 Newell Highway, Narrabri, NSW 2390
Ph: 02 6799 2201
Mb: 0448 847272
Email: m.j.walsh@sydney.edu.au

Andrew Guzzomi
University of Western Australia
35 Stirling Highway, Crawley, WA 6009
Ph: 08 6488 3883
Mb: 00428396262
Email: Andrew.guzzomi@uwa.edu.au

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5 years of Nitrogen research – Have we got the system right?

Richard Daniel, Rachel Norton, Anthony Mitchell, Linda Bailey, Denielle Kilby, Branko Duric and Lawrie Price, Northern Grower Alliance

Key words

Nitrogen, efficiency, soil movement, timing

GRDC code

NGA00004

Take home messages

- Over the 14 trials from 2014 to 2017, the efficiency of nitrogen (N) grain recovery from soil N was ~4 times that of fertiliser N that was applied in the year of cropping
- Maintaining high soil N levels is critical for cereal production efficiency due to the poor fertiliser N grain recovery
- Testing of grain, stubble and soil at harvest was able to account for a mean level of ~79% of the applied fertiliser N over 23 comparisons, however in 4 of the 23 comparisons, testing only accounted for 30-50% applied fertiliser N
- The majority of the additional N at harvest was recovered in the soil and averaged ~65% of the applied quantity
- The slow and shallow fertiliser N movement in soil is likely to be impacting on grain recovery efficiency
- Strategies to get fertiliser N deeper, more quickly, may provide useful efficiencies in uptake and reduce potential losses
- Strategies that can improve N contribution from the legume phase will be highly productive
- Fallow N fertiliser applications are likely to provide a benefit over at planting application in years with low in-crop rainfall.

Background

Northern Grower Alliance (NGA) have been heavily involved in nitrogen (N) management trials in wheat since 2012. The focus has always been on methods to improve the efficiency and economics of N nutrition in wheat but the specific focus shifted over time:

1) 2012-2014: Economics and fit of late application
2) 2014-2018: Impact of application method and timing.

In addition to generating answers on the two main themes, a large body of data had been created on N uptake efficiency together with measurements of soil movement and fate of N.

Rather than focusing on individual trial results, this paper focuses on N management 'system implications' and challenges whether we really have got the system right.

Grain nitrogen recovery

Grain N recovery in wheat has been calculated in trials from 14 individual locations conducted during the 2014-2017 seasons. A wide range of production conditions have been experienced with yields ranging from ~1 to 5t/ha. Three steps were taken in calculating the grain N recovery from fertiliser:

1. Grain N recovery for each treatment was calculated as yield (kg/ha) x % protein/100 x 0.175
2. 'Net' grain N recovery was then calculated by deducting the grain N recovery in the untreated (unfertilised treatment)

3. % grain N recovery was calculated by dividing the net recovery by the amount of N applied

Table 1. % grain N recovery from urea applications in 15 trials, 2014-2017

Season	2014		2015		2016		2017	
Method/ timing	All IBS		Drilled in fallow/IBS/ PSPE		Incorporated in fallow/IBS/ PSPE		Spread in fallow x 2/PSPE	
Variety(s)	EGA Gregory⦶		EGA Gregory⦶		Suntop⦶		Lancer⦶, Suntop⦶ & 5 other varieties	
# of trials	4		5		3		3	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Urea 50 kg N/ha	21%	13-34%	30%	<0-45%	23%	16-27%	15%	10-19%
Urea 100 kg N/ha	16%	12-26%	19%	<0-31%	18%	12-23%	9%	7-12%
Urea 200 kg N/ha	9%	5-17%	11%	<0-17%	10%	8-12%	5%	3-6%

NB Data from two trials at Billa Billa 2017 site included. IBS = Incorporated By Sowing, PSPE = Spread Post Sowing Pre Emergent. Recovery data for each urea rate was generated from one application timing in 2014 but 3 timings in all 2015-2017 trials.

Key points

1. As expected, the % grain N recovery reduces as the N application rate increases.
2. Trials were conducted over a range of varieties with no indication of a consistent difference in response to fertiliser N rate between varieties.
3. Most applications were incorporated but some were surface spread and not incorporated.
4. No indication of difference between incorporated versus spread but not incorporated.
5. Recoveries appeared lower in 2017 – low in-crop rain, low yields with reduced N responses.

Grain N recovery from available soil N was also calculated for all trials in 2016 and 2017. Soil N was measured to 120cm at both planting and harvest. (Data from 2014 and 2015 was not included as soil N was only assessed during the fallow for site selection and often to 60cm depth). Two steps were taken in calculating the grain N recovery from soil N:

1. The quantity of soil N 'used' was calculated by the amount in the soil at planting minus the amount at harvest.
2. % grain N recovery was calculated by dividing the untreated grain N recovery by the amount of soil N used.

NB: an estimate of the quantity of N mineralised during the cropping season was not included for any calculation but was assumed to be consistent for all treatments. Inclusion of an estimate of mineralised N would lower the % grain recovery for both soil and fertiliser but is unlikely to change the relative differences.

Table 2. % grain N recovery from soil only, fertiliser only or combined soil and fertiliser application in 6 trials 2016-2017

Season	2016		2017	
Number of trials	3		3	
N 'source'	Mean	Range	Mean	Range
Soil only	98%	73-112%	62%	55-70%
Fertiliser only	23%	16-27%	15%	10-19%
Soil & fertiliser	62%	54-74%	40%	33-46%

NB: The mean and range used for 'fertiliser only' is for the most efficient rate (50 kg N/ha) from Table 1.

Key points

1. The % grain N recovery when calculated on combined soil and fertiliser quantities is in line with industry convention (~40-60% N efficiency depending on year).
2. However, **each kg of soil N was ~4 times more efficient** (range 3-6 times) in producing yield and protein than each kg of fertiliser N – even when fertiliser was applied at the most efficient rate.

Situations of concern

N fertiliser recommendations are generally based on setting a target for yield and protein and then ensuring a quantity of soil and fertiliser N that is generally double that target (i.e. working on a 40-60% grain N recovery efficiency). This approach is generally effective, but on the basis of these results, will struggle when soil N levels become low. Common examples would be:

- Soil N levels are heavily depleted following an unexpectedly very high yielding crop (e.g. in 2012); and
- Following a very dry fallow where mineralisation is greatly reduced.

In these situations, N fertiliser application rates may need to be increased to commercially impractical and uneconomic levels to achieve the expected outcome. In some situations with very low starting N quantities, a change from cereal to a legume may be a much better option.

Why is the fertiliser efficiency so low in the year of cropping?

Movement of N

One possible reason for the low observed efficiency of grain N recovery from fertiliser applied in the year of cropping may be the amount and speed of N movement in soil. During 2015-2017 a primary objective has been to evaluate the impact of N application into a dry soil profile during the fallow. The hypothesis was that the applied N would move further with fallow rain events so that N would be deeper and more uniformly distributed by planting.

Figures 1 and 2 are indicative of the results achieved following N application during the fallow in 2015/16 and 2016/17.

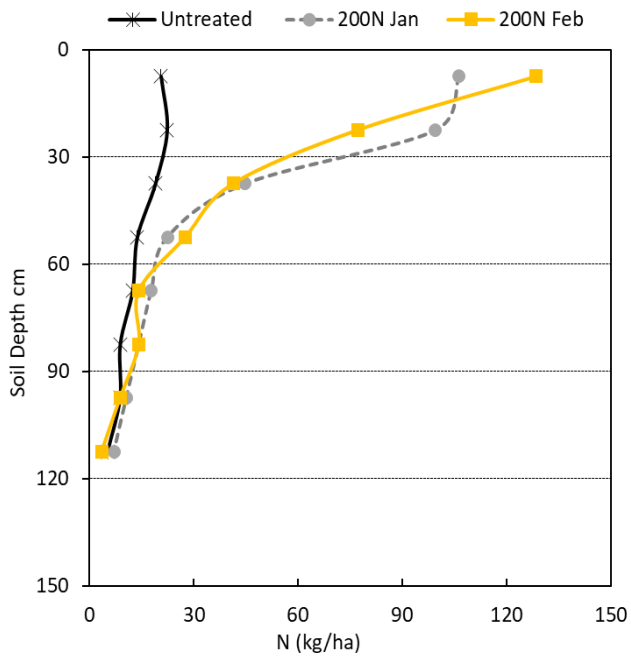

Figure 1. Soil distribution of N at Mullaley at planting (May 2017) following application of urea in January or February 2017. 175mm of rain was recorded between the January application and planting. 140mm of rain was recorded between the February application and planting.
(NB: Both N applications were spread and not incorporated. Sampling method - 6 individual 0-120cm depth cores taken per plot. Samples from each depth were bulked with a single sub sample taken for analysis. Not replicated.)

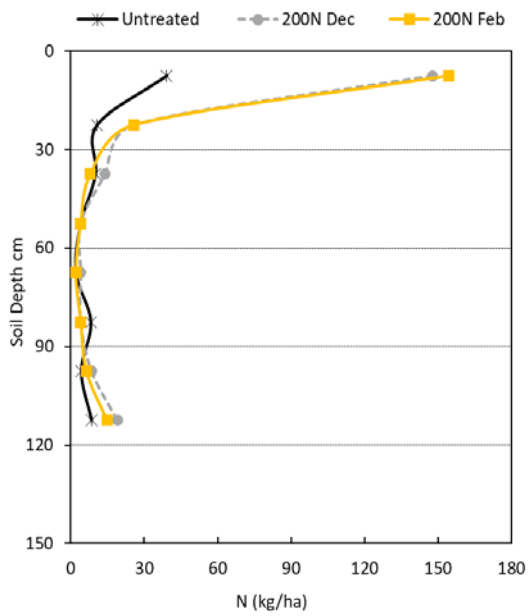

Figure 2. Soil distribution of N at Tulloona at planting (June 2016) following application of urea in December 2015 or February 2016. 225mm of rain was recorded between the December application (spread and incorporated) and planting. 65mm of rain was recorded between the February application (spread and not incorporated) and planting.
(NB: Sampling method - 6 individual 0-120cm depth cores taken per plot. Samples from each depth were bulked with a single sub sample taken for analysis. Not replicated.)

Key points

1. Even in a dry soil profile, the movement of N in these trials (predominantly vertosol soil types) was slower and shallower than expected.
2. The majority of N applied in fallow (either surface spread or incorporated to depths of ~3-5cm) was still in the 0-15cm soil segment at planting.
3. Sampling in smaller increments e.g. 5cm may reveal clearer differences in movement between application timings.

Implications of reduced N movement

The slower observed movement of N in soil may explain why in 10 of the 11 application timing trials there has not been a significant advantage from fallow N application compared to N applied at planting - as long as there were reasonable levels of in-crop rain. The 2017 season was however characterised by useful fallow rains (particularly in March) but with very low levels of in-crop rain (particularly June-September).

Billa Billa 2017

The site at Billa Billa in 2017 was the first to show a significant benefit from both fallow N applications compared to the same quantity applied at planting (or in-crop).

Figure 3 shows the distribution of soil N at planting from fallow application with the majority of N in the 0-15cm depth for both December and March 2017 applications, but with apparent increased movement from the December application. This site had the deepest movement of N recorded in any of the trials in 2016 or 2017.

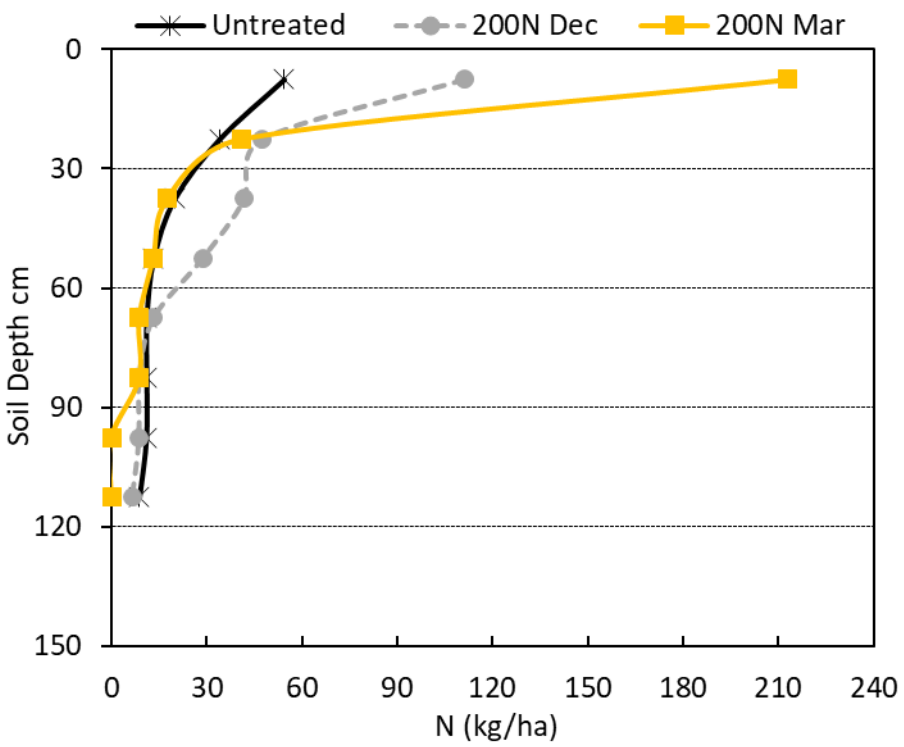

Figure 3. Soil distribution of N at Billa Billa at planting (May 2017) following application of urea in December 2016 or March 2017. 279mm of rain was recorded between the December application and planting. 154mm of rain was recorded between the March application and planting.
(NB: Both applications spread and not incorporated. Sampling method - 6 individual 0-120cm depth cores taken per plot. Samples from each depth were bulked with a single sub sample taken for analysis. Not replicated.)

Figure 4 shows the yield results (variety Lancer⦶) at this site. There was no significant N response from fertiliser applied at planting (or in-crop) at this site, with only 71mm of in-crop rain received between planting and the end of September. However applications in December or March provided a significant increase in both yield and protein (not presented).

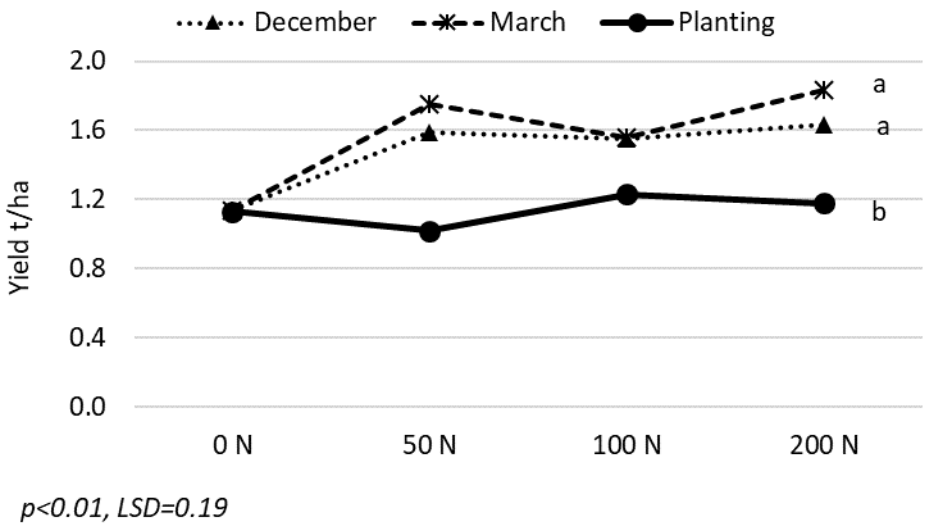

Figure 4. Effect of application timing and N rate on yield, Billa Billa 2017
(Treatments that share the same letter are not significantly different at P=0.05. All N rates were spread only)

Table 3 shows the distribution of N (in excess of untreated levels) by soil depth at harvest and the quantities of rainfall recorded between application and planting or harvest.

Table 3. Depth distribution of soil N at harvest (in excess of untreated levels) from 200 kg N/ha applications, Billa Billa November 2017

	December spread	March spread	Planting PSPE	In-crop Spread
Rainfall - application to planting	279mm	154mm	-	-
Rainfall - application to harvest	465mm	340mm	186mm	160mm
Soil depth	**Additional soil N kg/ha v untreated at harvest**			
0-15cm	32	70	36	82
15-30cm	48	48	4	2
30-45cm	35	11	4	4
45-60cm	20	7	4	4

NB There was no indication of any movement of fertiliser applied N deeper than 60cm. Soil recovery from PSPE application was very low with only 1mm of rain recorded 4 days after application, followed by 9mm at 37-38 days after application.

Key points

1. Although the majority of N from December or March application was still in the 0-15cm zone at planting (Figure 3), the yield and protein results indicate it had moved deep enough to be available to the crop in a season with very low in-crop rainfall.
2. Increased benefit from fallow N application compared to application at planting are likely in situations with good levels of fallow rainfall but followed by low levels of in-crop rainfall.
3. The majority of excess N applied in December was recovered in the top 45cm at harvest after a total of 465mm of rainfall.

4. The majority of N applied in March was recovered in the top 30cm at harvest after a total of 340mm of rainfall.

NB Soil recovery from the PSPE application was very low in this trial with the first useful rainfall (9mm) 37 days after application. Unfortunately soil sampling was not planned/conducted in plots where N was incorporated by sowing for comparison.

How much nitrogen was actually recovered at harvest?

Assessment of the fertiliser N fate (in grain, soil and stubble) was conducted in 2015, 2016 and 2017 but with no attempt to estimate the residual N in the root system. Table 4 shows the mean quantities of N, in excess of the level where no fertiliser N was added. In 2015, results were only assessed for 200 kg N/ha applied and incorporated by sowing. Results in 2016 and 2017 are a mean of 4 application timings. In 2016, 3 of the 4 applications were spread and not incorporated with all applications spread and not incorporated in 2017.

Table 4. Mean levels of N (kg N/ha) in grain, stubble and soil samples at harvest following application of 200 kg N/ha, in excess of untreated levels, 8 trials 2015-2017

Season	2015		2016		2017	
Number of trials	3		3		2	
	Mean	Range	Mean	Range	Mean	Range
Grain	0	-16-21	20	5-39	8	3-13
Stubble	17	6-48	17	3-43	8	1-26
Soil	79	58-102	136	50-221	128	54-234
Total	**96**	**85-134**	**174**	**66-263**	**143**	**60-258**

Key points

1. Over 23 individual application timing comparisons, ~79% of the applied rate was recovered between grain, stubble and soil.
2. On average ~21% of the applied N was not able to be accounted for in grain, stubble or soil.
3. The majority of additional N was recovered in the soil and on average accounted for 65% of the applied N.
4. In 18 of 23 comparisons, testing accounted for more than 60% of the applied N.
5. The lowest recoveries were from 2 sites in 2015 where N was incorporated by sowing – both 40-50%, one site in 2016 from spreading on wet soil at GS30 – 30-40% and one in 2017 from application PSPE – 30-40%.
6. Grain recovery is likely to be the most accurate measure with stubble and soil more variable due to issues such as sampling and uniformity of spreading.

Was nitrogen still available for the following crop?

Two of the trial sites from 2016 (Tulloona and Macalister) were planted to winter crop in 2017 and were monitored for response and benefits in the 'year 2' crop. Table 5 shows the soil test results taken at planting and harvest in year 2.

Table 5. Soil N levels (kg N/ha) at Tulloona and Macalister following application of N at different rates applied at wheat planting in 2016

	Tulloona		Macalister	
N rate at sowing in 2016	April 2017	Oct 2017	Aug 2017	Dec 2017
Untreated	53 b	29 b	78 c	44 b
50 kg N/ha IBS	76 b	32 b	99 bc	46 b
100 kg N/ha IBS	71 b	21 b	131 b	80 b
200 kg N/ha IBS	162 a	122 a	237 a	178 a
P value	*<.01*	*.04*	*<.01*	*<.01*
LSD	*33*	*75*	*39*	*62*

NB Sampling method - 4 individual 0-120cm depth cores taken per plot. Samples were separated into 0-30 and 30-90cm intervals with each depth bulked and a single sub sample taken for analysis. 4 replicates sampled in each treatment

Key points

1. The large LSD figures (least significant differences) highlight the variability that can occur with soil testing and that the number of soil samples collected should have been larger to account for this.
2. While acknowledging the above, soil testing ~12 months after N application (April and August 2017) showed significantly increased soil N levels in the 200 kg N/ha treatments (109-159 kg N/ha additional compared to untreated).
3. Differences were less clear from the 50-100 kg N/ha rates applied in 2016.
4. The lowest soil N levels at planting in 2017 were from the untreated samples.
5. At harvest of the year 2 crops, there was still an additional ~90-130 kg N/ha of soil N in plots that had received 200 kg N/ha in 2016.

NB At the Tulloona site, ~60 % of the additional soil N was still found in the top 45cm with 45% found between 15 and 45cm. At the Macalister site, ~49 % of the additional soil N was still found in the top 45cm with 31% found between 15 and 45cm.

The Tulloona site was commercially planted to chickpeas and the Macalister site was planted to wheat. At Tulloona, at the end of September it was visually apparent that all plots that had received the 200 kg N/ha rate in year 1 were 'greener' than the remaining plots and the trial warranted harvest. Previous wheat results had indicated the most consistent N response was in grain protein, so yield and grain quality were assessed at both sites. Figures 5 and 6 show the yield and protein responses in year 2.

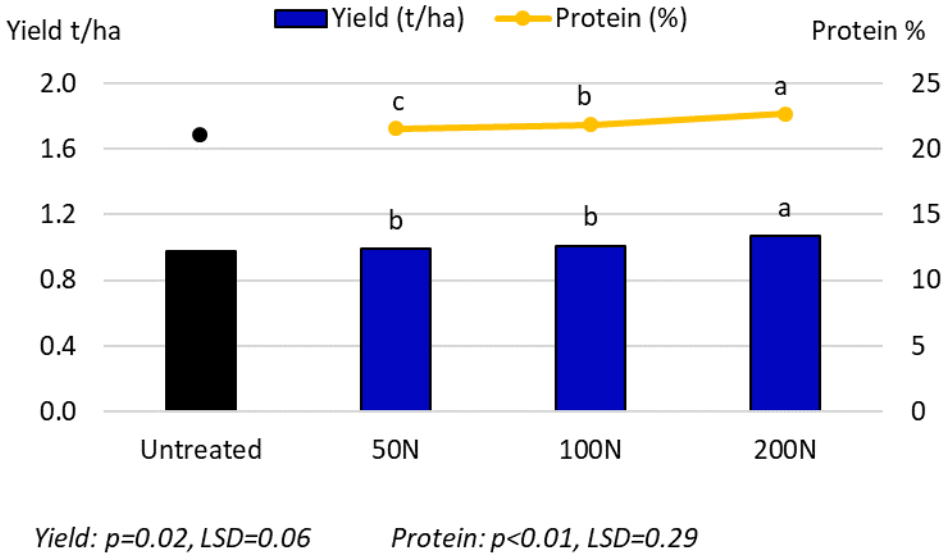

Figure 5. 2nd year impact of N rate - chickpeas, Tulloona 2017
(Treatments that share the same letter, within an assessment, are not significantly different at P=0.05. Results for each N rate are from a factorial of 3 timings x 2 varieties. Untreated not analysed and included for comparison only)

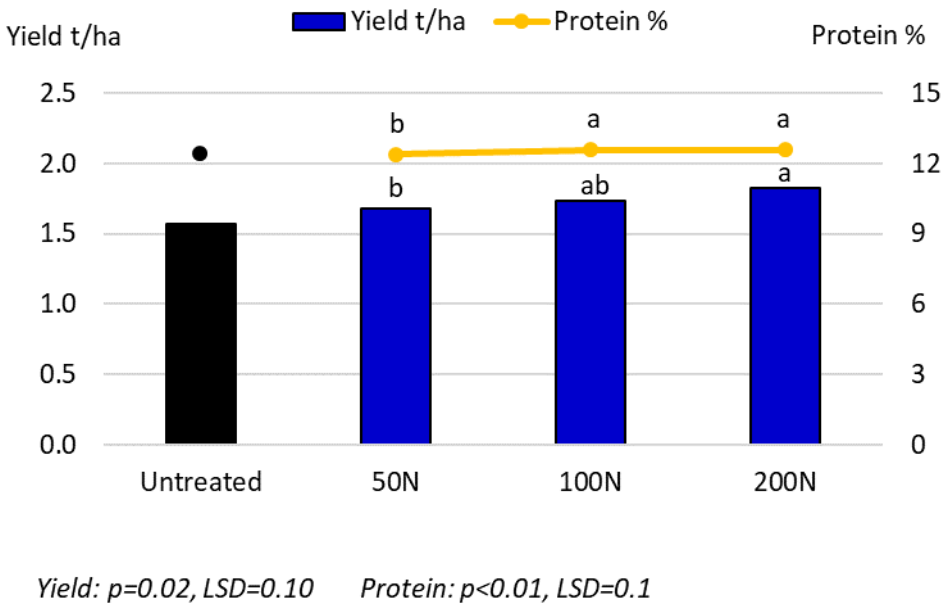

Figure 6. 2nd year impact of N rate - wheat, Macalister 2017
(Treatments that share the same letter, within an assessment, are not significantly different at P=0.05. Results for each N rate are from a factorial of 3 timings x 2 varieties. Untreated not analysed and included for comparison only)

Key points

1. Significant increases in both yield and grain protein were recorded in year 2 from the 200 kg N/ha rates applied in 2016 compared to the 50 kg N/ha rate at both sites.
2. Although soil testing did not show a significant difference in soil N between the 50 and 100 kg N/ha rates, there was a significant increase in grain protein recorded in both crops from the 100 kg N/ha treatments compared to the 50 kg N/ha rate.

Economic impact

Tulloona

- Wheat 2016: all nitrogen rates achieved at least break even in 2016 due to yield benefits (0.7-1.2t/ha) combined with increased grain quality in a ~4t/ha yielding situation
- Chickpeas 2017: although grain protein was increased by all rates of N applied in 2016, only the 200 kg N/ha rate resulted in a significant yield increase. This equated to an extra $60/ha net benefit
- Soil testing indicates an extra 90 kg N/ha is still available to benefit year 3 cropping from the 200kg N/ha applications.

Macalister

- Wheat 2016: there was no yield impact from applied N but increases in protein of ~2-3%. There was no net benefit with mean yields ~2.0-2.5t/ha
- Wheat 2017: significant yield increases were recorded from all 2016 rates compared to the untreated (0.1-0.25t/ha). Despite significantly increased protein from the 100 and 200 kg N/ha rates, all grain was H2 quality. Net benefits of $32-$73/ha were achieved in year 2
- The 50 kg N/ha rate was the only one to achieve a net benefit over the 2 years of ~$20/ha
- Soil testing indicates an extra 130 kg N/ha is still available to benefit year 3 cropping from the 200 kg N/ha applications.

Conclusions

This series of trials over 4 cropping seasons and 14 trial locations has provided results that question some of our current management practices.

- It has supported the general N grain recovery 'rule' applied in N budgeting of 40-60% of available soil and fertiliser N but highlighted a large difference in efficiency between the two sources
- It has highlighted the poor efficiency of fertiliser N grain recovery in the year of application with mean levels of ~15-20% applied N recovered in grain at common commercial rates (50 -100 kg N/ha)
- The relatively shallow and slow movement of the applied N is likely to be a major cause for this inefficiency
- Consider non-cereal options in paddocks with very low soil N levels
- Testing at harvest of grain, stubble and soil indicated nearly 80% of the applied N could be accounted for, although in a small number of situations this level dropped to as low as 30-50%
- There was no clear pattern of difference between urea surface spread or spread and shallow incorporated in terms of N recovery. They were both equally good (or bad)
- Initial assessment of response in 2nd year crops was encouraging with ~50% of the initial 200 kg N/ha rate still available for crop response in year 3
- At one of the two sites monitored in year 2, all of the net benefit from fertiliser occurred in year 2
- The errors associated with soil testing (e.g. core number, uniformity of sample mixing and sub sampling) make 'precise' recommendations on fertiliser N levels difficult.

Key industry challenges

- Ensure soil N levels do not continue to decline as the required levels of fertiliser N in the year of cropping would rapidly become uneconomic and impractical and cereal production less efficient
- We need to identify methods to get fertiliser N deeper in the profile, more quickly, to improve availability and efficiency
- Identify and if possible, manage the unaccounted losses from fertiliser N application.

Where to next?

The results from this work indicate we still have much to learn, or at least to refine, with the management of our most important and best understood nutrient for cereal production. Any practices that can improve the efficiency of N accumulation from the legume phase are going to be exceedingly valuable, together with methods to increase the efficiency of fertiliser N use in the year of cropping.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the author would like to thank them for their continued support.

NGA would particularly like to acknowledge the assistance from our trial co-operators during this series of trials: Scott Ferguson, Jason Schelberg, Lee Maxwell, The Frater Family, Drew Penberthy, Michael Leddingham, Hugh Ball, Simon Doolin, George Picton, Peter Butler and Anthony Martin, together with Kalyx staff for trial planting, maintenance and harvest. In addition we would like to thank AGT and Pacific Seeds for seed supply.

Contact details

Richard Daniel
Northern Grower Alliance
Ph: 07 4639 5344
Email: richard.daniel@nga.org.au

⁽ᵇ Varieties displaying this symbol beside them are protected under the Plant Breeders Rights Act 1994

Cover crops can boost soil water and protect the soil for higher crop yields

David Lawrence[1], Andrew Erbacher[1], David Freebairn, Neil Huth[2], Brook Anderson[2], Graham Harris[1] and Nikki Seymour[1]

[1] DAF Qld
[2] CSIRO

Key words

cover crops, millet, ground cover, soil water storage, fallow management, stubble, evaporation, infiltration, plant available water

GRDC code

DAQ00211

Take home messages

- Cover crops can increase fallow water storage, and improve crop performance and returns in northern farming systems
- In each experiment, a cover crop treatment provided the highest plant available soil water by the end of the fallow
- The best cover crop treatment depended on the length of the fallow. A later spray-out, with more resilient cover, was best in the longer fallow. However, delaying spray-out too long had a dramatic effect on water storage
- Cover crop saved 2-3 fallow herbicide sprays and dramatically improved establishment at one of the sites
- Yields and returns were increased by the best cover crop treatment at each trial, but yield effects appear to be in excess of those expected from the increased soil water storage
- Biology effects must be considered carefully; white French millet cover crops in the northern region have previously been shown to dramatically increase mycorrhizal colonisation of wheat (good), increase free-living nematodes (good), increase cellulase activity and bacterial abundance from additional fresh crop residues (good), but also increase root-lesion nematode populations (bad).

Cover crops in the northern region

Cover crops are not new. They have been used (mostly) by organic and low-input growers to protect the soil from erosion in low stubble situations, return biomass that helps maintain soil organic matter and biological activity, and to provide additional nitrogen when legumes are used.

However, growing cover crops uses water, and storing Plant Available Water (PAW) is 'king' in northern farming systems; only 20-40% of the northern region's rainfall is typically transpired by dryland crops, up to 60% of rainfall is lost to evaporation, and a further 5-20% is lost in runoff and deep drainage. Every 10 mm of extra stored soil water available to crops could increase dryland grain yields by up to 150 kg/ha, with corresponding benefits to dryland cotton growers as well. So, growing crops that do not produce grain or fibre is understandably considered 'wasteful' of both rainfall and irrigation water.

Yet, research is now supporting growers' experience that cover crops can provide many of their benefits with little or no net loss of soil water at the end of the fallow period. GRDC's Eastern Farming Systems project and Northern Growers Alliance (NGA) trials have both shown that cover

crops and increased stubble loads can reduce evaporation, increase infiltration and provide net gains in plant available water over traditional fallow periods. This suggests cover crops may be a key part of improved farming systems; providing increased productivity, profitability and sustainability.

The science of stubble and evaporation

Retained stubble provides ground cover that protects the soil from rainfall impacts and so improves infiltration to store more water in the soil. Conventional wisdom is that increased stubble loads can slow down the initial rate of evaporation, but that these gains are short-lived and lost from accumulated evaporation after several weeks. However, further rain within this period and the manipulation of stubble to concentrate stubble loads in specific areas, provide an opportunity to reduce total evaporation and to accumulate more plant available water.

In southern Queensland and northern NSW, cover crops are used to overcome a lack of stubble and protect the soil following low residue crops (e.g. chickpea, cotton) or following skip-row sorghum with uneven stubble and exposed soil in the 'skips'.

Growers typically plant white French millet or sorghum and spray them out within ~60 days to allow recharge in what are normally long fallows across the summer to the next winter crop. Allowing these 'cover crops' to grow through to maturity led to significant soil water deficits and yield losses in subsequent winter crops. However, the Eastern Farming Systems project showed only small deficits (and even water gains) accrued to the subsequent crops when millets were sprayed out after 6 weeks, with average grain yield increases of 0.36 t/ha. Furthermore, the Northern Growers Alliance showed that the addition of extra stubble (from 5-40 t/ha) after winter crop harvest appeared to reduce evaporation, with initial studies showing between 19 mm and 87 mm increases in plant available water. These gains will be valuable if validated in further research and captured in commercial practice.

Our current project is monitoring sites intensively to quantify the impact of different stubble loads on the accumulation of rainfall, the amount of water required to grow cover crops with sufficient stubble loads, the net water gains/losses for the following crops and the impacts on their growth and yield. This paper reports on the first two sites in southern Queensland, which will be used in simulation/modelling later in the project to assess the wider potential and economic impacts of cover crops in both grain and cotton production systems.

Experiment 1 – Yelarbon (pivot-irrigated cotton, short fallowed to pivot irrigated cotton)

The Yelarbon experiment was on a pivot-irrigated paddock that grew cotton in 2016/17. The crop was picked and root cut in May, before offset discs were used on 12 June 2017 to pupae-bust and to level wheel tracks of the pivot irrigator. Nine cover treatments (Table 1) with five replicates were planted on the same day using barley (100 plants/m^2), barley and vetch mixtures (30 plants/m^2 each) and tillage radish (30 plants/m^2). Rain that night aided establishment, and the surrounding paddock was planted two weeks later to wheat for stubble cover.

Three planned termination times matched key growth stages of the main cereal treatments: Early-termination at first node (Z31) when the crop begins stem development; Mid-termination at flag leaf emergence (Z41) when the reproductive phase begins; and Late-termination at anthesis (Z65) for peak biomass production. Biomass of the cover crop treatments at their relevant termination times ranged from 1166 kg dry matter (DM)/ha (early) to 8175 kg DM/ha when the crop was grown through to grain harvest (Table 1).

The subsequent cotton crop was planted on 15 November 2017 and irrigated on a schedule determined by the surrounding wheat crop that was harvested for grain. We included a 'grain harvest' treatment in our experimental plots to align with the farmer's practice. Above ground biomass was also monitored across the growth of the cover crops until termination and through the

subsequent fallow. Establishment was counted in all plots and hand cuts used to estimate cotton yields.

Table 1. Cover treatments applied at the Yelarbon site prior to planting cotton

Treatment	Cover crop	Termination time	Biomass (kg/ha)
1.	Control (Bare)		
2.	Cereal	Early-sprayout	1166
3.	Cereal	Mid-sprayout	4200
4.	Cereal	Late-sprayout	5104
5.	Cereal	Mid-sprayout + Roll	4200
6.	Cereal	Grain harvest	8175
7.	Cereal + legume	Mid-sprayout	4928
8.	Cereal + legume	Late-sprayout	4149
9.	Tillage radish	Mid-sprayout	4692

Soil water

Soil water was estimated using soil cores to measure gravimetric soil water at key times across the fallow and the subsequent cotton, along with regular neutron moisture meters (NMM) and EM38 readings in each plot. These NMM and EM38 readings and the percentage ground cover were recorded every two-to-four weeks while the cover crops were growing, and every four weeks once all cover crops were terminated, and until canopy closure of the following cotton was achieved. Final EM38 and NMM readings were recorded at cotton defoliation.

The water cost of growing the barley cover crops, relative to the control treatment in the early stages of the fallow was ~40 mm for the early-termination, ~70 mm for the mid-termination and ~120 mm for the late-termination (Figure 1). However, by the end of the fallow, and a subsequent 170 mm of rainfall/irrigation in 8 events from mid-termination to cotton plant, the mid-termination treatment caught up to the control, and the early-termination had accumulated an additional 14 mm of water. Not surprisingly, this early-termination proved to be the best cover crop treatment on the short fallow. The crop that continued to harvest was ~145 mm behind by the end of the fallow. This treatment mirrored the wider paddock and so set the following pivot irrigation schedule.

Crop performance

The irrigation schedule matched to the harvested crop provided more than adequate water across the cover crop treatments and yields for all cover crop treatments were similar. However, the Control with limited ground cover was the poorest performer, with ~3 bales/ha lower yield, lower infiltration in early growth stages and less extraction of water late in the crop.

The nominal costs to plant the cover crops ($50/ha) and to spray them out ($20/ha) were almost matched by the savings from three less fallow weed sprays ($60); so the measured cotton yield responses were very profitable. For grain growers, the extra 14 mm stored moisture from the early-termination cover crop would typically produce ~200 kg/ha grain in wheat at a water use efficiency of 15 kg grain/mm water, which is worth ~$50/ha (at $270/t) and would produce an overall return of $40/ha. Any further possible benefits from cover crops, which appear to have occurred in the cotton crop, have not been included.

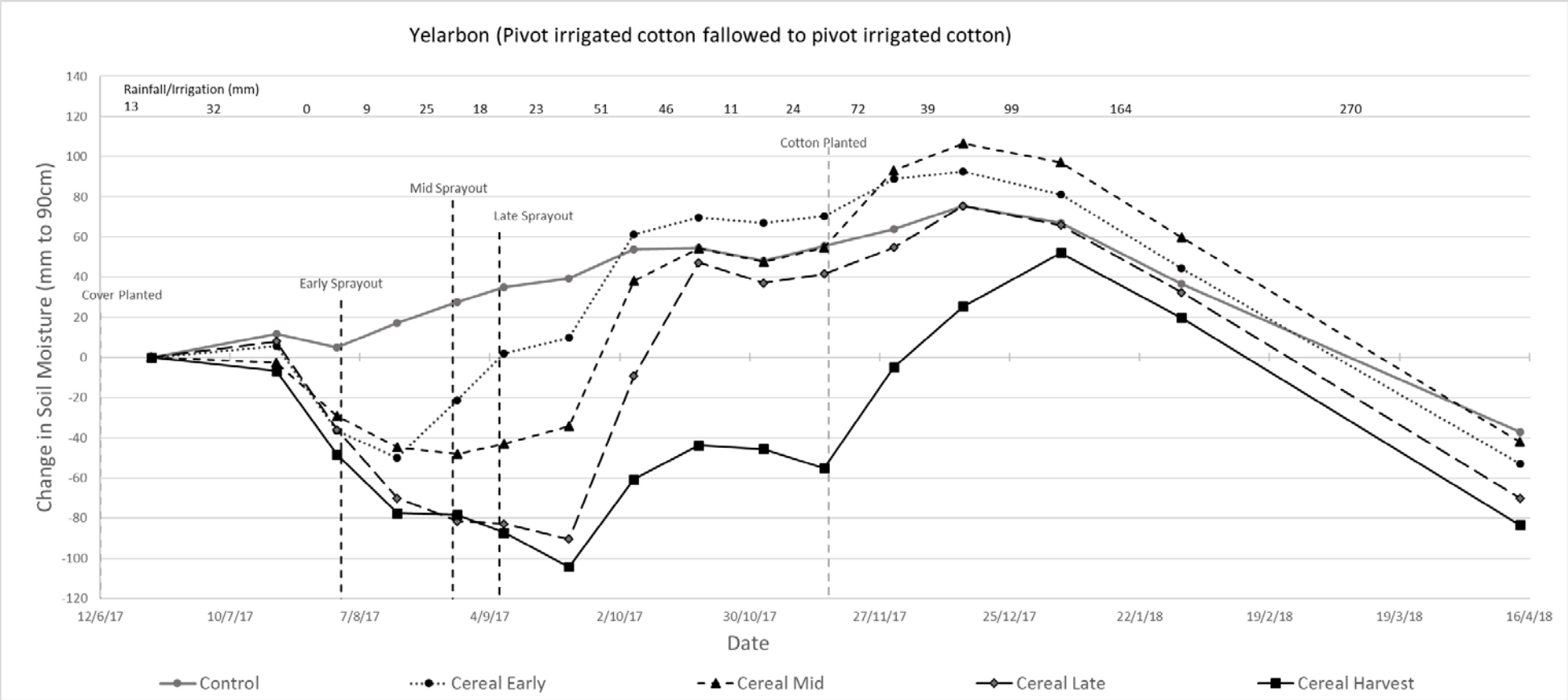

Figure 1. Changes in soil water (mm to 90 cm) from planting of key cover crop treatments until defoliation of the subsequent cotton crop at Yelarbon

Table 2. Net change in water storage over the life of the fallow (relative to the Control) and final cotton yield for each cover crop treatment at Yelarbon.

Treatment	Cover crop	Terminated	Water gain (cf control)	Cotton yield (bales/ha)
1.	Control (bare) Starting water ~100mm PAW		56 mm (fallow gain)	9.3
2.	Cereal	Early	+14 mm	12.9
3.	Cereal	Mid	-1 mm	12.7
4.	Cereal	Late	-14 mm	11.9
5.	Cereal	Mid + Roll	-2 mm	12.6
6.	Cereal	Harvest	-111 mm	14.1
7.	Cereal + legume	Mid	-16 mm	11.9
8.	Cereal + legume	Late	-7 mm	13.9
9.	Tillage radish	Mid	-40 mm	14.4

Experiment 2 – Bungunya (Skip-row sorghum, long- fallowed to dryland wheat)

The Bungunya experiment was in a long-fallow paddock following skip-row sorghum harvested in early February 2017. The paddock had deep phosphorus applied in August 2017 and was 'Kelly-chained' in September 2017 to level the paddock, which left it with little cover until the planned wheat crop. Cover crops were planted into ~120 mm of plant available soil water on 11 October. The subsequent wheat crop was planted on 1 May 2018, with hand cuts for yield done on 12 October and mechanical harvesting on 26 October. Soil water, cover crop and stubble biomass, ground cover, wheat establishment and yields were measured in the same way as the experiment at Yelarbon.

Table 3. Cover treatments applied at the Bungunya site prior to planting wheat

Treatment	Cover crop	Termination time	Biomass (kg/ha)
1.	Control (Bare)		
2.	Millet (White French)	Early-sprayout	1533
3.	Millet (White French)	Mid-sprayout	2327
4.	Millet (White French)	Late-sprayout	4365
5.	Millet (White French)	Mid-sprayout + Roll	2476
6.	Millet (White French)	Late-sprayout + Roll	4737
7.	Sorghum	Mid-sprayout	2481
8.	Lab Lab	Mid-sprayout	1238
9.	Multi-species (millet, lab lab, radish)	Mid-sprayout	1214

Soil water

The water cost of growing the millet cover crops, relative to the Control treatment in the early stages of the fallow was ~50mm for the early-termination, ~40 mm for the mid-termination and ~60 mm for the late-termination (Figure 2). The lab lab mid-termination treatment also cost ~60 mm to grow, relative to the Control treatment. These figures reflect rainfall and different rates of infiltration between soil water measurements:

- Plant to mid-termination, 65 mm in 3 events (12/10/17 to 22/11/17)
- Mid-termination to plant, 205 mm in 11 events (22/11/17 to 1/5/18)

- Follow crop plant to maturity 41mm in 3 events (1/5/18 to 10/10/18)
- Follow crop maturity to soil sample 72mm in 7 events (10/10/18 to 5/11/18)

By early March, with a subsequent 175 mm of rain in ten falls after the mid-termination, the millet treatments had all recovered to have effectively the same soil water as the Control, except where the late-terminated millet was rolled; it had gained ~20 mm more water than the other treatments.

When the subsequent wheat crop was planted, the mid-terminated millet had ~14 mm more soil water than the Control treatment, the late millet ~19 mm more, and the late millet that was also rolled had ~36mm more soil water (Table 4). Interestingly, water extraction by the wheat crop was greater from all of the millet cover crop plots than the Control, which had lower yields; perhaps due to, or resulting in less root development.

Crop performance

All cover crop treatments increased the yield of the final wheat crop (Table 4) and saved two fallow weed sprays (~$40/ha). However, the biggest yield increases were from the cereal cover crops, especially the late-terminated millet and the sorghum.

The water differences at planting (end of the fallow) may explain some of the yield difference. However, the establishment of the wheat crop was dramatically better where cover crops were used, more so where cereals were used but also for lab lab. The expected yield increases from the higher fallow water storage alone would typically be ~200 kg grain in wheat (WUE 15 kg grain/mm water) for the mid-terminated millet (worth ~$50/ha), ~280 kg grain for the late millet (worth $75/ha) and ~540 kg grain for the late +rolled millet (worth $150/ha). These gains would represent net returns of $20/ha, $45/ha and $120/ha respectively. However, the measured yield gains for these treatments were 950 kg/ha, 1461 kg/ha and 1129 kg/ha respectively, representing increase returns of between $250 and $380 /ha.

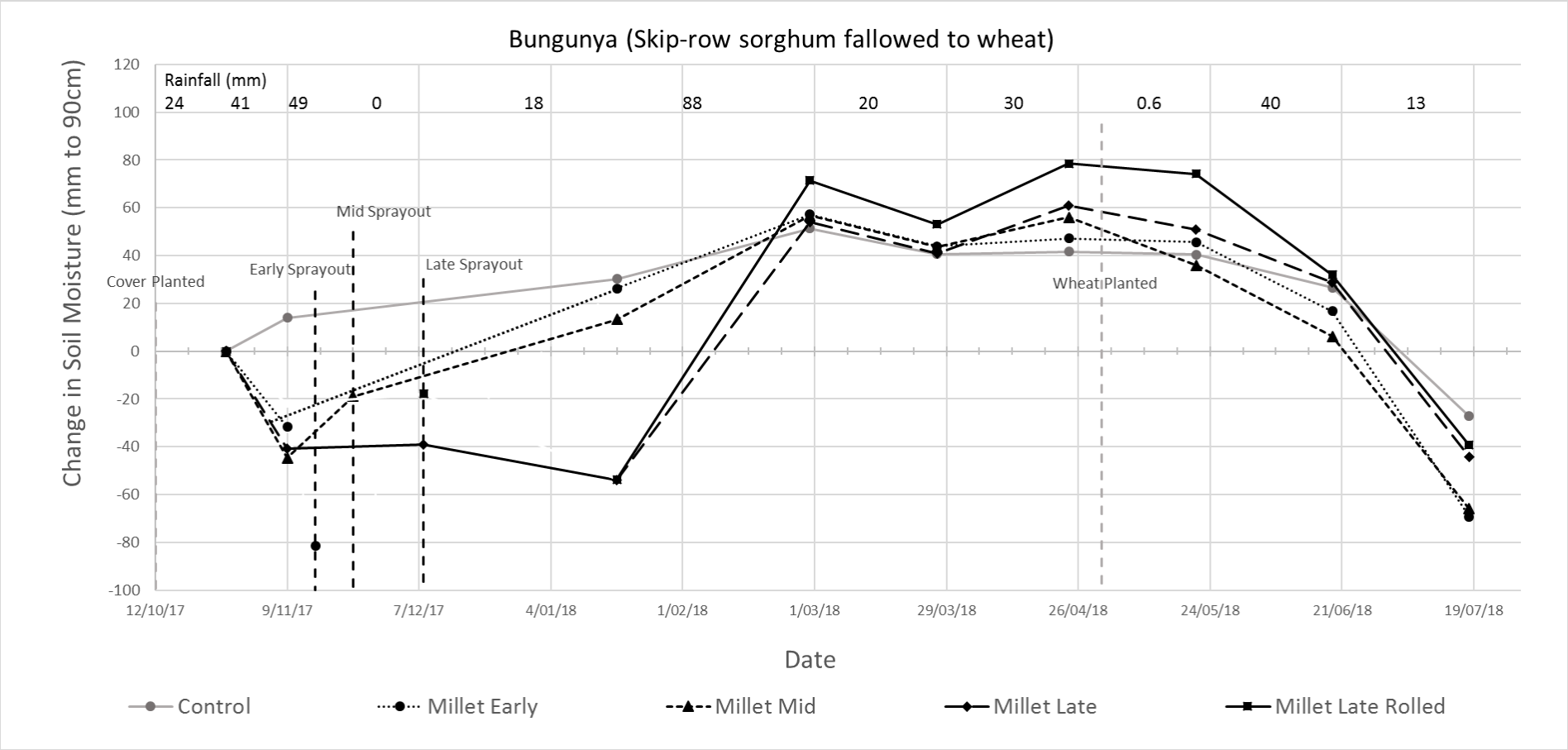

Figure 2. Changes in soil water (mm to 90 cm) from planting of the millet cover crop treatments sprayed out at different crop growth stages until harvest of the later wheat crop at Bungunya

Table 4. Net change in water storage over the life of the fallow (relative to the Control) and final wheat yield for each cover crop treatment at Bungunya.

Treatment	**Cover crop**	**Terminated**	**Water gain (cf control)**	**Wheat yield (kg/ha)**
1.	Control (bare) Starting water ~120mm PAW		42mm (fallow gain)	1436[f]
2.	Millet (White French)	Early	+5 mm	2223 [cd]
3.	Millet (White French)	Mid	+14 mm	2386 [bc]
4.	Millet (White French)	Late	+19 mm	2897 [a]
5.	Millet (White French)	Mid + Roll	+17 mm	2359 [bc]
6.	Millet (White French)	Late + Roll	+36 mm	2565 [b]
7.	Sorghum	Mid	+17 mm	2634 [ab]
8.	Lab Lab	Mid	-4 mm	1795 [e]
9.	Multi-species (millet, lab lab, radish)	Mid	+21 mm	1954 [de]

Potential biological impacts

These two experiments focused on soil water accumulation. Biological analysis was not undertaken, but some exploratory analyses will be included for selected treatments in future trials. However, past biological assessments on the Eastern Farming Systems project sites around Goondiwindi highlighted a range of biological effects following white French millet cover crops.

Mycorrhizal colonisation of roots in six-week-old wheat from 1.8% in the long-fallow following skip-row sorghum to 8.3% following an early terminated millet cover crop in the fallow (Seymour *et al.* 2006); crop growth was much stronger following the cover crop. Other positive biological effects included increases in free-living nematodes and cellulase activity that indicate a more active biological system with a greater food source from more residues; and increased Nematode Channel Ratios, which indicates greater bacterial activity from more disturbance and addition of higher quality residues (Table 5). Unfortunately, the white French millet cover crop also boosted root-lesion nematodes (*Pratylenchus* sp.), and so cover crop species must be selected carefully where root-lesion nematodes are a problem.

Table 5. Selected biological effects at wheat planting after a 15 month fallow from skip-row sorghum +/- a white French millet cover crop with different termination dates near Goondiwindi (Seymour *et al.* 2006)

District	**Treatment**	***Pratylenchus* sp/g soil**	**Free living nematodes/g soil**	**Nematode channel ration (0= fungal; 1= bacterial)**	**Cellulase assay**
Lundavra	Fallow	0.64	0.58	0.39	0.21
	Short-term millet	1.31	2.76	0.39	0.59
	Mature millet	2.51	7.33	0.57	0.89
North Star	Fallow	0.92	0.65	0.52	0.03
	Short-term millet	0.92	7.41	0.79	0.23
	Mature millet	1.45	5.25	0.87	0.11
LSD	(*P*=0.05)	0.51	2.96	0.19	0.31

Conclusions

The project results show that cover crops can indeed help increase net water storage across fallows that have limited ground cover. Importantly, these results were achieved in drier than normal seasons. For example, the Bungunya site with millet cover crops had a wet spring that allowed a well grown cover crop to develop, but was then followed by well below average rainfall through the fallow, with a few good storms in February/March. How often these soil water results will occur across different seasons will be explored across the rest of the project with further experiments and simulation modelling.

However, more dramatic are the early yield results for the subsequent cotton and wheat crops at each site. These yield responses are very large and represent big improvements in returns; far beyond what could be expected from the increases in net soil water storage across the fallows. Wheat establishment dramatically improved in the Bungunya experiment, and there was greater water extraction (especially at depth) in the Yelarbon experiment. How much of the responses can be attributed to these factors, how often such results might occur, and the contributions of other factors to these gains remains to be explored.

Acknowledgements

The research undertaken in this project was possible through the significant contributions of growers through both trial cooperation and the support of the GRDC, the CRDC, DAF Queensland, CSIRO and DPINSW. The authors would like to thank them all for their continued support. Special thanks to Glen Smith at 'Koarlo', David Woods at 'Coorangy', and the DAF Biometry, Technical and Research Infrastructure staff that supported the heavy management and monitoring loads of these experiments.

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Contact details

David Lawrence
DAF Queensland, Tor Street, Toowoomba
Mb: 0429 001 759
Email: david.lawrence@daf.qld.gov.au

Andrew Erbacher
DAF Queensland, Lagoon Street, Goondiwindi
Mb: 0475 814 432
Email: andrew.erbacher@daf.qld.gov.au

Investigating western farming systems

Andrew Erbacher[1], Jon Baird[2] and Jeremy Whish[3]

[1] DAF, Goondiwindi, Qld
[2] NSW DPI, Narrabri, NSW
[3] CSIRO Agriculture and Food, Queensland

Key words

Western farming systems, gross margin per mm, water use efficiency

GRDC code

DAQ00190, CSA00050

Take home messages

- Winter cereals showed improved water use efficiency (WUE) compared to legumes and summer grown crops at both Narrabri and Mungindi
- Generally, dollars per mm of crop water used was greater for winter crops ($2.20) than summer grown crops ($1.30)
- Although summer crops had lower WUE than winter crops there is a benefit in growing summer crops to manage root lesion nematodes
- Crop choice influenced the fallow efficiency (FE). The median fallow efficiency after winter cereals equalled 0.26, whereas fallow efficiency after chickpeas equalled 0.14
- Modelling suggests a high intensity cropping rotation can be the most profitable, if crops are planted on 100mm or more plant available water (PAW).

Introduction

While advances in agronomy and the performance of individual crops have helped grain growers to maintain their profitability, current farming systems are underperforming; with only 30% of the crop sequences in the northern grains region achieving 75% of their water limited yield potential.

Growers face challenges from declining soil fertility, increasing herbicide resistance, and increasing soil-borne pathogens in their farming systems. Change is needed to meet these challenges and to maintain farming system productivity and profitability. Consequently, Queensland Department of Agriculture and Fisheries (DAF), New South Wales Department of Primary Industries (NSW DPI) and CSIRO are collaborating to conduct an extensive field-based farming systems research program, focused on better use of the available rainfall to increase productivity and profitability, with the question;

"Can systems performance be improved by modifying farming systems in the northern region?"

In 2014 research began in consultation with local growers and agronomists to identify the key limitations, consequences and economic drivers of farming systems in the northern region; to assess farming systems and crop sequences that can meet the emerging challenges; and to develop the systems with the most potential for use across the northern region.

Experiments were established at seven locations; with a large factorial experiment managed by CSIRO at Pampas near Toowoomba, and locally relevant systems being studied at six regional centres by DAF and the DPI NSW (Emerald, Billa Billa, Mungindi, Spring Ridge, Narrabri and Trangie (red & grey soils)).

Table 1. Systems implemented at each of the locations. Trangie has systems applied on a red and grey soils. Pampas includes summer dominant, winter only and mixed opportunity cropping systems. Pampas also includes combinations (i.e. higher legume + diversity) not listed here.

	Pampas (Core site)			Regional sites					
System/ modification	**Summer**	**Winter**	**Mixed**	**Emerald**	**Billa Billa**	**Mungindi**	**Spring Ridge**	**Narrabri**	**Trangie**
Baseline	*	*	*	*	*	*	*	*	*
Higher crop intensity	*		*	*	*		*	*	
Lower crop intensity	*	*	*		*	**	*	*	*
Higher legume frequency	*	*	*	*	*	*	*	*	*
Diverse crop options	*	*	*		*	*	*	*	*
Higher nutrient supply	*	*	*	**	**	*	*	*	*
No. of systems	38			6	9	6	6	6	6

Farming system description

1. **Baseline** is typical of local zero tillage farming systems with approximately 1 crop per year grown using moderate planting moisture triggers of 60% plant available water capacity (PAWC). Crops grown in this system are limited to wheat/barley, chickpea and sorghum. These crops have nitrogen fertiliser applied to achieve 50th yield percentile as determined by the PAW prior to planting and based on APSIM yield simulations for each site.
2. **Lower crop intensity** reflects a conservative rotation to accumulate greater PAW for the next crop (80%). The same nutrient management as the *baseline* system is applied. Crops grown are also similar to the baseline, but may also include cotton as a high value crop at some sites.
3. **Higher crop diversity** allows a greater suite of crops to be grown to better manage disease, root lesion nematodes and herbicide resistance. Planting triggers and nutrition are the same as the baseline system. The unique rules for this system focus on managing root lesion nematodes, with 50% of the selected crops to be resistant to *Pratylenchus thornei,* and 1 in 4 crops resistant to *Pratylenchus neglectus.* To manage herbicide resistance, two crops utilising the same herbicide mode-of-action cannot follow each other. Crops grown in this system include wheat/barley, chickpea, faba bean, field pea, canola/mustard, sorghum, mungbean, maize, millet and sunflower.
4. **Higher legume** aims to minimise the use of nitrogen fertiliser by growing every second crop as a pulse (legume), with a preference for those that produce greater biomass and greater carry-over nitrogen benefits. Crops grown in this system are similar to the *baseline* (wheat/barley, chickpea, sorghum) with additional pulse options (faba bean, field pea, & mungbean). Crops will be fertilised (N) to achieve average yield potential for the PAW, with nitrogen only applied to the cereal crops.
5. **Higher crop intensity** aims to minimise the fallow periods within the system and potentially grow 3 crops every 2 years. Crops will be planted on lower PAW (30%) and have a greater reliance on in-crop rainfall. Crop choice is the same as the *baseline* system, but with mungbean added as a short double-crop option. These crops are fertilised (N) to achieve average seasonal yield potential for the PAW prior to planting.
6. **Higher nutrient supply** will have N and P fertiliser applied to match the fertiliser requirements of a 90th yield percentile crop; with the risk that crops will be over fertilised in some years. This system will be planted to the same crop as the baseline each year, so that the only difference is the amount of nutrients applied.

Discussion

Crop sequence

Six systems have been implemented at the Narrabri and Mungindi farming system site (Table 1). Due to the implementation of the system rules, different cropping sequences have evolved across both sites (Figure 1). The first two years of this experiment experienced wetter than average winters at both sites. The frequent rainfall allowed for all systems to meet planting triggers, even the low intensity systems, which require 80% PAW for crop sowing. The 2016/17 summer was exceptionally hot and dry, when both sites had cotton growing. Unfortunately, Mungindi received below average rain in 2017, missing the winter planting triggers. Narrabri had average rainfall in 2017 resulting in five of the six systems meeting PAW triggers. Both sites received low rainfall during 2018, but moisture accumulation in Mungindi did allow all six systems to meet planting triggers, while Narrabri missed the winter cropping period. Scattered rain in the 2018 spring allowed the planting trigger for sorghum in the high intensity system at Narrabri and a cover crop in Lower intensity at Mungindi. Further rain over the summer enabled three more systems to reach planting triggers at Narrabri.

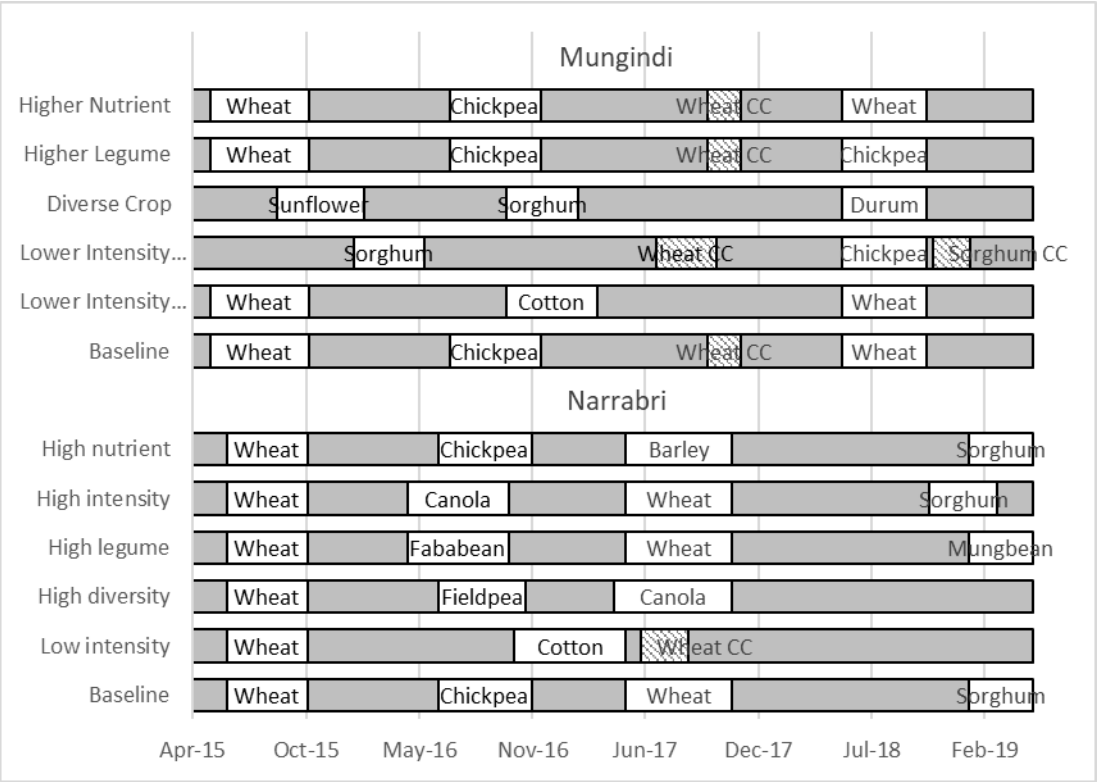

Figure 1. Crop sequences planted at Narrabri and Mungindi as a result of implementing the system rules.

System productivity (2015 to 2018)

To date, four systems have produced similar accumulated grain production at Narrabri – baseline, higher nutrients, higher legume and higher intensity. While at Mungindi, baseline, lower intensity (mixed), higher legume and high nutrients accumulated similar grain yields. The results show that modified farming system rules have not improved grain production in the western environment. Interestingly the higher diversity systems at both sites, had reduced grain production compared to the baseline system (Figure 2).

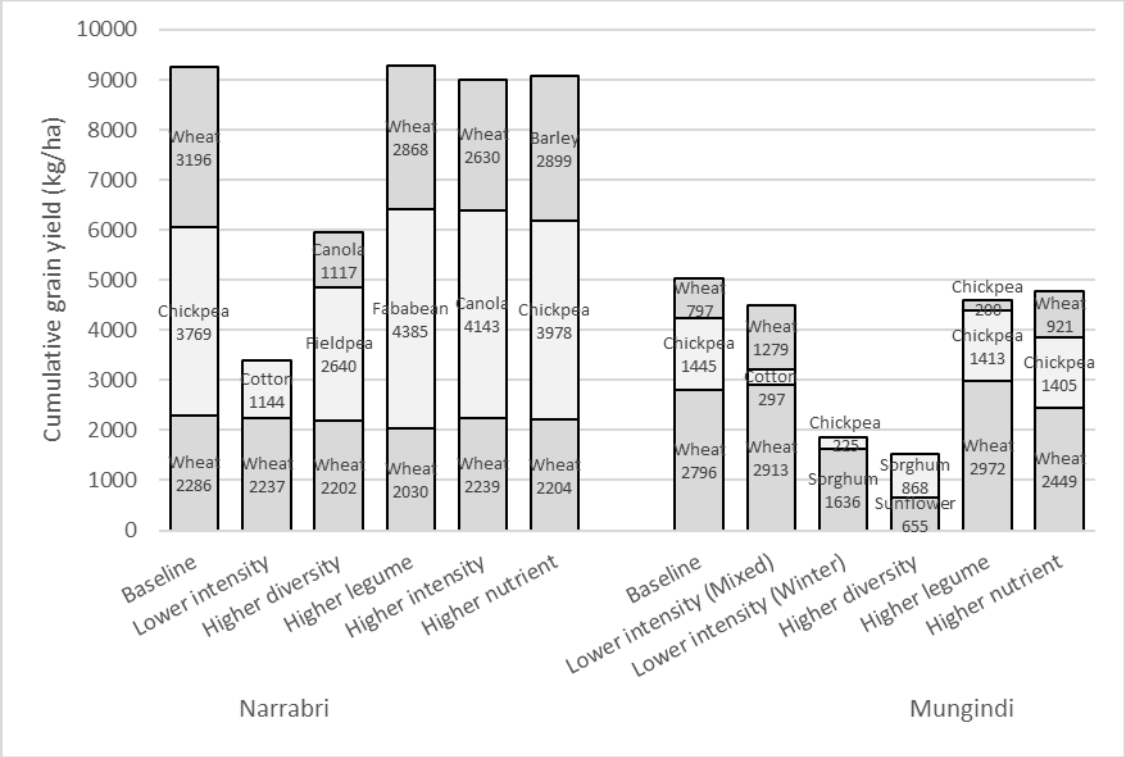

Figure 2. Cumulative grain yield at the Narrabri and Mungindi farming system experiments.

System economic analysis

Over the 4 years of experiments for each system, data has been collected on the crop yields, inputs costs including fertilisers, seed, herbicides, pesticides and machinery operations. This allows the calculation of the accumulated income and gross margins for each of the cropping systems deployed at each location. Consistent prices for each commodity (10-year average adjusted for inflation) were used to avoid introducing discrepancies in the data. All grain yields were corrected to 12% moisture to account for variable harvest moistures.

$$system\ WUE\ (\$\ GM/mm) = \frac{\sum\{(yield\ x\ price) - variable\ costs\}}{(\sum rain + \Delta\ Soil\ water)}$$

Table 2. Grain pricing used in calculations based on median prices over the past ten years, less $40/t cartage costs, for selected crops

Crop	$/t
Barley	218
Wheat (durum and APH)	269
Canola	503
Chickpea	504
Faba bean	382
Field pea	335
Sorghum	221
Maize	281
Mungbean	667
Sunflower	700
Cotton	1090 ($480/bale lint)

The baseline system at both the Mungindi and Narrabri sites resulted in the highest gross margin ($1008/ha and $2480/ha respectively)(Table 2). Both sites had similar cropping sequences in the baseline system; Narrabri: wheat – chickpea – wheat, and Mungindi: wheat – chickpea – cover crop – wheat.

Table 3. System gross margin comparison for Mungindi & Narrabri (2015-2018) showing total income, costs, gross margin, return on variable costs (ROVC), system water use efficiency and the maximum cash outlay experienced between profitable crops (Variable costs before the next positive cash flow)

Site	System	Total income ($/ha)	Total costs ($/ha)	Total GM ($/ha)	ROVC	System WUE ($ GM/mm)	Max. cash outlay ($/ha)
Mungindi	**Baseline**	**1581**	**573**	**1008**	**2.8**	**0.89**	**-271**
	Higher nutrient	1496	840	657	1.8	0.58	-297
	Higher legume	1487	654	833	2.3	0.75	-271
	Higher crop diversity	634	378	256	1.7	0.23	-274
	Lower intensity (mixed)	1287	680	607	1.9	0.54	-286
	Lower intensity (winter)	371	366	5	1	0	-266
Narrabri	**Baseline**	**3260**	**780**	**2480**	**4.2**	**1.36**	**-307**
	Higher nutrient	3263	916	2348	3.6	1.29	-354
	Higher legume	2902	718	2184	4	1.19	-286
	Higher crop diversity	1959	910	1049	2.2	0.58	-431
	Higher intensity	3304	878	2427	3.8	1.34	-381
	Lower intensity	1740	778	962	2.2	0.61	-395

Determining the right crop for improving WUE

Between 2015 and 2018 there have been 10 different crops grown between the Narrabri and Mungindi sites. The crops were grown across various seasons allowing the collection of data from high rainfall seasons (winter 2016) to below average seasons (2018). Winter crops have been consistently higher yielding than spring/summer crops. Although the sites had good soil moisture at sowing, low in-crop summer rainfall and excessive temperatures have impacted yields during the

project life (1.8 t/ha to 0.7 t/ha). Of the winter crops, faba beans have the highest mean yield (3.5 t/ha). This is more than 1.4 t/ha higher than field pea and 1.5 t/ha greater than wheat.

The high productivity has meant that faba bean used the most water (589 mm) compared to 205 mm for wheat. The high conversion of moisture to grain for wheat is highlighted by the water use efficiency (WUE) of 9.98 kg/mm, almost 4 kg/mm higher than faba bean and over 5 kg/mm higher than chickpea (Table 4).

For growers looking to improve their return on the conversion of rainfall to grain productivity ($/mm return), we evaluated the gross margin of the crops and applied the gross margin to crop water use. Again for the winter grown crops, faba bean had the highest gross margin per mm of rainfall ($2.45/mm). Winter cereals ranged from $2.27/mm to $2.00/mm. Field pea's had the lowest return for winter crops with $1.17/mm.

Of the three summer crops grown, sorghum was clearly the most efficient at grain production (4.18 kg/mm), while sunflowers and cotton had similar efficiency (2.42 kg/mm & 1.8 kg/mm). When we evaluated gross margin per mm, we found that sunflowers were the best crop for gross returns per water use ($1.37/mm), almost $1/mm greater than sorghum, which had the lowest return ($0.38/mm).

Table 4. Grain yield and water use efficiency of crops sown at the Mungindi and Narrabri farming systems sites (2015 – 2018)

Crop	Grain yield (kg/ha)	Crop water use (mm)	Water use efficiency (kg/mm)	Gross margin	$/mm
Wheat	2045	205	9.98	424	2.00
Barley	1583	220	7.18	501	2.27
Canola	1321	420	3.14	959	2.28
Chickpea	1417	308	4.60	629	2.04
Faba bean	3532	589	5.99	1442	2.45
Field pea	2132	529	4.03	620	1.17
Cotton	719	400	1.80	411	1.03
Sorghum	1636	177	9.23	236	1.33
Sorghum (failed)	0	214	0	-87	-0.41
Sunflower	655	271	2.42	372	1.37

Sowing moisture's role for water use efficiency

Interestingly, planting moisture appears to have played an important role in the individual crop's water use efficiencies (Figure 3). Increased plant available water (PAW) at sowing of wheat, chickpea and sorghum increased water use efficiency (WUE). Crops planted in the higher intensity systems (0-80mm PAW) had more crop failures and reduced grain potential than crops sown when PAW was greater than 150 mm. The exception to this rule has been the winter legumes of faba bean and field pea. Both crops had lower water use efficiencies when planted at higher PAW, most likely due to waterlogging and their sensitivity to saturated soils.

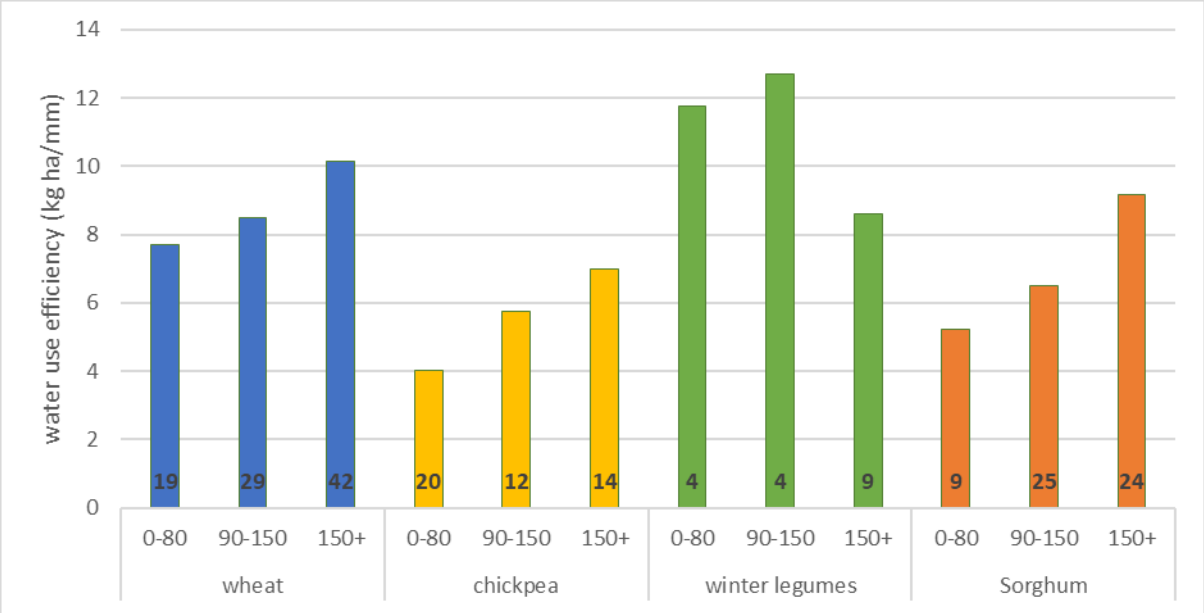

Figure 3. Sowing moisture influence on crop water use efficiency
(all farming system sites 2015 – 2018)

Selecting the right crop for nematode management

While winter crops produced both higher grain production per mm of crop water and dollar returns per mm, summer crops played an important role in the farming systems for managing nematode numbers. This was evident at both Narrabri and Mungindi sites where a rotation of wheat – chickpea increased root lesion nematode (*P.thornei*) populations to levels that will impact grain productivity of future susceptible crops (Figure 4). At Narrabri the sequence increased numbers from 1.8 nem./g soil to greater than 8.5 nem./g soil, while at Mungindi the system started with 10 nematode/g soil and increased to over 19 nem./g soil. Both sites have since decreased numbers due to extended fallow periods. Where summer crops were included in the sequence (during the same period), nematode numbers stayed below 2 nem./g soil at both sites. This allows for greater crop/variety choice for future rotations, as susceptible crops won't be as affected by the lower *P.thornei* numbers. This was evident at Mungindi, as *P.thornei* impacted the wheat yields in both the baseline and higher nutrients systems. The baseline and higher nutrient systems had wheat after a long fallow from chickpeas in 2016. Establishment was variable in these treatments, with the wheat yielding a mean of 0.8t/ha (8.5 kg/mm), whereas wheat in the low intensity system following cotton 2016/17 resulted in more even establishment and yielded 1.3 t/ha (11.4 kg/mm).

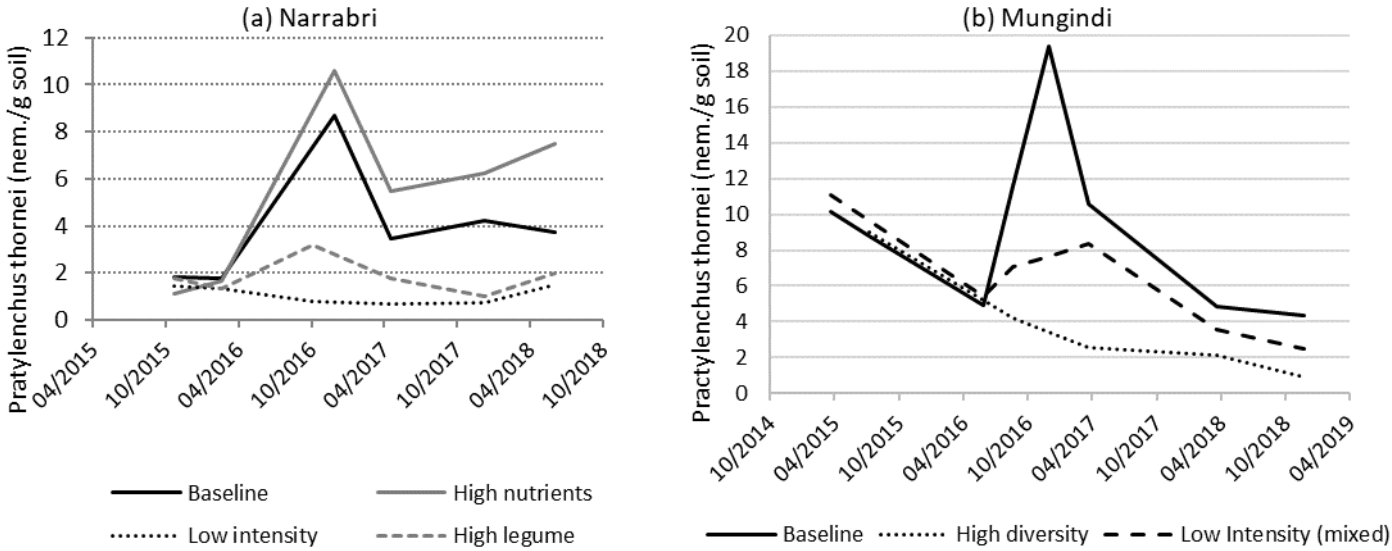

Figure 4. *Pratylenchus thornei* populations at (a) Narrabri and (b) Mungindi as impacted by different farming systems (2015 to 2018)

Crop-by-crop effects on fallow efficiency

At each farming systems site, fallow water accumulation was monitored (four years of data) and used to compare how different crop types impact subsequent fallow efficiencies (FE) (Figure 5). This data shows the high variability in fallow efficiency that occurs from year to year. However, there were also some clear crop sequence effects on subsequent fallow efficiencies.

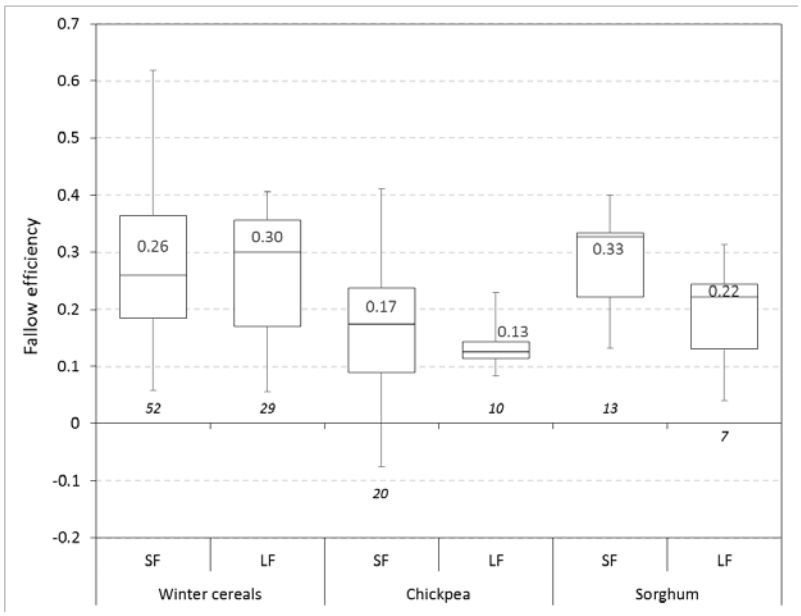

Figure 5. Summary of observed fallow efficiencies following different crops and different fallow lengths (SF – short fallows 4-8 months, LF – long fallows 9-18 months) across all farming systems sites and treatments between 2015 and 2018; winter cereals include wheat, durum and barley. Boxes indicate 50% of all observations with the line the median, and the bars indicate the 10th and 90th percentile of all observations. Italicised numbers indicate the number of fallows included for each crop.

Fallow efficiencies were higher following winter cereals than chickpeas. The median fallow efficiency (LF and SF) following winter cereals was 0.26, while following chickpea the median fallow efficiency

was 0.14. Median fallow efficiencies following sorghum were similar to wheat (0.26), but short-winter-fallows after sorghum were more efficient than long fallows. This difference between short and long fallows was less obvious following winter cereals. This is likely due to winter fallows being more efficient than summer fallows, due to lower evaporation losses, and possibly lower soil water content at the start of the fallow. Short winter fallows for sorghum production are more efficient, while long-fallows spanning into summer are less efficient. This also explains the similar fallow efficiency of short (summer) and long fallows (summer + winter) after winter cereals.

This means that the impacts of each crop on the accumulation of soil water in the following fallow should be considered in the cropping sequence. For example, a fallow receiving 400 mm of rain after a winter cereal would accumulate 108 mm on average, while the same fallow after a grain legume would have only accumulated 56 mm. This difference is likely to have a significant impact on the opportunity to sow a crop and/or the yield and gross margin of the following crop in the farming system.

How risky is your rotation – modelled outcomes

Rotation trials are traditionally phased, so that each crop in the rotation is grown every year. This project has based planting decisions on PAW triggers, so doesn't have fixed rotations that can be phased. Therefore, to build a greater understanding of crop sequence interactions in different environments, a series of simulations were run using the APSIM model.

Simulations

The APSIM systems framework was used to simulate crop rotations from historic climate records (1957-2017), with environmental signals used to trigger appropriate management decisions. However, these simulations only considered the dynamics of water and nutrients. Losses due to waterlogging, heat or frost shock events, disease, pests, weeds or crop nutrition other than nitrogen were not considered.

The simulations of all crop sequences were phased, so that each year of the rotation was exposed to each year of the climate record (1956-2016). All rotations were run at each of 6 sites (Table 1) to highlight the importance of matching crop choice and intensity to the environmental conditions. The selected sites represent an east-west rainfall gradient at both a northern (Pampas – Billa Billa – Mungindi) and southern latitude (Breeza – Gilgandra – Nyngan). There were only small differences between the two western sites, so this paper will focus on Mungindi (grey vertosol, APSoil No. 157, wheat PAWC – 186 mm, annual rainfall – 505 mm).

Rotations

This analysis looked at increasing crop intensity using both a fixed pattern and an opportunistic crop inclusion. A set of three base crop sequences were simulated, each with a low and a high crop intensity, with varying lengths of fallows and time in crop (Table 5). In these base rotations (high and low intensity) the crops in the sequence were sown every year (must sow crops) in a fixed pattern within their sowing window. If the sowing rule had not been met by the end of the sowing window, then the crop was sown at this time regardless. In contrast, an opportunistic sequence was then simulated; where the opportunity crop was either sown or remained in fallow based on the volume of soil water. Crops were only sown when the volume of soil water exceeded the critical threshold during the sowing window. Simulations were also conducted with two different soil water thresholds to trigger a planting event (Base – 150 mm PAW at sowing, and Aggressive – 100 mm PAW at sowing). A failed crop is one that returns a negative gross margin (including fallow costs).

Table 5. Description of low and high intensity rotations where all crops are sown every year. An opportunistic crop rotation is where some crops are only grown when soil water exceeds a minimum threshold (shown in grey with an underline).

Rotation Intensity	***Winter***		***Balanced - conservative***		***Balanced - aggressive***	
	Crops	/yr	Crops	/yr	Crops	/yr
Low	xW|xx|xCh|xx	0.5	Sx|xCh|xW|xx	0.75	Sx|xW|xx	0.66
High	xW|xW|xCh|xW	1.0	Sx|xCh|xW|Mgx	1.0	SCh|xW|Mgx	1.33
Opportunity	xW|xW|xCh|xW	0.5-1.0	Sx|xCh|xW|Mgx	0.75-1.0	SCh|xW|Mgx	0.66-1.33
Moderate					SCh|xW|xx	1
Mod. Opp.					SCh|xW|xx	0.66-1.0

S = Sorghum, W = Wheat, Ch = Chickpea, Mg = Mungbean, x = 6 month fallow. Opportunity crops are underlined.

At Mungindi, the most conservative rotation of xW|xx|xCh|xx, had the least crop failures at 15% (Table 6), but also had the lowest gross margin ($152 /ha/yr) (Figure 6A, Table 6). The annual gross margin is improved by planting winter crop every year (xW|xW|xCh|xW), but increased the proportion of failed crops. The opportunity approach to increasing cropping intensity in this rotation has provided the same higher gross margin as the higher intensity annual cropping rotation, but proportion of failed crops decreased for 32% to 22% as the opportunity crop is only planted in 40% of years (Table 6).

Adding sorghum into a low intensity system (Sx|xW|xx) increased cropping intensity slightly compared to the low intensity winter rotation (0.5 vs 0.66), but increased crop failures (35%) and returned a lower gross margin ($130 /ha/yr) (Figure 6c, Table 7). This is due largely to the high failure rate of the sorghum (45%) in this rotation. Within this balanced winter/summer cropping system, cropping intensity can be increased to 4 crops in 3 years (SCh|xW|Mgx, 1.3 crops/yr) for a similar gross margin to the low intensity system, however crop failure rates increase to 45%. However, by taking an opportunistic approach to increasing intensity (SCh|xW|Mgx), crop failures are reduced to 30%. This approach returned the highest gross margin of any approach modelled here ($260/ha/yr, Table 7).

The planting triggers of 100 mm or 150 mm demonstrated that in most cases the lower planting trigger (100 mm) provided the highest gross margin with minimal increase in risk of crop failure and led to the planting of twice as many opportunity crops. This is likely due to the crops being planted earlier in the planting window, and therefore maximising seasonal yield potential. The exception to this is sorghum. Sorghum is by far the highest risk crop in this environment, so it benefited from the higher PAW (150 mm) at planting, decreasing crop failure and increasing gross margin.

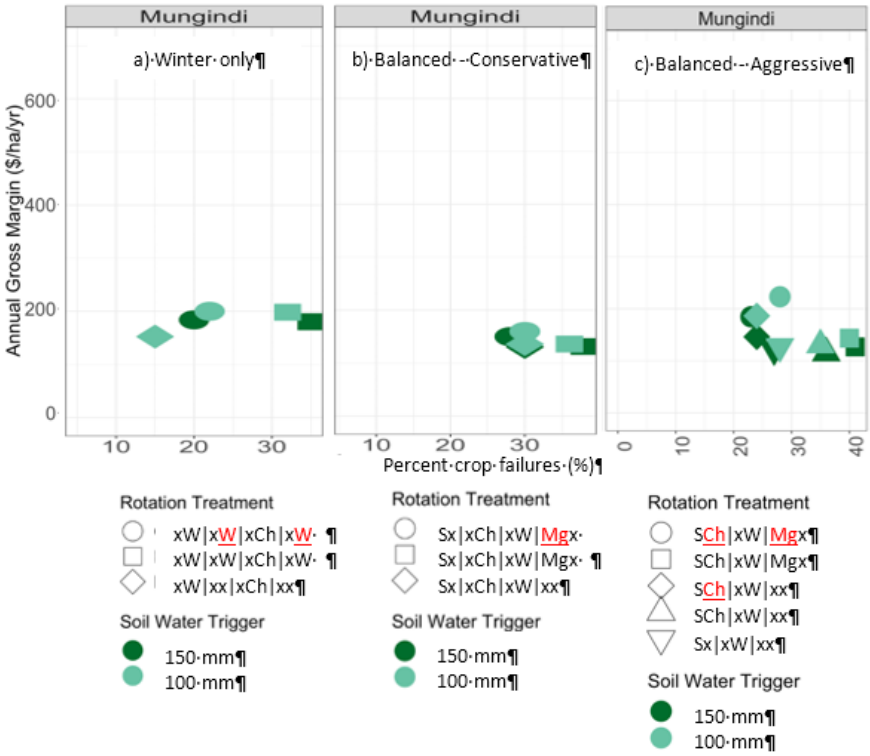

Figure 6. Average annual gross margin and proportion of planted crop failures (negative gross margin) for a range of fixed or opportunity cropped rotations at Mungindi. W= wheat, Ch= chickpea, S= sorghum, Mg = mungbean. Underlined crops are only planted in years the soil water trigger is met. Other crops are planted every year, once the soil water trigger is met or at the end of the planting window.

Table 6. Individual crop performance for the conservative rotation at the low rainfall site of Mungindi. All crops are sown each year in the low and high intensity rotations. However, in the opportunistic rotation, wheat crops in the long fallow are only sown if the 100mm and 150mm planting triggers are reached

Site	State	Low intensity xW|xx|xCh|xx			High intensity xW|xW|xCh|xW			Opportunistic xW|xW|xCh|xW		
		% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)
Mungindi	**60 yr ave**	**0.5**	**15**	**152**	**1.0**	**35**	**181**	**0.66**	**20**	**182**
Base soil water rule (150 mm)	Chickpea_1	100	8	395	100	27	282	100	12	377
	Wheat_1	100	22	214	100	40	132	100	28	190
	Wheat_2	0	0	0	100	40	129	33	25	251
	Wheat_3	0	0	0	100	32	179	30	17	283
Mungindi	**60 yr ave**	**0.5**	**15**	**152**	**1.0**	**32**	**198**	**0.71**	**22**	**200**
Aggressive soil water rule (100 mm)	Chickpea_1	100	8	395	100	25	311	100	13	376
	Wheat_1	100	22	214	100	38	142	100	30	178
	Wheat_2	0	0	0	100	38	136	43	27	255
	Wheat_3	0	0	0	100	27	204	42	16	323

†refers to the number of crops that failed relative to the percentage of crops sown

Table 7. Individual crop behaviour for different levels of cropping intensity conducted at the low rainfall site at Mungindi

Site	State	Low intensity Sx|xW|xx			Moderate intensity SCh|xW|xx			Opportunistic Mod-Int SCh|xW|xx			High intensity SCh|xW|Mgx			Opportunistic High-Intensity SCh|xW|Mgx		
		% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)
Mungindi Base soil water rule (150 mm)	**60 yr ave**	**0.66**	**35**	**132**	**1.0**	**41**	**115**	**0.70**	**26**	**211**	**1.3**	**45**	**126**	**0.82**	**28**	**218**
	Chickpea_1	0	0		100	58	-76	12	14	529	100	59	-32	10	17	466
	Mungbean_1	0	0		0	0	0	0	0	0	100	53	7	37	32	141
	Sorghum_1	100	43	179	100	32	260	100	40	191	100	37	236	100	35	257
	Wheat_1	100	27	184	100	33	160	100	25	186	100	31	176	100	28	199
Mungindi Aggressive soil water rule (100 mm)	**60 yr ave**	**0.66**	**35**	**126**	**1.0**	**42**	**130**	**0.76**	**28**	**241**	**1.3**	**43**	**140**	**0.94**	**30**	**267**
	Chickpea_1	0	0	0	100	55	-23	28	18	548	100	50	36	25	13	532
	Mungbean_1	0	0	0	0	0	0	0	0	0	100	56	6	58	40	168
	Sorghum_1	100	45	183	100	38	248	100	42	211	100	37	218	100	42	213
	Wheat_1	100	25	199	100	32	167	100	25	193	100	30	170	100	23	225

†refers to the number of crops that failed relative to the percentage of crops sown

Conclusions

At the western farming systems sites, the highest gross margins are being achieved by the baseline systems, which is also the case for the other five sites not reported in this paper. However, the benefits of (higher risk) summer break-crops becomes apparent when we look at the disease implications of this system (particularly root-lesion nematodes), with yield differences measured in 2018 wheat crops at Mungindi as a result of alternative crops in the rotation.

Results to date show that water use efficiency of most crops is improved by increasing plant available water at planting, with the exception of pulses that can suffer from waterlogging in wet seasons. However, fallows following crops with lower residual stubble cover (i.e. chickpeas) are less efficient at converting rainfall to PAW, particularly in long fallows. So, stubble cover needs to be considered when deciding whether to long fallow, or plant on a lower PAW.

Modelling suggests opportunity cropping is most profitable in this environment when 100 mm is available at planting. In comparison, fixed rotations with similar average cropping intensity produced more failed crops and therefore lower average gross margins.

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Acknowledgements

The research undertaken as part of this project (DAQ00190 and CSA00050) is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the author would like to thank them for their continued support. The trial was co-funded by CSIRO, Qld DAF and NSW DPI. We would also specifically like to thank all the farm and field staff contributing to the implementation and management of these experiments, the trial co-operators and host farmers.

Contact details

Jon Baird
Department of Primary Industries
Locked Bag 1000, Narrabri NSW 2390
Mb: 0429 136 581
Email: jon.baird@dpi.nsw.gov.au

Andrew Erbacher
Department of Agriculture and Fisheries
LMB 2, Goondiwindi Qld 4390
Mb: 0475 814 432
Email: andrew.erbacher@daf.qld.gov.au

Decision making after a prolonged drought: setting the business up for rational decisions to get margins back

Simon Fritsch, Agripath

Contact details

Simon Fritsch
Agripath
Mb: 0428 638 501
Email: simon@agripath.com.au

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Discussion session on recovery after the drought - strategies and decisions for getting back to productivity

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KEY CONTACTS

GRDC GRAINS RESEARCH & DEVELOPMENT CORPORATION

NORTHERN REGION

TOOWOOMBA
214 Herries Street
TOOWOOMBA, QLD 4350
northern@grdc.com.au
P:+61 7 4571 4800

APPLIED RESEARCH AND DEVELOPMENT GROUP

SENIOR MANAGER CROP PROTECTION (NATIONAL)
Emma Colson
Emma.Colson@grdc.com.au
M: +61 4 5595 8283

MANAGER AGRONOMY, SOILS AND FARMING SYSTEMS
Kaara Klepper
Kaara.Klepper@grdc.com.au
M: +61 4 7774 2926

MANAGER AGRONOMY, SOILS AND FARMING SYSTEMS
John Rochecouste
John.Rochecouste@grdc.com.au
M: +61 4 7774 2924

MANAGER CHEMICAL REGULATION (NATIONAL)
Gordon Cumming
Gordon.Cumming@grdc.com.au
M: +61 4 2863 7642

BUSINESS SUPPORT TEAM LEADER
Gillian Meppem
Gillian.Meppem@grdc.com.au
M: +61 4 0927 9328

CROP PROTECTION MANAGER
Vicki Green
Vicki.Green@grdc.com.au
M: +61 4 2904 6007

CONTRACT ADMINISTRATOR, CROP PROTECTION
Linda McDougall
Linda.McDougall@grdc.com.au
M: +61 4 7283 2502

CONTRACT ADMINISTRATOR
Tegan Slade
Tegan.Slade@grdc.com.au
M: +61 4 2728 9783

CONTRACT & TEAM ADMINISTRATOR
Brianna Robins
P: +61 7 4571 4800

GENETICS AND ENABLING TECHNOLOGIES GROUP

NATIONAL VARIETY TRIALS OFFICER
Laurie Fitzgerald
Laurie.Fitzgerald@grdc.com.au
M: +61 4 5595 7712

GROWER EXTENSION AND COMMUNICATIONS GROUP

SENIOR MANAGER EXTENSION AND COMMUNICATION (NATIONAL)
Luke Gaynor
Luke.Gaynor@grdc.com.au
M: +61 4 3666 5367

GROWER RELATIONS MANAGER
Richard Holzknecht
Richard.Holzknecht@grdc.com.au
M: +61 4 0877 3865

GROWER RELATIONS MANAGER
Susan McDonnell
Susan.McDonnell@grdc.com.au
M: +61 4 3662 2649

COMMUNICATIONS MANAGER
Toni Somes
Toni.Somes@grdc.com.au
M: +61 4 3662 2645

BUSINESS AND COMMERCIAL GROUP

MANAGER COMMERCIALISATION
Chris Murphy
Chris.Murphy@grdc.com.au
M: +61 4 2277 2070