GOONDIWINDI
QUEENSLAND

TUESDAY 5TH AND
WEDNESDAY 6TH
MARCH 2019

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

Goondiwindi Community Cultural Centre
Cnr Russell and Short Streets, Goondiwindi

GRDC Welcome

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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DAY 1 PROGRAM – TUESDAY 5 MARCH 2019

Time	Topic	Speaker (s)
10:00 AM	**Welcome**	***GRDC***
10:15 AM	**Climate change impact on northern farming systems.** How much change has already occurred? What is forecast? How will farming systems change?	***Steven Crimp*** *(ANU)*
10:50 AM	**New frontiers in cereal breeding for a changing climate.** Long coleoptile wheat, crop competitive varieties, new wheat types for late sowing windows & high temperature stress during grain fill	***Greg Rebetzke*** *(CSIRO)*
11:20 AM	**Infield spectrometer or NIR on your phone!** Real-time in-paddock measurement of grain moisture & protein, soil water & nitrogen, leaf nitrogen, micronutrients, types of starch/sugars & more!	***William Palmer*** *(Rapid Phenotyping) &* ***Matt Gardner*** *(AMPS Research)*
12:00 PM	Lunch	
1:00 PM	**Concurrent session 1** *(See concurrent sessions for details)*	
2:45 PM	Afternoon tea	
3:15 PM	**Concurrent session 2** *(See concurrent sessions for details)*	
5:00 PM	Close	
6.40 PM	**Networking dinner and drinks at the Royal Hotel, 48 Marshall Street** *(Supported by Nufarm)*	

DAY 2 PROGRAM– WEDNESDAY 6 MARCH 2019

Time	Topic	Speaker (s)
7:30 AM	**Early risers panel session: Nutritional implications of the drought & assessing nutritional needs for 2019.** (Main auditorium) ***Mike Bell*** *(QAAFI),* ***Richard Daniel*** *(NGA),* ***Bede O'Mara*** *(Incitec Pivot)* ***Paul Gardoll*** *(MCA). Facilitator:* ***Tony Cox*** *(NSW DPI)*	
8:30 AM	**Concurrent session 3** *(See concurrent sessions for details)*	
10:15 AM	Morning tea	
10:45 AM	**Concurrent session 4** *(See concurrent sessions for details)*	
12:30 PM	Lunch	
1:30 PM	**The Helicoverpa resistance management strategy** – why, what it looks like, how is it working? Plus: - Products to take pressure off Altacor® & Steward® - Preliminary data on NPV use in winter pulses	***Melina Miles*** *(DAF Qld)*
2:00 PM	**Why does 1% matter so much?** How small changes in management affecting price, yield, production cost or quality, result in large impacts on profit	***Ross Kingwell*** *(AEGIC)*
2:30 PM	**How large is the gap between actual & potential yield & what can we do about it?** A 4 year survey of 200 fields	***Harm van Rees*** *(Crop Facts)*
3:00 PM	Close	

LOCATION & TIMING OF CONCURRENT SESSIONS

	Main auditorium	River room	Training & Technology Centre
Day 1 Sessions 1 & 2	Chickpeas	Weeds	Cereal agronomy & disease
Day 2 Sessions 3 & 4	Soil constraints & root health	New technology	Farming systems

CONCURRENT SESSIONS

Chickpeas (Day 1, sessions 1 & 2)

Time session 1	Time session 2	Topic and Speaker (s)
1:00 PM	3:15 PM	**Fungicide spray timing relative to inoculation.** How long do fungicides protect chickpea from Ascochyta & is there usable kickback? ***Kevin Moore*** *(NSW DPI)*
1:30 PM	3:45 PM	**Chickpea harvest & desiccation timing impacts** ***Richard Daniel*** *(NGA)*
2:00 PM	4:15 PM	**The physiology & genetics of cold temperatures in chickpeas** ***Neroli Graham & Annie Warren*** *(NSW DPI)*
2:30 PM	4:45 PM	**What causes & how can we manage grain quality defects in chickpea?** ***Jenny Wood*** *(NSW DPI)*

Weeds (Day 1, sessions 1 & 2)

1:00 PM	3:15 PM	**Green on green camera spraying** - a game changer on our doorstep? ***Guillaume Jourdain*** *(CEO Bilberry France)*
1:30 PM	3:45 PM	**Chaff lining & chaff tramlining weed seeds.** Research & grower experience with northern weeds ***Annie Ruttledge*** *(DAF Qld) &* ***Peter Bach*** *(Grower)*
2:00 PM	4:15 PM	**Residual herbicides & sow(milk) thistle** - length of residual & efficacy ***Michael Widderick*** *(DAF Qld)*
2:30 PM	4:45 PM	**Targeted tillage** - a commercial reality for fallow weed control ***Michael Walsh*** *(U. Syd)*

Cereal agronomy & disease (Day 1, sessions 1 & 2)

1:00 PM	3:15 PM	**Barley agronomy: New varieties, their potential for early sowing & limitations.** Do really long season varieties fit in the north? ***Rick Graham*** *(NSW DPI)*
1:30 PM	3:45 PM	**New virulences in Net Form of Net Blotch (NFNB) in barley;** high level fungicide resistance in net blotch; & barley stem rust on the Downs in 2018. ***Lislé Snyman*** *(DAF Qld)*
2:00 PM	4:15 PM	**Crown-rot update:** - N interactions - New varieties & resistance - Using Predicta® B as an in-crop diagnostic - Root system health ***Steven Simpfendorfer*** *(NSW DPI)*
2:30 PM	4:45 PM	**The secret life of crown rot:** what happens after harvest? ***Toni Petronaitis*** *(NSW DPI)*

Soil constraints & root health (Day 2, sessions 3 & 4)

Time session 3	Time session 4	Topic and Speaker (s)
8:30 AM	10:45 AM	**Root health** - a key factor for cereal crop productivity ***Gupta Vadakattu*** *(CSIRO)*
9:00 AM	11:15 AM	**Subsoil constraints** - the whys & wherefores of sodium, chlorides & magnesium. Why & how do they impact soil? ***Neal Menzies*** *(UQ)*
9:30 AM	11:45 AM	**Wheat varietal tolerance to sodicity** - current varieties plus breeding lines ***Yash Dang*** *(UQ)*
9:40 AM	11:55 AM	**PhD SESSION** - The physiology of improved wheat growth on dispersive sodic soils ***Monia Anzooman*** *(UQ)*
9:50 AM	12:05 PM	**Using EM38 at the crop lower limit to identify subsoil constraints for site-specific soil & nutrient management** ***Yash Dang*** *(UQ)*

New technology (Day 2, sessions 3 & 4)

8:30 AM	10:45 AM	**Data sources to manage variability that won't break the bank** - what's out there? ***Brett Whelan*** *(Uni. Syd.)*
9:00 AM	11:15 AM	**Future farming technologies leading to automated application systems and variable rate control** ***Craig Baillie*** *(USQ)*
9:30 AM	11:45 AM	**Aqua-Till** - ultra high pressure liquid coulters for slicing surface residue ahead of tine or disc seeders ***Greg Butler*** *(SANTFA)*
9:55 AM	12:10 PM	**On the go protein sensors** - it's standard on some new headers. Using protein data for more profitable cropping decisions ***Brett Whelan*** *(Uni. Syd.)*

Farming systems (Day 2, sessions 3 & 4)

8:30 AM	10:45 AM	**Cover crop research to increase water infiltration & reduce evaporation** ***David Lawrence*** *(DAF Qld)*
8:55 AM	11:10 AM	**Farming systems** - GM & $ return/mm water ***Lindsay Bell*** *(CSIRO)*
9:15 AM	11:30 AM	**Multiple season nutrient balance.** P N & K export rates across crop sequence & strategies ***Jon Baird*** *(NSW DPI) /* ***Jayne Gentry*** *(DAF Qld)*
9:35 AM	11:50 AM	**Tactical decisions on crop sequencing** - opt in/ opt out decisions based on PAW triggers ***Jeremy Whish*** *(CSIRO)*
9:55 AM	12:10 PM	**Impact of crop sequence on soil water** ***Lindsay Bell*** *(CSIRO) /* ***Andrew Erbacher*** *(DAF Qld)*

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DAY 2 SESSIONS

SOIL CONSTRAINTS AND ROOT HEALTH CONCURRENT SESSION

NEW TECHNOLOGY CONCURRENT SESSION

FARMING SYSTEMS CONCURRENT SESSION

GENERAL PLENARY DAY 2

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DAY 1 SESSIONS

GENERAL PLENARY DAY 1

Predicted climate change impacts on northern farming systems

Steven Crimp 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 temperature has 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 400ppm and the CO_2 equivalent (CO_2-e) of all gases reaching 500ppm for the first time in at least 800,000 years (Foster *et al*., 2017).

In Australia, the pattern of warming (average temperature) has been largely similar to that experienced globally, with warming of just over 1°C since 1910 (BoM & CSIRO 2018). Examining the shift in the distributions of monthly day and night-time temperature shows that very 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 & CSIRO 2018). Very warm monthly minimum, or night-time, temperatures have shown a similar change from 2% of the time in the past (1951–1980) 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 & CSIRO 2018).

In the Goondiwindi region over the period 1950 to 2018 (length of the temperature record), warming has occurred in both minimum and maximum temperatures with mean temperatures now approximately 1.1°C warmer than in 1950. For the period 1950 to 1985 a maximum daily temperature of 29°C occurred, on average, 14% of the year. More recently (1986 to 2018) this temperature now occurs on average 35% of the year. Similarly mean minimum temperatures have warmed with the frequency of a minimum temperature of 21°C increasing from 48 to 102 times each year (Figure 1). Despite warming in both minimum and maximum temperatures the number of frost events (i.e. defined here as the temperatures below 0°C) has more than tripled during June to August, with an average of 9 events occurring most recently.

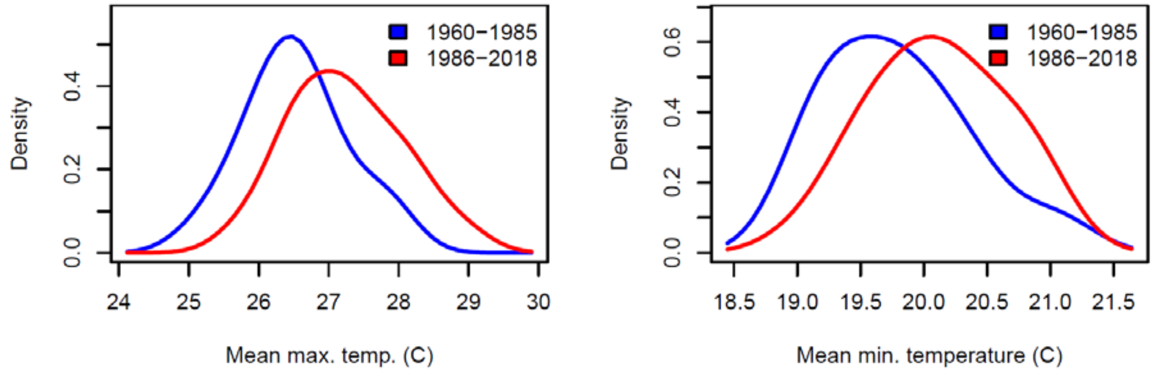

Figure 1. Probability distributions of mean daily maximum temperature (left) and mean daily minimum temperatures (right) for Goondiwindi for two periods, namely 1960 to 1985 and 1986 to 2018

The Goondiwindi rainfall record exhibits a declining trend, with declines during the June to August and September to November periods most pronounced. Mean dry spell lengths have also increased, with the average time between rainfall events now three days longer during June to August (i.e. an average dry spell length of 12 days for the period 1986 to 2018) (Figure 2). Similarly, the number of heavy rainfall events (i.e. greater than the 90th percentile) across the whole year has declined, again most notably during the June to August and September to November periods. The maximum number of consecutive dry days has increased across the whole year with March to May, June to August and September to November periods increasing by 3, 4 and 5 days respectively (i.e. now 33, 28 and 22, days respectively).

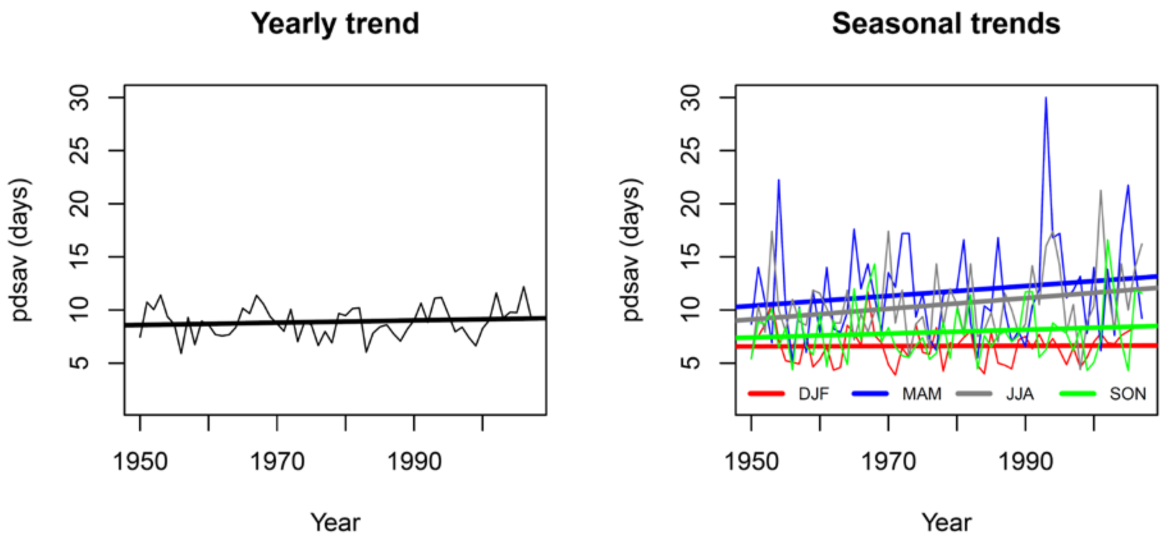

Figure 2. Mean annual dry spell length (left) and seasonal dry spell length for December to January (DJF), March to May (MAM), June to August (JJA) and September to November (SON). Dry spell lengths are expressed in days.

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 *et al*., 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 a long-term warming trend (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 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 (Huong *et al*., 2018) 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 eastern Downs region (Goondiwindi represents a southern town in this study region) are summarised in Table 1. In addition to warmer temperatures and declines in mean annual rainfall, evaporation rates are likely to increase. The annual potential evaporation (1986-2005) for the region is 1539 mm. By 2050 the median value of annual potential evaporation is projected to increase by 6 % under a high emissions scenario.

Table 1. Projected changes in temperature and rainfall for eastern Downs region (Goondiwindi is on found on the southern 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.

Variable	Season	Historical Mean (1986 to 2005)	2030	2050	2070
Mean Temperature Change (°C Change)	Annual	19.4°C	1.1 (0.5 to 1.6)	1.9 (1.1 to 2.6)	2.9 (2.0 to 3.8)
	Summer	25.4°C	1.1 (0.4 to 1.8)	2.0 (1.0 to 2.9)	3.0 (2.0 to 4.3)
	Autumn	19.8°C	1.0 (0.1 to 1.6)	1.8 (0.9 to 2.6)	2.9 (1.8 to 3.6)
	Winter	12.4°C	1.0 (0.1 to 1.7)	1.9 (1.2 to 2.5)	3.0 (2.1 to 3.8)
	Spring	20.0°C	1.1 (0.5 to 1.8)	1.9 (1.0 to 3.2)	3.0 (2.0 to 4.2)
Mean Rainfall Change (% Change)	Annual	614mm	-5 (-20 to +7)	-6 (-23 to +14)	-9 (-23 to +13)
	Summer	246mm	0 (-15 to +21)	0 (-23 to +27)	-2 (-21 to +29)
	Autumn	132mm	-3 (-28 to +27)	-4 (-33 to +36)	-8 (-42 to +41)
	Winter	86mm	-1 (-25 to +13)	-14 (-39 to +13)	0 (-49 to +14)
	Spring	151mm	-6 (-22 to +20)	-8 (-34 to +12)	0 (-42 to +21)

The impacts of climate change on wheat production for the Goondiwindi region have been simulated using the Agricultural Production Simulator (APSIM). The simulations are based on a continuous wheat rotation with a Hartog wheat variety, grown on a black vertosol soil. The simulations where run using daily climate data for the period 1990 to 2018, with future scenarios for 2030, 2050 and 2070 produced by scaling daily temperature and rainfall from the historical baseline period by the mean annual values found in Table 1.

If the 1990 to 2018 climate were to change, with a mean increase in temperature of 1.1°C and a 5% decline in annual rainfall (i.e. the mean 2030 projection) small improvements (approximately 80 kg per hectare) might be possible for 5th and 25th percentile yields (Figure 3). The 75th percentile yields could also improve by as much as 200 kg per hectare, however the 95th percentile yields could decline by as much as 500 kg per hectare (Figure 3).

If temperatures were to increase by 1.9°C and annual rainfall where to decline by 6% from the 1990 to 2018 base period, significant reductions in large yields (i.e. 75th percentile and above) are possible. In this simulation the 95th percentile yields decline by almost 100 kg per hectare (Figure 3). Median to lower percentile yields remain similar to the baseline yields.

If the 1990 to 2018 climate were to change, with a temperature increase of 2.9°C and a 9% decline in annual rainfall, simulated yields decline by between 200 kg per hectare (i.e. 5th percentile yields) and 1000 kg per hectare (i.e. 95th percentile yields).

This simple example highlights the sensitivity of wheat production at Goondiwindi to temperature increases and modest changes in annual rainfall, but does not take into consideration the compounding effects such as changes in runoff (Figure 4). 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.

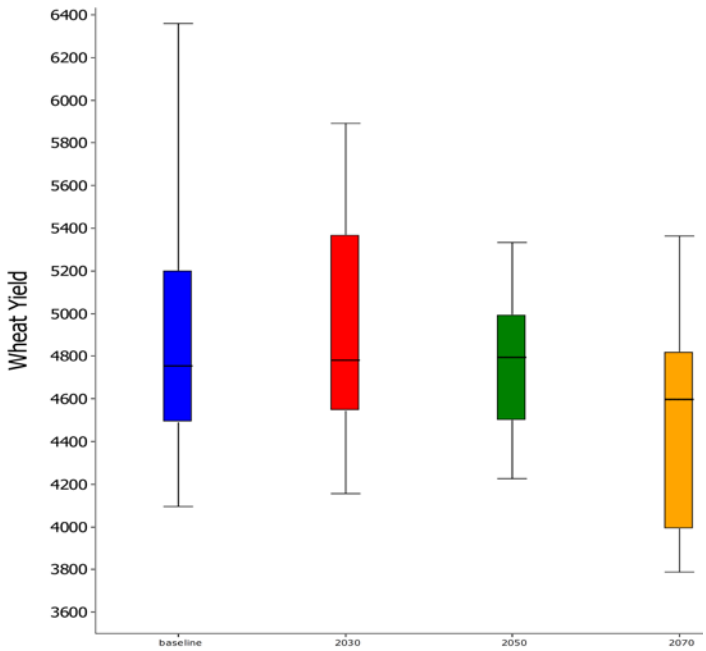

Figure 3. Boxplots of wheat yield for Goondiwindi for the period 1990 to 2018 (baseline), for a 28 year period centred on 2030, 2050 and 2070. Simulations were undertaken using APSIM based on a continuous wheat rotation with the Hartog wheat variety on a black vertosol soil. Yields are expressed in kilograms 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 ¾ and ¼ 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.

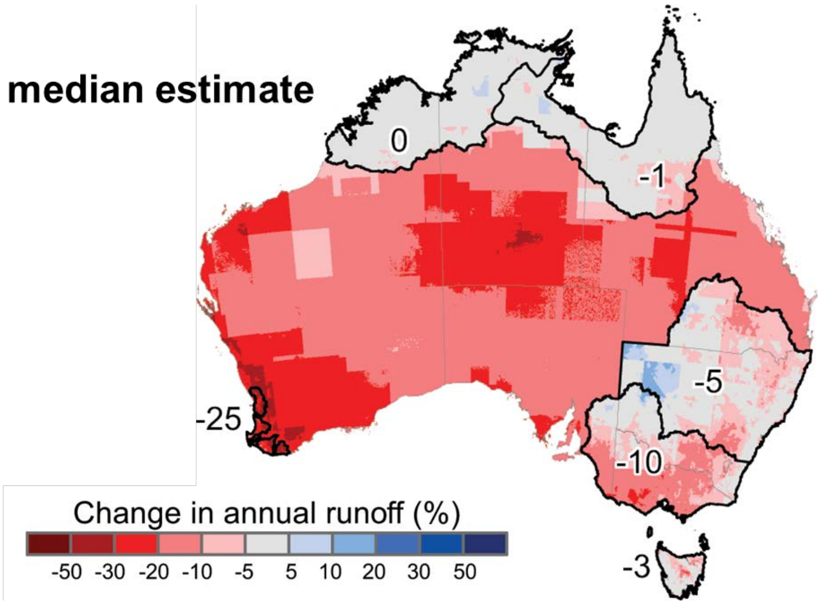

Figure 4. Mid-range assessment of changes in average runoff per degree global temperature increase (IPCC 2014). Run-off integrates the effects of changes in temperature, rainfall and evaporation. For example, where the map shows a 25% reduction in runoff per degree and global temperatures rose by 2°C then runoff is likely to halve (i.e. 2 times 25%) with major implications for water resource management including for irrigated agriculture.

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 a number of 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 (Ghaharamni *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 and 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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New genetics to improve wheat establishment with deep sowing

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Key words

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

GRDC code

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

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 extends 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 dressing and pre-emergent herbicides will reduce this coleoptile length even further to affect establishment.

The green revolution *Rht-B1b* and *Rht-D1b* 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.

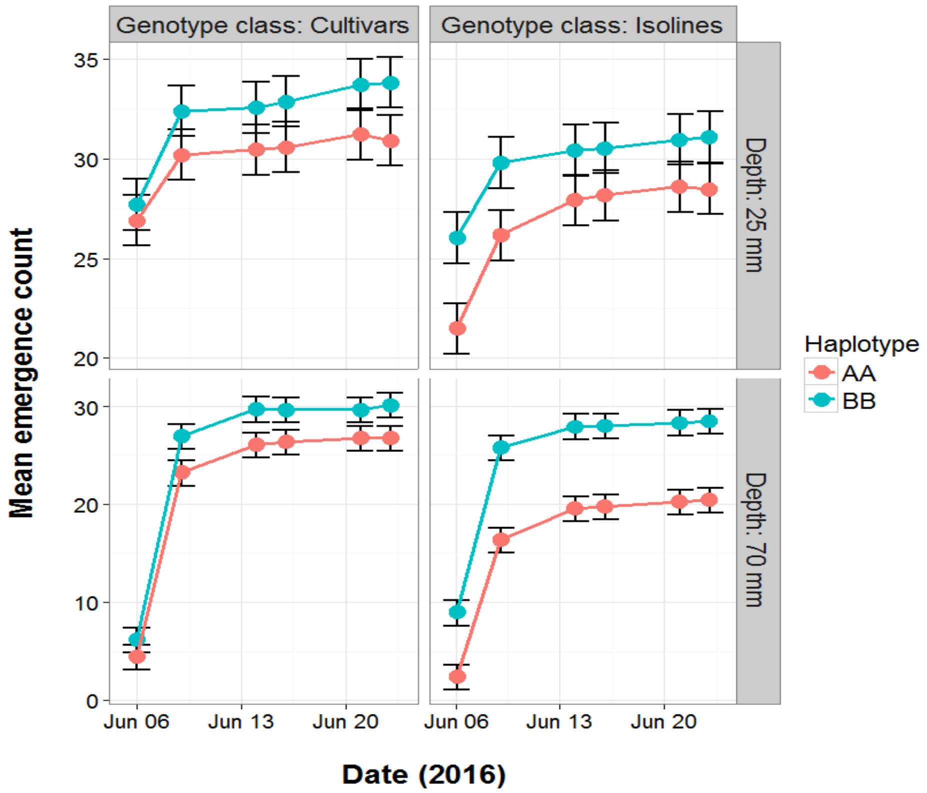

Figure 1. Emergence of wheat cultivars carrying conventional dwarfing genes and tall isolines in Young background in the NSW MEF at Yanco in 2016. Sowing depth treatments were 25 mm and 70 mm depth. 12 cultivars and 12 isolines were grouped according to the presence of the coleoptile length promoting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

Preliminary sowing depth field studies

Field studies have commenced on these Halberd-based dwarfing gene lines and show that lines containing these 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.

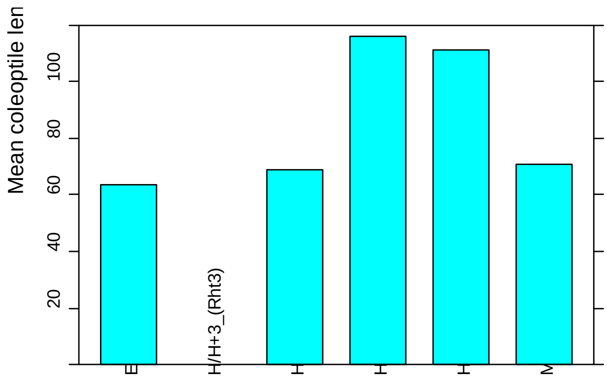

Figure 2. Coleoptile lengths of a tall wheat genotype (Halberd) and genotypes with dwarfing genes *Rht-B1b (syn. Rht1)* and *Rht8* in a Halberd background. Emu Rockᶲ and Maceᶲ are current commercial cultivars with *Rht-B1b* and *Rht-D1b*, respectively.

The most likely useful new dwarfing genes, *Rht13* and *Rht18*, have been bred into a range of current commercial wheats (Figs 4 and 5). Long coleoptile wheat breeding lines in Maceᶲ, Scoutᶲ, Espadaᶲ, EGA Gregoryᶲ and Magentaᶲ 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.

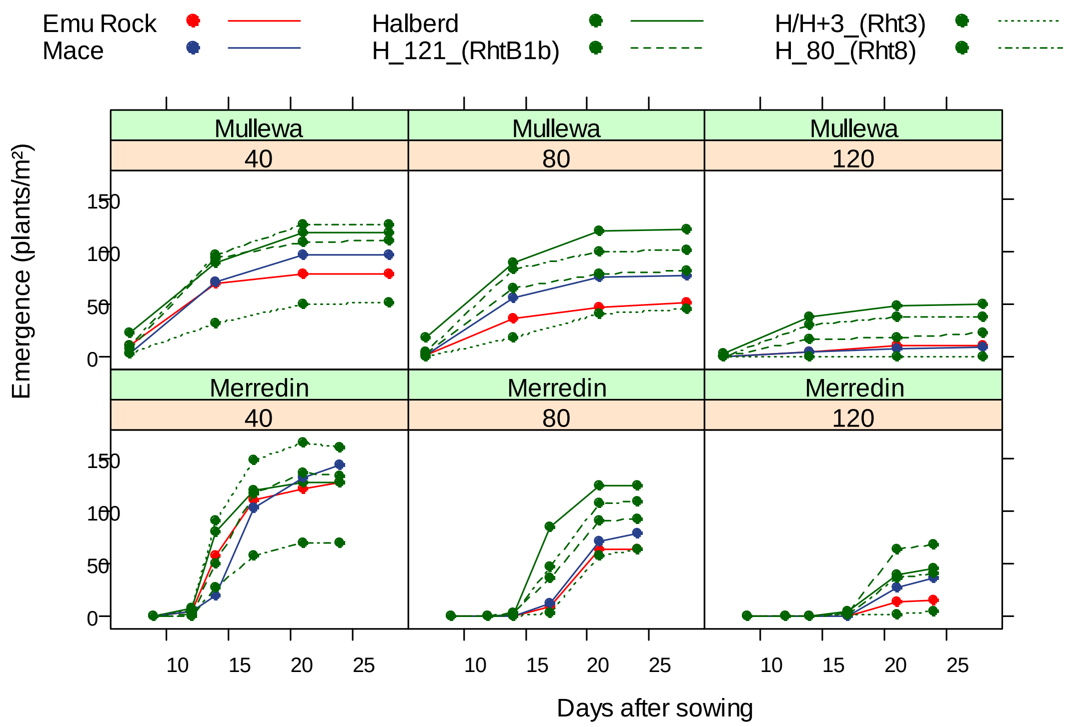

Figure 3. Patterns of emergence of wheat genotypes with different dwarfing genes sown at target depths of 40, 80, or 120 mm at Mullewa and Merredin in 2016 (after French *et al.* 2017).

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

Supplementary images

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.

Infield spectrometer and NIR on your phone

Dr William Palmer[1] & Matt Gardner[2]

[1] Rapid Phenotyping
[2] AMPS Research

Key words

chemical testing, in-field, instant data

Take home messages

High-throughput screening is a recent innovation which allows testing of soil, liquid, plant and grain samples to happen quickly. A sample is scanned, with the resulting spectral signature sent to the machine learning platform, and then decoded for the quantitative or qualitative variables of interest that the user specifies for that sample.

Using this technology, a handheld device has been developed which allows high-throughput analysis of a large range of chemical components in crops, liquids, soil and grain. This technology has the capacity to completely change the decision-making process on farms by providing increased data and accessibility to chemical testing in real time for a large range of variables, including nutrients such as nitrogen potassium, phosphorous, moisture, pH and many other variables.

This will improve farming practices by allowing greater knowledge of key quality and production indicators.

High-throughput screening

A hand-held platform has been developed to provide instant measurement of a range of chemical traits of commodities, or in broader terms any solid or liquid. Within the agriculture industry this has significance throughout the cropping/farming cycle from measuring soil nutrients, plant nutrient uptake and then protein, moisture or oil content of the grain. It can also be used to track supply chain of the commodity, with implications around confirming the provenance of the food being consumed.

This paper outlines the research and development that has made this platform possible and what are the next steps for use on the farm.

How it works

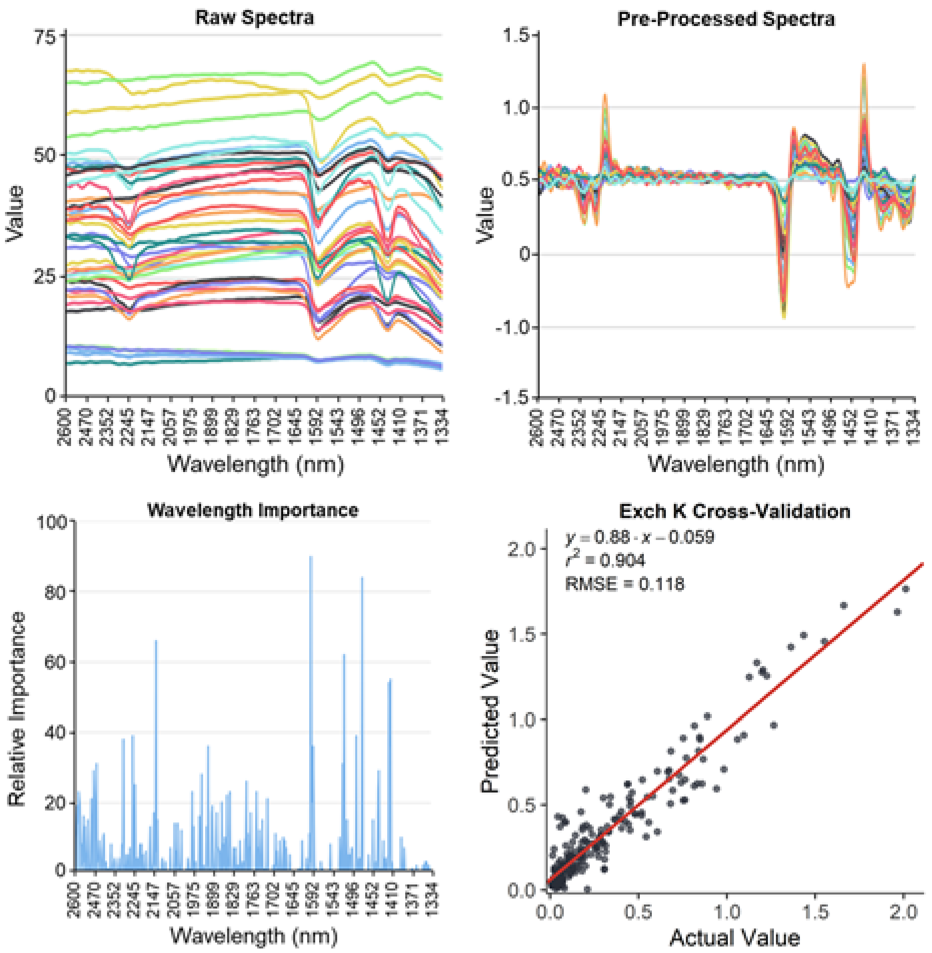
A handheld device has been developed which uses near infrared (NIR) and other spectral techniques for compositional analysis of a sample. When a sample is scanned, a spectral signature or molecular fingerprint is taken. This signature or fingerprint contains the information about chemical bonds within the sample. When light reflects or passes through a sample it is altered depending on what wavelengths are absorbed or reflected by the material in question. It is this difference that is then recorded by the detector providing information about what the chemical make-up of the material being scanned is, ie. wet soil will return a different spectrum to that of dry soil as the water will absorb some of the infrared light being applied to the sample.

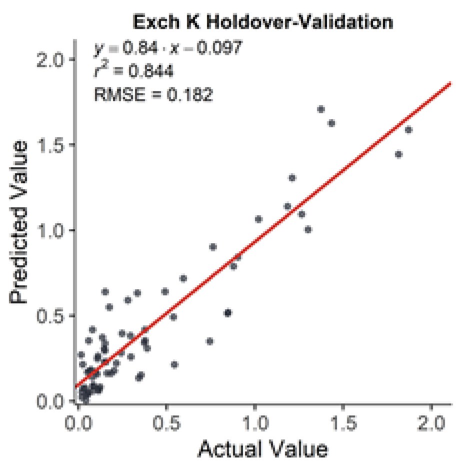
To decode this spectrum, data is transferred to the cloud via a phone application and decoded for the quantitative or qualitative variables of interest that the user specifies for that sample.

To analyse a chemical trait of interest the computer must first be taught what to look for in the spectrum signature. To do this, around 500 samples are analysed using traditional ‘wet chemistry’ methods, like what is done at gold standard labs.

An ensemble of algorithms and artificial intelligence techniques are then applied to teach the computer how to decode the relevant information contained within the spectrum, eliminating the need to conduct further ‘wet chemistry testing’. The analytical system called ‘Hone Prophecy’™ has been developed to decode these spectral signatures for a range of chemical compounds.

Below is a representation of exchangeable K and the artificial intelligence processing that happens in the background to deliver the results in real-time.





Holdover Validation Metrics

Date/time validated	30/01/2019 17:23:56
Holdover record count	51
RMSE	0.18
Effective model range	0.018-1.871
RMSE as % of mean	55.40%
RMSE as % of range	9.13%
R^2	0.84
Accuracy	-6.93

Figure 1. A representation of exchangeable K and the artificial intelligence processing that happens in the background to deliver the results in real-time

Once the algorithm for that variable of interest has been generated it is loaded into the platform and can predict the relative abundance of that chemometric trait. From one spectrum many variables of interest can be measured using this technique. The platform runs through a phone application and can be used on farm in real-time on compatible devices.

Hone is developing two devices for agricultural industries, RapidLab and RapidLab+.

Figure 2. An example of the RapidLab+ product

Both devices use multispectral technology to maximise the number of compounds that can be analysed in the field. RapidLab has been designed to perform a 'whole of farm' analysis tool including grain, soil and in-plant testing for key traits. To compliment this, RapidLab+ is designed to incorporate the ability to test liquids using differing spectral sources.

Testing takes less than a minute for key metrics such as nitrogen, potassium, phosphorous, moisture, pH and many other variables.

Benefits to agriculture

The opportunities and benefits for this technology in agriculture will vary significantly depending on the sector and end user.

It is not necessarily what can be measured that is the exciting part to this technology, it is rather the versatility of what can be measured and scanned by one device, lower cost of measurements compared to 'wet chemistry' and the speed at which the results/data are returned to the user and the ease of platform use.

These traits logically lead to; improved decision-making process, improved data legacy and improved production efficiency.

Decision making process

Ultimately, this technology will enable faster, more informed decisions to be made reliably on a time frame that is currently unavailable. Soil and plant analysis typically take 1-10 days from sample collection to receiving the results, depending on the test required. Using a field portable handheld device with this technology enables real-time decisions or diagnosis to be made for soil, plant, water and grain samples.

The greatest impact to growers from this type of technology will be the ability to track changes in plants or soils chemical composition over time. Early detection of these changes may be used to inform agronomic decisions at the critical stages of a plants growth and development leading to greater crop productivity.

Once appropriate calibrations are in place, it is envisaged that this technology would become a valuable tool for the adviser/grower and become a key tool in regular use.

Improved data legacy

Given the ease of use and range of things that can be measured, it is expected that more testing will occur, and more data will be produced. This could allow changes in the soil, water and plants to be more accurately tracked through time. Each farm would essentially have a greater data legacy that would enable interrogation and comparison of data between paddocks, seasons, farms and crops. As an example, if say Magnesium was found to be important for increased photosynthesis then a model can be developed and all samples previously scanned, even years ago, can be analysed without having to rescan the sample.

Improved production efficiency

Ultimately the technology has the potential to accelerate the transition of the Australian and global agriculture sector to the era of precision agriculture and improve production efficiency. Increased data and accessibility to testing will improve farming practices by allowing greater knowledge of key quality and production indicators and thus better prediction of farming outcomes. It would allow us to more easily connect the dots between what is available in the soil, what the plant has accessed and what is removed in the harvested product. Greater knowledge of this process can only lead to greater efficiency with inputs.

Furthermore, greater knowledge of the end product/commodity may give the capacity to extract more value. If a detailed analysis of grain, well beyond moisture, protein and oil content, could easily and reliably be produced then commodities could be marketed in a completely different way. This would already have immediate application in closed loop trading systems.

Conclusion

This technology has the capacity to change the way we farm daily. In particular, it is the versatility of what can be measured, the speed at which results are returned and to the ease of use. This will essentially improve the efficiency of production through the capacity to make more informed decision in an unprecedented time frame.

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CHICKPEA CONCURRENT SESSION

Chickpea Ascochyta research: what if I miss a spray – are there salvage options with new chemistry; how long do fungicides persist?

Kevin Moore, Steve Harden, Kristy Hobson and Sean Bithell, NSW DPI, Tamworth, NSW

Key words

chickpea, Ascochyta, management, fungicide persistence, missed spray, fungicide kickback

GRDC code

Grains Agronomy & Pathology Partnership - A strategic partnership between GRDC and NSW DPI (DAN00213)

Take home messages

- Follow latest advice for managing Ascochyta - applying fungicides before rain is a key component of this advice
- Chlorothalonil and mancozeb fungicides are persistent and rain fast (up to 50mm rain in 10 minutes)
- If you miss an Ascochyta fungicide spray, research indicates salvage sprays with new chemistry may be an option within tight timeframes, but this requires field confirmation
- Do not rely on salvage fungicide sprays as part of your 2019 Ascochyta management plan – aim to spray crops prior to rainfall events.

Background

Traditional chickpea Ascochyta blight fungicides e.g. chlorothalonil and mancozeb need to be applied before rain because they are protectants only. However, new chemistry and formulations offer the possibility of limited salvage fungicide options for Ascochyta if applied soon after infection (rainfall) events. Efficacy of these fungicides is far more reliable when applied prior to an infection event. Prophylactic use of efficacious fungicides applied prior to infection events, is and should remain the bedrock of Ascochyta management plans.

Likely scenarios when a preventative i.e. pre-rainfall, fungicide application is missed are:

- rain occurs when it was not predicted
- un-availability of spray contractors
- machinery breakdowns before or during application
- insufficient time to spray entire chickpea crop prior to rain.

This paper summarises recent research that shows chickpea Ascochyta blight may be able to be controlled if a pre-rainfall fungicide application is missed.

2017 Tamworth chickpea Ascochyta salvage spray field trial (FUN17)

The aims of this trial were to (i) evaluate efficacy of applying fungicides to a crop in which Ascochyta had established and (ii) to determine if newer fungicides had any 'kickback' activity when applied after a rain event.

Treatments

1. Nil (tap water)
2. Aviator Xpro® @ 400 mL/ha in 100 L/ha water backpack (registered but restrictions on number of applications per season and stage of crop development); no claim for kickback activity. Actives: 75g/L bixafen + 150g/L prothioconazole
3. Unite 720® @ 1000 mL/ha in 100 L/ha water backpack (registered); no claim for kickback activity. Active: 720g/L chlorothalonil
4. Veritas® @ 1000 mL/ha in 100 L/ha water backpack; no claim for kickback activity. Active 200g/L tebuconazole + 120 g/L azoxystrobin (registered, but restrictions on number of applications per season)

Operations

Kyabra⸙ sown 30 May 2017, seed treated P-Pickel T, plots 4 m x 11 m; 4 reps as a randomised complete block (RCB)
Inoculated 14 Jul in rain (15.2mm)

Post-inoculation rain and spray applications

14 Jul	15.2 mm
20 Jul	2.0 mm
4 Aug	20.0 mm
3 Sep	3.0 mm
5 Sep	1st sprays 41hr post rain
14 Sep	8.0 mm
18 Sep	1st Ascochyta scores

Methodology

Ascochyta was deliberately allowed to establish in the trial to provide high disease pressure under which to test the aims of the trial. Ascochyta was established by spraying the trial during a rain event with a suspension of Ascochyta inoculum containing 483,333 conidia/mL at a water rate of 100L/ha. This resulted in uniform infection ie every plant in the trial developed Ascochyta. High disease pressure was favoured further by waiting for three more infection cycles (rain events on 20 Jul, 4 Aug and 3 Sep) before applying the first fungicide sprays on 5 Sep. Ascochyta was scored on 18 Sep by assessing each plot on a scale of 1-5 where 1 = least disease and 5 = most disease.

Key findings

Aviator Xpro and Veritas reduced Ascochyta compared with Unite 720 and the nil control (Table 1). There was no difference in control of Ascochyta between Aviator Xpro and Veritas. Unite had no post-infection efficacy on Ascochyta. The lower Ascochyta score compared with the control in Table 1 reflects the prophylactic activity from the application on the 5th of September for the 14th of September infection event.

The best management recommendation for Ascochyta control remains that fungicide should be applied prior to forecast rain to provide the greatest level of protection. Post-infection sprays should not be a planned part of your standard Ascochyta management plan.

Table 1. Ascochyta (AB) severity score (1-5) on Kyabra⒟ chickpeas sprayed with Aviator Xpro, Veritas, Unite or Water (Nil) 41 hours after rain started in 2017 Tamworth field trial (FUN17)
F pr AB<0.001; l.s.d AB Score = 0.884; AB score 1 = least disease, 5 = most disease

Treatment	Rate/ha	Mean AB Score (18 Sep 2017)
Aviator Xpro	400 mL	1.75
Veritas	1000 mL	1.75
Unite	1000 mL	3.00
Nil (water)	Water only	5.00

2018 Tamworth chickpea Ascochyta salvage glasshouse experiments

Two glasshouse experiments were conducted in 2018 to provide additional evidence to support the 2017 field trial, FUN17.

Experiment 1 (FUN18GH)

In the first replicated experiment, chickpea plants (cv Kyabra⒟) with 4-5 nodes were inoculated with Ascochyta twice to optimise infection. Plants were allowed to dry for 30- 60 minutes between 1st & 2nd inoculations. The rate was 8.3 x 10^5 conidia/mL applied to run-off and incubated in a rainfall simulator.

Twenty-four (24 hr) or 48 hours after inoculation, treatments of Unite 720 @ 1000 mL/ha, Aviator Xpro @ 400mL/ha, Veritas @ 1.0L/ha were applied with a water-only treatment as the nil control. The plants were placed under glasshouse conditions conducive to Ascochyta development (23C, 80% RH).

Only Aviator Xpro and Veritas stopped Ascochyta development and they did so at both application times. Unite 720 (chlorothalonil) had no post inoculation activity - there was just as much Ascochyta with the Unite 720 treatments as with the Nil water control. All reps of the Unite 720 and Nil treatments had maximum Ascochyta disease score of 5 (on 1-5 scale); the other treatments all scored 1 (no disease).

Trial results indicate Aviator Xpro and Veritas provided control of Ascochyta blight infections when applied 24 and 48 hours post- infection.

Experiment 2 (FUN18GH)

In the second experiment, Aviator Xpro @ 400 mL/ha and Veritas @1000 mL/ha were applied to Kyabra⒟ chickpeas with 14 nodes at four times: 24, 48, 72 and 96 hours after inoculation with a water-only treatment as the Nil control.

Inoculation, incubation and experimental conditions were as for experiment 1. The number of petioles, leaves and stems with at least one Ascochyta lesion were counted 14 days after inoculation. Data was analysed using the glmer function from the R package lme4; means were compared by the Tukey method.

Ascochyta developed on all tissues at all times in the Nil water control (Tables 2-4). No Ascochyta developed on any tissue when Aviator Xpro or Veritas were applied 24 or 48 hrs after inoculation and very little or none developed when Aviator Xpro or Veritas were applied 72 hrs after inoculation (Tables 2-4). However, applying Aviator Xpro or Veritas 96 hrs after inoculation did not stop

Ascochyta with no significant difference in numbers of petioles, leaves or stems with Ascochyta between these fungicides applied at 96 hrs after inoculation and the Nil control (Tables 2-4).

Table 2. Number of petioles with Ascochyta at 14 days after inoculation on chickpeas sprayed with Aviator Xpro, Veritas or water (Nil) 24, 48, 72 and 96 hours after inoculation

Tissue & treatment	24h	48h	72h	96h
Petiole Aviator Xpro	0.0	0.0	0.25a	4.75b
Petiole Veritas	0.0	0.0	0.50a	5.50b
Petiole Nil	7.5	7.0	7.50b	7.25b

numbers followed by the same letter are not significantly different within timings, P =0.05

Table 3. Number of leaves with Ascochyta at 14 days after inoculation on chickpeas sprayed with Aviator Xpro, Veritas or water (Nil) 24, 48, 72 and 96 hours after inoculation

Tissue & treatment	24h	48h	72h	96h
Leaf Aviator Xpro	0.00	0.0	0.25a	4.25b
Leaf Veritas	0.00	0.0	0.75a	5.25b
Leaf Nil	8.75	9.0	8.00b	6.50b

numbers followed by the same letter are not significantly different within timings, P =0.05

Table 4. Number of stems with Ascochyta at 14 days after inoculation on chickpeas sprayed with Aviator Xpro, Veritas or water (Nil) 24, 48, 72 and 96 hours after inoculation

Tissue & treatment	24h	48h	72h	96h
Stem Aviator Xpro	0.0	0.0	0.25	3.75a
Stem Veritas	0.0	0.0	0.00	4.50a
Stem Nil	6.0	7.5	6.50	5.75a

numbers followed by the same letter are not significantly different within timings, P =0.05

The results of the 2018 glasshouse experiments looking at the impact of Ascochyta infection period prior to application of Aviator Xpro and Veritas need to be validated in field trials.

However, the results indicate if growers wait 72 hours after rain starts before spraying, Ascochyta may still develop and if they wait to 96 hours they will not stop the disease.

If a pre-rainfall spray is missed, one management option available to growers may be to apply Aviator Xpro (before late flowering (BBCH 69) with a maximum of two sprays during the season) or Veritas (may be applied twice in a season, with no restriction on use at flowering).

However, growers are encouraged to implement the current recommended management practice of applying before rain .

2007 Tamworth chickpea Ascochyta fungicide rain fastness experiment

This replicated experiment was designed to answer a question many agronomists and growers have asked i.e. "Yesterday, I sprayed my chickpeas with an Ascochyta fungicide and today it rained - is my crop still protected?"

Chickpeas cv Jimbour with 3-5 nodes were sprayed with Bravo® (720g/L chlorothalonil), Dithane™ Rainshield™ (750g/kg mancozeb) or water (Nil fungicide). Fungicides were applied with a backpack at standard rates ie Bravo @ 1000 mL/ha or Dithane Rainshield @ 2kg/ha in 100L/ha water by placing pots on ground and walking at 6.0 km/h. As soon as the fungicides had dried, the plants were placed in a rainfall simulator and exposed to 50mm, 100mm or 150mm of 'rain' at a rate of 50mm per 10 minutes; plants not exposed to rain were the Nil rain (Dry) control. After exposure, plants were inoculated with Ascochyta, placed in a humid chamber for 48 hours and assessed 10 days later.

Bravo was very rain fast – 150mm rain in 30 min did not appear to reduce efficacy compared with 50mm in 10 min.

Dithane Rainshield was not as rain fast with 150 mm having significantly more stem lesions than 50mm. However, it's highly unlikely a chickpea crop in southern Australia would ever be exposed to 50mm rain in 10 min (the lowest intensity we could get with this simulator).

So, the answer to the growers' questions is "Yes – your crop is still protected, although new growth emerging post-fungicide is not".

2018 Tamworth chickpea Ascochyta fungicide persistence glasshouse experiment

A glasshouse experiment was conducted to determine how long a fungicide protects tissue to which it has been applied. Fungicides (Unite 720 @ 1000 mL/ha, Aviator Xpro @ 400 mL) were applied once to Kyabra⁽ᵇ⁾ or PBA Seamer⁽ᵇ⁾ with 4-5 nodes and inoculated with Ascochyta 1, 2 or 4 weeks later; water was the Nil control. New growth was removed every 2-3 days to remove tissue that had not been sprayed from the experiment. Ascochyta was assessed on petioles, leaves and stems on a 1-9 scale where 1= nil disease and 9 = tissue dead. The data was analysed using the lme function of the R package nlme.

The findings were similar for petioles, leaves and stems. No Ascochyta developed on either variety with Aviator Xpro at any time of inoculation. There was little or no disease with Unite 720. For the Nil control, Kyabra⁽ᵇ⁾ had more Ascochyta than PBA Seamer⁽ᵇ⁾ and disease scores tended to be lower for later inoculation.

This experiment supports previous research that showed chickpea Ascochyta fungicides provide lasting protection for the tissues to which they have been applied.

Chickpea Ascochyta management in 2019

The current recommendation for cost-effective management of chickpea Ascochyta includes:

- Treat all planting seed with a registered fungicide, applied properly. Seed treatment protects against seed transmitted Ascochyta, Botrytis and a range of opportunistic soil fungi that can attack seedlings if seed has lower vigour, is planted deep or if conditions don't favour rapid emergence e.g. cold, wet soil, herbicide residues.
- Paddock selection – avoid planting chickpeas in the same paddock for at least 3 years. Avoid planting chickpea immediately next to last year's chickpea crop.
- Grow varieties with the highest level of Ascochyta resistance suitable for your area
- For NSW and southern QLD, in high risk Ascochyta situations i.e. paddocks that had chickpeas in 2016, 2017 or 2018, apply a preventative fungicide before the first post emergent rain event
- In central QLD, where the Ascochyta risk is lower compared to southern regions, grow the highest yielding varieties but have in place an Ascochyta plan. In most seasons in CQ, there will be no cost benefit of applying a fungicide before Ascochyta is detected. When conditions do favour Ascochyta, a reactive foliar fungicide program and protective pod sprays are warranted. Monitor the crop 10-14 days after each rain event.

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The impact of harvest management in chickpeas

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Key words

chickpea desiccation, harvest losses, grain quality

GRDC code

NGA00004: GRDC Grower Solutions for northern NSW and southern Qld

Take home messages

- Across 9 trials, there was no impact on yield or grain quality from any registered harvest management option, when applied ~2 weeks prior to anticipated harvest
- All treatments increased leaf discolouration and leaf drop, however the clearest differences were observed in impact on stem dry down
- The most effective treatments for stem dry down were the mixture of Weedmaster® ARGO® + Ally® or the mixture of Gramoxone® 250 + Sharpen WG®
- Decisions on harvest management choice should be determined by cost, attitude to Ally plant back restrictions, weed spectrum present at harvest and speed of desiccation required
- There was no indication that any harvest management treatment increased the level of screenings when assessed with the slotted screen size used for defective grain assessment. However, when crop harvest was delayed by ~14 days, grain moisture was significantly reduced and screenings were increased, even in the untreated plots
- Application of Reglone® or Gramoxone 250 at less mature crop stages (~3 weeks prior to anticipated harvest) resulted in a significant reduction in both yield (~10%) and test weight (2-3kg/hL)
- Large levels of grain losses were measured at the header front in small plot trials (~200 kg/ha) with no indication of any shattering or pod drop prior to harvest
- Large levels of grain losses were also measured at the header front in a commercial case study (~160 kg/ha). These losses were primarily intact pods and losses were reduced by ~50% when harvested with the air front turned on
- Further research into improving harvest management of chickpeas appears warranted.

Background

In recent years, chickpeas have transitioned from being generally considered a rotation option between cereal crops to becoming a ‘pillar’ crop of the northern farming system. Historically, harvest management has fitted around the cereal harvest rather than being specifically driven by maximising the chickpea return. An improved understanding of the impacts of harvest management may enable improved financial returns or avoid significant losses.

NGA are currently involved in two aspects of harvest management evaluation; trials conducted during 2017 and 2018 to help improve the understanding and impact of current crop desiccation tools and in 2018, initial activity to evaluate the impact of desiccation timing and delayed harvest on crop yield, quality and harvest losses.

Chickpea desiccation evaluation 2017

An evaluation of desiccation options was conducted at five sites. Application at each site was when crops were estimated (by the grower or agronomist) to be ~2 weeks prior to harvest. Table 1 shows key details from these trials. NB harvest was delayed at some sites during to rain events after desiccation.

Table 1. Product evaluation trials 2017

Location	Variety	Date of application	Harvest date	Days before harvest
Warra	PBA Seamer⦶	10/10/2017	14/11/2017	35
Pittsworth	PBA Seamer⦶	20/10/2017	10/11/2017	21
Pallamallawa	PBA HatTrick⦶	18/10/2017	1/11/2017	14
Bellata	PBA Seamer⦶	3/11/2017	16/11/2017	13
Mullaley	PBA Seamer⦶	3/11/2017	27/11/2017	24

Chickpea desiccation evaluation 2018

A second season of product evaluation was conducted in 2018. Application timing was planned for a crop stage with ~85-90% of pods mature. Table 2 shows key details from these trials.

Table 2. Product evaluation trials 2018

Location	Variety	Date of application	Crop stage at application	Harvest date	Days before harvest
Warra	PBA Seamer⦶	2/11/2018	85% pods mature	16/11/2018	14
Mt Tyson	PBA HatTrick⦶	30/11/2018	91% pods mature	11/12/2018	11
Tulloona 1	PBA HatTrick⦶	26/10/2018	82% pods mature	12/11/2018	17
Tulloona 2	PBA Seamer⦶	23/10/2018	92% pods mature	7/11/2018	15

Trial results 2017

All treatments improved % leaf discolouration and leaf drop compared to the untreated but generally with only minor differences between treatments.

A 'twist test' assessment was conducted to evaluate stem dry down. This assessment was designed in an attempt to provide an objective 'harvest readiness' measure. Tested 10 plants/plot. Each plant was evaluated separately using a double twist motion. Data was recorded as the % of plants where stems snapped following the twist test.

Yield, grain moisture and protein were assessed at all sites. Test weight and screenings were evaluated at 3 sites. Screenings were assessed using a 4 mm slotted screen as an indication of % defective grain.

Figure 1 shows the combined analysis from all sites for the twist tests conducted 10-17 days after application.

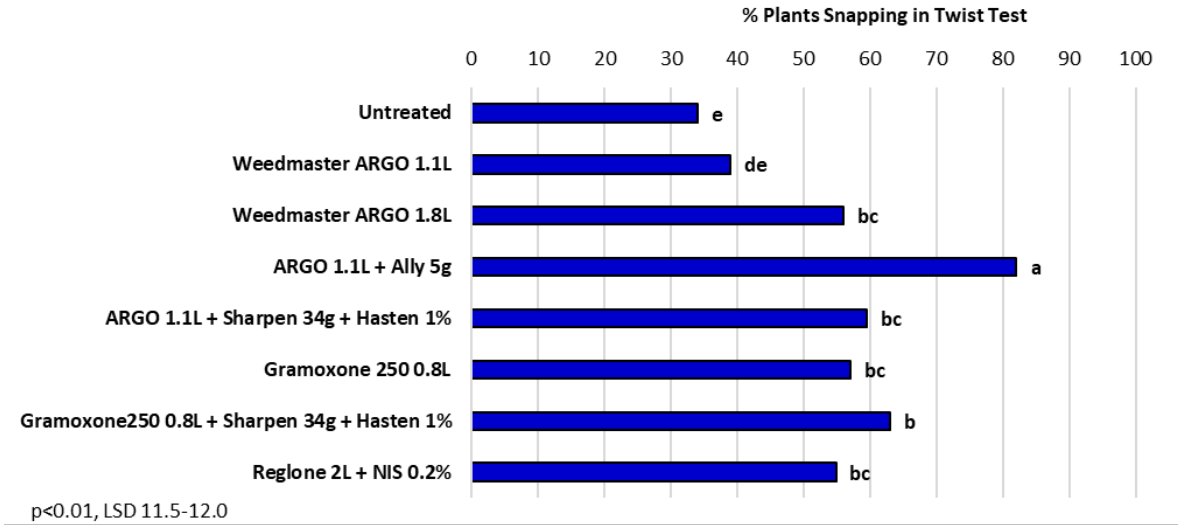

Figure 1. Stem twist test results 10-17 days after application, as an indication of stem dry down. *(Mean of 5 trials 2017)*

NIS = non-ionic surfactant

Trial results 2018

Assessment of leaf discolouration showed similar patterns to 2017, however the magnitude of difference between treatments and the Untreated was reduced. No treatment provided any significant improvement in leaf drop compared to the Untreated. A twist test assessment was again conducted. All trials were harvested with yield and grain quality assessed at all sites.

Figure 2 shows the combined analysis from all sites for the twist tests conducted at 7-15 days after application.

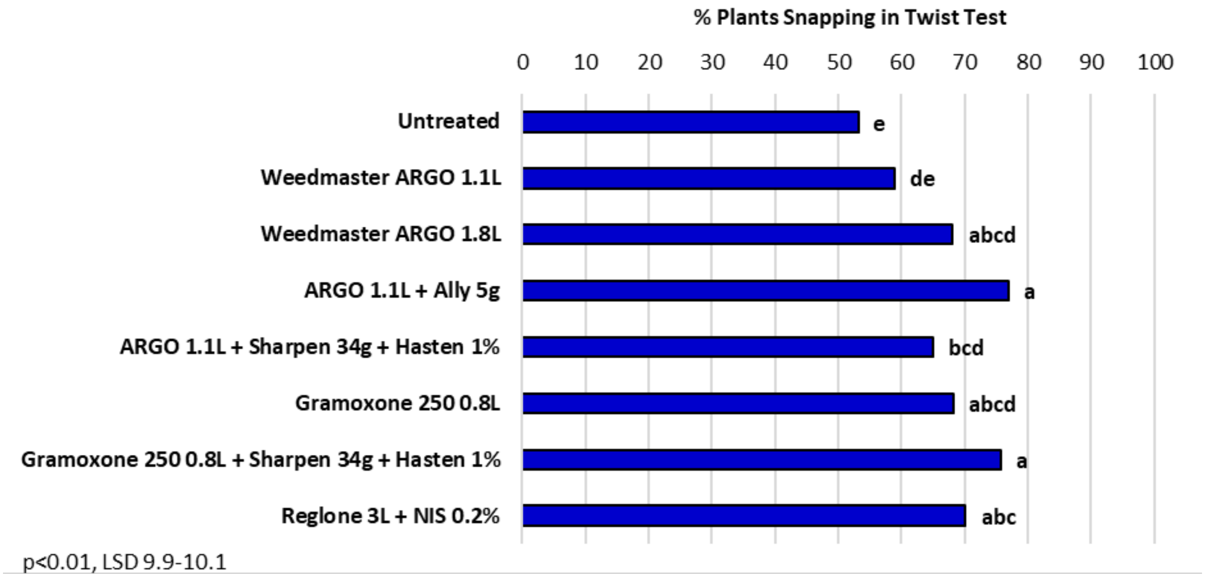

Figure 2. Stem twist test results 7-15 days after application, as indication of stem dry down. *(Mean of 4 trials 2018)*

NIS = non-ionic surfactant

Key Points 2017 and 2018

Leaf discolouration and drop

- All treatments increased % leaf discolouration and % leaf drop but without consistent differences between treatments
- Improvements in % leaf discolouration and % leaf drop compared to the Untreated were greater in 2017, where high levels of October rainfall encouraged crop regrowth.

Stem dry down

- Similar patterns of performance were seen in both seasons, however the differences between treatments were reduced in 2018
- The most effective options for stem dry down were either the mixture of Weedmaster ARGO + Ally or the mixture of Gramoxone 250 + Sharpen
- There was a dose response to glyphosate with increased stem snapping from the 1.8 L/ha rate
- There was no consistent difference between Weedmaster ARGO 1.8L, Gramoxone 250 or Reglone alone, or the mixtures of Sharpen with either Weedmaster ARGO or Gramoxone 250

Yield and grain quality

- There was no significant difference in yield recorded in any of the 9 trials
- There was no significant difference in test weight or % screenings in any of the 9 trials.
- Similar patterns were observed for grain % protein
- There was no significant difference in grain moisture in 8 of the 9 trials. Grain moisture was ~8-10% in Untreated grain in these trials
- However all harvest management treatments reduced grain moisture by ~1% in a 2017 trial where regrowth had been evident and the Untreated grain was ~13% moisture. There was no difference between harvest management treatments in this trial.

Overall

- Harvest management treatments increased both chickpea leaf and stem desiccation but had no impact on crop yield or grain quality. (It should be noted that the use of desiccants is not recommended when the grain is destined for use as seed, as germination % can be affected.)

Desiccation and harvest timing evaluation 2018

Field observations in 2017, suggested significant chickpea yield losses can occur when harvest of ripe crops is delayed. (This was supported by observations from QDPI agronomist Mike Lucy in the early 2000's). A series of split plot trials were designed to evaluate a combination of desiccant product and application timing combined with harvest timing.

Trials were conducted in commercial crops with desiccation targeted to commence when the crop was ~3 weeks prior to harvest with separate applications at both 2 and 1 week prior to expected harvest. The same treatments were applied with harvest delayed by ~2 weeks. The first application was designed to evaluate the impact from an application where crop maturity was considered 'immature'. (NB: at Tulloona 2 the first application was delayed and was only ~2 weeks prior to commercial harvest. It was hoped the second timing would be close to current commercial recommendations with a final 'conservative' timing.)

Pod maturity was assessed at each application on 10 main branches per plot. Pods were considered mature when a 'yellow beak' was starting to extend on the enclosed grains. This stage often corresponded with a purplish tinge appearing on the pod coat. Table 3 shows the key trial details.

Table 3. Desiccation and harvest timing impact 2018

Location	Variety	Dates of application	Crop stages at application	Harvest dates	Days before harvest
Warra	PBA Seamer⦶	19/10/2018 2/11/2018 9/11/2018	52% pods mature 85% pods mature 90% pods mature	1. 16/11/2018 2. 30/11/2018	28/14/7 42/28/21
Tulloona 1	PBA Seamer⦶	16/10/2018 26/10/2018 5/11/2018	58% pods mature 83% pods mature 88% pods mature	1. 12/11/2018 2. 27/11/2018	29/17/7 44/33/22
Tulloona 2	PBA HatTrick⦶	18/10/2018 23/10/2018 30/10/2018	82% pods mature 91% pods mature 100% pods mature	1. 7/11/2018 2. 20/11/2018	20/15/8 33/28/21

NB: the Tulloona 2 site was a late replacement and was only ~ 2 weeks prior to harvest at the first application timing. Tulloona 1 and 2 used different varieties than assessed in the product evaluation project.

Trial results

Assessment of leaf discolouration and leaf drop were conducted, however the main focus was impact on yield from varied desiccant application timings and the impact from harvest delay. Consistent small plot header settings were attempted but environmental and other conditions varied between harvest dates.

Application timing

- Desiccant applications ~prior to the industry standard recommendation of <15% green pods present in chickpeaswith Gramoxone 250 or Reglone significantly reduced test weight (by ~2-3 kg/hL) and grain yield by ~10% (~120 kg/ha)
- However, there was no impact on % protein, % moisture or % screening from any product

Harvest timing

- Inconsistent results were observed on the impact of harvest timing on yield:
  - A significant reduction in yield was measured at Tulloona 1 (by 28% or ~300 kg/ha) when harvest was delayed by 15 days
  - No difference at Tulloona 2
  - A significant increase was measured at Warra (by 13% or ~130 kg/ha) when harvest was delayed by 14 days. NB High levels of harvest losses occurred at this site, particularly from the first harvest.
- Grain moisture was significantly lower at the delayed harvest timing when analysed over all trials
- There was a significant increase in % screenings (increased from 7 to 11%) at the delayed harvest timing in all individual trials, with no significant product impact.

Harvest losses

An assessment of harvest loss was conducted at all sites. Pre-inspection showed there was no shattering loss of grain or pod drop prior to either harvest. Individual grain, pods and splits were counted together with the number of grain/pod and grain weight.

Two types of harvest loss were assessed. 'header front' losses were pods or grain that did NOT physically get into the header for processing and were found where the crop had been harvested but before any losses from the back of the header.

Losses were also assessed directly behind the header. These losses were the combination of any header front loss plus the 'header processing' loss. The difference between the two was the amount of grain that was lost over the sieves. This loss is largely determined by the header set-up.

Small plot headers were used in all trials. Increased header processing losses are likely compared to commercial headers, however header front losses would generally be considered low due to operation speed and the ability to harvest at very low heights.

- There was no evidence of any pod drop or shattering loss prior to either harvest timing
- Header front losses (grain or pods 'lost' at the front of the header) averaged ~100 grains/m^2 (~200 kg/ha)
- In these 3 trials, the header front losses represented an extra ~15-20% of harvested yield

Commercial harvest loss evaluation 2018

Commercial observations and comments indicated that high levels of header front loss of grain and pods were also being experienced, particularly in crops with reduced height or yield potential. Commercial scale data was generated at one site where an air front was in operation on a crop of PBA Seamer⦶.

Replicated areas were assessed where the only difference was whether the air front was operating or turned off. Individual grain, pods and splits were counted together with the number of grain/pod and grain weight. Harvest monitor estimates indicated the yield ranged from ~0.5 to 1.0 t/ha.

- When the air front was turned OFF, header front losses were ~160 kg/ha (~$135/ha). This was the equivalent of ~15-30% of the harvested yield
- When the air front was turned OFF, ~90% of the header front losses were intact pods (~145 kg/ha)
- When the air front was turned ON, the header front losses were reduced by ~80-90 kg/ha (saving ~$70-75/ha)
- Header front losses were ~85% of the total grain losses i.e.: the header processing losses were ~25 kg/ha

Conclusions

The comparison of registered harvest management options in chickpeas has shown no impact from any option on crop yield or grain quality when products are applied at currently recommended crop maturity stages.

However, application on less mature crops, particularly with desiccants such as diquat or paraquat, are likely to reduce yield with grain test weight also impacted in these trials. There was however no indication that desiccation treatments were having an impact on screening levels.

The clearest difference in product performance was observed in the stem dry down 'twist test' where the addition of Ally to glyphosate or Sharpen to paraquat resulted in the largest % of plants with dry stems. These treatments may provide a benefit in situations where stem dry down is of concern and likely to cause harvest difficulties.

The level of header front grain losses is of concern and warrants more detailed evaluation than conducted in this initial activity. Although these losses may have been more evident in 2018 due to lower yielding and possibly poorer feeding crops, a better understanding of header management appears warranted. In the commercial case study, a benefit of $70-75/ha was achieved by the use of an air front.

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The physiology and genetics of cold temperatures in chickpeas – what do we know and where is the research heading?

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NSW Department of Primary Industries

Key words

Chilling tolerance, early flowering, *Cicer arietinum*, breeding, prebreeding

GRDC code

BLG111

Take home messages

- During flowering, chickpeas are sensitive to cold (< 15°C) temperatures which cause flower abortion and results in a delay between flowering and pod onset
- While early sowing has the potential to reduce the risk of terminal drought, it moves the flowering window to cooler temperatures
- Current work aims to identify new sources of chilling tolerance for chickpea variety development and to assess the suitability of elite breeding lines for flowering and podding during cool conditions

Introduction

Chickpeas are well adapted to the northern cropping region in Australia and provide a valuable, economically sound, broadleaf rotation in our farming systems. However, various biotic and abiotic factors cause actual yields to fall between 1.7–2.7 t/ha below potential yield across the region (Yield Gap Australia, 2018). Cold temperatures during the flowering window can significantly reduce crop yield through delaying and interrupting pod set, causing loss of early pods. In 2016, agronomists estimated yield losses due to cool spring temperatures in north-west NSW ranged from 0.5–0.7 t/ha. Chickpeas can suffer damage during the flowering window from both frosts, when temperatures fall below -1.5°C, and “chilling” where average day temperature does not exceed 15°C. In this paper, we will focus on chilling temperatures and their impacts on flowering and podding.

While cool spring temperatures have been historically avoided through late sowing, changes to our farming systems mean there is a greater need for flexibility to sow chickpeas earlier to increase subsequent cropping options and to avoid heat and terminal drought at the end of the season. This however, pushes the flowering window to coincide with cooler ambient temperatures. In north west NSW (Tamworth region), average daily temperatures are not consistently above 15°C until late September and in the cool 2016 season, average temperatures remained below the critical temperature until late October (Figure 1). In addition, short bursts of cool temperatures occurring weeks after temperatures have begun to rise can interrupt pod and seed set even in areas that generally experience warm spring temperatures.

This paper outlines current knowledge of chickpea’s physiological response to cool temperatures during flowering and what opportunities and challenges exist for improving chilling tolerance through breeding and variety selection.

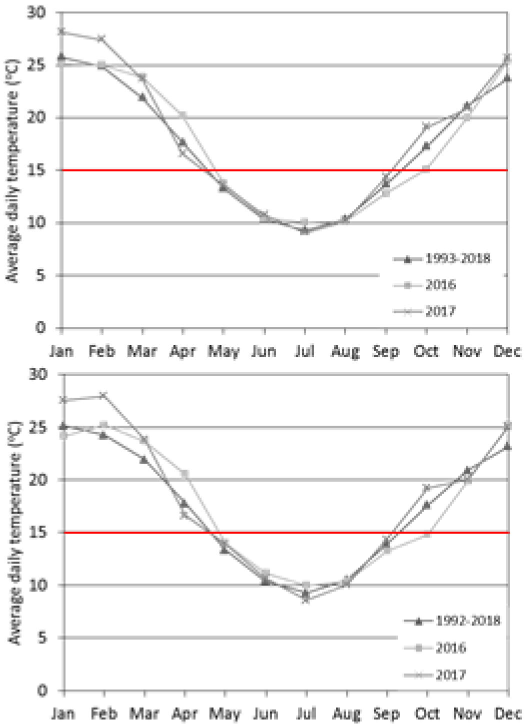

Figure 1. Average daily temperature for Tamworth (top) and Dubbo (bottom) shows cool spring conditions can continue into late September and October

The story so far

Early sown chickpeas consistently suffer from an extended gap between commencement of flowering and first pod appearance. In ideal conditions, chickpeas will produce pods within a couple of days of flowering (Clarke & Siddique, 1998). However, under cool conditions, the time from the beginning of flowering to the first pods appearing can be more than 2 months if temperatures remain consistently cool (Berger et al., 2005). At Warwick, early flowering genotypes took more than 30 days to begin podding when average temperature after flowering did not exceed 14.4°C (Berger et al., 2004). While the length of time between flowering and pod initiation varies across locations and between varieties, the delay in podding remains closely linked to temperature (Berger et al., 2004; Berger et al., 2005; Berger et al., 2012). For every degree drop in average daily temperature between 14 and 10°C, the time between flowering and podding is extended 12 days (Berger et al., 2005). During this time plants may continue to produce flowers that are subsequently aborted, or may cycle back into and out of a vegetative state.

While chickpeas may continue flowering under cool conditions, most flowers are subsequently aborted rather than producing pods. In their work with early sown chickpea in Western Australia, Siddique and Sedgley (1986) found only 38% of flowers carried through to produce harvestable pods among early sown plants, compared to 83% in later sowings. This difference was largely due to flower abortion at low temperature – up to 800 flowers/m^2 were aborted when average daily temperature was below 15°C, but no flower abortion occurred once temperature rose above this critical value (Table 1).

Siddique and Sedgley observed that although early sown crops suffer a high flower abortion penalty, this does not necessarily result in inferior yields when compared to later sown crops. Despite high flower abortion, the earliest sown chickpeas still produced the greatest yield. Across 72 genotypes and 5 locations, Berger et al. (2004) found early flowering cultivars were consistently the highest yielding, especially in locations that suffered end of season drought. Flower abortion under cool temperatures therefore constitutes a significant lost opportunity, as early flowering plants that also set pods early have the greatest potential to produce high yields.

Table 1. Effect of cool temperatures at 50% flowering on flower abortion at Merredin, Western Australia 1983

Planting date (1983)	Mean Daily temperature (°C) at 50% flowering	Aborted flowers (m^{-1})
May 17th	12.5	800
May 31st	13.6	500
June 14th	14.7	200
June 30th	16.8	0
July 20th	17.7	0

Note: Modified from Croser et al., 2003

On the small scale…

Cool temperatures reduce pollen vigour and ovary and style size of chickpea flowers, alterations that have been implicated in reduced flower fertilisation and increased flower abortion (Srinivasan et al., 1999). Pollen development and function is affected by cool temperature from the early stages of pollen production from 9 days before anthesis through to pollen tube growth and ovary fertilisation (Figure 2). Cold spells during key points in pollen development at either 9 or 4–6 days prior to anthesis can reduce pod set by 30–60% in susceptible varieties (Clarke & Siddique, 2004). Cool temperature may also decrease the quantity of pollen reaching the flower stigma due to reduced pollen release from anthers as well as a reduction in ovary and style size (Srinivasan et al., 1999). The resulting mismatch increases the difficulty of pollen transfer from anther to stigma (Srinivasan et al., 1999). Once pollen reaches the stigma, pollen germination can be reduced by 30% in susceptible varieties, although some susceptible varieties exhibit normal pollen germination (Clarke & Siddique, 2004; Srinivasan et al., 1999).

Once pollen has germinated on the stigma, pollen tube growth is particularly sensitive to cool temperatures. As a result, far fewer pollen tubes reach the ovary for fertilisation. Srinivasan et al. (1999) found while 100% of flowers at an average temperature of 20°C had pollen tubes reach the base of the style, as few as 23.5% of flowers at 10°C had more than 10 fully grown pollen tubes 1 day after flower opening. This resulted in fertilization of as few as 8% of flower ovules. In highly susceptible varieties, no pollen tubes will reach the ovary within 24 hours of pollen germination under cool conditions (Clarke & Siddique, 2004). As average day temperature increases from 5°C to 25°C, rate of pollen tube growth increases exponentially with only marginal increases in growth rate between 5–15°C (Srinivasan et al., 1999). Knowledge about these specific impacts of cool temperatures on chickpea reproduction have led to development of breeding practices such as pollen selection (Clarke et al., 2004) that are better able to target chilling tolerance.

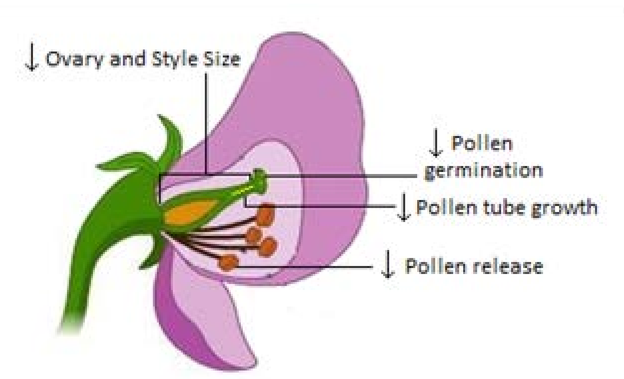

Figure 2. Impacts of cool temperature (< 15°C) on male and female reproductive organs of chickpea flowers

Note: Modified from Science Learning Hub – Pokapū Akoranga Pūtaiao (2011)

Opportunities for breeding chilling tolerant varieties

While cool temperature during flowering is a relatively new issue for the northern region, it has been identified as yield limiting across southern and western Australia since the early introduction of the crop. As a result, significant work has been conducted in Western Australia to develop chilling tolerant material for breeding programs. Clarke et al. (2004) developed two chilling tolerant cultivars, Rupali and Sonali, that could produce pods at 10–12°C and as result pod 20–27 days earlier than existing Western Australian varieties. However, these cultivars have insufficient disease resistance and do not yield comparably to the best yielding varieties in the northern region (K.Hobson, *pers comm*). In addition, time from flowering to podding can range from 30–70 days at temperatures ranging from 10–12°C (Berger et al., 2005). While not suited to northern environments, both Rupali and Sonali have been included in the northern breeding program since 2011 in an attempt to produce well adapted varieties with the ability to set pods at lower ambient temperature. However, the chilling tolerance during flowering and early pod set of progeny derived from either Rupali or Sonali has been insufficient to confer a significant improvement in the ability to set pods early under cool temperatures.

Limited genetic variation within domesticated chickpea restricts further progress in producing cultivars capable of podding at low temperature. However, some wild relatives of chickpea show considerably greater chilling tolerance and are able to set pods within 20 days of the beginning of flowering under cool temperatures, compared to the best chickpea cultivar doing so at 30 days (Berger et al., 2005). While chickpea pod production is reduced by 3–5 times when plants are kept at an average temperature of 10°C compared to 19°C, one particularly promising accession of *Cicer echinospermum* showed no reduction in pod set, setting more than 6 times the number of pods compared to chickpea at the lower temperature (Berger et al., 2012). There is, therefore, potential to include hybrids between chickpea and its wild relatives in breeding programs to make faster progress towards varieties that produce pods and seeds under suboptimal temperatures.

Where are we now?

Current research aims to identify useful sources of tolerance to suboptimal temperatures that can be used in breeding programs to improve future varieties. In Western Australia, both collections of chickpea and wild relatives are being screened by researchers at CSIRO as potential new sources for chilling tolerance during the early reproductive phase. Since current methods for identifying chilling tolerant chickpea lines is an expensive and labour-intensive process, several projects are working on developing tools to streamline identification of chilling tolerant breeding lines. At the University of Western Australia, Dr J Croser and her team are working to improve controlled environment screening for chilling tolerance amongst a wide set of chickpea genotypes. The underlying genetics of early flowering and chilling tolerance in chickpea during flowering is being investigated by NSW DPI at Wagga Wagga and Tamworth to improve knowledge about genetic control of early flowering and podset to potentially work towards developing genetic markers. This project uses a set of recombinant inbred lines formed from hybridisation between domestic chickpea and the wild relative *Cicer echinospermum* which were observed to flower and pod comparatively early in 2016.

In northern and southern NSW, current varieties and elite breeding lines are being assessed for flowering and pod set characteristics under cool spring temperatures through manipulation of sowing date. The aim of this work is to; quantify yield loss from cool temperatures during flowering in the northern and southern NSW regions, expand knowledge of drivers that may improve chilling tolerance, and identify future breeding directions. In 2018, field trials were conducted to benchmark current varieties and identify breeding lines with potential superior chilling tolerance when compared to existing varieties in northern environments. Data collected from the 2018 season is currently being processed for analysis.

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What causes and how can we manage grain quality defects in chickpeas

Jenny Wood, NSW DPI

Key words

chickpea, profitability, defective seed, seed markings, weather damage, harvest

GRDC code

DAN00196

Take home messages

- Seed defects were estimated (by extrapolation of survey responses across the whole industry) to cost growers up to $242 million for the 2017 chickpea crop.
- To reduce the likelihood of blotch/tiger stripe seed markings in your harvested seed, avoid early sowing of chickpeas in environments where tiger stripe/blotch seed markings are known to occur and avoid sowing blotch/tiger stripe marked seeds as this may increase the risk of marked seeds at harvest.
- To reduce the likelihood of weather damaged, stained and sprouted defective seed (and maximise yield), time harvest (and desiccation, if used) to avoid rainfall on mature/dry crops as much as possible and aim to harvest when seed is at 14% moisture content. This will maximise yield (through maximising seed weight) and minimise both seed loss (pod drop, shattering, cracked seeds) and risk of price penalties from quality loss (cracked seeds, weather damaged, stained and sprouted).
- Ensure combine harvester settings are optimised for every crop to minimise harvest loss, to capture the best quality seed and to remove immature green and small shrivelled seeds.
- Avoid storage of grain when fresh green seeds are present as this increases the likelihood of mould developing during storage. Desiccation prior to harvest will help reduce this potential issue by drying any new green growth at the top of the plants prior to harvest. However, desiccation with glyphosate should not be used on crops that are to be kept for seed, as it reduces seed germination. Only use recommended registered chemicals
- If weather damage occurs, do not retain this seed for planting as it will have lower germination and viability. Always test seed prior to planting.

Background

The Eliminating Grain Defects project was pre-emptive research aimed at protecting the superior quality of Australian chickpeas by increasing our understanding of seed defects to minimise future potential risks to the industry.

The project was triggered by reports that PBA Pistol⍉ had very noticeable blotch/tiger striping in the 2013 central Queensland environment. Pre-harvest weather damage leading to seed quality downgrading was also a significant issue for growers in some years. Hence, the project was developed to focus on understanding these two defects aiming to reduce the potential risk through breeding and/or management.

Experimental outline

This 4-year project conducted field trials, controlled experiments and laboratory evaluations to unravel the causes of chickpea seed defects.

Grower survey

An online anonymous grower survey was conducted to capture the scale and impact of chickpea defects at delivery for the 2017 crop. The survey was promoted in social media several times (both facebook and twitter) and was open from February till July 2018. The results were analysed for individual growers and then averaged to gain an overall picture of the scale of defects detected and the impact on growers. Economic analysis was then performed.

73 growers completed the survey, including some very large growers harvesting over 1,000 ha of chickpeas in 2017.

55% of the growers who responded had one or more of their chickpea deliveries discounted or rejected due to defects at the delivery point. Almost half of these had more than 50% of their chickpea crop discounted or rejected.

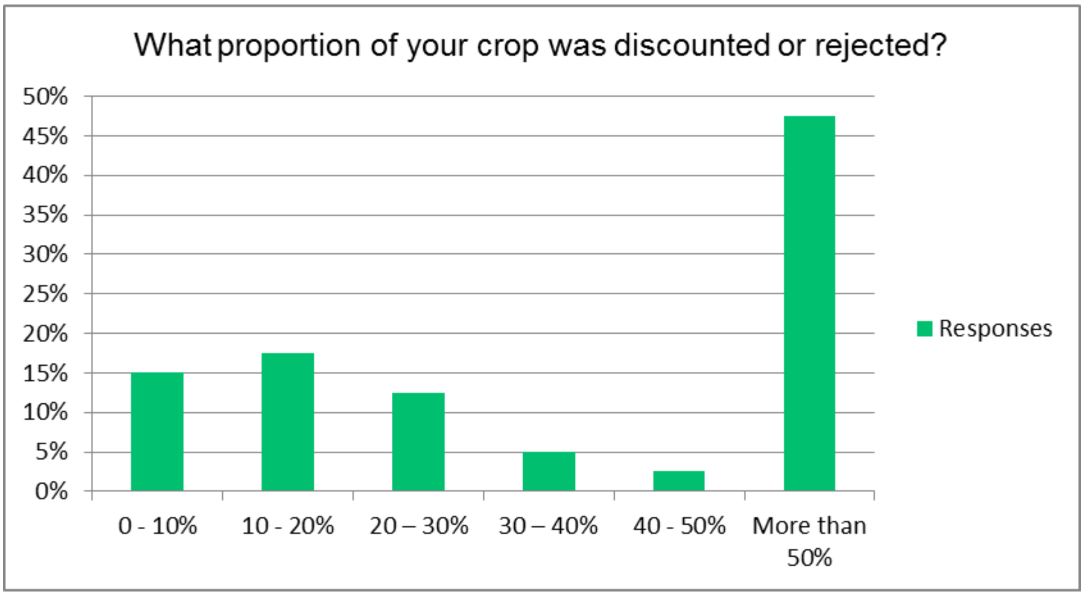

Figure 1. Grower responses to the proportion of their crop that was discounted or rejected

The size of the discount varied widely (Figure 2). Discounts were most often $10 – $100 per tonne (62.5% of responses) and rejections were also high (22.5% of responses).

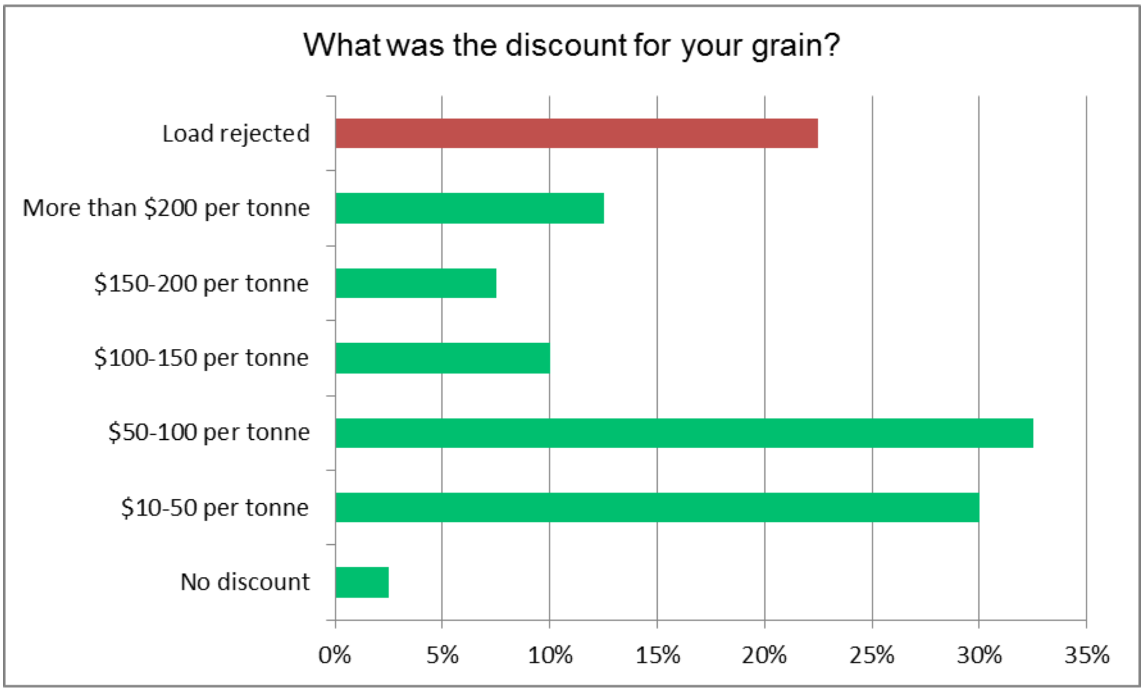

Figure 2. The cost to growers of seed defect discounts and load rejections ($/tonne)

The defects, for which growers were penalised, varied and included mould, stained, poor colour, shrivelled, green and foreign material. Many growers were penalised for more than one of these defects (average of 1.7 defects per grower), the highest was 5 defects.

The cost of seed defects to the Australian chickpea industry

Assuming that grower responses to this survey can be extrapolated across the whole Australian chickpea industry, the total cost of chickpea defects to the Australian chickpea growers from the 2017 crop ranged between $44.36 Million to $242.41 Million (average of $143.39 Million).

This equates to 5-28% of the gross value of Australian chickpeas (average of 16%).

The range of the estimate is wide due to the nature of the survey questions. In addition, the number of growers in 2017 was likely higher than the 2015 numbers used in the calculation, so the cost to the industry was probably higher than these figures calculated. Conversely, it is possible that growers with issues were more likely to respond to the survey than growers with no issue and, if so, this may overstate the size of impact.

Notwithstanding, there is much room for improvement in breeding and agronomic practices to restore this 5-28% loss to grower's pockets. Given the potential scale of these losses, a more targeted annual survey may be warranted in future. The average cost to Australian growers is shown in Figure 3.

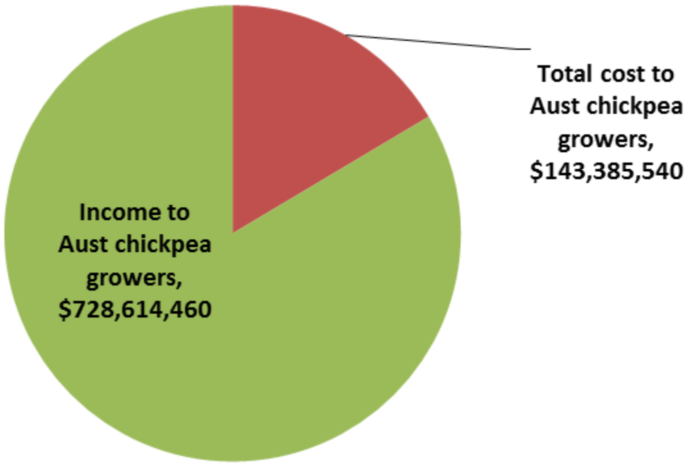

Figure 3. Estimated cost of seed defects (average) to Australian chickpea growers, 2017 crop. (NB: Does not include additional costs such as seed cleaning and delivery delays/costs)

Note that these calculations have only used penalty discounts and do not include the extra costs to growers associated with additional seed cleaning/grading and delivery delays/costs. Comments from growers on these aspects included:

- Grading and cleaning costs in the region of $30-45 per tonne
- Further transport costs in the region of $20-40 per tonne; up to 500 km extra distance for rejected grain
- Harvest stoppages and other delays due to rejected loads, further transport and cleaning. These delays also lead to further risk of defects occurring for any crops not yet harvested, especially if storms occur (causing weather damage) or crops are becoming too dry (leading to pods dropping off plants and shedding of cereals)

It is clear that grain defects are having an impact on grower profitability.

Identification of grain defects

Whilst many growers were penalised for 'mould' in the survey, there were reports that seed markings like blotch/tiger stipe and mosaic markings were mistakenly classified as 'mould'. Evidence of this misclassification was found on Twitter, where chickpeas containing some mosaic seeds were penalised on delivery due to a 'mould' misclassification (Figure 4). Mistakes like this at grain receival are costly to growers, as the tolerance for mould is much lower than for poor colour.

Figure 4. Tweet from a well-known grower who had chickpeas penalised after misclassification of mosaic seeds as 'mould'. The tolerance for mould is much lower than for poor colour

Growers told us in the survey that they wanted:

1. to know how to prevent seed defects (and what causes the defects),
2. new testing methods at receival sites (fewer visual tests and more measurements), and
3. improved training for delivery site staff and better identification of seed defects.

So, what exactly do seed markings look like? Images of the two main seed markings are shown in Figure 5.

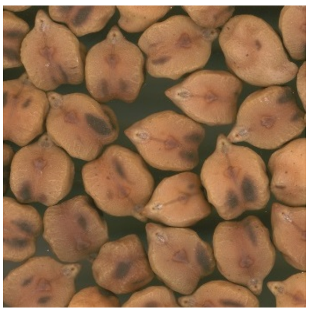		
Blotch/tiger stripe (mild)	*Blotch/tiger stripe (heavy)*	*Mosaic*

Figure 5. Seed marking types examined in this project: blotch/tiger stripe and mosaic markings

These seed markings are not related to disease, mould or shrivelled seeds. There is no mark on the underlying cotyledons and the mark only affects the seed coat.

The 2018/19 Australian Pulse Trading Standards state that "tiger striping" is not classified as defective, however they can look similar to diseased or damaged seeds. In addition, they do detract from the clean and uniform appearance preferred by our export customers, so may be discriminated against in the market.

Mosaic markings are classified as defective, but generally occur at a lower percentage within most harvested crops. Images of weather damage are shown in Figures 6 and 7.

Hail damage (bruising)	*Discolouration/staining from weather damage*	*Sprouted (radicle tip just starting to emerge)*	*Fully sprouted*

Figure 6. Weather damage seed defects are classified as defective: Hail damage, discolouration/staining and sprouting.

Weather damaged seed will also be more prone to cracked seed coats and splitting of seed during harvest and subsequent handling.

Split seeds not only reduce yield but are also classified as defective in the 2018/19 Australian Pulse Trading Standards.

Figure 7. Cracked seed coats and split seeds are more likely to result from weather damaged grain

Summary of results – blotch/tiger stripe seed markings

- The blotch/tiger stripe seed marking defect is under strong genetic control. PBA PistolⒹ and SonaliⒹ were found to be the most susceptible varieties. The worst sample evaluated during the 4 years had 47% of its seeds affected, however <10% is more typical
- The blotch/tiger stripe seed markings can begin to appear on seeds when they are large and green just prior to physiological maturity. Surprisingly, one marked seed and one unmarked seed can reside within a single pod
- Planting seeds with blotch/tiger stripe seed markings is likely to result in an increased proportion of blotch/tiger striped seeds in the subsequent harvest, possibly due to an epigenetic effect. So, it is recommended that marked seeds are not kept for sowing

- It was difficult to determine the exact environmental factors involved in the expression of the blotch/tiger stripe seed markings due to the complex nature of the environment over many different sites, sowing dates and seasons. However,
    - The defect does appear to be more prevalent and severe in the northern regions compared to southern Australia; we hypothesise due to increased UV priming of biochemical pathways during plant growth
    - There is evidence from several different trials suggesting that moisture (rainfall or irrigation) with cooler days during grain filling could promote the defect
    - Further research would be required to confirm these new theories
- In most, but not all sowing date trials, susceptible genotypes expressed higher levels of blotch/tiger stripe markings when sown earlier, than at later sowing dates. Hence, avoiding early sowing dates may minimise the risk of blotch/tiger stripe incidence and severity
- This type of seed marking is a good candidate for molecular marker development. A robust molecular marker will allow the PBA chickpea program to screen breeding material at an early generation stage (where manual seed defect evaluation would be ineffective due to the small amount of seed available).

Summary of results – mosaic seed markings

- Mosaic markings, whilst are often visually more obvious than some other seed defects, occur at a low percentage (<4% of seeds affected) within most harvested crops
- These markings are under more environmental influence, while still being more prevalent in some genotypes than others. There are large G x E interactions.
- Sowing mosaic seeds led to:
    - Increased mosaic defect in harvested grain from a susceptible breeding line in all 3 years, but not for PBA Pistol⦇ or Howzat⦇
    - Higher percentages of blotch/tiger stripe marked seeds in harvested grain in 2 of the 3 years for PBA Pistol⦇, Howzat⦇ and the susceptible breeding line
    - Further research is required to confirm whether the blotch/tiger stripe defect and the mosaic defect are independent or genetically related defects, as we have evidence from different experimental paths suggesting both theories.

Summary of results – weather damaged crops

Delaying harvest can cause major losses, such as:

- Loss of grain yield through;
    - Losses due to pod drop (abscission); more likely when plants become too dry and brittle or suffer from weather damage
    - Losses due to pod splitting (dehiscent pods and shattering) where seeds fall to the ground (Figure 4)
    - Losses due to increased seed coat cracking and seed splitting
    - Lower grain weight due to excessive moisture loss
    - Reduction in grain weight occurs in weather damaged grain due to enzymes breaking down seed components to provide energy for sprouting.

Figure 8. Examples of pod splitting (dehiscent pods) and pod shattering resulting in seed loss

- Loss of quality including;
    - Reduction in grain weight and increased brittleness of the seeds as enzymes degrade storage components for energy
    - Higher percentage of split seeds – classified as defective
    - Visually sprouted seeds – classified as defective
    - Darkening/staining of seeds, especially where pods were in contact with soil due to lodging or where pod splitting has allowed water entry – classified as defective
    - Hail damaged seeds – classified as defective

Up to 44% yield loss was recorded in our harvest delay trials, and this does not consider the additional financial impact of defective seeds reducing price/tonne or possible load rejections at delivery.

Even a single rain event on a mature and dry chickpea crop has the ability to reduce seed weight by a small but significant amount, the financial impact being magnified over large areas.

Summary of results – weather damaged seeds

- Germination rate and vigour of planting seed is reduced by weathering; visually sprouted seeds are not viable. Do not retain weather damaged seed for planting
- Even mildly weather damaged seeds (those where sprouting is not yet visible) have altered quality, functionality and food processing characteristics compared to “sound” seeds
- Objective methods were developed to detect levels of deleterious weather damage in pulse seeds. These now need to be validated in a wider range of varieties and environments.

How to maximise yield and reduce the likelihood of weather damaged, stained and sprouted defective seed

- Time harvest (and desiccation, if used) to avoid rainfall on mature/dry crops as much as possible
- Harvest when seed is at 14% moisture content. This will maximise yield and minimise both seed loss and risk of price penalties from quality loss
- Ensure you optimise your combine harvester settings for every individual crop to capture the best quality seed and to remove defective material (such as immature green seeds, small shrivelled seeds and split seeds). Test it in the crop and adjust. This simple step can negate the need for seed cleaning prior to delivery
- Avoid harvesting when fresh green seeds are present, as this increases the likelihood of mould developing during storage. Desiccation prior to harvest will help reduce this potential issue by drying any new green growth prior to harvest. However, desiccation using glyphosate is not recommended for crops that are to be kept for seed, as glyphosate treatments may reduce seed germination.
- If weather damage occurs, do not retain this seed for planting as it will have lower germination and viability. Always test seed prior to planting.

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

WEEDS CONCURRENT SESSION

Green on green camera spraying - a game changer on our doorstep?

Guillaume Jourdain, Bilberry

Key words

green on green, camera spraying, spot spraying, technology

Take home messages

- Green on green camera technologies is now used on farms. This will lead to important financial benefits for growers but will also have impacts on farm management
- Growers need to understand the benefits but also the limitations of these new technologies. This is only way it will bring real benefits.

Overview of vision systems for spraying and identifying weeds

In this paper, we will only focus on systems embedded on sprayers or spraying equipment, and thus we will not talk about drones. Drones are a very interesting technology, however there are current limitations on their convenience of use such as regulation, the need for a pilot, necessity of good weather conditions (no wind or rain), and ground resolution is often not as high as with embedded sensors.

Systems on the market and their limitations

Two optical camera systems to spray weeds have been on the market for several years, WEEDit and WeedSeeker. These systems are now commonly used in Australia for green on brown applications. Previous analysis of these can be found in a GRDC Update paper:

https://grdc.com.au/__data/assets/pdf_file/0015/117231/pa-in-practice-ii-incrop.pdf.pdf

and here is a link to a factsheet from the Australian Society of Precision Agriculture, SPAA:

https://spaa.com.au/pdf/456_9056_SPAA_fact_sheet_(Weed_Sensing)_A4.pdf

Summary of key facts for these sensors

- Active sensors – chlorophyll sensing
- High number of sensors (one per meter for WEEDit and one per nozzle for WeedSeeker)
- Significant reduction in chemical usage
- High cost ($4000 / meter)
- Day and night usage
- Limited speed (15 km/h for WeedSeeker and 20 km/h for WEEDit)
- Boom stability is important, so wheels are usually added on the booms
- Calibration is needed on the WeedSeeker, while the WEEDit has an autocalibration mode
- Both technologies cannot work on green on green applications.

Systems under development

Many companies, both start-ups, large corporations and universities are now developing systems with green on green capability. The technology used is similar: artificial intelligence with cameras (sometimes RGB/colour cameras, sometimes hyperspectral cameras).

Examples of companies working on green on green technologies:

- Bilberry, a French AI based start-up that specialises in cameras for recognising weeds (more below)
- Blue River Technology, acquired by John Deere in September 2017 for more than $300M, developing a See and Spray technology - a spraying tool with smart cameras, trailed by a tractor, that can spray weeds very accurately at about 10 km/h
- Ecorobotix, a Swiss based start-up developing an autonomous solar robot that kills weeds. They are also developing the camera technology
- AgroIntelli, a Danish company developing an autonomous robot to replace tractors, that will also include spraying capacity. They are also developing the camera technology
- Bosch, the German company, that is more and more involved in agriculture has launched a project call Bonirob a couple of years ago, a robot that includes smart cameras to kill weeds in a more efficient way

Figure 1. From top left to bottom right: Agrointelli robot, Blue River Technology tool, Bosch robot and Ecorobotix robot.

Artificial intelligence to detect weeds

Past research

Recognising weeds within crops is a topic that has been interesting companies and researchers for a very long time. First patents on this topic are from the 1990s. The main approach was to differentiate weeds from crops thanks to their colour and shape. Through mathematical formulas, a range of colours and a range of shapes for each weed (we can call these algorithms conventional algorithms) would be created.

To give a very simplistic example, one could define, through experimentation, that radish colour would be within a specific green range, as shown on the graph below.

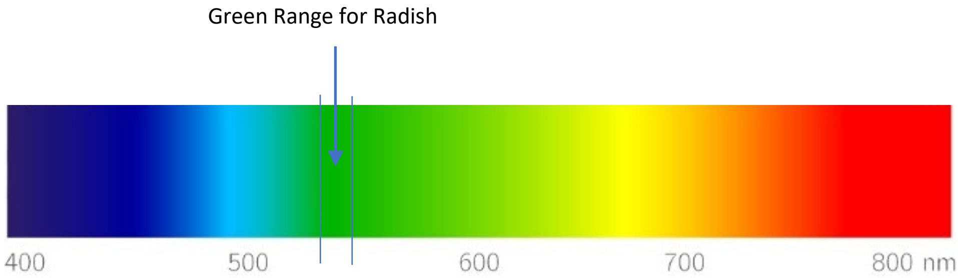

Figure 2. Simplistic example of conventional algorithms mechanism

This way of working gave good results in the lab, because they have excellent conditions, that can be replicated easily: the light is constant and homogeneous, there is no wind, all crops and weeds are from the same variety and are not stressed etc. Since all these conditions are very controlled, it is often true that you can differentiate two types of weeds / crops thanks to colour and shape.

However, paddock conditions are completely different. Indeed, the sun can be high or low, in your back or in your eyes, there can be clouds, there can be shadows from the tractor/sprayer cabin or from the spraying boom, crops can be wet in the morning (which would create sun reflection), soils always have different colours …

It became clear that conventional algorithms could not work in field conditions.

Artificial intelligence as a game changer

Artificial intelligence and especially deep learning is another way of working on images to recognise different objects. It is now the most widely used technology for computer vision when it comes to complex images (recognising weeds within crops, or on bare soil, is definitely a complex image). Complex images could be defined as images that show high variability between the same category of object (an object being a cat, a dog, a human, or a weed).

Deep learning is part of the family of machine learning and is inspired by the way the human brain works (deep learning often uses deep neural networks architecture). The learning part can be either supervised or unsupervised. We will discuss supervised learning and how to apply it to weed recognition more in depth below.

Below is an example of different kind of deep learning architectures applied to computer vision.

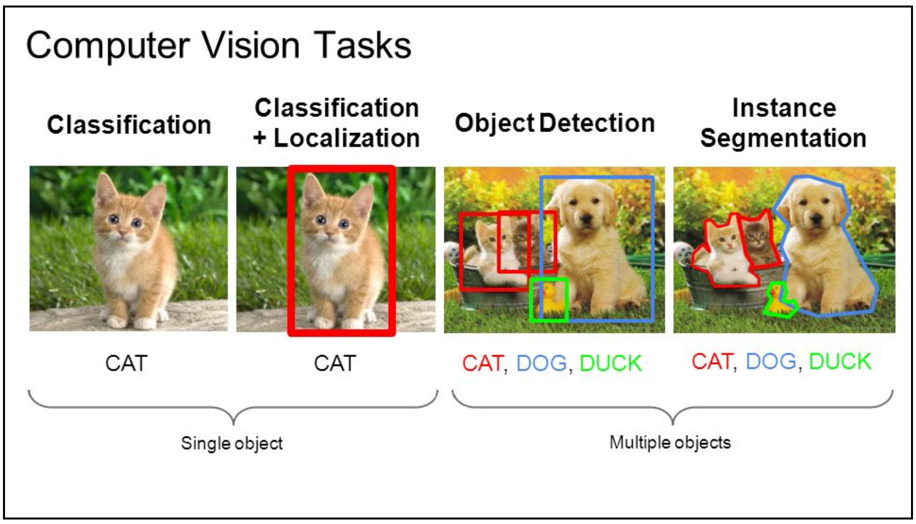

Figure 3. Different deep learning architectures

Deep learning is now possible on embedded systems

Research on deep learning also started in the 90s, however it only became widely used in the 2010s. There are 3 key components needed to develop deep learning applications, and these 3 key components have only been available for very few years. These are:

1. Plenty of data
2. High computing power
3. Powerful algorithms

Data generation has grown at an incredible speed since the early 2000s and the fast development of internet. We now have access to data about almost everything, in very large quantity.

Computing power is needed twice for deep learning: firstly during algorithm training and secondly during the "inference", which is the moment the algorithm is being used. Deep learning is run on GPUs (Graphics Processing Unit), and these GPUs became really powerful with the development of autonomous vehicles.

Since more powerful processing units were available, more powerful algorithms were also developed by engineers.

The 3 conditions above are now met and so deep learning is therefore applicable to many situations and is especially relevant for farming.

Supervised process for deep learning

Here is the classical process to develop a deep learning algorithm with the supervised method:

- Define algorithm usage and objectives
    - Example with weed recognition (WR): Recognize flowering radish in wheat with > 90% accuracy
- Gather data
    - WR: Take pictures in the fields of flowering wild radish in wheat
- Sort and label data
    - WR: On each picture, indicate what is wheat, what is wild radish etc.
    - WR: Also separate all images into 2 sets, training set and testing set. Training set is only used for training, and testing set is only used for testing (images cannot be on both sets)
- Train algorithm
    - WR: Show the training set (thousands of times) to the algorithm so that it can learn patterns
- Test algorithm
    - WR: Show the test set (one time) to the algorithm to compare the results of the algorithm with the reality
    - WR: Once happy with the results of the algorithms, go into the paddock to test (paddock testing is the most crucial part of the process)
        - Note: It NEVER works first time …
- Repeat until you reach your objectives

Two of the most important steps are data gathering and paddock testing (these 2 steps happen in the field). What is especially complex and important about data gathering is to be able to capture the diversity of situations. Below is an example of different situations, where the aim is to spray any live weed on bare soil.

Figure 4. Different situations for summer spraying in Australia (sandy soils, high stubble, no stubble)

Research and results at Bilberry

Bilberry presentation

Bilberry was founded in January 2016 by three French engineers, with the idea to use artificial intelligence to help solve problems in agriculture. The main product of Bilberry is now embedded cameras on sprayers. They scan the paddocks to recognise the weeds and then control the spraying in real time to spray only on weeds and not the whole paddock. Bilberry also develops cameras that recognize weeds on rail tracks. The technology is similar, with just a higher speed (60 km/h) and day and night applications.

The biggest focus to develop this product is now Australia, with several sprayers already equipped with Bilberry cameras. One of the reasons of this focus is the huge interest among Australian growers and agronomists towards green on green spot spraying.

On the booms of the sprayer, there is one camera every 3 meters and then computing modules (to process the data) and switches (to distribute power and data to each camera). In the cabin, there is one screen to control the system.

Figure 5. Bilberry cameras on an Agrifac 48 metre self-propelled sprayer

Results achieved until now

Three algorithms are now validated and usable directly by growers in the field (two are more focused on Australian growers):

- Weeds on bare soil detection (using AI, but same application as WEEDit or WeedSeeker)
- Rumex (dock weed) in grasslands
- Wild radish in wheat (especially when they are flowering) (link to a video for wild radish spraying, watch in HQ to see the sprays better: https://drive.google.com/file/d/1vUfCC7hN77VI2Jp2S6XDEFr8CJ_pU7LL/view

It is important to note that large chemical savings are made with the cameras, however it is also a very interesting tool to fight resistant weeds, potentially enabling the use of products that cannot be currently used in crop due to either cost or crop impact.

Below are some pictures taken by our cameras and what is seen by the algorithm.

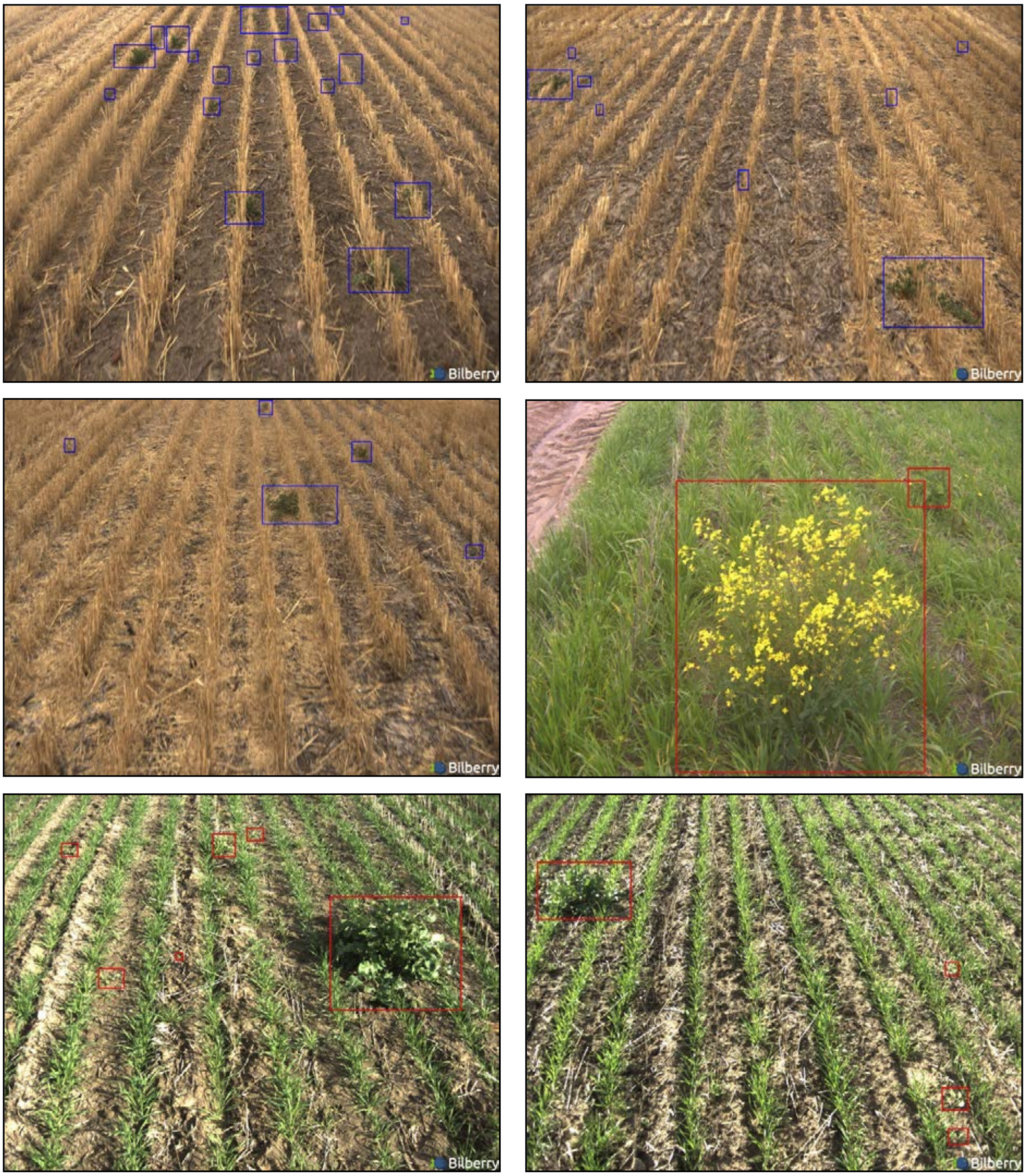

Figure 6. Weed detection on bare soil (3 first pictures) and wild radish detection in wheat (3 last pictures) - Images taken from Bilberry cameras - results in real time

Main usage conditions of the Bilberry camera

The cameras are used at up to 25 km/h speed and can be used on wide booms (widest boom used is 49 metres, but could be more if needed). This means there is a very high capacity with the sprayer equipped with cameras.

Theoretical camera capacity = 25 km/h * 48 meters = 120 ha/hour

In real spraying conditions, capacity is of course lower, since the speed is not always 25 km/h and the sprayers need to be refilled.

Summer spraying in Australia (New South Wales example)

One Agrifac 48 metre boom is equipped with cameras in a farm in New South Wales. Before the cameras were used by the grower and his team, a comparative test was made with current camera sprayer technology. It was then decided to use Bilberry cameras as much as possible on the farm.

Figure 7. Test field after spraying with dye

Thus, the cameras have been used since the beginning of the 2018-2019 summer spraying season, directly by the grower and his team. Over a 3 weeks period, here are the most important figures:

Table 1. Figures from the 2018-2019 summer spraying season

Total area sprayed	Ha / day	Ha / hour	Chemical savings
6199 ha	413 ha	75 ha	93.5%

The carrier volume used was generally set at 150 litres / ha.

It is very important to note that the chemical savings are directly linked to the extent of weed infestation in the paddocks. A paddock with high weed infestation will get little savings whereas a paddock with low weed infestation will get high savings.

Spraying dock weeds in grasslands (Netherlands)

In the Netherlands, a 36 meters Agrifac boom is equipped with Bilberry cameras and uses an algorithm to spray dock weeds on grasslands. The same testing process as described earlier was used to ensure the algorithm was working properly.

Once the grower validated that the algorithm was working, it was used during the whole spraying season. About 500 ha were sprayed during the season, and the average chemical savings were above 90 %. The cost of the chemical is about 50€/ha for this specific application, which means 45€ chemical savings / ha with the cameras.

Here is a link to see the machine spraying dock weed (to see the sprays happening, play the video in high quality): https://drive.google.com/file/d/1EF1qqIRjzj0pVCYf67cSBlHvh47xDHKz/view

Future machine capabilities

Obviously, the biggest focus is to develop new weeding applications (which means new algorithms) to be able to use the cameras more often.

Other important development focuses we have right now include:

- Working at night (already working on rail tracks, but not on sprayers)
- Working at 30 km/h
- Delivering a weed map after a spray run (already working on rail tracks, but not on sprayers), to compare with the application map
- New weed applications

In the future, we believe that every time the sprayer goes in the field, the cameras should be able to bring value to the grower. Sometimes it would mean direct application (for instance for weed spraying) and other times it would mean building maps (maps to give growth stage throughout the paddock or disease status or anything that could help growers and agronomists do their job).

We will also look into algorithms for modulating nitrogen and fungicide applications.

In a completely opposite direction, spraying with cameras will generate a lot of data. The data will be very precise (because the data is saved with the GPS coordinates) and will give agronomists and farmers new tools to improve their overall farm management strategy.

Concrete implications for growers

Cameras that detect green on green bring multiple new possibilities for growers. The most important and immediate consequences are new possibilities to fight resistant weeds and impressive chemical savings and reduced herbicide environmental load. The potential to reduce the area of crop sprayed with in-crop selective herbicides, may also assist by reducing stress on stress interactions that are sometimes associated with in-crop herbicide use.

It is also very important to note that, as for any new technologies, it will only work well if growers get to know the technology, how it works, its limitations and possibilities. The first and most important thing for growers will be to be very attentive to the results of each spraying: first, are all weeds killed, and second, how much did I save? The cameras might work perfectly on 90% of their paddocks, and for some reason not perform as well on 10%. This can definitely be corrected within the algorithms (see above how to train an algorithm), but to correct an algorithm the designer of the cameras must be made aware there is an issue.

Acknowledgements

Presenting this green on green technology has been possible thanks to the interest and passion of the GRDC Update coordinators and the support of the GRDC to bring me to Australia to present at the Updates. I would also like to express my thanks to the first growers that believed in Bilberry in Australia.

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Impact of chaff lining and chaff tramlining on survival of weed seeds

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Key words

chaff lining, chaff tramlining, harvest weed seed control, annual ryegrass, brome grass, wild oats, turnip weed, common sowthistle

GRDC code

US00084 (innovative crop weed control for northern region cropping systems)

Take home messages

- There is no evidence that weed seeds deposited in chaff lines and chaff tramlines will decay more rapidly than if deposited outside of concentrated chaff
- A proportion of winter weed seeds buried in tramlines and chaff lines were still capable of germination in the following autumn and could compete with winter crops
- Tramlines and chaff lines should be monitored and emergence controlled if necessary
- The key reason to use chaff lining or chaff tramlining is to concentrate weed seeds into a narrow area for targeted, more efficient control of weed emergence

Background

Herbicide resistance is a major concern for northern region crop production due to the increasing frequency of resistance in key weeds. Non-herbicide weed management alternatives are needed to delay the spread and onset of further herbicide resistance (Walsh *et al.,* 2013). One such alternative is harvest weed seed control (HWSC). Harvest weed seed control (HWSC) refers to a suite of management practices - all of which target the seed of weeds present at harvest and borne at harvest height (typically around 15cm above ground height, depending on header set-up).

Current HWSC systems include narrow windrow burning, chaff tramlining/chaff lining, chaff carts, bale direct and seed destruction (Walsh *et al.* 2013). Chaff lining and chaff tramlining have potential for wide-spread adoption in northern Australia owing to their low cost and ease-of-implementation relative to some other HWSC practices. Chaff tramlining is the practice of concentrating the weed seed bearing chaff material on dedicated tramlines in controlled traffic farming (CTF) systems, typically using a chaff deck to deposit chaff into 2 lines (one per wheel track). Chaff lining is a similar concept, where the chaff material is concentrated using a chute into a single narrow row between stubble rows and directly behind the harvester (i.e. not specifically onto the tramlines).

Aims

Anecdotal reports suggest weed seeds decay rapidly when deposited in chaff tramlines/chaff lines, but so far this remains scientifically unsubstantiated. The experiments described in this study were designed to:

- Investigate weed seed survival over time under barley chaff in tramlines created using Draper and Shelbourne header fronts, compared to weed seeds outside of tramlines.

- Evaluate the influence of different types of chaff on weed seed survival in chaff lines, compared to weed seeds outside of chaff lines.

Method

Field experiments were set up at Wagga Wagga in NSW and Irongate in southern Queensland. For the experiment in Wagga Wagga, seeds of annual ryegrass (ARG), brome grass, and wild oats were placed in bags under chaff lines of wheat, barley, and canola. For the control treatment, bags were placed next to the chaff line. For each crop type there were 4 replicates for each weed species. Bags of weed seeds were put out in December 2017 and removed in April 2018. Seeds recovered from the bags were used in a germination test lasting 21 days. The number of germinated and filled (i.e. embryo present) seeds was used to calculate weed seed survival as a percentage of the seed initially placed into each bag (100 seeds per species per bag).

For the study at Irongate, near Mount Tyson in Queensland's eastern Darling Downs, two field experiments were set up following the 2017 winter crop harvest. Chaff was directed onto tramlines during barley harvest using Draper (conventional) and Shelbourne (stripper) fronts. Bags containing seeds of annual ryegrass, wild oats, turnip weed, and common sowthistle were placed under the chaff tramlines. For the control treatment, bags containing weed seeds were placed outside of chaff tramlines, in a nearby part of the paddock. For each trial (Shelbourne and Draper) and each sampling time there were 3 or 6 replications (for the control and tramline treatments, respectively) for each of the four weed species tested. The bags containing weed seeds were originally placed in the field in November 2017 and were removed on two occasions; in April 2018 and September 2018. Seeds recovered from the bags were used in a germination test lasting 28 days, where the number of germinated and filled (i.e. embryo present) seeds was used to calculate weed seed survival as a percentage of the seed initially placed into each bag. For common sowthistle, germination alone was used to calculate seed survival. The total seed initially placed in each bag was 133/bag (ARG), 106/bag (wild oats), 200/bag (turnip weed), and 250/bag (sowthistle). The number of seeds used for each species differed to account for variation in initial seed viability among the species, so that there would be 100 viable seeds per packet.

Results and discussion

Results from the barley tramlines at Wagga Wagga showed significant differences in seed survival between each of the 3 weed species after 5 months in the field (annual ryegrass 95%, Brome 84%, wild oats 23%, l.s.d.=7.1%), but there was no significant difference between the control and the chaff line treatments. In canola (Figure 1), there was a significant interaction between weed species and treatment (i.e. chaff line and control). Brome had significantly higher seed survival under the chaff lines compared to the control treatment (seed bags not under the chaff line). The reverse occurred in annual ryegrass, where seed survival was significantly higher in the control treatment. Seed survival of wild oats did not differ significantly between the chaff line and control.

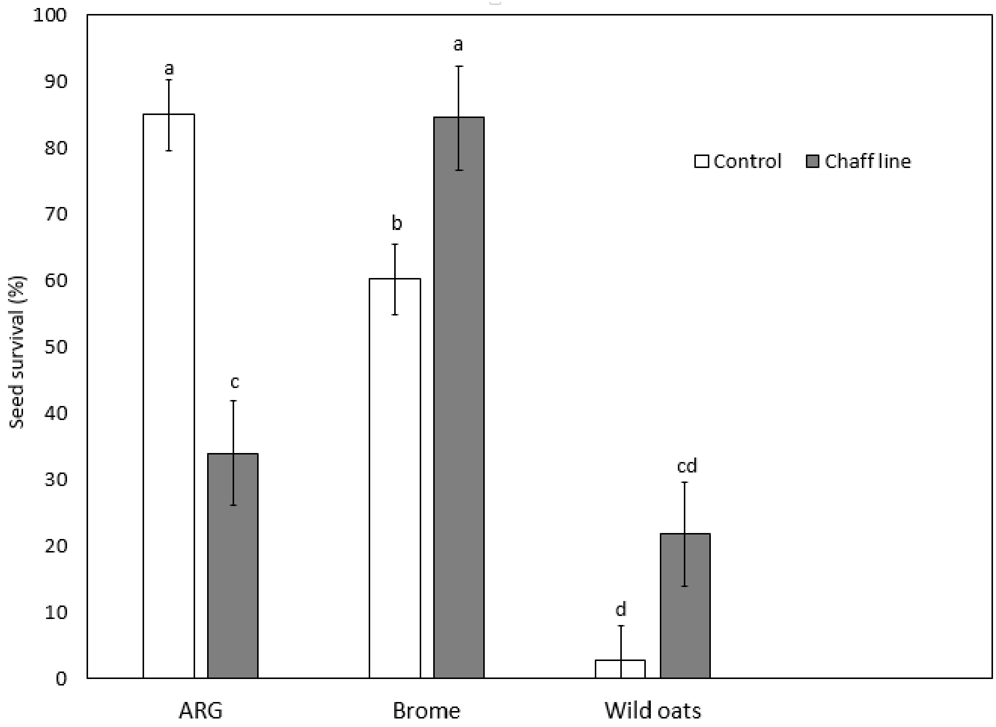

Figure 1. Survival of weed seeds (% of initial viable seed) placed under a canola chaff line compared with the control treatment (non-chaff line) at Wagga Wagga, NSW. The l.s.d is indicated using the error bars. Predictions with the same letter are not significantly different

In wheat (Figure 2), there was again a significant interaction between species and location (i.e. near or under the chaff line). Again, there was significantly higher seed survival for brome in the chaff line treatment compared with the control treatment, but there was no significant difference between chaff line and control for the other 2 species.

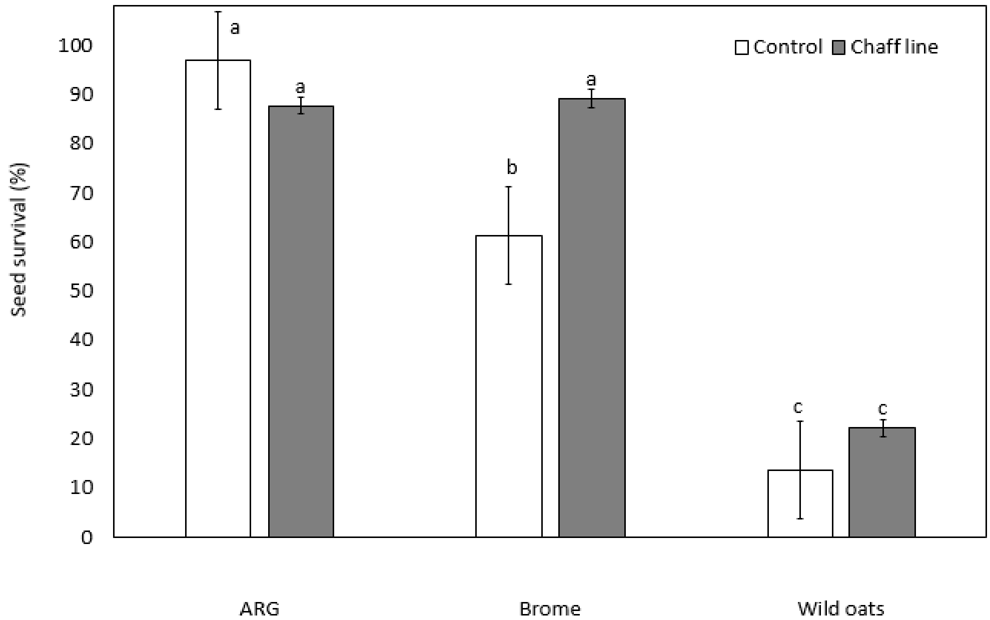

Figure 2. Survival of weed seeds (% of initial viable seed) placed under a wheat chaff line compared with the control treatment (non-chaff line) at Wagga Wagga, NSW. The l.s.d is indicated using the error bars. Predictions with the same letter are not significantly different.

The data from the Draper tramlining study at Irongate (Figure 3) showed a significantly higher average survival for seeds placed under the tramlines (18.4%) compared to the control (8.9%). There was a significant 2-way interaction between species and time, because the change in seed survivorship over time differed among species. In an analysis of species x time (combined for chaff lining and control treatments), seed survival of turnip weed did not change significantly between sampling times (7% April 2018 and 6% September 2018), but there was a significant decline in seed survival for annual ryegrass (29% April 2018 and 6% September 2018) and common sowthistle (7% April 2018 and 0.8% September 2018), and a highly significant decline in survival of wild oats (87% April 2018 and 0.8% September 2018).

The data from the Shelbourne tramlining study at Irongate (Figure 4) had a significant 3-way interaction between species and time. When analysed separately for each species, seed survival declined significantly over time in annual ryegrass (37% April 2018 and 11% September 2018) and common sowthistle (19% April 2018 and 3% September 2018), and in wild oats the decline approached significance (Fprob=0.063), but there was little remaining wild oat seed at both time periods (6% April 2018 and 0.3% September 2018). Seed bags containing wild oats appeared to have been predated by mice. For turnip weed, there was a 2-way interaction of tramline treatment and time. Seed survival declined dramatically for turnip weed in the control treatment (39% April 2018 and 7% September 2018), but there was no significant difference in the tramlining treatment (17% April 2018 and 22% September 2018). The slight but non-significant increase in seed survival in the September sampling is likely the result of reduced germination in the first sampling period, potentially due to seed dormancy. The suggestion is that decay of turnip weed is more rapid in a non-tramline environment and could have contributed to the overall lower seed survival across weed species in the control environment compared with Draper tramlines.

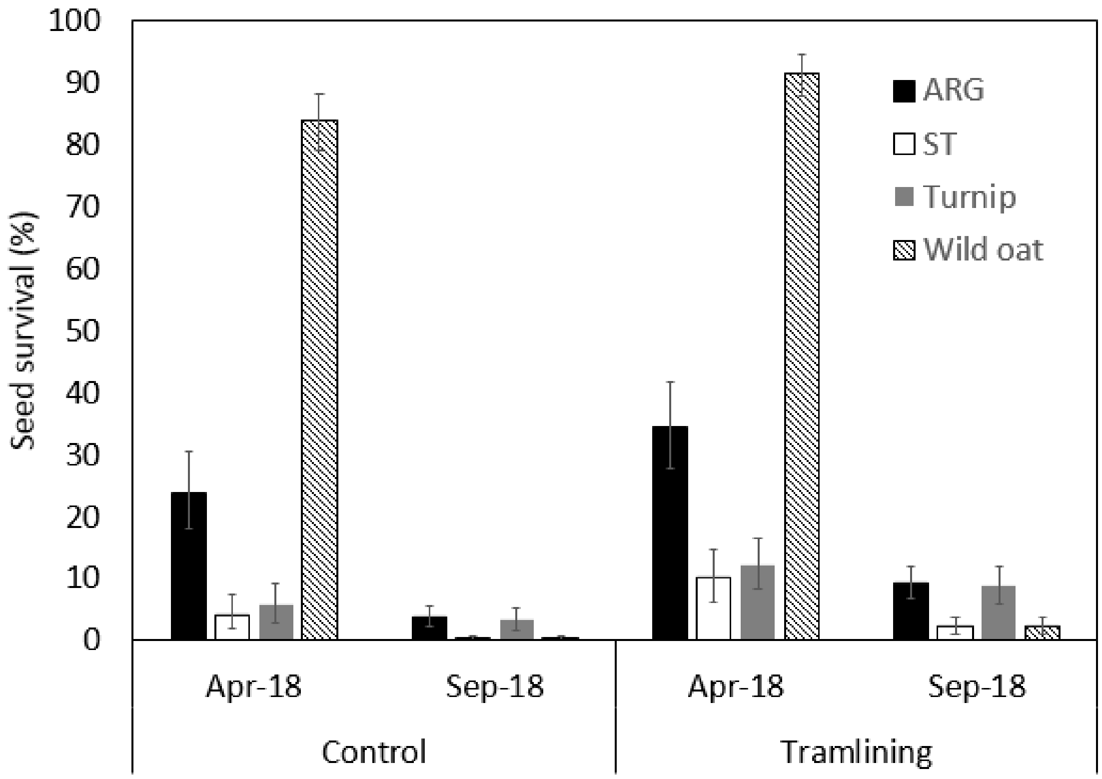

Figure 3. Survival of weed seeds over time in tramline and control (non-tramline) treatments in the Draper barley trial at Irongate in QLD. The error bars represent the back-transformed standard errors of the means. There was a significant main effect of treatment and interaction between species and time (these effects were fitted to obtain the predictions).

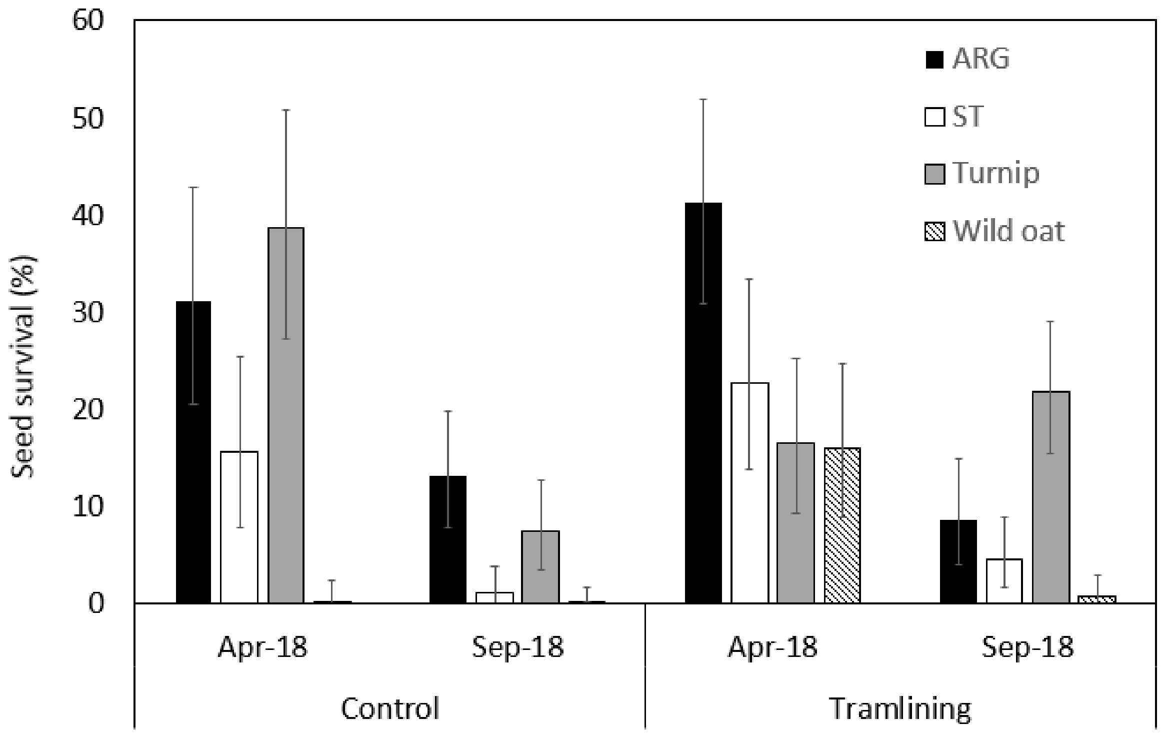

Figure 4. Survival of weed seeds over time in tramline and control (non-tramline) treatments in the Shelbourne barley trial at Irongate in QLD. The error bars represent the back-transformed standard errors of the means. There was a significant interaction between treatment, species and time.

The above results indicate that weed seed survival under chaff lines and chaff lines is influenced by both chaff type and weed species. The differences between the Draper and the Shelbourne study in barley indicate that chaff volume could also play a role, with stripper fronts like Shelbourne known to have less chaff output (Broster *et al.,* 2018). However, the lack of consistent trends in the data point towards the involvement of other factors beyond those measured or controlled for in these trials. It is clear from the scientific literature that factors influencing weed seed persistence are many and varied. Some weeds have transient seed banks, with seeds that germinate within a year of initial dispersal, while others can form persistent seed banks with seeds that remain in the soil for longer than a year. Losses of seed from the seed bank result from genetically controlled physiological responses to environmental cues including light, temperature, water, oxygen tension and chemical stimulants; as well as interaction with animals and pathogens leading to death (Simpson *et al*., 2012).

Conclusions

It is evident that weed seeds of key northern species can remain viable in chaff lines and chaff tramlines until the following autumn, which is the key period of recruitment for winter species. Weeds that emerge at this time have the potential to compete with winter crops.

It is important to monitor chaff lines and chaff tramlines, so that weed seedlings can be controlled at an early growth stage, while they are relatively easier to control and before they substantially impact the crop.

The key benefit of using chaff lining and chaff tramlining is not to promote decay of weed seeds, but to concentrate weed seeds captured during harvest into one or two lines per header pass, rather than spreading the weeds throughout the paddock. The advantages are that weed seedlings are easily visible in chaff lines and chaff tramlines, and emerging seedlings can be monitored and controlled in a targeted manner (e.g. using high labelled rates and a shielded sprayer) with potential gains in weed management efficacy.

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.

Our sincere appreciation to the farmers who have hosted trials on their properties. Your commitment to furthering this type of research is critical in our war against weeds.

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Residual herbicides and sowthistle - length of residual and efficacy. Trials in CQ and Darling Downs

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Key words

residual herbicides, herbicide resistance, common sowthistle

GRDC code

UQ00062

Take home messages

- Residual herbicides can offer an effective, alternative chemical approach for the fallow control of common sowthistle
- Residual herbicides provide a range of different herbicide modes of action that when used in rotation can reduce the risk for herbicide resistance
- The efficacy of residual herbicides can be different in different environments. Therefore, residual herbicides should be applied in combination with other effective weed control tactics as part of an integrated approach
- Terbyne® Xtreme® and Valor® provided the best residual control of common sowthistle as stand-alone residual herbicides and as mix partners with 'grass active' herbicides
- Herbicide mixtures provided improved control of sowthistle and are likely to provide wider spectrum control of a range of weed species
- The presence of crop residue resulted in an increased emergence of common sowthistle but did not influence the efficacy of the herbicides
- When using residual herbicides, be mindful of plant back restrictions for subsequent susceptible crop species. In dry years, residual herbicides can persist longer.

Introduction

Herbicide resistant weeds are becoming common place in farming systems throughout Australia. One such weed is common sowthistle (*Sonchus oleraceus*). In the subtropical cropping region of Queensland and northern New South Wales, herbicide resistance to fallow applied, knockdown herbicides, especially glyphosate, is making reliable control of key summer and winter fallow weeds difficult.

The first population of glyphosate resistant common sowthistle in Australia was confirmed in 2014, in a population from the Liverpool Plains, NSW (Heap, 2019). A recent (2016/17) collection of sowthistle populations from throughout Queensland and NSW is currently being evaluated for susceptibility to glyphosate. Results to date have shown that out of 154 populations tested, 26 have been confirmed resistant to glyphosate (≥20% survival) while another 17 have been identified as developing resistance (11-19% survival). The identified resistant populations are distributed throughout the northern cropping region (Figure 1). A further 59 populations are yet to be tested.

In addition to glyphosate resistance, there are sowthistle populations with resistance to chlorsulfuron (Group B). Also, poor control of sowthistle is achieved with the commonly applied fallow herbicide mixture of glyphosate + 2,4-D, due to antagonism.

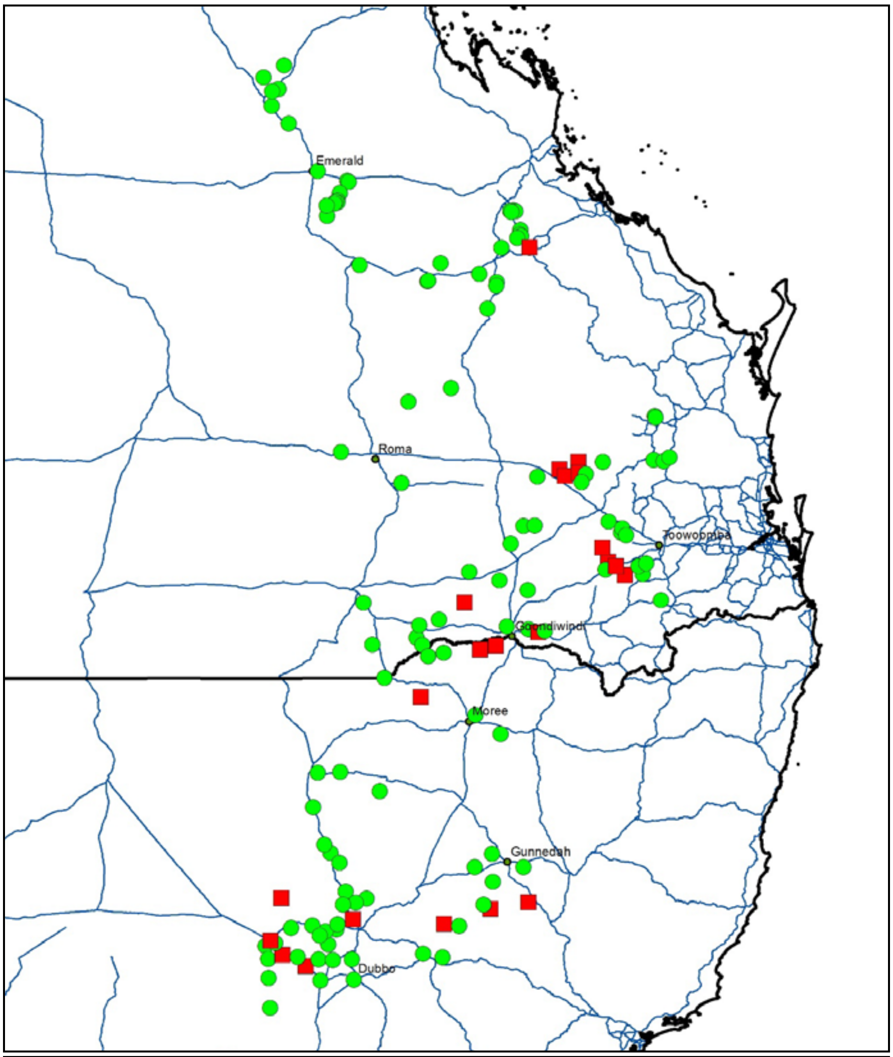

Figure 1. Map of glyphosate resistant (squares) and susceptible (dots) sowthistle (*Sonchus oleraceus*) populations across the northern grain cropping region.

Herbicide resistance in sowthistle has been caused by an over-reliance on the same herbicide and herbicide modes of action. Herbicide resistance is best managed and prevented by using a diverse range of weed management tactics in combination. Such an integrated approach may include both chemical and non-chemical weed management tactics.

Alternative tactics for sowthistle control are required. This includes examining the impact of non-chemical approaches such as targeted tillage, growing a competitive crop and cover cropping. However, there are also some potential herbicide-based options for effective fallow weed control which when used in combination with non-chemical approaches could provide effective control of sowthistle.

Residual (pre-emergent) herbicides offer an alternative to knockdown chemistries and are often able to provide longer term weed control. However, the efficacy of residual herbicides is influenced by a wide range of external and environmental factors including water run-off, volatilisation and decomposition (Figure 2). These factors will impact on the persistence and availability of residual herbicides. As such, the reliability of residual herbicides can be variable. In addition, they can persist for a long time and cause damage and yield reduction in subsequent susceptible crops.

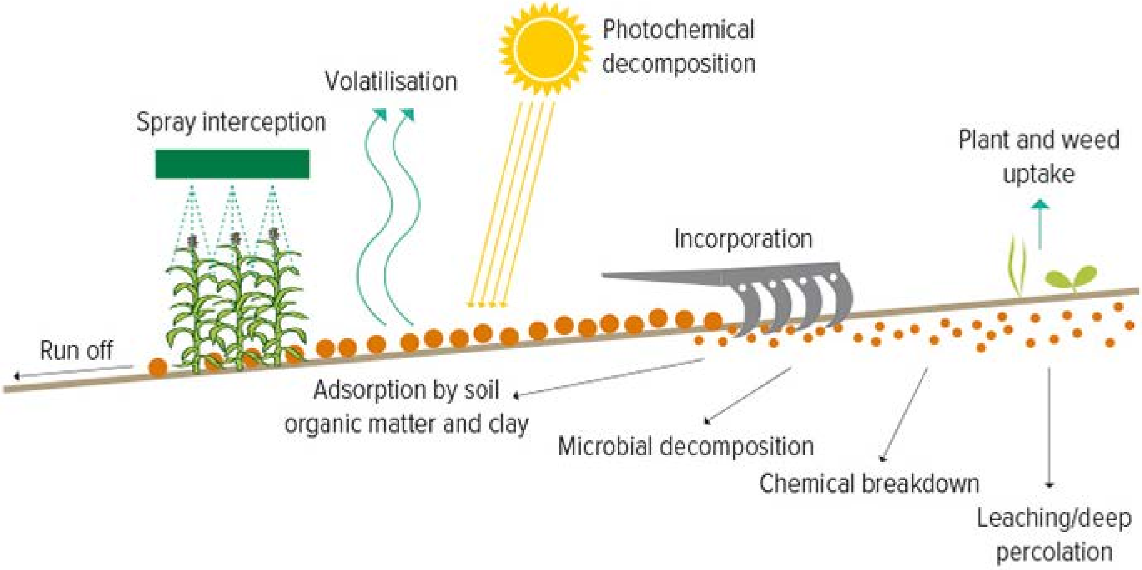

Figure 2. Factors that influence the persistence, availability and efficacy of residual herbicides *(Source: Congreve and Cameron, 2018)*

Recognising the increasing difficulty in effective fallow control of sowthistle and the potential role of residual herbicides, a series of field trials were established across Queensland to compare efficacy of residual herbicide treatments.

Materials and methods

A series of nine fallow field trials were conducted across grain growing regions of Queensland (south-west Queensland, Darling Downs and central Queensland) (Table 1) during summer/autumn 2016/17 to evaluate the efficacy and persistence of a range of residual herbicides for the control of sowthistle in fallow. Sites were selected that had a recent history of sowthistle infestation. Unfortunately, one site (Callandoon) did not have any sowthistle emerge, and two sites (Mt McLaren and Gindie 1) had populations too low to measure significant differences. The site at Jondaryan (1) also had additional treatments of crop residue retained and removed.

Residual herbicides were applied to small plots (ranging in size from 3 x 12m^2 to 6 x 20m^2) along with two unsprayed controls (Table 2). The herbicides were evaluated in combination with grass weed residual herbicides, as fallow grass weeds were also a target. Herbicides were applied using a quad-bike at 100L/ha of water with an air-inducted course (C) droplet size. Sowthistle emergence counts were made after each flush of emergence, following sufficient rain, and any emerged weeds were sprayed out with a knockdown herbicide so as to avoid double counting.

Table 1. Location of trial sites and other details.

Site location	Soil type	Treatments applied	Sowthistle (yes/no)
South-west Queensland			
Callandoon	Alluvial box flat	27 October 2016	No
Yagaburne	Brigalow	20 April 2017	Yes
Mungindi	Coolibah	3 March 2017	Yes
Darling Downs			
Jondaryan (1)	Black Vertosol	9 November 2016	Yes
Jondaryan (2)	Black Vertosol	27 April 2017	Yes
Jandowae	Grey Vertosol	23 November 2016	Yes
Central Queensland			
Mount McLaren	Open downs	3 May 2017	Low
Gindie (1)	Open downs	5 April 2017	Low
Gindie	Brigalow	27 April 2017	Yes

Table 2. Residual herbicide treatments applied at 6 Queensland sites for the control of common sowthistle. Please note: Not all products tested are registered for use in fallow or pre-sowing. Products not registered for use in fallow or pre-sowing have been expressed by their mode of action (MOA) group only. Please check labels for use patterns and only apply as per label.

Trt no	**Product/s**	**Grams active ingredient (g.a.i.)/L or kg**	**MOA**	**Rate (/ha)**	**Registered control of Grass (G), Broadleaf (B), Sowthistle (ST)**	**Number of sites** (out of 5 or 6 field trials) with significant reduction in sow thistle emergence.	**Indicative price ($/ha)**
1	Untreated control		-				
2	Flame® (imazapic)	240	B	200 mL	G, B	1/6	4
3	Terbyne® Xtreme® (terbuthylazine)	875	C	1.2 kg	B, ST	4/6	35
4	Group C triazine	900	C	3.3 kg	G, B, ST	1/6	26
5	Stomp® Xtra* (pendimethalin)	455	D	3.3 L	G, B, ST	0/6	53
6	Balance® (isoxaflutole)	750	H	100 g	G, B, ST	2/6	16
7	Dual® Gold (S-metolachlor)	960	K	2 L	G, B, ST	0/6	26
8	Valor® (flumioxazin)	500	G	280 g	G, B, ST	4/6	53
9	Flame® (imazapic) + Balance (isoxaflutole)	240 + 750	B + H	200 mL + 100 g		4/6	20
10	Terbyne® Xtreme® (Terbuthylazine + Flame® (Imazapic)	875 + 240	B + C	1.2 kg + 200 mL		5/6	39
11	Terbyne® Xtreme® (terbuthylazine + Stomp Xtra* (pendimethalin)	875 + 455	C + D	1.2 kg + 3.3 L		5/6	88
12	Group C (triazine) + Dual® Gold (S-metolachlor)	900 + 960	C + K	2 kg + 2 L		2/5	42
13	Valor® (flumioxazin) + Flame® (imazapic)	500 + 240	G + B	280 g + 200 mL		4/6	57
14	Stomp Xtra* (pendimethalin) + Balance (isoxaflutole)	455 + 750	D + H	3.3 L + 100 g		3/6	70
15	Flame® (imazapic) + Stomp Xtra* (pendimethalin)	240 + 455	B + D	200 mL + 3.3 L		3/6	57
16	Balance (isoxaflutole) + Dual® Gold (S-metolachlor)	750 + 960	H + K	100 g + 2 L		1/6	42
17	Terbyne® Xtreme® (terbuthylazine + Balance (isoxaflutole)	875 + 750	C + H	1.2 kg + 100 g		4/6	50
18	Flame® (imazapic) + Dual® Gold (S-metolachlor)	240 + 960	B + K	200 mL + 2L		3/6	30
19	Valor® (Flumioxazin) + Dual® Gold (S-metolachlor)	500 + 960	G + K	280 g + 2 L		5/6	80

*Stomp Xtra no longer registered, but other products with pendimethalin are available

Results

The efficacy of the residual herbicide treatments was not consistent across sites. However, there were some treatments that provided more consistent, effective suppression of sowthistle emergence (Table 2). Terbyne Xtreme (terbuthylazine) and Valor (flumioxazin) applied alone provided effective control of sowthistle at four out of six trial sites. Mixtures with these two herbicides, also provided good control when Terbyne Xtreme (terbuthylazine) was mixed with Flame (imazapic) (5/6), Balance (isoxaflutole) (4/6) or Stomp Xtra* (pendimethalin) (5/6) and when Valor (flumioxazin) was mixed with Flame (imazapic) (4/6) or Dual® Gold (s-metolachlor) (5/6). Good control was also achieved from a mixture of Flame (imazapic) with Balance (isoxaflutole) (4/6) and with Flame (imazapic) + either Stomp Xtra* (pendimethalin) or Dual® Gold (s-metolachlor) (3/6).

The duration of control differed for the different residual herbicide treatments. For example, at the Yagaburne site, all residual treatments initially provided a significant reduction in sowthistle emergence at 40 days after application (DAA). However, at 187 DAA, efficacy was greatly reduced in all but six of the treatments (Figure 3). The duration of persistence will impact on the efficacy of weed control but can also impact on the potential damage to subsequent susceptible crops. Dry years, such as we have had recently, will generally increase the persistence of many residual herbicides beyond the time frames stated on labels.

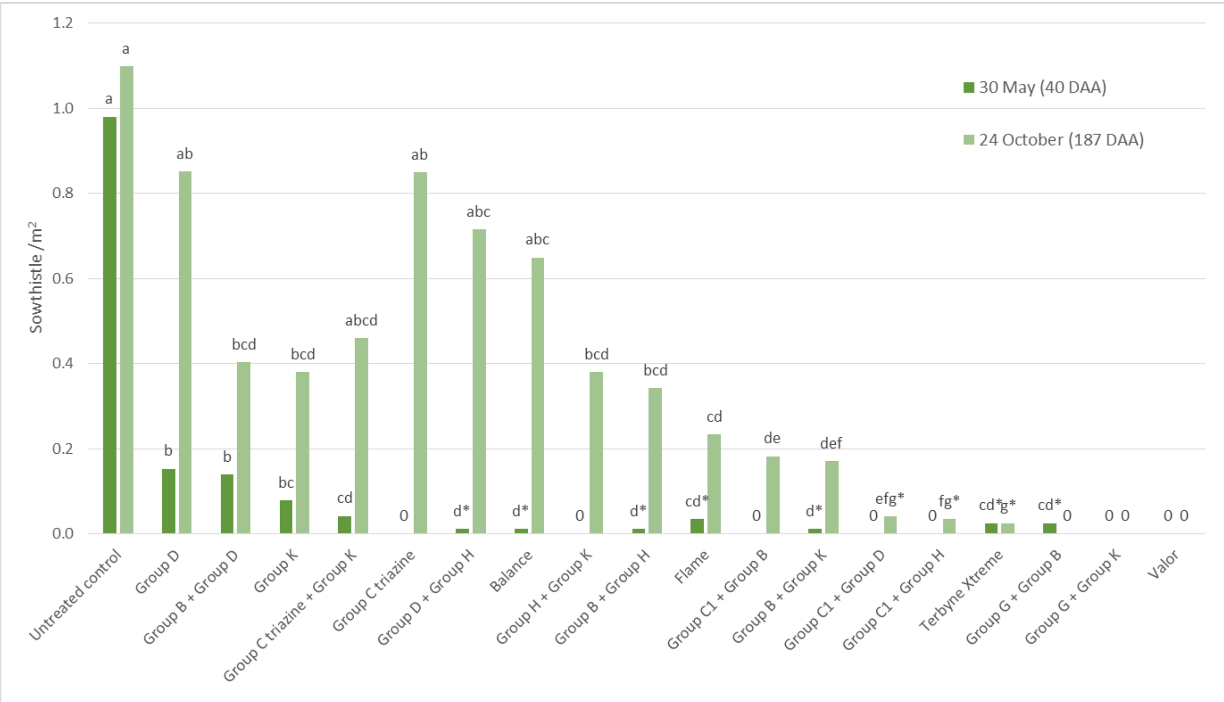

Figure 3. Sowthistle emergence (plants/m²) at Yagaburne following application of residual herbicides and counted 40 Days after application (DAA) (30 May 2017) and 187 DAA (24 October 2017). Columns within the same assessment with similar letters are not significantly different * = not significantly different to 0. (P=0.05).

Retaining crop stubble resulted in an increase in the emergence of sowthistle (Figure 4). Sowthistle requires an extended period (three days) of moisture to germinate and it is likely moisture was retained for longer under the crop stubble than in a bare fallow. Stubble did not have any influence on the efficacy of the residual herbicides, with the same trend in control being achieved with or without crop stubble (Figure 4). However, previous research has shown crop residues can intercept large proportions of residual herbicides, stopping them from getting to the soil target.

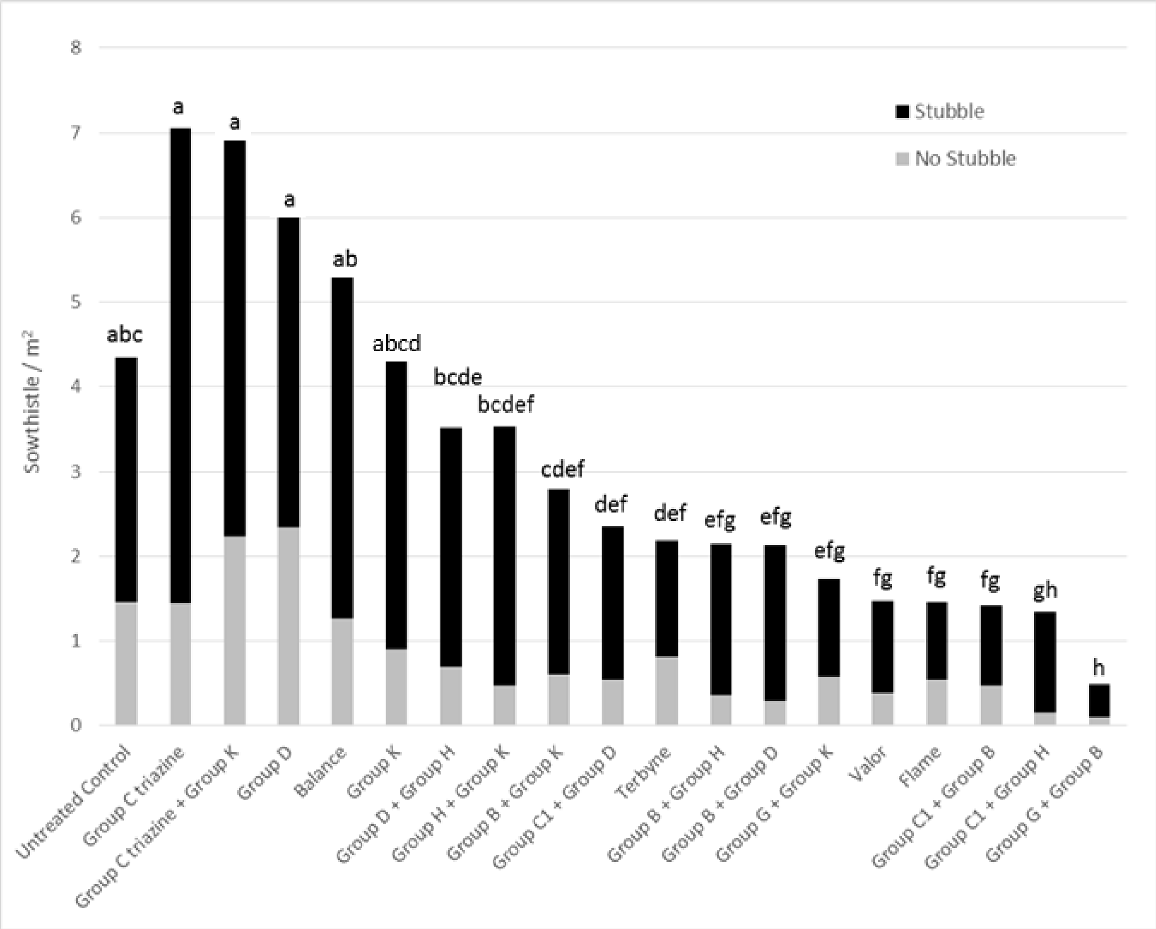

Figure 4. Sowthistle emergence (plants/m^2) at Jondaryan (1) following application of residual herbicides in plots with crop stubble and without crop stubble. Counts were made 147 DAA (5 April 2017). Columns with similar letters are not significantly different (P=0.05)

Conclusion

Rotating weed control tactics is a key strategy in the management and prevention of herbicide resistance. Weed management shouldn't be prescriptive but should consider the environment (soil type, likely rainfall etc.) and future cropping aspirations. As such the results presented in this paper are to help inform decision making and are not a recommendation for weed control.

Our results show there are residual herbicide options for the effective suppression of sowthistle emergence in fallows. Residual herbicides offer an opportunity for prolonged control of multiple flushes of sowthistle emergence and for mode of action rotation. Applying residual herbicides in mixture, while more costly, is likely to provide better control of a broader spectrum of weeds.

As residual herbicides can be variable in their efficacy, it is important to use residual herbicides in combination with other weed management tactics. For example, if applying a residual for fallow weed control, make sure any weed escapes are controlled, either with knockdown herbicides, targeted tillage or manual removal. Consider planting a subsequent competitive crop to provide added control.

Many herbicides require moisture to break down. With our recent run of hot, dry seasons, be mindful that some residual herbicides can persist for longer than described on their labels. A test plot of your planned subsequent crop can give you a good idea of whether crop damage is likely to occur. Current research is looking at developing a quick test for testing soils to determine concentration of the herbicide and risk of damage for subsequent susceptible crops.

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.

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"Weed Chipper": site-specific tillage for fallow weed control

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Key words

targeted tillage, site-specific weed control, rapid response tyne

GRDC code

UWA00171, US00084

Take home message

- "Weed Chipper" is a targeted tillage system developed for site-specific fallow weed control based on a rapid response tyne
- Pre-commercial testing of "Weed Chipper" is now underway

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.

Aims

1. To develop a rapid response tyne based on a hydraulic breakout tyne
2. To establish the weed control efficacy of the developed response tyne for site-specific tillage weed control

Method

Development of a rapid response tyne

A rapid response tyne system has been developed with the operational specifications of being able to cultivate target weeds in a field when present at densities of up to 1.0 plant/10m^2 at a travelling speed of 10km/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 configurations. Although hydraulic systems are not traditionally used in such dynamic environments, to aid timely adoption and acceptance by farmers it was decided to not deviate too far from currently accepted and widely adopted agricultural machinery.

The traditional cultivator bars on currently accepted and widely adopted agricultural machinery are designed for continuous tillage and full-time tool-soil interaction. However the new application required detailed engineering to modify the hydraulic system and mechanism functionality and optimise performance while being highly constrained by the existing geometry. Therefore, developing an efficient and elegant rapid response tyne around a conventional cultivator was not straightforward.

The initial proof-of-concept design focussed on minimising the number of additional components and keeping the design simple whilst achieving the chipping action similar to a conventional hoe in approximately a third of 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 other rigs were used for weed kill testing (Figures 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 rapid response tyne 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 the efficacy of the response tyne on the targeted weeds species established at eight growth stages (Table 1) was investigated.

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 weed.

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 400ms 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, 2 and 3). The survival of any weeds during testing was due to the design of the current cultivator sweeps not being suitable for the targeted tillage being carried out by the Weed Chipper. 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 the side of the sweep. There was also reduced efficacy when weeds were excessively large. When Feathertop Rhodes grass was >70cm diameter there was only poor control (Table 3). The system is highly effective on both broadleaf and grass weeds with the resultant soil disturbance potentially being low (Figure 2).

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

Growth stage	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

The dash (-) indicates no treatments where there was partial contact of the tyne with the weed.

Table 2. Response tyne efficacy on two winter weed species at three growth stages, Gatton Qld, 2017

Weed Size	Wild oats	Sowthistle
	Control (%)	
Small (10-20cm)	-	100
Medium (20-40cm)	100	85
Large (40-70cm)	98	75

The dash (-) indicates that established weeds were either missed by the tyne (alignment issue) or the tyne did not activate.

Table 3. Response tyne efficacy on three summer weed species at three growth stages, Gatton and Hermitage, Qld 2017

Summer 2016/2017	Weed size	Barnyard grass	Feathertop Rhodes grass	Windmill grass
		Control (%)		
Gatton	Medium (20-40cm)	100	94	100
	Large (40-70cm)	96	91	100
	X-Large (>70cm)	99	87	96
Hermitage	Medium (40cm)	98	78	100
	Large (40-70cm)	92	33	100
	X-Large (>70cm)	83	8	-

The dash (-) indicates that established weeds were either missed by the tyne (alignment issue) or the tyne did not activate.

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

Inclusion of weed detection technologies

The efficacy of targeted tillage for weed control is firstly 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 optical detection systems (Weed Seeker 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 the more suitable technology for the Weed Chipper and has now been incorporated into the pre-commercial Weed Chipper rig. Trials using the system coupled the 6m pre-commercial Weed Chipper, Figure 1D, are currently underway.

Conclusion

The response tyne's mechanical nature enables it to control weeds with greater flexibility around environmental conditions such as surface temperature inversions, wind, humidity and heat. Its ability to handle a vast range of weeds at varying growth stages 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 the Weed Chipper system is an efficient tactic suitable for integration in an Integrated Weed Management system.

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The research undertaken as part of this project is made possible by the significant contributions of growers throughout the trials, 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.

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Barley agronomy: new varieties, their potential for early sowing & limitations

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Notes

Virulence in net form of net blotch in barley

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Key words

barley, net form of net blotch, *Pyrenophora teres* f. *teres*, NFNB, virulence

GRDC code

DAQ00187 – National Barley Foliar Pathogen Variety Improvement Program (NBFPVIP)

Take home messages

- Continuous barley cropping increases the risk of net form of net blotch (NFNB)
- The NFNB pathogen is seed-and stubble-borne
- NFNB is best controlled by using resistant varieties (rated MS or better), crop rotation, seed treatment, regular crop monitoring and timely fungicide application
- Virulences are dynamic and fluctuate in response to available host genotypes
- No new virulences were identified in 2018.

Background

Net blotch in barley is caused by one of two forms of *Pyrenophora teres* (*P. teres*). Net form of net blotch (NFNB) is caused by *P. teres* f. *teres* (*Ptt*) and spot form of net blotch (SFNB) is caused by *P. teres* f. *maculata* (*Ptm*). The two forms are morphologically identical and can only be distinguished by symptoms and molecular characterisation (McLean *et al.* 2009). Symptoms of NFNB are characterised by net like dark brown necrotic lesions, whereas SFNB symptoms are characterised by dark circular or elliptic brown spots surrounded by a yellow chlorotic area.

NFNB occurs regularly in the northern region (NR) and samples are collected from crops on an annual basis. Thirty-three NFNB samples were collected and pathotyped in QLD and NSW in 2016 and 35 in 2017. However, with the dry conditions, only a single NFNB isolate was submitted for pathotyping in 2018. That isolate was collected from a research trial with no samples being received from commercial crops during that year.

DAF is funded by GRDC through the national barley foliar pathogen variety improvement program to conduct annual pathotype surveys to monitor pathotypes and pathotype changes in the NFNB population in Australia. Results have been reported at the GRDC updates in both 2017 and 2018.

Pathotype determination

The virulence of a pathotype is determined by its responses on a suite of varieties. Currently a set of 30 varieties is used to differentiate pathotypes.

Previous research has identified four distinct groups of isolates across Australia. Collectively these isolates have the ability to infect most varieties. The level of disease development will however depend on the isolate/variety combination. The four groups are assigned on the basis of varieties that they are virulent on, resulting in a susceptible infection type.

Group 1: Binalong, Cowabbie, Fairview, Grimmet, Skiff, Tantangara, Yambla

Group 2: Gilbert, Grimmet

Group 3: Commander, Grout, Keel, Mackay, Navigator, Prior

Group 4: Beecher, Maritime⊕, Roe⊕.

Pathotypes from Isolate Groups 1, 2 and 3 are commonly present in the northern region.

Pathotype survey results suggest that the cultivation of regionally adapted varieties result in the evolution of *P. teres* f. *teres*, with increased virulence for the resistance profiles in the particular varieties, which in turn lead to higher incidence and severity of NFNB infection. This was clearly demonstrated with an increased prevalence of pathotypes virulent on the varieties Commander⊕ and Shepherd⊕. Pathotypes able to infect these varieties were earlier considered to be rare. Compass⊕, a derivative of Commander⊕ demonstrates a similar response to NFNB infection at the seedling stage, however develops adult plant resistance (APR) after stem elongation. Commander⊕ is now regarded as susceptible. This was communicated at the Grains Research Updates in Goondiwindi in 2017 and 2018. The continued cultivation of these varieties provides a selective host for virulent pathotypes to increase.

In 2017 isolates virulent on Maritime⊕ and on the variety Urambie⊕ were identified. These isolates are not expected to pose a threat to northern region varieties. Virulence was detected to all genotypes tested, except Clho 5791 indicating that this genotype carries effective resistance against all current Australian isolates. No isolates virulent on Algerian and Vlamingh⊕ were detected in the northern region in 2017. All isolates were virulent on the genotypes Corvette, Gilbert, Harrington, Commander⊕, Compass⊕ , Bass⊕ and Navigator⊕. Isolates virulent on Oxford were identified from both the northern region and WA in 2017. Out of 16 isolates from WA pathotyped in 2018, five were highly virulent on Oxford. This variety is not widely grown in the northern region. Virulence on Beecher, common in WA (not present in the northern region), was detected in a single WA isolate in 2017 and none in 2018.

Environmental conditions play a major role in the development of NFNB. Disease development and infection is favoured by frequent wet periods and mild temperatures. As mentioned before, no isolates were collected in the NR in the 2018 season due to the dry conditions.

Disease management

NFNB is best controlled by sowing varieties rated MS or better to NFNB and a combination of cultural practices.

Resistant varieties

All current barley varieties and varieties considered for release are rated for resistance to a suite of diseases and pathogens through the National Variety Trial disease screening process. They are categorised in 9 resistance categories rating from resistant (R) to very susceptible (VS). These genotypes are screened annually in nationwide disease nurseries, with disease ratings assigned and reviewed on a yearly basis. Growing a high yielding well adapted resistant variety provides the most economic and environmentally friendly means of disease control. Information on resistance ratings are available in the crop variety sowing guides for QLD and NSW.

Stubble management and crop rotation

The NFNB pathogen persists on plant residue. The adoption of stubble retention practices has led to an increase in the incidence of NFNB. Planting successive barley crops in the same paddock increases the incidence of NFNB and cultivation of the same variety will lead to an increase in the presence of pathotypes virulent on that particular variety and put increased pressure on effective resistance genes. Best practice includes crop rotation with non-host crops such as wheat, canola and chickpea.

Seed treatment

The NFNB pathogen is seed-borne and can spread with infected seed. Ensure seed is treated adequately. Various seed treatment products are registered for the control of NFNB.

Fungicide application

Foliar fungicides are applied routinely in most barley crops and should be aimed at protecting the top two leaf layers. NFNB isolates with reduced sensitivity to demethylase (DMI) fungicides have been identified in WA. All isolates tested from NSW and QLD thus far were sensitive to fungicides. To ensure that fungicides remain effective, it is important to limit fungicide application by spraying only when necessary, rotate fungicides with different modes of action and use fungicides at recommended rates. Avoid using tebuconazole as a stand-alone product in barley for scald or powdery mildew to avoid indirect fungicide resistance selection. By applying it for control of one of these diseases, you can indirectly select for NFNB or SFNB isolates resistant to tebuconazole without the intention of controlling those diseases. Isolates resistant to fungicides can be spread through infected seed. It is beneficial to all to ensure that we use fungicides in such a way that we protect their longevity.

Crop monitoring

Fungicide applications are more effective if applied before NFNB becomes established in the crop. This requires regular monitoring to ensure crops can be sprayed at the first sign of disease. When conditions are favourable for disease development, more frequent crop inspections will be needed and repeat fungicide applications may be necessary.

The absence of NFNB in 2018 in the northern region does not mean that we can get complacent. With the right environmental conditions, the pathogen will continue to cause yield and quality loss and we have to make the right decisions to ensure that we can stay ahead of disease development and the evolution of the pathogen.

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⅌ Varieties displaying this symbol beside them are protected under the Plant Breeders Rights Act 1994.

Barley stem rust on the Darling Downs in 2018

Lislé Snyman, Dept. Agriculture and Fisheries Queensland

Key words

barley, stem rust, NVT

GRDC code

DAQ00189 – National Variety Trial Services

Take home messages

- All isolates identified as Scabrum rust – will not infect wheat crops
- The stem rust pathogen is a biotroph and needs a living host for survival – not stubble-borne
- Most barley varieties are vulnerable to stem rust infection and will host wheat, rye and scabrum rusts
- Susceptible varieties contribute to inoculum pressure and increase the risk of breakdown of resistance in other varieties
- Need to manage green bridge to limit pathogen survival

Background

In late 2018, stem rust was reported in QLD barley crops from Brigalow, Chinchilla, Dalby, Brookstead and Jandowae. These reports came as a surprise to many due to the dry conditions experienced throughout much of eastern Australia. Generally, most crops were planted in June - not particularly late for the Darling Downs. Most crops did not receive fungicide applications early in the season as a result of the dry conditions. Exceptionally good rainfall in early October resulted in the appearance of late tillers, increasing the vulnerability to stem rust and delaying maturity and harvest.

Stem rust of barley

The rust diseases are regarded as some of the most important diseases of cereals worldwide. Their importance can be attributed to their adaptability to a range of environments, their capacity to mutate rapidly and attack previously resistant cultivars, their rate of disease development and the ability of spores to remain viable when dispersed over long distances. The rust pathogens are highly specialised and have relatively narrow host ranges. They are obligate parasites and require a living host for survival.

Stem rust is primarily a disease of wheat, barley and triticale, but also infects some grass species. It is caused by the pathogenic fungus *Puccinia graminis*, comprising species that are specialised to different hosts. For example, *P. graminis* f. sp. *tritici* is specific to wheat and barley and cannot infect oats, whereas *P. graminis* f. sp. *avenae* is specific to oats and cannot infect wheat and barley.

Barley can be infected by up to three different forms of the stem rust pathogen, wheat stem rust (*P. graminis* f. sp. *tritici*), rye stem rust (*P. graminis* f. sp. *secalis*) and ʼscabrumʻ rust. The latter is regarded as a hybrid between the wheat and rye stem rust pathogens and is most commonly found on *Elymus scaber* (formerly *Agropyron scabrum*), a native grass.

The stem rust pathogen is favoured by humid conditions and warmer temperatures (15-35°C). Following infection, disease symptoms are generally visible within 5-8 days and sporulation occurs in 7-14 days. Severe infection hinders plant growth and can lead to lodging, resulting in yield loss and shrivelled grain. Stem rust can destroy seemingly healthy crops in a short period of time with 100% yield loss reported in susceptible varieties.

Stem rust is characterised by reddish-brown, elongated pustules. They can occur on stems, glumes and both sides of the leaves and pustules have a characteristic torn margin. At the end of the season, dark brown to black spores, known as teliospores are produced mainly on leaf sheaths and stems.

In recent years, Australia has seen a decline in stem rust levels and sample numbers for pathotype analysis. In some years, no infection was recorded in any commercial wheat or barley crop in Australia. The most recent stem rust outbreak in Australia was on triticale in 1982. Breeding for resistance to stem rust in wheat has been a priority in breeding programs and combined with green bridge control and pathogen surveys, played an important role in controlling the disease. In contrast, active resistance breeding for stem rust in barley has been a low priority since infection generally occurs late in the season with most barley crops maturing early, particularly in the northern region.

Heavy rust infection was observed on the native grass species, *Elymus* at most sites visited during a survey on the Darling Downs in January 2018. Rust samples collected are being pathotyped by the Plant Breeding Institute, University of Sydney.

Australian barley (*Hordeum vulgare*) varieties are categorised into 9 resistance categories through the National Variety Trial (NVT) disease screening process. The resistance ratings are assigned by the pathologists working group collating data from national disease nurseries conducted annually. These categories range from resistant (R) to very susceptible (VS) and are communicated to industry via the NVT website, field days and industry presentations.

Most barley varieties are vulnerable to stem rust. Fewer than 10% of varieties screened for stem rust in QLD in 2018 received a resistance rating higher than susceptible (S). Data to be available on the NVT website shortly.

Discussion

The reason(s) for stem rust outbreak in QLD in 2018 is not fully understood. However, the outbreak could be related to delayed sowing and conditions favourable for disease development late in the season. Active resistance breeding for stem rust in barley and research on the pathogen has been a low priority and resulted in limited knowledge about the disease in Australia.

All samples analysed to date have been identified as ’scabrum’ or hybrid stem rust. The pathogen is not able to infect wheat. Therefore, barley crops infected with ’scabrum’ rust pose no threat to wheat production. All rust pathogens are biotrophs, requiring a living host for survival. Hence they cannot survive in stubble. Volunteer plants, including native grasses such as *Elymus*, however allow these pathogens to survive over summer and controlling the green-bridge plays an important role in limiting pathogen survival.

Stem rust requires higher temperatures and tends to appear later in the crop season. Application of fungicide at early growth stages would not be effective for stem rust control. For chemical application to be successful, fungicide should be applied at the first sign of disease. Ensure thorough coverage. Application after successful establishment of the pathogen may reduce efficacy. Consider follow-up application if conditions favour disease development. Contact your adviser for suitable fungicides.

Rust samples are crucial to effectively identify the rust pathogen affecting barley. Rust samples can be sent to Lislé Snyman at 604 Yangan Rd, Warwick QLD 4370. Send up to a maximum of 20 infected stems/leaves with as much rust as possible in paper envelopes, do not use any plastic wrapping or plastic lined packages. Samples will be sent on to the Plant Breeding Institute, Cobbitty for pathotyping.

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Fungicide resistance in net blotch

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Key words

fungicide resistance, barley, DMI, spot form of net blotch, net form of net blotch, *Pyrenophora teres*

GRDC code

CUR00016, CUR00023

Take home messages

- Reduced levels of sensitivity to several DMI fungicides was detected in Western Australia in the net blotch pathogen
  - net form of net blotch from **2013**
  - spot form of net blotch from **2016**
- All isolates from the Northern region tested up to date remained sensitive to fungicides
- Control of both NFNB and SFNB is best achieved by
  - Use of resistant varieties
  - Reduce inoculum load by managing stubble and good farm hygiene
  - Only spray if necessary – limit applications
  - Use best fungicide management practices such as lowest effective dose & rotating fungicide groups
  - Treat seed to limit spread of seed-borne NFNB isolates

Background

The two forms of net blotch in barley, net form of net blotch (NFNB) and spot form of net blotch (SFNB) are caused by one of two forms of *Pyrenophora teres* (*P. teres*). NFNB is caused by *P. teres* f. *teres* (*Ptt*) and SFNB is caused by *P. teres* f. *maculata (Ptm).*

Symptoms of SFNB are characterised by dark circular or elliptic brown patches surrounded by a yellow chlorotic region, whereas NFNB are characterised by net like dark brown necrotic lesions. The two forms are morphologically identical and can only be distinguished by symptoms and molecular characterisation (McLean *et al.* 2009).

Control of both NFNB and SFNB is best achieved by the use of resistant varieties, reducing inoculum load by stubble management, crop rotation, good farm hygiene and fungicide application. In recent years, resistance to particular fungicides have been observed in both pathogens.

Fungicides are essential in maintaining healthy crops and are applied routinely in most barley crops. The choice of fungicide is determined by registration, efficacy, availability and price. The Australian market is dominated by a small number of systemic actives from a single mode of action (MOA) group, these being the DMI's or Group 3 triazole fungicides. Fungicide efficacy varies with disease. When conditions are favourable for disease development, a repeat application may be required for effective disease control.

The efficacy of some fungicides have been impacted by the development of resistance in pathogens. Most modern fungicides have a single-site mode of action and act on a specific biochemical pathway in the target fungal pathogen. Repeated use of fungicides with the same mode of action, selects for isolates in the fungal population with reduced sensitivity to the fungicide. Multi-site fungicides are less prone to resistance development in target pathogens and play an important role in the strategy against the development of fungicide resistance (FRAG-UK 2018).

In Australia, fungicide resistance in barley pathogens have been identified to date in powdery mildew, spot form of net blotch (SFNB) and net form of net blotch (NFNB). Pathogen populations are routinely monitored by the Centre for Crop and Disease Management (CCDM) Fungicide Resistance Group (FRG) based at Curtin University in Western Australia (WA). Disease samples are collected Australia wide and submitted to CCDM for analysis to determine resistance levels in a range of pathogens to the fungicides registered for control. More information is available on the FRG website: http://ccdm.com.au/frg/

Demethylase inhibitor (DMI) fungicide resistance in NFNB

NFNB isolates with reduced levels of sensitivity to several DMI fungicides were detected in WA from 2013 onwards via discriminatory dose screening (Table 1). Strains were classified as either sensitive (S), moderately resistant (MR), or highly resistant (HR) based on 50% effective concentrations (EC_{50}) to the Group 3 compounds prothioconazole, tebuconazole and epoxiconazole (Table 2). EC_{50} of sensitive isolates were derived from samples collected by DPIRD and from field trips, at eight locations: Amelup, Badgingarra, Esperance, Jerramungup, Kalannie, Merredin, Pithara, and Wongan Hills. Moderately resistant strains were first found in samples from a bait trial in the Great Southern (Kojonup) region in 2013, and subsequently detected throughout the wheatbelt and Great Southern regions in samples collected by collaborators from Bakers Hill, Dandaragan, Mount Barker, Scaddan, Tenterden and West Arthur, as well as from a bait trial in Beverley. Highly resistant isolates were found in the Esperance (Scaddan), southern wheatbelt (West Arthur) and central wheatbelt (Dandaragan) regions from 2017 onwards.

Table 1. Number of NFNB isolates tested in each year showing proportion that are sensitive, moderately resistant or highly resistant to Group 3 (DMI) fungicides. [a]From 2018 season onwards, strains were reisolated and tested only where molecular detection had previously confirmed presence of resistance mutations in samples.

	1995-2009	**2012-2013**	**2014**	**2015**	**2016**	**2017**	**2018[a]**
S	7	3	11	44	29	21	0
(%)	*100.0*	*60.0*	*68.8*	*93.6*	*93.5*	*91.3*	*0.0*
MR	0	2	5	3	2	1	0
(%)	*0.0*	*40.0*	*31.3*	*6.4*	*6.5*	*4.3*	*0.0*
HR	0	0	0	0	0	1	4
(%)	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*4.3*	*100.0*
Total	7	5	16	47	31	23	4

Table 2. Mean effective concentration 50 (EC_{50}) in µg/mL of thirteen Group 3 moderately resistant isolates, three highly resistant isolates, and 8 sensitive NFNB isolates collected 1996–2012. Resistance factors (fold number difference between EC_{50} values from resistant isolates and average of sensitive isolates) are given in brackets. Cultures were grown at different concentration ranges of the fungicides tebuconazole, epoxiconazole and prothioconazole.

	Tebuconazole	Epoxiconazole	Prothioconazole
Sensitive (1996 – 2012)	0.23	0.11	0.07
Moderately resistant (MR)	3.72 (16.2)	0.17 (1.5)	0.18 (2.8)
Highly resistant (HR)	17.36 (75.4)	0.69 (6.1)	0.77 (11.5)

Analysis of the target gene for the Group 3 fungicides, called *Cyp51A*, revealed the presence of one mutation in MR and HR isolates. In MR isolates, there was a single fungicide target gene with the mutation. However, in HR isolates, up to 10 additional fungicide target genes carrying the mutation were detected. These extra mutated target genes are probably involved in the over-production of the Group 3 fungicide target which could explain the higher levels of resistance of HR isolates to the fungicides tested.

DMI fungicide resistance in SFNB

SFNB isolates with reduced levels of sensitivity to several DMI fungicides were detected in Western Australian from 2016 onwards via discriminatory dose screening (Table 3). *In vitro* testing sorted strains into sensitive (S), moderately resistant (MR), and highly resistant (HR) groups based on EC_{50} concentrations to the Group 3 compounds prothioconazole, tebuconazole and epoxiconazole. The MR and HR groups showed a similar level of reduced sensitivity to epoxiconazole (Table 4). EC_{50} of sensitive isolates were derived from samples collected by DPIRD and from field trips, at the following locations: Albany, Amelup, Boscabel, Durham Ox, Esperance, Irvingdale, Jerramungup, Kebaringup, Lumeah, Mooree, Morawa, Munglinup and Muresk, as well as from bait trials at Kojonup and Meckering. Moderately resistant strains were detected in samples collected in field trips in the Esperance region (Gibson, Coomalbidgup and Cascade) from 2016 onwards, and highly resistant isolates were found in samples sent by collaborators from the Great Southern (South Stirling and Wellstead) and Esperance (Dalyup) regions from 2017 onwards.

Table 3. Number of SFNB isolates tested in each year showing proportion that are sensitive, moderately resistant or highly resistant to Group 3 (DMI) fungicides. [a]From 2018 season onwards, strains were reisolated and tested only where molecular detection had previously confirmed presence of resistance mutations in samples.

	1995-2009	2012-2013	2014	2015	2016	2017	2018[a]
S	10	13	48	51	30	40	3
(%)	*100.0*	*100.0*	*100.0*	*100.0*	*96.8*	*76.9*	*8.1*
MR	0	0	0	0	1	1	3
(%)	*0.0*	*0.0*	*0.0*	*0.0*	*3.2*	*1.9*	*8.1*
HR	0	0	0	0	0	11	31
(%)	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*21.2*	*83.8*
Total	10	13	48	51	31	52	37

Table 4. Mean effective concentration 50 (EC_{50}) in µg/ml of five Group 3 moderately resistant isolates, fifteen highly resistant isolates, and the mean of a reference population of 23 sensitive SFNB isolates collected between 1995 and 2013. Resistance factors (fold number difference between EC_{50} values from resistant isolates and average of sensitive isolates) are given in brackets. Cultures were grown at different concentration ranges of the fungicides tebuconazole, epoxiconazole and prothioconazole.

	Tebuconazole	**Epoxiconazole**	**Prothioconazole**
Sensitive (1995 – 2013)	0.31	0.17	0.07
Moderately resistant (MR)	2.56 (8.6)	1.72 (10.6)	0.49 (6.8)
Highly resistant (HR)	16.69 (55.9)	1.45 (8.9)	1.67 (22.9)

Analysis of the group 3 fungicide target *Cyp51A*, revealed the presence in MR and HR isolates of two different mutations that were not observed in sensitive isolates. In MR isolates, the mutation was a small fragment of DNA that was inserted in the fungicide target gene. This small fragment of new DNA was found at three different positions and its effect was the over-production of the fungicide target. The presence of more fungicide target requires an increase in the amount of fungicide necessary to kill the MR isolates.

The small DNA fragment was also found in HR isolates but at a different position, together with another mutation, F489L. This latter mutation has been previously observed in the closely related pathogen *P. teres* f. *teres*, the causative agent of net form of net blotch (NFNB), where it has been correlated with reduced sensitivity to a range of DMI fungicides (Mair *et al*. 2016).

Net blotch in the Northern Region (NR)

Both forms of the net blotch pathogen occurs regularly in the Northern Region and isolates are collected annually, however in 2018 disease pressure was very low due to the dry conditions. A total of 12 NFNB isolates were collected in the NR between 2009 and 2017, mostly from baiting trials. None of these isolates showed reduced sensitivity to fungicides applied. As NFNB is a seed-borne pathogen, the use of an appropriate seed-dressing will aid in limiting the spread of isolates with reduced sensitivity or resistance to fungicides.

Management

In addition to using cultivars with good disease resistance levels, stubble management strategies to reduce disease load, crop rotation and maintaining good farm hygiene, the following chemical management strategies are recommended:

- Only spray if necessary – limit applications
- Choose mixtures with different modes of action (if available). Overuse of fungicides with the same mode of action will speed up fungicide resistance
- Never apply the same Group 3 fungicide twice in a row
- Avoid applying the same mode of action fungicides from the Groups 7 and 11 twice
- Incorporate the use of seed dressing (Group 7), in-furrow (Group 11) and foliar products containing fungicide mixtures from different chemical groups (such as 3 (DMI), 7 (SDHI) and 11 (QoI)) - in combination with limited use of propiconazole and no stand-alone tebuconazole use
- Avoid using tebuconazole as a stand-alone product in barley for any disease to avoid indirect fungicide resistance selection

- Ideally use DMI-based mixtures (e.g. Prosaro® containing prothioconazole and tebuconazole) only once, followed by mixtures containing other actives (preferably from groups 7 or 11)
- If resistance is present, or suspected, avoid or minimise use of that mode of action - this will only further select for resistance
- Do not exceed label rates

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What pathogens were detected in central and northern cereal crops in 2018?

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PREDICTA®B, in-crop sampling, wheat, barley, crown rot, common root rot, take-all, net blotch, yellow spot, root lesion nematodes, AMF

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Take home messages

- Disease surveys are important to stay abreast of developing issues within farming systems
- Fusarium crown rot and common root rot (*Bipolaris*) were widespread in cereal crops in 2018 and are potentially dominating other diseases such as take-all
- The yellow spot fungus was detected in all 102 wheat crops surveyed and surprisingly also in 43 of the 46 (94%) barley crops. This presumably highlights how effective the yellow spot fungus is as a saprophyte of dead barley tissue
- Spot form of net-blotch was detected more frequently and at higher DNA concentrations in barley crops than net-form of net blotch in 2018. Saprophytic colonisation of wheat as an alternate host appeared lower with net-blotch compared to yellow spot
- PREDICTA® B assays appear to be a valuable tool to rapidly quantify a wide range of fungal pathogens, nematode pests and beneficial fungi within wheat and barley crops.

Introduction

Regular crop surveys are important for monitoring changes in disease prevalence, distribution and importance in changing farming systems. Structured survey data can be used to:

a) guide priorities for continued research
b) inform integrated disease management (IDM) decisions i.e. ensure correct disease identification
c) ensure breeding efforts are targeted at priority and/or changing pathogen populations
d) determine success of recommended IDM strategies
e) provide a mechanism for proactive surveillance for new e.g. exotic or spread of new pathotypes or sporadic diseases e.g. Fusarium head blight (FHB) and viruses and
f) maintain industry awareness and preparedness.

What did we do?

In collaboration with a range of locally based agronomists, a total of 150 winter cereal crops were surveyed in 2018 between the start and end of grain filling. The GPS location and background information for each paddock were recorded, but to maintain confidentiality data is presented here based on broad Local Land Service (LLS) boundaries. A total of 39 paddocks were surveyed in the central west (32 wheat and 7 barley), 83 paddocks in the north west (47 wheat, 12 durum and 24 barley), 17 in the northern tablelands (3 wheat and 14 barley), 9 in southern Qld (8 wheat and 1 barley) and 2 on the north coast (1 wheat and 1 barley). In 2018, survey sites and numbers were dictated to some extent by crop availability in a relatively dry season. The two north coast samples were excluded from this current paper due to limited commercial relevance, and in the north west the bread wheat and durum sample data were combined and treated as wheat.

Within each crop, a diagonal transect (~500 m) was created starting at least 50 m in from a road or fence line and avoiding obvious barriers such as trees or dams. Five consecutive whole plants (roots with adhering soil, stems and heads) were collected along the planting row from ten separate sampling points across the diagonal transect (total of 50 plants/crop). Samples were transported to Tamworth and stored at 4°C before processing;

- 100 random tillers (two/plant) were assessed for incidence of basal browning (crown rot), leaf diseases (e.g. yellow spot or net blotch) and head infections (e.g. bunt, smut or Fusarium head blight (FHB))
- Fifty crown and stem bases (one/plant) are currently being rated for the severity of basal browning and scored for root health prior to plating on laboratory media to the determine the incidence of *Fusarium* (crown rot) and *Bipolaris sorokiniaina* (common root rot) infection.

The 100 tillers used for visual assessments were further separated into root and shoot (crown, stem, leaves and heads) samples, dried at 40°C for 48 hrs and then couriered to SARDI to assess fungal DNA concentrations using a range of existing PREDICTA® B assays. The dried shoot samples were put through a fine plant grinder prior to DNA analysis. A 20 g subsample of ground shoot material, and the whole dried root samples were mixed with a set quantity of sterile sand before extraction of total DNA and PREDICTA B analysis. All DNA data, picograms (pg) or 1000 DNA copies (kDNA) were then converted to per gram of dry root or shoot weight. Due to the availability of data at the time of writing the rest of this paper predominantly outlines the DNA results.

What did we find?

PREDICTA B DNA assays are extremely sensitive with specificity to the target fungal pathogen or plant parasitic nematode of interest. Hence, because these organisms are plant pathogens they become concentrated in the tissues they infect.

The approach used in this survey is quite different from traditional PREDICTA B soil testing where calibrations have been developed to determine the relative risk of infection prior to sowing. A soil test detects DNA of the target pathogen in the soil, old plant roots and stubble residues, particularly those added when following the recommended PREDICTA B sampling strategy. This approach defines the risk of infection developing within a season.

In this survey we collected plant samples during grain filling and washed them to remove soil and any old stubble residues. Hence, the DNA tests in this context are determining the level of pathogen burden within the roots or shoots of the plant at a specified growth stage and not residues from previous crops.

The key point being, the DNA values presented in the following tables should ***not*** be compared with current PREDICTA B pre-sowing risk levels or population densities for the different pathogens. Furthermore, the DNA values within roots or shoots have been assigned to a purely arbitrary low, medium or high category based on the spread of data across sites in 2018. They should ***not*** necessarily be interpreted as low, medium or high infection levels.

For example, the 2018 season was generally dry which was not conducive to the development of leaf diseases such as yellow spot in wheat and net blotches in barley. Hence, even though DNA of the causal fungal pathogens was detected in shoots in 2018, these levels are probably considerably lower than what is likely to be detected in a wetter year. However, DNA concentrations did correlate with visual assessments of disease incidence e.g. crops with higher incidence of basal browning had elevated *Fusarium* DNA levels. DNA data at this stage should be considered for comparative purposes only with continued surveys and research, hopefully developing relationships between pathogen burden in roots and shoots and disease severity and yield loss.

What was interesting using this new approach with PREDICTA B assays?

***Fusarium* crown rot (*Fusarium* spp.)**

Two DNA assays detect *Fusarium pseudograminearum* with a third detecting *F. culmorum* + *F. graminearum* but cannot distinguish between these two species. All three *Fusarium* species cause basal infection of cereal stems resulting in crown rot and the expression of whiteheads when heat and/or moisture stress occurs during grain filling. When wet weather occurs during flowering, these species, especially *F. graminearum*, can also infect heads causing Fusarium head blight (FHB). DNA data for all three tests were combined for this interpretation. The incidence of crown rot, based on basal browning, was high across the survey area in 2018 (data not shown).

Fusarium DNA was detected in the shoots (crown, stem, leaves and heads) of 99% of the 148 cereal crops surveyed in 2018 (Table 1). The DNA levels were most likely associated with crown rot infection of the crown and lower stem sections. However, FHB was visually recorded in a limited number of crops in the north west region in 2018 (Liverpool Plains) which had proportionally higher levels of *F. culmorum/F. graminearum* DNA in shoot samples (data not shown). *Fusarium* DNA levels tended to be lower in shoots in the northern tablelands compared with the other regions.

The 2018 season was quite conducive to the development of Fusarium crown rot with DNA levels in shoots highlighting the continued importance of this disease across the region (Table 1). *Fusarium pseudograminearum* is primarily considered a crown and lower stem pathogen but interestingly high incidence and levels of DNA were also detected in root samples across regions. Only 4% of root samples had no detection of *Fusarium* spp. (Table 1). Voss-Fels *et al.* (2018), recently investigated genetic variability in 215 international wheat lines to *Fusarium* root rot (FRR) caused by *F. graminearum*. Interestingly, the authors found FRR resistance accumulated in European winter wheat germplasm which also had reduced browning of stem bases. These preliminary DNA results indicate that a similar study may be warranted on the importance and genetic resistance to FRR caused by *F. pseudograminearum*.

Table 1. Proportion of paddocks (%) with varying levels of *Fusarium* spp. (crown rot) DNA detected in wheat and barley roots or shoots in 2018

Fusarium spp. (pg DNA/g)	Roots				Shoots			
Region (no. paddocks)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central west (39)	0	15	3	82	3	28	33	36
North west (83)	4	13	13	70	1	24	26	49
Northern tablelands (17)	6	47	12	35	0	76	12	12
Southern Qld (9)	11	22	11	56	0	33	0	67
All regions (148)	***4***	***18***	***10***	***68***	***1***	***32***	***24***	***43***

Common root rot (*Bipolaris sorokiniana*)

Bipolaris primarily infects the sub-crown internode causing dark brown to black discolouration of this tissue. This would be reflected in DNA levels in root samples in this survey. Tiller bases and surrounding leaf sheathes can also be brown in common root rot infected tillers which would be reflected in shoot DNA levels.

Bipolaris DNA was detected in 95% of root and shoot samples (Table 2). DNA levels in the roots were relatively consistent across regions but a larger proportion of crops in north west (34%) and southern Qld (56%) had high DNA levels in the shoot samples compared with the central west and northern tablelands crops which had no crops in the high category (Table 2).

Table 2. Proportion of paddocks (%) with varying levels of *Bipolaris sorokiniana* (common root rot) DNA detected in wheat and barley roots or shoots in 2018

Bipolaris (pg DNA/g)	Roots				Shoots			
Region (no. paddocks)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central west (39)	3	21	50	26	10	49	41	0
North west (83)	6	12	48	34	2	23	41	34
Northern tablelands (17)	12	24	41	23	6	41	53	0
Southern Qld (9)	0	11	56	33	0	0	44	56
All regions (148)	***5***	***16***	***49***	***30***	***5***	***30***	***43***	***22***

***Gaeumannomyces graminis* var. *tritici* (*Ggt*, take-all)**

Take-all predominantly causes black discolouration of infected roots, but sub-crown internodes and tiller bases can also appear black, especially in seasons with wet conditions during spring causing "black sock" symptoms. The take-all fungus (*Ggt*) hosts on all winter cereal crop species and a range of grass weeds. Take-all is generally not considered a significant pathogen of cereal crops in northern NSW and Qld compared with southern NSW, SA and Victoria. However, DNA *Ggt* was detected in 99% of root samples and 79% of shoot samples, mostly at low concentrations in 2018. Although the number of paddocks surveyed in southern Qld in 2018 were relatively small (9), this region had a higher proportion of crops with medium *Ggt* DNA levels in both the roots and stems (Table 3). Given the similar host range of *Ggt* and Fusarium crown rot fungi, plants with medium *Ggt* DNA levels also tended to have medium to high *Fusarium* DNA concentrations (data not shown). This raises the issue as to whether the importance of take-all in this region is potentially going unrecognised due to symptoms being masked by crown rot infection.

Table 3. Proportion of paddocks (%) with varying levels of *Gaeumannomyces graminis* var. *tritici* (*Ggt,* take-all) DNA detected in wheat and barley roots or shoots in 2018

Ggt (pg DNA/g)	Roots				Shoots			
Region (no. paddocks)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central west (39)	0	77	21	2	28	72	0	0
North west (83)	1	76	23	0	10	86	4	0
Northern tablelands (17)	6	82	12	0	71	29	0	0
Southern Qld (9)	0	56	44	0	0	89	11	0
All regions (148)	***1***	***76***	***22***	***1***	***21***	***76***	***3***	***0***

Root lesion nematodes

Root lesion nematodes (RLN, *Pratylenchus* spp.) are microscopic plant parasites which feed on crop roots. Two important species are known to infect crops in eastern Australia, namely *Pratylenchus thornei* (*Pt*) and *P. neglectus* (*Pn*). *Pt* is known to be the more important species in higher clay content soils in northern NSW and southern Qld while *Pn* is generally more prevalent in lighter soil types in south-eastern Australia and WA.

Only root samples were assayed for RLNs with a known conversion used to express DNA values as nematode numbers. Sharma *et al.* (2001) reported for *Pn* that 0-1000 *Pn*/g root caused no yield loss in cereals; 1000-10000 caused up to 15% yield loss whilst >10,000 caused 15-30% yield loss in WA. Similar data on dry root RLN densities was not found for *Pt*. These values were used as a rough guide to set arbitrary densities categories in Table 4.

Pt was detected in roots of a higher proportion (60%) of cereal crops than *Pn* (39%) but did vary by local land services (LLS) region. *Pn* was detected in 92% of central west crops but was present at lower incidence in northern tablelands (41%), north west (17%) and southern Qld (11%). RLN densities detected in root systems were generally in the low category with only 18% of crops in the central west having medium *Pn* densities while 5% of crops in the north west had medium *Pt* densities based on the Sharma *et al*. (2001) categories (Table 4).

Table 4. Proportion of paddocks (%) with varying densities of the root lesion nematodes *Pratylenchus thornei* or *P. neglectus* in wheat and barley roots in 2018

Root lesion nematodes	*P. thornei* (no./g)				*P. neglectus* (no./g)			
Region (no. paddocks)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central west (39)	44	56	0	0	8	74	18	0
North west (83)	31	64	5	0	83	17	0	0
Northern tablelands (17)	65	35	0	0	59	41	0	0
Southern Qld (9)	67	33	0	0	89	11	0	0
All regions (148)	***40***	***57***	***3***	***0***	***61***	***34***	***5***	***0***

White grain disorder (*Eutiarosporella* spp.)

White grain disorder (WGD) can be a sporadic issue to cereal production, primarily in southern Qld, when wet weather occurs during flowering. Infection produces symptoms similar to Fusarium head blight with premature bleaching of infected sections in heads and, as the name implies, production of white grains. WGD is caused by three different species of the fungus *Eutiarosporella* (formerly thought to be *Botryosphaeria*) in Australia, namely *E. tritici-australis* (*Eta*) and *E. darliae* (*Ed*) or *E. pseudodarliae* (*Ep*). There are two DNA assays to allow detection of these species with one for *Eta* and a second that detects both *Ed+Ep,* with combined data presented (Table 5).

Eutiarosporella does not appear to have been a significant pathogen of cereal roots in 2018 with only low DNA levels detected in 14% of crops. The incidence of *Eutiarosporella* DNA was higher in shoot samples being detected in 55% of cereal crops including all nine crops surveyed in southern Qld (Table 5). Incidence and DNA levels of *Ed+Ep* tended to be higher than *Eta* in each region (data not shown).

Table 5. Proportion of paddocks (%) with varying levels of *Eutiarosporella* (white grain disorder) DNA detected in wheat and barley roots or shoots in 2018

Eutiarosporella (kDNA/g)	Roots				Shoots			
Region (no. paddocks)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central west (39)	90	10	0	0	67	23	10	0
North west (83)	88	12	0	0	41	48	7	4
Northern tablelands (17)	76	24	0	0	41	59	0	0
Southern Qld (9)	67	33	0	0	0	56	11	33
All regions (148)	***86***	***14***	***0***	***0***	***45***	***43***	***8***	***4***

Charcoal rot (*Macrophomina phaseolina*)

Charcoal rot, caused by the fungus *Macrophomina phaseolina*, is primarily a disease of summer crops including sorghum, soybean, mungbean and sunflower in northern NSW and Qld. Infection causes light brown lesions on crowns and roots and results in increased lodging and/or premature plant death when stress occurs late in the growing season. In 2014, charcoal rot was reported to cause premature senescence of lupin crops in WA when they were exposed to high temperatures and moisture stress during pod set. *Macrophomina phaseolina* has a wide host range of more than 500 weed and crop species including winter cereals.

Pathogen DNA was detected at low levels in 84% of cereal root samples and 42% of cereal shoot samples (Table 6). Medium levels of *Macrophomina* DNA was detected in 22% (2 of 9) of shoot samples from crops in southern Qld. This pathogen has not been recorded as a significant pathogen of winter cereal crops but certainly appears to be hosting on roots and shoots of wheat and barley crops across the survey region.

Table 6. Proportion of paddocks (%) with varying levels of *Macrophomina phaseolina* (charcoal rot) DNA detected in wheat and barley roots or shoots in 2018

Macrophomina (kDNA/g)	Roots				Shoots			
Region (no. paddocks)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central west (39)	13	84	3	0	59	41	0	0
North west (83)	16	82	2	0	53	43	4	0
Northern tablelands (17)	12	88	0	0	65	35	0	0
Southern Qld (9)	11	89	0	0	33	45	22	0
All regions (148)	***14***	***84***	***2***	***0***	***55***	***42***	***3***	***0***

Yellow spot (*Pyrenophora tritici-repentis*)

Yellow spot is a stubble-borne disease of durum and bread wheat caused by the fungus *Pyrenophora tritici-repentis* (*Ptr*). Wet weather favours infection and production of tan lesions with a yellow margin on the leaves of susceptible wheat varieties. Repeated rainfall events during the season are required for yellow spot infection to progress up the canopy of a wheat plant. Given the generally dry conditions in 2018, the visual incidence of yellow spot lesions on the top three leaves during grain filling was low. However, in many crops the presence of yellow spot lesions on the lower leaves was noted when the plant samples were collected (data not shown). Although *Ptr* is a leaf pathogen of wheat, it is also an effective saprobe (feeds on dead tissue) and can colonise dead leaves and stubble of barley late in the season under wet conditions. Hence, both wheat and barley shoot samples were assayed for *Ptr* DNA levels.

Ptr DNA was detected in every wheat crop surveyed and surprisingly also in 94% of barley crops (Table 7). Medium to high *Ptr* DNA levels were measured in wheat crops across all regions, especially southern Qld and northern tablelands; but low sample numbers in these areas limit severity estimates.

The proportion of barley crops with medium to high *Ptr* DNA in shoots was lower compared to wheat except in the central west (Table 7). This highlights underlying differences in rotation sequences or rainfall patterns in 2018 between these regions, which have not currently been explored. This initial survey however, certainly highlights that barley should not be considered a break crop for yellow spot in wheat. Presumably Ptr is growing as a saprophyte on dead barley tissue and requires further investigation.

Table 7. Proportion of paddocks (%) with varying levels of *Pyrenophora tritici-repentis* (yellow spot) DNA detected in wheat and barley shoots in 2018

Yellow spot (kDNA/g)	Wheat				Barley			
Region (no. paddocks wheat, barley)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central west (32, 7)	0	38	37	25	15	15	42	28
North west (59, 24)	0	38	47	15	0	71	21	8
Northern tablelands (3, 14)	0	0	0	100	15	71	7	7
Southern Qld (8, 1)	0	0	62	38	0	100	0	0
All regions (102, 46)	***0***	***33***	***44***	***23***	***6***	***63***	***20***	***11***

Spot form of net-blotch (*Pyrenophora teres* f. *maculata*)

Spot form of net-blotch (SFNB) is a stubble-borne pathogen of barley crops causing brown circular lesions with a limited yellow margin on infected leaves. Similar to yellow spot in wheat, prolonged wet weather favours initial infection and progress up the canopy of susceptible barley varieties. The SFNB fungus was detected in the shoots of 95% of the barley crops surveyed at generally low to medium DNA concentrations (Table 8). SFNB was detected in 50% of wheat crops surveyed at largely low DNA concentrations. It is not clear if this reflects a lower saprophytic capacity with *P. teres* compared with *Ptr* or varying sequencing of wheat and barley crops within rotations. That is, barley tends to follow wheat within rotations rather than the other way around. This would tend to favour saprophytic colonisation of *Ptr* on barley compared with *P. teres* hosting on wheat as its alternate host.

Table 8. Proportion of paddocks (%) with varying levels of *Pyrenophora teres* f. *maculata* (spot form or net-blotch, SFNB) DNA detected in barley and wheat shoots in 2018

SFNB (kDNA/g)	Barley				Wheat			
Region (no. paddocks barley, wheat)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central West (7, 32)	0	43	43	14	69	31	0	0
North West (24, 59)	0	54	42	4	37	59	2	2
Northern Tablelands (14, 3)	14	57	29	0	67	33	0	0
Southern Qld (1, 8)	0	100	0	0	63	37	0	0
All regions (46, 102)	***5***	***54***	***37***	***4***	***50***	***48***	***1***	***1***

Net form of net-blotch (*Pyrenophora teres* f. *teres*)

Net form of net-blotch (NFNB) is a stubble-borne pathogen of barley crops causing brown elongated lesions with a net-like cross hatch appearance on infected leaves. Similar to yellow spot in wheat and SFNB in barley, prolonged wet weather favours initial infection and progress up the canopy of susceptible barley varieties.

The NFNB fungus was detected in a lower proportion (69%) of barley crops (Table 9) compared with SFNB (Table 8) in 2018. The concentration of NFNB DNA in barley shoots also tended to be lower than with SFNB. NFNB was also only detected in 8% of wheat crops across the survey area only at low DNA concentrations with all eight wheat crops in the north west region.

Table 9. Proportion of paddocks (%) with varying levels of *Pyrenophora teres* f. *teres* (net form or net-blotch, NFNB) DNA detected in barley and wheat shoots in 2018

NFNB (kDNA/g)	Barley				Wheat			
Region (no. paddocks barley, wheat)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<1000)	Medium (<10000)	High (>10000)
Central west (7, 32)	57	43	0	0	100	0	0	0
North west (24, 59)	17	79	4	0	86	14	0	0
Northern tablelands (14, 3)	43	50	7	0	100	0	0	0
Southern Qld (1, 8)	0	100	0	0	100	0	0	0
All regions (46, 102)	***31***	***65***	***4***	***0***	***92***	***8***	***0***	***0***

Other DNA test results

The cereal cyst nematode, *Heterodera avenae*, was not detected in any of the root samples while DNA of the eyespot fungus (*Oculimacula yallundae*) and septoria tritici blotch fungus (*Zymoseptoria tritici*) were not detected in any of the shoot samples. *Rhizoctonia solani* (AG8) DNA was only detected in the root sample from one surveyed wheat crop near North Star in 2018 at a relatively low concentration (58 pg DNA/g root) and was not detected in any shoot samples.

Low levels of *Pythium* clade f DNA, a pathogen usually associated with seedling blight in wet soils, was detected at low levels in roots from 44% of cereal crops surveyed with higher detection (82%) in Central West crops (Table 10). Medium *Pythium* DNA levels were recorded in one barley crop near Yallaroi in North West NSW; and separate barley and wheat crops near Inverell in the Northern Tablelands.

Arbuscular mycorrhizae fungi (AMF) colonise roots of host plants and develop a hyphal network in soil which reputedly assists the plant to access phosphorus and zinc. Low levels of AMF have been associated with long fallow disorder in dependent summer (cotton, sunflower, mungbean and maize) and winter crops (linseed, chickpea and faba beans). Although wheat and barley are considered to be low and very low AMF dependent crops respectively, they are hosts and are generally recommended to grow to elevate AMF populations prior to sowing more AMF dependent crop species.

There are two DNA assays for AMF with combined results presented. It is important to remember that in contrast to all the other pathogen assays, AMF is a beneficial so nil or low DNA levels are the actual concern. AMF DNA was not detected in 39% of cereal root samples with the highest proportion of nil detection (59%) in central NSW crops (Table 10). The proportion of cereal crops with higher concentrations of AMF DNA in roots appeared to be greater on the northern tablelands, than north west, than the Central West. None of the nine paddocks surveyed in Southern Qld in 2018 had above a low level of AMF DNA in the roots (Table 10). The implication of these levels within cereal roots on AMF populations across a rotation sequence is not clear and cannot be determined from this current survey.

Table 10. Proportion of paddocks (%) with varying levels of *Pythium* or arbuscular mycorrhizae fungi (AMF) DNA detected in wheat and barley roots in 2018

Other	*Pythium* (pg DNA/g)				AMF (kDNA/g)			
Region (no. paddocks)	Nil	Low (<1000)	Medium (<10000)	High (>10000)	Nil	Low (<100)	Medium (<1000)	High (>1000)
Central west (39)	18	82	0	0	59	33	8	0
North west (83)	70	29	1	0	33	41	25	1
Northern tablelands (17)	53	35	12	0	24	29	41	6
Southern Qld (9)	67	33	0	0	44	56	0	0
All regions (148)	***54***	***44***	***2***	***0***	***39***	***39***	***21***	***1***

Conclusion

Molecular testing, such as PREDICTA® B assays used in this survey, are a powerful tool for quantifying levels of fungal pathogens, nematode pests or beneficial fungi (AMF) within crop tissue. Dividing plant samples into root and shoot (crown, stem, leaf and heads) samples prior to DNA testing allows an additional level of interpretation. At present DNA concentrations within root or shoot tissue can only be used for comparative purposes between regions, crops, seasons, rotation sequences, climatic conditions etc. Continuing surveys and associated research are required to understand what the actual impact of different DNA concentrations within root or shoot tissue has on crop production.

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The secret life of crown rot: what happens after harvest?

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Key words

Fusarium pseudograminearum, stubble management, inoculum level, durum wheat, bread wheat, barley

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Take home messages

- A preliminary survey of cereal stubble from 2017 showed that in the northern region (NSW and Qld) the crown rot fungus is commonly present from the crown up to 18 cm, with detection up to 33 cm within tillers at harvest
- However, moist conditions can promote further growth of the crown rot fungus post-harvest in inoculated cereal stubble (increasing by almost 1 cm up from the crown per day at 100% humidity)
- Inoculum levels in post-harvest stubble are not static and may fluctuate as different weather patterns are experienced
- Planting different bread wheat, durum wheat and barley varieties may not be useful for supressing inoculum growth in stubble after harvest
- Reducing cereal stubble height may limit inoculum build-up in crown rot affected paddocks by restricting the capacity for further fungal growth post-harvest. This could also help reduce dispersal of infected residues when harvesting shorter break crops such as chickpea, but field validation of this management option is required.

Introduction

Crown rot is a significant disease of winter cereal crops in northern NSW and southern Qld. The disease is estimated to cause $37 m loss to wheat production and $6 m loss to barley production each year in this region (Murray and Brennan 2009a, 2009b). In Australia, *Fusarium pseudograminearum* (*Fp*) is the dominant fungal species causing crown rot (Backhouse *et al.,* 2004). The fungus infects through the roots, crown, lower stem or leaf sheaths of growing plants. Once infection has been established, fungal mycelium can colonise the entire stem (Mudge *et al.,* 2006) and survive in these residues for at least three years after initial infection (Summerell and Burgess, 1988). Stubble retention practises help preserve inoculum in stubble and have contributed to an increase in the incidence of crown rot globally in the last three decades (Kazan and Gardiner, 2018).

To date, a large effort has been made to investigate the pathogenic (infectious) phase of crown rot in winter cereals in Australia (e.g. disease mechanisms, disease impacts, yield loss analyses, breeding etc.). However, stubble-borne pathogens such as *Fp* spend the majority of their life cycle in their saprophytic phase (i.e. surviving in stubble after the plant matures and dies). This phase has received much less research attention over the years, even though inoculum survival in stubble is a major challenge for crown rot management. Specifically, there is limited knowledge about the drivers of *Fp* saprophytic growth.

To begin investigating this problem and benchmark the natural incidence of crown rot inoculum at different heights within stubble, a preliminary survey was conducted using cereal stubble collected from the 2017 harvest through the National Paddock Survey (BWD000025) and National Variety Trials (NVT).

Vertical colonisation of cereal stubble - preliminary survey data

Segments (1.5 cm in size) were taken from main tillers at 4 cm intervals (at 0 cm, 5.5 cm, 11 cm, 16.5 cm) up to harvest height. Segments were surface sterilised and plated on laboratory media to assess the presence of *Fp* at the different stubble heights. This data was used to approximate how far, on average, the fungus had progressed within stubble in northern (NSW and Qld), southern (Vic and SA) and western (WA) regions (Table 1).

Table 1. Vertical incidence of the crown rot fungus *F. pseudograminearum* (%) recovered from four different heights in the 2017 post-harvest stubble survey. Incidence was averaged for each region.

Incidence *F. pseudograminearum* (%)			
Stubble sample height (cm)	Northern (n = 27)	Southern (n = 6)	Western (n = 26)
0 – 1.5 (crown)	46	25	17
5.5 – 7	40	7	16
11 – 12.5	26	8	7
16.5 – 18	19	0	3

Sites in the northern region (NSW and Qld) had higher incidence of inoculum at all stubble heights measured in 2017 compared with the other two regions (Table 1). This ranged from 46% in the crown section and gradually declined to 19% at 16.5 – 18 cm. Inoculum was found as high as 33 cm (tallest sample recieved) but the sample size (n) of stubble intact at this height was insufficient to include in the table of averages.

Inoculum assessment in post-harvest stubble is most routinely isolated from the crown and/or 5 cm up the stem. However, this preliminary survey shows that inoculum is retained within stubble not just in the bottom 0-5 cm, but substantially higher. Almost one in five tillers collected in the north contained inoculum at 18 cm in 2017 (Table 1). Crown rot inoculum retained in stubble around this height could become problematic when pulses such as chickpea are used as break crops due to their lower harvest height requirements. Harvesting of shorter stature break crops could potentially spread crown rot infected cereal residues from previous years into “clean” inter-row spaces where the fungus can more readily infect a new cereal crop sown into this space.

Another concern is that *Fp* has the potential to further increase in stubble (i.e. the fungus will grow saprophytically up the length of stubble) if conditions are favourable. For example, Summerell and Burgess (1988) observed an increase in inoculum levels at 20 cm above the crown in 18-month post-harvest wheat stubble following a wet summer. They suggested the moisture was facilitating the fungus to grow up the standing stubble. However, it is still unknown exactly what environmental conditions are required for vertical growth in standing cereal stubble, and how far or fast the fungus will colonise residues under these conditions. Therefore, a controlled environment experiment was conducted to identify if specific cereal stubble types (durum wheat, bread wheat or barley) or moisture conditions (wet, wet then dry and dry) promote *Fp* growth in post-harvest stubble.

Saprophytic growth in stubble - controlled environment experiment

Factors such as the individual saprophytic fitness of different *Fp* isolates have previously been investigated in Australia, where certain isolates were faster growing than others (Melloy et al., 2010). However, the effect of different cereal stubble types (e.g. durum wheat, bread wheat or barley) and moisture conditions on saprophytic growth has not been reported. Thus, the following factors were used to further explore *Fp* saprophytic fitness: moisture conditions (wet, wet then dry and dry), cereal type (durum wheat, bread wheat and barley), and isolate (isolate A from Wongarbon, NSW and isolate B from Horsham, Vic).

Treatments in the controlled environment experiment were randomised in a split plot design, where moisture treatments were randomly assigned to humidity chambers (main plots), while combinations of cereal type and isolate were randomly assigned to plates (sub plots) within each humidity chamber. Each treatment combination, being the combination of moisture treatment, cereal type and isolate, was replicated four times over repeated runs of the experiment.

Stubble of durum wheat (DBA Bindaroi⁽ᵇ⁾), bread wheat (Suntop⁽ᵇ⁾) and barley (Commander⁽ᵇ⁾) were collected from paddocks at the Tamworth Agricultural Institute in 2017. Stubble pieces were sterilised (autoclaved on two consecutive days) and one end inoculated with an agar plug of an isolate (Figure 1a) before being inserted upright onto nail plates to simulate standing stubble (Figure 1b). Each nail plate consisted of four stubble pieces of the same cereal type, infected with the same isolate. Nail plates were subsequently placed into one of three humidity chambers. Humidity chambers were set up to achieve a wet (0.5 L sterile water in the base of a closed 10 L container for five days), wet then dry (as per wet treatment but water drained and lid propped open after 2.5 days) or dry (no water added with container lid propped open) moisture treatment, all run in a room with alternating ultra-violet light (12 h light/12 h dark) at constant 25 °C. Tinytag data loggers (Gemini Data Loggers, Chichester UK) were used to log temperature and relative humidity.

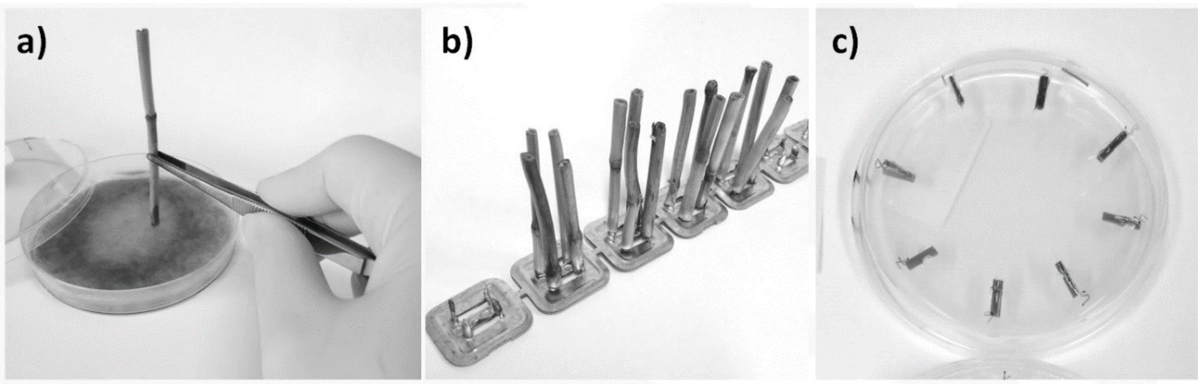

Figure 1. (a) Sterile stubble inoculated with an *F. pseudograminearum* agar plug by pressing stubble into the isolate culture. **(b)** Stubble pieces set vertically onto nail plates after inoculation. **(c)** Stubble trimmed into 1 cm pieces and plated onto agar for culturing after being subject to wet, wet then dry or dry environments for five days

After five days, tillers were removed and trimmed into eight 1 cm sections, with the inoculated end (0.5 cm of base) discarded. Sections (1 cm – 8 cm) were sequentially plated on laboratory media (Figure 1c) and incubated under alternating ultra-violet light (12 h light/12 h dark) at 25 °C. Each tiller section was scored for the presence of *Fp* after four days to measure the maximum height achieved.

Results - controlled environment experiment

Moisture conditions significantly affected the extent of *Fp* colonisation in stubble (Figure 2). After five days, the wet treatment (Table 2) resulted in the highest fungal growth, with a maximum extent of colonisation ranging from 3.8 – 4.2 cm (isolate A) and 4.3 – 4.6 cm (isolate B) (Figure 2). In comparison, the wet then dry treatment resulted in approximately half the growth, 1.7 – 2.2 cm (isolate A) and 1.8 – 2.4 cm (isolate B). The dry treatment promoted the least fungal growth, with average colonisation of 0.4 – 0.5 cm (isolate A) and 0.3 – 0.6 cm (isolate B). The rate of *Fp* growth observed was equal to almost 1 cm per day under high (100%) humidity in the wet treatment.

Temperature was unlikely to have affected colonisation as conditions were similar across treatments (Table 2).

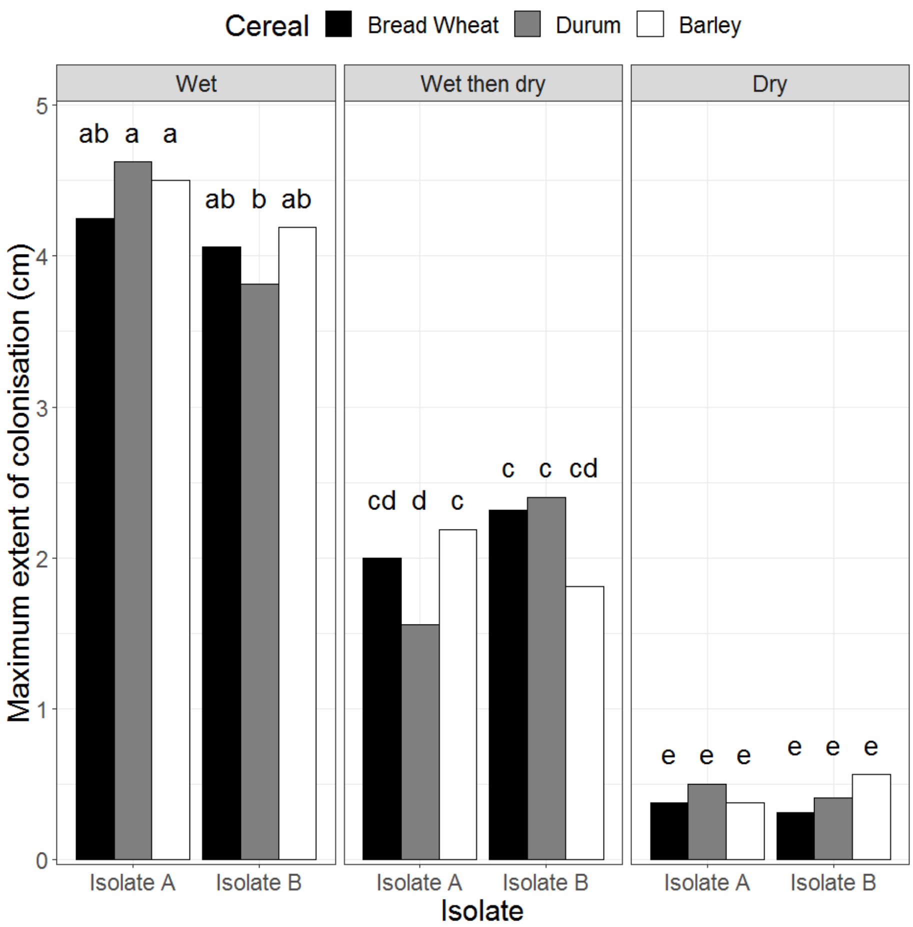

Figure 2. The saprophytic colonisation (in cm) of cereal stubble (bread wheat, durum wheat and barley) inoculated with *F. pseudograminearum* (isolates A and B) after five days in a wet, wet then dry or dry environment.

Table 2. Average relative humidity and temperature conditions for each moisture treatment (wet, wet then dry and dry) captured by Tinytag data loggers (averaged across reps).

Moisture treatment	Relative humidity (%)	Days exposed	Temperature (˚C)
Wet	100	0 – 5	24.7
Wet then dry	100	0 – 2.5	24.6
	55.4	2.5 – 5	24.6
Dry	53.4	0 – 5	24.6

Although the moisture treatments in this study show the largest effect on saprophytic growth, the interaction between isolate, moisture treatment and cereal type was also significant (P = 0.0364, Figure 2). However, trends are difficult to ascertain for isolates or cereal types. Both isolates still produced a substantial rate of vertical growth (almost 1 cm per day at 100% humidity) over the five days, with moisture significantly driving saprophytic fitness of *Fp.*

In summary, wet conditions (i.e. high humidity) appear to have the potential to cause an explosive increase in the saprophytic growth of *Fp* in cereal stubble. This reinforces that inoculum levels are not static within stubble, and they may fluctuate with different weather patterns during fallow or break crop periods. Furthermore, if moisture conditions allow, *Fp* is likely to progress up the stem after harvest regardless of stubble type. This means any yield advantages in the presence of high crown rot infection shown by different cereal types (e.g. crown rot tolerance in barley) are unlikely to slow saprophytic growth in post-harvest stubble. This supports existing recommendations that cereal or variety selection can increase yield, but not reduce inoculum levels, under crown rot pressure (Simpfendorfer, 2016).

Implications for crown rot management

One way to restrict the extent of saprophytic growth of *Fp* within stubble after harvest could be to reduce stubble length (e.g. by lowering the harvest height). This would limit the suitable substrate and resources available for the fungus to colonise, even if moisture conditions are suitable for growth. Reducing pre-planting *Fp* inoculum by half has been associated with a yield benefit of 6 to 8% in durum wheat, 2 to 9% in bread wheat, and 1% in barley in years conducive to disease development (Hollaway *et al.,* 2013). Keeping inoculum levels low is therefore necessary to reduce the risk of infection and outbreaks, and limit yield loss to crown rot in future cereal crops.

Further controlled environment experiments and field validation of results is required before specific recommendations can be developed. One such recommendation may be to match the harvest height of the cereal crop to the expected harvest height of the next crop in rotation. For example, if planning to sow a chickpea crop next season, the grower may decide to harvest their current cereal crop shorter. This could provide benefit in two ways. Inoculum build up would be limited by removing the available habitat for the fungus and capping saprophytic *Fp* growth at a lower height. Additionally, when harvesting the break crop (e.g. chickpea), the cereal stubble proportion of header trash would be reduced, thereby reducing the amount of stubble (and potentially *Fp* inoculum) dispersed. This would help ensure clean inter-row spaces for the next cereal crop to be sown into, with the aim of preventing crown rot infection by avoiding contact between existing *Fp* stubble inoculum and emerging cereal plants. This type of management strategy may also provide benefits with a range of other stubble-borne cereal diseases including common root rot (*Bipolaris sorokiniana*), yellow leaf spot (*Pyrenophora tritici-repentis*) and net blotch (*Pyrenophora teres*) which all survive in retained cereal stubble.

The trade-off between harvesting low to reduce stubble-borne inoculum levels and the benefits of harvesting high will require further consideration. For example, harvesting high (e.g. 40-60 cm using stripper fronts versus 15 cm using a conventional header) has been shown to increase harvest efficiency and reduce harvesting costs by 37-40% in south-west NSW (Swan et al., 2017). Therefore, early identification of paddocks which would benefit from having reduced stubble height is essential to balancing disease risk and overall profitability.

This paper highlights the importance of being aware of inoculum levels in retained stubble to inform crown rot management decisions. Some seasons (e.g. wet finish) and varieties (e.g. barley) are not always conducive to crown rot expression even when infection is present (Simpfendorfer, 2016). This means inoculum can be found in stubble without observing obvious symptoms (e.g. whiteheads or extensive stem browning). This ‘silent inoculum’ could lead growers to believe they have clean stubble, when in reality there is *Fp* inoculum waiting to infect the next cereal crop. At present, crown rot diagnostic services through NSW DPI and risk predictors such as PREDICTA®B can be used to determine the presence of crown rot inoculum in suspect paddocks to guide disease management decisions.

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Notes page for early riser's discussion

SOIL CONSTRAINTS AND ROOT HEALTH CONCURRENT SESSION

Root health – a key factor for cereal crop productivity

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Key words

root health, soilborne disease, pathogen, paddock survey, yield gap

GRDC code

BWD00056

Take home messages

- Root health issues were observed in all regions and seasons suggesting that significant potential exists to benefit from improving root health
- Multiple diseases were commonly observed in a single field
- Agro-ecological region based distribution variation of specific diseases was also found
- Agro-ecological region based variation in the types of root disease suggest the need for different management solutions. Recurring major diseases *versus* multiple diseases in single paddocks require different combinations of control measures in an integrated disease management program
- Root disease observations coupled with water-limited yield estimations and paddock data, indicated that root diseases are one of the key factors causing significant yield gaps in cereal crops.

Background

Soilborne root diseases are a major constraint for Australian cereal crop production with more than $800 million annual costs (Murray and Brennan 2010). In the northern region, there are a number of soilborne fungal and nematode diseases which collectively cost grain growers over $370 million each year. Good root health is critical for higher water use efficiency and plant nutrition in terms of ability to access nutrients from soil organic matter mineralisation. Nitrogen mineralised from the soil organic matter and crop residues makes a substantial contribution (~50%) to crop N uptake (Angus and Grace, 2017).

Cereals cropped continuously are at high risk from soilborne diseases, in particular from crown rot and Rhizoctonia bare patch, for which there is no reliable chemical or plant resistance based control measures (Gupta *et al.* 2015). Therefore, effective disease control requires the management of pathogen inoculum, in order to reduce the infection process and disease severity.

The most important soil-borne pathogens in the northern region are: crown rot and root lesion nematode (see pathogen distribution maps at: http://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b) in particular *Pratylenchus thornei*. Control strategies only provide good control at low to medium inoculum levels and their effectiveness declines as inoculum levels increase and where soil biological disease suppressive activity is low.

The aim of the GRDC-funded National Paddock Survey Project (2015 to 2018) is to quantify the yield gap on 250 paddocks nationally and to identify factors driving yield limitations in cereal crops across northern, southern and western grain production regions. The term yield gap refers to the difference between achieved and potential yield. On average, Australia's wheat growers currently achieve about half their water-limited yield (Hochman *et al.* 2016). Root health assessments are a crucial factor assessed in this context. Further, the projects aims to provide growers with information and the tools required to close the yield gap.

Methods

On average 250 paddocks per annum nationally, 80 in each of northern NSW/Qld and WA and 90 in southern NSW, Vic and SA, were monitored intensively over a four-year rotation (2015 to 2018). Consultants and farming systems groups undertook monitoring and sample collection for pathogen inoculum and root diseases. Two zones in each paddock were monitored at five geo-referenced monitoring points along a permanent 200 to 250m transect. Each monitoring point was visited four times per season (pre- and post-season soil sampling, and in-crop at the equivalent crop growth stages of GS30 and 65).

For root health assessments, wheat and barley root samples were collected at the GS31 stage from cropped fields (10 plants from each of five GPS locations on a 200 metre transect) from up to 200 fields/year. Seminal and crown roots were independently scored for general root health using a 0-5 rating scale (0=healthy; 5=80% of roots were diseased or showed abiotic damage). Additionally, the roots were collectively scored for the incidence and severity of seven major soilborne diseases on a 0-2 scale, based on presence and severity (0=no disease; 2=50% of roots infected with the disease). The seven different diseases were: take-all, Fusarium crown rot, Pythium root rot, Bipolaris root rot, Rhizoctonia root rot, Phoma root rot and nematode damage (cereal cyst nematode & *Pratylenchus*). Roots were also scored for non-biological damage and other root diseases. Subsamples of roots with typical symptoms of known diseases, and difficult to diagnose disease symptoms, were analysed using DNA based identification tests. Pre-sowing soils from each location were analysed (PREDICTA®B) to quantify the pathogen DNA loads of a range of cereal root pathogens.

Results and discussion

Overall root health

Root health in cereal crops is a general concern in all regions, localities and fields in all three seasons. In general, plant roots sampled across all regions contained at least some root damage and only a few fields (<20%) had plants without disease symptoms (Figure 1). However, few fields (on average 20%) had an overall root disease score of 3 or above. In general field level root disease scores were higher in the 2016 and 2017 seasons, when compared to disease scores in the 2015 season in all regions. Results show widespread moderate levels of root disease in cereal crops across Australia. Average root disease scores across all regions during 2015 to 2017 were: southern=1.5 to 1.8, western=1.2 to 2.7 and northern=1.5 to 3.4.

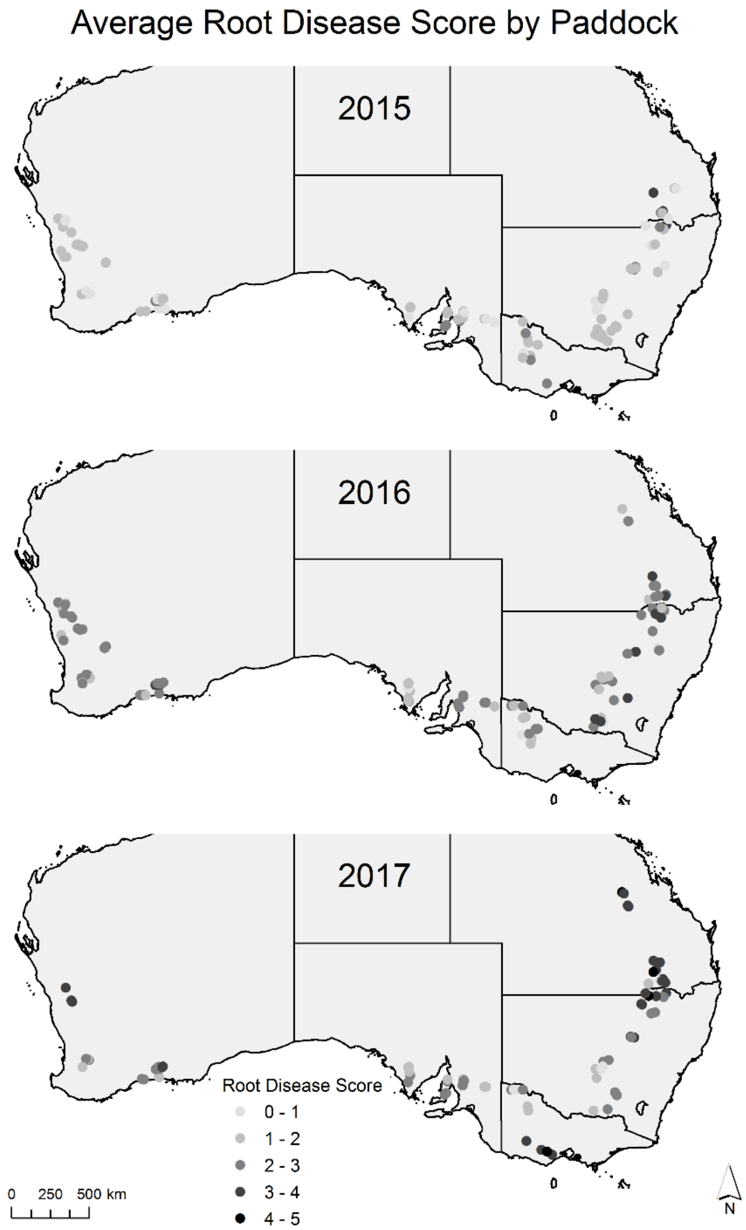

Figure 1. Root disease incidence score (on a 0-5 scale; 0=healthy and 5=diseased) for each field across all regions during the 2015 to 2017seasons. Average root disease score varied between fields within a region, between regions and seasonally

As good root health is essential to access nutrients and water from the entire soil profile in the rainfed cropping regions of Australia, these results suggest that there is a significant potential to benefit from improving root health by adopting management practices that reduce pathogen inoculum levels and improve soil biological activity (disease suppression) to buffer against disease impacts on crop performance. It is generally recommended that most effective strategies to minimise yield losses in cereals caused by soil-borne diseases must be implemented before sowing. It is important to know which soil-borne disease poses the greatest risk to the planned crop for the development of effective management strategies.

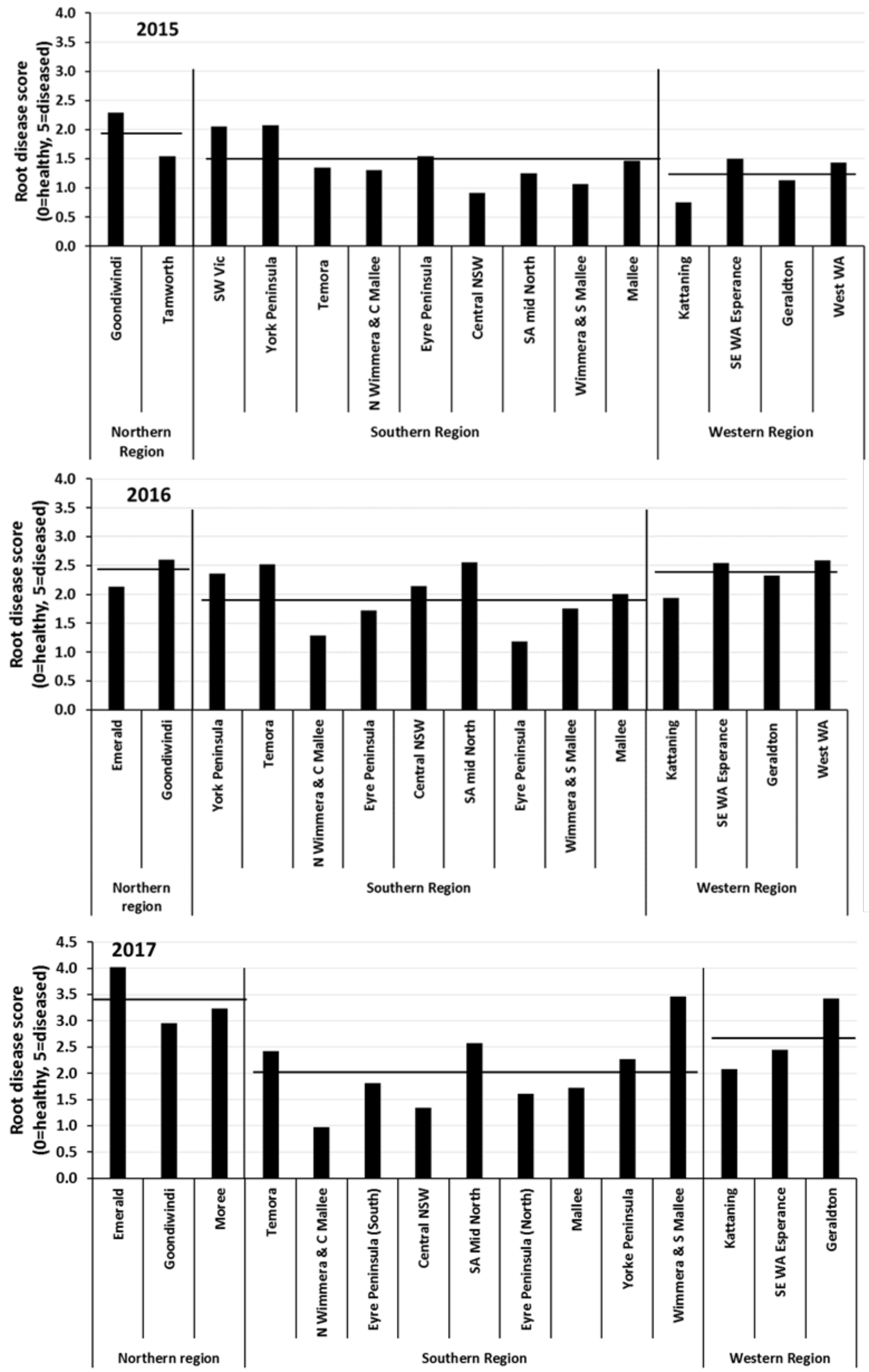

Figure 2. Average root disease ratings in cereal crops sampled 8 weeks after emergence from paddocks monitored by the National Paddock Survey project during 2015 to 2017. Horizontal lines represent the regional average.

Within each region there were clear locality (district) based differences (e.g. Goondiwindi, Emerald) in terms of overall root health (root disease ratings) in all seasons (Figures 1 and 2). Also, within each locality there were significant between field differences in overall disease scores and the distribution of different diseases. Observations from the Predicta B DNA test results for farmer fields during the last decade have shown distinct regional based differences and seasonal variation in the distribution of various soilborne pathogens (http://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b). Together, these observations indicate that soilborne disease risks are wide spread across all grain crop growing regions. In general, each 0.5 unit increase in root disease score above a base of 0.5 units can reduce yield by 10%. This means average yield losses caused by soil-borne diseases in the northern region could exceed 20% per annum. However, management and environmental factors such as seasonal conditions would influence the level of impact on production. For example, the 2015 season in the northern region was characterised by little rainfall in spring and hot grain-fill temperatures, by contrast, 2016 generally had above average rainfall and minimal moisture stress during grain fill. Root health was generally worse in 2016 in comparison to 2015, as evidenced by an increase in the root disease score.

Regional distribution and recurring problems

Diseases such as Fusarium, take-all and Bipolaris root rot and root lesion nematodes were observed in multiple regions, whereas Rhizoctonia root rot was seen in southern and western regions only (Figure 3 and Figure 4). This type of regional distribution can be related mainly to environmental factors such as amount and seasonal distribution of rainfall, temperature, and soil properties such as clay content and pH. While the distribution of root lesion nematodes (*Pratylenchus*) was observed in all regions, when developing a management program, it is important to know which species are present within individual paddocks, e.g. *P. thornei* or *P. neglectus*, as each can have a different host range including differential effects on varieties. For example, in the northern region, *P. thornei* is considered as the most important nematode causing yield loss.

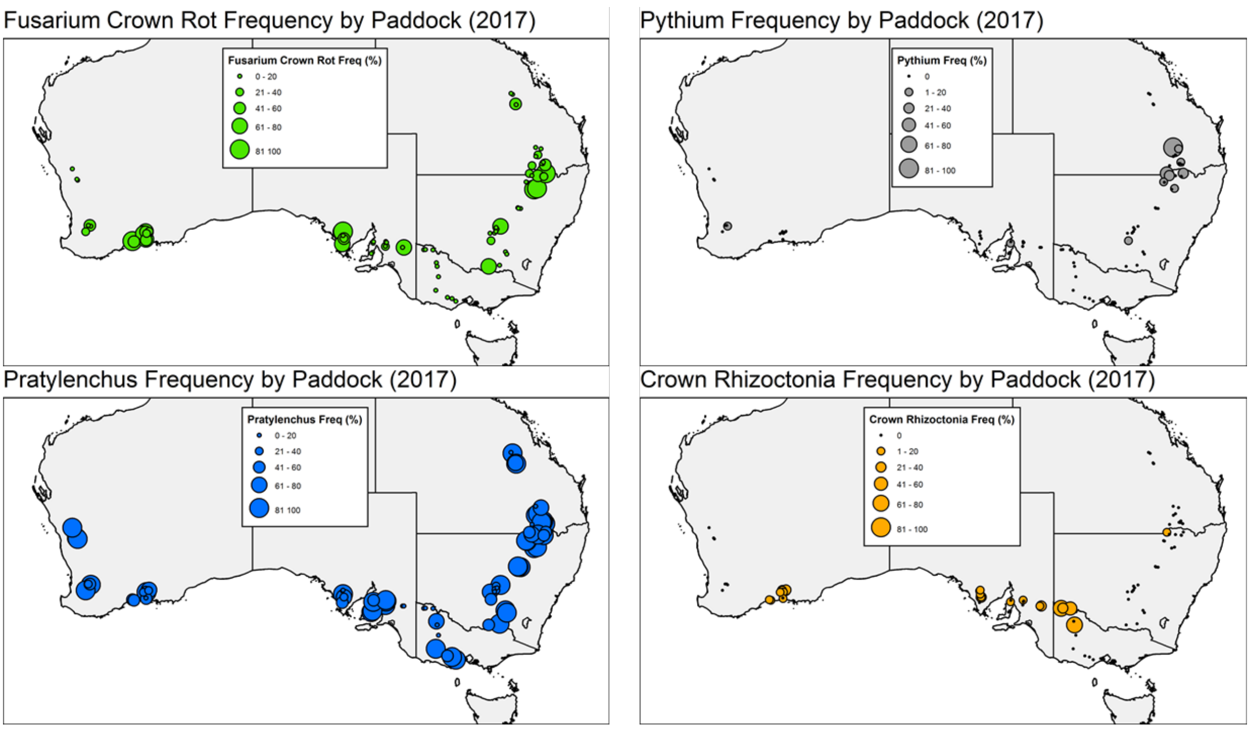

Figure 3. Frequency of occurrence (% plants showing the disease) of individual diseases in each field/paddock for major diseases during 2017 crop season.

Results over four seasons have clearly indicated the recurring nature of some of the soilborne diseases in all the regions although the severity of these diseases may vary between seasons. For example, Pythium root rot and *Pratylenchus* were commonly observed in the northern region (Figure 4). Similarly, the risk for Fusarium crown rot in the northern region was observed in all seasons, in particular in continuous cereal crop rotations, but the disease impact may only be seen in some years based on seasonal rainfall. Additionally, some of the recurring diseases in one region could be seasonally dependent in other regions, for example, Pythium root rot in the northern region is a recurring disease, but in the southern region it is only severe in wet seasons. Recurring diseases requires management intervention to avoid higher losses, mainly through adopting practices that reduce pathogen inoculum levels. For example, continuous vigilance is recommended to avoid inoculum build-up of pathogens like take-all and to reduce the potential impact on production in seasons of optimal conditions for disease expression.

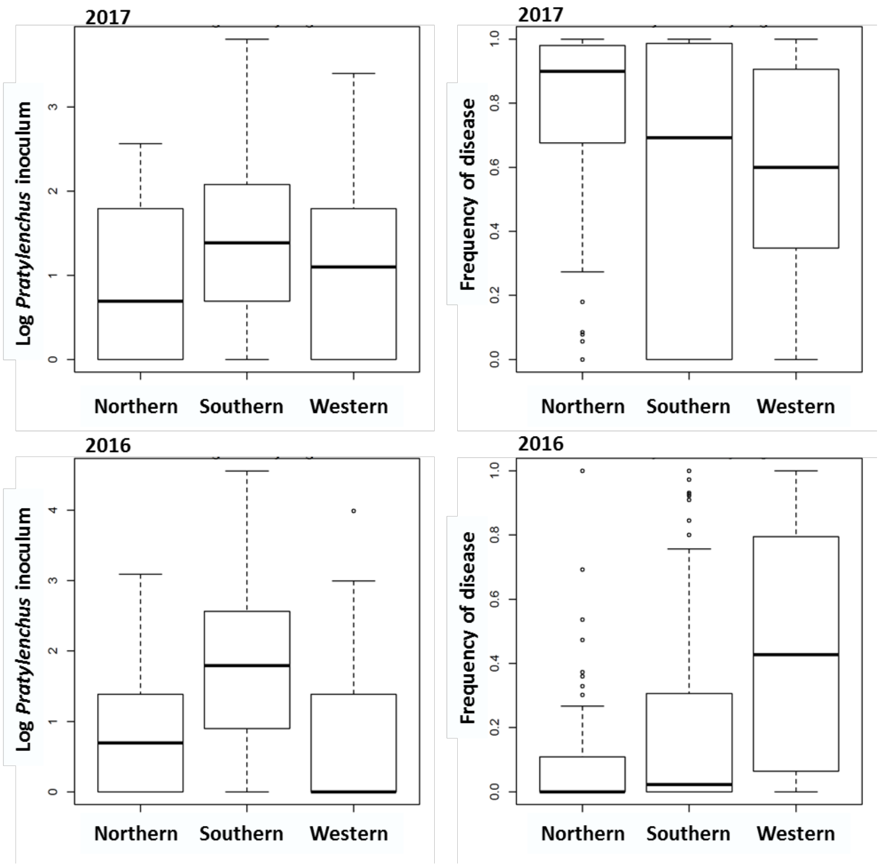

Figure 4. Regional average pathogen inoculum level (log DNA copies per gram soil, left) and frequency of disease incidence (right) in fields within a region for *Pratylenchus* in 2016 and 2017.

Disease complexes

Results have shown the presence of multiple diseases i.e. more than one soilborne disease, in single paddocks with the presence of at least two diseases in most fields surveyed in the northern region. Significant levels of specific or multiple soilborne pathogens were also found in the pre-crop soil samples (data not presented). However, the combination of specific diseases varies in different fields, localities and regions (Figure 5). For example, in the northern region, the commonly observed soil-borne diseases found within a single paddock are Fusarium crown rot, *Pratylenchus thornei* and Common (*Bipolaris*) root rot (Figure 5). In seasons receiving above average rainfall, especially during the early growing season, Pythium root rot is also a common occurrence. It is suggested that interactions between multiple pathogens could exacerbate yield losses, however the magnitude of yield loss from different combinations of diseases is not well known. Previous research by NSW DPI researchers (Steven Simpfendorfer and team) has shown that yield losses associated with crown rot (*Fusarium*) and common root rot infection, increased when both pathogens occurred together, and the primary driver of losses varied depending upon rainfall conditions. In the southern region, root diseases caused by *Rhizoctonia solani* AG8 and root lesion nematode were the most common multiple diseases. In such situations, pre-sowing analysis of soil using Predicta-B testing, would inform the disease risk for various diseases, thereby assisting to identify management options that limit the impact from multiple diseases and improve overall root health. In addition to pathogen load, abiotic factors (rainfall, soil fertility, residual herbicides), biotic factors (presence of suppressive microorganisms) and crop management practices (crop rotation and fertilizer additions), play an important role in determining the extent to which root disease symptoms are expressed. Therefore, effective management of soilborne diseases require both the reduction of pathogen inoculum through crop rotation, stubble management, restricting infection through improved soil biological activity (biological disease suppression capacity) and use of resistant varieties where available. Research in southern and western Australia has shown that adoption of management practices that increase carbon inputs and turnover (e.g. retention of stubble and no-till practices) and maintain biological activity during non-crop season over 5-7 years will improve biological disease suppression of soilborne diseases (Gupta *et al.* 2015).

Specific issues and other issues

In addition to the commonly observed diseases described above, other soilborne diseases and non-biological root health problems (e.g. residual herbicide impacts) can either directly affect root health or exacerbate disease impacts. The common root rot (*Bipolaris*) disease was observed in all regions, with its frequency of incidence and severity highest in the northern region. The brown root rot caused by *Phoma scleroitedes* was less commonly recorded, but occurred mostly in the southern and western regions.

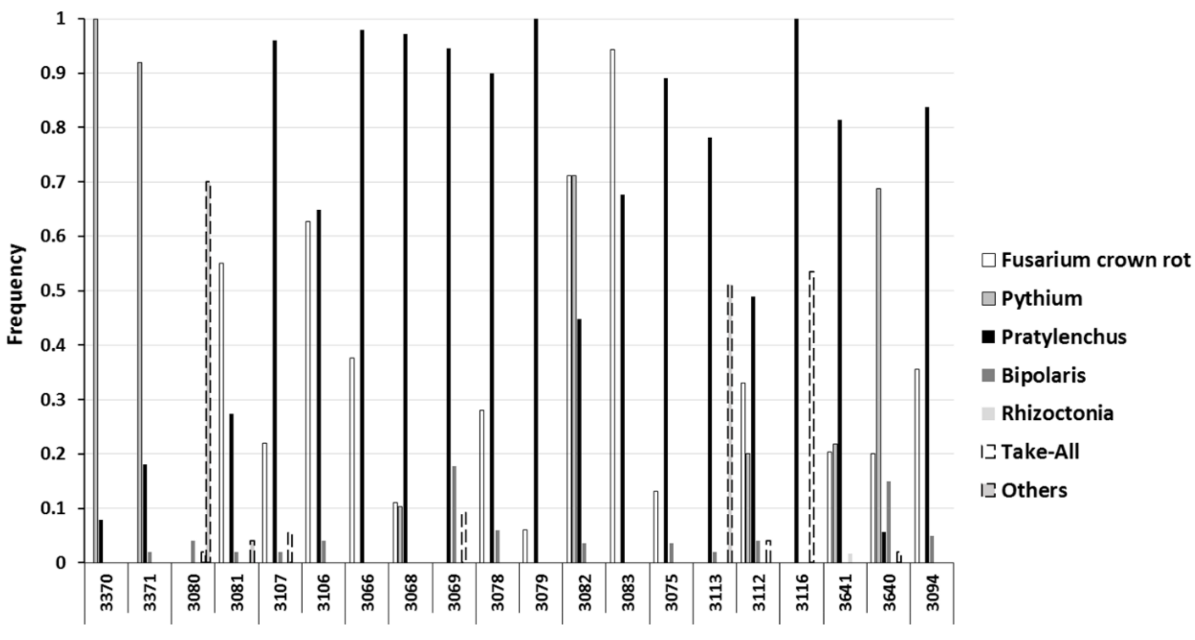

Figure 5. Frequency of specific disease occurrence in each field zone in the Northern region during 2017 crop season (transect numbers for individual field zones are shown on X-axis).

Implications

The National Paddock Survey project is helping to understand the critical drivers of the yield gap across Australia. Results indicated that multiple and interacting factors contribute to the yield gap in cereal crops and no significant relationship was observed between yield gap and any one single factor e.g. N fertiliser application, in-crop rainfall, weeds, disease (Lawes *et al.* 2018). Multiple season observations of root health, incidence of diseases and severity coupled with water-limited yield estimations and paddock data, indicated that root diseases are one of the key factors causing significant portions of the yield gaps in wheat and barley crops (Lawes *et al*. 2018; Van Rees *et al.* 2019). In the northern region, growing season rainfall, applied N and root disease score, were the three most important variables contributing to the yield gap. For example, crop rotation with legumes can have a significant impact on disease inoculum along with soil N dynamics and thus play an important role in alleviating root health and explaining the size of the yield gap. Whereas recurring diseases may require more than one season of non-host crops along with other management practices, e.g. sowing date, stubble management, fertilizer N addition, to reduce pathogen levels and disease impacts. In the case of disease complexes, an integrated disease management program is needed to reduce the impact from individual pathogens requiring different management interventions for reducing inoculum levels, restrict infection, improve nutrient availability during early seedling phase and remove abiotic constraints to root growth etc. Poor root health also restricts plants accessing soil N and water, hence improving root health is also essential to increase nutrient and water use efficiency. Other research has shown that there is potential to reduce the size of the yield gap with more targeted N management and crop rotation for disease and weed issues. Overall, farmer field based observations in the NPS project have demonstrated that, with the wide scale adoption of intensive cropping systems and as crop management becomes more sophisticated, knowledge about the reasons for crops' failure to perform at their potential is essential for the selection of appropriate management practices. The only way to achieve this is to keep records of what is happening in the soil, crop and weather and to make use of these records in deciding the crop management practices to be adopted (van Rees *et al.* 2019).

Useful resources

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Gupta VVSR et al. (2015) Management of soilborne Rhizoctonia disease risk in cropping systems. MSF 2014 Compendium articles, MSF Inc, Mildura.1-5 http://msfp.org.au/wp-content/uploads/2015/02/Vadakattu_Rhizoctonia-disease-risk.pdf

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Subsoil constraints: the many challenges of sodium, chloride, and salinity and what you can do about them

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Key words

sodicity, salinity, alkalinity, dispersion, calcium deficiency, gypsum

Take home messages

Clay soils, with poor surface structure because of excessive sodium, respond well to gypsum application. Application of gypsum to these soils is typically an economically attractive proposition. Non-clay soils with poor surface structure require different management approaches, such as variety selection to improve crop establishment.

Subsoil salinity can be ameliorated by increasing the leaching increment to move the salt deeper into the soil profile. In dryland agriculture, the only means of increasing the leaching increment is to increase infiltration (and reduce runoff). Gypsum application may help to achieve this.

Poor subsoil structure as a result of excess sodium is difficult to address. Deep ripping with considerable gypsum placed into the rip-lines has been successful, but it is expensive and has not been widely evaluated.

Introduction

We recognise a field as having a subsoil constraint when crops are unable to proliferate roots at depth to exploit water and nutrients that may be present there. We most commonly see this expressed as fields where the crop is particularly susceptible to water stress – and if we go to the effort of assessing the soil profile moisture distribution under these water stressed crops, we find that the surface soil is dry, but considerable water may remain in the subsoil. Things become more complicated when we start to consider why the crop's roots have not been able to exploit the subsoil, as there are a range of problems that all result in the same endpoint; failure of roots to grow to depth. From a practical standpoint, this is a substantial problem as there is no single treatment that can be applied to address all of the problems – different problems need different interventions.

Potential subsoil constraints include salinity, high bulk density, lack of aeration, calcium deficiency, sodium and chloride toxicity. Discussion of these various constraints is made complex by their inter-related nature. A subsoil that contains a lot of sodium chloride (NaCl), will impact on plant growth because of the osmotic effect of the salt making water less available. It may also result in a toxicity effect because of the high sodium (Na) and chloride (Cl) concentrations present in the soil solution, or the high Na concentration may induce calcium (Ca) deficiency.

'Subsoil constraints' is an enormous subject, and it would take a reasonable size book to relate the state of our understanding of the subject. For those of you who are interested, we refer you to the excellent book edited by Malcolm Sumner and Ravi Naidu "Sodic Soils, Distribution, Properties, Management and Environmental Consequences", 1998 Oxford University Press, New York. We have drawn on it liberally in this paper. Within this paper we address several subsoil constraints, in each instance initially covering the underlying science, then providing some commentary on strategies to ameliorate the problem, including when these are likely to work and when they are likely to fail.

While we are primarily focusing on subsoil constraints here, our interventions to address the subsoil problem often focus on the surface – for example surface application of gypsum. So, surface soil condition will frequently come into our discussion.

Finally, there is little truly new here from a scientific perspective. That sodic soils are a problem, and that gypsum is a part of the solution, has been known for a long time. Here is a view from 120 years ago – "This evil admits of cure by treatment with gypsum" (Warington 1900). Our problem is knowing how to apply our scientific knowledge in a practical and economically attractive way – so this paper will step away from science a little in order to focus more on the practical.

Effects of sodium on the physical properties of soil

Sodic soils have extremely poor physical characteristics which in agricultural soils lead to problems managing soil water and air regimes. The adverse effects of sodicity on surface soils, and their impact on crop performance are well known. The lack of soil structural stability results in dispersion of the surface during rainfall to form a seal. This seal limits infiltration partitioning a greater proportion of rainfall to runoff. This reduces water availability for crops growing in the soil and increases the risk of erosion. On drying, the seal hardens as a crust that can prevent emergence of germinating seeds and result in poor crop establishment. In addition, sodic soils are difficult to cultivate and have poor load-bearing characteristics. In the subsoil, poor structural stability as a result of excess sodium is likely a key contributor to high bulk densities, and the consequent low hydraulic conductivity and poor soil aeration.

These behaviours are a result of the influence of sodium on the clay fraction in the soil. When the cation exchange is occupied by calcium or magnesium, the individual clay platelets aggregate as illustrated in Figure 1, and the soil behaves in many respects like a silt or sand because the aggregates of hundreds of clay platelets constitute 'particles' of similar physical size. An aggregated clay soil has good structural characteristics. When the exchange is occupied by sodium, the individual clay platelets repel each other, and these aggregates of clay platelets break up. The soil structure is destroyed, the clay disperses in water and is easily eroded. The breakaway gullies we commonly encounter in duplex soils are an excellent illustration of how easily sodium saturated clays are eroded – the soil literally melts away. In a cultivated soil, much lower levels of sodium saturation result in the various adverse agronomic outcomes that occur as a result of only a small portion of the clay dispersing. It is always important to remember that sodicity is a problem that impacts on the clay fraction of the soil. In a sand with little clay fraction, sodicity will not result in adverse physical conditions, though there may still be adverse chemical effects as we will discuss later.

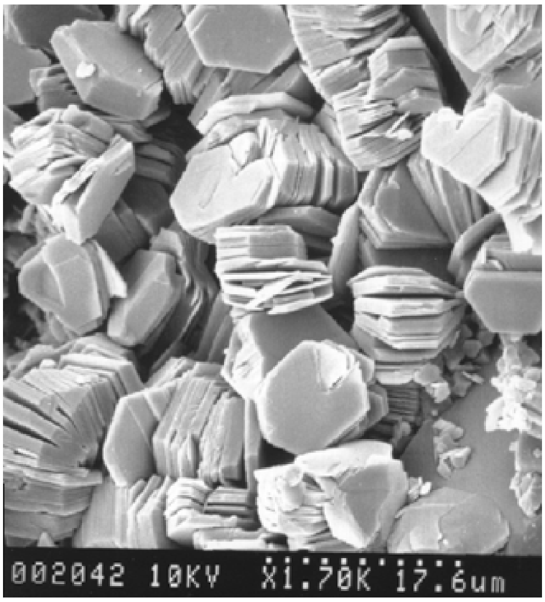

Figure 1. Scanning electron micrograph of aggregated clay platelets

Figure 2. Breakaway gully formation illustrates the ease with which sodium saturated clay can be dispersed and eroded

The composition of the soils cation exchange capacity (CEC) dictates the soils' physical behaviour, with dispersion being the interaction of multiple factors including the type of cation held on the CEC, clay mineralogy, soil texture, organic matter content, etc. Hence, rigid 'rules' and classification systems are not particularly effective at predicting soil structural behaviour. This is where an understanding of the underlying processes (and a great deal of experience) are needed to permit us to manage soil sodicity.

At a mechanistic level, two processes, 'swelling and dispersion', are responsible for the behaviour of sodic soils, with these two processes governed by the soil surface charge and how it is balanced by exchangeable cations. Last time I spoke to the GRDC on this topic, I provided a refresher on introductory soil science. We will not repeat this material here, but you can find the earlier talk at https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/02/soil-sodicity-chemistry-physics-and-amelioration

The take home message is that the extent of soil swelling in soils with montmorillonite type minerals (Vertosols), and the risk of dispersion of clay particles, increases as the level of exchangeable sodium increases.

The most common ameliorant applied to sodic soils to correct soil structural problems is gypsum. It acts to promote flocculation through two mechanisms; increasing soil solution ionic strength and by supplying divalent calcium ions to displace monovalent sodium from exchange sites. The first of these effects (increased ionic strength) is immediate and can be achieved by relatively low rates of gypsum application, but the effect is short lived (especially if the application rate is low). The effect of replacing sodium with calcium is permanent, unless additional sodium is supplied which will displace the calcium (for example, through the use of poor-quality irrigation water).

Gypsum application can be particularly effective as a means of improving soil surface conditions, providing better soil tilth and reducing crusting. However, the effectiveness of gypsum application in improving subsoil conditions is less well established. If we are considering surface application of gypsum, then the rates of application needed to displace sodium from the exchange throughout the soil profile would be considerable. In Table 1, we have provided data for a grey clay soil and the calculated rate of gypsum required to reduce the sodium saturation of the CEC to below 5%. The assumptions here are that replacement is perfect, i.e. that all of the calcium from gypsum replaces sodium and none is leached, the gypsum is pure, and the soil bulk density is $1.2 g/cm^3$. For this soil, 17 t/ha would be required to replace sodium to 60 cm, and 33 t to treat to 90 cm. Clearly these rates of application would not be economically attractive! Even if they were, we would need to consider the time it would take to move the gypsum derived calcium through the soil profile. Gypsum solubility is approximately 2.5 g/L, so it will take 40 mm of rainfall to dissolve 1 t/ha of gypsum. In an environment with 700 mm/year rainfall, it would take 2 years for the gypsum to dissolve from the soil surface. However, it will take a great deal longer for the gypsum to move to depth. If we assume that 10 mm/year leaches beyond 90 cm (this estimate is derived from salinity / leaching work on the western Darling Downs), then it would take 65 years for the gypsum to reach the bottom of the soil profile.

Table 1 provides us with a couple of really important points to keep in mind when thinking about sodic subsoils and their management. If the only option we have available to address subsoil sodicity is the surface application of gypsum, then it will take a considerable investment in gypsum, and a long time to see the benefit. There is also some cause to question if simply leaching calcium into a compacted sodic subsoil would help. The high bulk densities in sodic subsoils reflect the effect of high overburden pressure (the weight of the overlying soil) limiting shrink swell behaviour. In order for aggregation of the subsoil to occur, reducing the bulk density and permitting water and air movement, the overlying soil must be moved upward. As a thinking exercise; if we wanted to reduce the bulk density of a soil from 1.6 to 1.4, from 30 cm to 100 cm depth in the soil profile, the surface level of the soil would need to rise by 10 cm – effectively lifting 15,000 t/ha. Where would the energy to do this come from?

Deep ripping combined with gypsum application has been reported to result in increased crop yields, but the effect has often been short lived (2-3 years). However, it is important to look at what was done, and if we would expect long-term benefits. For example, McBeath *et al.* (2010) used a gypsum slurry to place gypsum into the subsoil, but the rate of application they could achieve was limited; in one soil they applied 0.5 t/ha, in another 1.4 t/ha. If we consider this in the light of the preceding discussion of short-term (increased soil solution ionic strength) and long-term (replacement of sodium by calcium) effects, the low application rate used would only provide the short-term benefit. In contrast, Armstrong *et al.* (2015) used deep ripping with 7.5 t/ha of gypsum placed into the slot with a boot on the ripping tine. This rate of gypsum would be expected to provide both a short-term benefit, and a longer-term benefit by lowering exchangeable sodium levels. Substantial yield benefits were obtained for the four-year duration of the trial, and it is reasonable to expect that they would be sustained beyond the life of the trial.

Ripping gypsum into the subsoil speeds the rate at which a beneficial effect on the subsoil could be expected. Deep placement would also be expected to reduce the total amount of gypsum needed. This is because we do not need to treat the entire volume of subsoil in order to exploit the water it contains – water can move from untreated soil to roots growing in treated rip-lines. Ripping invariably brings some of the highly sodic subsoil to the surface, so a surface application of gypsum is also needed to ameliorate this subsoil material.

Table 1. Exchangeable cation data for a grey clay soil, and the estimated gypsum requirement for different depth increments in the profile, and rainfall required to leach this gypsum into the soil.

Depth	CEC	Sodium (Na)	5% of CEC	Na reduction	Gypsum	Leaching requirement
cm	$cmol_{(+)}$/kg	$cmol_{(+)}$/kg	$cmol_{(+)}$/kg	$cmol_{(+)}$/kg	t/ha	mm
0-10	29	2.3	1.5	0.8	0.8	30
10-20	30	4.2	1.5	2.7	2.8	110
20-30	29	4.0	1.5	2.5	2.6	100
30-60	32	5.1	1.6	3.5	10.8	430
60-90	30	6.8	1.5	5.3	16.3	650
					33.3	1320

While the preceding discussion of remediation of subsoil sodicity has indicated that we still have much to learn, the situation for surface soils is much more clear-cut. Surface soil amelioration is achieved at much lower rates of gypsum application than is required to displace all of the sodium. The expectation from these smaller additions is that they will help to ameliorate the surface soil, increasing infiltration, and encouraging more uniform crop establishment. Repeat applications are typically needed to sustain the surface soil improvement. Such small applications can be economically attractive. In the GRDC funded Combating Subsoil Constraints project (SIP08), a one-time surface applied gypsum @2.5 t/ha increased cumulative gross margins by $207/ha over 4 crops (wheat 2005, chickpea 2007, wheat 2008 and sorghum 2009-10), removed 115 t sodium chloride from the rooting depth and increased plant available water capacity by 15 mm (Dang *et al*. 2010). Unfortunately, gypsum application is not always profitable, and more effective prediction of gypsum response is needed.

We need to divert briefly here to discuss alkalinity. Where sodium is the dominant cation in soil solution, the pH can rise to higher values than occurs where calcium or magnesium is the dominant cation. This is a simple reflection of the solubility of the respective carbonates of these cations. Calcium and magnesium carbonates are not very soluble, while sodium and potassium carbonates dissolve readily in water to form solutions with very high pH (once again, more detail in the earlier GRDC paper https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/02/soil-sodicity-chemistry-physics-and-amelioration. So, we can have soils that contain a great deal of calcium present as $CaCO_3$ but still have a high level of sodium on the CEC. If we add gypsum to an alkaline subsoil to try to increase the exchangeable calcium, the calcium supplied will precipitate as $CaCO_3$. This will lower the soil pH but will not raise the exchangeable calcium concentration as much as desired. If the soil pH is greater than 8.5, precipitation of calcium as $CaCO_3$ is likely. An alternative approach to this problem would be to add an acidifying agent (like elemental sulfur) to lower the pH, increasing the solubility of the $CaCO_3$ present, and in this way reducing the exchangeable sodium. The rate of sulfur needed to achieve a pH change is much lower than the rate of gypsum to achieve the same pH change, so deep injection of sulfur with ripping may be an effective strategy for dealing with sodic subsoils containing $CaCO_3$. While plants growing on alkaline soils express a range of nutritional problems, most of these would only be apparent when the whole soil profile is alkaline and are unlikely to be a problem when it is only the subsoil that has an excessively high pH. Sulfur application as suggested above is intended to address soil physical problems, rather than nutritional ones.

Finally, it is worth considering by what mechanism a sodic subsoil may be limiting root growth, and the likelihood that this can be ameliorated. The most direct effect of a sodic subsoil on root growth would be that the high bulk density, and resultant high soil strength, preventing roots from penetrating into the soil. Amelioration of this effect would require a change in bulk density and soil strength; something that may be achieved rapidly through deep ripping (and hopefully stabilised by deep placement of gypsum) within the cultivated layers, or potentially achieved over a much longer timeframe through gradual leaching of calcium to depth and the effects of repeated wetting and drying to develop soil structure. Closely related is the potential that root growth into sodic subsoils is limited by poor aeration. Given the very low air-filled porosities that are considered to exist in these dense subsoils, this is a very likely limitation to root growth and function. Like the soil strength limitation, this could only be overcome by changing subsoil structure. Another potential limitation to root growth is calcium deficiency. Under conditions of inherently low soil solution calcium, combined with high concentrations of soil solution sodium, plant roots may suffer calcium deficiency. Calcium cannot be translocated through the plant to growing root tips - it must be present in adequate levels in the soil solution at the place the root is growing. Root elongation is profoundly affected by calcium deficiency, without any distinctive symptoms showing on plant tops – other than the crop being susceptible to drought because of its poor root system. If calcium deficiency was limiting root growth, simply supplying more calcium, without the need for soil structural change, should improve root growth. Of course, these various limitations do not exist in isolation from each other, and poor root growth in a sodic subsoil is likely to be the net result of several limitations.

Effects on excess salt on plant growth

Salinity is considered to reduce plant growth and performance by several mechanisms including alterations in water relations within the plant, deficiencies or toxicities, and oxidative stress. Salinity is also considered to reduce the plant availability of soil water, with the osmotic effect on soil water potential reducing plant water uptake. As the salinity of the soil increases, so does the soil water content at which permanent wilting point (PWP) is reached. Saline subsoils may therefore remain wet even when the crop growing above them has wilted.

The amount of salt in a soil profile, and its distribution, is a reflection of the balance between long-term input of salt, and the leaching of this salt from the profile in deep drainage. In dryland systems salt input is predominantly in rainfall, while in irrigated systems salt input in irrigation water is likely to dominate. If we change the hydrology of the soil profile, causing more leaching without adding to the salt input, then the profile salt content will drop. This effect is well demonstrated by the Brigalow Catchment Study, where an area of brigalow scrub was cleared in 1982 for pasture and for cropping, and the salinity in the profile monitored periodically (1983, 1985, 1987, 1990, 1997, 2000). Silburn *et al.* (2009) provide an excellent analysis of the study and its implications. Before clearing, soil under the brigalow scrub contained about 40 t/ha of sodium chloride (NaCl) in the surface 1.5 m of soil, and the level of deep drainage was low (0.13 to 0.34 mm/y). Use of the land for cropping, increased deep drainage to 19.8 mm/y, causing displacement of salt from the soil profile. At the new equilibrium for the cropped soil profile, almost all of the 40 t/ha of salt in the surface 1.5 m will have been displaced. The approach to equilibrium is exponential, with rapid gains initially as salt is displaced from the upper layers of the profile, but progressively slower changes as salt is leached from lower levels. Silburn *et al.* (2009) calculated time to equilibrium at 50 to 200 years – but considerable reduction in the surface 1m was apparent within the first 6 years.

In dryland agriculture, our only option for increasing the leaching increment (beyond the change already achieved by converting native vegetation to cropping) is by increasing infiltration. If we can improve surface soil structure, resulting in greater infiltration and less runoff, we should be able to displace salt from the subsoil, increasing the depth of water extraction by the crop and the lower-limit soil water content. It is interesting to note that this did not happen in the brigalow catchment study where no change in lower-limit water contents or depths of soil water extraction were recorded. In this instance, the starting salinity levels were only marginally limiting to crop growth, so perhaps a change in crop performance should not have been expected. However, other factors complicate our analysis of the system. Leaching sodium chloride from a saline soil can leave us with a sodic soil, with its attendant poor soil structure and permeability. Of course, improving surface soil structure and infiltration will provide yield benefits in many years – reduction of subsoil salinity would be a bonus!

The preceding discussion has primarily considered the osmotic effect of salinity. Salinity may also limit crop growth through toxicity of sodium and chloride. While the mechanism of limitation to the crop is different, the same solution to the problem works for specific toxicities and the osmotic effect – reduce the levels of sodium and chloride by leaching them out of the root zone.

Of course, it may not be possible to remove the salt, so we need to consider strategies to "live with" the problem. Selection of crops that are more tolerant of salinity/sodium/chloride provides an option to manage the problem, and investment in screening/breeding for tolerance to high sodium and chloride could considerably improve this option for the future.

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Wheat varietal tolerance to sodicity with variable subsoil constraints

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Key words

calcium concentration, EM38, plant available water, soil constraints, wheat varieties

GRDC code

UA00159 Improving wheat yields on sodic or magnesic or dispersive soils

Take home messages

- Common soil constraints in semi-arid regions such as the northern region include; high sodicity in surface and subsoil, high salinity and phytotoxic concentration of chloride (Cl) in subsoil, and alkaline surface soils with acidic subsoil
- The yield penalty due to soil constraints is greater in years with below average in-crop rain (ICR)
- Yield ranking at sites without soil constraints is not a good predictor of performance at sites with soil constraints
- Certain genotypes rank relatively more tolerant to sodic soils with variable subsoil constraints than others
- Less water extraction occurs between emergence and anthesis (plant available water capacity, (PAWC)) at constrained sites as compared to sites without soil constraints
- Wheat grain yield increased significantly with increasing calcium concentrations in young mature leaves

Introduction

High sodicity in surface soil and subsoil, high salinity and phytotoxic concentration of chloride (Cl) in subsoil, as well as alkaline surface soils with acidic subsoil are common soil constraints in many semi-arid regions worldwide and in particular in Australia. These constraints reduce the ability of crop roots to extract water and nutrients from soil. Sodic soils tend to have severe soil structural problems including poor aeration and restricted water transmission, resulting in reduced root growth (Dang *et al.* 2006). Subsoil constraints, reduce the ability of crop roots to extract water and nutrients from the deeper layers in the soil, especially from layers high in salt content and soil chloride concentrations (Dang *et al*., 2008).

Successful dryland crop production in the north-eastern grain growing region of Australia depends on utilising soil moisture accumulated in the period preceding sowing. Due to the high clay content of soils in this region, these soils can potentially store 200-250 mm of water in the soil profile or more. However, soil constraints, especially in the subsoil, reduce the effective rooting depth thus also limiting plant access to water and nutrients and as a result, limiting crop yield (Dang *et al*., 2006). Several soil physiochemical constraints in the surface and subsoil interact with each other to determine the local environment for root growth. Rarely do the various soil constraints occur independently (Nuttall *et al*., 2003). The effects of soil constraints vary both spatially and over time. Spatial variation can occur within a field, across the landscape and with depth in the soil profile. There are also complex interactions that exist among the various physio-chemical constraints (Dang *et al.* 2006). These complicated interactions limit the agronomic and management options. The variable impact on crop growth and yield is compounded by the complex interactions between the range of soil constraints and environmental factors. In particular the timing and amount of rainfall relative to the crop growth stage. Selection of genotypes tolerant to soil constraints and identification of traits for pre-selection may provide a long-lasting tangible solution to improve wheat yields on these soils.

Materials and methods

A series of paired experiments were conducted during 2015-18 to evaluate wheat genotypes on two sites in southern Queensland. Sites were a distance of 0.5 to 5 km apart, with one site containing a range of soil constraints predicted to reduce wheat yields (Dang *et al.* 2006), with the other relatively non-constrained. The long-term average annual rainfall for the area is 617 mm with an average in crop rainfall for wheat growing season (mid-May to mid-November) of 170 mm. Each year the exact location of both experimental sites was changed, but they were within the same area on similar soil type. The soils at both sites were grey Vertosols. Sites were on a <1% slope and sown to wheat genotypes in mid-May to mid-June each year. Wheat genotypes were selected to represent the diversity of Australian wheat germplasm, including current and older varieties with a range of morphological and physiological traits (Table 1).

Soil and plant sampling and analysis

Two soil samples were taken per location, using a 50-mm diameter tube and a hydraulic sampling rig. Soil samples were extruded onto a plastic liner and then sub-sampled into a surface interval (0.0–0.1 m), then successive 0.2 m intervals to 1.5 m and analysed for soil physical and chemical properties.

At anthesis, 50 youngest fully mature leaves (YML) were obtained randomly from each replicate plot of each genotype, rinsed with distilled deionized water and dried at 70˚C for 48 hours. Dried plant samples were ground into a fine powder to pass a 0.5-mm sieve. To determine concentrations of sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), phosphorus (P), aluminium (Al), boron (B), copper (Cu), iron (Fe) and manganese (Mn), plant material was digested in a di-acid mixture of nitric and perchloric acid. Concentrations of ions were measured on an inductively coupled plasma-optical emission spectrometer (ICP). For chloride, ground samples of YML were extracted in hot water at 80˚C for 4 hours. The chloride concentration was determined using an auto-analyser.

Crop water use

We used an electromagnetic induction (EMI) instrument (Geonics EM38®) to measure apparent electrical conductivity in a vertical coplanar at critical wheat growth stages (emergence, stem-elongation, mid-tillering, anthesis, heading and maturity) to monitor crop water use. Since EMI provides only qualitative values for electrical conductivity, calibration is needed. Volumetric water content was measured on a separate 50-mm diameter soil sample to 1.5 m taken using the hydraulic soil sampling rig.

Statistical analyses

Analysis of variance for data on soil water, grain yield for each site was done using Genstat 16. The effect of sites and genotypes was analysed in a two-way factorial design. Significant differences between treatments were assessed using Fisher's l.s.d. (*P*=0.05). We used a paired t-test to examine whether, at a particular depth in the profile, the mean of a soil attribute differed significantly between the sodic and non-sodic sites.

Results and discussion

Soil constraints

Average and standard errors of soil constraints for the four sites are given in Figure 1. Compared to non-sodic sites, the sodic sites had significantly higher exchangeable sodium percentage (ESP) up to 0.6 m soil depth, significantly higher electrical conductivity (EC) and chloride concentrations to depth of 1.5 m. A value of ESP ≥6% in the surface soil would result in poor germination and water infiltration in soil (Rengasamy 2002). The sodic sites had chloride concentration >800 mg/kg below approximately 0.6 m soil depth, a threshold that generally results in reduced water and nutrient uptake and yield reduction in bread wheat (Dang *et al.* 2008). The non-sodic site had higher soil pH (>8.0) to a depth of 0.4 m soil and significantly lower pH (<5.0) below 0.9 m soil depth as compared to non-sodic sites. Acidic subsoils at sodic site containing toxic levels of aluminium or deficient amounts of calcium also restrict root proliferation.

Table 1. Details of wheat varieties (adapted from Anzooman *et al.* 2018)

Name	Type	Breeder[1]	Grade[2]	Target Australian region, comment
Axe ⓓ	Cultivar/Hexaploid	AGT	AH	SA, relatively drought tolerant
Aurora ⓓ	Cultivar /Durum	DBA	ADR	NSW and Qld
Baxter	Cultivar/Hexaploid	QDAF	APH	NSW and Qld
Batavia	Cultivar/Hexaploid	QDAF	APH	NSW and Qld
Bremer ⓓ	Cultivar/Hexaploid	AGT	AH	WA
Corack ⓓ	Cultivar /Hexaploid	AGT	APW	WA, relatively drought tolerant
Caparoi ⓓ	Cultivar /Durum	NSW DPI	ADR	Qld, NSW, WA and SA
Dharwar	Cultivar/Hexaploid	India		Indian cultivar, drought tolerant, deep rooted, tall
Elmore ⓓ	Cultivar/Hexaploid		AH	Nematode and rust tolerant
Emu Rock ⓓ	Cultivar/Hexaploid	InterGrain	AH	WA
Flanker ⓓ	Cultivar/Hexaploid	LPB	APH	NSW and Qld, resistance to stripe, stem and leaf rust
EGA Gregory ⓓ	Cultivar/Hexaploid	EGA	APH	NSW and Qld
Gladius ⓓ	Cultivar/Hexaploid	AGT	AH	
Hyperno ⓓ	Cultivar /Durum	AGT	APDR	SA,NSW- performs well in high yielding environment
Hartog	Cultivar/Hexaploid	QDAF	APH	NSW and Qld
Hydra ⓓ	Cultivar/Hexaploid	InterGrain	APW	WA
Impala ⓓ	Cultivar/Hexaploid	LPB	ASFT	NSW and Qld
Krichauff	Cultivar/Hexaploid	UA	ASW	South
Test line 1	Elite breeding line			NSW and Qld
Lancer ⓓ	Cultivar/Hexaploid	LPB	APH	NSW and Qld
Mace ⓓ	Cultivar/Hexaploid	AGT	AH	NSW and Qld, less susceptible to downgrading
Mitch ⓓ	Cultivar/Hexaploid	AGT	AH	NSW and Qld
Magenta ⓓ	Cultivar/Hexaploid	InterGrain	APW	WA
Pelsart	Cultivar/Hexaploid	QDAF		NSW and Qld
Janz	Cultivar/Hexaploid	QDAF	APH	Once widely grown in eastern Australia
Jandaroi ⓓ	Cultivar/Durum	NSW/DPI		NSW, SA, rust diseases resistant
Scout ⓓ	Cultivar	LPB	APW	Victoria and SA, resistant to leaf rust
SeriM82	Breeding line	CIMMYT		Once grown in many countries but not Australia
Spitfire ⓓ	Cultivar/ Hexaploid	LPB	APH	NSW and Qld
Sunco ⓓ	Cultivar/Hexaploid	AGT	AH	NSW and Qld
Suntop ⓓ	Cultivar/Hexaploid	AGT	APH	NSW and Qld
Sunmate ⓓ	Cultivar/Hexaploid	AGT	APH	NSW and Qld
Trojan ⓓ	Cultivar/hexaploid	LPB	APW	South and WA
Tammarin Rock ⓓ	Cultivar/Hexaploid		AH	WA
Wallup ⓓ	Cultivar/Hexaploid	AGT	APH	WA
Westonia	Cultivar/Hexaploid		APW	WA, widely adapted in international trials
Wyalkatchem ⓓ	Breeding line	InterGrain	APW	WA
Ventura ⓓ	Cultivar/Hexaploid	AGT	ADR	NSW and Qld
Viking ⓓ	Cultivar/Hexaploid	LPB	APH	NSW and Qld
Wylie ⓓ	Cultivar	EGA	AH	NSW and Qld
Yitpi ⓓ	Cultivar/Hexaploid	AGT	AH	SA and Victoria
Zen ⓓ	Cultivar/Hexaploid	InterGrain	ASW	WA

[1] Breeding program abbreviations: Australian Grain Technologies (AGT), International Maize and Wheat Improvement Centre (CIMMYT), Commonwealth Scientific and Industrial Research Organisation (CSIRO), Enterprise Grains Australia (EGA), International Centre for Agricultural Research in the Dry Areas (ICARDA), Long Reach Plant Breeders (LPB), Queensland Department of Agriculture and Fisheries (QDAF), Durum Breeding Australia (DBA), University of Adelaide (UA).[2]Grain quality grade abbreviations: Australian Hard (AH),Australian Premium White (APW), Australian Standard White (Kumaraswamy), Australian Premium Durum (Florentino et al.), Australian Soft (ASFT), Australian Standard Noodle Wheat (ANW), Australian Premium White Noodle (APWN) is classified in the WA zone only, Australian Prime Hard (APH) is classified for the Northern & South Eastern zone only.

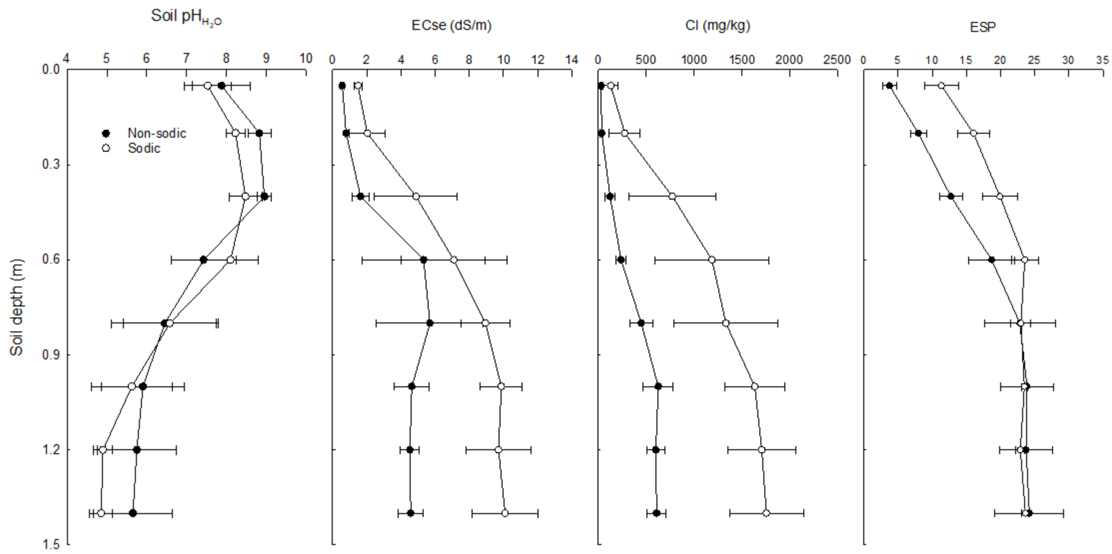

Figure 1. Average and standard errors of soil constraints for the sites during 2015-18 experiments

Yield penalty in sodic soil with subsoil constraints was seasonally variable

Substantially higher in-crop rainfall in 2015 and 2016 led to high average wheat grain yields at both sites with no significant differences between the sites for the 36 and 38 genotypes, respectively (Table 2). High in-crop rainfall allowed crops to grow with reduced reliance on extraction of water from the deeper soil profile. However, near average in-crop rainfall in 2017 and 2018 resulted in significantly reduced average wheat yield at the sodic site as compared to the non-sodic site. Sadras *et al*. (2003) in southern Australia hypothesised that plant available water is the key link between crop functionality and complex combinations of subsoil constraints, and that negative responses of subsoil constraints were more frequent in sites where conditions contributed to severe water deficits, i.e. low in-crop rainfall, less available water at sowing, and greater evaporative demands. Hochman *et al*. (2004), using APSIM simulation of wheat grown over 100 years in southern Queensland on relatively low and high subsoil constraint grey Vertosols, showed that yield differences vary from <200 kg/ha in some years to nearly 3 t/ha in others. The yield penalty due to subsoil constraints was seasonally variable; in-crop rainfall in the early part of the season (1 May to 15 August) was positively correlated with differences in grain yield ($P < 0.001$). Dang *et al.* (2008) in northern grain region showed that the presence of substantial higher chloride concentration (>800 mg Cl/kg) in the sodic subsoils restrict the ability of roots to extract subsoil water. Dang et al. (2010) analysing the results of 44 field trials in the case of bread wheat conducted in the northern region showed that yield penalty due to high subsoil chloride (>800 mg Cl/kg) was significantly higher in average in-crop rainfall seasons compared to high in-crop rainfall seasons.

Table 2. Date of wheat sowing (DOS) and harvesting (DOH), in crop rainfall (ICR) and site mean yield for wheat genotypes grown on non-sodic and sodic sites in 2015-18. Site wheat grain yield within a year followed by same letter are not significantly different (*P*<0.05)

Year	Field operations		in-crop rainfall (mm)		Wheat grain yield (t/ha)	
	Date of sowing	Date of harvest	Non-sodic	Sodic	Non-sodic	Sodic
2015 (36)	19.5.15	22.10.15	209	209	4.06[a]	3.64[a]
2016 (38)	25.5.16	10.11.16 (S) 17.11.16 (NS)	325	374	4.02[a]	4.00[a]
2017 (44)	10.6.17	31.10.17	132	128	1.61[a]	0.37[b]
2018 (18)	24.5.18	02.11.18	133	133	2.37[a]	1.16[b]

Numbers in parenthesis indicate the number of wheat genotypes grown in each year.

Yield ranking at non-sodic sites is not a good predictor of performance at sodic sites

Year 2015

Due to the timely in-crop rainfall (Figure 2), wheat grain yields at both sites were higher than normal and the grower reported his best crop yield ever at both sites. Site mean yields were 4.06 t/ha (sodic) and 3.64 t/ha at the non-sodic site (Table 2). In this 'non-water limited season', a number of genotypes exhibited higher yields at the sodic site than at non-sodic site (Figure 3). These included the breeder's line LPB10-2555. Cultivars Baxter, Gregory and Mace which have been shown to perform well under subsoil constraints, also exhibited higher yield at the sodic site than the non-sodic site as did the land race Dhawar Dry.

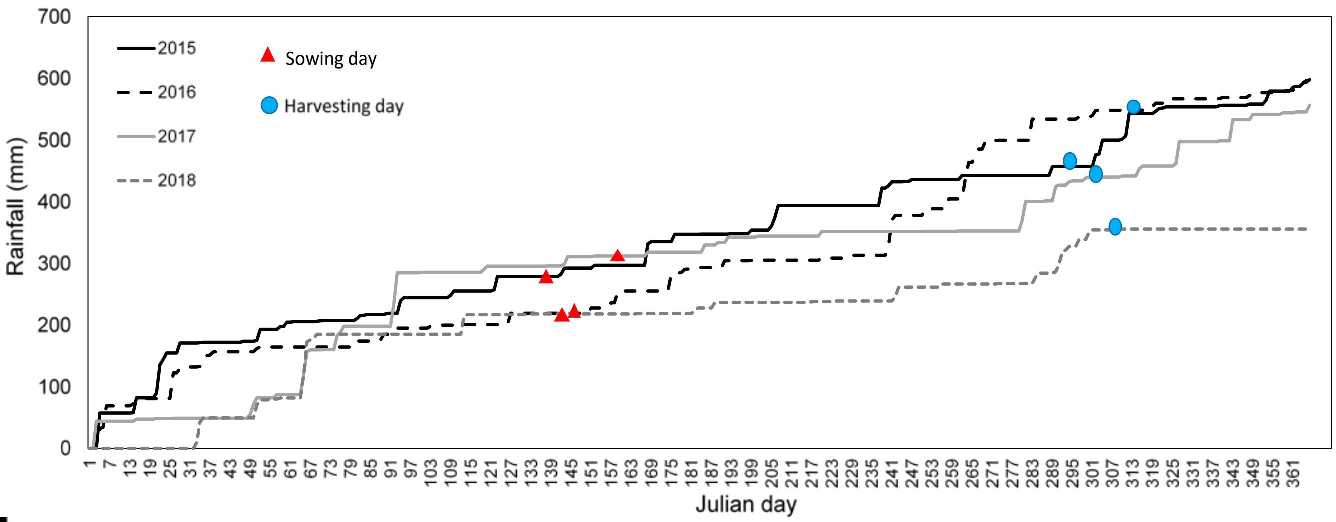

Figure 2. Cumulative rainfall during 2015-18 at the sites

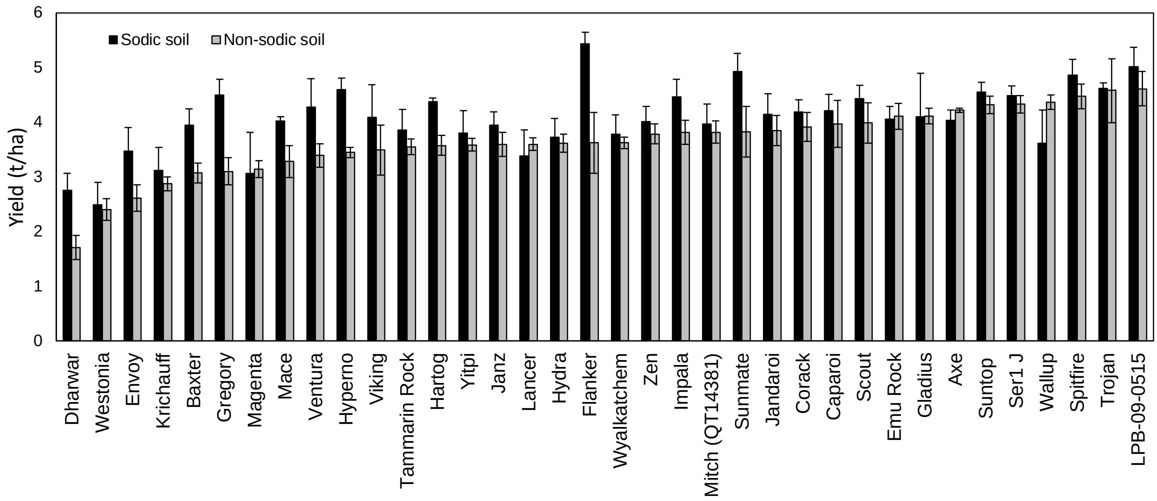

Figure 3. Genotype mean yields of 36 wheat lines at the non-sodic and the sodic site in 2015, ranked in ascending order of yield at the non-sodic site

Year 2016

Significant in-crop rainfall also occurred in 2016 just prior to each of the most critical crop developmental stages. As a result, the crop experienced little if any water-stress (Figure 2). This led to high grain yields at both sites with the non-sodic site averaging 4.02 t/ha and the sodic site 4.00 t/ha , with no significant difference between sites. Trial mean yield levels in 2016 were similar to those in 2015. A small number of genotypes exhibited higher yields at the sodic site versus the non-sodic site (Figure 4). These included Mitch bread wheat and Aurora durum. Baxter exhibited lower yield than many other genotypes at the sodic site. This result contrasts with 2015 where Baxter has been a better performer than many other lines on the sodic site. Baxter is favoured by the grower at the sodic site as the historically best performing cultivar at this site. This result suggests that results in both 2015 and 2016 are likely to be a poor indication of performance in the terminal drought environments that are more common in this region.

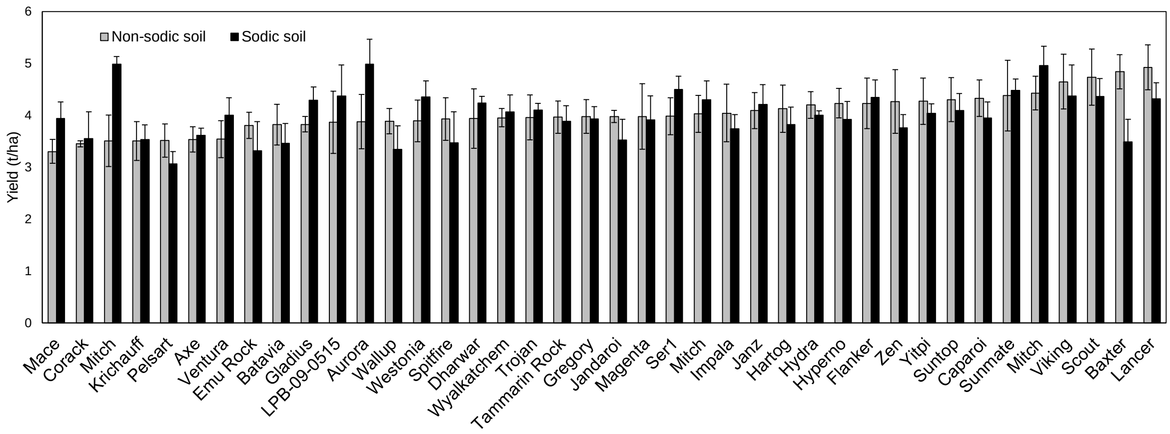

Figure 4. Average yields of 38 wheat lines at the non-sodic and sodic sites in 2016, ranked in ascending order of yield at the non-sodic site from left to right

Despite similar yields at the two sites in 2016, some symptoms of stress during early crop development were evident at the sodic site. The trial at the non-sodic site exhibited a mean emergent plant density of 86 m^2 which is close to the target population density of 100 m^2. In contrast, strong crust formation at the sodic site (Figure 5) resulted in reduced emergence averaging only 38 m^2.

Figure 5. Crust formation at the sodic site in 2016 significantly reduced emergence. Crust segments in the lower portion of the image were removed to reveal etiolated (yellow) seedlings that failed to emerge when trapped beneath the crust

In addition to the difference in emergence between sites, there was also a difference in crop duration to anthesis. The average period from sowing to anthesis at the sodic site was 112 DAS (days after sowing), which was considerably shorter than at the non-sodic site (124 DAS). Plants at the sodic site seemed to have exhibited a remarkable ability to compensate for these early setbacks, likely due in large part to plentiful late season rainfall.

Year 2017

Crop establishment was reduced at both the sites due to dry top soil and a lack of follow up rainfall after sowing (Figure 2). However, the effect was much greater at the sodic site where establishment was 26% less than that at the non-sodic site. The lack of rainfall also meant that a surface crust failed to form at the sodic site as occurred in 2016. This suggests that the reduction in establishment observed at the sodic site was not mainly due to soil crusting. Wheat genotypes grown at the sodic site exhibited substantial yield reductions (62%-83%; av. 76%) as compared to the non-sodic site (Figure 6).

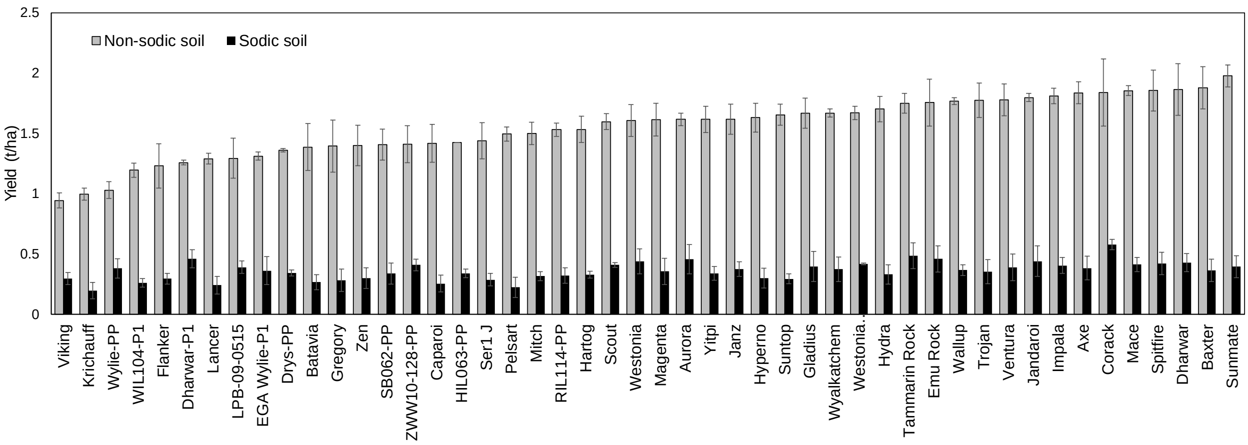

Figure 6. Mean grain yields of wheat lines at the sodic and the non-sodic site in 2017, ranked in descending order of yield at the non-sodic site.

As anticipated, northern adapted lines such as Baxter and Sunmate⟨ꟾ⟩ were highly ranked at the non-sodic site. However, rankings at the non-sodic site were not a good indicator of rank at the sodic site. Southern and western region lines such as Corack⟨ꟾ⟩, Tammarin Rock⟨ꟾ⟩ and Emu Rock⟨ꟾ⟩ were highly ranked at sodic site (Figure 6). Durum genotypes were not poorly ranked at the sodic site, suggesting that sodium toxicity was not an important driver of yield. Mapping population parents Batavia and Pelsart both ranked poorly at the sodic site and there was little difference between the two. This suggests that the Batavia x Pelsart mapping population is not likely to be useful in dissecting the genetics of tolerance to sodicity with variable sub-soil constraints.

Year 2018

Crop establishment was reduced at both sites due to dry top soil and a lack of follow up rainfall after sowing. The impact was greater at the sodic site where establishment was 35% less than that at the non-sodic site (Figure 7). Similarly to 2017, the lack of rainfall after sowing failed to form surface crusting at the sodic site as occurred in 2016. This suggests that the reduction in establishment observed at the sodic site in 2018 was not largely due to soil crusting. Some other physical and/or chemical impacts of sodicity probably resulted in poor establishment. Wheat genotypes grown at the sodic site exhibited significant yield reductions (33%-66%; av. 51%) as compared to the non-sodic site. Although differences between wheat genotypes were not significant (P<0.09), the yield ranking for wheat genotypes between sites were similar to those observed in 2017. Wheat genotype yield rankings at the non-sodic site do not give a good indication of ranking at the sodic site. The ranking of certain wheat genotypes changed significantly in the presence of soil constraints. The cultivars Corack⟨ꟾ⟩, Mitch⟨ꟾ⟩, Trojan⟨ꟾ⟩ and Mace⟨ꟾ⟩ ranked highly at the non-sodic site. The wheat genotypes LBP10-255, Corack⟨ꟾ⟩, Janz and Sunco ranked highly at the sodic site.

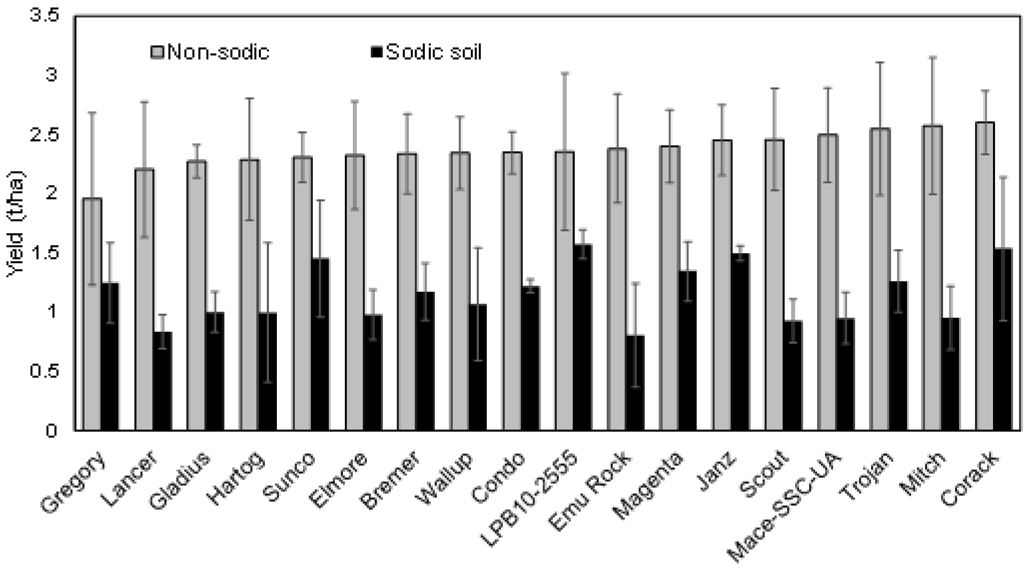

Figure 7. Mean grain yields of wheat lines at the sodic site in 2018, ranked in ascending order of yield at non-sodic site in 2018.

Soil water extraction was correlated with yield

Extraction of soil water from the soil profile was examined using the difference in the soil electromagnetic conductivity measured using an EM38 at near full soil water profile at sowing and that measured at different wheat growth stages (emergence, early tillering, mid-late tillering, head emergence and anthesis). In 2015 and 2016, there were no significant differences in the water extraction between sites and genotypes (data not shown). In 2017, the relationships between wheat grain yield and difference in EM38 reading between sowing and different growth stages of wheat were positive, however, this relationship was strongest at anthesis when soil water depletion was near its greatest. Further, this relationship was stronger in sodic soils as comparted to the non-sodic site (Figure 8). Positive relationships between grain yield of wheat genotypes and differences in water extraction between sowing and anthesis were obtained at both sodic and non-sodic sites.

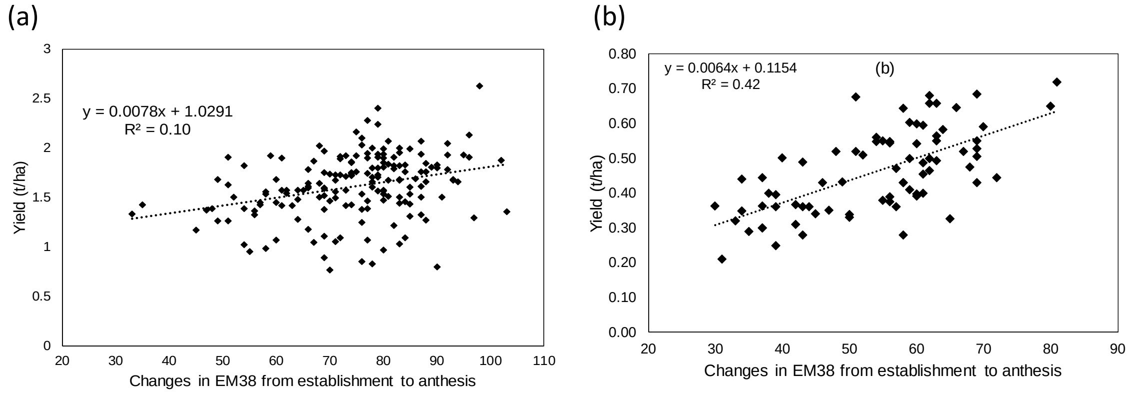

Figure 8. Relationships between soil water extraction between sowing and anthesis with wheat grain yield at (a) non-sodic site and (b) sodic site in 2018.

Calcium concentration in young mature leaf was correlated with higher yield

In 2015 and 2016, there were no significant differences in the concentration of elements measured in the youngest mature leaves between sites and genotypes (data not shown). By contrast, in 2017 and 2018, calcium and potassium concentrations were significantly higher in the youngest mature leaves at the non-sodic site than in the sodic site (Figure 9). However, the differences between wheat genotypes were significant only for calcium. This suggests that leaf calcium concentration might be useful to distinguish performance between sites and genotypes. This result agrees with observations made in previous seasons, where good discrimination in performance was observed between sodic and non-sodic sites (Dang *et al.* 2016).

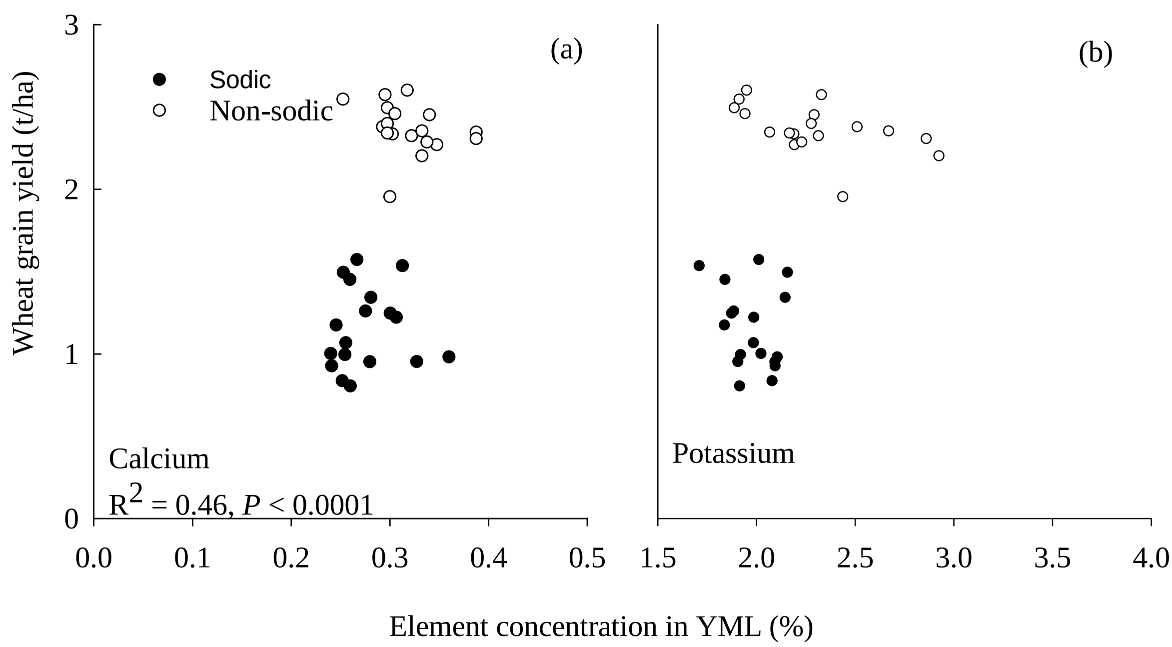

Figure 9. Relationships between element concentration in young mature leaf of wheat at anthesis and wheat grain yield at (a) non-sodic site and (b) sodic site in 2018

Discussion

Crop performance under non-sodic conditions is not a good indicator of that in the presence of sodicity

Experiments in 2017 and 2018 indicated substantial differences between performances of wheat genotypes under sodic soil conditions with subsoil constraints. Results indicated that performance under non-sodic conditions were not a good indicator of performance in the presence of sodic soils with variable subsoil constraints. Comparing the grain yields of wheat genotypes grown at the sodic site to that at the non-sodic site, significantly higher ESP to a depth of 0.6 m in the sodic soil resulted in reduced grain yields of wheat genotypes. It has been shown that ESP >6 % in the surface soil (Rengasamy *et al.* 2002) and >19 % in the subsoil (Nuttell *et al.* 2003) reduce grain yield of most crops. Grain yield on sodic soils is often less than 50% of the potential yield. Dalal *et al.* (2002) found that wheat yield in north-eastern Australia decreased from 3.5 t/ha to <2 t/ha as a result of sodicity (expressed as ESP) increasing from 4 to 16 % in the topsoil (0-0.1 m soil depth). In southern Australia, Rengasamy *et al.* (2002) reported a nearly linear decline in grain yield with increasing ESP in the surface soil for 30 different crop and pasture types. It is important to note that although all genotypes of wheat had reduced grain yield when grown at the sodic site compared to the non-sodic site in 2017 and 2018, the ranking of different genotypes varied at the different sites. In general, wheat cultivars Baxter and Sunmate⦶ were highly ranked at the non-sodic site. However, rankings at the non-sodic site were not a good indicator of rank at the sodic site. Southern and western regions lines such as Corack⦶, Tammarin Rock⦶ and Emu Rock⦶ were highly ranked at the sodic site. These results suggest that selection and recommendation of wheat genotypes for sodic sites needs to be based on testing done in the presence of soil constraints.

Differences in soil moisture extraction was the major determinant of performance differences in sodic soils with sub-soil constraints

All genotypes of wheat grown at the sodic site had reduced water extraction as compared to the non-sodic site in 2017 and 2018. Shaw (1997) showed a strong negative relationship between the effects of exchangeable sodium in the root zone on measured PAWC over the rooting depth of a crop in clay soils. Dalal *et al.* (2002) reported decreased PAWC from 120 mm to 80 mm with increasing ESP from 5 to 30% in the top 0.6 m soil depth in clay soils from north-eastern Australia. In the present study, the presence of high chloride concentration in the subsoil (below 0.90 m soil depth) at the sodic site likely further restricted water extraction, resulting in further reduction in PAWC. Dang *et al.* (2008) showed that subsoil chloride concentrations had a greater effect in reducing soil water extraction and grain yields of five crop species studied than did salinity or sodicity, per se. Subsoil chloride in the 0.90-1.10 m soil depth layers at >800 mg/kg has been shown to reduce wheat grain yield by 10% (Dang *et al.* 2008). In the present study, the chloride concentration in the subsoil at the sodic site was well above this threshold chloride concentration.

Concentrations of calcium in wheat may provide a useful surrogate trait to select for adaptation to sodic soil with variable subsoil constraints

The relationship between calcium concentration in youngest mature leaves with grain yield of wheat genotypes grown on the sodic and non-sodic sites was clear. The calcium concentration in youngest mature leaves of wheat genotypes grown on sodic soil was <0.35% and most genotypes had calcium concentration ≤ 0.25%. These levels were less than the critical limit (0.25%) for plant growth (Reuter *et al.* 1997). Most wheat genotypes grown at the sodic site had sodium concentrations <0.05% (data not shown). Generally, sodium becomes physiologically toxic to wheat at plant tissue levels greater than 0.1% (R. Munns, *pers. comm*.). Most of the wheat genotypes in the present study had sodium concentration <0.1% which corroborates with an earlier report suggesting that most of the Australian wheat genotypes accumulate sodium in the tissue well below the critical level (Liu *et al.*

2000). Wheat accumulated higher concentrations of potassium in the youngest mature leaves, but the differences between genotypes grown on the sodic site compared to the non-sodic site were not significant. Potassium concentration in the youngest mature leaves of wheat was well above the critical concentration for the growth of wheat (Reuter *et al.* 1997). The decrease in grain yield of wheat genotypes in the present study, beside other factors, is likely due to a combination of factors that include decrease in water extraction and calcium concentration in the plant tissues in the sodic soil.

Conclusions

Differences in wheat grain yield between sites varied greatly between seasons. In 2017 and 2018, wheat yields were lower at the sodic sites with variable subsoil constraints. In contrast, there was little difference in yield between sites in 2015 and 2016 due to higher than normal in-crop rainfall which reduced reliance on stored soil water. The yield ranking for genotypes at the non-sodic sites was not well correlated with that at sodic sites. Thus, selection for yield potential at non-sodic sites is not a good predictor of performance at sodic sites. However, yield rankings of genotypes continued to differ between unconstraint and constraint sites. Overall, certain genotypes tended to rank relatively more tolerant to sodic soils with variable subsoil constraints than others. The difference in water extraction between emergence and anthesis (PAWC) was significantly different between genotypes at sodic site as compared to non-sodic. Most wheat genotypes grown at the sodic sites had calcium concentrations below the critical level of <0.25% in the youngest mature leaves. Wheat grain yield increased significantly with increasing calcium. We successfully identified and quantified useful genetic variation in tolerance to sodic soils with variable subsoil constraints suggesting potential to breed new cultivars with superior tolerance.

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Understanding the physiological basis for improved wheat seedling growth on dispersive sodic soils

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Key words

emergence, germination, root angle, surface crust, seedling, sodicity and wheat

GRDC code

UA000159 Improving wheat yields on sodic or magnesic or dispersive soils

Take home messages

- Genetic differences in the speed of seedling germination and emergence are important factors determining whether seedlings can emerge from surface crusted sodic soils
- Selection of wheat genotypes with greater seedling emergence force and greater hypocotyl cross sectional area may potentially help to improve wheat seedling emergence in surface crusted sodic soils
- Selection for narrow seminal root angle may potentially help to identify wheat genotypes that are better adapted to sodic soils
- Wheat tolerance to the chemical constraints of sodicity might be governed by the ability of genotypes to take up calcium in roots.

Introduction

Globally, 581 million hectares (ha) of land is affected by sodicity. Australia has the most widespread area of sodic soils in the world, covering 340 million ha (Rengasamy & Olsson 1991; Rengasamy 2002). Soil sodicity is a major constraint limiting grain production, occurring in nearly 60% of the soils used for grain cropping in Australia. It is estimated to cost Australian growers $1460 million/year in forfeited grain yields (Orton *et al.,* 2018), with grain yield on sodic soils often less than 50% of the potential yield. Rengasamy (2002) reported that grain yield decreased linearly with increasing sodicity in surface soils. Similarly, Dalal *et al.* (2002) found that actual wheat yield in the north-eastern grain growing region decreased from 3.5 t/ha to <2 t/ha as a result of sodicity (expressed as exchangeable sodium percentage (ESP) increasing from 4 to 16 in the topsoil (0-10 cm soil depth).

The pressure to increase the use of sodic soils for productive agriculture poses a range of challenges. Approximately 105 M ha of land, representing about 14 % of Australia, has a sodic surface soil [0 to 15 cm; (Searle 2014). These sodic surface soils are often prone to surface crusting and hard setting. Soil crusting is a major problem in the semi-arid tropics particularly when heavy showers are followed by rapid drying after sowing (Richards 1953; Parker & Taylor 1965). This surface crust imposes a mechanical resistance to emerging seedlings. If the emergence force exerted by the seedling is lower than the mechanical resistance of the surface crust, seedlings will fail to emerge (Awadhwal & Thierstein 1985). Previous studies have reported the impact of soil crust on emergence of a range of crop species, including wheat, pearl millet *(Pennisetum glaucum),* maize *(Zea mays),* sorghum *(Sorghum bicolor)* and barley *(Hordeum vulgare*) (Hanks & Thorp 1956; Chaudhary & Prihar 1974; Soman *et al.,* 1984; Braunack & Dexter 1988; Abu-Awwad & Kharabsheh 2000).

Root system characteristics are of fundamental importance to a plant for soil exploration and below-surface resource acquisition, and hence are strongly related to plant adaptation to sub-optimal conditions (Manschadi *et al.,* 2006). The distribution of roots in the soil influences the pattern of water and nutrient uptake. The seminal root angle has been associated with temporal and spatial acquisition efficiency of soil resources (Manschadi *et al.,* 2008). Nakamoto and Oyanagi (1994) demonstrated significant genotypic variation in the angle of wheat seminal roots and argued that deeply-rooted wheat genotypes exhibit narrower seminal root angles, while genotypes with a shallower root system tend to grow their seminal roots more horizontally. Thus, wheat genotypes with a narrow seminal root angle may be more likely to extend deeper into the soil, which could provide an advantage for plants growing in sodic soils.

In addition to the physical constraints caused by dispersion, sodic soils can also have chemical constraints, including sodium and chloride toxicity, and deficiencies in essential plant nutrients, e.g. calcium, potassium. Calcium deficiency can particularly be a problem in Australian sodic soils, where calcium concentrations in the soil solution are often very low (<1 mM) (Reuter & Robinson 1997), and high sodium: calcium ratios can potentially cause a nutritional imbalance. Similarly, potassium is also often found at low levels, although potassium can be released in many sodic soils because of the presence of illite and borate (Cartwright et al. 1986). Numerous studies have shown that an increase of ESP causes a significant decrease in potassium availability and an increase of sodium in plant tissue of various crop plants, e.g. cotton *(Gossypium) (*Dodd *et al.,* 2010; Rochester 2010), rapeseed *(Brassica napus)* (Porcelli *et al.,* 1995), sugarcane *(Saccharum officinarum)* (Dang *et al.,* 1999), rice *(Oryza sativa) (*Qadar 1995), aloe vera *(Aloe barbadensis miller)* (Rahi *et al.,* 2013), barley *(Hordeum vulgare)* (Dang *et al.,* 2016) and wheat *(Triticum aestivum .L)* (Chhipa & Lal 1995; Wright & Rajper 2000).

Improving our ability to manage sodic soils requires innovative approaches. Rather than ameliorating sodic soils, a complementary approach can be to identify genotypes with improved productivity in these soils. In general, the development of genetic approaches for improving productivity in sodic soil requires the expression of tolerance to several soil constraints. Therefore, to develop sodicity tolerant crops and genotypes, both the physical and chemical constraints of sodic soils need to be considered. Identification of crop genotypes tolerant to physical and chemical impacts of sodic soils might be beneficial in improving crop productivity in these soils.

This study aimed to determine if the differences in seedling emergence between wheat genotypes grown in soils with a surface crust could be related to traits associated with superior emergence from sodic soils e.g. kinetics of seed germination, seedling emergence force, root traits and adaptability of these genotypes. It is intended that the information from this study will assist breeders, researchers and agronomists to improve wheat production on sodic soils.

Materials and methods

Experiment 1: Characterising seed germination

A total of 38 wheat genotypes were selected (Appendix A, Table A1), many widely grown in Australia. All seed samples originated from a harvest site at the Queensland Government research farm at Kingsthorpe, Queensland, Australia (27.52 °S, 151.79 °E) in 2015. Laboratory germination tests (Petri dish assays) were used to test the germination of wheat genotypes in the absence of soil constraints. Germination was assessed by placing 100 seeds of each genotype on filter paper in Petri dishes moistened with 5 ml deionized water, with two replicates per treatment. The Petri dishes were maintained at 20 °C, being in the dark for the first 5 d and then in a light/dark regime (12 h / 12 h) for a further 3 d. Relative germination proportion was calculated by counting the number of germinated seeds after 3 and 5 d. After a total of 8 d, seeds without visible swelling due to imbibing water were considered as non-germinating seeds.

Experiment 2: Impact of surface crust of sodic soils on emergence of wheat genotypes

The aim of this experiment was to determine the impact of surface crust on seedling emergence. A soil was chosen to be representative of the sodic dispersive soils affecting wheat crops in the western Darling Downs cropping region of Queensland. This sodic dispersive soil was collected from a property near Goondiwindi in southern Queensland (28.23 °S, 150.31 °E). Surface soil samples (0-10 cm depth) were air-dried and ground to pass through < 2 mm sieve. Soil pH (ISO 1994) and electrical conductivity (ISO 2005) were measured in 1:5 soil:water extracts. Exchangeable sodium concentrations and the cation exchange capacity were determined using a 1 M NH_4Cl (pH 8.5) extracting solution (Tucker 1954). Field water holding capacity was calculated using the column method (Asher *et al.,* 2002), and bulk density measured in the field using the method described by McKenzies *et al.* (2002). Prior to extraction, soluble salts were removed by pre-washing with 60% aqueous alcohol. The extracts were analysed for the exchangeable cations on an inductively coupled plasma-optical emission spectrometer. Exchangeable sodium percentage ESP was calculated from the amount of exchangeable sodium relative to the cation exchange capacity (Tucker 1985).

The experiment consisted of 76 treatments, resulting from the factorial combination of 38 wheat genotypes and two soil crust strengths, with each treatment having six replicates. For the 38 genotypes with six replicates, a total of 19 pots per soil crust treatment were required, in total 38 pots for two crust treatments. Each pot was randomly allocated a strong or weak crust treatment. Each genotype was randomly allocated to one of the twelve positions within each pot where the position is the experimental unit for genotype. A single seed was allocated to each position within a pot. The air-dried surface soil was placed in rectangular plastic pots, 70 cm long × 22 cm wide × 11 cm deep (overall pot depth of 16 cm). Soils were watered to 70 % of field capacity by repeatedly spraying deionized water evenly onto the soil over a 24 hr period. After wetting the soil to 70 % field capacity, seeds were placed on the surface of this soil. Once the seeds were placed on the surface of the soil in the appropriate pots, they were then covered with an additional 3 cm of dry soil .

The pots were then placed in the spray cabinet and two rainfall treatments were used to create crusts of two different strengths. Specifically, we used total rainfall treatments of 10 mm/pot and 24 mm/pot. Hereafter, these two treatments are referred to as 'weak crust' (10 mm/pot) and 'strong crust' (24 mm/pot). After treatments, pots were removed from the spray cabinet and placed in the glasshouse. In order for both treatments to receive the same total amount of water, the weak crust treatments were further watered manually (lightly sprayed on the soil surface) to provide an extra 14 mm/pot, with this water applied 2 and 3 days after the simulated rainfall treatment. The pots were left in the glasshouse for a total of 12 days to allow the seeds to germinate and emerge, during which time we measured soil crust strength and thickness, seedling emergence and time of emergence.

Experiment 3: Emergence force of 16 genotypes in the absence of growth-limiting factors

This experiment examined 16 wheat genotypes, comparing their emergence force in controlled conditions to determine if genetic variability exists in the ability of the seedling coleoptile to push or displace superficial mechanical obstacles. These 16 wheat genotypes were selected from those found previously to differ markedly in their emergence in Experiment 1.

This experiment was performed in a laboratory, maintained at a constant temperature of 20 °C. To determine differences in seedling emergence force, 16 wheat genotypes were randomly allocated to blocks using a randomised block design with a total of six replicates. A mechanical device was developed (Figure 1) to record the force exerted by the seedling coleoptile. The device consisted of a stainless-steel beam of 0.4 mm thickness and a width of 20 mm suspended above a seed. A strain gauge was attached to the beam to measure the displacement of the beam over time. The wheat seed was placed in a slot cut within a piece of foam that was held underneath the stainless-steel beam. A 100 mL container of 1 mM $CaCl_2$ [ionic strength (I) of 0.003 M L-1] was placed underneath the foam and cotton strings coming out from the foam were placed in the solution. The simple nutrient solution contained 1 mM $CaCl_2$ as it is known that a root elongation requires a continuous supply of calcium due to its low mobility in the phloem (Burstrom 1953; Amor & Marcelis 2003). By using this approach, the foam remained moistened and provided a continuous supply of calcium. The wheat seeds were germinated inside the foam and grown for total 14 days. When the seedling emerged, it pushed against the beam, with the strain gauge measuring the movement of the beam from which the emergence force of the seedling could be calculated. The strain gauge was connected to a data logger (Quantum X data acquisition system DA, MX840B, HBM, Germany). To convert measured strain to emergence force (N) a calibration was developed, with strain measured at loads ranging from 0 to 9 N at 1.0 N intervals.

After completion of the seedling emergence force experiment, each seedling was carefully removed from the foam and cleaned to assess the cross-sectional area of the hypocotyl. This was measured by collecting images of each seedling . The images were analysed to determine the cross-sectional area. The measured emergence force of each genotype was correlated with the hypocotyl cross sectional area to quantify any significant correlation between seed parameters and seedling emergence force.

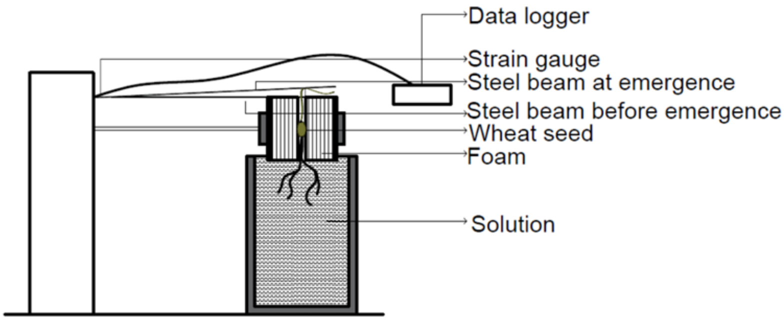

Figure 1. Experimental device designed to measure seedling emergence force

Experiment 4: Variation in root angles of 16 wheat genotypes

Experiment 4 aimed to determine whether wheat genotypes vary in seminal root angle in sodic soils. This experiment consisted of 16 genotypes grown in a soil with an ESP of 10% and a bulk density of 1.2 g/cm3, with nine replicates in a complete randomised design. Each pot contained 24 positions and each position contained one seed of a randomly allocated genotype. Root angle were measured using the "clear pot" method described by Richard *et al.* (2015). Transparent plastic pots of 200 mm diameter and 190 mm height (3 L) were used for the experiment, each one filled with a soil of ESP 10.

Prior to filling the pots, soils were moistened to 70% of field capacity using deionized water and left overnight at room temperature. During planting, pots were filled with soil to 4.5 cm depth before the seeds were carefully placed along the pot wall to ensure root growth would be visible during growth. The pots were then filled to the brim with soil before being placed inside 4 L black pots to exclude light from the developing coleoptile. During the course of the experiment, soil water was maintained at field capacity, and the pots were placed in a controlled growth cabinet of constant temperature at 20°C. The root angle of each seedling was recorded daily for 14 days, starting 3 days after sowing. Images were taken from each pot. The root angle and maximum coleoptile length was measured.

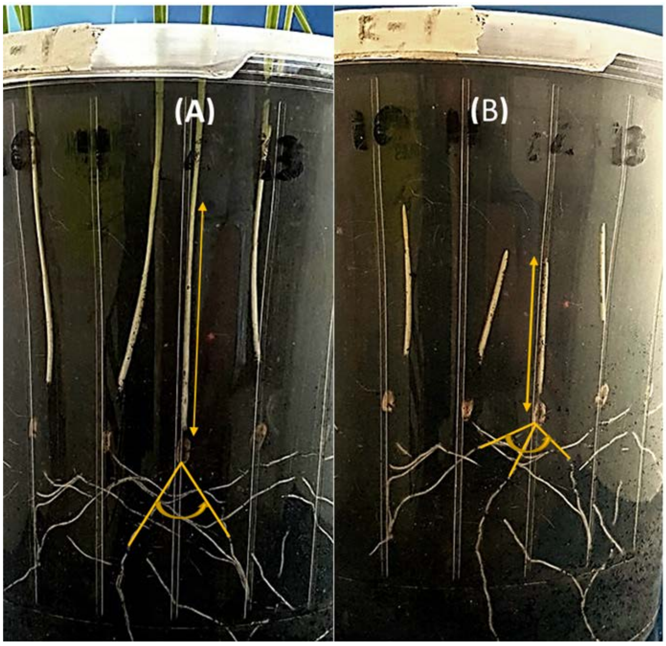

Figure 2. Maximum coleoptile length and seminal root angles (yellow lines) of wheat genotypes in Experiment 1 on 14 days after sowing in soil with ESP values of (A) 4 % and (B) 17 %

Experiment 5: Wheat seedling response to ionic imbalance

This study aimed to determine the impact of high sodium concentrations on seedling emergence, sodium-induced calcium deficiency, nutrients concentration in youngest mature leaf (YML) and root, shoot and root growth of four selected wheat genotypes (Baxter, EGA Gregory⚗, Spitfire⚗ and Ventura⚗) at five different sodium adsorption ratio (SAR) values (0, 10, 20, 30, and 60) using solution culture.

A solution culture experiment was conducted to investigate the impact of high SAR conditions on growth of wheat. The five different SAR values (0, 10, 20, 30 and 60 $(mmol_cL^{-1})^{0.5}$) tested, were equivalent to soil ESP values of 0, 13, 23, 31 and 47. These ESP values are commonly found in many of the surface and subsoils of the region (Dang *et al.* 2006).

For each genotype, 10 seeds were placed on piece of shade cloth that was supported using foam cups and were suspended in the 10 L buckets. There were four cups in each bucket, yielding 40 seeds per genotype in each replicate. This allowed seeds to take up moisture from below but ensured that they were not covered by the solution. Seeds were then covered by white polypropylene beads. At the end of the experimental period, 14 days after sowing, plants were harvested before being separated into root, stem plus petiole, and youngest mature leaf (YML). Images were taken of the roots from each pot. Root length were measured from these images. Roots were washed in deionized water to remove any adhering solution. The various plant parts were dried at 65 °C for 72 hrs and the dry matter (DM) of the shoots and roots recorded before measurement of concentrations of Ca, Cu, Fe, K, Mn, Mg, Na, P, S and Zn in the youngest matures leaves and root tissues.

Results

Experiment 1: Characterising seed germination in absence of soil constraints

All 38 genotypes were found to have ≥ 80 % germination other than Batavia (76 %) and Jandaroi (78 %) (Figure 3). There was significant interaction between genotypes and day of germination (*P<0.0001*), indicating that not only did the genotypes differ in the proportion of seeds that germinated, but that there were differences in how quickly they germinated. Specifically, genotypes that germinated quickly included Westonia, Ventura, Wallup, Trojan, Yitpi, Tammarin Rock, Gladius, Krichauff, Hydra and Viking (all having > 80 % germination after 3 days), while Jandaroi, Emu Rock, Impala, Magenta, Suntop, Aurora, Axe and Pelsart all had < 50 % germination after 3 days.

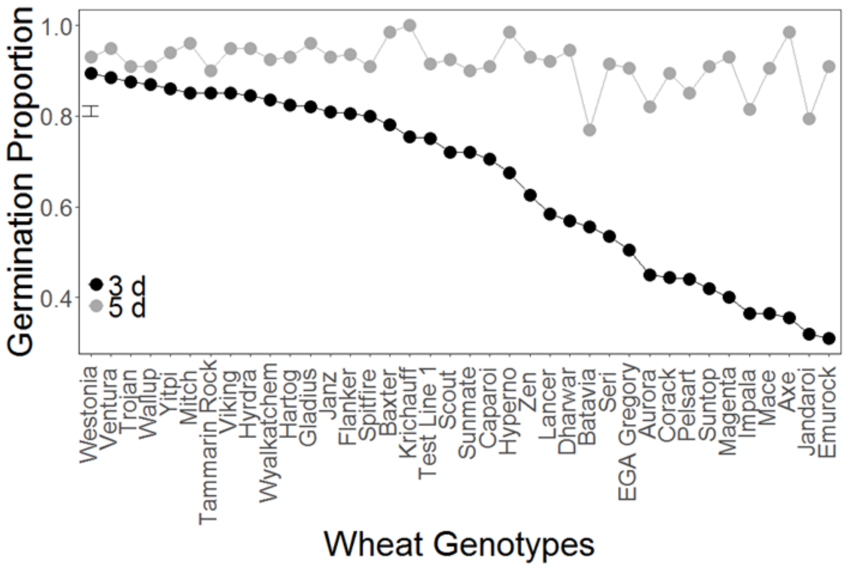

Figure 3. Germination of wheat genotypes after 3 and 5 days in a Petri dish (Experiment 1). The analysis showed that there was a significant interaction effect between genotype and time (days) (*P<0.001*). The vertical bar on the left indicates the LSD between genotypes. Varieties Ventura, Trojan, Wallup, Yitpi, Mitch, Tammarin Rock, Viking, Hydra, Wyalkatchem, Gladius, Flanker, Spitfire, Scout, Sunmate, Caparoi, Hyperno, Zen, Lancer, EGA Gregory, Aurora, Corack, Suntop, Magenta, Impala, Mace, Axe, Jandaroi and Emu Rock are protected under the Plant Breeders Rights Act 1994.

Experiment 2: Seedling emergence of wheat genotypes varied in crusted sodic soils

Soil crust strength and thickness in Experiment 2 varied between the two crust treatments (weak and strong). For the weak crust treatment (10 mm/pot) the increase of crust strength and thickness over time was slower compared to the strong crust treatment. At the time of seedling emergence (from 4 to 10 days), soil strength ranged from 0.78 to 1.2 kg/cm^2 (76 to 117 kPa) in the weak crust treatment, whereas it ranged from 1.47 to 2.69 kg/cm^2 (144 to 263 kPa) in the strong crust treatment. Importantly, the crust strength in the strong crust treatment was close to that recorded in the field in June 2016. The crust thickness also increased with time. At the time of emergence, crust thickness ranged from 0.51 to 0.95 cm in the weak crust treatment and from 1.37 to 2.16 cm in the strong crust treatment.

Seedling emergence differed significantly between the two crust treatments (*P*<0.001) with the average emergence in the strong crust treatment (20% emergence) being significantly lower than in the weak crust treatment (69% emergence, Figure 4). For example, the genotype Ventura had high overall emergence, but emergence in the strong crust treatment (69%) was lower than in the weak crust treatment (100%, Figure 4). Similarly, Aurora, Axe, Baxter, Corack, and EGA Gregory all had emergence > 50% greater than 0.50 proportional emergence in the weak crust treatment but did not emerge in the strong crust treatment (0% emergence).

Experiment 3: Emergence force of 16 genotypes

Significant differences (*P<0.001*) were observed between the emergence forces of the 16 wheat genotypes when grown in a simple nutrient solution of 1 mM $CaCl_2$, varying almost five-fold from 0.07 to 0.36 N (Figure 5). The genotypes Ventura⦶, Viking⦶, Seri and Spitfire⦶ were found to have a relatively higher emergence force than the other genotypes (mean emergence force >0.18 N). Genotypes Corack⦶, Batavia, Wyalkatchem⦶, Impala⦶, Krichauff, Dharwar and Lancer⦶ tended to have intermediate emergence force (0.11 to 0.17 N), while EGA Gregory⦶, Aurora⦶, Baxter, Mitch⦶ and Axe⦶ had low emergence forces (ranging from 0.07 to 0.10 N) (Figure 5).

Significant differences (*P<0.001*) were also observed between the hypocotyl cross sectional area of the 16 wheat genotypes when grown in a simple nutrient solution, varying almost three-fold from 1.26 to 3.45 mm^2 (Data not shown). The genotypes Ventura⦶, Viking⦶, Seri and Spitfire⦶ have relatively large hypocotyl cross sectional areas compared to the other genotypes (mean hypocotyl area > 2.88 mm^2). A positive relationship was observed between hypocotyl cross sectional area and seedling emergence force of the 16 wheat genotypes (R^2=0.54).

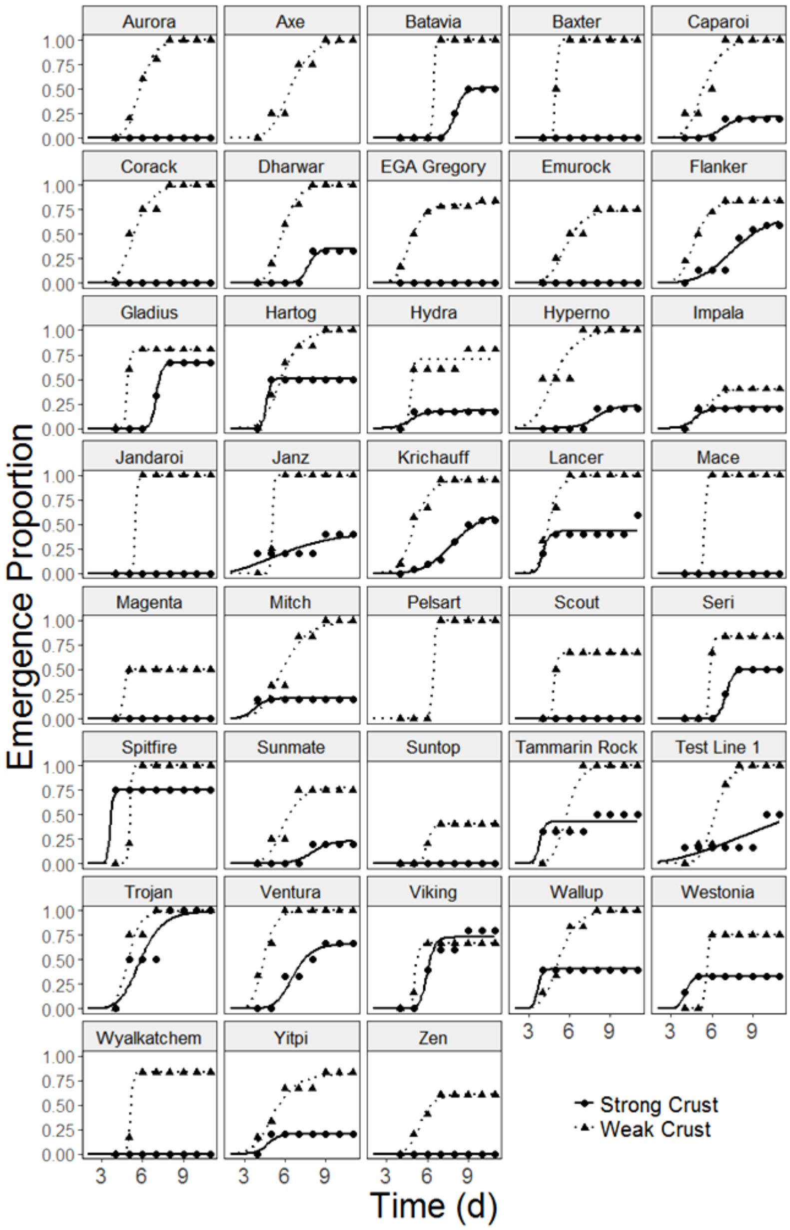

Figure 4. Seedling emergence proportion of wheat genotypes in the weak and strong crust treatments along with time. Genotypes (Axe, Pelsart) which exhibited insufficient germination in the strong crust treatment are excluded from this analysis, and the line is not shown (Experiment 2). Varieties Venturaᶲ, Trojanᶲ, Wallupᶲ, Yitpiᶲ, Mitchᶲ, Tammarin Rockᶲ, Vikingᶲ, Hydraᶲ, Wyalkatchemᶲ, Gladiusᶲ, Flankerᶲ, Spitfireᶲ, Scoutᶲ, Sunmateᶲ, Caparoiᶲ, Hypernoᶲ, Zenᶲ, Lancerᶲ, EGA Gregoryᶲ, Auroraᶲ, Corackᶲ, Suntopᶲ, Magentaᶲ, Impalaᶲ, Maceᶲ, Axeᶲ, Jandaroiᶲ and Emu Rockᶲ are protected under the Plant Breeders Rights Act 1994.

Experiment 4: Variation in coleoptile length and root angles of 16 wheat genotypes

Significant differences were observed in the root angle for different genotypes (*P<0.001,* Figure 6). The root angle of 16 wheat genotypes ranged from 88° to 126°. Wheat genotypes Wyalkatchemᶲ, Corackᶲ, Mitchᶲ, Auroraᶲ, Axeᶲ, Baxter, Impalaᶲ, Lancerᶲ, Batavia and EGA Gregoryᶲ had wider root angles ranging from 109° to 126°, whereas Venturaᶲ, Vikingᶲ and Spitfireᶲ had narrower root angles ranging from 88° to 91°. Wheat genotypes Seri, Dharwar and Krichauff had intermediate root angles ranging from 103° to 105°.

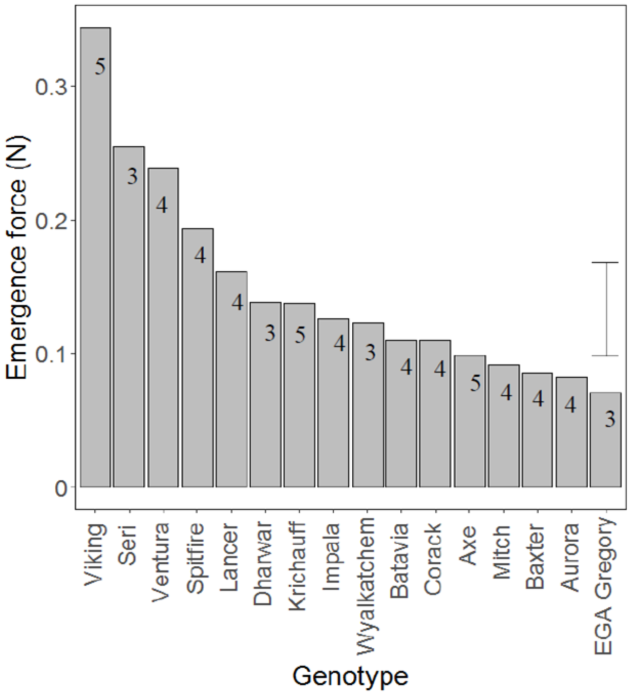

Figure 5. The emergence force for 16 wheat genotypes in Experiment 1. There were significant differences between genotypes (P<0.001), with the vertical bars showing the LSD between genotypes. Values inside the bars represent the number of seeds germinated out of six replicates of each genotype sown (Experiment 3). Results were analysed based on the germinated seeds only. Varieties Viking⏀, Ventura⏀, Spitfire⏀, Lancer⏀, Impala⏀, Wyalkatchem⏀, Corack⏀, Axe⏀, Mitch⏀, Aurora⏀ and EGA Gregory⏀ are protected under the Plant Breeders Rights Act 1994.

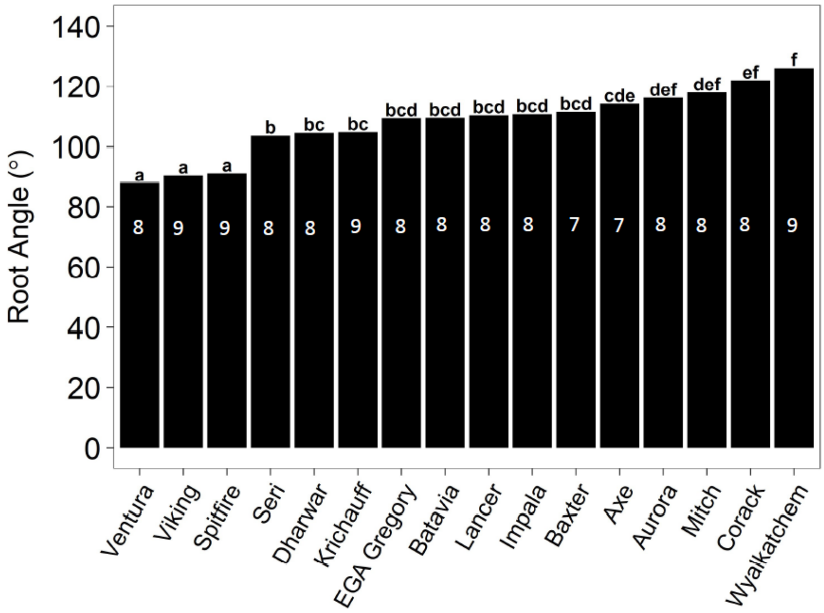

Figure 6. Mean root angle of wheat genotypes in sodic soil (ESP 10 %, bulk density 1.2 g/cm^3), Experiment 4. Treatments with the same letter are not significantly different. Numbers inside the bars represent the number of seeds germinated for each genotype out of nine replicates sown. Varieties Ventura⏀, Viking⏀, Spitfire⏀, EGA Gregory⏀, Lancer⏀, Impala⏀, Axe⏀, Aurora⏀, Mitch⏀, Corack⏀ and Wyalkatchem⏀ are protected under the Plant Breeders Rights Act 1994.

Experiment 5: Wheat seedling response to ionic imbalance

A significant (*P<0.001*) negative correlation was found between seedling emergence and SAR of the solutions for all four genotypes (*P<0.0001*). At a SAR value of 0, all the four genotypes had ≥ 80% seedling emergence. The emergence rate decreased significantly as SAR increased, with significant differences between the four genotypes at SAR 60 (*P<0.05*). Shoot dry matter of all the four genotypes was reduced with increasing SAR (*P<0.0001*). At SAR 0, shoot dry matter of the four genotypes ranged from 0.26 to 0.31 g, while at SAR 60, shoot dry matter ranged from 0.04 to 0.13 g. A significant interaction was found for root dry matter, with the pattern of decrease in root dry matter with increasing SAR depending upon the genotype (*P<0.001*). Specifically, for Baxter, Spitfire⦶, and Ventura⦶, root DM decreased from 0.21-0.25 g at SAR 0 to 0-0.03 g at SAR 60, while for EGA Gregory⦶ the root DM remained constant (0.2-0.23 g) irrespective of SAR.

For all four genotypes, the calcium concentration of the youngest mature leaves tended to decrease as SAR increased. This decrease was largest for Ventura⦶ (decreasing from 0.68 to 0.04%). and smallest for Spitfire⦶ (decreasing from 0.58 to 0.33%). For all four genotypes, the potassium concentration of the youngest mature leaves tended to decrease as SAR increased. This decrease was largest for Ventura⦶ (decreasing from 3.83 to 0.42 %) and smallest for EGA Gregory⦶ (decreasing from 4.14 to 3.01 %). In contrast to calcium and potassium, the concentration of sodium in the youngest mature leaves increased significantly with increasing SAR till 30 for all the four genotypes. Though no significant variation (*P*=0.09) was observed between the genotypes in sodium concentration. A significant difference was found in the potassium: sodium ratio in wheat youngest mature leaves between treatments (*P<0.0001*).

For all four genotypes, the calcium concentration of the roots tended to decrease as SAR increased (Figure 7). This decrease was largest for Ventura⦶ (decreasing from 0.45 to 0.18%). and smallest for EGA Gregory⦶ (decreasing from 0.45 to 0.29%). Significant differences in potassium root concentration were observed for all the four genotypes in response to SAR (P<0.01, Figure 7). This decrease was largest for Ventura⦶ (decreasing from 3.96 to 1.11%) and smallest for Spitfire⦶ (decreasing from 2.58 to 2.01%). In contrast to calcium and potassium, the concentrations of sodium in the roots were significantly higher for all four wheat genotypes grown in SAR 10, 20 and 30 as compared to SAR 0 (P<0.0001, Figure 7). The average sodium concentration in roots was almost 11-fold higher in SAR 30 compared to SAR 0 (Figure 7). However, for genotypes Baxter and Spitfire⦶ the concentration of sodium concentration in roots was lower at SAR 60 compared to SAR 30. EGA Gregory⦶ and Spitfire⦶ (1.34 and 1.99%) trended towards higher sodium concentration in the roots than Ventura⦶ and Baxter (0.43 and 0.39%, Figure 7).

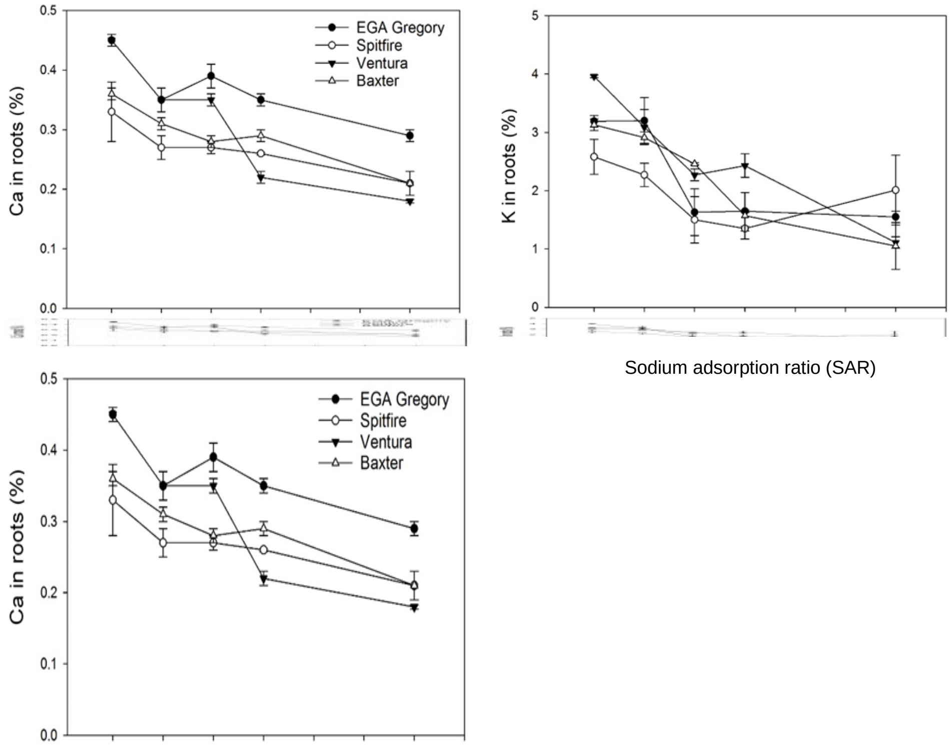

Figure 7. Nutrient concentration in roots of four wheat genotypes in five different SAR treatments averaged over four replicates (Experiment 5). The bars in the graphs present the standard error between the replicates. Varieties EGA Gregory⦶, Spitfire⦶ and Ventura⦶ are protected under the Plant Breeders Rights Act 1994.

Discussion

Surface soil crust and seedling emergence

One of the major physical constraints that occur in sodic soils is the formation of surface crusts. In southern Queensland wheat is often grown on sodic soils. In this region, wheat is generally sown in May or early June. Seedling emergence generally occurs within 14 days after sowing. Probability analysis of average rainfall for a typical location (Burilda Station) in this region (Figure 8) from 15th May to 14th June over 58 years showed that the probability of getting rainfall ≥ 30 mm is more than 50% in the period of plant emergence or just after sowing, which might create a surface crust of strength 1.47 to 2.69 kg/cm^2.

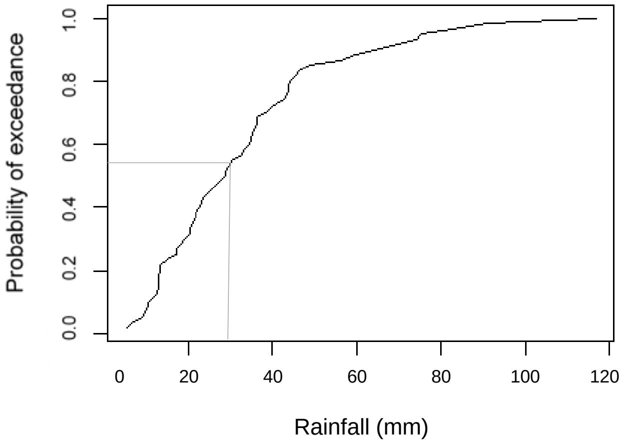

Figure 8: Probability of exceedance of rainfall (from 15th May to 14th June) (mm) data of Burilda station (28.16°S, 150.28°E), from 1960 to 2018; *(Australian Government. Bureau of Meterology 2016)*

In Experiment 2, surface crusting relevant to field condition was shown to reduce the capacity of wheat seedlings to emerge through the thicker layer of a 'strong crust'. All the wheat genotypes tested achieved higher seedling emergence when planted in a soil with a 'weak crust' compared to those with a 'strong crust'. In the 'weak crust', seedlings of most of the wheat genotypes tested emerged easily within four to seven days (Figure 4). In 'strong crust', the thickness and strength of the crust increased with time and genotypes showed variability in their ability to emerge. Four different scenarios were observed in the strong crust. Firstly, some genotypes emerged easily and achieved higher seedling emergence in strong crust (Figure 9a), e.g. Spitfire⸰. Secondly, seedlings of some wheat genotypes were able to push against the thick surface crust, which resulted in successful but delayed emergence (Figure 9b), e.g. Trojan⸰. Thirdly, the coleoptiles of some genotypes started growing underneath the crust and searched for a crack through which to emerge, which resulted in delayed emergence (Figure 9c), e.g. Ventura⸰. Finally, seedlings of some genotypes were unable to achieve any of these three successful outcomes and remained curled up underneath the crust. Thus, seedling emergence was prevented even though successful germination occurred (Figure 9d), e.g. EGA Gregory⸰.

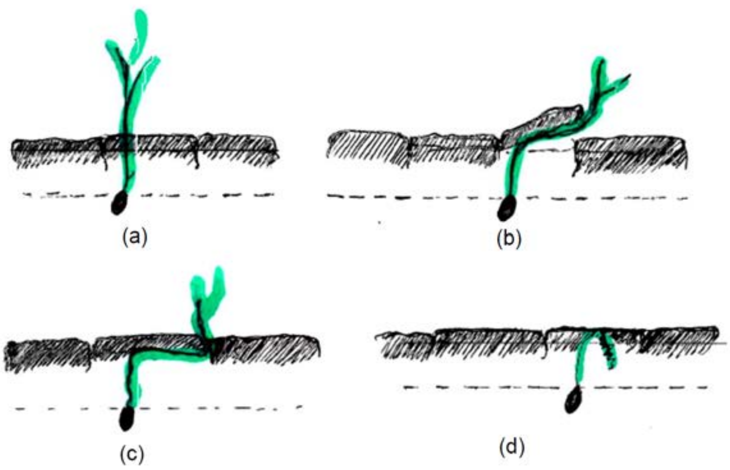

Figure 9. Four different mechanisms of seedling emergence that occurred in the strong crust condition of sodic soils in Experiment 2

Overall seedling emergence was reduced in the strong crust condition (Figure 4). The significant variation in the ability of different genotypes to emerge through a 'strong crust', indicated that particular traits must exist to allow these genotypes to emerge more successfully through crusted soil.

Relation with seedling emergence in the field

The results from the current study were compared to field results made available from a study performed independently of this work. In 2016, University of Queensland researchers conducted a field trial on the property "Binara", near Goondiwindi in southern Queensland (28.23 °S, 150.31 °E). Soils used to measure seedling emergence in Experiment 2 were collected from the same property. At the site, 38 wheat genotypes were sown in 6m x 2m plots. Genotypes were chosen to represent cultivars that were available to growers in the region, as well as cultivars known to vary in adaptation to the prevailing soil stress conditions. Seedling emergence was counted at the early tillering stage of the crops for each plot and compared to the target population of 100 plants per square metre of area. The mean proportional emergence [(seedling/m^2)/100] of seedlings of each genotype was compared with the seed emergence rate obtained from the glass house study in Experiment 2 at two different crust conditions (Figure 10).

A significant positive relationship was observed between seedling emergence in the field and seedling emergence from the strong crust treatment in Experiment 2 (R^2=0.82). Field crust strength ranged from 1.2 to 3 kg/cm^2, which was close to the range of 1.47 to 2.69 kg/cm^2 for strong crust created for the pot experiment. In contrast, the emergence rate was higher in the weak crust pot experiments compared to the field with no clear correlation (R^2=0.07) as the crust strength of the weak crust treatment was lower than the field situation (Figure 10).

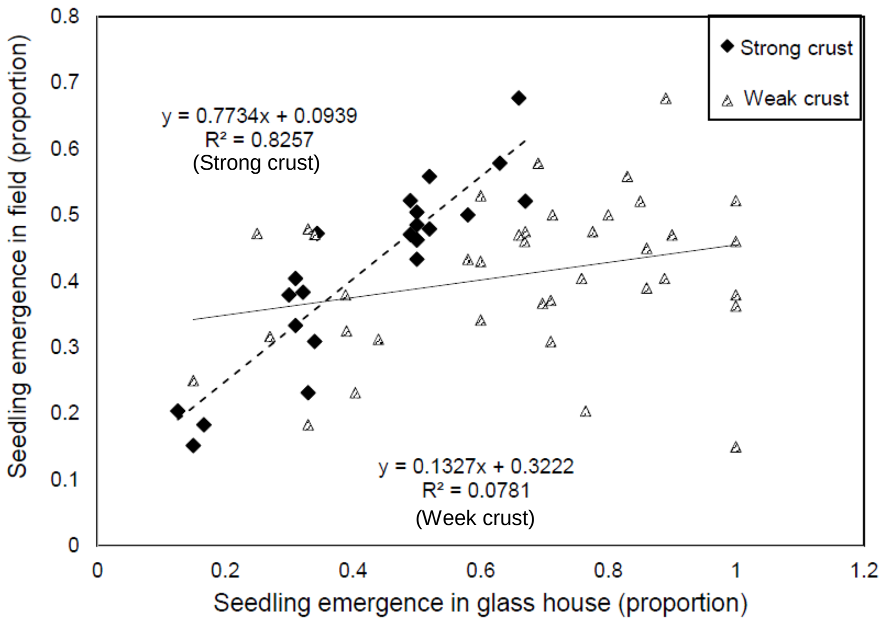

Figure 10. Correlation between seedling emergence in control environment (strong crust and weak crust, Experiment 2) and relative field emergence

Plant traits influence seedling emergence from crusted soil

Rapid germination allowed seedlings to emerge before crust was fully developed

The seedlings that germinated quickly successfully emerged before full crust strength was developed. Correlation between seed germination rate on day 3 using Petri dish assays in the control treatment (indicated that early germination of wheat genotypes can be an important factor driving seedling emergence in surface crusted sodic soils. In the absence of soil constraints , the germination of seedlings did not vary significantly between genotypes after 5 days. However, the germination rate on day 3 showed that some genotypes were able to germinate earlier (e.g. Ventura⦶) was earlier than others (e.g. Mace⦶). The genotypes that germinated on day 3 were able to emerge through the soil crust while crust strength and thickness were still relatively low (strength of <1.3 kg/m2 and thickness <1.3 cm) (Figure 11) and thus emerge easily (Figure 9a). The seeds that germinated on day 6 however, had to emerge through a higher crust strength (≥2 kg/cm2) and thickness (≥1.5 cm) (Figure 11). As a result, some genotypes (e.g. Mace⦶, Suntop⦶) that germinated later had delayed or even failed emergence (Figure 9c and d).

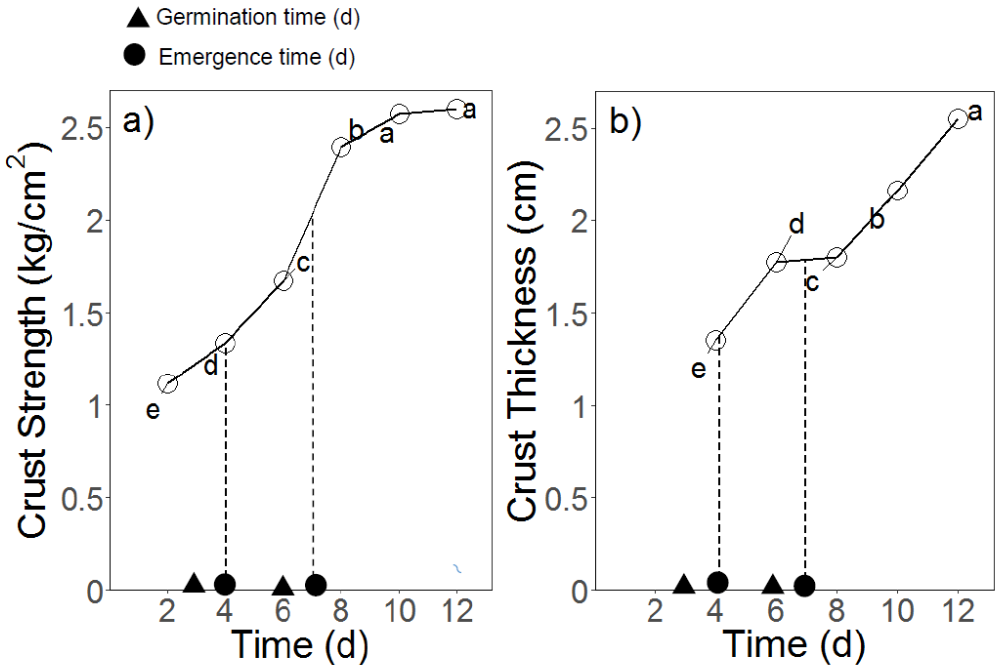

Figure 11. Development of (a) crust strength and (b) thickness along with time of strong crust (Experiment 2) and time of seed germination and seedling emergence along with time. Letters in figures present least significant difference (LSD) between times

Germination results of wheat genotypes suggest that early seed germination can be a driving factor to achieve higher emergence in the presence of a surface soil crust. These results have been supported by many studies that have found that in the presence of soil crusts, rapid germination can be beneficial for seedling emergence (Maguire 1962; Agarwal *et al.* 1986).

Higher seedling emergence force led to improved seedling emergence

Some seedlings were also able to emerge through soil crust by displacing the crust. Studies have reported that seedling emergence force can be a driving trait for seedling emergence in surface crusted soil (Gerard 1980) and variation in emergence force between species can occur (Sinha & Ghildyal 1979). As a result, the seedling emergence force of 16 wheat genotypes was examined to determine if variation between genotypes contributed to the differences in emergence observed (Experiment 3). At the time of emergence, if the seedling force (F2) is greater than the opposing force from the crust (F1), the seedling will be able to emerge. In Experiment 3, the maximum deflection of a beam at the time of emergence indicated the magnitude of seedling emergence force. Certain genotypes (e.g. Ventura⦶, Spitfire⦶) were able to exert higher emergence forces (F2 > F1) and emerge through the strong crust (Figure 9b). On the other hand, where F2<F1, genotypes failed to push through the crust and resulted in reduced or delayed emergence (Figure 9c and d).

In order to understand why differences in seedling emergence force existed between genotypes, the relationship between seedling emergence force and hypocotyl cross sectional area was examined. A positive correlation was observed between seedling emergence force and hypocotyl cross sectional area, which indicated that genotypes with thicker hypocotyl diameters are able to produce greater force (R2=0.54). This finding is supported by Gerard (1980) who found a significant linear relationship (R2 = 0.95) between emergence force and hypocotyl cross sectional area of cotton seedlings. The greater reserves in the larger hypocotyl might have the potential to produce a stronger seedling with a large emergence force (Sparks 2017).

Narrow root angle was associated with greater seedling emergence through surface soil crust

Significant differences between the seminal root angles were observed between the 16 wheat genotypes in Experiment 3 (Figure 6). This is similar to the results observed by other authors, who have found a significant variation in seminal root angles for different wheat genotypes (McDonald 2010; Christopher *et al.* 2013; Richard *et al.* 2015). For example, McDonald (2010) tested the seminal root angles of 52 wheat genotypes and found that seminal root angles ranged from 56° to 113°.

The root angle of wheat genotypes was found to be an important trait that influenced relative seedling emergence through strong sodic soil crust. A significant negative correlation between root angle and relative seedling emergence was reported in Experiment 4 (R^2=0.89) indicating that genotypes with a narrower root angle achieved higher emergence through strong soil crust (Experiment 2). Narrower seminal root angles have also been observed to have a positive effect on wheat growth in other studies. Oyanagi (1994) reported that plants with narrow seminal roots angle tended to be more able to use water from the subsoil. Narrow root angles have been identified as proxy traits to select genotypes with drought tolerance for wheat breeding programs (Manschadi *et al.* 2008; Manschadi *et al.* 2010; Christopher *et al.* 2013).

The volumetric moisture content of the soil in the pots with strong crusts in the glasshouse pot experiments described in Experiment 2 varied with depth and time (Figure 12). In Experiment 2, the volumetric moisture content was similar throughout the profile at the beginning of the experiment from 3-11 cm depth (70% bulk density; 1 day). After sowing, the seed was covered with 0-3 cm depth of dry soil. After rainfall simulation, the pots were brought to field capacity. However, when drying started, the top soil formed a crust and dried more quickly than the soil at lower depth. As a result, soils below 5.5 cm had higher moisture content on day 6 and day 14 (Figure 12). Genotypes that had a maximum root depth <5.5 cm, which is more likely with a wider root angle, may thus have had a lower moisture uptake. However, genotypes that had greater root depth, which is more likely with a narrow root angle, may have been able to take up more soil moisture (Figure 9 a, b and c). With increased water uptake such seedlings could potentially have been able to maintain greater turgor pressure and exert more emergence force, leading to a higher proportion of emergence.

The seedling emergence of wheat genotypes through surface soil crust created in pot experiments (strong crust, Experiment 2) was correlated with both seedling emergence force and root angle. Given this, and the fact that these two traits were measured in two different media (i.e. soil versus solution), there is a need to investigate the impact of root angle on seedling emergence force of wheat genotypes when they are grown in the same growth medium. Investigation of seedling emergence force and root angle in soils with a wider range of ESP while measuring seedling emergence in crusted soils in the same experiment might also provide a clearer insight into the relationship between these traits.

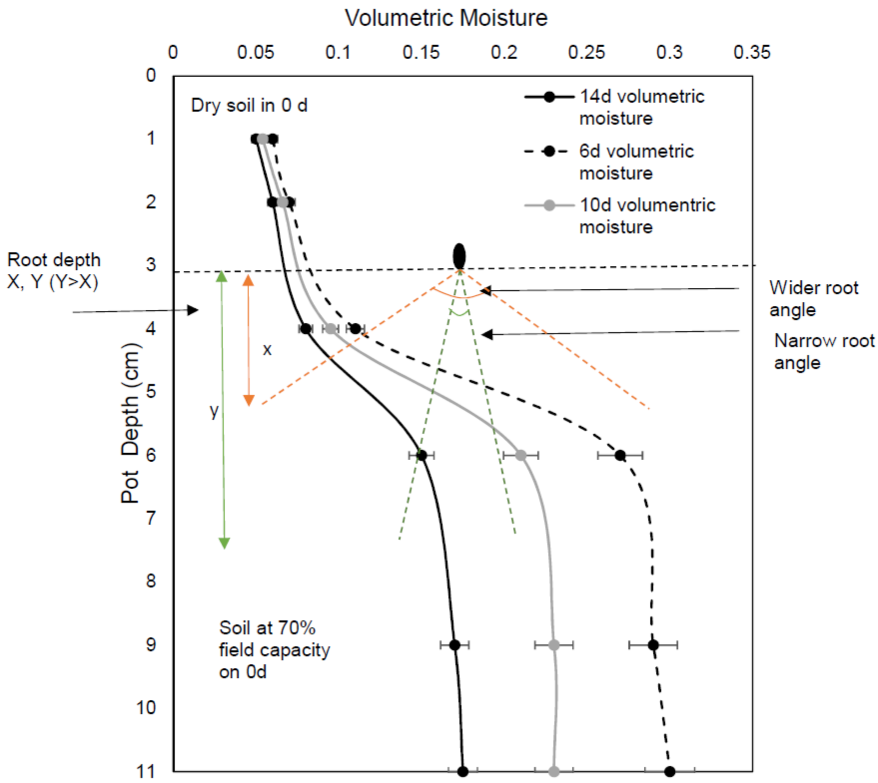

Figure 12. Volumetric moisture content of strong crust pots (Experiment 2) at three different times (6d, 10d and 14d) and a hypothetical presentation of rootangles in the soil profile

Traits to identify genotypes adapted to sodium toxicity and sodium induced calcium deficiency

Higher calcium concentrations in roots was correlated with a greater ability to maintain both root (R2=0.77, Figure 13) and shoot dry matter (R2=0.54). The observed variation in tolerance to the chemical constraints in soil solution might be governed by the calcium concentrations in roots of these genotypes in high sodic conditions (SAR 30 and above). Tolerant genotypes generally had higher calcium concentration in roots, whereas relatively susceptible genotypes exhibited sodium-induced calcium deficiency (at SAR 60). However, concentration of these nutrients in the youngest mature leaves was not a limiting factor below SAR 30 for calcium and SAR 60 for potassium for the more sensitive genotypes. Thus, potassium and calcium concentration in youngest mature leaves might not be a useful trait at common field levels of sodicity (SAR <30). However, calcium concentration in roots may still have potential to be used as an identifying trait of wheat genotypes tolerant to high sodium concentration and calcium deficiency in high SAR solution or in high ESP soils. These findings are supported by other researchers (Kurth *et al*. 1986; Shen *et al*. 1993; Reuter & Robinson 1997; Dang *et al.* 2016) who found positive correlation between calcium concentration in leaves and roots and shoot and root biomass.

However, seedling emergence of genotypes Baxter and EGA Gregory⁽ᵈ⁾ was affected due to the slight increase of SAR (0 to 10) which might cause yield differences in field soils with an equivalent soil ESP. This study only identified the traits considering the chemical constraints of sodic soil in solution culture and these do not necessarily correlate with tolerance to physical constraints of sodic soil, e.g. soil crust. The tolerance of these genotypes under field conditions requires further investigation.

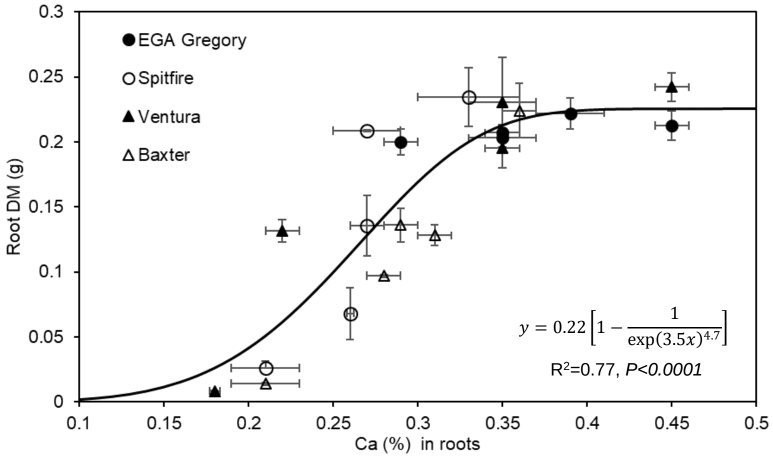

Figure 13. Relationship between root DM and concentrations of Ca (R^2=0.77, *P<0.001*) in root tissues of four wheat genotypes in four replicates grown in five SAR treatments, Experiment 5

Conclusions

We have shown that genetic differences in the speed of seedling germination and emergence are important factors determining whether seedlings can emerge from crusting sodic soils. This study also indicated that wheat seedling emergence can be increased and the surface crusting effects of sodic soils on seedling emergence reduced by i) identifying and developing genotypes that exert more emerging force, and ii) developing genotypes that develop a thicker pushing hypocotyl under stress. Further study suggested that selection for narrow seminal root angle may potentially help to identify wheat genotypes that are better adapted to sodic soils.

We also found that at early growth stage, wheat tolerance to the chemical constraints of sodicity might be governed by the ability of genotypes to accumulate calcium in roots. Tolerant genotypes generally had higher calcium concentration in roots and whereas relatively more susceptible genotypes exhibited sodium-induced calcium deficiency (at SAR >30).

This study indicated that both seedling emergence force and root angle influenced seedling emergence in crusted sodic soils. It seems quite counter intuitive that root angle was more significant than emergence force in determining seedling emergence from crusted sodic soils. Given this, and the fact that these two traits were measured in two different media (i.e. soil versus solution), there is a need to investigate the impact of root angle on seedling emergence force of wheat genotypes when they are grown in the same growth medium. Investigation of seedling emergence force and root angle in soils with a wider range of ESP while measuring seedling emergence in crusted soils in the same experiment might also provide a clearer insight into the relationship between these traits.

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Using EM38 at the crop lower limit to identify subsoil constraints for site-specific management

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Key words

electromagnetic induction, EM38, nutrient management, plant available water, productivity, soil management, subsoil constraints

GRDC code

DNR00008 Advanced techniques for managing subsoil constraints

Take home messages

- Salinity, sodicity, acidity and phytotoxic concentrations of chloride in soil are major constraints to crop production costing 2 billion per annum in lost production to Australian grains growers
- Large scale spatial and temporal variability in soil constraints: Identification is the first step
- EM38 is an important tool for mapping soil variability, however, ground-truthing is necessary
- Site-specific soil and nutrient management are cost-effective, economical and environmentally positive

Introduction

Water supply is undisputedly the major factor that determines crop growth in the northern grains region (NGR). Moreover, characteristic soil attributes of the region such as high salinity, sodicity, acidity, and phytotoxic concentrations of chloride, constrain the ability of plant roots to extract water as well as nutrients (Dang *et al.* 2006). These soil constraints vary both laterally across the landscape and vertically within the soil profile. By identifying the spatial variability of soil constraints, we can help grain growers to develop appropriate site-specific agronomic management strategies.

Soil sampling to identify the distribution of soil constraints is time-consuming and expensive. Robertson *et al.* (2007) suggested that soil mapping using proximal and remote sensing is likely to be more cost-effective than interpretation of conventional soil maps. Sensing technologies allow the user to locate and monitor areas of potential soil constraints, providing both practical and economic advantages (O'Leary *et al.* 2003). We can infer the spatial pattern of soil constraints through the spatial pattern of crop yield. Where crops fail over multiple years to pass a certain yield threshold, then we might reasonably suspect the presence of some temporally stable limiting factor, such as a soil constraint.

This study was aimed to investigate the use of proximal sensing (Geonics EM38) and remote sensing to identify potential management classes and to develop a framework to estimate economic and environmental benefits of site-specific management options.

Materials and methods

The study used seven arable fields across Queensland and northern New South Wales (Figure 1). The land managers of each site harvested their crops with machinery fitted with yield monitoring equipment, linked to a differentially corrected global positioning system (dGPS). Each set of yield monitor data was cleaned to remove spurious observations associated with harvester dynamics, speed changes, cutting overlaps and turns (Blackmore and Moore 1999; Taylor *et al.* 2007). The VESPER software (Whelan *et al.* 2001) was then used to krige, on 20-m blocks, the cleaned yield data for each crop, using a local exponential variogram. The interpolation locations were taken as the nodes of a 5-m grid overlaid to each field.

Figure 1. Location of the study sites

Electromagnetic induction surveys

The electromagnetic induction technique measures electrical conductivity (EC_a) by inducing a small current within the soil (McNeill 1992). In this study we recorded EC_a using a Geonics EM38, linked to a data-logger and a dGPS. The dGPS was mounted on a vehicle, with the sensor towed behind on a conveyor-belt mat (Dang *et al.* 2011).

Soil sampling and analysis

A minimum of two locations were randomly selected within each stratum for soil sampling. Two soil samples were taken per location, using a 50-mm diameter tube and a hydraulic sampling rig. Soil samples were extruded onto a plastic liner and then sub-sampled into a surface interval (0.0–0.1 m), then successive 0.2-m intervals to 1.5 m and analysed for soil physical and chemical properties.

On-farm experimentation

To determine if management by the potential classes was justifiable over conventional uniform field management, field-scale replicated trials were applied at three sites. At the site in Biloela, three treatments applied to the strips were 0, 23, and 46 kg N/ha at sowing. Each strip received a uniform application of 10 kg P/ha through zincated monoammonium phosphate at sowing. The nitrogen requirement at 50% nitrogen efficiency for each class was calculated using realistic yield potential (RYP) in the presence of soil constraints (Dang *et al.* 2010), the protein goal (13.0%) and NO_3-N concentration in soil to 0.9 m soil depth. At the site in Goondiwindi, two experiments were conducted. At sowing, strips of 0, 40, and 80 kg MAP/ha, each replicated three times, were applied across the field, aligned in the direction of management operations. The second trial was conducted to evaluate wheat yield response to gypsum in the lowest-yielding management class. Gypsum was spread at 2.5 t/ha on the soil surface and incorporated to a depth of 0–0.05 m. Cumulative gross margins were obtained for a one-off application of gypsum (Dang *et al.* 2011). At the site in Garah, strips of 20, 50 and 100 kg N/ha, gypsum at 2.5 t/ha and compost at 5 t/ha were applied across the field, aligned in the direction of management operations. Each strip was replicated twice. Barley grain yield was measured with a yield monitor at the end of the season.

Results

Relationships of soil EC_a with measured soil properties

The variation of EC_a to Crop Lower Limit (CLL), averaged over the profile (0–1.5 m), was explained principally by EC_{se}, followed by soil moisture at CLL. The former explained the largest proportion of the variation of EC_a-CLL for the surface soil (0–0.1 m), shallow subsoil (0.1–0.5 m) and deep subsoil (0.5–0.9 m). In the very deep subsoil (0.9–1.5 m), the variation of EC_a was explained primarily by soil chloride. In subsoils, the ability to correlate EC (as measured by the EM38) with CLL was stronger than for surface soil. A similar pattern of relationships was seen at the drained upper limit (DUL), but the ability to correlate EC (as measured by the EM38) with DUL was not as strong and there was more variance than when using EC to reflect CLL. As EC increased, yield decreased, with this relationship being stronger at CLL than at DUL. Therefore, we consider only EC_a measurements at CLL for identifying potential management classes (data not shown).

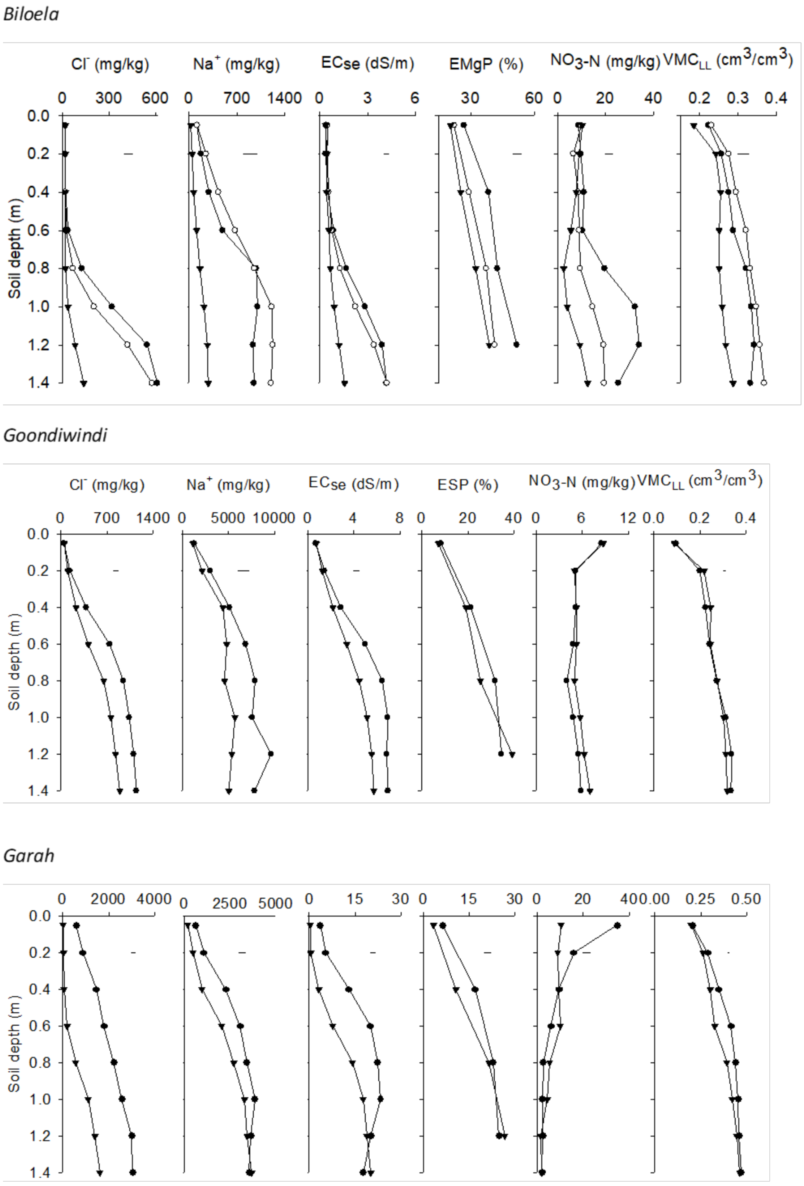

Figure 2. Soil constraints at Sites in northern region

Relationships of soil EC_a with measured grain yield

Figure 3 shows the relationships of EM38 readings for EC_a, stratified into five quantiles (i.e. top 20% --- lowest 20%), with the mean grain yield associated with each quantile. As EC_a increased, there was a strong decline in grain yield, with the level of decline stronger at CLL than at DUL. Therefore, we consider only EC_a measurements at CLL for identifying potential management classes.

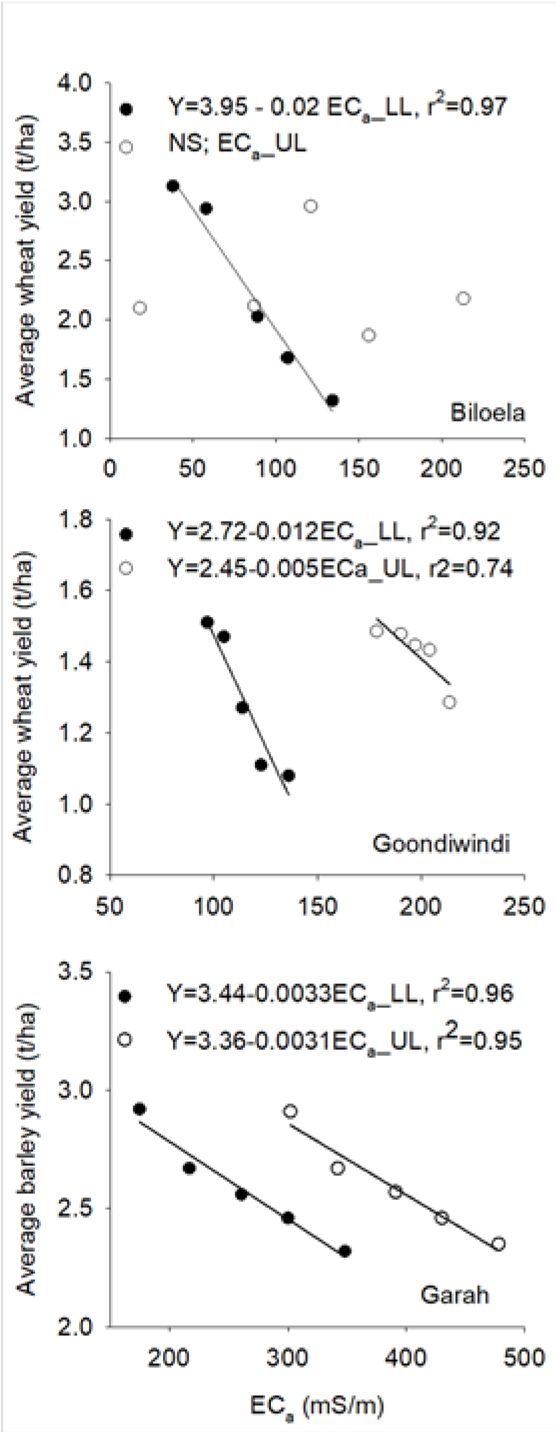

Figure 3. Relationships between average grain yield and average EC_a measurements, stratified into five quantile intervals at drained upper limit (DUL) and crop lower limit (CLL).

Potential management classes

At the Biloela site, from a 64-ha field in crop production since 1960, three potential management classes were justified (Figure 4 (top)): (i) a low-yielding class (mean yield = 1.27 t/ha) that has relatively high in EC_a-CLL (mean = 122 mS/m) and relatively low clay content (range of 38–44%), whose pre-clearing native vegetation was scattered brigalow (*Acacia harpophylla*); (ii) a medium-yielding class (mean yield = 2.22 t/ha) with intermediate in EC_a-CLL (mean = 89 mS/m) and relatively high clay content (range of 53–59%), whose pre-clearing native vegetation was also brigalow; and, (iii) a high-yielding class (mean = 3.36 t/ha), with relatively low in EC_a-CLL (mean = 56 mS/m), clay contents in the range 47–55%, and pre-clearing vegetation of softwood scrub. Soil chloride concentrations and EC_{se} were significantly higher below 0.7 m depth in the low- and medium-yielding classes when compared with the high-yielding class. Both soil chloride and EC_{se} followed a similar pattern throughout the soil profile. Water-soluble sodium concentrations were significantly lower in the high-yielding class when compared with the low- and medium-yielding classes; however, differences between low and medium-yielding classes were not significant throughout the soil profile. Exchangeable magnesium percent (EMgP) was greater in the low-yielding class when compared with the medium and high-yielding classes at all soil depths, however, differences between the medium and high-yielding classes were significant only at 0.4 and 0.8 m soil depth.

The soil of the Goondiwindi site (257 ha) is a grey Vertosol (Figure 4 (middle)). The western side of the field, which shows substantial surface slaking after cultivation, yields poorly in most years (mean wheat yield = 1.06 t/ha for the yield maps available), while the eastern side of the field has a relatively higher yield (mean = 1.44 t/ha). Mean EC_a-CLL for the western side was 121 mS/m, compared with 104 mS/m for the eastern side. The most notable soil differences in the potential management classes were significantly higher chloride and sodium concentrations and EC_{se} in soil below 0.5 m, for the low-yielding class. Surface-soil ESP was significantly higher for the low-yielding class, above the threshold of ESP >6, than in the high-yielding class to 0.5 m soil depth. Differences in soil NO_3-N were not significant between classes. Soil moisture at CLL was significantly different between the low-yielding class and the high-yielding class only between 0.3–0.7 m soil depth.

The Garah site (189 ha) has relatively little lateral variability in clay content and is classified as a grey Vertosol (Figure 4 (bottom)). The central and southern parts of the field have poor water infiltration and are low yielding (mean barley yield = 2.42 t/ha) compared with the rest of the field (mean barley yield = 2.75 t/ha). Additionally, the middle part of the field has relatively high in EC_a-CLL (mean = 281 mS/m) compared with the remaining field (mean = 235 mS/m). In general, the whole field had relatively high chloride concentrations, but concentrations were significantly lower in the high-yielding class at all soil depths. There was also a significant difference in water-soluble sodium concentrations and EC_{se} between the classes between 0.3 and 1.1 m in the profile. In general, both soil sodium and EC_{se} followed a similar pattern throughout the soil profile. ESP values to 0.5 m depth were significantly higher for the low-yielding class when compared with high-yielding class. NO_3-N concentrations were significantly higher in low-yielding class compared with the high-yielding class up to 0.4 m soil depth. In general, soil profile moisture contents at CLL were slightly higher for the low-yielding class than the high-yielding class at depths between 0.5 and 0.9 m.

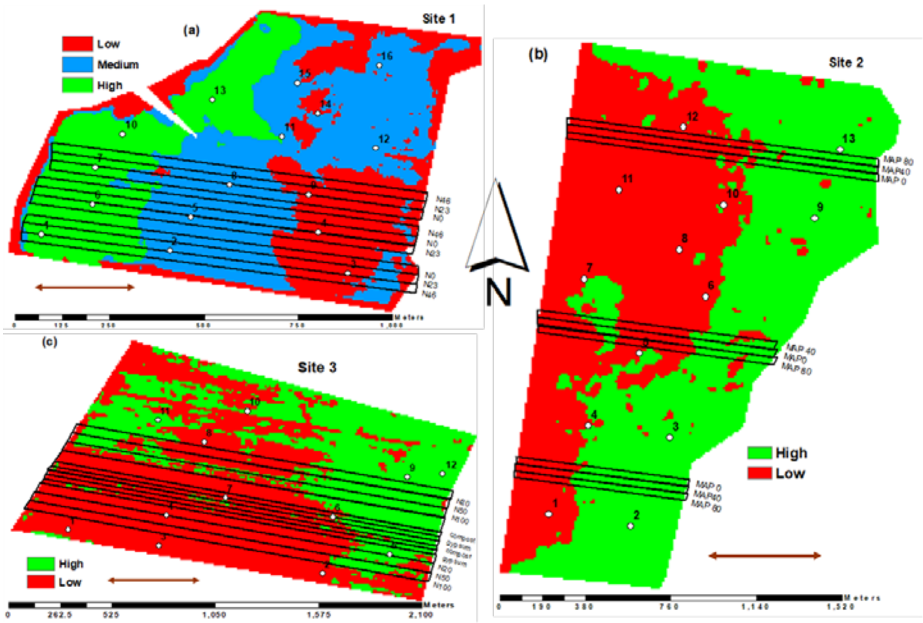

Figure 4. Potential management classes based on grain yield and EC_a-LL for: (a) Site 1, Biloela, (b) Site 2, Goondiwindi and (c) Site 3, Garah. The brown arrow in each is the direction of field operations. White dots and numbers denote the locations of the soil samples taken in each field.

Managing spatial variability

Figure 5 shows the yield response to applied nitrogen for the three potential management classes at the Biloela site. No significant response to applied N was obtained in the low-yielding (constrained) class; however, significant linear increases were obtained for wheat grain yield for both the medium- and high-yielding (unconstrained) classes. The nitrogen requirement for each management class (Table 1), calculated using realistic yield potential, soil nitrogen to 0–0.9 m, and a protein goal, showed that the low-yielding class (20 ha) had substantial un-utilised NO_3-N in the soil profile. Application of 46 kg N/ha to this class—the farmer's conventional practice—results in net wastage of 2.0 t of urea.

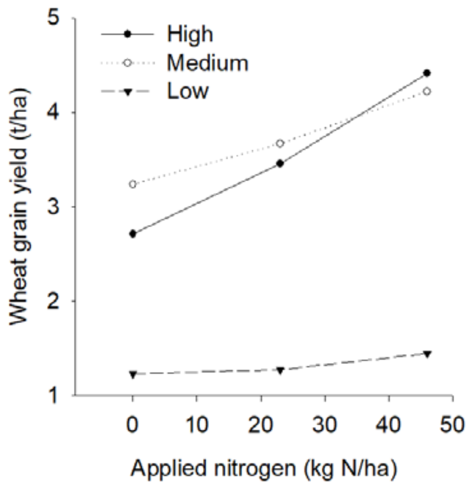

Figure 5. Wheat yield response to applied nitrogen in the low-, medium-, and high-yielding management classes at Biloela

At a standard price of nitrogen, this is worth $46/ha/annum and is coupled to potential environmental pollution due to nitrate-N leaching into ground water. The conventional application for the medium-yielding class appears to be well-prescribed, with negligible wastage evident. The high-yielding class (16 ha), on the other hand, is under-fertilised by the conventional application rate, with an additional 3.9 t urea required.

At the Goondiwindi site, wheat yield showed a characteristic non-linear response to the different rates of MAP application for the high-yielding (unconstrained) class (Figure 6a), with yield maximised at the conventional application rate of 40 kg MAP/ha/year. In contrast, the low-yielding (constrained) class showed negligible response to MAP. The gross margins at 40 kg MAP/ha were estimated to be $12.0/ha/annum for the unconstrained class and $21.0/ha/annum for the constrained class. The gross margins at 80 kg MAP/ha were negative for both classes. These results suggest a sensible variable-rate management strategy for MAP applications on the field: retain the conventional MAP application rate for the unconstrained class but stop application of MAP to the constrained class. Under this rationale, assuming that the responses in Figure 6a apply equally to the constrained area of the whole paddock, the financial benefit of variable-rate management would represent a saving of $32/ha/annum.

Table 1. Nitrogen need analysis for comparisons between field-uniform application of nitrogen (46 kg N/ha) and for optimised variable rate for the Biloela site

	Low-yielding class (20 ha)	Medium-yielding class (28 ha)	High-yielding class (16 ha)	Field average (64 ha)
Average wheat yield (t/ha)	1.27	2.22	3.36	2.21
Nitrogen requirement (kg/ha)	59	100	150	101
Available NO_3-N in 0–0.90 m soil (kg/ha)	119	55	36	70
Actual N required (kg/ha)	0	45	114	31
Consequence of uniform N application	2.0 t urea wasted	0.06 t urea required	3.9 t urea required	2.0 t urea Required

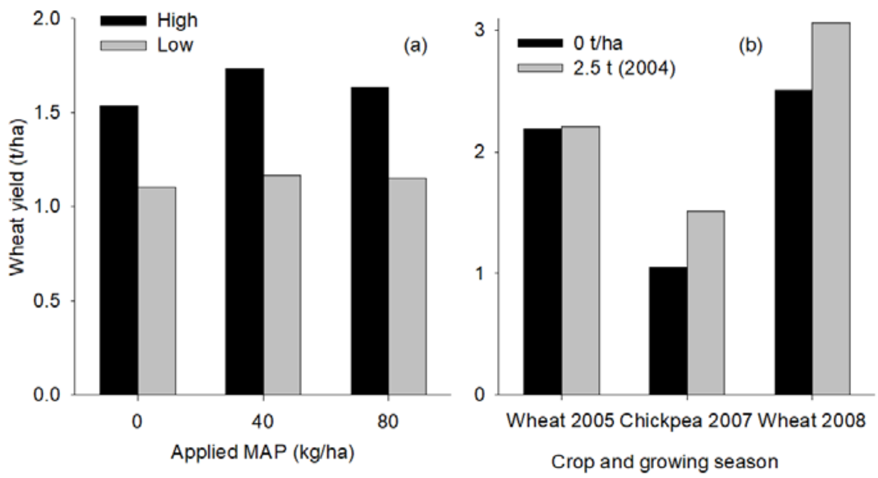

Figure 6. Results of on-farm experiments at the Goondiwindi site: (a) wheat yield response to applied MAP for the low- and high-yielding classes; and (b) yield response to applied gypsum seen on constrained areas.

Gypsum applied to adjoining farm at 2.5 t/ha in 2004 had no effect on wheat grain yield in 2005, but significantly increased chickpea grain yield by 0.46 t/ha in 2007 and significantly increased wheat grain yield by 0.56 t/ha in 2008 (Figure 6b). The delayed effect of the applied gypsum was expected because its movement through the soil profile is dependent on rainfall. The cumulative economics of a single gypsum application to the constrained class, for two wheat crops and one chickpea crop, would translate to an accumulated profit of $232/ha/3 yr.

At the Garah site, applied N up to 50 kg N/ha significantly increased barley grain yield in both the low-yielding (constrained) class and the high-yielding (unconstrained) class (Figure 7). However, in the constrained class, the gross margin was $45/ha at 50 kg N/ha and decreased to -$12/ha at 100 kg N/ha, while in unconstrained areas the gross margin was $49/ha at 50 kg N/ha and decreased to $10/ha at 100 kg N/ha. Both gypsum and compost significantly increased barley grain yield in both the constrained and unconstrained classes in the first year of its application (Figure 7).

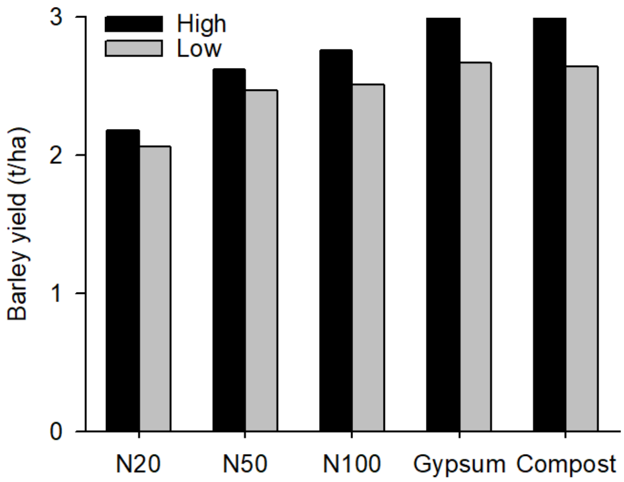

Figure 7. Barley yield response to applied nitrogen, gypsum and compost in the low-and high-yielding classes at Garah

Discussion

Using EC_a to partition soil into regions of similar production potential as a means to describe within-field variability and create management classes requires an understanding of the relationships between EC_a and grain yield. In the present study, at all three sites there was a strong negative relationship between EC_a-CLL and mean grain yield (Figure 2), allowing identification of management classes based on ranges of EC_a-CLL. The results further suggest that the soil properties integrated in EC_a-CLL observations are related to yield limitations in these soils. However, inconsistent relationships have been reported between EC_a and crop yields across years and locations among published reports (Kitchen *et al.* 1999; Johnson *et al.* 2003). In areas with high rainfall, the relationships between EC_a and grain yield tends to be positive (Kitchen *et al.* 1999) while in semi-arid regions, especially for winter crops, the relationship between EC_a and grain yield has been found to be negative (Johnson *et al.* 2003). This could be due to the fact that EC_a primarily measures salt concentrations (McNeill 1992) and the impact of high salt concentrations is evident mainly in drier years (Sadras *et al.* 2003; Dang *et al.* 2010). Jung *et al.* (2005) showed that the sign of the correlation between EC_a and grain yield for claypan soils followed the pattern of in-crop rainfall (ICR): there was a positive correlation in years with >150 mm of in-crop rainfall, compared with a negative correlation for years with <150 mm of in-crop rainfall. In the former, higher rainfall dilutes the salt concentration in the soil solution, thus minimising the salt effect on crop yields while in the latter, high salt concentrations in the soil solution of readily soluble sodium and chloride adversely affect crop yields. They summarised that rainfall affected grain yield more than the variations in soil properties. In the present study, all three sites were in semi-arid regions, where insufficient in-crop-rainfall (i.e. in most years <150 mm) poses the primary limitation to crop production. Under these climatic conditions EC_a-CLL may be a more consistent predictor of winter cereal grain yield potential than EC_a-DUL values.

For farmers to adopt class-based site-specific management, the development of management classes must be simple, functional and economically feasible. We have assumed that all the fields we studied could be partitioned into at least two management classes. Taylor *et al.* (2007) stated that it is rare for more than three classes to be justified, regardless of the size of the field. As a first approximation, the classes could be delineated using farmer's personal observations of the variability of grain yield in an individual field. We have found that experienced farmers have a fairly good understanding of yield variability within their fields. This is supported by the findings of Oliver *et al.* (2010). By working closely with farmers and using EM38 surveys, it is possible to devise a class-based management strategy for individual fields.

Site-specific soil and nutrient management

Identifying the spatial variability of soil constraints could provide an opportunity to ameliorate soil, resulting in economic and environmental benefits. For example, in the present study, gypsum application provided a financial benefit of $207 ha over 3–4 years at Site 2, and also provided a significant yield response at Site 3 with the expectation of recovering the variable costs in subsequent years. The potential environmental benefits would be increased rooting depth, increased PAWC and reduced concentrations of sodium chloride in the soil profile (Dang *et al.* unpublished data), with increased infiltration and improved surface drainage (Jaywardane and Chan 1995). The range in potential economic benefits by reducing input costs is similar to the benefits derived by others (Robertson *et al.* 2007; Fisher *et al.* 2009). The environmental benefits can be significant when using site-specific management in which the right amount of input is applied to each location. The presence of un-utilised nitrate-nitrogen in the constraint areas poses greatest risk to N-leaching (Wong *et al.* 2006).

Conclusion

Vertosols exhibited the greatest variation in soil properties associated with soil constraints, including EC_{se}, soil chloride and sodium concentrations integrated over a soil depth of 1.5 m for the three sites considered. The EMI (electromagnetic induction) provided the best estimates of the deep subsoil properties and especially soil chloride and soil moisture. This is important because high concentrations of chloride below 0.9 m (0.9–1.5 m) restrict water extraction by crop from the subsoil and is associated with reduced grain yield. Since solid-solution phases of gypsum contributes to low and relatively similar EC_a at different soil moisture contents, and gypsum is common in many soils of the region, it is suggested that EC_a measurements should be functionally related to soil solution sodium and chloride.

The EC_a showed strong negative correlations between grain yields both at DUL and CLL but more strongly with the latter. Strong correlations among EC_a-CLL, soil properties associated with soil constraints and winter cereal grain yields indicated that EC_a-CLL portioned management classes satisfactorily. Simple on-farm experiments provided an excellent framework for economic and environmental assessment to make management more precise by targeting constraint areas of the paddock or farm.

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NEW TECHNOLOGY CONCURRENT SESSION

Data sources to help manage variability that won't break the bank - what's out there?

Brett Whelan and Mario Fajardo, University of Sydney

Key words

yield data, publicly available data, digital agriculture, machine learning

GRDC code

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Take home messages

- The pool of publicly available off-farm data that may be relevant to combine with on-farm data is increasing and can now be swiftly gathered for any farm or field. Collecting and using this data to make more informed decisions is an opportunity for growers, and opportunities for inclusion in decision making tools needs to be explored
- Machine learning, and hybrid models derived from large data sets and field validation should be tested against crop simulation models currently in use for estimating yield potential and input requirements/crop response
- Using these powerful techniques provides the opportunity to use large data sets that cover a local area for analysis of the drivers of variability in crop performance and profit rather than just using individual field data in the analysis as is the current Precision Agriculture technique
- Building a freely available weather database at a much finer scale than is available now to improve predictions should be an industry and government imperative
- Using power output or fuel use data recorded while working with ground-engaging implements may be a low-cost, novel way to map changes in soil strength/type.

Background

Australian broadacre crop production currently provides approximately 35% of agricultural GDP and the nations farmers export approximately 75% of production into competitive international markets. This is achieved with a very low level of external financial support compared to almost all competitors Producer Support Estimate (PSE) 2017, Australia = <2%; OECD = 18%, USA and Canada = 10%, Kazakhstan = 4%). Optimum business performance in a competitive environment requires the application of relevant information to critical decisions relating to improving efficiencies and production quantity/quality. In cropping businesses which operate in a variable environment, information on variability in resources, environmental conditions and output is an important component of the relevant information required.

Low cost information

Yield monitor data

In terms of high value low cost information for broadacre cropping, yield monitor data should be high on a cropping managers list. With the overwhelming majority of farms already accessing high accuracy global navigation satellite systems (GNSS) and yield monitors becoming standard equipment on most harvesters, the yield mass (t/ha), grain moisture (%) and elevation (m) data available from these systems automatically during harvest operations comes at a low financial cost. The elevation data can be used to produce a range of useful information relating to changes in the landscape and its impact on soil development, water movement and solar radiation aspect. Calibrated crop yield and moisture data directly records variability in production across fields and years, and the high spatial resolution yield data is a simple yet crucial method for monitoring or modelling the effect of management changes on production and is a layer of data vital to ground-truth data gathered from off-farm.

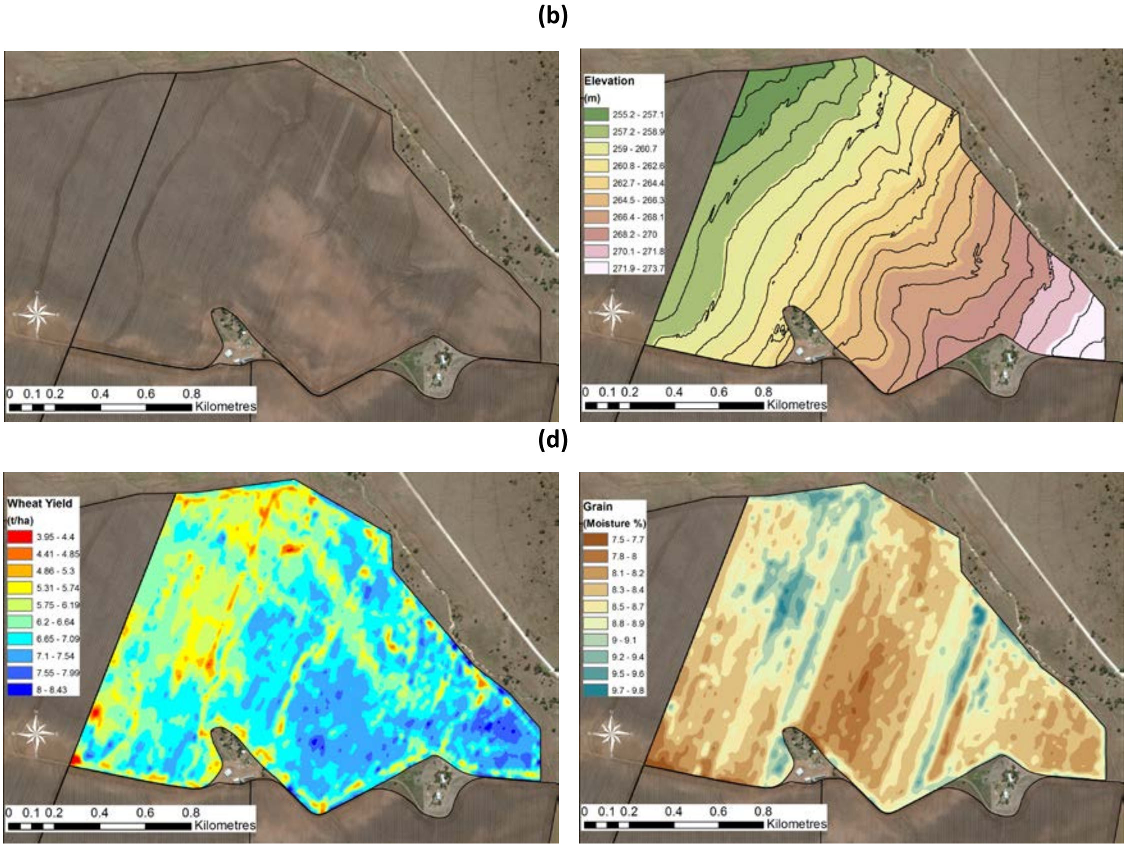

Figure 1. Paddock imagery on Google Earth (a), elevation data (b), crop yield data (c) and grain moisture(d)

Vehicle performance data

Performance data is routinely recorded by newer tractors and self-propelled implements. Data on variation in fuel use and other relevant operational parameters can have economic and efficiency dividends. Novel ways to use this free data include using power output or fuel use while working with ground-engaging implements to map changes in soil strength/type (Figure 2). There is also the potential to use the fuel use data in a carbon and nitrogen auditing process.

(a) (b)

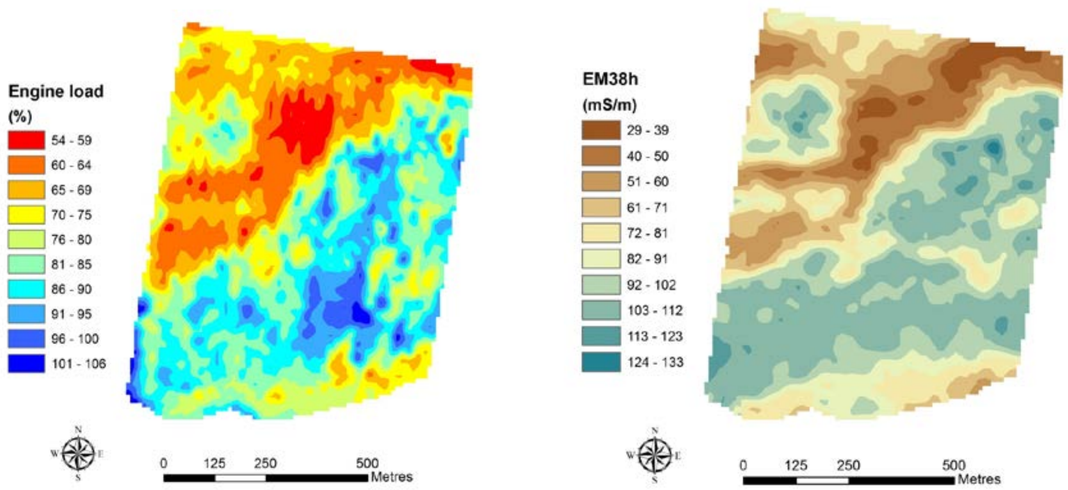

Figure 2. Tractor engine load recorded during the sowing operation (a) and soil apparent electrical conductivity (ECa) (b). Correlation coefficient = 0.85.

Publicly available data

The progress towards increasing use of digital data in agriculture is being led by a combination of improvements in sensor development, computing power, data storage/delivery, data analytical techniques and reduced costs. The synchronisation of these occurrences has in turn fuelled a greater interest in the data and its potential, thereby stimulating more development in all areas. A complementary benefit has been a rising number of data sources being made publicly, and more easily, available. Table 1 records a number of the most relevant as of early 2019.

Publicly available information can be downloaded from a range of individual providers (e.g. Geoscience Australia, CSIRO, ESA and NASA). This can be achieved on a number of platforms (e.g. Python, R and Android) using Application Program Interface (APIs).

Table 1. Public sources of data for potential use in describing variability in resources and production.

Provider	Resource	Data	Spatial Resolution	Temporal Resolution
CSIRO	SLGA	Bulk density, organic carbon, clay, sand, silt, pH, available water capacity, total N, total P, effective cation exchange capacity, depth of regolith, soil depth, coarse fragments.	90 x 90 x 2 m	Static
BOM	Gridded Daily Data	Rainfall, temp, vapour pressure, solar exposure, NDVI, atmospheric circulation	5 x 5 km	Daily from 1889
NASA	SRTM	Digital Elevation Model (DEM)	90 x 90 m	Static
Geoscience Australia	ELVIS	Digital Elevation Models (DEM) and (DEM-S)	5 x 5 m	Static
Geoscience Australia	ELVIS	Hydrological DEM (Hydrological features are enhanced)	30 x 30 m	Static
ESA	Sentinel 2	13 bands from ~ 430 to 2190 nm	10-20-60	Weekly
Geoscience Australia	AWAGS	Radiometric map of Australia	100 x 100 m	Static
NASA	ASTER	14 Bands from visible to thermal IR	15-30-90 m	Weekly from 2000
NASA	MODIS	36 spectral bands	250-500-1000 m	Weekly until 2010
NASA	LANDSAT 7	8 bands from ~450 to 2350 + ~10.400 to 12.500	15-30-60 m	Second week
NASA	LANDSAT 8	11 bands from ~435 to 2294 + ~10.600 to 12.500	15-30-60 m	Second week
NASA	SMAP	Soil moisture and Carbon Net Ecosystem Exchange	9 x 9 km	Weekly and Second week
QANDL	Financial	Futures and commodity exchange data	-	various

In 2010, Google released the "Google Earth Engine" - a platform dedicated to providing access to a multitude of different data layers (including most listed in Table 1) at the cost of registration time only. A substantial advantage of this platform is that all the information is stored in a database standardised to different resolutions, in the same geographic reference system. Data can be downloaded in user-configurable locations and resolutions for use as required. For example, yield data (or the location of yield data points) can be uploaded to Google Earth Engine as private data and then the public data layers can be extracted to match the geographic locations and extent of the input layers. Alternatively, boundaries of farms or fields can be used to clip and extract data layers. The platform also enables real-time analysis using Google's computing infrastructure that runs processes across thousands of computers in parallel, enabling large analytical tasks to be performed or task time to be drastically reduced.

Machine learning and data fusion approaches

The increase in availability of digital data and processing capabilities is leading to the application of data fusion techniques and machine learning to search for new insights from the data. There have been significant developments in machine learning analytical methods, which differ from mechanistic or process-based models that are commonly used in cropping because they use data-driven approaches to discover relationships between variables.

A major advantage is that they can make use of both quantitative and qualitative data from a wide range of data sources. On-farm data from sensors currently used in precision agriculture, along with what will be an increasing variety of sources, volumes, scales and structures of off-farm data (from other local/regional farms and the non-farm domains shown above) can be input into analysis and decision-making back on-farm.

GRDC future farm program

The future farm program (CSIRO, UYSD, USQ, QUT, AGVIC) aims to utilise this off-farm data, historical on-farm data and re-examine and improve the way in which current in-season field monitored data (soil, crop, climatic) are used to inform decisions about input management. The outcome should be a way of automating the process from data acquisition, through analysis, to the formulation and implementation of decision options with manager input. The initial focus is on improving the efficiency and profitability of applied nitrogen (N).

The initial operational parameters are:

- N fertiliser decision making should be supported by measures of plant N status (which in turn requires estimation of biomass), soil N status and soil water status/availability i.e. a multi-sensor approach is required
- In-season sensor data will be a key input and employ machine learning methods of data integration for development of location-specific decision options
- Both remote and proximal sensing of the crop canopy will make an important contribution to N fertilizer decision making, but this should be supported by some form of on-farm experimentation, with a zero N treatment (plot or strip) a critical enabler for interpretation
- The process should be deployable in a way that will be complementary to the inclusion of other inputs/assessments that managers may also bring to bear in decision making.

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A review of the state of the art in agricultural automation. Part IV: Sensor-based nitrogen management technologies

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Keywords

machine vision, optical plant sensors, sensor-carrying platforms, 3D-imaging, unmanned aerial vehicle (UAV), unmanned ground vehicles (UGV), vis-NIR

GRDC code

USQ00022

Take home message

Crop nitrogen (N) management is one of many important agricultural applications that can benefit from crop sensing. The technologies in this field are advancing rapidly, including: (1) sensor-carrying platforms, (2) the sensors themselves, and (3) the analytical techniques used to derive actionable information from the data.

A review of commercially and semi-commercially available platforms was undertaken to inform sensor mounting, with particular focus on unmanned aerial vehicle (UAV) sensor platforms and unmanned ground vehicle (UGV) sensor platforms. The UAV and UAG platforms provide indirect and direct measurements for crop monitoring and N mapping with the goals of being low-cost, on-site, and versatile.

Optical crop sensing techniques and systems for N management are also discussed, because destructive sampling and laboratory analyses are expensive and often not practical for site-specific management of N. The optical properties of the plant are significant because they are related to water content, leaf senescence, disease, and nutrient status, which can inform farming decisions. Additionally, Red, Green and Blue (RGB) imaging can provide a plant height assessment for multiple measurements, including: yield potential, biomass, density, uniformity, and planter skips.

The work reported in this paper includes a comparison of various optical sensors for plant measurements, including: vis-NIR, machine vision, and 3D-imaging, with camera varieties such as multispectral, fluorescence, hyperspectral, thermal, and visible. Key recommendations have been provided for the development of data aggregation and decision support tools including the data sources to be used in development of machine learning models, software/data standardisation efforts, and corporate collaborations regarding big data. In conjunction with the sensors and their platforms, this advancing field of management technology can provide intelligent sensing and intelligent decisions.

Introduction

This paper, the fourth in a series of four, includes a comparison of various optical sensors for plant measurements, including: vis-NIR, machine vision, and 3D-imaging, with camera varieties such as multispectral, fluorescence, hyperspectral, thermal, and visible, respectively. The other three papers in this series (Baillie *et al.,* 2018a-b; Thomasson *et al.,* 2018) critically review commercially-available sensing technologies for optimization of machine operations and farm inputs, the on-farm communications and connectivity, and the agricultural machinery navigation systems, respectively.

The current reference technique for measurement of plant nitrogen (N) status is plant tissue sampling following by analysis of total N using Kjeldahl-digestion and Dumas-combustion (Oxenham *et al.,* 1983), which are both time consuming and costly laboratory techniques (Muñoz-Huerta *et al.,* 2013). To quantify N deficiency, the N content in plant material is then referenced to critical threshold concentrations. These are defined as the minimum N content required for optimal growth or beyond which no additional yield would be expected (e.g., Rochester, 2011). These values are determined experimentally (using field trials) and are dependent on the crop growth stage or above ground biomass (e.g., Justes *et al.,* 1994). The N status can be also represented as a N nutrition Index (NNI) calculated as a ratio of the actual measured N content and the critical N content for the given dry weight (Mistele and Schmidhalter, 2008). The analysis of plant tissue to determine N status has some advantages over soil testing in that the complexities of other soil, plant and environmental factors that will ultimately influence plant uptake are effectively accounted for by measuring the plant response directly. For macronutrients, good correlation is usually found between plant concentrations and nutrient status as measured by yield (van Maarschalkerweerd and Husted, 2015). Analysis of plant tissue however is regarded as impractical for site-specific management of N. Soil mineral N is highly variable (McBratney and Pringle, 1999) and although not practical, it has been suggested that analysis and differential fertilizer application should occur at a spatial resolution of 1-m to maximize benefits of site specific N management, recognizing that variability in yield potential and fertilizer needs exist at this resolution (Raun, 2005). There has therefore been a considerable effort in the development of rapid, low cost optical sensing techniques for analysis of plant N status.

Optical crop sensing techniques for nitrogen management

Optical sensing provides a cost effective and rapid technique for the measurement of plant biophysical and biochemical status. The optical properties of the plant are related to water content, leaf senescence, disease and nutrient status (Muñoz-Huerta *et al.* 2013). However, optical sensing techniques are typically indirect, and are unable to measure N content of the plant directly (Raun *et al.,* 2002). They are instead based on measurement of compounds such as chlorophyll, which can be used as an indicator of N status (Živčák *et al.,* 2014a-b). Sensing techniques can be defined by the region in the electromagnetic spectrum in which they operate and their measurement range (e.g., tractor mounted) or remote levels (e.g., airborne or satellite platforms). Sensors can rely on existing ambient lighting (passive) or use active light sources to improve measurements in variable lighting conditions and also allow operation at night. Sensors may be deployed on airborne vehicles (e.g., UAVs) or may be limited to ground vehicles (e.g., UGVs and tractors). When compared with other sensing techniques (e.g., soil sensing), optical plant sensing is relatively easy to perform and a range of sensing techniques and sensors are commercially available (Table 1). Optical sensor measurements are rapid and low cost and can therefore provide the high spatial and temporal resolution required for N management.

Reflectance (multispectral)

Reflectance sensors in the visible-near infrared range utilize the principle of healthy plant tissue absorbing light in the photosynthetic active radiation (PAR) region of the spectrum, and reflecting in the infrared region (Galambošová *et al.,* 2014). Sensors typically measure reflectance in the red wavelength range that corresponds primarily to absorption by chlorophyll A, and NIR wavelengths at approximately 800-nm. Reflectance sensors can be active, which allows operation at night and improves response under variable lighting conditions. They can also operate passively and so the technique is suitable for remote sensing (UAV or satellite). Some commercial sensors (e.g., OptRx, CropSpec) and the RapidEye satellite also utilize the 'Red Edge' band (690-730 nm) at the inflection point in the absorption spectrum, which can improve response in high-plant density and later growth stages. Using the reflectance measurements in these different bands, vegetation indices are calculated relating to the plant vigor, biomass or chlorophyll content. These indices are then related to the N status of the plant. A number of different indices, such as the normalized difference vegetation index (NDVI) have been developed for these purposes (e.g., Rodriguez et al., 2006; Chen et al., 2010). Sensors can be mounted on a tractor for on-the-go measurement and therefore they have seen considerable attention for N management (Table 1). An overview of the commercially available reflectance sensors and their application to N management is provided by Whelan (2015).

Table 1. Optical plant sensing for nitrogen management.

Sensing mechanism	**Measured properties (Indices)**	**Wave length range**	**Energy**	**Sensing range (level)**	**Autonomous deployment**	**Sensing resolution at field scale[1]**	**Measure ment of N status[2]**	**Commercial products**	**References**
vis-NIR Reflectance (multispectral)	Chlorophyll (NDVI, SRI, VI …)	Vis-850nm	Active / Passive	Leaf / canopy / remote	UAV / UGV / Satellite	+++	++	GreenSeeker, CropCircle, CropSpec, Yara N-Sensor, OptRx, Field Scout	Rodriguez *et al.* (2006), Raun *et al.* (2005)
vis-NIR Transmittance	Chlorophyll, Polyphenols (NBI)	650nm and 940nm	Active	Leaf	UGV	+	++++	SPAD Duelex Cropscan 3000H	Prost and Jeuffroy (2007), Debaeke *et al.* (2006), Chen *et al.* (2010)
Fluorescence	Chlorophyll, Polyphenols (Anth, Chl, Flav, NBI)	UV (excitation) - vis-NIR	Active / *Passive*	Leaf / canopy	UGV	++	+++	Mulitplex, MiniVeg	Cendrero-Mateo *et al.* (2015), Cerovic *et al.* (2012), Tremblay *et al.* (2012), Tartachnyk *et al.* (2006), Chaerle *et al.* (2007)
vis-NIR Reflectance (hyperspectral)	Nutrient status, water content (empirical calibration)	Vis-2500nm	Active / Passive	Leaf / canopy	UGV	++	+++	Fieldspec (ASD), Ocean Optics, ...	Hansen & Schjoerring (2003), Kusnierek & Korsaeth (2015), Chen *et al.* (2010)

Sensing mechanism	Measured properties (Indices)	Wave length range	Energy	Sensing range (level)	Autonomous deployment	Sensing resolution at field scale[1]	Measure ment of N status[2]	Commercial products	References
Machine vision (visible)	Plant height, Stalk diameter, Structure, Leaf area	Vis	Passive (typically)	Leaf / canopy / remote	UGV / UAV	++++	++	Licor canopy analyser for LAI	Sadeghi-Tehran et al. (2017), Li *et al*. (2010), Casadesus & Villegas (2013)
Machine vision (multispectral)		Vis-1000nm	Active / Passive	Leaf / canopy / remote	UAV / UGV	++++	+++	Survey2 (MAPIR) RedEdge/Parrot Sequoia (Micasense)	Tilling *et al.* (2007), Vigneau *et al.* (2011)
Machine vision (fluorescence)	Chlorophyll, Polyphenols, Biotic stress (Anth, Chl, Flav, NBI)	UV (excitation) - vis-NIR	Active	Leaf / canopy / (remote)	UGV	+	+++	Walz (IMAGING-PAM M-Series)	Bauriegel and Herppich (2014), Kuckenberg *et al.* (2009)
Machine vision (thermal)	Water stress, Biotic stress	LWIR	Passive	Leaf / canopy / remote	UAV / UGV	++++	+	FLIR, Xenics	Tilling et al. (2007), Costa *et al*. 2014
3D Imaging (LIDAR, TOF, stereo vision, laser profiling…)	Plant height, stalk diameter, structure, leaf area, tiller counting	Vis, IR	Active / Passive	Leaf / canopy	UAV / UGV	++++ (UAV plant height) ++ (other)	+	Photogrammetry software for point cloud generation (Pix4D, Agisoft), SICK scanners, + others	Duan *et al*. (2016)

[1]Sensing resolution is a function of sensor speed, sensor resolution, potential for remote deployment etc. (+ offers low or poor resolution, ++++ indicates high resolution, potential for 1~m2 spatial resolution as suggested by Raun *et al.* (2005). [2]Indicates the usefulness (or directness) for measurement of N status or informing N management decisions (+ indicates indirect measurement, low correlation, ancillary information only while ++++ indicates high correlation to plant N status).

Rodriguez et al. (2006) performed canopy reflectance measurement using a spectrometer (FieldSpec, ASD, 350-2500 nm) to evaluate a range of reflectance indices for the measurement of N stress, calculated from shoot N and shoot dry weight. The canopy chlorophyll content index (CCCi) and modified spectral ratio (mSRPi) indices were able to explain 68% and 69% of the variation in N stress, despite variation in water stress and canopy density. Chen et al. (2010) evaluated a number of vegetation indices calculated from hyperspectral reflectance measurements for the measurement of plant N concentration in wheat and corn. The results of the regression analysis (R2) were generally low for all indices in wheat (0.17-0.56) although measurements were diverse and included multiple growth stages. A new N index was later proposed, the Double-peaked Canopy Nitrogen Index (DCNI), which could explain 72% and 44% of the variation in plant N concentration for corn and wheat, respectively. In a later study (Chen, 2015) correlation of spectral indices with N concentration in wheat statistics improve on a growth stage basis with approximately 60% and 80% of the variation in N content explained by all indices at the Feekes 4 and Feekes 7-8 growth stages, respectively. Mechanistic models relating spectral indices and N nutrition index (NNI) validated well (R2: 0.82-0.94) and were independent of phenology.

Mistele and Schmidhalter (2008) used a spectrometer to measure wheat canopy reflectance and calculate the red edge inflection point (REIP). REIP and the N nutrition index NNI were highly correlated (R2 =0.95). The NIR/NIR indices (R760/R730) was reported to be the most reliable index for measurement of N status (Erdle *et al.,* 2011). The response of the NDVI indices become saturated and was unable to distinguish between high N treatments. While active sensors provide greater versatility in operation, the wide spectral information that can be obtained from passive sensors may be needed for phenotyping certain traits (Erdle *et al.,* 2011).

There are limitations in the use of reflectance sensor for measurement of plant N content. Reflectance sensors are ultimately a measure of biomass/chlorophyll content, and this can be slow to change in response to most environmental changes and is not solely related to stress (Tremblay *et al.,* 2012). The chlorophyll content and biomass of the crop may only be indirectly related to the adequacy of N supply, and therefore empirical calibration of applied N to sensor response during crop growth is necessary for inference. Methods for predicting N requirements and calculating N response index using reflectance sensors are described by Whelan (2015). Calculating a response index is typically performed using reference strips where fertilizer is applied in non-limiting rates and sensor response in this area is used to inform application rates in the remainder of the field. Limitations for this approach are selecting a reference strip area that is representative of the field (e.g., Samborski *et al.,* 2017) and that it is effective only when N is the main growth limiting factor (e.g., Zillmann *et al.,* 2006). Further limitations of this sensor technique for N management include chlorophyll saturation where sensors are unable to distinguish between adequate and excess supply of N (Ruiz Diaz et al., 2008) and they are sensitive only when the fraction of vegetation cover is low (Maier and Günther, 2003). The available commercial sensors also differ in their use of active or passive techniques, wavelength ranges and the signal output can also differ with measurements based on different vegetation indices. Crop sensors need to be calibrated for different cultivars, sites and seasons (Craigie *et al.,* 2013).

Transmittance (multispectral)

Measurement of chlorophyll can also be performed using transmission based (absorption) methods. The basic principle is as for the reflectance based methods described earlier. Commercial sensors are available, including the SPAD chlorophyll sensor (Minola Osaka Company, Ltd., Japan), which measures absorption using red (650-nm) and infrared (940-nm) LEDs in a leaf clip arrangement. SPAD measurements correlate well (R2 >0.70) with plant N concentration in both corn and wheat combined and over multiple years, and growth stages (Chen *et al.,* 2010). Prost and Jeuffroy (2007) evaluated the use of SPAD measurements in the assessment of wheat N status as an alternative to the N nutrition index (NNI) and found that a significant relationship (R2 = 0.89) exists between SPAD measurements and NNI (at flowering), which was independent of cultivar. Debaeke *et al.* (2006) related normalized SPAD measurements to NNI and found them to be closely related irrespective of year, cultivar or growth stage.

Measurement of flavonoids in the leaf epidermis can also be used as an indicator of N status because plants produce these compounds under stress conditions (e.g., N stress) (Muñoz-Huerta et al., 2013). UV light is also absorbed by these compounds in the leaf epidermis and so flavonoid content can be estimated using absorption methods (e.g., Duelex® sensor, Force-A, Orsay, France) (Tremblay *et al.,* 2009; Cerovic *et al.,* 2012). The Duelex® sensor uses both fluorescence and light transmission through the leaf to calculate both chlorophyll content and epidermal UV-absorbance (Flv). This forms the basis of the N balance index (NBI) calculated as a ratio of the chlorophyll to flavonoid content. A limitation of transmission techniques is that they are contact-based measurements, and therefore not suitable for on-the-go or large area sensing. Similarly, automated measurements are also difficult to perform. The technique measures chlorophyll concentration as a proxy for N content and so limitations in this assumption will also apply (as for reflectance measurements).

Transmission methods can also be applied post-harvest for the measurement of grain protein and water content, and commercial sensors are available (e.g. the CropScan 3000H) for on harvester measurement and mapping. Combined with yield data, these measurements provide useful information on N use and may be used to inform variable rate N management (Long *et al.,* 2005).

Chlorophyll fluorescence

The principles of chlorophyll fluorescence sensing are described in Tremblay et al. (2012). Of the incident solar radiation in the photosynthetically active region (PAR) (400-700 nm), 75% is absorbed by leaves with the majority of this energy dissipated thermally and a small fraction (3%) converted to organic matter. On absorbing energy at a given wavelength chlorophyll molecules also re-emit this energy at a longer wavelength through electron excitation (fluorescence). Measurement of chlorophyll fluorescence at these wavelengths is related to leaf chlorophyll content (Tremblay et al., 2012). Chlorophyll fluorescence can be measured in two ways: (1) by using the variable (dynamic) changes in fluorescence corresponding to changes in the photosynthetic reactions (Kuckenberg et al., 2009; Tremblay et al., 2012), and (2) using the ratio of fluorescence emissions at different wavelengths, which are more suitable for in-field application and measurements at the canopy level. These measurements can be passive, using sun-induced fluorescence or active; e.g., laser-induced fluorescence (Schächtl *et al.,* 2005). Commercial sensors are available, including the Multiplex® (Force-A, Orsay, France) and the MiniVeg-N laser-induced fluorescence sensor (Fritzmeier, Germany). Chlorophyll fluorescence can also be used to measure polyphenolic compounds (e.g., flavonoids) compounds in the leaf epidermis. UV light is also absorbed by these compounds in the leaf epidermis and by comparing chlorophyll fluorescence induced by both UV and red light; the flavonoid content can be estimated (e.g., Quemada *et al.,* 2014).

When used for sensing plant N status, an increase in fluorescence emission indicates a reduction in photosynthetic efficiency, which increases at the early stage of most stress conditions (Chaerle *et al.,* 2007). As measurements are based on fluorescence signals (and not reflected), fluorescence sensing can provide highly sensitive information on plant N status that is independent of soil interference, leaf area or biomass status (Tremblay *et al.,* 2012). Tremblay *et al.* (2012) suggest that fluorescence sensors could be used for non-invasive detection of stress long before reflectance based measurement of chlorophyll content or biomass, which are long-term effects of stress and also potentially a response to other environment changes. The sensing technique has seen limited application in N management, possibly due to the relative ease of reflectance-based measurements (e.g., for on-the-go). When using variable fluorescence measurements, dark adaptation is required, which is time consuming (10-20 minutes).

Reflectance (hyperspectral)

Spectroscopic analysis of the canopy using visible and near-infrared reflectance (vis-NIR) could provide greater information relating to plant status than indices derived using discrete wavelengths (Meng and Dennison, 2015). For plant analysis, several N absorption features exist below 2500-nm; however, water absorption bands in the NIR region limit use on plant samples that have not been processed (dried) and therefore field application (Chen *et al.,* 2010). Several spectrometers are commercially available and have been used for plant analysis (e.g., FieldSpec, Analytical Spectral Devices (ASD), Boulder, Colorado). Spectrometers are generally expensive, with some exceptions such as the DLP® NIRscanTM sensors (Texas Instruments) covering the 900-2490 nm range. A potential advantage of spectrometers for canopy reflectance measurement is that full spectral information can be retained and multiple vegetation indices estimated simultaneously. Using chemometric approaches, it is also possible to simultaneously derive estimates of water status to separate N from water stress occurring simultaneously (e.g., Kusnierek and Korsaeth, 2015; Lamptey et al., 2017), and potentially the status of other nutrients that are relevant to N decision support (e.g., van Maarschalkerweerd and Husted, 2015).

Machine vision

Most optical sensing mechanisms can also be applied to machine vision (Hague *et al.,* 2000). Image sensors are available that cover visible and near-infrared ranges (e.g., multispectral and hyperspectral cameras). These can be used to image the crop or plant at wavelengths surrounding the ‘red edge’ region, and thus capable of computing the vegetation indices of other reflectance-based optical sensors (e.g., GreenSeeker). Imaging has advantages over these sensors: (1) cameras deployed on remote platforms (UAV) can be used to capture canopy reflectance or thermal measurements with full field coverage at high spatial resolution, (2) ground-based machine vision sensors can better isolate soil influence on the signal by first segmenting leaves and plants within the image, and (3) the image resolution offered by cameras can also be used to resolve structure information at the plant and leaf level that could be utilized for N management of the crop. Several camera systems are commercially available at relatively low cost, and lightweight cameras have been released for UAV application. For example, the Survey2 by MAPIR (San Diego, California) and the RedEdge by MicaSense (Seattle, Washington) that can be installed with a range of filter options for crop vegetation imaging (e.g., NDVI).

Figure 1 (after Li *et al.,* 2010) shows the use of a standard digital camera for measurement of crop N status. Camera measurement of the crop canopy cover correlated well with N status and also with NDVI of the GreenSeeker and Yara N-Sensor, respectively. However, correlation with N status was strong only during the vegetative and early stem elongation phases.

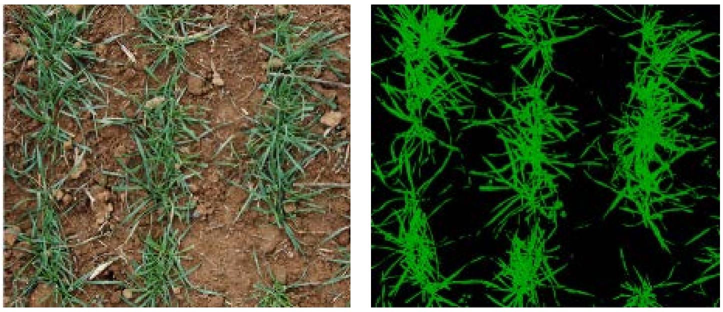

Figure 1. A digital camera image of wheat crop with segmentation of leaf area (after Li et al. 2010).

Thermal imaging can be used to measure the leaf surface temperature, which is influenced by the cooling effects of transpiration due to stomatal conductance (Irmak *et al.,* 2008). This mechanism responds to a number of stress conditions both abiotic and biotic (Chaerle *et al.,* 2007; Yeboah *et al*., 2017). Water or nutrient deficiency causes increase in leaf temperature by disrupting the transport of nutrient and water throughout the plant, causing the stomata to close to prevent further moisture loss (Mee *et al.,* 2016).

Tilling et al. (2007) used ground-based spectral (vis-NIR) and airborne multispectral and thermal imagery to quantify N and water stress in wheat (Figure 2). The Canopy Chlorophyll Content Index (CCCI) using the ground-based spectrometer was well correlated with a Nitrogen Stress Index (NSI) derived from plant samples, but correlation was lower with airborne spectral measurements. A major limitation of remote sensing is the influence of the soil background when partially vegetated, but the thermal sensing of water stress could be useful for decisions on N application (Tilling *et al.,* 2007).

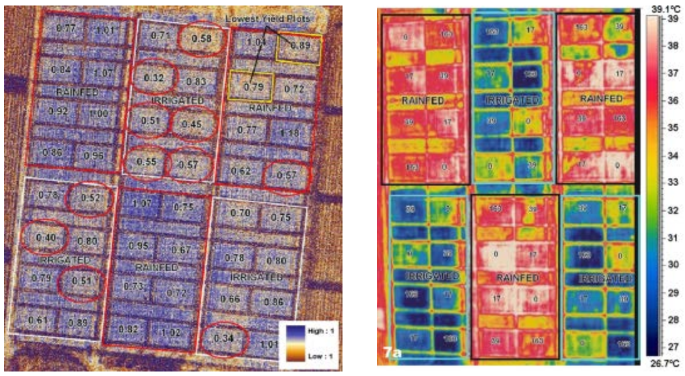

Figure 2. Airborne images of Canopy Chlorophyll Content Index (CCCI) (left image) derived using a 3-band multispectral camera (670, 720, 790-nm) and thermal imagery (right image) (after Tilling *et al.,* 2007).

The measurement of plant physical properties, or structure, can be used as an indicator of plant N status, yield prediction, and N demand. Measurement of leaf area is important for predicting crop growth and yield, and can be well correlated with canopy N content (e.g., Yin et al., 2003; Gebbers *et al.,* 2011; Tavakoli *et al.,* 2014). LAI can be detected remotely using UAV platforms. For N management, Hunt *et al. (*2010) used a standard digital camera (without infrared blocking filter) and modified with an interference filter to derive a Green Normalized Difference Vegetation Index (GNDVI). With images captured from the UAV platform correlation of GNDVI to LAI was R2 >0.80, but saturated above a LAI of 2.5 m2 m-2.

Sadeghi-Tehran et al. (2017) developed a computer vision framework for the automated monitoring of ear emergence and flowering in wheat using an RGB camera in-field conditions. The accuracy in detection of ear emergence was reported as >90%, depending on the size of training dataset, and accuracies ranged from 80% to 93% for detection of flowering time. Both hyperspectral and chlorophyll fluorescence sensing techniques can also be implemented in computer vision providing information on plant transpiration and photosynthesis relating to N, water and disease status.

Vigneau *et al.* (2011) evaluated the use of a hyperspectral camera (push broom CCD) with a spectral range from 400 nm to 1000 nm at 3.7 nm resolution. The camera was tractor-mounted on a gantry at a height of 1-m above the crop canopy, and the camera motion along the gantry was used to provide the second imaging dimension. An empirical calibration was used to estimate the leaf N concentration using a chemometric approach from hyperspectral data. Models developed using measurement of individual leaves in both greenhouse and field environment showed good predictability (R2 >0.85).

Machine vision sensors can be used for detection of biotic stress due to pathogens or insect damage. While this is not a direct measurement of plant N status, such information could be useful in decision support systems; for example, by validating the assumption of N stress as the primary factor affecting other optical measurements of plant chlorophyll or biomass (Bauriegel and Herppich, 2014). Biotic stress may also induce yield loss that is assumed to be N-related, machine vision sensors may therefore assist in identifying the cause of yield loss before using this data in N and crop modelling.

3D imaging

3D Imaging of crops using for example LIDAR, stereo cameras or time of flight (TOF), can provide plant physical or structural information. Application of these techniques to date is mostly in high throughput screening and plant phenotyping for breeding. However, in a field context this information could be used normalize measurements from other sensors, that is, account for biomass and growth stage, to support decisions in N management. Commercial sensors are available, as well as software for photogrammetry and point cloud generation. For plant phenotyping, Duan *et al.* (2016) used multiview camera imaging to reconstruct 3D images of wheat plants (point clouds) using the Multi-View Stereo and Structure From Motion (MVS-SFM) algorithm (Figure 3). From the 3D point cloud, Duan *et al.* (2016) were able to automatically determine several phenotyping traits, including: tiller and leaf number, plant height and leaf properties useful for N management and yield prediction.

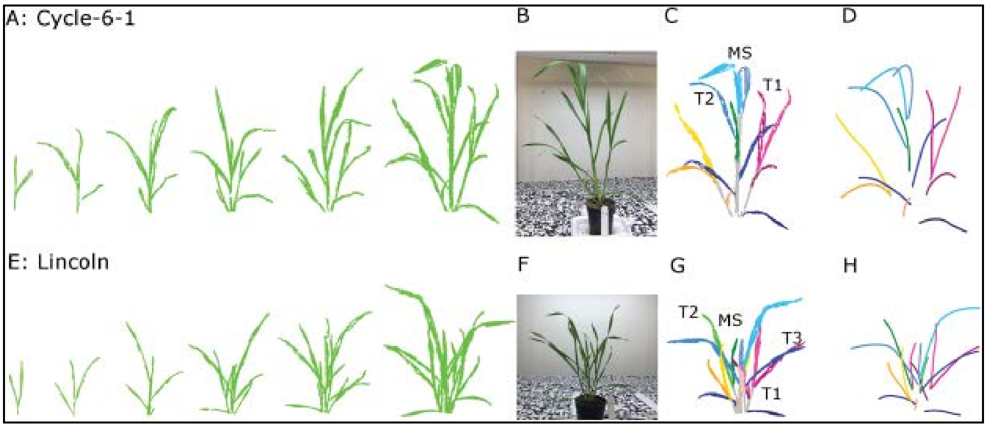

Figure 3. Measuring plant structure using multiview camera imaging (after Duan *et. al.,* 2016).

Optical sensing of nitrogen stress: confounding factors and sensor fusion

Spectral features assist the detection of plant nutritional-related stress when only one factor is causing such stress (Mee *et al.,* 2017). This makes it challenging when trying to discriminate sources of stress influencing plant physiological performance at the same time. This is the case when sources of stress can have similar impacts on the plant's physiological response (e.g., N and water) consequently leading to the observation of similar spectral responses (Thomason *et al.,* 2007). Peteinatos *et al.* (2015) evaluated the use of multiple optical sensors, including reflectance (spectrometer), and calculated multiple indices: the CLAAS Isaria® crop sensor, and the Multiplex® to identify stress due to water and N deficiency, weed and fungal infection in wheat. In their study, it was hypothesized that these sensors could be used to detect individual stressors in the presence of others. It was found that some indices, such as the FRFUV provided by the Multiplex® sensor, responded only to N stress whereas indices such as FERRG and ANTHRG responded only to fungal infection. Other indices from the Multiplex® and HandySpec® sensor respond to multiple stress factors. Variability in sensor response due to plant growth stage was more significant than variability due to stress factors (Peteinatos *et al.,* 2015). Therefore, growth stage needs to be considered to define a stress threshold.

Discussion

Analysis of plant tissue to determine nitrogen (N) status has some advantages over soil testing in that the complexities of other soil, plant and environmental properties influencing plant uptake of N are effectively accounted for by measuring the plant directly (e.g., Antille *et al.,* 2015, 2017). For macronutrients, good correlation is usually found between plant concentrations and nutrient status as measured by yield (e.g., Antille *et al.,* 2014; van Maarschalkerweerd and Husted, 2015). Optical sensors typically measure compounds (such as chlorophyll) that relate well to N status. However, this relationship can break-down when soil N availability is high, and as several other factors affect chlorophyll synthesis, it could be difficult to make environmentally-sound decisions on N application based on optical sensors (Tremblay *et al.,* 2009; Galambošová *et al.,* 2014).

Considering the range of sensing techniques available, reflectance-based measurements are easy to perform, show reasonably good correlation with plant N status, can be performed remotely providing high resolution, and several commercial sensors are available. Consequently, site-specific management of N has traditionally focused on reflectance-based technologies. However, a limitation of these technologies is the inconsistency in the relationship with N status based on crop growth stage, biomass and other growth factors, therefore requiring calibration on a site and seasonal basis. There are also different vegetation indices reported in the literature, and there is little consistency in the reported performance of such indices. Alternative sensing techniques, such as transmission-based measurements appear to be more reliable for estimating N status (e.g., SPAD measurements). However, it may not be possible to apply this technique at the spatial resolution required for N management (e.g., 1-m). Transmission-based measurements applied post-harvest (e.g., on-harvester protein-sensing) could also provide valuable information for N modelling, and in estimating N removal from soil.

For the measurement of N status, fluorescence-based techniques have some advantages over reflectance (Živčák *et al.,* 2014a-b), such as no influence of soil background and measurement of polyphenols. This latter enables the calculation of the N buffer index (NBI). Therefore, these may offer improvements in measurement of N status, although the additional measurement and sensor requirements (close range) may not warrant the use of such sensors alone. It had been reported that an on-the-go version of the Multiplex® sensor (A-Force, France) was under development, but this version has since been discontinued. However, factors limiting deployment of sensor technologies, such as active fluorescence sensing or transmission methods, may be addressed within a future autonomous framework; for example, with such sensor deployed using UGV to provide calibration/ground-based referencing of remote sensor measurement.

Using machine vision sensing of reflectance or fluorescence has potential to address some of the limitations in other techniques, such as segmenting of plants prior to calculation of indices and removing soil background effects, although sensor and computation requirements are greater. Deployed on airborne platforms (e.g., UAV), image sensors can provide reflectance measurements at high spatial and temporal resolution. When deployed on a ground vehicle, the camera can measure plant physical properties such as leaf area and height, potentially enabling independent estimates of biomass and chlorophyll content. At the leaf level, machine vision may also allow detecting biotic stresses. While not directly applicable to N decision support, these measurements could be used in diagnosing yield reduction, improving the quality of data applied to modelling and machine learning.

It is also difficult to directly compare sensing techniques for the measurement of crop N status, with the accuracy reported by studies undertaken in different conditions. However, a general classification of sensor performance for N stress measurement was presented in Table 1, which could be used to assist sensor selection.

Conclusions and recommendations

Optical sensor measurements of nitrogen (N) status are indirect, sensors respond to plant stresses that could be induced by a number of biotic and abiotic factors. Sensor measurements are also often dependent on other dominant factors, such as growth stage. A multi-sensor approach may provide a more accurate or reliable indication of N status, and better isolate those factors.

Optical sensing should also be applied post-harvest (e.g., for protein monitoring), and this could provide information on N uptake during crop growth, and quantifying N removed by the crop. There is a requirement for engagement with the tractor / harvesting manufacturers (e.g., John Deere, CNH, CLAAS) to further develop these applications.

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Aqua-Till liquid coulter

Greg Butler, South Australian No-Till Farmers Association

Key words

residue, stubble, sowing, liquid coulter, Aqua-Till

GRDC code

9175919

Take home messages

- The AquaTill liquid coulter has significant residue cutting capacity and is especially useful for seeding into matted and damp residues
- The Liquid Coulter is well suited to wide row planting (> 361mm / 15”) and can deliver compatible liquid fertilisers such as UAN
- The Liquid Coulter is currently in the early stages of commercialisation.

An independent assessment at the Agricultural Machinery Research and Design Centre at the University of South Australia has concluded “*The AquaTill Liquid Coulter demonstrated a high potential for crop residue cutting and is confirmed to be a great technology fit for assisting residue handling in no-till planting applications, particularly in wet stubble and soft soil environments where traditional mechanical coulters fail*”.

AquaTill technology uses a fine stream of liquid travelling at three times the speed of sound that can cut through living or decaying plant material. The liquid stream is generated using an Ultra-High-Pressure (UHP) pump from Flow International Corp. that operate at more than 50,000 psi (3,800 bar).

An evaluation of AquaTill UHP waterjet cutting technology for use as a liquid coulter in no-till seeding has confirmed it has high cutting capability on wheat straw and is a ‘great fit’ for residue handling in no-till planting applications.

The potential value of this technology, conceived and initially developed by SANTFA, is reinforced by new data showing it is particularly effective in wet stubble and soft soil environments normally considered the most challenging for seeding/planting operations and in which traditional mechanical coulters often fail.

The technology was found to operate most efficiently when wet residue was placed under moderate compression, providing a valuable pointer to development of machinery to apply this technology in the field.

Waterjet cutting technology is well suited to wider row spacings, where a given cutting capacity can be achieved with relatively less water per ha. Results from this research, undertaken by the Agricultural Machinery Research and Design Centre at the University of South Australia and funded by GRDC, indicate that a nominal 150L/ha volume of water could sustain straw stem cutting capacities of up to 12.5t/ha, 19t/ha and 35t/ha at 300mm, 500mm and 1000mm row spacing respectively.

When used as a liquid coulter, an AquaTill unit is set up so the high-velocity cutting stream penetrates vertically downwards, slicing through surface residue to allow clean access the underlying soil (Figure 1).

Figure 1. SANTFA conceived the AquaTill 'Liquid Coulter' as a means of slicing cleanly through moist residue using aqueous liquid fertiliser (*Source: G Butler 2016*)

Residue cutting capacity is defined as the quantity of biomass residue (t/ha) able to be fully cut under a specific set of conditions. The project selected four machine factors (pressure, nozzle size, stand-off distance and speed) and three straw factors that could realistically be controlled in the field for evaluation in laboratory experiments. The aim was to quantify residue loads that might be expected to be adequately cut under different conditions. The researchers then set out to evaluate the machine factor relationships affecting the efficacy of UHP waterjet nozzles cutting cereal stubble loads under conditions representative of no-till field conditions at seeding. This was done using multiple layers of uniform straw stems calibrated to a known stem load quantity (t/ha). This provided a repeatable basis for generating data on the technology's residue cutting capability.

The straw was laid in stubble-holding trays, designed and built by the research team, each with three separate chambers able to hold 25, 40 or 50mm depth of uniform stubble stems, between a top and bottom interlocking plate assembly (Figure 2). This configuration allowed a large number of cutting locations to be assessed in each test.

Once they were uniformly filled with straw stems, the chambers designed with open-ended longitudinal slots to accommodate the waterjet were able to be compressed to an adjustable level of up to 62%.

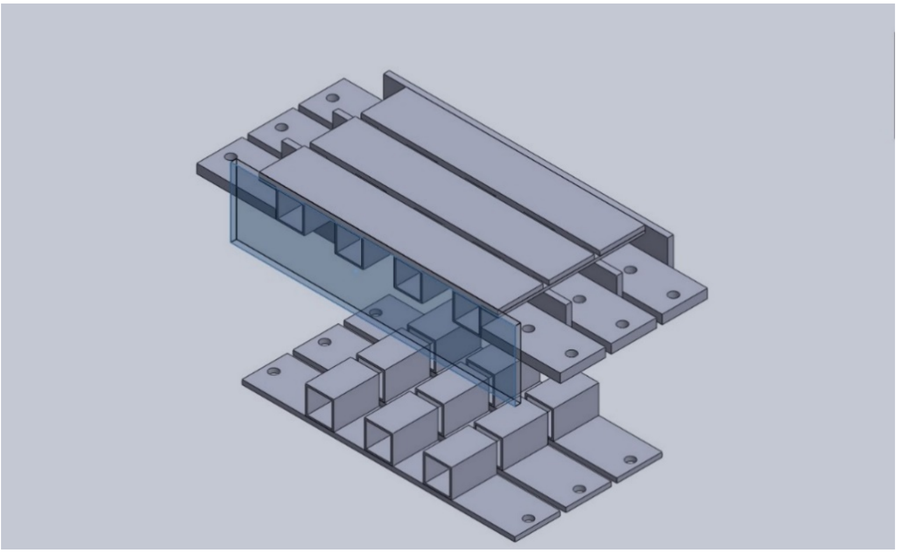

Figure 2. 3D view of the holding tray with interlocking plates for adjustable compression

Two trays were built, one that oriented straw at 30° to the line of cutting and one that held it at 90° to the direction of travel (Figure 3).

Figure 3. Top view of holding tray after cutting with top plates fitted (left) and removed (centre). The bottom sections are designed to locate the straw stem axes at 90° (centre) and 30° (right)

The experiments were conducted using 2016-season baled wheat straw that had been stored under cover and which had not been subject to wetting. Internode stem portions of uniform width (diameter) were selected from loosened bale biscuits (disregarding any obvious 'outlier' sizes) and cut to a length of 125 mm to provide a source of uniform stems. Nodes were excluded to maximise uniformity of the straw specimens.

The stem cross-sections were mainly 'flattened' due to the harvesting and baling process, but their physical uniformity was deemed suitable for laboratory evaluation.

An average of 33, 53 and 66 stems were required to uniformly fill the three chambers in each tray before any compression was applied. A constant number of straw stems per chamber depth was part of the methodology used to increase the uniformity of chamber samples and the efficiency of experimental runs. It also enabled assessment of cutting capacity based on a known number of stems.

An average stem unit weight (mass per unit of length) was calculated using measurements of the length and weight of 200 random stems in their dry state. This figure was used to convert the number of stems per chamber to a stem weight per chamber that was then used to estimate an equivalent residue stem load per ha. This provided a reference link between paddock stubble load (t/ha) and the number of stems in each experiment.

This residue load parameter was named 'straw stem load' and quantified in units of t/ha.

Process

The cutting process was carried out by driving the straw-holding trays at a given speed through a stationary waterjet cutting nozzle operating at specific pressures and flow rates (Figure 4).

The height of each straw tray was accurately set to achieve a known nozzle stand-off distance - the distance between the nozzle and the residue – with the cutting slot carefully centred to the nozzle orifice and aligned to the travel direction.

The nozzle was powered by an ultra-high-pressure (UHP) triplex pump from Flow International rated to 60 thousand pounds per square inch (kpsi - 414 MPa). The pump used in the experiments had previously been modified by SANTFA to be driven by a tractor PTO, which was the power source for the research project (Figure 5).

Figure 4. University of SA mobile rig driving the straw sample tray at controlled speeds (left); close-up view of the sample-holding tray and stationary nozzle holder (right).

Figure 5. Tractor PTO-powered direct-drive triplex UHP pump and water supply kit provided by SANTFA/Flow International

The first series of tests assessed the impact of straw stem moisture content, stem compression status and stem orientation on the cutting capability of the AquaTill jet at a set operating pressure (55kpsi/379MPa). Nozzle orifice size was 0.008” (0.2mm), stand-off distance 5mm and travel speed 6km/h.

The moisture content of the air-dried stems averaged around 8% (wet basis), which became the dry straw moisture reference. Wet straw was generated by immersing bunches of prepared stems in water for 45 minutes, allowing them to drain for 15 minutes then keeping them in a sealed container during the following 3-4 hour testing period. Test periods were minimised to lessen any interference from environmental factors such as relative humidity and temperature.

The wetting treatment increased the straw stem moisture content to 69% (wet basis) on average, which revealed the high capacity of wheat straw to absorb water (an average of 2.2 times its dry weight).

Compression treatments were applied by tightening the interlocking plate assembly against spacers set at pre-determined levels. In uncompressed treatments the top plate acted only as a lid over the straw stems with minimal compression (<3%) to minimise unwanted free movement of straw during cutting.

The effect of pressure on straw cutting capability was assessed using a response curve technique in which a simple curve-fitting procedure was applied to results from single replicate tests conducted at additional pressures (namely: 50, 45, 40, 35 and 25 kpsi).

The same response curve methodology, which enables a conclusion to be drawn from the results of randomised single-replication tests conducted over the targeted range, was also used to assess the impact of straw stem compression intensity.

Size and speed

The cutting capacities of six nozzle sizes - 0.006” (0.152mm), 0.007” (0.178mm), 0.008” (0.20mm), 0.009” (0.229mm), 0.010” (0.254mm) and 0.012” (0.305mm) – operated at 10mm stand-off distance under 55kpsi (379MPa) water pressure were evaluated at 6, 9.2 and 12km/h travel speeds.

This assessment was carried out with wet straw (moisture content (m_c) = 69 %), with stubble angle to direction of travel (β) = 90° and percent of residue compression (Δ) = 50%; parameters considered to represent realistic field conditions.

The straw chamber depths were set at either 25, 40 and 50mm to ensure unaffected straw remained beyond the depth of cut achieved, with the range of nozzle capacities.

Test runs showed the standard chamber height (25mm = 21.8t/ha calibrated load) to be appropriate for nozzle sizes of 0.006”, 0.007” and 0.008” while for 0.010”and 0.012” nozzles, the extended heights of 40mm (35t/ha calibrated load) and 50mm (45.6t/ha calibrated load), respectively, were required.

Results

Figure 6 shows the relationships of cutting capacity with UHP water pressure for a subset of four stem conditions for stems oriented at 90° to the angle of travel at a given nozzle size (0.008” = 0.2mm), stand-off distance (5mm) and speed (6km/h). The graphed data show:

- Positive quadratic relationships (R^2 = 0.94-0.99) between cutting capacity and water pressure
- The significantly increased cutting capacity measured in wet (m_c = 69%) residue under these conditions
- The dramatic benefit of residue compression (Δ = 62%).

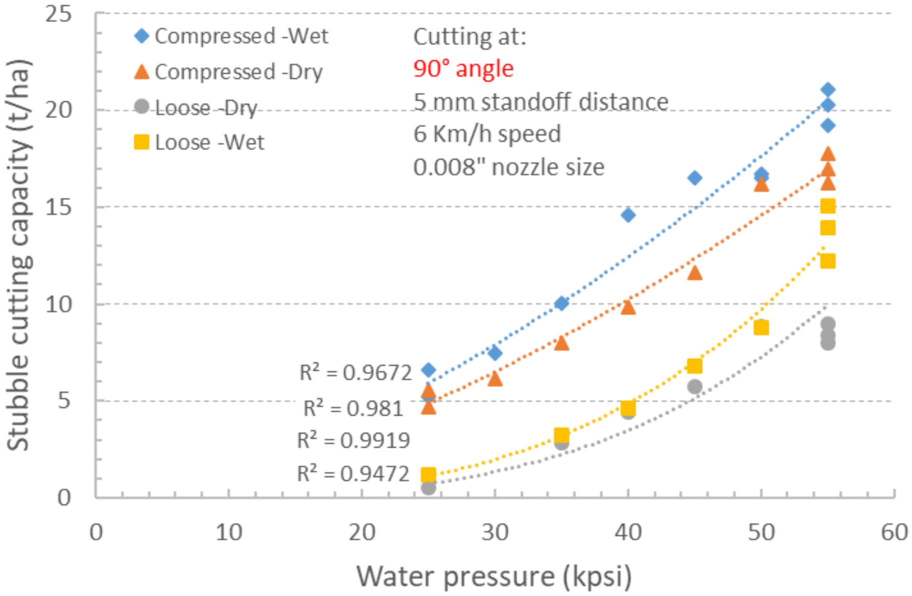

Figure 6. Cutting capacity relationships with water pressure for a subset of four stem conditions with the stems at 90° to the angle of travel and constant machine settings

These results, which are consistent with the literature knowledge (Ligocki and Harms, 2003), show that residue compression strongly influences cutting performance, with major implication for the design of machinery for field use of liquid coulter technology.

The impact of compression on cutting efficacy is explained by the fact that the gaps (spaces) between and within stubble diffuse the energy density and coherence of the UHP waterjet, resulting in significant loss in jet power. This effect is highest under loose stem conditions and least under tightly compressed stem conditions. Another mechanism likely to enhance waterjet cutting in compressed straw is the greater exposure efficiency of stems held under pressure with their flattened sides exposed to the jet and unable to move away during cutting.

These data also suggest that timing paddock use to target moist residue can significantly assist with maximising cutting capacity, especially under compressed residue conditions. This is explained by there being less power loss due to jet diffusion because there is less air between and within the stubble stems and greater stem inertia (wet mass = 3.2 x dry mass) which reduces straw movement under the water jet.

Its ability to perform better in damp conditions represents a critical advantage for this technology because wet residue typically poses the greatest seeding-time challenges to mechanical cutting such as by a coulter disc blade and is the common cause of residue hair-pinning that can result in significant crop establishment losses.

AquaTill thus has a particularly good fit in addressing current residue handling limitations under no-till cropping.

Compression

Compressing straw stems is the most effective way to maximise the cutting capacity of a given waterjet nozzle. Figure 7 shows the impact of straw stem compression on waterjet cutting capacity of a 0.008” (0.2 mm) nozzle operated at 55 kpsi (379MPa) water pressure.

The data in Figure 7 shows:

- Increasing the compression level from minimal to a maximum of 62% doubled the cutting capacity. It is possible to compress straw beyond 62% but the amount of energy required rapidly increases
- A significant portion (60%) of the full benefit was achieved by just 22% compression, which suggests that the benefits are from reduction in air spaces between the straw and restriction in straw stem movement during cutting
- Applying 50% compression results in 90% of the cutting capacity achieved at 62% compression.

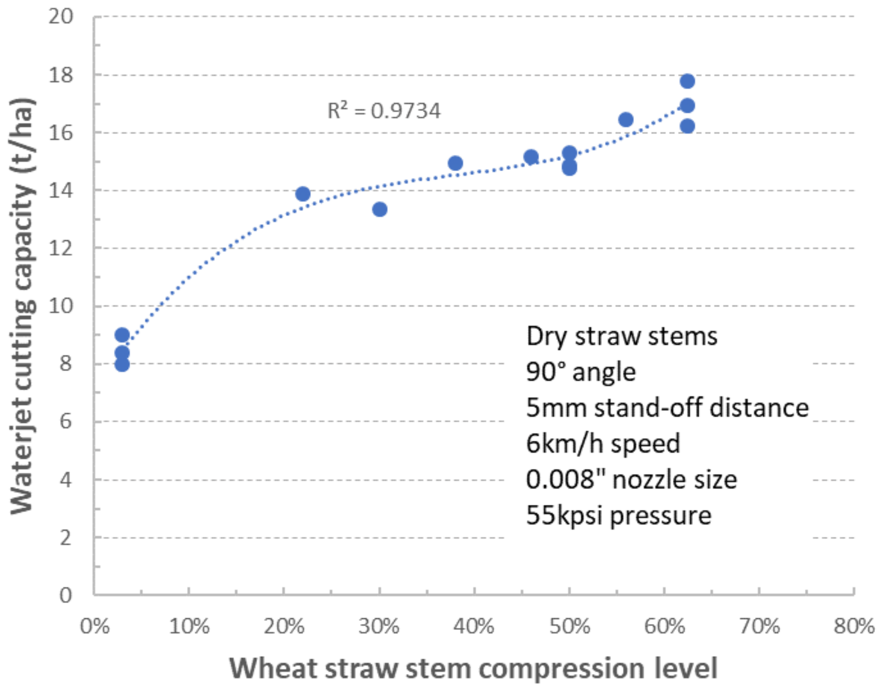

Figure 7. Waterjet cutting capacity of a sample nozzle with straw stems under various compression levels

The main implication of these findings is that any machine using this technology in the field will need to be able to apply a certain amount of pressure to the straw at the point of cutting in order to maximise waterjet cutting efficiency. If this optimum pressure varies in different paddock environments, adjustability may be required, particularly since compressing beyond the optimum is likely to increase cost and may induce other stubble management issues such as raking.

While further investigation of interactions between compression level, speed and nozzle size is needed, these results reveal no detectable impact of nozzle stand-off within the 5-70mm range under the experimental conditions. This finding is very positive, since a short stand-off distance could prove problematic in the field, while being able to set the nozzle further away from the stubble surface may open the way for simpler design options and reduced costs.

Cutting capacity

Figure 8 compares the impact of nozzle orifice size and travel speed on the cutting capacity of wet straw stems under a specific set of settings, namely: 90° angle, 55 kpsi (379MPa) pressure, 10mm stand-off and 50% compression. The data show:

- The cutting capacity significantly improves with greater orifice size, with a 26t/ha increase in cutting capacity over the range of nozzles.

- Faster speeds tend to reduce cutting capacity, especially with larger nozzle sizes (0.009"-0.012"), but not in proportion to the speed change. For instance, halving the speed from 12 to 6km/h and doubling exposure time and water consumption resulted in a 6-29% increase (18% on average) in cutting capacity under the larger nozzles (0.009"-0.012"); significantly more than the 2-10% increase (6% on average) under the smaller nozzles (0.006"- 0.008").

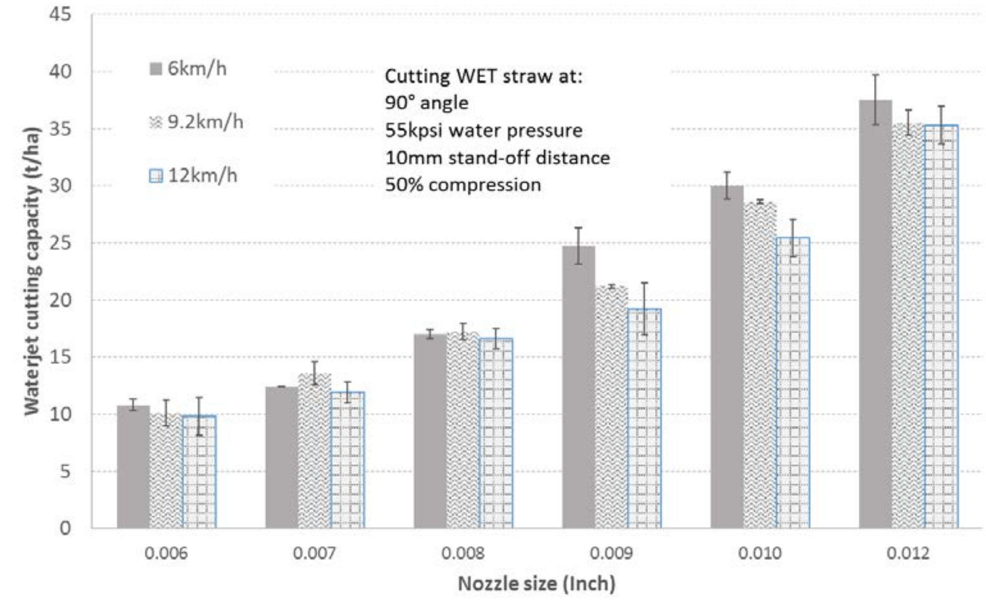

Figure 8. Cutting capacity of a range of nozzle sizes operating at different travel speeds
(NB: Error bars are ±1 standard error of the mean)

Relating nozzle size to water use per ha at a given row spacing provides a useful perspective on the relationship between cutting capacity, speed and nozzle size. Figure 9 displays the empirical relationships between t/ha cutting capacity and water volume/ha, with speed and nozzle size as parameters defining a set of response curves linking the two variables.

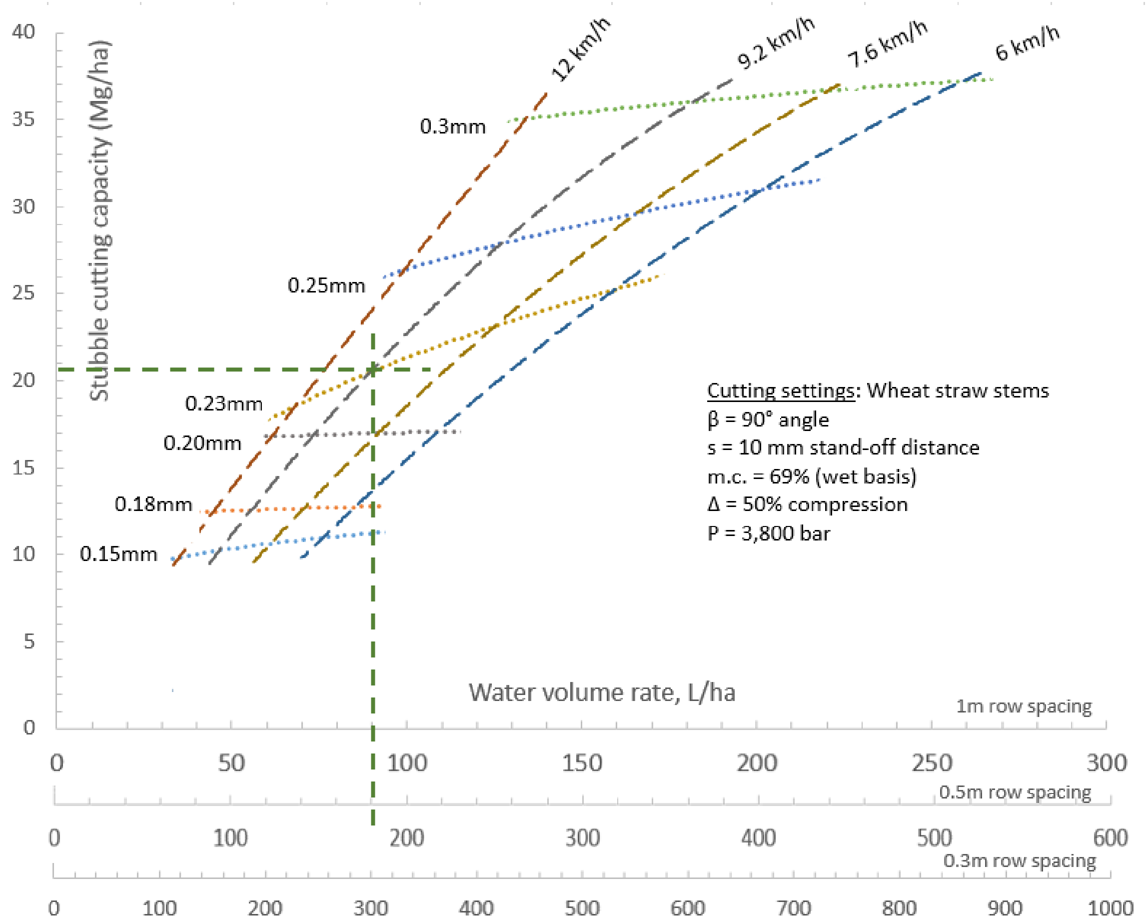

Figure 9. Mapping of residue cutting capacity vs volume rate at three row spacings for a range of nozzle sizes and forward speeds

The water consumption per hectare for each nozzle was calculated based on their nominal flow rate of 55kpsi/379MPa (data supplied by Flow International) and the travel speed at 300mm, 500mm and 1000mm nozzle spacing to provide summer and winter crop planting contexts.

The graph shows that given constant water consumption and with nozzles operated under equal pressures (here 55kpsi), travelling at a higher speed with a larger nozzle results in a greater cutting capacity than travelling at a lower speed with a smaller nozzle.

Importantly, more power is required to achieve the higher flow rates of the larger nozzles.

This graph can also be used to estimate the nozzle size and speed requirements to successfully operate in a particular quantity of crop residue in a field situation.

Also, as the Figure 9 graph originates from laboratory measurements of pre-arranged straw stems, it is expected that a field correction factor (yet to be developed) will be required to account for aspects such as randomness and material variability intrinsic to field residues.

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On-the-go protein sensors

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Key words

grain protein, crop quality, site-specific gross margin, nitrogen

GRDC code

CSP1803

Take home messages

Recording the spatial pattern in grain protein content, yield and moisture during harvest provides information that farmers and advisers can use to fully assess the outcomes of their agronomic programs. This information also provides a unique opportunity to better understand and improve crop nitrogen management and add value to product marketing in a range of circumstances. Australian farmers should explore the use of protein sensors to boost financial and environmental outcomes.

Background

Profits from grain crops are not just derived from yield, the quality of the grain delivered is critical to ensuring maximum profits for some grains. For cereals, the quality is largely determined by the grain protein content. For canola, corn and soybeans, the oil content is important.

Protein and oil content in the grain is determined by:

- grain crop type
- crop variety
- nitrogen in the soil and applied as fertiliser and
- moisture availability during the growing season.

Accurately measuring grain protein or oil content can be used to manage quality of marketed grain and when used in conjunction with yield, is useful in assessing how well crop nitrogen nutrition was managed in the harvested season and for locating areas where management may be altered in the future.

Grain quality monitors can be mounted on a harvester to measure protein and oil content during harvest operations. These sensors use near infrared spectroscopy (NIRS) - the same technology used in grain receival depots. Grain samples are presented to a light source; the light interacts with specific chemical bonds within the grain and is slightly modified because the bonds absorb some of the light energy. The reflected or transmitted light is recorded and when run through a calibration algorithm, this provides a measure of grain protein, moisture and oil content.

Instruments that use near-infrared transmittance (NIT) need to capture a stationary sample, so the measurement readings are obtained every 7–15 seconds (a measurement cycle of 0.14–0.07 Hz). Using near infrared reflectance (NIR), a continuous grain flow can be used, and the measurement taken more frequently.

Using grain protein content in Precision Agriculture (PA)

Within-farm and within-field variation in grain protein content, like grain yield, is widespread (Figure 1). The difference in sampling intensity between the yield (measured at 1 Hz) and the protein (measured at 0.08 Hz) produces a difference in observation density (yield~725 obs/ha and protein

~65 obs/ha) as seen in Figure 2. However, the density is more than enough to produce detailed maps as seen in Figure 1b.

(a) (b)

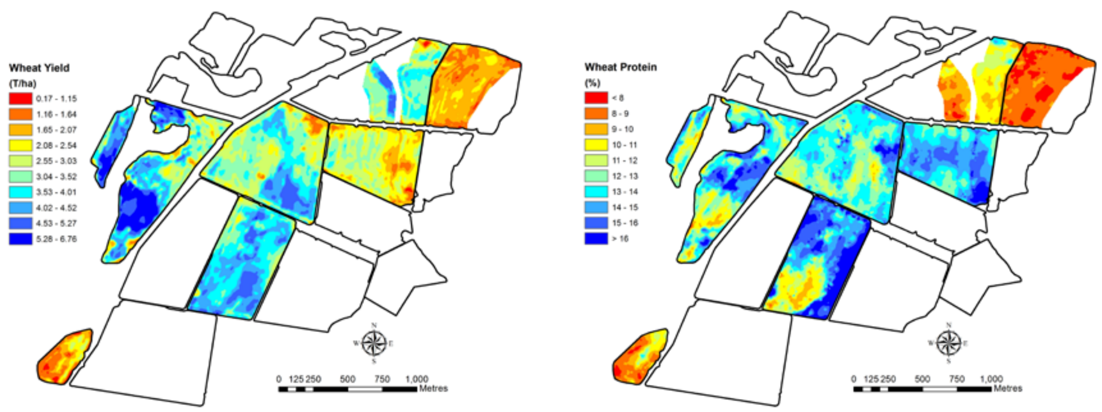

Figure 1. Spatial pattern of wheat grain yield (a) and wheat grain protein content (b) across a farm in northern NSW.

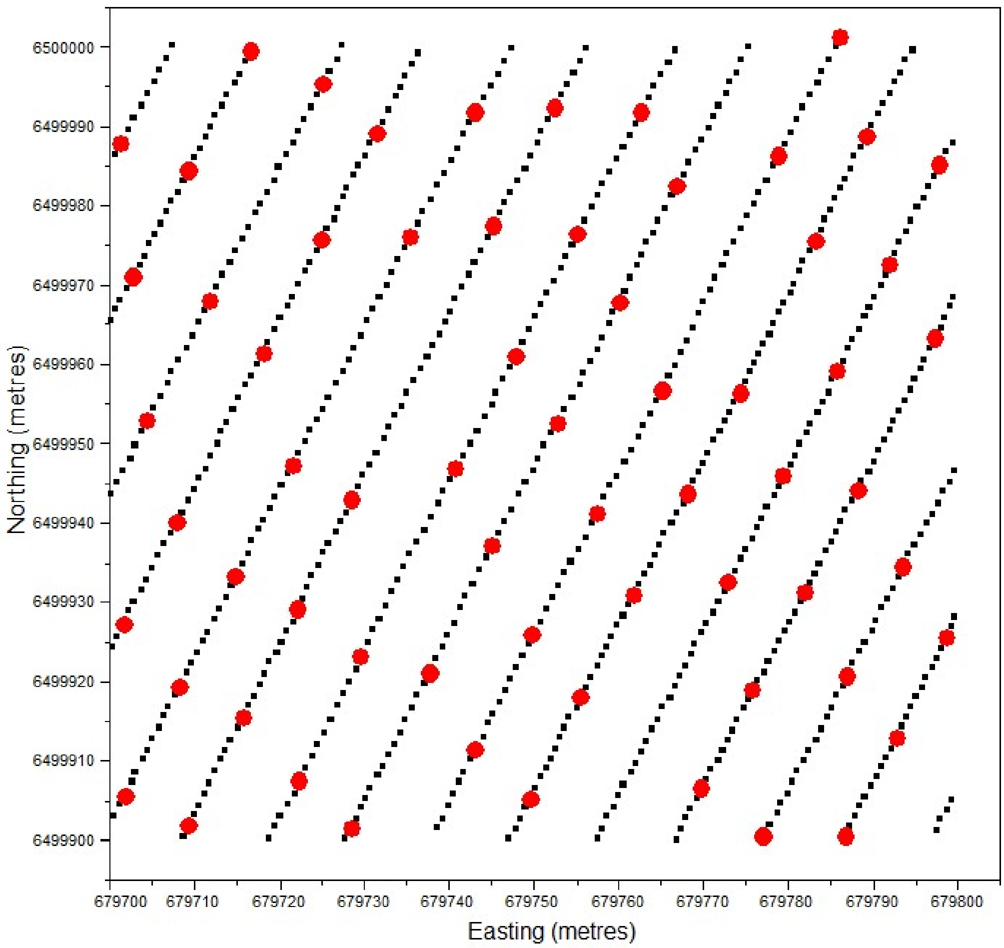

Figure 2. Grain yield data gathered on-harvester once every second (smaller black dots) and grain protein content data gathered in the same harvest operation once every 12 seconds (larger red dots)

Post-harvest grain segregation or bulk grain quality control

Monitoring the quality of grain in real-time during harvest provides opportunities to segregate grain based on quality or mix grain based on quality. Several commercial examples from Australia are explained in Clancy (2017).

Identifying areas within a field or farm where grain with specific protein levels can be harvested may provide premium marketing and increased profit opportunities.

Growers who can provide grain at a consistent quality may be in a better position to obtain premium contracts. In highly variable years, the ability to segregate part of the crop based on protein percentage may allow growers to meet contracts when the average quality of the farm output fails to meet the contract specifications (provided that the entire crop is not under contract). In these scenarios a protein sensor opens the possibility of strategic harvesting to target grain quality.

It is important to remember that quality monitoring can be done at any stage of the supply chain and should be performed regularly to assure quality levels and to maximise market segregation opportunities. NIRS quality monitors have been used successfully off-harvester (e.g. on a ground auger) to segregate/manage grain for delivery based on protein content. This does not provide spatial information on protein variability within fields but can be very effective as a differential marketing technique. The malting barley market is one example where this technique of off-harvester segregation is being used in Australia to maintain delivered product within a contracted quality window.

Gross margin maps

In Australia, grain protein is an important consideration in quality grading and therefore final grain sale price, particularly wheat and barley varieties. Currently for wheat, a small bonus payment is made on a 0.1% sliding scale above the base rate in each receival grade. For malting barley, there is a restricted window of receival standards to make Malting 1 grade (9-12% protein;>70% retention) and all grades must be below 12.5% moisture. Malting 3 grade accepts grain with protein up to 12.8% and retention rates down to 58% but applies a sliding penalty scale based on 0.1% protein increments and 1% retention rate decrements. With yield, moisture and protein maps available it is therefore possible to calculate more accurate revenue figures and produce maps of how the gross margin of production varies within a field and across a farm (Figure 3). These maps should be very useful to a farm manager, particularly for identifying problem areas for investigation, planning more profitable crop agronomy and rotations, or identifying repeatedly unprofitable areas for alternate uses.

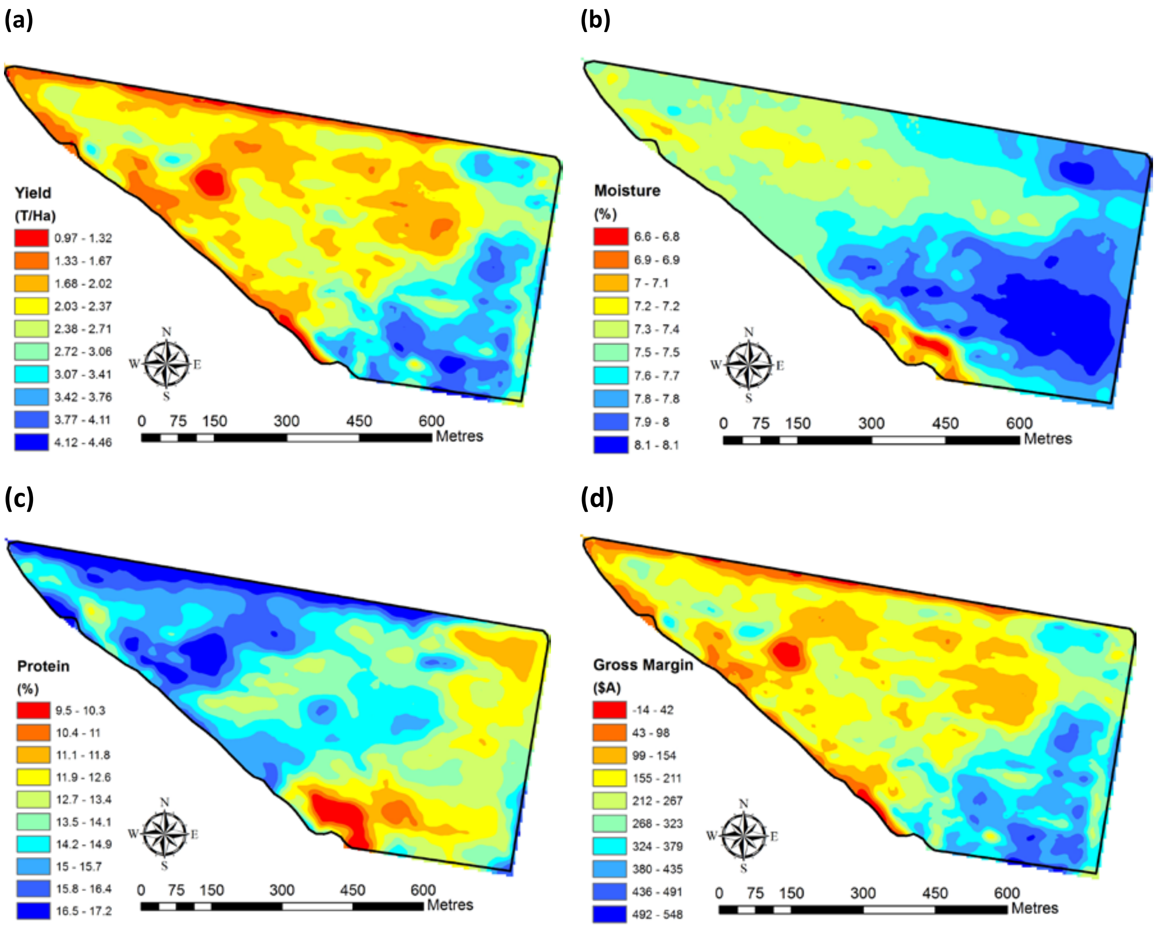

Figure 3. Grain yield (a) grain moisture (b) grain protein content (c) and site-specific gross margin (d) maps made by combining all three data layers, applying quality premiums/discounts and subtracting uniform variable costs of production.

Nitrogen agronomy

Conditions that might increase the range of grain protein content found within a field include:

- variation in nitrogen availability within-field. Where different soil type or soil texture occurs, there may be variation in nitrogen supplies to the crop; and
- variation in moisture availability within-field. The interaction between topography, soil type and seasonal climatic conditions will result in spatial variation in the amount of water available to a crop across a field. This impacts on nutrient uptake, grain filling and yield, which all control final grain protein content.

Locations in a field where grain protein content is identified as lower provide an opportunity to direct investigations into nitrogen availability and inform options for management intervention. If investigations suggest that a field has received adequate nitrogen for the growing season, then in the simplest situation, a map of nitrogen removal may become an option to guide variable-rate nitrogen application in the following season. The amount of nitrogen removed from the production system through harvested grain can be calculated by multiplying the mass of grain yield by the percentage of protein in the grain (Figure 4).

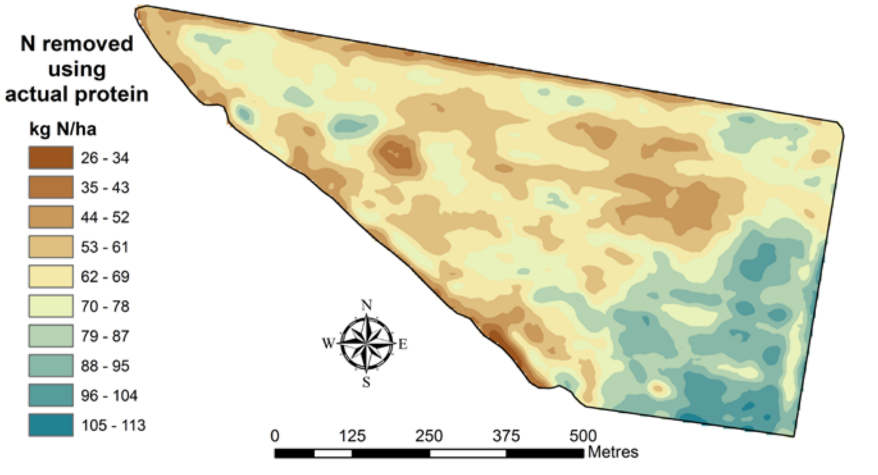

Figure 4. Nitrogen removed in grain using both yield and protein monitor data.

It is generally considered that there is a negative correlation between grain yield and grain protein in cereal crop plants. This means that as yield increases, then protein is expected to decrease. A positive correlation would mean that as yield increases, protein would also be seen to increase. The type of relationship (negative, positive or none) can tell managers something about a crops access to nitrogen and water. With measurements of yield and protein across a field using on-harvester monitors, it is possible to explore whether the relationship between the two is constant or does it change across a field (Figure 5). While negative correlations often dominate within a field, areas of positive correlations do occur in most fields as do areas where there is no definable relationship. These changes in the relationship usually form a pattern as seen in Figure 5.

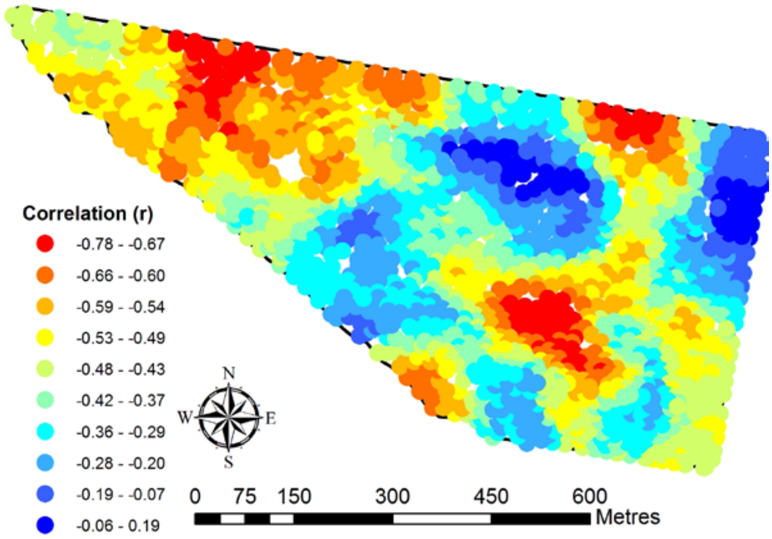

Figure 5. Local correlation between grain yield and grain protein within-field. The spatial pattern could be used to investigate nitrogen and water supply issues.

It is speculated here that areas within a field where the yield to protein relationship is negative could mean that access to N by the crop has been relatively uniform but the access to moisture has been variably limited by soil/landscape conditions. Where the relationship is positive, access to available moisture may have been more uniform but the amount of available N was changing. Areas where no relationship is seen (correlations close to 0) could be interpreted as regions where the relationship is changing between positive and negative. Sampling for soil nitrogen and available water holding capacity within these different regions could provide useful information for building better variable-rate N management plans.

Calibration and maintenance of quality sensors

Factory calibrations are supplied with quality sensors, however, a local calibration check is advisable. A number of grain samples can be analysed at the local receival silo and then passed through the harvester sensing system or a set of standard samples purchased for use. It is wise to check calibrations for all crop types and varieties to be harvested. Dust and material other than grain will affect the operation of these sensors and efforts should be made to keep the grain sample as clean as possible.

Conclusions

Protein monitors provide useful information by themselves, both at harvest for optimising marketing options and in further analysis to assess the past season's agronomic management. Together with grain yield and moisture monitors, benefits can also be found in improved economic analysis of production, targeting strategic investigative sampling and in aiding future N management decisions. Australian farmers are encouraged to explore their use.

Acknowledgements

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FARMING SYSTEMS CONCURRENT SESSION

Cover crops can boost soil water storage and crop yields

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Key words

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

GRDC code

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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

Cover crops in the northern region

Growers typically use cover crops 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, cover crops also offer an opportunity to increase infiltration and fallow moisture storage for better and more profitable grain and cotton crops across the northern region of New South Wales (NSW) and Queensland.

Advances in agronomy and commercial agronomist support have seen growers better use their available soil water and improve individual crop performance. However, more effective capture and storage of rainfall across the whole farming system remain as major challenges for northern grain and cotton growers where only 20-40% of rainfall is typically transpired by dryland crops, up to 60% of rainfall is lost to evaporation, and a further 5-20% lost in runoff and deep drainage. Every 10 mm of extra stored soil water available to crops could increase dryland grain yields for growers by up to 150 kg/ha, with corresponding benefits to dryland cotton growers as well.

GRDC funded farming systems projects (DAQ00192/CSA00050) are assessing ways to improve this system water use, and to achieve 80% of the water and nitrogen limited yield potential in our cropping systems. GRDC's Eastern Farming Systems project and Northern Growers Alliance (NGA) trials both suggest that cover crops and increased stubble loads can reduce evaporation, increase infiltration and provide net gains in plant available water over traditional fallow periods.

Consequently, cover crops may be a key part of improved farming systems; providing increased productivity, enhanced profitability and better sustainability.

Scientific rationale

Stubble and evaporation

Retained stubble provides ground cover, 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.

Dryland grain systems

Cover crops are used in southern Queensland and northern NSW 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 and 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 the 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 to wheat for stubble cover two weeks later.

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 in line with the surrounding crop that was taken through to harvest. We consequently included a 'grain harvest' treatment in line with the farmer's practice, which was used to determine the farmer's irrigation schedule for the wider paddock and our experimental plots. Above ground biomass was also monitored across the growth of the cover crops until termination and through the subsequent fallow. Establishment counts were taken on each plot 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; 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 this early-termination cover crop would typically produce ~200 kg 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.

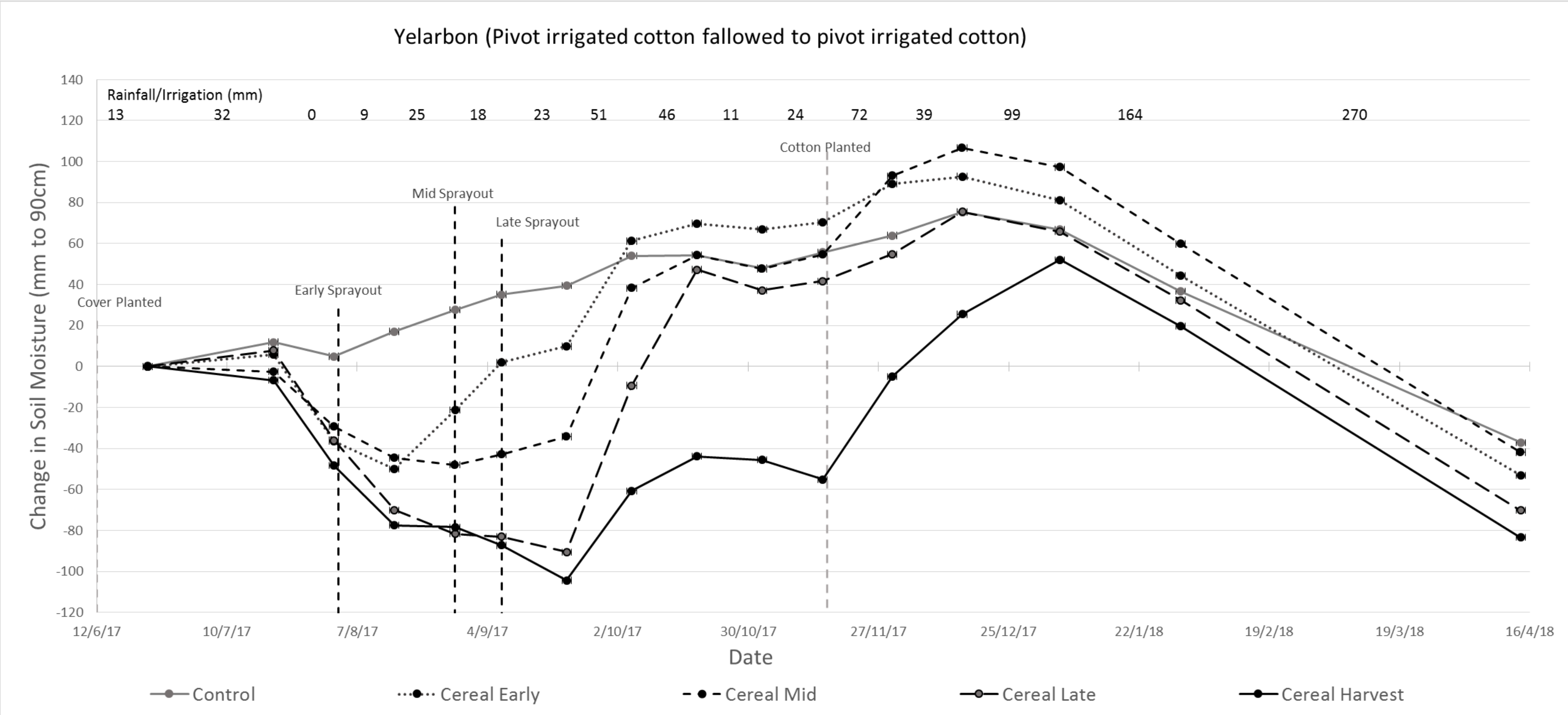

Figure 1. Changes in soil water (mm to 90 cm) from planting of key cover crop treatments until defoliation of the subsequent cotton crop at Yelarbon

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	Terminate	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 that was 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 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)
- Plant to maturity 41mm in 3 events (1/5/18 to 10/10/18)
- 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, these 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.

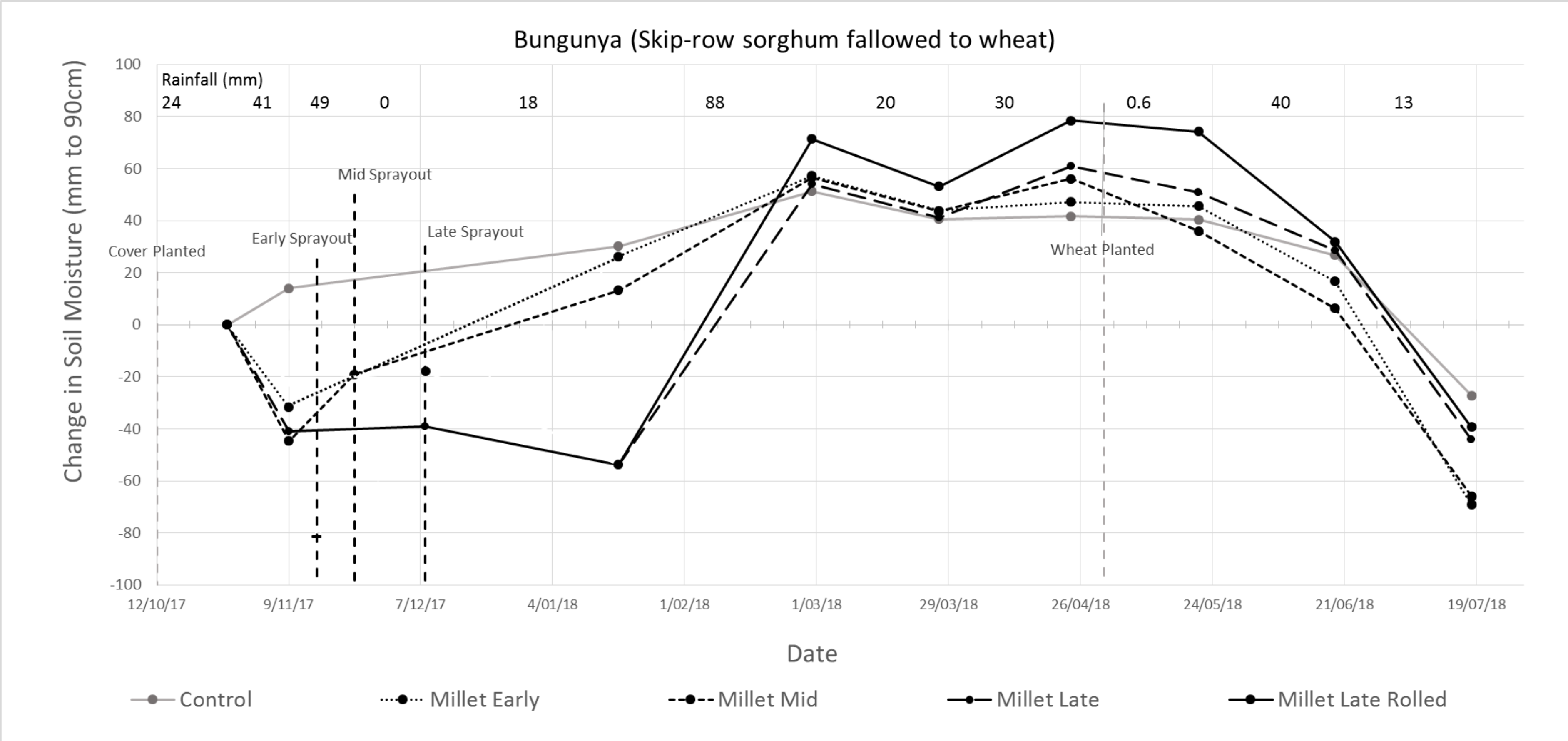

Figure 2. Changes in soil water (mm to 90 cm) from planting of the millet cover crop treatments sprayed out at different crop growth stages until harvest of the later wheat crop at Bungunya

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**	**Terminate**	**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

Conclusions

The project results show that cover crops can indeed help increase net water storage across fallows that have limited ground cover. 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 was 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 different factors to these gains remains to be explored.

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Economic performance and system water-use-efficiency of farming systems

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Take home messages

- Large gaps in profitability are possible between the best and worst systems – differences of $200-700 per year were found between systems at each site
- Intensity is the major factor driving good/poor economic performance of the farming system - more so than crop choice. Matching intensity to environmental potential seems to be the most important lever to optimise farming system profitability
- Increasing crop intensity increased costs and risks, and either reduced or equalled the system water use efficiency (WUE) of baseline systems across all sites over the experimental period
- Lower crop intensity had lower system WUE and gross returns, but because of lower inputs and costs may achieve a more favourable return on investment at lower risk. These systems had similar profitability under lower rainfall conditions but were suboptimal in more favourable environments
- Increasing legume frequency can achieve similar profitability and system WUE, especially if nutrient balance differences were considered, but often had higher production costs
- Increasing crop diversity and growing alternative crops as a means of managing diseases or weeds had significant costs at many sites, but in some locations was able to increase or equal system profitability. These systems were more favourable at locations with more available rainfall
- Increasing nutrient supply incurred higher costs and hence, rarely increased system profitability, but if costs of system nutrient balance systems were attributed (i.e. nutrient export – inputs), similar or higher system WUE ($/mm water use) were achieved.
- We found that a system water use efficiency of $2.50 of crop income/mm of rainfall over the cropping sequence is achievable and could be used to benchmark current farming systems.

Introduction

Leading farmers in Australia's northern grains region perform well in terms of achieving the yield potential of individual crops. However, the performance of the overall system is harder to measure and less frequently well considered. Analysis suggests that fewer than one third of crop sequences achieve more than 80% of their potential water use efficiency despite having adequate nitrogen fertiliser inputs (Hochman et al. 2014). The key factors appear not to be related to in-crop agronomy but to the impact of crop rotations and are thought to relate to issues occurring across the crop sequence such as poor weed management, disease and pest losses, sub-optimal fallow management and cropping frequency. Similarly, farming systems are threatened by the emerging challenges of increasing herbicide resistance, declining soil fertility and increasing soil-borne pathogens, all of which require responses to maintain total system productivity. Questions are emerging about how systems should evolve to integrate practices that:

- Maximise capture and utilisation of rainfall particularly when using high-value, low-residue crops
- Reduce costs of production and the likelihood of climate-induced risk
- Respond to declining chemical, physical and biological fertility
- Improve crop nutrition and synchrony of nutrient supply
- Suppress or manage crop pathogen populations
- Reduce weed populations and slow the onset, prevalence and impact of herbicide resistance.

Because of the multi-faceted nature of these challenges, an important need is for a farming systems research approach that develops an understanding of how various practices or interventions come together, quantifies synergies or trade-offs and shows how these interventions impact on whole-of-system productivity, risk, economic performance and sustainability of farming systems.

As a result, research was initiated in 2014 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 test the impacts of modifications of the farming system on multiple attributes (e.g. nutrients, water, pathogens, soil health, and economics) across multiple sites. Experiments were established at seven locations; a large factorial experiment at Pampas near Toowoomba, and locally relevant systems being studied at six regional centres across central and southern Qld (Emerald, Billa Billa, Mungindi) and northern NSW (Spring Ridge, Narrabri and Trangie).

Assessing how changes to the farming systems alter the profitability and efficiency of the farming system is critical. This paper examines the economic performance of different modifications that we have tested. This will help quantify the costs or benefits of changing the farming system to deal with a particular issue (e.g. weeds or disease issue), and the trade-offs for the different cropping intensities and nutrient strategies.

In this research we used the key metric of "system water use efficiency" to compare system productivity or profitability per mm of rain across environments and cropping systems. Most agronomists and farmers would be familiar with the concept of crop water use efficiency (i.e. kg grain yield/mm crop water use) for comparing how efficiently crops under different management or environments perform. However, for comparing the cropping system as a whole across multiple years with different crops, a different approach is required. This also needs to account for both rainfall capture and loss during the fallow over a sequence of crops, the differences in the inputs required, as well as the productivity of different crops which may be influenced both positively, or negatively, by previous crops in the sequence or rotation. Hence, in the farming systems project we have been evaluating the system WUE as the $ gross margin return per mm of system water use (i.e. **rain minus the change in soil water content**) over the period of interest.

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

System modifications

Across these projects a common set of farming system strategies were used to examine how changes in the farming system aimed at addressing particular challenges impact on multiple aspects of the farming system. These different farming system strategies are not predetermined and hence play out differently in different locations, based on the environmental (climate & soil) conditions at that location. Below we outline the common set of farming system modifications employed across the farming systems experimental sites over the past 3.5 years.

- ***Baseline*** – an approximation of current best management practice in each district against which each of the system modifications are compared: involves only dominant crops used in the district; sowing crops on a moderate soil water threshold (i.e. 50-60% full profile) to approximate moderately conservative crop intensities (often 0.75-1 crop per year); and fertilising to median crop yield potential
- ***High crop intensity*** – aims to increase the proportion of rainfall transpired and reduce unproductive loses by increasing the proportion of time that crops are growing; this is implemented by reducing the soil water threshold required to trigger a planting opportunity (e.g. 30% full profile) so that cropping intensity is increased relative to the baseline
- ***Low crop intensity systems*** – this aims to minimise risk by only growing crops when plant available soil water approaches full (i.e. > 80% full) before a crop is sown and higher value crops are used when possible. This requires longer fallows and will lower crop intensity relative to the baseline
- ***High legume frequency*** – crop choice is dictated to have every second crop as a legume across the crop sequence and uses high biomass legumes (e.g. fababean) when possible.
- ***High crop diversity*** – a greater set of crops are used with the aim of managing soil-borne pathogens and weed herbicide resistance risk through crop rotations. This implemented by growing 50% of crops resistant to root lesion nematodes (preferably 2 in a row) and 2 alternative crops are required before the same crop is grown in the crop sequence
- ***High nutrient supply -*** increasing the fertiliser budget for each crop based on 90% of yield potential rather than the baseline of 50% of yield potential.

At several sites there are also some additional, locally relevant system modifications being implemented. These include higher fertility treatments where the high nutrient supply system is also complimented with the additions of a large amount of organic amendments with the aim of boosting background soil fertility. The aim is to see if this can be maintained when used in combination with the higher nutrient input strategy. At Emerald, a system aimed at implementing an integrated weed management package is included. This tests the implications of using combinations of agronomic management options particularly focussed on summer grass weeds (e.g. feather-top Rhodes grass) such as higher levels of crop competition and use of multiple herbicide modes of action. At Mungindi, two low intensity systems have been implemented, one involving only grain crops and the other implementing cotton in the rotation when conditions are appropriate.

Finally, at the core experimental site at Pampas, each of these system modifications are being tested in a factorial where some modifications are combined. These are also being tested across rotations spanning those employed across the northern region, either winter-crop focussed, mainly summer crops, or a mix of both which is driven entirely by soil water.

Economic calculations

Over the 3.5 experimental years of experiments conducted for each system we have collected data on the grain yields of crops, the total inputs of fertilisers, seed, herbicides and other pesticides, and operations. This allows us to calculate the cash-flow, accumulated income (sum of grain yield x price for all crops in the sequence) and gross margins (income minus costs) for each of the cropping systems deployed at each location (Table 4 and 5). We have used consistent prices for each commodity and inputs across all locations to avoid introducing discrepancies in the data (Table 1). All grain yields were corrected to 12% moisture irrespective of harvest moisture levels. Grain commodity prices used were based on inflation corrected average grain prices for each crop over the past 10 years.

Table 1. Commodity prices (10-year average) for each crop grown across the farming systems experiments

Crop	$/t grain#
Barley	218
Wheat (durum & APH)	269
Canola	503
Chickpea	504
Fababean	382
Fieldpea	350
Sorghum	221
Maize	281
Mungbean	667
Sunflower	700
Cotton	1090 ($480/bale lint)

#farm gate price with grading & additional harvesting costs already deducted

Prices for inputs of fertilisers, herbicides, other pesticides and seed were based on market prices at purchase for each input. Costs for operations differed by crop to reflect different contract rates or machinery requirements, but fertiliser applications ($8/ha) and each spraying operation ($3/ha) were held constant. It should be noted we have not attempted to correct for overhead or other fixed costs associated with the farming enterprise, as these are likely to vary significantly from farm to farm and region to region.

Cropping sequence deployed

Tables 2 (core site) and 3 (regional sites) show the diversity and differences in crop sequences that have been deployed across the various farming systems at each experimental location over the first 3.5 years of the farming systems experiments. These tables are intended as a guide for interpreting the subsequent analysis of profitability across these various systems, and what differences in crop sequence are associated with those. This is also relevant for subsequent papers in this series presenting results on the nutrient use and balance and soil water dynamics across the various farming systems.

Table 2. Summary of crop sequences deployed across the 3.5 years of the experiment (winter – WIN, summer – SUM, year season started) across the various farming systems at the core site at Pampas. Crop abbreviations: W – wheat, Cp – Chickpea, Fb – Fababean, Fp – Fieldpea, Cn – Canola, Dm – Durum wheat, Mg – Mungbean, Sg – Sorghum, Mz – Maize, Ct – Cotton, Sf – Sunflower, (m) – millet cover crop

System		Win15	Sum15	Win16	Sum16	Win17	Sum17	Win18	Sum18
Mixed Opportunity	***Baseline***	**W**	**x**	**x**	**Sg**	**Cp**	**x**	**x**	**Sg**
	Higher nutrient	W	x	x	Sg	Cp	x	x	Sg
	Higher legume	Fb	x	x	Sg	Cp	x	x	Sg
	Crop diversity	Cn	x	x	Sg	Cp	x	x	Ct
	Crop div. + nutrient	Cn	x	x	Sg	Cp	x	x	Ct
	Higher leg. + diversity	Fp	x	x	Sg	Cp	x	x	Ct
	Lower intensity	W	x	x	Ct	W	x	x	x
Higher intensity	***Baseline***	**W**	**Mg**	**x**	**Sg**	**Cp**	**Sg**	**x**	**Sg**
	Higher nutrient	W	Mg	x	Sg	Cp	Sg	x	Sg
	Higher legume	Fb	Mg	x	Sg	Cp	Sg	x	Mg
	Crop diversity	Cn	Mg	x	Sg	Dw	Sf	x	Sg
	Crop div. + nutrient	Cn	Mg	x	Sg	Cp	Sf	x	Sg
	Higher leg. + diversity	Fp	Mg	x	Sg	Cp	Sf	x	Mg
Summer	***Baseline***	**W**	**x**	**x**	**Mz**	**x**	**Sg**	**x**	**x**
	Higher nutrient	W	x	x	Mz	x	Sg	x	x
	Higher legume	Fb	x	x	Mz	x	Mg	x	x
	Crop diversity	W	x	x	Ct	x	Sg	x	x
	Crop div. + nutrient	W	x	x	Ct	x	Sg	x	x
	Higher leg. + diversity	Fb	x	x	Ct	x	Mg	x	x
	Lower intensity	x	Mz	x	Mg	x	x	x	Ct
Winter	***Baseline***	**W**	**x**	**Cp**	**x**	**W**	**x**	**x**[#]	**x**
	Higher nutrient	W	x	Cp	x	W	x	x	x
	Higher legume	Fb	x	W	x	Cp	x	x	x
	Crop diversity	Cn	x	Dm	x	Cp	x	x	x
	Crop div. + nutrient	Cn	x	Dm	x	Cp	x	x	x
	Higher leg. + diversity	Fb	x	Dm	x	Fp	x	x	x
	Lower intensity	W	x	x	x	Cp	(m)	x	x

[#] no sowing opportunities occurred within the acceptable window in this season

Table 3. Summary of crop sequences deployed across the 3.5 years of the experiment (winter – WIN, summer – SUM, year season started) across all regional sites for the different farming systems. Crop abbreviations: W – wheat, B – Barley, Cp – Chickpea, Fb – Fababean, Fp – Fieldpea, Cn – Canola, Dm – Durum wheat, Mg – Mungbean, Sg – Sorghum, Ct – Cotton, Sf – Sunflower, (lower case) indicates terminated crop.

Site	*System*	Win15	Sum15	Win16	Sum16	Win17	Sum17	Win18
Billa Billa	***Baseline***	**W**	**x**	**B**	**x**	**W**	**x**	**Cp**
	Higher nutrient	W	x	B	x	W	x	Cp
	Higher fertility	W	x	B	x	W	x	Cp
	Higher legume	W	x	Fb	Mg	x	Sg	Cp
	Crop diversity	W	x	Fp	Sg	x	x	Cn
	Higher intensity	W	Mg	x	Sg	W	Sg	x
	Lower intensity	W	x	x	Sg	x	x	W
Emerald	***Baseline***	**W**	**x**	**Cp**	**x**	**W**	**Sg**	**x**
	Higher nutrient	W	x	Cp	x	W	Sg	x
	Higher fertility	W	x	Cp	x	W	Sg	x
	Higher legume	Cp	x	W	x	Cp	Sg	x
	Higher intensity	W	Mg	W	x	W	Sg	x
	IWM	W	x	Cp	x	W	Sg	x
Mungindi	***Baseline***	**W**	**x**	**Cp**	**x**	**(w)**	**x**	**W**
	Higher nutrient	W	x	Cp	x	(w)	x	W
	Higher legume	W	x	Cp	x	(w)	x	Cp
	Crop diversity	x	Sf	x	Sg	x	x	Dm
	Lower intensity (cotton)	W	x	x	Ct	x	x	W
	Lower intensity (grain)	x	Sg	x	x	(w)	x	Cp
Narrabri	***Baseline***	**W**	**x**	**Cp**	**x**	**B**	**x**	**x**
	Higher nutrient	W	x	Cp	x	B	x	x
	Higher legume	W	x	Fb	x	W	x	x
	Crop diversity	W	x	Fp	x	Cn	x	x
	Higher intensity	W	x	Cn	x	W	x	x
	Lower intensity	W	x	x	Ct	(b)	x	x
Spring Ridge	***Baseline***	**W**	**x**	**Cp**	**x**	**W**	**x**	**x**
	Higher nutrient	W	x	Cp	x	W	x	x
	Higher legume	W	x	Fb	x	W	x	x
	Crop diversity	W	x	Fp	x	W	x	x
	Higher intensity	W	x	x	Sg	Cp	x	x
	Lower intensity	W	x	x	x	x	Ct	x
Trangie	***Baseline***			**W**	**x**	**W**	**x**	**B**
	Higher nutrient			W	x	W	x	B
	Higher legume			W	x	Cp	x	W
	Crop diversity			W	x	Cp	x	Fp
	Lower intensity			W	x	x	x	B

Economic performance of farming systems

As would be expected the total income and gross margins varied substantially across all sites, owing to the difference in rainfall, and hence crop productivity, and input costs required (Tables 4 & 5). While we have used a common approach and assumptions for calculating total income, costs and gross margin returns across all sites, care should be taken when comparing the economic performance between sites. There are large cost differences incurred between sites, due to differences in starting nutrient levels and weed status, which greatly influence the GM outcome between sites. For this reason, we focus mainly on comparing the economic outcomes between systems at the same site.

Best and worst system gross margins

Within each experimental comparison there was a significant gap between the best and the worst cropping system (Table 4 & 5). The difference between the highest grossing and lowest grossing system over the 3.5 experimental years (in $/ha/yr) was $550 at Billabilla, $304 at Emerald, $214 at Mungindi, $434 at Narrabri, $210 at Spring Ridge, $329 for the mixed opportunity systems at Pampas, $348 for summer rotation systems at Pampas, and $766 for winter rotation systems at Pampas. Overall, this highlights that there is a significant difference in the profitability of farming systems within a particular situation.

The best (or worst) system at each location was also not consistent. At most regional sites (except Emerald), the baseline cropping system designed to replicate current best management practice in a district performed the best or as well as any altered system. At Emerald, the High legume and High fertility systems performed the best, $150/ha/yr. higher than the baseline. Amongst the Pampas systems, the gross margin returns of the baseline systems was exceeded by systems with higher crop diversity or high legume frequency by $120-$380 per year over the experimental period.

Across all comparisons, the systems that produced the lowest gross margins were those where cropping intensity was altered. Higher crop intensity achieved the lowest gross margin at Billabilla, Emerald, Spring Ridge and lower crop intensity the lowest GM at Narrabri, Pampas and Mungindi. What this means is that getting cropping intensity wrong for your environment is a major driver of suboptimal system performance.

System modification effects on economics

While there was significant variation in the relative performance of different system modifications across sites, there were several consistent impacts from some of the system modifications.

- Higher nutrient strategy increased input costs significantly due to the higher fertiliser inputs to meet the crop nutrient budget that matched crop yield potential. Across all sites, this increased system costs by $150-$300 per ha over the crop sequence (or $50-$100 per year). So far we have seen few yield or economic responses to this higher nutrient supply approach (except Emerald), so this reduced gross margins compared to the baseline, and resulted in lower return on costs at most sites.

- Higher crop diversity has not significantly altered the costs of the production system, though there are some notable site differences (Table 2). The performance of the alternative crops at each location has been the central driver of how these systems have performed relative to the baseline. Across the regional sites gross margins were between $223 and $1430 less over the whole crop sequence ($64-$400 per year lower). At Pampas diversifying the cropping system has consistently exceeded the returns of the baseline crop sequence by between $372 and $1180 of the 3.5 years ($106-$340/year higher).

- Higher legume frequency systems have increased the variable costs of production in most cases, mainly due to higher costs for pesticides. While in several locations these systems achieved similar or higher GM to the baseline, because of these higher costs they have a lower return on costs in most cases.
- Lower crop intensity systems generally incurred lower costs but this was not universal across all sites; 5 of the 8 lower intensity systems had lower costs than the baseline with the 3 sowing cotton having similar or slightly higher costs. Despite the more conservative approach of waiting until the soil profile was full to sow a crop, this did not necessarily increase the outlay required to run such a system. At most sites, the maximum cash outlay required in the low intensity system was similar to the baseline, and in some cases lower (e.g. Spring Ridge).
- Higher intensity systems did not increase total crop income at any of the regional sites as expected and typically brought about an increase in costs, so that net returns were generally lower and the return on costs was dramatically lower. This highlights the risks associated with these systems. At Pampas, there was an increase in total crop income from increasing crop intensity of $500-$900 over the experimental period ($140-$300), but costs also increased which diminished the benefit to GM to less than $150/ha/yr.

Benchmarks for system WUE

The data generated here could provide a useful benchmark for farmers and advisers to compare their own current production system performance against. As mentioned above, the costs of production are likely to vary significantly across different situations, based on soil nutrient status, weed burdens, and operating costs. For this reason, examining potential total income per mm may be helpful to assess system productivity. Across all sites and systems, the maximum achieved income was $3.0 /mm, but a benchmark of $2.50/mm would be an achievable target at most locations (i.e. 80% of the potential).

Table 4. Total revenue generated, costs of production (fertilisers, seed, operations, chemicals), gross margins (GM), returns on variable costs (RVOC, ratio of income to costs), system WUE ($ gross margin/mm water use) and the maximum cash outlay achieved over the 3.5 years for each farming system tested at each of the 5 regional locations across the northern grains region.

Site	System	Total income ($/ha)	Total costs ($/ha)	Total GM ($/ha)	ROVC	Syst. WUE ($ GM/mm)	Max. cash outlay ($/ha)
Billa Billa	**Baseline**	**3946**	**672**	**3274**	**5.9**	**2.26**	**-284**
	Higher nutrient	3942	878	3065	4.5	2.16	-293
	Higher fertility	3579	826	2753	4.3	1.91	-289
	Higher legume	3606	853	2753	4.2	2.08	-306
	Crop diversity	3176	758	2419	4.2	1.83	-257
	Higher intensity	2288	973	1315	2.4	0.93	-513
	Lower intensity	2287	597	1690	3.8	1.29	-298
Emerald	**Baseline**	**3013**	**1341**	**1673**	**2.3**	**0.91**	**-449**
	Higher nutrient	3278	1383	1895	2.4	1.06	-454
	Higher fertility	3537	1373	2164	2.6	1.20	-449
	Higher legume	3409	1201	2209	2.8	1.20	-352
	Higher intensity	2549	1404	1146	1.8	0.64	-365
	Integrated Weed management	3307	1360	1947	2.4	1.08	-449
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
	Crop diversity	634	378	256	1.7	0.23	-274
	Lower intensity (cotton)	1287	680	607	1.9	0.54	-286
	Lower intensity (grain)	371	366	5	1.0	0.00	-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	4.0	1.19	-286
	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
Spring Ridge	**Baseline**	**3248**	**1381**	**1867**	**2.4**	**1.56**	**-840**
	Higher nutrient	3083	1449	1634	2.1	1.37	-840
	Higher legume	3388	1512	1875	2.2	1.54	-971
	Crop diversity	3041	1396	1644	2.2	1.38	-855
	Higher intensity	2531	910	1621	2.8	1.36	-431
	Lower intensity	3130	773	2357	4.0	1.58	-578

Table 5. Total revenue generated, costs of production (fertilisers, seed, operations, chemicals), gross margins (GM), returns on variable costs (RVOC, ratio of income to costs), system WUE ($ gross margin/mm water use) and the maximum cash outlay achieved over 3.5 years for each farming system tested the core experimental site at Pampas across mixed opportunity, summer-dominated or winter-dominated cropping systems.

	System modification	Total Income ($/ha)	Total Costs ($/ha)	Total GM ($/ha)	ROVC	Syst. WUE ($ GM/mm)	Max. cash outlay ($/ha)
Mixed opportunity	**Baseline**	**3466**	**769**	**2697**	**4.51**	**1.51**	**-263**
	Higher nutrient	3555	1106	2448	3.21	1.36	-355
	Higher legume	3976	919	3057	4.33	1.71	-296
	Crop diversity	3736	667	3069	5.60	1.73	-252
	Crop div. + nutrient	3699	1058	2641	3.50	1.49	-426
	Higher leg. + diversity	3153	723	2430	4.36	1.36	-283
	Lower intensity	3753	953	2800	3.94	1.65	-516
Higher intensity	**Baseline**	**3940**	**994**	**2945**	**3.96**	**1.66**	**-255**
	Higher nutrient	3889	1385	2504	2.81	1.39	-313
	Higher legume	4208	1139	3070	3.70	1.72	-289
	Crop diversity	4411	828	3583	5.33	2.04	-221
	Crop div. + nutrient	4268	1411	2857	3.02	1.64	-406
	Higher leg. + diversity	3994	977	3017	4.09	1.69	-262
Summer	**Baseline**	**3167**	**649**	**2518**	**4.88**	**1.44**	**-366**
	Higher nutrient	3386	863	2522	3.92	1.46	-410
	Higher legume	3725	883	2842	4.22	1.60	-422
	Crop diversity	4330	831	3499	5.21	2.02	-477
	Crop div. + nutrient	4664	1153	3511	4.05	2.03	-549
	Higher leg. + diversity	4818	1010	3807	4.77	2.19	-489
	Lower intensity	2835	471	2364	6.02	1.37	-228
Winter	**Baseline**	**3775**	**698**	**3077**	**5.41**	**1.90**	**-312**
	Higher nutrient	3746	884	2862	4.24	1.77	-330
	Higher legume	4667	741	3926	6.29	2.28	-237
	Crop diversity	4807	549	4257	8.75	2.44	-237
	Crop div. + nutrient	4295	1020	3275	4.21	2.01	-430
	Higher leg. + diversity	4580	664	3915	6.89	2.22	-220
	Lower intensity	2444	601	1844	4.07	1.07	-411

System WUE adjusted for nutrient balance

One of the complications with comparisons across the various sites here is that there were significant differences in starting soil N status which greatly influenced the need for fertiliser inputs and hence costs at those sites. For example, at Billabilla there was a large amount of mineral N at the start of the experiment (> 300 kg N/ha), and hence for the first 3 years no N fertilisers were needed to satisfy crop nutrient budgets. Hence, this site had significantly lower N fertiliser costs which arbitrarily biases the system WUE (GM$/mm). Similarly, accounting for differences in system nutrient export or balance will help to better define the real cost of the farming system. In an attempt to adjust for these differences, in Table 6 we have adjusted the system WUE to take into consideration the different nutrient balances across sites and some systems. This reduces the system WUE (GM$/mm) of sites which have exploited a high soil mineral N and adjusts for differences in P application relative to P export across sites.

What this shows is that across sites the differences in system WUE (GM$/mm) between the baseline and higher nutrient or higher legume systems is diminished once these factors are considered. Hence, taking into consideration the impacts of the farming system on the natural resources (in this case nutrients) can significantly alter the relative profitability of different farming systems over the long-term. This clearly shows that if the costs of nutrients exported from the farming system are accounted for, and not treated as an externality, it demonstrates the value of systems aimed at maintaining long-term soil fertility.

Table 6. Gross margin return per mm under baseline, and systems with higher nutrient, higher legume frequency and higher intensity when corrected for site and system differences in nutrient balance (i.e. change in soil mineral N, net P balance (export – applied) and K removal). Nutrients were valued at $1.3/kg N, $2.5/kg P, $0.9/kg K.

Site	Baseline	High nutrient	High legume	High intensity
Pampas - Opportunity	1.28	1.16	**1.45**	
Pampas - Summer	1.18	1.25	**1.38**	1.40
Pampas - Winter	1.61	1.52	**1.99**	
Billa Billa	**1.98**	**1.99**	1.85	0.70
Emerald	0.84	1.01	**1.12**	0.62
Narrabri	**1.31**	1.27	1.12	
Spring Ridge	**1.50**	1.36	1.45	
Mungindi	**0.89**	0.62	0.72	

Cross-site analysis of system WUE

While there are several interesting differences between different farming systems at each experimental location, here we examine across the full range of sites how modifications to the farming system that were common across several sites (i.e. *higher nutrient, higher legumes, crop diversity, higher intensity, lower intensity*) have influenced the economic performance compared to the baseline at each site. This was done by calculating the system WUE ($ GM/mm) and the return on investment (i.e. income:cost ratio) as a proportion of that achieved in the baseline. Hence, the baseline achieves a value of 1.0, and systems achieving 0.8 have a 20% lower value and systems achieving 1.2 have a 20% higher value for these economic metrics.

Across the various sites there are some variable and some consistent results in terms of the relative performance of the farming systems.

- Higher nutrient supply achieved a 10% lower system WUE (GM$/mm) at most sites, due to the higher costs associated with supplying nutrients to satisfy a 90th percentile crop yield rather than fertilising for the median yield. Only at Emerald did we observe a positive yield response to additional nutrient supply and hence this is the only location where system WUE was increased – though return on investment was similar. At Mungindi the additions of more nutrient reduced grain yield and hence income in one year and added significantly to the costs of this system. We may expect this result with only good seasonal conditions expected to realise the benefits of such a strategy.
- Increasing legume frequency achieved either higher or similar system WUE (GM$/mm) to the baseline across most sites. However, interestingly the return-on-investment for these systems was lower in most cases owing to higher costs for growing legumes.
- Increasing crop diversity was either equally or more profitable than the baseline system at Spring Ridge and Pampas across all crop rotation systems (summer, winter and opportunity). However, at all other locations system WUE (GM$/mm) was reduced by 20-70% through implementing more diverse crop rotations. Few sites had significant soil-borne disease issues at the initiation of the study and hence rotational benefits have not yet been observed. The exception was Pampas where there have been rotation benefits for subsequent crops. This demonstrates that there can be significant costs or risks associated with implementing alternative crops to address weed or pathogen issues.
- Increased crop intensity has only achieved a slightly higher systems WUE (GM$/mm) at Pampas while at most locations there has been significant downsides. These systems also have higher costs and hence the return on investment is typically lower.
- Lower crop intensity systems have also achieved lower system WUE (GM$/mm) at most locations, and lower than most other system modifications. The exceptions are where a sufficiently high value crop has been grown (e.g. cotton) that has offset the longer fallows required. However, because of the lower inputs and costs associated with these systems they achieve much more favourable return on investment often equal to other system modifications.

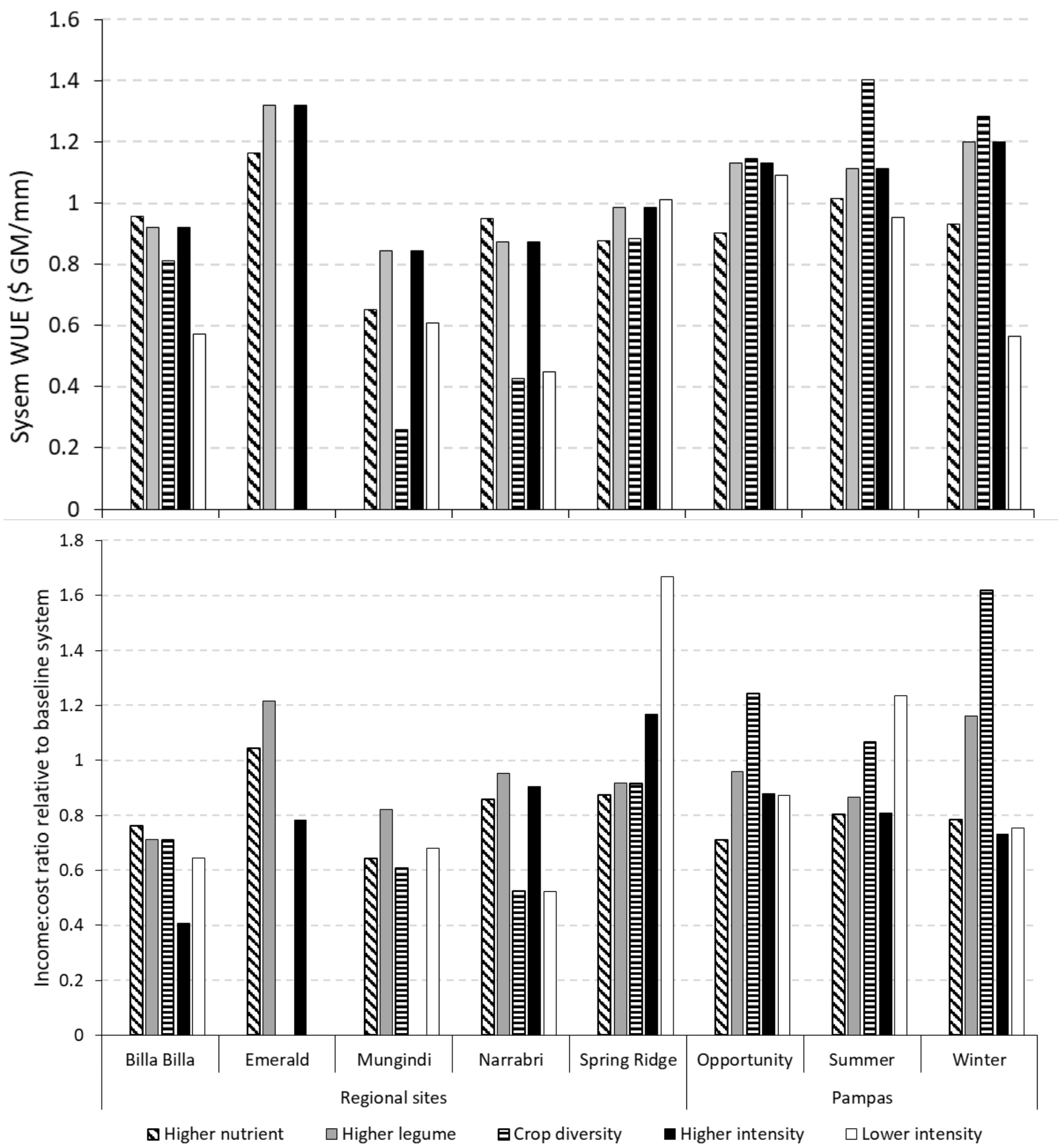

Figure 1. Relative system water use efficiency (i.e. $ GM/mm) of modifying farming systems compared to the baseline at 5 regional sites and under 3 different seasonal crops at the Core site (Pampas).

In order to explore any environmental response of economic performance of the different farming systems, in Figure 2 we plot across all experimental sites the relationships between total system water use and economic returns over the experimental period. These plots demonstrate several important findings.

Firstly, as expected the revenue or income generated increased as the amount of water available increased. That is, the locations that received the lowest rainfall over the 3.5 years of the experiment (Mungindi and Spring Ridge) had lower total income and lower sequence GM. However, this relationship did not continue to increase as the amount of rainfall increased, reaching a maximum at around 1500-1600 mm. This may suggest that the systems that used more rainfall than this failed to convert the additional rainfall effectively into higher incomes or gross returns. Secondly, it can be seen that different farming systems responded differently for their return per mm of water use across the various environments.

- The low intensity systems had a very flat relationship – they achieved similar income and system GM (GM$/mm) to the other systems under dryer conditions, but as the amount of water available increased they fell below the other systems. This indicates that these system are favourable under lower rainfall situations, but less so under more favourable conditions.

- Figure 6 shows that systems with increased crop diversity and higher legume frequency had an advantage over the baseline in locations that had more available rainfall. This is shown by the triangles (crop diversity) and squares (higher legume) exceeding the filled circles (baseline) consistently at locations that used > 1600 mm of rainfall over the experimental period. This suggests that there is likely to be greater benefit from employing these system modifications in more favourable conditions than in lower rainfall environments, where risks for alternative break crops or legumes are higher.

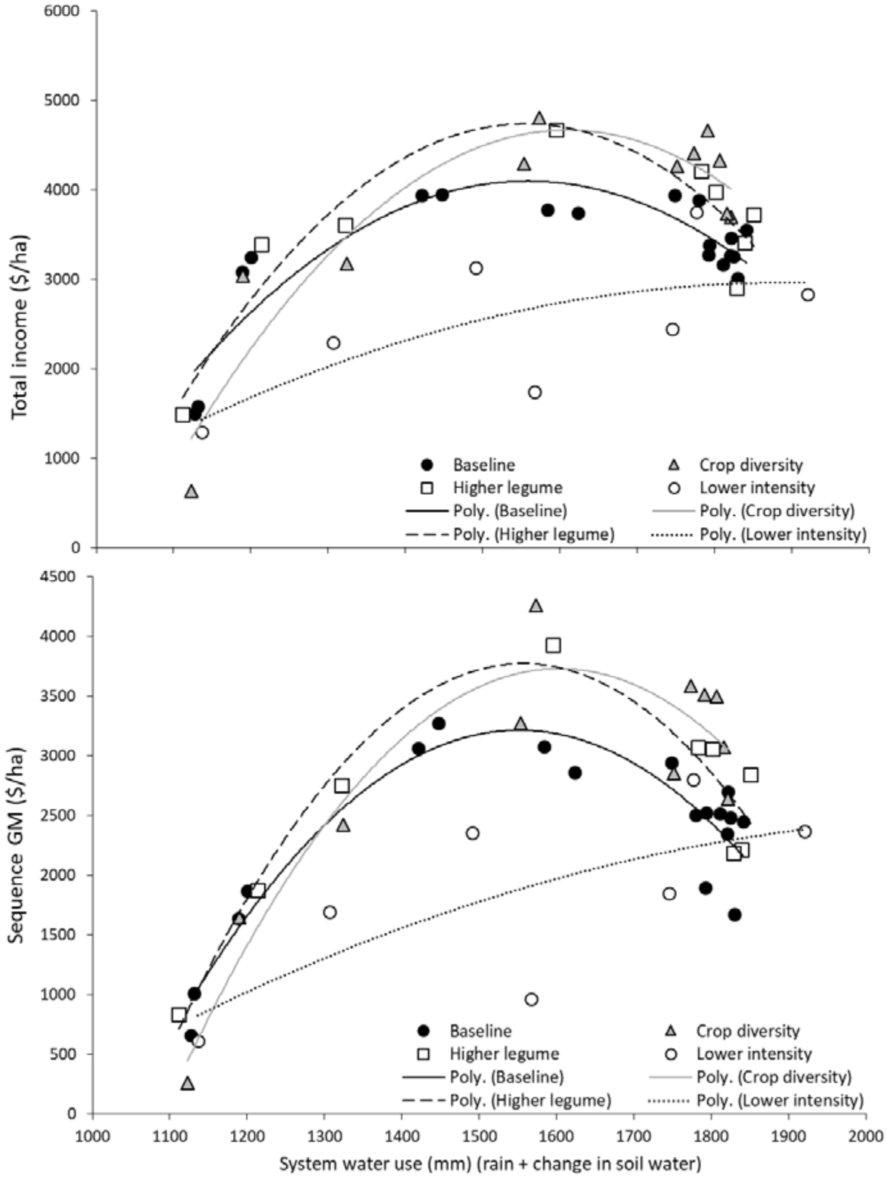

Figure 2. Relationships across sites between total system water use (rain - change in soil water) and sequence, total income and sequence total income ($/ha) (top), and sequence gross margin GM ($/ha) (bottom) over 3.5 years between different farming systems modifications – baseline (black circles), increasing crop diversity (grey triangles), increasing legume frequency (squares) and low intensity (hollow circles).

Conclusions

The economic performance of the farming system integrates many of the various factors that may influence their short and long-term productivity (water use efficiency, nutrient inputs and balance, yield responses to crop rotation). Across all farming systems sites, several of the modified farming systems could achieve similar or even greater profits, however this was not consistent across all sites. That is, in many cases there are options to address particular challenges (e.g. soil-borne diseases or weeds, nutrient rundown) that can be profitable. However, in some locations the options seem much more limited, particularly where risky climatic conditions (or challenging soils) limit the reliability of alternative crops in the farming system. The results here provide a snapshot in time over only a 3.5 year period. The longer term impacts of some of these farming systems strategies may yet to be fully realised and hence, some consideration of these results against this longer-term view is also required.

References

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The impact different farming systems have on soil nitrogen, phosphorus and potassium

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Take home messages

- Most farming systems extract more nutrients than are supplied by common fertilisation strategies
- Increasing the frequency of legumes doesn't necessarily reduce N inputs required across the crop sequence and increases export of potassium
- High yielding legume crops export more N and extract soil mineral N to a similar extent to cereals, often resulting in little additional mineral N for subsequent crops
- We found little difference in soil N extraction or subsequent mineralisation between various grain legumes, challenging assumptions that fababean or field pea provide greater N benefits to the farming system
- The high fertiliser application in the *higher nutrient* system (fertilising to crop yield potential) has maintained higher soil mineral N levels but has rarely increased grain yield or total system N use. Around 50% of additional N applied has remained available in the mineral N pool for subsequent crops
- Increasing crop intensity did not greatly increase nutrient export, but did increase fertiliser inputs across the farming system.

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 developing farming systems to better use 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; 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)).

One of the central aspects of this research was to examine how farming systems compared in terms of their requirements for nutrient inputs and their long-term impacts on soil nutrient status and cycling. Several system modifications (described below) explicitly targeted increasing the nutrient efficiency and overall nutrient supply in the farming system to see how these would impact on system productivity and nutrient balance and use-efficiencies. In this paper we examine some of these key system comparisons to explore the following questions:

1. Will increasing the frequency of grain legumes lower the N fertiliser requirements or improve N utilisation in the crop sequence? How does this impact on other important nutrients?
2. What are the consequences of increasing fertiliser inputs to ensure crops maximise their yield potentials? How does this influence system nutrient cycling and balances?
3. What are the implications of increasing crop intensity for nutrient use and requirements?
4. How do different crops (legumes, cereals, others) impact on N cycling and accumulation for subsequent crops?

Farming system descriptions

The following paper focussed on system comparisons between the following systems being implemented across the range of farming systems experimental sites. The systems varied in the following ways from a *baseline* system at each location:

- ***Baseline*** – an approximation of common farming system practice in each district: dominant crops only used; sowing crops on a moderate soil water threshold to approximate common crop intensities (often 0.75-0.8 crops per year); and fertilising to median crop yield potential
- ***High crop intensity*** – increasing the proportion of time that crops are growing by reducing the soil water threshold required to trigger a planting opportunity (e.g. 30% full profile)
- ***High legume frequency*** – crop choice aims to have every second crop as a legume across the crop sequence and uses high biomass legumes (e.g. fababean) when possible
- ***High nutrient supply -*** increasing the fertiliser budget for each crop based on a 90% of yield potential rather than the baseline of 50% of yield potential.

Trial details

Sites were selected to represent a range of climatic conditions, soil types, nutritional status and paddock history. Each site was comprehensively soil tested at the beginning of the project. There is a considerable range in soil fertility across the sites (Table 1) which dramatically influenced the requirements for inputs of N fertilisers in particular at some sites (e.g. Billa Billa and Pampas) where high levels were present at the start of the experimental period.

Table 1. Nutrient status of sites at the beginning of the project

Site	Mineral N (kg/ha)	Colwell P (mg/kg)		BSES P (mg/kg)		Colwell K (mg/kg)	
	0 – 90 cm	0-10 cm	10-30 cm	0-10 cm	10-30 cm	0-10 cm	10-30 cm
Billa Billa	366	22	3	33	7	518	243
Pampas	200	64	35	728	711	480	291
Spring Ridge	199	66	19	71	40	670	286
Trangie (grey)	106	50	6	62	10	506	235
Emerald	99	45	12	70	21	438	225
Narrabri	58	44	10	433	407	588	209
Mungindi	61	19	5	111	86	752	428
Trangie (red)	19	30	9	53	15	427	268

Experimental procedures included measuring mineral nitrogen (nitrate and ammonium), both pre-sowing and post-harvest for each crop planted over the past four years. Grain content was also analysed for nitrogen (N), phosphorus (P) and potassium (K).

How does increasing legume frequency impact on system N inputs and use?

Grain legumes are integral in current farming systems with areas consistently increasing. This increase in frequency of legumes has been due to several factors including high grain prices but also a belief that they improve soil fertility and reduce overall N fertiliser input costs. Here we compare the impact of increasing the frequency of legumes on the N inputs, exports, and total system N use compared the baseline system. It is important to note here that as the project only has four years of data all these systems have only planted 1 or 2 extra legume crop compared to the baseline.

Higher legume systems exported more N from the system in grain than the baseline systems in 8 out of the 11 comparisons across the farming system sites (Table 2). On average across all sites the high legume sequences exported an additional 30 kg of N from the system (ranging from 78 to -7 kg/ha). The higher legume system showed mixed results in relation to reducing the amount of N fertiliser required for a cropping system (Table 2). For example, the higher legume system reduced nutrient inputs at some sites, such as Emerald which reduced the total N fertiliser requirement by 83 kg N/ha compared to the baseline system. While at Trangie (grey soil) and Pampas, the higher legume system actually increased N fertiliser required in subsequent crops by 25 kg N/ha compared to the local baseline system. Altogether across all sites there was little saving in the N inputs used in cropping systems employing higher frequencies of grain legumes. This was also reflected in the total system N use (soil mineral N depletion plus fertiliser N inputs) over the 3.5 years of cropping systems employed so far. Only 6 of the 11 higher legume systems reduced total N use compared to the baseline system, with the largest reduction of 88 kg at Emerald. However, the other sites recorded higher total N use from the legume system.

Overall these results indicate that across our farming systems experiments the implementation of additional legume crops in the crop sequence has had little positive benefit on reducing N fertiliser input needs or reducing soil N use. The legumes are utilising soil mineral N to the same extent as cereal crops and have higher N export which offsets N fixation inputs. Also notable is that this result is consistent across the full range of starting soil N conditions, from locations with very high starting mineral N status to locations with low mineral N status where legumes would require to fix N to meet their needs. These results significantly challenge the common held assumption that grain legumes will have benefits for reducing N fertiliser needs in the crop sequence. As our capacity to grow high yielding grain legumes has increased as has our harvest index and hence the ratio of N removed in grain to that left in biomass, thereby diminishing the contributions of residual N after the crop.

Table 2. Cumulative nitrogen dynamics for the *baseline and higher legume* systems at 11 sites (Northern grains region) between 2015 and 2018

Site	N export (kg/ha)		Applied fertiliser N (kg N/ha)		Mineral N change (kg N/ha)		System total N use (kg N/ha)	
	Baseline	Higher legume	Baseline	Higher legume	Baseline	Higher legume	Baseline	Higher legume
Billa Billa	220	259	12	17	249	194	261	211
Emerald	227	249	91	8	52	47	143	55
Mungindi	79	80	54	54	-22	-6	32	48
Narrabri	177	227	127	127	43	36	170	163
Spring Ridge	227	305	211	211	25	35	236	246
Trangie (grey soil)	113	106	54	80	-213	-221	-167	-141
Trangie (red soil)	108	117	84	78	-31	-38	53	40
Pampas (mod intensity)	271	309	13	39	248	257	261	296
Pampas (high intensity)	249	303	101	108	285	280	386	388
Pampas (summer)	237	233	78	109	288	231	366	340
Pampas (winter)	287	347	42	17	275	274	317	291

Note: Total N use is calculated from applied fertiliser and the mineral N balance - (ammonium and nitrate N) prior to sowing 2015 minus the mineral N post the 2018 harvest

How does increasing legume frequency impact on soil phosphorus and potassium export?

Phosphorous export has been variable across sites, with some higher legume systems exporting more and some less compared to baseline (Table 3). However, the higher legume system did increase the amount of potassium exported on average across all sites relative to the baseline system (14 kg K/ha). Pampas (mixed) had the greatest amount of exported potassium, a total of 31 kg K/ha from 2015 to 2018. Although this is not unexpected as legume seed has more than double the K content than cereal grains, K levels will need to be monitored to ensure the system does not cause deficiencies for future crops. In situations where K deficiency may be an emerging issue or where levels are marginal, this greater export under a higher legume system may mean that nutrients need to be replaced sooner or a higher level of replacement will be required.

Longer term trends of underlying fertility will be assessed with further collection of soils and benchmarking these results in 2019 against the initial baseline levels that were measured at the start of the project.

Table 3. Cumulative phosphorus and potassium removal of the higher legume systems at 11 sites in the northern grains region (2015 – 2018)

Site	P export (kg/ha)		Applied fertiliser P (kg N/ha)		K export (kg K/ha)	
	Baseline	Higher legume	Baseline	Higher legume	Baseline	Higher legume
Billa Billa	41	34	27	36	57	66
Emerald	29	32	22	21	56	63
Mungindi	12	14	7	7	24	25
Narrabri	26	34	24	24	42	54
Spring Ridge	32	35	33	33	53	64
Trangie (grey soil)	15	14	35	35	19	22
Trangie (red soil)	17	19	35	35	23	26
Pampas (mod intensity)	37	42	23	20	53	84
Pampas (high intensity)	41	41	25	29	59	87
Pampas (summer)	40	33	21	21	45	70
Pampas (winter)	40	46	18	22	66	95

Note: P and K export calculated by grain content (%) x DW grain yield (kg/ha)

What are the consequences of increasing fertiliser inputs on nutrient balance and use?

With declining soil fertility across the northern region there is increasing interest in identifying ways to either halt or reverse this trend. Past research suggests that maximising biomass production is one way to achieve this; more biomass will increase soil organic matter levels which will build the natural supply of nutrients such as N and P. To maximise biomass production, supplying adequate crop nutrition is critical, along with providing nutrients to promote soil microbial processes.

The capacity to address nutrient depletion and increase crop biomass and yield potential under favourable conditions was investigated, by implementing a system that increases nutrient supply budgets to target 90th percentile yield (higher nutrient) compared to only 50th percentile yields in the baseline.

As predicated the higher nutrient system increased the amount of N fertiliser applied at each site over the cropping sequence. On average across all sites an extra 83 kg N/ha was applied between 2015 and 2018 relative to the baseline system. The additional N increased N export at seven of the eleven sites. This was most significant at Trangie (red soil), which exported 49 kg N/ha more than the baseline system (Table 4). It is interesting to note that this site had the lowest starting mineral N levels, resulting in the highest N application rates during the first four years of the project.

The additional N that was applied in the higher nutrient system reduced the depletion of background soil mineral N status at ten of the sites. On average across all sites the higher nutrient system had 43 kg more soil mineral N at last sampling than the baseline – meaning about 55% of the additional N applied was found in the mineral N pool at this time or we are recovering about 55% of the additional previous N applications in subsequent years. However, this recovery % varied greatly across the sites, ranging from full recovery (e.g. Billa Billa, Pampas summer rotations) to low recovery of less than 10% (e.g. Mungindi and Pampas winter rotations). This value is likely to be highly dependent on the timing of sampling influenced by the previous crop, residue loads and types, and soil moisture conditions.

These results show that applying N fertiliser to aim for a 90th percentile yield potential may reduce the mining of soil available N, especially in soils with high fertility (such as Billa Billa) and that significant amounts of additional N applied remains in the mineral N pool and is available in subsequent crops. To confirm this, longer term trends of underlying soil fertility such as organic carbon or total N pools will need to be assessed.

Table 4. Cumulative nitrogen export, inputs in fertiliser, depletion of the soil mineral N pool (starting soil N – final soil N) and total system N use (soil mineral N use + applied N) between the higher nutrient and baseline system at 11 sites in northern grain region (2015 – 2018)

Site	N export (kg/ha)		Applied fertiliser N (kg N/ha)		Mineral N extraction (kg N/ha)		System total N use (kg N/ha)	
	Baseline	Higher nutrient	Baseline	Higher nutrient	Baseline	Higher nutrient	Baseline	Higher nutrient
Billa Billa	220	253	12	62	249	190	261	252
Emerald	227	246	91	147	52	33	143	180
Mungindi	79	86	54	125	-22	-26	32	99
Narrabri	177	158	127	201	43	15	170	215
Spring Ridge	227	235	211	316	25	-2	236	314
Trangie (grey soil)	113	96	54	160	-213	-174	-157	-14
Trangie (red soil)	108	157	84	261	-31	-225	53	36
Pampas (mod intensity)	271	257	13	89	248	229	261	318
Pampas (high intensity)	249	278	101	209	285	193	386	402
Pampas (summer)	237	243	78	116	288	235	366	351
Pampas (winter)	287	277	42	100	275	267	317	367

Note: Total N use is calculated from applied fertiliser and the mineral N balance - (ammonium and nitrate N) prior to sowing 2015 minus the mineral N post the 2018 harvest

The additional P applied to the higher nutrient system did not influence grain P export across the first four seasons in the Farming System project, as sites resulted in minor variances between the higher nutrient and baseline systems. Similarly, there was no difference between K export of the higher nutrient systems and the baseline systems at the eleven sites in the northern grains region, as we did not see significant yield responses to the higher nutrient application strategies.

Table 5. Cumulative phosphorous and potassium removal and phosphorus inputs from the higher nutrient system and the baseline system across northern farming systems experiments (2015 – 2018)

Site	P export (kg/ha)		Applied fertiliser P (kg N/ha)		K export (kg K/ha)	
	Baseline	Higher nutrient	Baseline	Higher nutrient	Baseline	Higher nutrient
Billa Billa	41	42	27	66	57	58
Emerald	29	32	22	35	56	60
Mungindi	12	11	7	22	24	20
Narrabri	26	24	24	33	42	42
Spring Ridge	32	31	33	33	53	54
Trangie (grey soil)	15	13	35	35	19	16
Trangie (red soil)	17	21	35	35	23	29
Pampas (mod intensity)	37	39	23	34	53	56
Pampas (high intensity)	41	41	25	46	59	61
Pampas (summer)	40	40	21	31	45	46
Pampas (winter)	40	38	18	39	66	64

Note: P and K export calculated by grain content (%) x dry weight (DW) grain yield (kg/ha)

What are the implications of increasing crop intensity for nutrient use and requirements?

The Northern region farming system is centred on growing crops mainly on stored soil moisture. With very low fallow efficiencies, the belief is often, “use it or lose it”. However, the grains industry are often unsure the impact a higher crop intensity cropping system has on underlying soil fertility. The question is often asked, “will growing more crops improve or reduce soil fertility?” So far across the various farming systems sites, four have significantly increased the cropping intensity compared to the baseline crop sequence (Billa Billa, Emerald, Pampas). The NSW sites (Narrabri and Spring Ridge) did not meet water thresholds to trigger planting additional crops. They were fertilised with the same regime as *baseline* i.e. 50th yield potential.

Although Billa Billa, Emerald and Pampas did grow extra crops between 2015 and 2018, there was no increase in cumulative grain yield and thus N, P and K export was actually lower or similar across the three sites between the higher intensity and the baseline systems (Table 6).

At Pampas the higher intensity system had an additional 88 kg N/ha applied to the cropping sequence compared to the baseline (Table 6), but the cumulative exported N was lower by 22 kg N/ha. Interestingly the higher intensity system at Pampas resulted in a reduction of 37 kg N/ha mineral N more than the baseline system. This means that the extra crop produced at Pampas resulted in a loss of 137 kg N/ha (of plant available N) from the system, while the baseline system increased mineral N by 10 kg N/ha. It is unclear where this N has ended up, but it is possible this has been accumulated in the soil carbon pool. Analysis of soil carbon levels and the completion of additional seasons will help to answer the impact cropping intensity has on soil fertility.

Table 6. Cumulative nitrogen dynamics of the higher intensity and baseline systems at 3 sites in northern grains region (2015 – 2018)

Site	N export (kg/ha)		Applied fertiliser N (kg N/ha)		Mineral N change (kg N/ha)		Total system N use (kg N/ha)	
	Baseline	Higher intensity	Baseline	Higher intensity	Baseline	Higher intensity	Baseline	Higher intensity
Billa Billa	220	195	12	13	249	220	261	233
Emerald	227	211	91	94	52	30	143	124
Pampas	271	249	13	101	248	285	261	385

Note: Total N use is calculated from applied fertiliser and the mineral N balance - (ammonium and nitrate N) prior to sowing 2015 minus the mineral N post the 2018 harvest

Table 7. Cumulative phosphorus and potassium removal from the higher intensity and baseline systems at 3 sites in the northern grains region (2015 – 2018)

Site	P export (kg/ha)		Applied fertiliser P (kg N/ha)		K export (kg K/ha)	
	Baseline	Higher intensity	Baseline	Higher intensity	Baseline	Higher intensity
Billa Billa	41	31	27	29	57	40
Emerald	29	29	22	29	56	43
Pampas	37	41	23	25	53	59

Note: P and K export calculated using grain content (%) x DW grain yield (kg/ha)

How do different crops impact on N cycling and fallow accumulation?

Grain legumes fix N and are renowned for increasing mineralisation during the subsequent fallow period prior to the next crop. Also some legumes are thought to be more efficient at doing this than others (e.g. fababean provides more N benefit than chickpea). The diversity of crops grown across various sites in this project provides an opportunity to compare the mineral N dynamics in-crop and also in the fallow period after harvest for various crop types across multiple seasons.

In three of four comparisons between chickpea and wheat that were grown in the same season (Emerald 2015 and 2016, Pampas 2016) we did not observe any additional N accumulation after chickpea compared to wheat and had the same mineral N available for subsequent crops. There may have been a small amount of extra N at the end of the chickpea crop but this was often associated with a higher N at sowing and hence crop N extraction was similar or in some cases higher. For example at Emerald in 2016, chickpea utilised 130 kg N/ha from the soil mineral pool compared to 114 kg N/ha for wheat. The one exception across these comparisons was during a long-fallow at Pampas after winter crops in 2015. This showed that following chickpea accumulated an additional 38 kg of N accumulated compared to wheat, but owing to lower soil N at harvest there was still actually less mineral N available following chickpea than wheat.

A further comparison of mineral N dynamics between different legumes grown in the same season occurred across 3 locations (Narrabri and Spring Ridge in 2016, Pampas 2015). These results show very little significant difference between the various legumes in N utilisation, and accumulation during the subsequent fallow.

While these results suggest there has been little N benefit for subsequent crops following grain legumes across sites, because mineral N status is affected by mineralisation rates, denitrification, and microbial tie-up, it may be that these crops may provide additional N supply in the subsequent crops. This does raise questions about the commonly held belief that legumes will provide N benefits for subsequent crops and that some legumes are better than others. More seasons and sites may be required to more fully understand this.

Table 8. Comparisons of crop effects on soil N use and subsequent fallow N accumulation across multiple sites and seasons in the northern grains region

Site Season	Crop	Sowing mineral N (kg N/ha)	Harvest mineral N (kg N/ha)	End of fallow mineral N (kg N/ha)	Subsequent fallow mineral N accumulation (kg N/ha)
Emerald 2015					
	Wheat	105	59	153	94
	Chickpea	78	32	126	94
Emerald 2016					
	Wheat	126	12	114	102
	Chickpea	153	23	141	118
Narrabri 2016					
	Chickpea	69	38	43	5
	Fieldpea	86	41	49	8
	Fababean	77	41	38	-3
Spring Ridge 2016					
	Chickpea	157	173	277	105
	Fieldpea	169	156	248	92
	Fababean	160	154	237	84
Pampas 2015 – long fallow					
	Wheat	184	117	179	62
	Fababean	186	58	153	97
	Chickpea	203	68	168	100
	Field pea	190	94	217	123
	Canola	186	93	183	90
Pampas 2016 – short fallow					
	Wheat	83	17	61	44
	Chickpea	93	34	76	42

Discussion

The first four years of the farming system project showed that modifying crop systems through higher nutrients, higher intensity and the higher frequency of legumes provided limited benefits for improving nutrient status relative to localised growers practice (baseline). Only when higher nutrients were provided did we manage to balance the net export of all nutrients (N, P, K) relative to the inputs in several cases. However, there have been few cases where we have seen a positive yield advantage from providing these additional nutrients. However as soils age and their inherent fertility declines this may change.

It must be noted that although nutritional benefits were limited in the first four years of the project between systems, there were legumes (in particular chickpea) planted commonly within the baseline systems (20-33% of crops planted). Growing chickpea in the baseline system has followed current local grower practice, however has resulted in smaller differences between the higher legume, higher nutrients and baseline systems.

Future comprehensive soil analysis across all sites will be interesting to investigate to detect changes in other parameters such as total N and organic carbon levels. Longer-term examination of cropping systems may lead to greater differentiation between systems and geographical location, providing greater insights into the impact different farming systems have on nutrient balances and long-term soil fertility.

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Tactical decisions on crop sequencing - opt in/opt out decisions based on plant available water (PAW) triggers

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Key words

rotation, stored soil water, opportunistic crops

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Take home messages

- Planting an opportunistic crop to reduce fallow lengths can improve economic returns if strict rules are followed
- Increasing the intensity of a rotation beyond the environmental potential of the area reduces the returns across the whole rotation.
- Planting on less than 100mm of stored soil water in eastern environments and less than 150 mm in western environments significantly increases the probability of failed (negative gross margin) crops.

Introduction

This paper reports on some of the work conducted as part of GRDC's northern farming systems project. One of the goals of this project is to use both experimental research and simulation modelling to understand the benefits and trade-offs associated with different crop rotations across the northern grains region. For this paper we will use the term rotation to mean a sequence of crops and fallows that regularly follow each other in a cyclic pattern. We are aware that not all grain growers follow a structured fixed rotation and we are not advocating this approach. However, by examining rotations in this structured way, key features (benefits and costs) of the sequence can be observed.

Long fallows are a feature of northern grain production and are mainly used to move between summer and winter phases and/or in more marginal areas to accumulate water to reduce the risk of crop failure. However, there are times when the crop sequence could be intensified by replacing a long fallow with a double crop to move between summer and winter phases or incorporate an additional wheat crop that reduces a long fallow to a short fallow.

Our previous modelling analyses have shown that time in fallow/crop are key drivers of system water use efficiency, profitability and risk. In most production environments, cropping sequences with higher intensity (i.e. more time in crop) have higher average returns over the long-term however this comes with increased risk (frequency of crops with negative gross margins). However, our previous analysis only considered strict rotations where all crops were sown irrespective of soil water conditions and hence, crops are frequently sown on marginal soil water levels in higher intensity systems. Hence, the question we have examined here is how much can risk be mitigated by only taking opportunities to sow double crops in the rotation when soil water triggers are met. We have tested some opportunistic rules to try and identify when to plant an opportunity crop and what effect it has on the overall rotation. In particular we aim to identify where, when and how the rotation can be intensified to increase profitability without significantly increasing production risk, and what triggers to use to make these decisions. This analysis will help guide answers to the questions:

- What soil water do I need to put that additional opportunity crop in?
- What affect will it have on the rest of the rotation and subsequent crops?
- Is it worth the additional risk?

Methods

Simulations

This study is a simulation analysis that uses the APSIM systems framework (Holzworth *et al.*, 2015) to simulate crop rotations from historic climate records (1957-2017). APSIM has a long history of simulating northern farming systems (Carberry *et al*., 2009; Whish *et al*., 2007) and uses environmental signals to trigger appropriate management decisions. However, these simulations only consider 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 by these simulations.

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 sites were selected to represent an east-west rainfall gradient at both a northern (Pampas – Billabilla – Mungindi) and southern latitude (Breeza – Gilgandra – Nyngan). Each site used a locally representative soil among the higher plant available water capacity (PAWC) in each district (Table 1).

Table 1. Soil details used in simulations at the 6 locations across the northern grains region

Location	Soil description	APSoil No.	Soil plant available water capacity (PAWC) (mm)				Annual rain
			Wheat	Sorghum	Chickpea	Mungbean	(mm)
Pampas	Black vertosol	006	290	234	290	211	698
Billabilla	Grey vertosol	220	188	188	167	140	619
Mungindi	Grey vertosol	157	186	201	186	141	505
Breeza	Black vertosol	123	264	273	210	207	680
Gilgandra	Clay loam	249	195	195	195	89	560
Nyngan	Sandy clay	1162	188	188	188	108	445

Rotations

This analysis is designed to look in detail at increasing intensity both in a fixed pattern and using 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 2). The three sequences were chosen to span different cropping intensities that will match different production environments simulated. 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 (Table 2). If the sowing rule had not been met by the end of the sowing window then the crop was sown at this time. In contrast to these higher and lower intensity systems an opportunistic sequence was simulated where a crop was either sown or remained in fallow based if the soil water did not reach the critical threshold during the sowing window (Table 3). Simulations were also conducted with two levels of soil water thresholds required to trigger a planting event (base – higher PAW at sowing, and aggressive – lower PAW at sowing) (Table 3). To ensure that the rotations did not get out of sequence and could be phased, specific parts of the rotation were fixed so these crops were sown every year despite the rules.

Table 2. Description of low and high intensity rotations where all crops are sown every year and opportunistic crop rotation 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	SCh|xW|xx	1.0
High	xW|xW|xCh|xW	1.0	Sx|xCh|xW|Mgx	1.0	SCh|xW|Mgx	1.33
Opportunistic	xW|xW|xCh|xW	0.5-1.0	Sx|xCh|xW|Mgx	0.75-1.0	SCh|xW|Mgx	0.66-1.33
					SCh|xW|xx	0.5-1.0

W= wheat, Ch = chickpea, Mg = mungbean, x= 6 month fallow.

Table 3. Summary of key management rules to trigger sowing, and crop agronomic management rules applied to crops across the set of simulations

Crop	Sowing window	Minimum planting soil water (mm)		APSIM Variety used	Row spacing (cm)	Plant density (#/m^2)	Starter fertiliser (N kg/ha)
		Base	Agg.				
Wheat	15 May-1 Jul	150	100	Gregory	25	100	25
Chickpea	1 May-1 Jul	150	100	Amethyst	50	30	0
Sorghum	15 Oct – 15 Jan	150	100	Buster	100	7	25
Mungbean (spring)	15 Oct-15 Nov	100	60	Green Diamond	50	30	0
Mungbean (double crop)	15 Nov – 15 Jan	100	60				

Economic analysis parameters

Average annual gross margin (GM) analysis was conducted for each phased crop sequence using the equation below. Long-term average grain prices (2008-2017) and current variable input prices were used and these were held constant across all locations. Insurance and levy costs together were 2% of the grain income value and were deducted from grain prices. The price for nitrogen (N) fertiliser applied was set at $1.30/kg N and each fallow spray was set at $17/ha. The simulations did not account for application losses of N fertilisers; therefore, an additional 30% of applied N was used to ensure fertiliser N reached the soil mineral N pool. The baseline “variable cost” for each crop included planting, non-N nutrients and in-crop pesticide applications. Harvesting costs, N fertiliser and fallow spray frequency were included separately, as these varied between the crop sequences or if crops failed. Crops were considered as failed if the yield was less than the thresholds (Table 4) and harvesting costs were not included. Machinery costs were based on an owner-operated production system; therefore, fuel, oil, repairs and maintenance (FORM) costs where included in variable costs.

$$GM_{seq}(\$/\mathrm{ha/yr}) = \frac{\sum\{(\text{Grain yield} \times \text{price}) - (\text{kg N} \times 1.3) - (sprays \times 17) - \text{variable costs} - \text{harvest costs}\}}{no.of\ years}$$

Table 4. Crop prices and variable costs used in gross margin calculations for crop sequences

Crop	Average price ($/t)[#]	Harvest cost ($/ha)	Variable costs ($/ha)	Failed crop threshold (kg/ha)
Wheat	264	40	175	500
Sorghum	225	55	218	800
Chickpea	569	45	284	340
Mungbean	710	55	276	300

[#]*farm gate price with grading & additional harvesting costs already deducted*

Results

There are a large range of combinations of crop sequence by locations that were generated in this analysis. Only a selection of the most illustrative results will be presented to highlight how the different options behave in the different environments.

Winter crop sequence

The conservative low intensity rotation (xW|xx|xCh|xx) is commonly used in more marginal western sites and has been previously shown to be effective for minimising risk in such environments. A large gap exists between the low intensity rotation (xW|xx|xCh|xx) and the more intensive sequence (xW|xW|xCh|xW) when sown at Pampas, Breeza, Billabilla or Gilgandra because these environments are too reliable for such a conservative strategy and can support a more intensive crop rotation. However, at Nyngan and Mungindi about 50% of the time each of the high and low intensity sequences are the best – the higher intensity in better seasons and the lower intensity in poorer years (Figure 1). This analysis shows by employing an opportunistic strategy fills the gap between the conservative and the high intensity strategy to capitalise on the good seasons and remain conservative in poorer seasons.

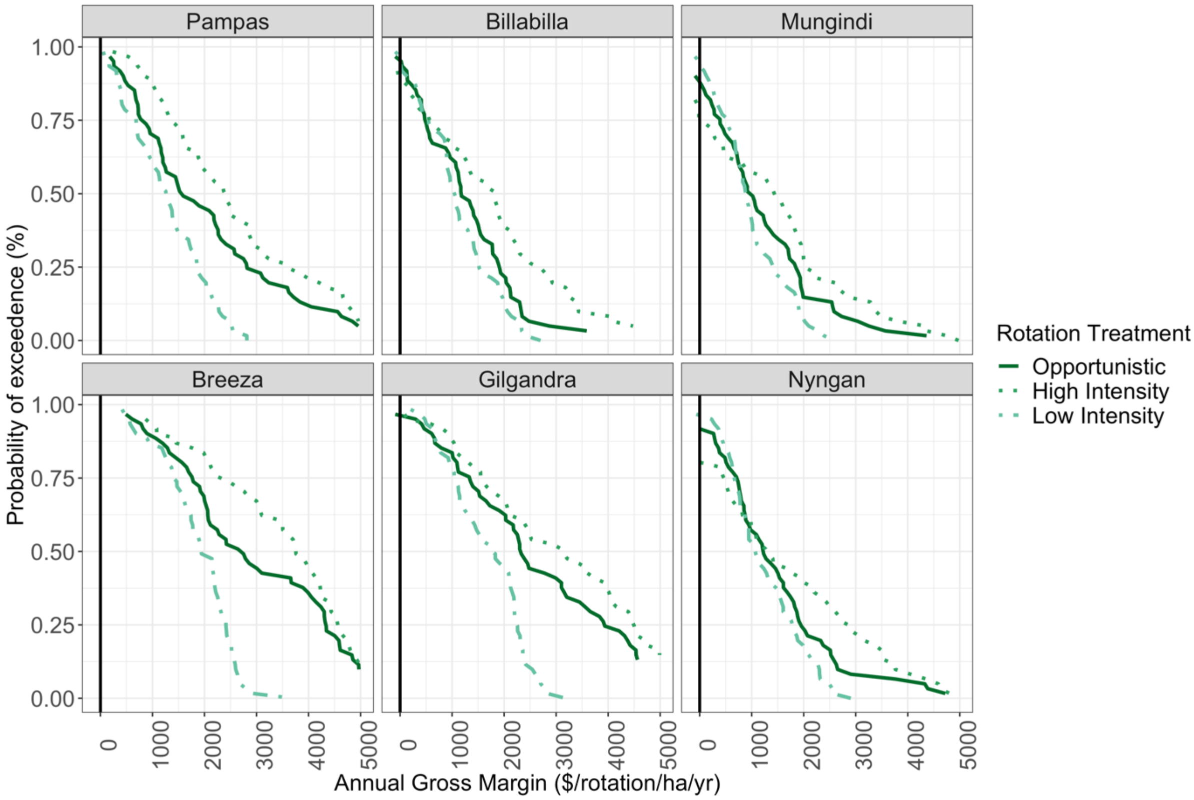

Figure 1. Comparison of the three winter-based crop rotations of low intensity (dot dash), high intensity (dot dot), and with opportunistic crop decisions (solid) at each of the six sites examining their probability of exceeding an annual gross margin. The solid black line marks the zero gross margin point with negative gross margins occurring to the left of this line.

Increasing risk is associated with increasing intensity and the risk of a producing a negative gross margin is one way to assess this risk (Figure 2). The environments of Pampas, Breeza, Billabilla and Gilgandra have few failed crops - less than 1 crop in 20 did not break-even. However, in the more marginal areas imposing a rotation that has an intensity of 1 crop per year (xW|xW|xCh|xW) resulted in over 15% of crops failing. Using the opportunistic rule, the average gross margin was similar to this more intensive system, but the risk was significantly reduced to around 1 crop in 20 failing.

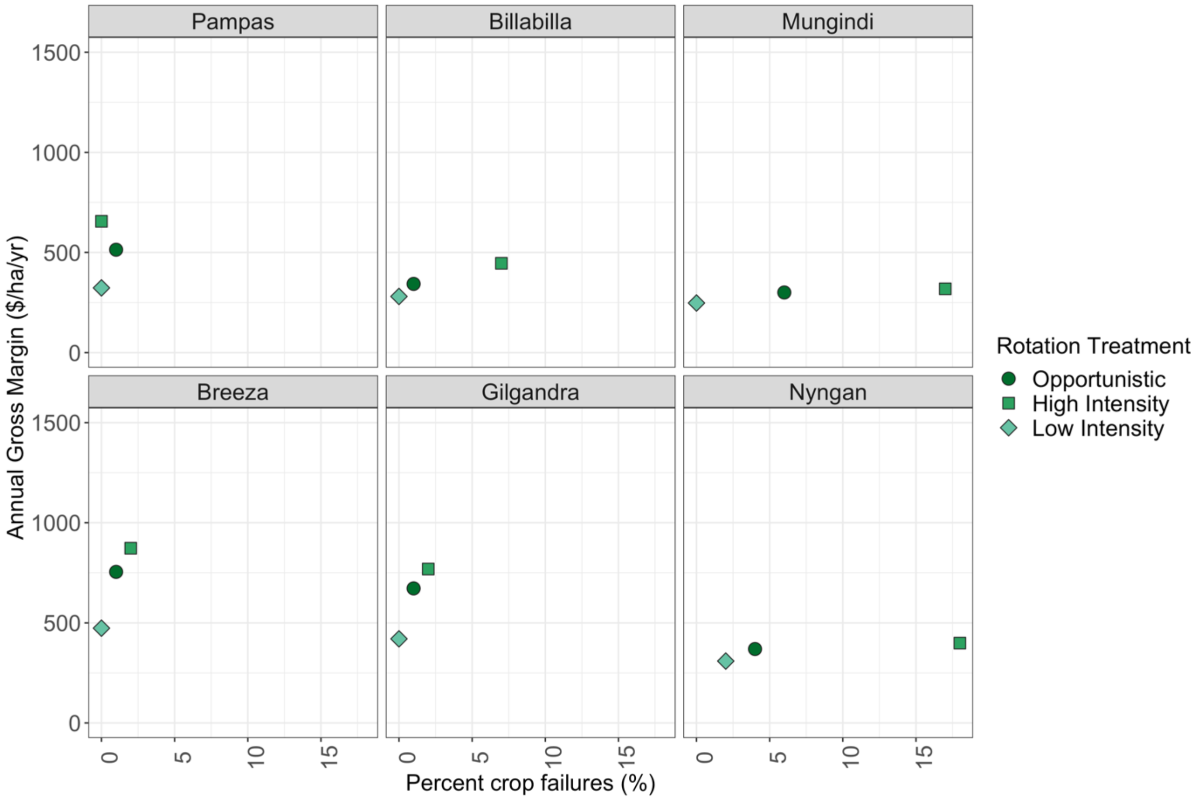

Figure 2. Mean annual gross margin compared to the percentage of failed crops for winter-based rotations of low intensity (Dimond), high intensity (Square) and using an opportunistic sowing rule (Circle).

Looking more closely at the individual components of the rotation (Table 5) highlights how the opportunistic decision, but more importantly the decision not to sow affects the rotation.

The second and third wheat crops (wheat_2, wheat_3) were the opportunistic crops and were only sown when 150 mm of soil water had accumulated in the sowing window. At Mungindi this meant that only 1 in 4 years would the additional wheat crops be sown. Hence, crop intensity only increases from 0.5 crops per year in the low intensity system to 0.66 crops per year. The average return from these crops sown only when the soil water threshold was met was more than twice the average return from crops that were sown every year and all crops broke even at least. The returns from the scheduled wheat crop 1 and chickpea crop 1 (sown every 2 years) was also increased significantly ($140-170/ha). This was because when crops are sown on marginal soil water and fail they consume resources that are no longer available to following crops reducing their subsequent yields and gross margin. On average the opportunistic strategy improved returns over the low intensity rotation by more than $50/ha/yr.

Table 5. Individual crop behaviour for each of the conservative rotations conducted at the low rainfall sites of Mungindi and Nyngan for a low and high intensity crop rotation where all crops are sown each year or an opportunistic system where wheat crops may be sown in-between when soil water exceeds 150 mm during the sowing window.

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	**Per year**	**0.5**		**247**	**1.0**		**319**	**0.66**		**298**
	Chickpea_1	100	5	624	100	21	470	100	10	595
	Wheat_1	100	8	365	100	26	254	100	16	333
	Wheat_2				100	28	253	27	10	430
	Wheat_3				100	23	296	27	0	448
Nyngan	**Per year**	**0.5**		**308**	**1.0**		**399**	**0.64**		**364**
	Chickpea_1	100	2	713	100	18	513	100	5	688
	Wheat_1	100	3	522	100	21	346	100	8	485
	Wheat_2				100	21	352	33	0	492
	Wheat_3				100	20	386	33	0	608

Balanced - conservative

The balanced- conservative rotation is designed to have both summer and winter phases (Sx|xCh|xW|xx), which was intensified through the the use of either a scheduled (sown every year) or opportunistic mungbean crop (Sx|xCh|xW|Mgx) to move between the winter and summer phase. At most locations the inclusion of mungbeans opportunistically matched the returns of the high intensity strategy where they were sown every year for majority of the seasons. A few occurrences occurred around the average when the opportunistic crop was not sown and subsequently a good season enabled a good yield and return. Pampas and Breeza show a distinct difference between conservative 3 crops in four year rotation (SxxChxWxx) and the higher intensity system which have 1 crop per year (Sx|xCh|xW|Mgx). This suggests that in these environments there is still room for intensification to at least 1 crop per year. The minimal difference between the different rotations at Mungindi and Nyngan suggest this level of intensity is too high for this environment.

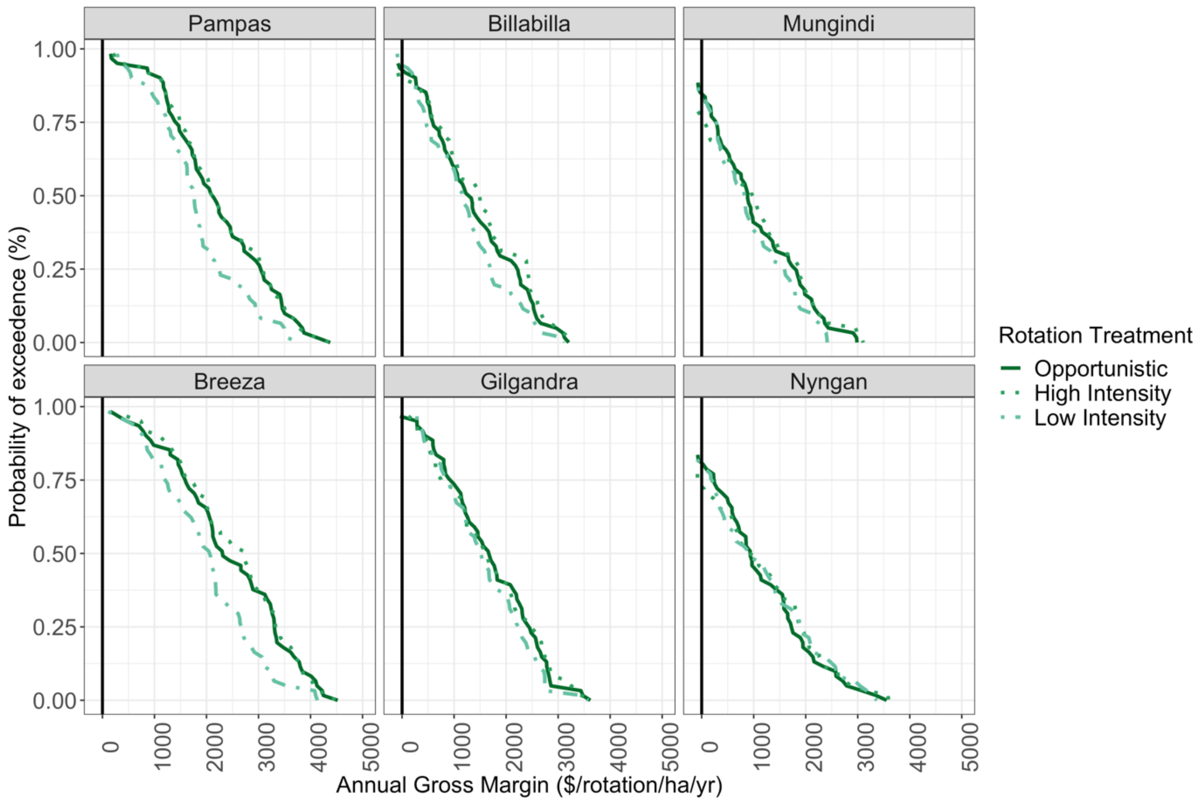

Figure 3. Comparison of the three balanced- conservative crop rotations of low intensity (dot dash), high intensity (dot dot), and with opportunistic crop decisions (solid) at each of the six sites examining their probability of exceeding an annual gross margin. The solid black line marks the zero gross margin point with negative gross margins occurring to the left of this line.

The opportunistic use of mungbeans reduced the risk of crops with negative gross margins compared to a crop sequence where these were sown every year. In fact, the risk of crop failures was hardly higher than the low intensity system where mungbeans were not used at all. The examination of the number of failed crops highlights the limitations of the such a crop sequence in the dryer environments of Mungindi and Nyngan.

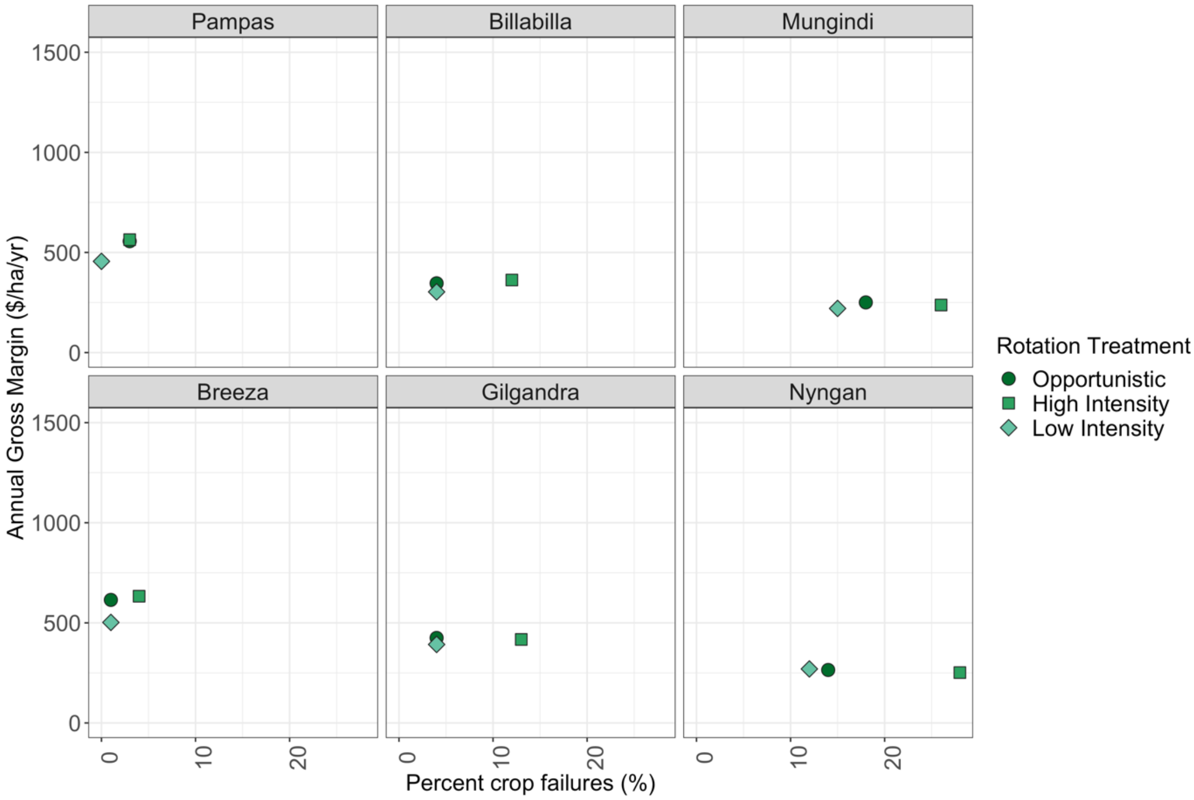

Figure 4. Mean annual gross margin compared to the percentage of failed crops for balanced conservative rotations of low intensity (Dimond), high intensity (Square) and using an opportunistic sowing rule (Circle). The opportunistic sowing of mungbean achieved a gross margin similar to or better than the high intensity rotation with similar risk to the low intensity rotation.

Examining the components of the rotation (Table 6) highlights the importance of only planting a crop when resources are present to give it the best possible chance of success. The fixed rotation that sowed mungbeans every year had 31% and 49% of crops failing at Billabilla and Gilgandra. In comparison, the opportunistic rotation had 5% and 22% of mungbean crops failing. At the same time the annual gross margin was increased by $60 per ha at Billabilla, but at Gilgandra the high risk of mungbean crops meant that of these sequences the low intensity system was probably a better option based on returns and risk.

Table 6. Individual crop behaviour for each of the balanced rotations conducted at the medium rainfall sites of Billabilla and Gilgandra

site	State	Low intensity Sx|xCh|xW|xx			High intensity Sx|xCh|xW|Mgx			Opportunistic Sx|xCh|xW|Mgx		
		% crops sown	% crops fail	GM ($/ha)	% crops sown	% crops fail	GM ($/ha)	% crops sown	% crops fail	GM ($/ha)
Billabilla	**Per year**	**0.75**		**409**	**1.0**		**489**	**0.85**		**463**
	Chickpea_1	100	4	753	100	4	755	100	7	759
	Mungbean_1				100	31	264	40	5	517
	Sorghum_1	100	7	539	100	11	581	100	4	554
	Wheat_1	100	9	345	100	9	357	100	9	349
Gilgandra	**Per year**	**0.75**		**527**	**1.0**		**561**	**0.85**		**517**
	Chickpea_1	100	0	999	100	0	1028	100	0	1014
	Mungbean_1				100	49	5	40	22	247
	Sorghum_1	100	16	414	100	2	517	100	11	470
	Wheat_1	100	2	697	100	2	696	100	2	703

Balanced - aggressive

The intense rotations tested here were examined to see how much there is capacity to capitalise on the higher rainfall conditions in more eastern environments of Breeza and Pampas. In these sequences two options for intensifying the farming system involving a chickpea double crop sown either every year or opportunistically following sorghum (S**Ch**|xW|xx) and further intensifying the system with a mungbean double crop sown either every year or opportunistically following wheat (S**Ch**|xW|**Mg**x). These three different options provide a wide range of crop intensities to emerge in response to the environment ranging from 2 crops in 3years (0.66 crops/yr) to 4 crops in 3 years (1.3 crops per yr). The data falls into 2 clumps, but the key message is that in the eastern environments of Pampas and Breeza the opportunistic rotations matched the fixed rotations in terms of gross margin for the majority of seasons with little difference between the opportunistic and the intense (Figure 5) apart from risk (Figure 6).

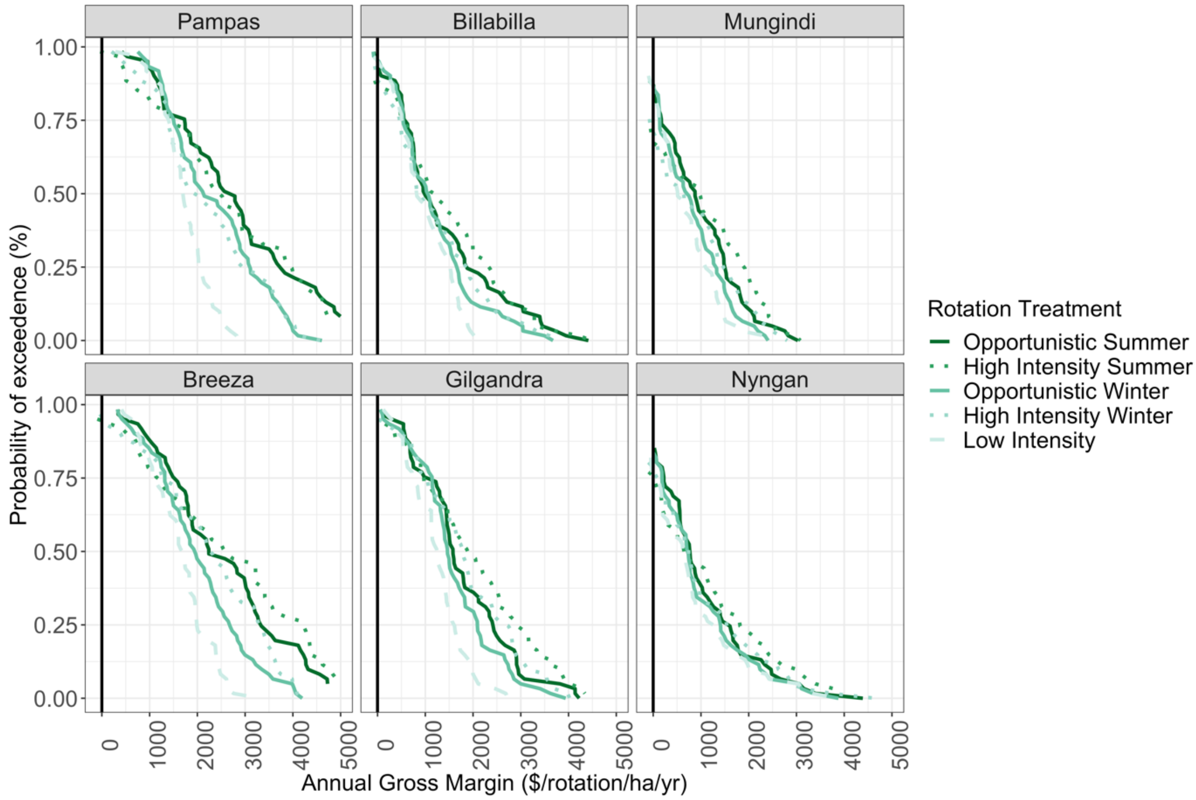

Figure 5. Comparison of the balanced- aggressive crop rotations of low intensity (light grey dash), high intensity (dot dot), and with opportunistic crop decisions (solid). The summer opportunity rotations are dark and the winter rotations are grey. The solid black line marks the zero gross margin point with negative gross margins occurring to the left of this line.

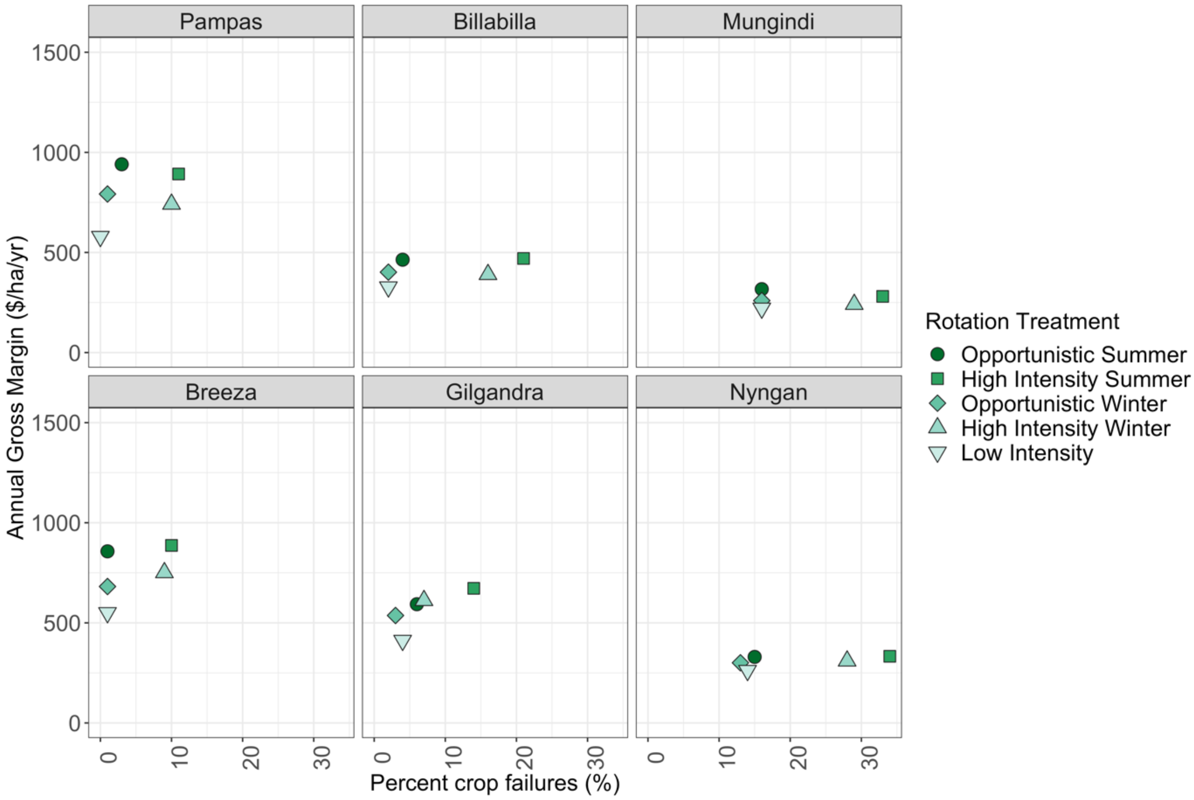

Figure 6. Mean annual gross margin compared to the percentage of failed crops for balanced-aggressive rotations of low intensity (downward triangle), high intensity summer(square), high intensity winter (upward triangle), using an opportunistic sowing rule for summer (circle) and using an opportunistic sowing rule for winter (diamond). The opportunistic sowing of mungbean and chickpea reduce the fallow length and achieved a high gross margin with minimal risk when sown in the eastern environments of Pampas and Breeza

The use of the opportunistic planting rules significantly reduced the number of crops producing a negative gross margin, while increasing the average returns from each of the individual crops. For example, by only sowing the chickpea double crop after sorghum when 150 mm of soil water was present, this reduced the frequency of crop failures from 21 at Breeza and 31% at Pampas to 0 and 3% respectively. This also increased the average gross margin for these crops by over $500/ha, though crops were only sown 1 in 3 years at Breeza and 2 in 3 years at Pampas. A similar story was also true for the opportunistic incorporation of mungbeans into the cropping system. Overall, utilising an opportunistic approach to double-crops of chickpea and mungbeans in these environments was predicted to achieve equal or higher overall average annual returns and dramatically reduced risk compared to a scheduled approach. (Table 7).

Table 7. Individual crop behaviour for each of the intense rotations conducted at the high rainfall sites of Pampas and Breeza

Site	State	Low intensity Sx|xW|xx			Moderate intensity SCh|xW|xx			Opportunistic - mod SCh|xW|xx			High intensity SCh|xW|Mgx			Opportunistic - high 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)
Breeza	**Per yr**	**0.66**		**542**	**1.0**		**755**	**0.77**		**715**	**1.35**		**910**	**0.98**		**904**
	Chickpea_1				100	21	560	32	0	1087	100	21	535	26	0	1182
	Mungbean_1										100	20	505	68	0	718
	Sorghum_1	100	3	755	100	3	815	100	3	791	100	3	772	100	2	804
	Wheat_1	100	0	889	100	3	890	100	2	909	100	2	884	100	2	987
Pampas	**Per yr**	**0.66**	**0**	**579**	**1.0**		**748**	**0.87**		**798**	**1.35**		**912**	**1.12**		**956**
	Chickpea_1				100	32	364	60	3	913	100	33	320	49	3	922
	Mungbean_1										100	10	637	85	11	668
	Sorghum_1	100	0	1144	100	0	1221	100	0	1186	100	2	1089	100	0	1134
	Wheat_1	100	0	613	100	0	659	100	0	654	100	0	657	100	0	692

Conclusions

This paper has demonstrated that opportunistic sowing rules can be employed to increase the intensity of the farming system and increase returns relative to low intensity conservative approaches at the same time as managing risk. All the results presented above used the base sowing rules of 150mm of stored water at sowing for all crops apart from mungbean that used 100mm. Further analysis comparing these rather high soil water thresholds with lower and more aggressive soil water thresholds (100mm for all crops and 60mm for mungbeans) was also conduced but not presented here to save space. In summary reducing the soil water trigger made no impact on the results at Breeza and Pampas. However, using lower soil water threshlds increased risk of crop failures by a few percent at Billabilla and Gilgandra, but was increased this considerably at Mungindi and Nyngan.

This work shows there are considerable benefits of opting out of a crop if the conditions are not favourable or opting in to crops opportunistically based on soil water triggers. The rules presented are robust when run over a 60 year period and show the carryover effect of a failed crop can reduce the returns of those crops that follow. However, it is always easier to not plant a crop while sitting on a computer and not looking at a pile of expensive seed in the shed. This is a difficult decision but knowing how much water you have in the soil and how forgiving your environment is can help answer the question should I opt in or opt out.

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Impacts of crops and crop sequences on soil water accumulation and use

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fallow, water-use-efficiency, gross margin, grain legumes, cereals, soil water

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Take home messages

- Efficiencies of fallows over the crop sequence were 22% ± 4% - this can be used to estimate average fallow water accumulation but large variation in fallow efficiency (FE) exists for individual fallows
- Lower fallow efficiencies can be expected in low intensity crop sequences (i.e. waiting for full profile before sowing) and in systems with high frequency of legumes
- Higher intensity systems where crops are grown on lower soil water thresholds have higher fallow efficiencies
- While grain legumes (chickpea, fababean, fieldpea, mungbean) often leave more residual soil water at harvest than cereals, this difference is diminished due to lower subsequent fallow efficiencies and hence soil water is often similar at the sowing of the next crop
- Despite the inefficiencies of fallows and similar efficiencies of rainfall use, accumulating more water prior to sowing crops typically increases Crop water use efficiency (WUE), and crop gross margins and achieved higher returns per mm an individual crop.

Introduction

The efficiency that soil water accumulates during fallows and availability of that soil water for use by crops are key drivers of farming system productivity and profitability. Using fallows to accumulate soil water to buffer subsequent crops against the highly variable climate is critical in northern grain production systems. A range of factors can influence the efficiency of fallows (i.e. the proportion of rain that accumulates in the soil profile) including ground cover, seasonality or timing of rainfall events, the length of the fallow and residual water left at the end of the proceeding crop. Further, while accumulating more soil water prior to sowing a crop is always preferable, this often requires longer fallow periods, meaning there are additional costs for maintaining that fallow and the number of crops grown declines. Here we analyse the data from farming systems experiments across seven locations (Emerald, Pampas, Billa Billa, Mungundi, Narrabri, Spring Ridge and Trangie) over the past four years to explore the question; ‘how much does the farming system (i.e. mix of crops and their frequency) and different crops influence the accumulation and utilisation of water?’

We explore several factors influencing the accumulation of water during fallows and the availability of water for subsequent crops.

1. How does crop intensity (i.e. the proportion of time in crop or fallow) influence the accumulation and use of water in the farming system?
2. How much does crop choice (e.g. legume vs cereal or other) impact on water extraction and subsequent fallow water accumulation?
3. What is the value of additional soil water for subsequent crop productivity and water use efficiency, and is this sufficient to compensate for longer-fallows required to build this soil water?

Across these projects a common set of farming system strategies have been employed to examine how changes in the farming system impact on multiple aspects of the farming system (outlined below).

Cropping system strategies impacts on rainfall utilisation and soil water dynamics

Here we compare the differences between different farming system strategies over the whole 4 experimental years to see how they differ in terms of fallow efficiency and water use. That is, how efficiently is water used in the system if it is modified to increase/decrease crop intensity, change the mix of crops to grow grain legumes or other break crops more frequently, or increase the nutrient supply to the farming system. Across 10 different contexts we compare the following modifications to the farming system strategies:

- ***Baseline*** – an approximation of common farming system practice in each district: dominant crops only used; sowing crops on a moderate soil water threshold to approximate common crop intensities (often 0.75-1.0 crops per year); and fertilising to median crop yield potential
- ***Higher crop intensity*** – increasing the proportion of time that crops are growing by reducing the soil water threshold required to trigger a planting opportunity (e.g. 30% full profile)
- ***Lower crop intensity systems*** – only growing crops when plant available soil water approaches full (i.e. > 80% full) before a crop is sown and higher value crops are used when possible
- ***Higher legume frequency*** – crop choice aims to have every second crop as a legume across the crop sequence and uses high biomass legumes (e.g. fababean) when possible
- ***Higher crop diversity*** – a greater set of crops are used with the aim of managing soil-borne pathogens and weeds. This implemented by growing 50% of crops resistant to root lesion nematodes (preferably 2 in a row) and 2 alternative crops are required before the same crop is grown
- ***Higher nutrient supply -*** increasing the fertiliser budget for each crop based on a 90% of yield potential rather than the baseline of 50% of yield potential

Efficiency of fallows under different farming systems

Here we have analysed the efficiencies of all fallows within different farming systems across sites in order to examine how different strategies may impact on the efficiency of water accumulation during fallow periods (Table 1). That is, we calculated the ratio of all rain falling during fallow periods to the total accumulated soil water over these fallows across the whole crop sequence (not just individual crops).

Firstly, this shows that there are significant environmental influences on the efficiency of fallows, associated with the timing of rainfall events. Over our four experimental years, environments with more winter-dominated rainfall had lower fallow efficiencies – this is likely due to smaller and less frequent rainfall events occurring during summer fallows meaning that soil water accumulates less efficiently. Overall, though most baseline systems tended to achieve fallow efficiencies of 22% ± 4% over the whole cropping sequence. This is consistent with long-term simulations which show fallow efficiencies of 21-24% for cropping systems with crop intensities of 0.75-1.0 crops per year (i.e. 66-75% time in fallow). Robinson & Freebairn (2017) show fallow efficiencies of 25-30% under no-till in historical research but our data suggests that using a generic 30% FE may over-estimate fallow water accumulation in most cases. Earlier research mostly examined systems where winter cereals were a larger component of the farming system, and cropping systems used now with higher proportion of legumes and summer crops are likely to achieve lower fallow efficiencies (see further results below).

Significant differences in the efficiency of fallows are also found between different farming systems treatments tested across the sites. Key findings are:

- Higher crop intensity increased fallow efficiencies at most sites. This is due to less time in fallows and fallows having lower soil water content meaning higher infiltration rates. The higher crop intensity system at Narrabri so far has similar crop intensities and hence fallow efficiency is similar to the baseline system
- Conversely, systems with lower crop intensity systems had lower fallow efficiencies owing to longer fallows and a greater proportion of rain and time in fallows. The main exception here was at Mungundi where the low intensity system has achieved a similar fallow efficiency to the baseline at this point in time
- Systems with higher legume frequencies had lower fallow efficiencies (5% lower), particularly where they were reliant on summer rain accumulation. At several locations this effect was large, particularly where legumes were followed by a long-fallow period. This is due to the lower and less resilient cover provided by grain legume crops than cereals
- On average, systems aimed at increasing crop diversity have achieved similar fallow efficiencies to the baseline systems. However, there was large site-by-site variability, half the sites had an increase and half lower FE. There was significant differences in how increasing crop diversity is achieved across the various locations (e.g. some involve alternative winter break crops, some involve long fallows to sorghum or cotton), which is likely to bring about these variable results.

Table 1. Comparison of efficiencies of fallow water accumulation (i.e. change in soil water/fallow rainfall) amongst different cropping system strategies at 7 locations across the northern grains region. Colouring of numbers indicate the difference from the baseline system – black = reduction, light grey = increase.

Crop system	CORE - Pampas			Billa Billa	Narrabri	Spring Ridge	Emerald	Mungundi	Trangie (red soil)	Traingie (grey soil)	All site average
	Mix	Win	Sum								
Baseline	0.26	0.30	0.25	0.24	0.30	0.20	0.23	0.17	0.08	0.20	**0.22**
High Nutrient	0.23	0.28	0.32	0.29	0.29	0.16	0.23	0.17	0.13	0.29	**0.24**
High diversity	0.21	0.27	0.28	0.28	0.25	0.12		0.34	-0.13	0.23	**0.21**
High Legume	0.13	0.21	0.25	0.22	0.25	0.13	0.19	0.14	-0.08	0.28	**0.17**
High intensity		0.48		0.35	*	0.28	0.22				**0.33**
Low intensity	*	0.07	0.21	0.29	0.12	0.16		0.19	-0.03	0.19	**0.16**

*Crop system does not yet vary from the baseline in this regard

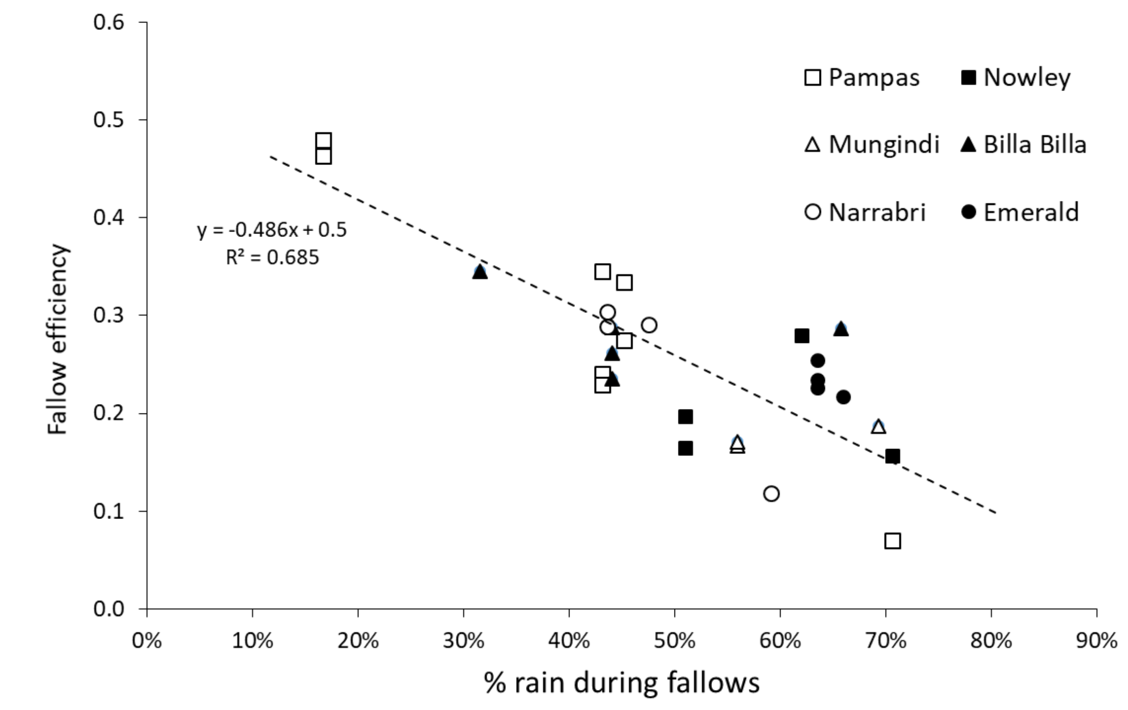

Figure 1. Relationship between the proportion of rain falling during fallow periods (i.e. time in fallow) and efficiency of fallows in the crop sequence (i.e. proportion of fallow rain accumulated in soil) across all farming system locations. Only baseline, low and high intensity systems are plotted, excluding altered crop diversity or legume frequency as this changes fallow efficiencies (see Table 1).

The effect of crop intensity on fallow efficiency is further illustrated in Figure 1. This shows a negative relationship between % of rain falling during fallows (i.e. time in fallow) and the fallow efficiency across all sites. That is, fallow efficiency declines dramatically as the time in fallow (or rain during the fallow) increases. This shows that at a point where 70% of the rain at a location is falling during the fallow that fallow efficiency is declining to 0.16, while in a system where 50% of rain falls during fallows the fallow efficiency is 0.25. What this means is for an environment receiving an average of 600 mm of rainfall per year, a farming system that captures 50% of the rain in fallows (1.3 crops per year), would accumulate 77 mm of water/yr during the fallow period (i.e. 0.5 x 600 mm = 300 mm in fallow @ 0.25 fallow efficiency = 77 mm) and 300 mm/yr would occur in-crop – Total crop water use = 377 mm (63% of rainfall). In contrast a farming system receiving 70% of rain in the fallow period (e.g. 0.6-0.7 crops per year), would accumulate 67 mm in fallow/yr and in-crop rain would be 180 mm per year – Total crop water use = 247 mm per year (41% of rainfall). These results are consistent with the differences in rainfall utilisation between cropping systems of different intensities across all the farming systems research sites (see Table 2).

What this means is that a crop grown after a longer fallow in a lower intensity system must generate 1.5-times the gross margin per mm of water used to be equally profitable. This is achievable in most cases (see results later in this paper) but it does mean that these crops must be managed to maximise their WUE in order to make up for the lower utilisation of water across the system.

Table 2. Differences in the percentage of total rainfall that was used by crops (i.e. in crop rain + change in soil water from sowing to harvest) between cropping systems treatments varying in crop intensity across farming systems experiments.

Systems	CORE - Pampas			Billa Billa	Narrabri	Spring Ridge	Emerald	Mungundi
	Mix	Win	Sum					
Baseline	68	84	86	67	85	63	56	48
Higher intensity	+26	+10	+8	+17	*	*	-2	
Lower intensity	*	-40	-39	-8	-39	-18		-16

*Crop system does not yet vary from the baseline in this regard

Crop-by-crop effects on fallow efficiency

Across the farming systems sites we have monitored fallow water accumulation following a range of different crops – over the 4 research years, we have collected data on residual soil water and final soil water for over 306 different crops. Here we have collated this data in order to compare how different crop types impact on subsequent fallow efficiencies (Figure 2). This data shows the high variability in fallow efficiency that occurs from year to year but is also demonstrates some clear crop effects on subsequent fallow efficiencies.

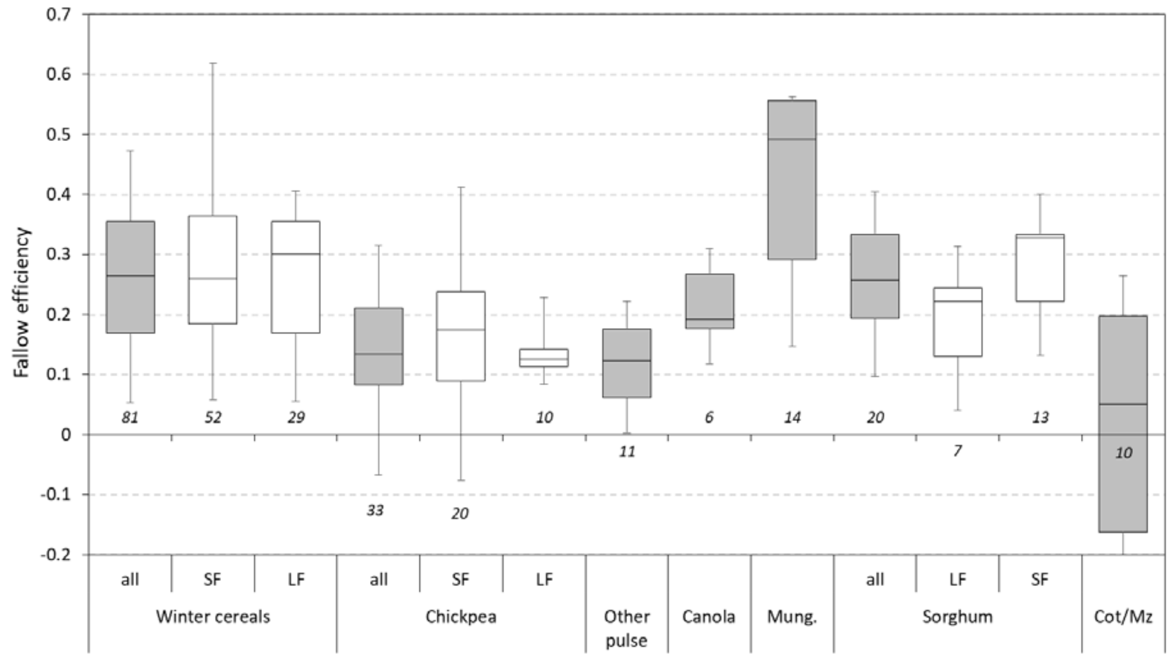

Figure 2. Summary of observed fallow efficiencies following different crops and different fallow lengths (SF – short fallows 4-8 months, LF – long fallows 9-18 months) across all farming systems sites and treatments between 2015 and 2018; winter cereals include wheat, durum and barley; other pulses include fababean and fieldpea. 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.

This data clearly shows the higher fallow efficiencies that can be achieved from a winter cereal crop than winter grain legumes and to a lesser degree, canola. The median fallow efficiency following winter cereals was 0.27, while following chickpea and other grain legumes this was 0.14, with canola intermediate (0.19). Median fallow efficiencies following sorghum were also similar to wheat (0.26), but efficiencies of short-fallows during winter 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). Hence, short fallows after sorghum occurring in winter 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.

What this means is that, the impacts of a particular 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 could have a significant impact on the opportunity to sow a crop and/or the gross margin of the following crop in the cropping sequence.

Residual water and fallow efficiency effects on soil water after legumes vs cereals

While we have observed lower fallow efficiency following grain legumes in the farming system, a frequently mentioned benefit of legumes is the residual soil water left at harvest that can be used in subsequent crops. In Table 3 we have compiled cases where chickpeas and wheat have been grown in the same season to compare the residual water at harvest and the accumulation of water until the sowing of the following crop. On numerous occasions we observed higher residual soil water at harvest after pulse crops (chickpeas, fababeans or field peas) compared to after wheat. This was often associated with rainfall later in the crops development where the winter cereals were able to extract this water while the pulses were finishing and did not utilise this additional water. On average across these 7 comparisons chickpea had 41 mm more soil water post-harvest compared to wheat, however, at the end of the subsequent fallow this difference was greatly reduced so that on average only 10 mm more water remained in the soil profile after chickpea compared to wheat or barley. What this means, is that you shouldn’t bank on the additional moisture after a grain legume translating into additional soil water available for subsequent crops.

Table 3. Residual soil water at harvest and subsequent fallow water accumulation between chickpea and wheat compared across 7 sites/years

Crop	Residual water at harvest (mm PAW)	Fallow efficiency	Fallow rain (mm)	Final soil water (mm PAW)
***Emerald** - Oct 15 to May 16*				
Wheat	44	0.20	525	150
Chickpea	71	0.19	568	177
***Emerald** - Oct 16 to Apr 17*				
Wheat	93	0.16	341	147
Chickpea	89	0.20		158
***Emerald** – Sep 17 to Jan 18*				
Wheat	56	0.33	364	177
Chickpea	76	0.23		157
***Pampas** – Nov 15 to Sep 16*				
Wheat	61	0.38	459	238
Chickpea	106	0.26		198
***Pampas** – Nov 16 to Apr 17*				
Wheat	41	0.47	299	182
Chickpea	47	0.41		167
***Pampas** – Nov 16 to Sep 17*				
Wheat	9	0.25	344	96
Chickpea	91	0.11		129
***Pampas** – Oct 17 to Apr 18*				
Wheat	28	0.18	228	69
Chickpea	141	0.0		139

Fallow length effects on crop water use efficiency and gross margin

While we have shown above that there are a range of factors that affect fallow efficiency, it is important to factor in how effectively the subsequent crop turns the water available into grain and gross margin. From the seven farming systems sites, 42 crops had eight common crops at the end of fallows of varying length (Table 4). These comparisons showed that in 41 of the 42 crops, longer fallow periods (under the same seasonal conditions) have resulted in more plant available water (PAW) at planting of the common crop. The only crop that didn't increase was an 18 month fallow, which didn't increase from 2/3 full despite 700mm rainfall over a 12 month period.

In every comparison, higher PAW at planting resulted in increased grain yield, which in seven of the eight comparisons improved crop water use efficiency (WUE) i.e. grain yield/(in-crop rain + change in soil water) (WUE). The comparison where higher grain yield didn't translate to higher water use efficiency was the highest yielding crop, with the highest WUE in these comparisons (ie. sorghum at Pampas in 2016/17). However, it is important to also factor-in the fallow rain required to achieve the higher plant available water at sowing. Here we have calculated this as the rainfall use efficiency (RUE) of these crops, i.e. grain yield/ (prior fallow rain + in-crop rain). This shows that once the efficiency of fallow water accumulation is considered then in most cases there was little difference in productivity of the systems in terms of kilograms grain produced per mm of rain (exclusions were a chickpea crop following a 18-month fallow at Pampas in 2017 and a sorghum double-crop at Pampas in 17/18).

While this shows that across fallow lengths leading into crops there is little difference in system productivity, this does not necessarily translate to system profitability. The crops with a longer fallow lead in had higher crop gross margins due to their higher yields. In 6 of the 8 comparisons between crops, higher gross margin returns per mm were achieved for crops with a higher PAW at sowing due to longer fallows prior. The two cases where the shorter fallow crops (wheat at Emerald in 2016, and sorghum at Pampas in 2016/17) had higher $ GM/mm, both had higher crop margins and high starting PAW (> 100 mm) at sowing. Across these comparisons the marginal gain in profit per mm of additional water at sowing ranged from $0.5-14.9, but was mainly between $1.1/mm and $2.2/mm.

Table 4. Comparison of yield and water use of crops with varying lengths of preceding fallow, for a range of crops and locations. Double crop is 0-4 month fallow; Short fallow is 4-8 month; long fallow is 9-18 months.

Site	Fallow prior	Pre-plant PAW (mm)	Grain yield (t/ha)	Crop WUE (kg/mm)	Rainfall Use Efficiency (kg/mm)	Crop gross margin ($/ha)	$/mm rain
Wheat							
Emerald, 2016	Double crop	100	2.35	8.3	5.3	512	1.15
	Short fallow	177	3.36	9.9	4.2	678	0.85
Billa Billa, 2017	Double crop	65	1.13	5.6	4.2	211	0.78
	Short fallow	125	1.49	6.7	4.5	278	0.84
Pampas, 2017	Double crop	53	1.56	3.4	3.4	258	0.56
	Short fallow	169	1.83	5.2	3.5	424	0.81
Sorghum							
Billa Billa, 16/17	Short fallow	131	0.62	2.3	1.7	-138	-0.37
	Long fallow	212	1.31	3.8	2.3	34	0.06
Pampas, 16/17	Short fallow	147	4.51	10.8	8.2	1033	1.88
	Long fallow	238	5.66	10.6	6.8	1082	1.30
Pampas, 17/18	Double crop	96	0.65	2.2	2.2	30	0.10
	Short fallow	146	4.02	8.4	7.2	775	1.39
Chickpea							
Pampas, 2017	Double crop	45	1.30	3.6	3.6	455	1.26
	Short fallow	169	1.68	6.4	3.8	651	1.47
	Long fallow	162	1.80	6.6	1.6	547	0.49
Billa Billa, 2018	Double crop	163	0.82	4.5	2.7	209	0.69
	Short fallow	203	1.48	6.8	3.1	628	1.31

Conclusions

Overall these farming systems experiments have shown that systems with less time in fallow increases system water use and WUE through higher fallow efficiencies. However, significantly higher returns for crops sown on higher plant available water more than compensates for the low efficiencies of fallow water accumulation. This trade-off will be further influenced by the cost structure and risk appetite of the farming enterprise and the availability of labour, since higher intensity systems will increase inputs of labour and machinery and increase risk of crop failures. This is explored further in other papers. Though, this does mean that it is more critical to optimise management and inputs for crops following long-fallows in order to convert the extra water efficiently into yield outcomes.

Further reading

Water use and accumulation

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Helicoverpa armigera resistance management in pulses, and recent research findings on Rutherglen bug

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Key words

Helicoverpa armigera, resistance, chickpeas, mungbeans, soybeans, Rutherglen bug, canola

GRDC code

DAQ00196, UM00048 (NIRM)

Take home messages

- The *H. armigera* resistance management strategy is designed to prolong the useful life of the newer chemistry currently available to pulse growers. Familiarise yourself with the strategy and the full range of options available for *Helicoverpa* control in chickpeas, mungbeans and soybeans. Consider what products you will use if a second spray is required in these crops
- Rutherglen bug adults are present in canola crops much earlier than was previously thought. Females are depositing eggs in the soil and leaf litter from early spring through to harvest. At this point, there is no obvious option for preventing the build-up of large populations of nymphs in canola stubble, but recent work is helping to understand how these populations develop.

The *Helicoverpa armigera* resistance management strategy (RMS)

This material has been extracted from the "Science behind the strategy" document available at https://ipmguidelinesforgrains.com.au/ipm-information/resistance-management-strategies/

General rationale for the design of the strategy

Chickpeas and mungbeans are currently, and for the foreseeable future, the most valuable grains crops influenced by the RMS. Therefore, the resistance management strategy (RMS) is primarily focused on insecticide Modes of Action (MoA) rotation in these systems and is built around product windows for Altacor® and Steward® because:

1. Altacor® (chlorantraniliprole) is at risk from over-reliance in pulses, but resistance frequencies are currently low.
2. Steward® (indoxacarb) is at risk due to genetic predisposition (high level genetic dominance and metabolic mechanism) and pre-existing levels of resistance in NSW and QLD (with elevated levels in CQ during 2016-17). In addition, the use of indoxacarb in pulses may increase as generic products come on to the market.

There are two regions within the RMS, each with their own resistance management strategy designed to make the most effective products available when they are of greatest benefit, whilst minimising the risk of overuse:

1. Northern Grains Region: Belyando, Callide, Central Highlands & Dawson (Table 1)
2. Central Grains Region: Balonne, Bourke, Burnett, Darling Downs, Gwydir, Lachlan, Macintyre, Macquarie & Namoi (Table 2)

- The RMS provides windows-based recommendations common to these regions because *H. armigera* moths are highly mobile and have the capacity to move between these regions.

- No RMS is currently proposed for the Southern and Western grain regions (Victoria, South Australia and Western Australia) for winter crops. Biological indicators suggest that that the risk of *H. armigera* occurring in winter crops, at densities where control failures may occur, is presently considered low. *Helicoverpa* control in summer crops in these regions should use the Central Grains region RMS.

Use of broad-spectrum insecticides

The early use of synthetic pyrethroids (SPs) in winter pulses (August – early September) is adopted where the assumption is made that early infestations of *Helicoverpa* will be predominantly *H. punctigera* which are susceptible to SPs. Similarly, the use of carbamates to delay the application of Group 28 or Group 6 products, carries risks. If adopting this strategy, be aware of the following risks:

- Recent monitoring with pheromone traps has shown *H. armigera* to be present in all parts of the Northern Grains region from early August (www.thebeatsheet.com.au)
- Reduced efficacy of SPs and carbamates against *H. armigera* can be masked when treating very low population densities (< 3/sqm)
- If *H. armigera* are present, even at low levels in a population treated with SPs or carbamates, the treatment will select for further resistance. Whilst initial applications may be effective, later treatments may be significantly less effective.

Table 1. Grains resistance management strategy for *Helicoverpa armigera* across Australia. Best practice product windows and use restrictions to manage insecticide resistance in *H.armigera.* **Northern Region: Belyando, Central Highlands, Dawson and Callide.**

Increasing ↑ SELECTIVITY ↓ Decreasing

Insecticide	June				July				Aug				Sept				Oct				Nov				Dec				Jan				Feb				Mar				Apr				May			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Bacillus thuringiensis																																																
Helicoverpa viruses																																																
Paraffinic oil (Note 1)																																																
Chlorantraniliprole (Note 2, 3)																																																
Indoxacarb (Note 4)																																																
Spinetoram (Note 2, 4, 5)																																																
Emamectin benzoate (Note 2, 4, 5)																																																
Carbamates (Note 2, 4 6)																																																
Pyrethroids (Note 2, 4, 7)																																																

No restrictions	**DO NOT USE during this period**	**No more than one application per crop per season**	**No more than two applications per crop per season**

ADDITIONAL INFORMATION

Notes:

1. Some nC27 paraffinic spray oils can be used to suppress Helicoverpa populations and are best used as part of an IPM program.
2. Observe withholding periods (WHP). Products in this group have WHP 14 days or longer.
3. Maximum one spray of chlorantraniliprole alone or in mixtures per crop per season.
4. Refer to label for warning of insecticide risk to bee populations.
5. Maximum two consecutive sprays alone or in mixtures per crop per season.
6. MODERATE RESISTANCE IS PRESENT IN *H.ARMIGERA* POPULATIONS – FIELD FAILURES LIKELY.
7. HIGH RESISTANCE IS PRESENT IN *H.ARMIGERA* POPULATIONS – FIELD FAILURES EXPECTED!

Table 2. Grains resistance management strategy for *Helicoverpa armigera* across Australia. Best practice product windows and use restrictions to manage insecticide resistance in *H.armigera.* **Southern QLD, Central & Northern NSW Regions: Balonne, Bourke, Burnett, Darling Downs, Gwydir, Lachlan, Macintyre, Macquarie & Namoi.**

Increasing ↑ SELECTIVITY ↓ Decreasing

Insecticide	June				July				Aug				Sept				Oct				Nov				Dec				Jan				Feb				Mar				Apr				May			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
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Table 3. Explanatory notes for product windows in all regions

Insecticide	Number of insecticide windows	Duration of insecticide windows	Maximum number of applications/crop/season
Chlorantraniliprole (Altacor®)	2	10 weeks	1
• 10 week windows restrict selection to a maximum of 2 consecutive generations of *H. armigera* (includes 2-3 weeks residual beyond the end of each window i.e. 12-13 weeks total exposure). • Start date of first window correlates well with historical data relating to average daily temperatures that result in early pod-set. • Exposure of 2 consecutive generations is off-set by long non-use periods (8 weeks in southern/central region and 18 weeks in northern region). • Use is not recommended in spring mung beans as there is less likelihood of both *H. armigera* and bean pod borer being present.			
Indoxacarb (e.g. Steward®)	Northern - 3 Central - 2	6 weeks	1
• 6 week windows restrict selection to a single generation of *H. armigera*. • Each window is followed by a non-use period of a minimum of 6 weeks. • Indoxacarb is an important early season rotation option for chickpeas and faba beans, and provides a robust selective alternative to Altacor® when Helicoverpa pressure is high.			
Bacillus thuringiensis	1	Season long	No restrictions
Helicoverpa viruses			No restrictions
Spinetoram (e.g. Success Neo®)*			2
• Low resistance risk and not widely used.			
Emamectin benzoate (e.g. Affirm®)*	1	Season long	2
• Very low resistance frequency and not used widely. • However, emamectin benzoate is a good option for rotation to spread resistance risk away from Altacor®. • BUT industry needs to become more confident with using this product for it to be of value in resistance management.			
Carbamates	1	Season long	1
Synthetic pyrethroids			
• *H. armigera* resistance is present at moderate to high levels, but one strategic application per season in regions where *H. punctigera* predominates in early spring may be effective. • Carbamates are a rotation tool for indoxacarb and Altacor® either early season in chickpeas or late season in mungbean.			

*Resistance monitoring for selective products is a key component of the RMS and changes in resistance frequencies will result in the introduction of product windows for those insecticides not currently windowed.

The number of uses in the RMS is more restrictive than stated on the Altacor® label, why?

To avoid repeated use of either Steward® or Altacor® within the use window, the number of allowable applications is 1 per crop. In some instances, the label registration may allow for more than one application; the recommendations were developed in consultation and supported by the chemical companies. It is anticipated that changes to product labels will follow to ensure consistency between labels and the RMS.

Does the RMS impact on recommendations for insecticide use in cotton and other crops?

The RMS is not intended to compromise the ability of the cotton industry to use any products registered for *Helicoverpa* in Bollgard® cotton. This is because selection for insecticide resistance is considered low due to the high likelihood that survivors of conventional sprays used in Bollgard cotton would be killed by Bt toxins expressed in plants. For further information go to: http://www.cottoninfo.com.au/publications/cotton-pest-management-guide.

Similarly, the RMS does not attempt to align the use of the Group 28s in mungbeans and chickpeas with use in other grain crops or horticulture. To do so would add a level of complexity that would make the RMS impractical.

Shouldn't other modes of action (MoA) be windowed to prevent the potential development of resistance to these products?

There is little evidence to suggest that other products should be windowed now to slow the development of future resistance. Both Affirm® (emamectin benzoate) and Success Neo® (spinetoram) show no sign of reduced susceptibility in testing (L. Bird, CRDC data). This result is consistent with the relatively limited use of these products in the grains industry to date. If a shift in susceptibility is detected in future testing, it is the intention that the product/s will be windowed to limit selection pressure.

The SPs and carbamates are not windowed because there are already well established, relatively stable moderate-high levels of resistance to these MoAs and limiting their use will not change this situation.

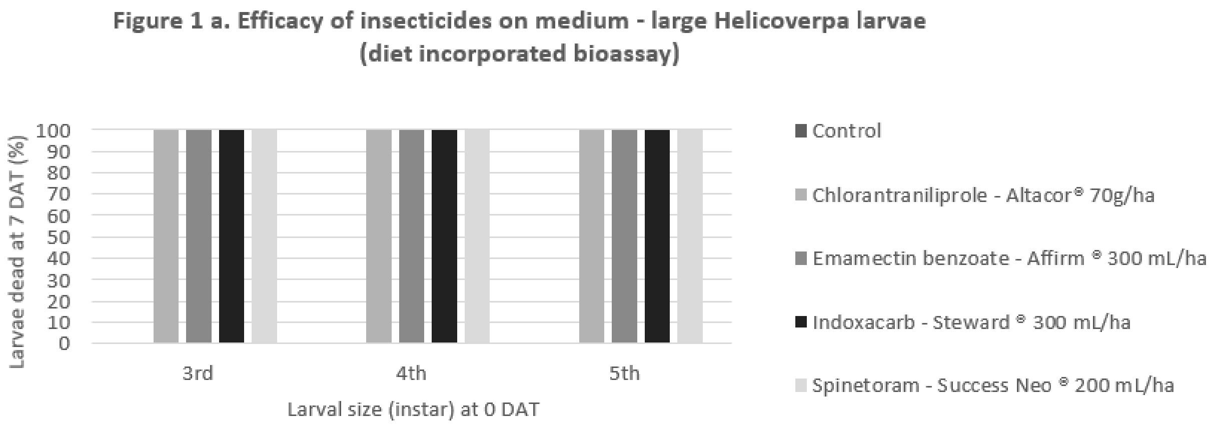
By restricting the use of just the 'at risk' products, keeping the RMS as simple as possible, and allowing maximum choice of registered products, we anticipate that the grains industry will be more inclined to use the RMS.

What is the relative efficacy of the 'softer' options for Helicoverpa control in mungbeans and chickpeas?

In 2017, QDAF entomology undertook a number of trials to compare the knockdown/contact efficacy, and residual efficacy (persistence in the crop) of Altacor®, Steward®, Affirm® and Success Neo®. The purpose of these trials was to provide agronomists and growers with information on how well each of the products worked, and to provide confidence to use another option, rather than relying solely on the Group 28 products.

The results show that these products are equally effective on 3rd, 4th or 5th instar larvae that receive a lethal dose of the product – as would be achieved with good spray coverage (Figure 1a). However, there is considerable benefit in products persisting in the crop to control larvae that may hatch after the spray, or emerge from flowers, buds or pods where they may have been protected from an earlier application. The long residual efficacy of Altacor® has been a major factor in its popularity. The data in Figure 1b shows the relative efficacy of these products from 0 – 20 days after treatment in the field (at 5-day intervals).

For more information on the relative performance of these products in terms of feeding potential and recognising larvae affected by the different insecticides, see recent articles on the Beatsheet blog (https://thebeatsheet.com.au/).



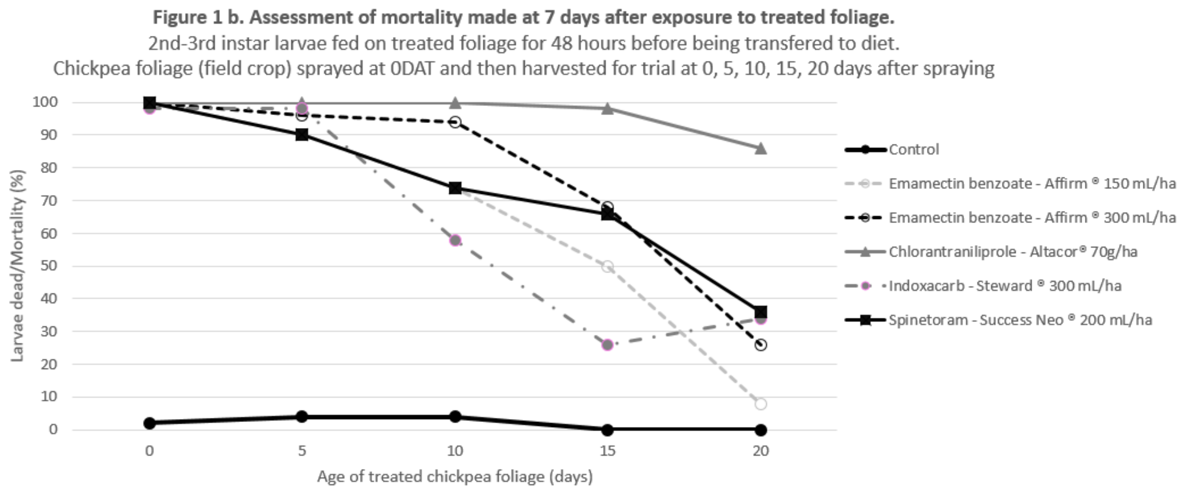


Figure 1. Relative efficacy (a) direct contact and (b) residual, of softer options for Helicoverpa control in chickpea and mungbean crops.

Nucleopolyhedrosis virus (NPV) – an option for some pulses?

Along with the conventional chemistry options discussed above, NPV may also be an option for reducing selection pressure on Helicoverpa, particularly in pulses. In 2017, QDAF Entomology looked at the potential to use NPV with repeated application of lower rates. Low rates of NPV do not pose a resistance risk as there is no risk of resistance developing to NPV – it is a disease, not a chemical. The opportunity that presents is to include NPV with fungicide applications in chickpeas, faba beans, lentil and field peas. The concept is that by supressing the Helicoverpa population during the vegetative and flowering stages, the density will stay below threshold through pod fill – or at least delay the build-up of a damaging population. In 2017, there was little need for repeated fungicide applications in chickpea because it was dry, so in the trial we applied 2 applications of NPV about 2 weeks apart. The NPV-treated plots sustained lower populations and did not exceed threshold (3.5 larvae/m^2 in this instance) for the duration of the crop (Figure 2). The strategy for deploying NPV effectively requires additional investigation, as does the potential loss that may accumulate from sustained sub-threshold populations which may result from this approach.

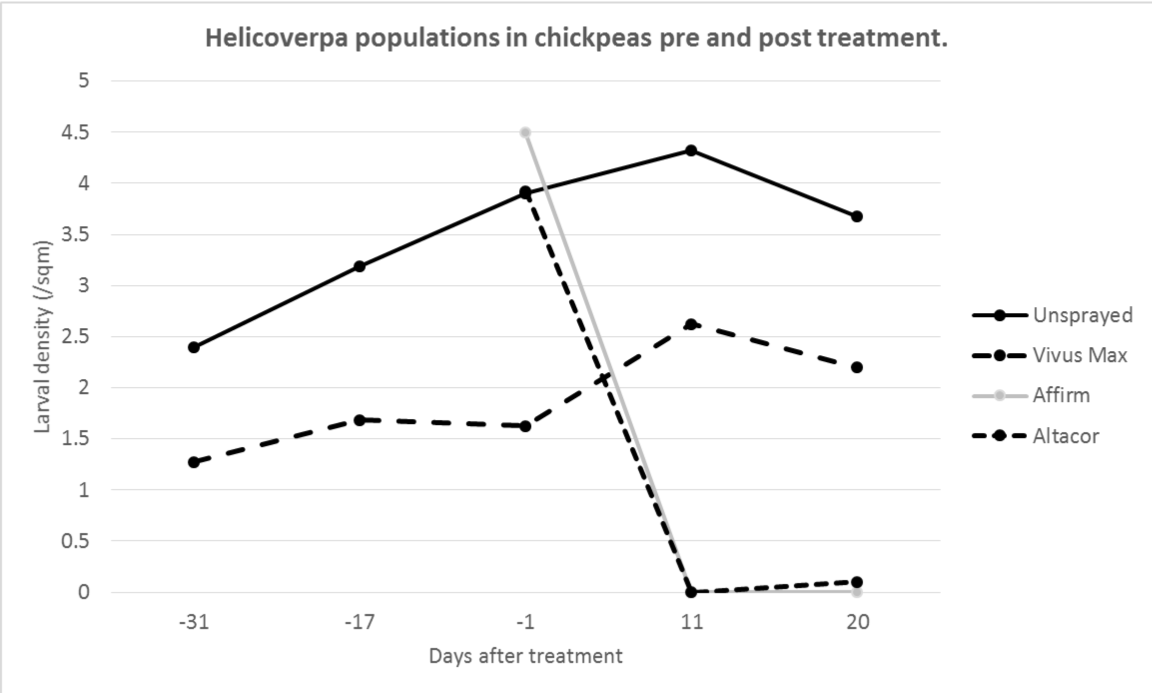


Figure 2. Helicoverpa population density in chickpeas treated twice (day -31 and day -17) with low rate NPV. Affirm® and Altacor® were applied when the Helicoverpa density reached threshold in the untreated plots.

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.

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NIRM (2018) Science behind the Resistance Management Strategy for *Helicoverpa armigera* in Australian grains. https://ipmguidelinesforgrains.com.au/ipm-information/resistance-management-strategies/

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Why do one percenters matter so much?

How small changes in management that affect prices, quality, yields or production costs can result in large impacts on profit

Ross Kingwell, AEGIC

Key words

Yield, profit, markets, production cost, profit

Take home message

Success in farming is not only about getting the big decisions right. It's also often about getting the detail right as well! Seemingly small "one percent" decisions do matter, simply because we often operate at low gross margins. When gross margins are tight, small improvements in productivity significantly amplify how much profit is generated. Also, small changes in annual profit have a beneficial compounding effect over several years, helping support business growth.

It's part of the sporting coach's lexicon: "Do the one percenters!" These are the little acts, on and off the field, that in aggregate are sometimes the difference between losing and winning. At least that's the coaching mantra we are encouraged to believe. But does that coaching slogan apply to farming? It's often sold to us in terms of continuous improvement, skill upgrades, machine upgrades, crop improvements and keeping an eye on the detail. Do these small changes really add up to much? Are we just being kept busy, or are these improvements an essential part of the real business of farming?

For businesses operating in fiercely competitive environments where margins are slim, such as is often the case in farming, the answer is 'yes; one percenters matter'. In commercial environments where profit margins matter and where those margins often are tight or slight, then managerial 'one percenters' matter.

The business environment of Australian farming is highly competitive. Often an Australian farmer's competitors are not just other farmers in Australia but overseas farmers as well. Australia's farmers, by international comparison, largely rest on their own mettle. There is no featherbed of overly generous taxpayer support to bolster farm incomes; no subsidised crop insurance; no special set-aside or environmental payments; and no similar quality of education, health, social and communication services as is available to most city folk.

Australian farm businesses are shaped by their ability to remain internationally competitive, rather than by their political and social skill to garner substantial government support. Market forces ultimately determine which farm businesses prosper in Australia. In the long run it is the most efficient and prosperous businesses that survive. Almost by definition, businesses that establish, protect and grow their profit margins are those with sound commercial prospects.

Here are some illustrations of the importance of one percenters. Suppose you are a wheat producer and your farm-gate wheat price is $250 per tonne; your wheat yield is 2 tonnes per hectare and all your entire costs of production (i.e. variable, fixed and imputed costs) amount to $450 per hectare. Your profit per hectare calculation is:

Profit = wheat price x wheat yield – wheat costs of production

50 ($/ha) = 250 ($/t) x 2 (t/ha) – 450 ($/ha)

Therefore, if you had 1,000 hectares of wheat, your business profit would be $50,000.

Now imagine your skill as a manager improves and, like a good footy player, you capture a range of improvements that each are the one percenters. You lift your wheat price by 1%, through skilfully avoiding price downgrades via on-farm blending. You improve your crop yield by 1% through slightly better timeliness of sowing and slightly more effective weed and pest control. In addition, you lower your costs of production by 1% through negotiating better prices for some inputs and by slightly reducing inputs on your worst, very low-yielding paddocks. What's the impact on profit? Do these three 1 percenters lift profit by 3%?

No, profit improves by almost 30%! Really? How come? Look at the figures in Table 1.

Table 1. The impact on wheat profit of three 1 percenters.

		Original base case	A 1% lift in the wheat price, a 1% increase in wheat yield; plus a 1% decline in production costs	
price	$/t	250	252.5	
yield	t/ha	2	2.02	
costs	$/ha	450	445.5	
Profit	**$/ha**	**50**	**64.55** →	**29% increase**

So, if this farmer grew 1,000 hectares of wheat his overall profit would jump from $50,000 to $64,550. That is a 29% jump in profit.

What about a mixed enterprise farm where livestock are also feature? Suppose you maintain a sheep enterprise on 500 hectares of pasture at a stocking rate of 5 DSE per hectare. The costs of production (i.e. variable, fixed and imputed costs) are $300 per hectare and the income (wool and sheep sales) per hectare is $375 per hectare.

Now suppose you lift stocking rate by one per cent through improved fodder management (e.g. introducing a dual-purpose crop). The increase in stocking rate means more wool and sheep sales. Moreover, through slightly improved grass weed seed management you lift the fleece quality and so increase the farm-gate wool price by one per cent. Yet despite the lift in sheep production, assiduous cost control allows you maintain your costs of production.

What's the impact on profit? Do these 1 percenters lift profit by 3%?

No, profit improves by almost 9%! How come? Look at the figures in Table 2.

Table 2. The impact on sheep profit of a few 1 percenters.

		Original base case	A 1% lift (or decline)	
Stocking rate	DSE/ha	5	5.05	
Wool price	$/kg	10	10.1	
Wool production	kg/ha	18	18.18	
Sheep sales	$/ha	210	212.1	
costs	$/ha	325	unchanged	
Profit	**$/ha**	**65**	**70.72**	→ **9% increase**

What about managing grain quality, to the extent that it is possible? Suppose you are a canola producer. Your farm-gate canola price reflects the oil content of the canola you grow. There is a base price for canola at 42% oil content but then an oil bonus or penalty applies worth 0.15% of the base price for every 0.1% oil, above or below the 42% oil content. The oil bonus is uncapped in SA, Vic, NSW and QLD; but in WA it's capped at 44.5% oil. So, imagine the base price at the farm-gate is $525 per tonne and your yield is 1.3 tonnes per hectare and your entire costs of production are $600 per hectare. Your profit per hectare calculation is:

Profit = canola price x canola yield – canola costs of production

82.5 ($/ha) = 525 ($/t) x 1.3 (t/ha) – 600 ($/ha)

So, if you had 1,000 hectares of canola your enterprise profit would be $82,500.

But imagine you chased an improvement in the oil content of the canola by slightly better timeliness of sowing, slightly better weed control and better targeted N applications such that you were able to lift the oil content by 1%, without incurring yield reductions or production cost increases. Your profit is now:

92.74 ($/ha) = (525*1.015) ($/t) x 1.3 (t/ha) – 600 ($/ha)

This is a 12% increase in enterprise profit for a 1% lift in the quality of the canola, in terms of oil content increasing from 42% to 43%.

The profit results in preceding examples of wheat, sheep and canola production are attributable firstly to profit margins often being slight in the base cases. Any lift from a low base, ends up mathematically as a large percentage increase. Secondly, farm profit has multiplicative ingredients. For example, crop revenue comprises yields multiplied by crop prices. These multiplicative consequences, combined with additive impacts, fuel the magnitude of the percentage increases in farm profit.

The single year snapshots in the enterprise examples described above inadequately tell the dynamic story of profit impacts. The compounding effect of small changes can greatly affect farm profits. By illustration, suppose each year for 10 years you very carefully and thoroughly devote your energies to incremental improvement of your farm operations. For example, you sequentially lift your profit margin by one per cent each year for 10 years. If you farmed 3,000 hectares and your overall profit margin was $50 per hectare (i.e. $150,000 per year), then the additional profit you would generate over the 10 years would be $85,025. In the last year your farm profit would be over 10 per cent higher than if you just maintained your farm profit at $150,000.

So, sticking to gradual, persistent improvement in profit margin management can generate large payoffs. Small changes, small improvements, eventually can greatly matter.

Transformation versus incrementalism

An additional point worth emphasising about one percenters is the importance of balancing the need to invest in these incremental, persistent endeavours of small improvements versus transformative, breakthrough innovations that might transform farm profitability or enhance the biological resilience or sustainability of farming. Both types of investment are essential to preserve the domestic and international competitiveness of Australian agriculture.

There can be a tendency to resist investment in transformative activity, as it is perceived to be too risky or too expensive. There can also be an opposite tendency whereby media-savvy, innovation champions with rose-coloured goggles capture substantial funding, leading to underinvestment in essential incremental R,D & E (i.e. the one percenters) that form the main bedrock of farm profitability.

However, even transformative change can be incremental. Take the example of canola production in my home state of Western Australia. In the early 1990s the WA government and industry annually committed $140,000 to canola R&D. Two full-time canola specialists were employed. One investigated the rotational value of canola in farm systems, the advantages of herbicide-tolerant canola, and the identification of blackleg resistant and early flowering genetic material. The second researcher interacted with farmers to discover their information and agronomic needs in order to better inform future research.

Unfortunately, after 5 years of incremental effort (see the shaded area in Figure 1), there was not much evidence of the value to farmers from growing canola. However, persistence paid off as the maintained R,D&E effort led to canola being widely grown in WA agricultural regions. Canola production now injects over a billion dollars of sales revenue each year into the WA economy and farming systems in WA have been transformed by the inclusion of canola.

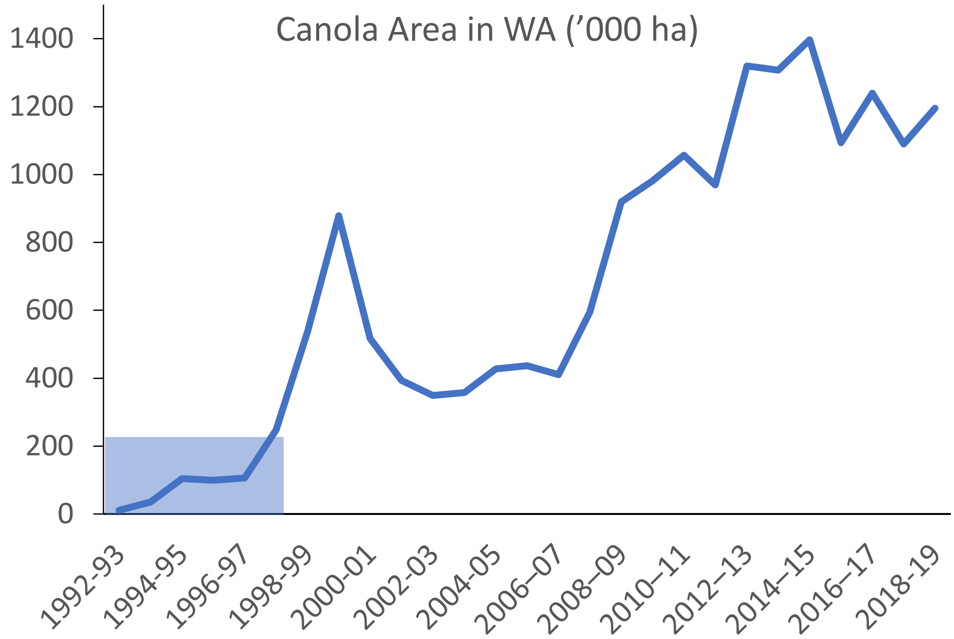

Figure 1. Canola area in WA ('000 ha) for the period 1992-2019

What is the simple message in this paper? It is that the wisdom of sports coaches does apply to farming, insofar as one percenters matter.

Key message: Success in farming is not only about getting the big decisions right. It's also often about getting the detail right as well! The one percenters do matter.

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National paddock survey – closing the yield gap and informing decisions

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Take home messages

(from work undertaken on 35 paddocks in N NSW & S Qld, 2015 to 2018)

- Intensive monitoring of soils and crops over a rotation sequence has identified why crops do not achieve their potential yield
- Reviewing paddock performance at the end of the season and using paddock records is essential for sustained improvement in agronomic performance. The average yield gap of wheat and barley over four years of monitoring in N NSW and S Qld was 10%. Preliminary data analysis suggests that the yield gap for sorghum is of a similar order
- Over the four-year rotation 70 paddock zones were intensively monitored. Insufficient nitrogen was the main cause for the yield gap - especially in 2016. Diseases, weeds and insects also resulted in some crop damage but were paddock specific.

Yield gap is the term applied to the difference between achieved and potential yield, where potential yield is estimated from simulation models. On average, Australia's wheat growers are currently estimated to be achieving about half their water-limited potential yield (Hochman *et al*. 2016, Hochman and Horan, 2018). A national overview of the estimated yield gaps can be viewed at www.yieldgapaustralia.com.au.

The National Paddock Survey (NPS) is a four-year (2015 to 2018), GRDC-funded project designed to quantify the yield gap on 250 paddocks nationally and to determine the underlying causes. Further, its aim is to establish whether management practices can be developed to reduce the yield gap to benefit farm profitability. The project aims to provide growers and their advisers with information and the tools required to close the yield gap.

Method

Nationally, 250 paddocks (80 in each of WA and N NSW/Qld, and 90 in S NSW, Vic and SA) were monitored intensively over a four-year rotation (2015 to 2018). Consultants and farming systems groups undertook the monitoring. Two zones in each paddock were monitored at five geo-referenced monitoring points along a permanent 200 to 250m transect. Each monitoring point was visited four times per season (pre and post-season soil sampling and in-crop at the equivalent crop growth stages of GS30 and GS65). Yield map data was obtained for each paddock which enabled the yield of each zone to be determined accurately. Table 1 lists the annual monitoring undertaken in each zone.

All paddocks were simulated with APSIM (Holzworth *et al*. 2014) and during the season. Yield Prophet was available to all consultants and farmers.

The whole data set (four years x 500 paddock zones) is being analysed by Roger Lawes, CSIRO for factors primarily responsible for the yield gap in each of the three GRDC regions (Lawes *et al*. 2018).

This paper outlines the results of thirty-five paddocks monitored by Jeremy Dawson from MCA. The results are discussed as a paddock specific yield gap analysis over four seasons focused on outcomes for the farmer and the farm group.

Results are presented as the modelled APSIM simulations in which:

- Ya = actual yield (as determined for each zone from yield map data)
- Ysim = simulated yield (for the same conditions as those in which the crop was grown)
- Yw = simulated water limited, nitrogen unlimited yield (for the same conditions as those in which the crop was grown, but with N supply unlimited). Yw is considered the potential yield for the crop.

Note: APSIM currently accurately simulates wheat, barley, canola and sorghum. We have not attempted to simulate the other crop types grown (lupins, lentils, fababeans, chickpeas, vetch, field peas).

The yield gap is calculated as the % difference between Yw and Ya using the equation ((Yw-Ya)/Yw).

Table 1. Overview of monitoring and data collected per zone for each NPS paddock

Monitoring	**Timing**	**Monitoring**	**Timing**
Deep soil test 4 depths (0-100cm)	Pre-sow	Paddock yield and yield map data	Post-harvest
PREDICTA®B (0-10cm)	Pre-sow	Crop density, weeds, foliar diseases, insects (/m^2)	GS30
Deep soil test 4 depths (0-100cm)	Post-harvest	Cereal root sample to CSIRO	GS30
Crop and cultivar		Weeds, foliar diseases, insects /m^2)	GS65
Sowing date and rate		Cereal stubble/crown for *Fusarium*	Post-harvest
Fertiliser, herbicide type, rate, date		General observations	
Temperature buttons (1 per paddock)	GS60-79		

Data was entered via the NPS website and stored in a purpose-built SQL server database.

Results and discussion

Annual individual paddock results

Data from two paddocks in S Qld are presented as examples of outputs as informed by the paddock monitoring.

Example 1 - Paddock S Qld, NPS 3060. Rotation: Sorghum (2014), followed by chickpea, wheat, wheat, sorghum.

Zone A: red loam over clay (chromosol)

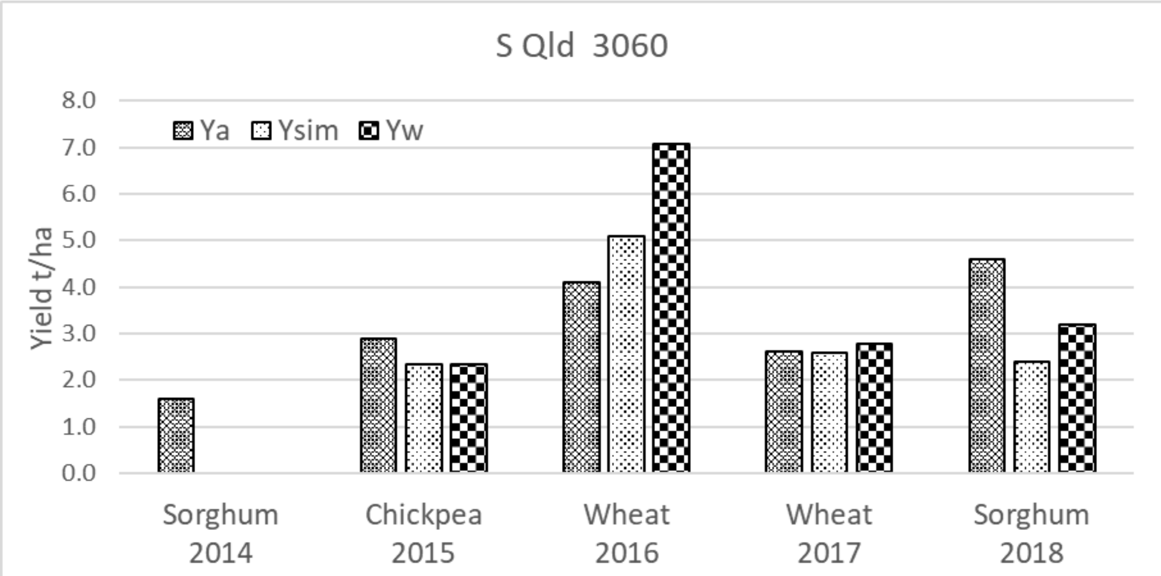

Figure 1. S Qld rotation: Sorghum (2014), followed by chickpeas, wheat, wheat, sorghum (Ya=actual yield; Ysim=simulated yield; Yw=water limited N unlimited yield (potential yield))

Paddock and crop information over the rotation

Available soil nitrogen and water pre-sowing

	Available N kg/ha	Available water mm
2015 (following sorghum)	125	117
2016 (following chickpeas)	143	105
2017 (following wheat):	88	186
2018 (following wheat)	93	0

Disease

PREDICTA B:

- 2015 no disease detected
- 2016 no disease detected
- 2017 *Pratylenchus neglectus* moderate
- 2018 not tested

Wheat/Barley root health GS30:

- 2016 root health score: moderate infection on seminal and crown roots
- 2017 root health score: high infection level on seminal roots, moderate level on crown roots, *P. neglectus* high, Fusarium low

Cereal stubble - *Fusarium*:

- 2016 28% of stems, rating low
- 2017 41% of stems, rating low

In-crop GS65:

- 2017 *Fusarium* at low levels

Weeds (in-crop GS65)

- 2015 mintweed 3 /m^2
- 2016, 2017 and 2018 no weeds detected

Insects

- 2018 Rutherglen bug 80, mirids 12 and sorghum midge 2 /m^2

Heat and frost

Table 2. Days of heat and frost during GS60-79 (flowering to grain-filling)

		Heat > 34 °C	Frost 0 to -2 °C	Frost -2 to -4 °C
2015	Chickpeas	0	2	0
2016	Wheat	0	0	0
2017	Wheat	0	4	0
2018	Sorghum	12	0	0

(note: temperature records from nearest Bureau of Meteorology site)

Consultant notes

- 2015: Heat blast (1/7/15)
- 2017: *Fusarium* present in crop
- 2017-18: Sorghum double cropped into wheat stubble; *Fusarium* and heat damage (GS9)

Interpretation

- Crop 2014: Sorghum
- Chickpeas 2015: Ya=Ysim=Yw no weeds, disease, weeds or insects recorded
- Wheat 2016: Ya<Ysim<Yw the difference in potential yield between Ysim and Yw of 2 t/ha indicates the crop was N deficient (pre-sowing soil N levels were relatively low and no N fertiliser other than starter N, Zincstart, was used). Low level of *Fusarium* was observed on the stems.
- Wheat 2017: Ya=Ysim=Yw average yield 2.8t/ha. *Fusarium* was present at low levels
- Sorghum 2018: Ya>Ysim<Yw Sorghum simulation has a problem

Example 2. Paddock S Qld. NPS 3072. Rotation: Wheat (2014), followed by chickpea, wheat, sorghum, chickpea

Zone A: grey Vertosol

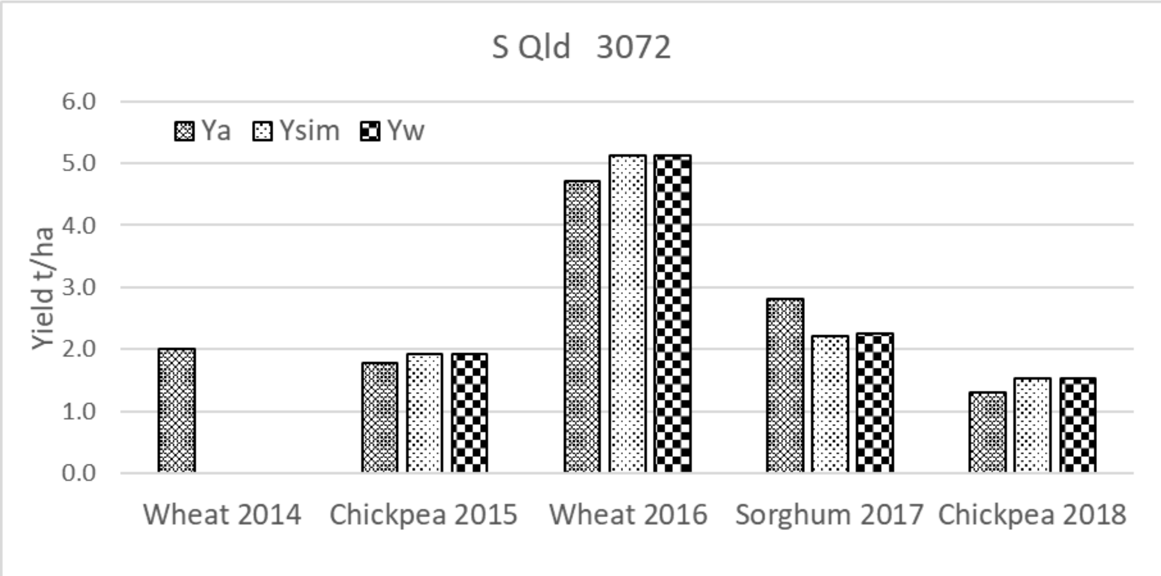

Figure 2. S Qld Rotation: wheat (2014), followed by chickpea, wheat, sorghum, chickpea (Ya=actual yield; Ysim=simulated yield; Yw=water limited N unlimited yield (potential yield))

Paddock and crop information over the rotation

Available nitrogen (soil N pre-sowing)

- 2015 (following wheat): 141kg/ha
- 2016 (following chickpeas): 393kg/ha
- 2017 (following wheat): 153kg/ha
- 2018 (following sorghum): 97kg/ha

Available water (soil water pre-sowing)

- 2015: 91 mm
- 2016: 94 mm
- 2017: 0 mm
- 2018: 68 mm

Disease

PREDICTA B:

- 2015 Fusarium high, *Pratylenchus thornei* moderate
- 2016 *Pratylenchus thornei* moderate
- 2017 & 2018 not tested

Cereal root health GS30:

- 2016 root health score: high level infection on seminal and crown roots; *Fusarium* high

Cereal stubble - *Fusarium*:

- 2016 *Fusarium* at low level

Disease in-crop GS65:

- 2015, 2016, 2017 and 2018 not observed

Weeds (In-crop GS65)

- 2015, 2016, 2017 and 2018 not observed

Insects

- 2017 Mirids 7, Rutherglen bug 20 /m^2
- 2015, 2016 and 2018 not observed

Heat and frost

Table 3. Days of heat and frost during GS60-79

	Heat > 34 °C	Frost 0 to -2 °C	Frost -2 to -4 °C
2015	0	0	0
2016	0	0	0
2017	17	0	0
2018	0	0	0

(note: temperature records from nearest Bureau of Meteorology site)

Consultant observations

- 2015: chickpeas GS6 - Phytophthora root rot along the transect
- 2017: sorghum GS9 - low level bird damage

Interpretation

- Chickpeas 2015: Ya=Ysim=Yw. Crop not limited by abiotic or biotic stress.
- Wheat 2016: Ya=Ysim=Yw. N not limiting (Ysim=Yw) – note high soil N level at sowing 2016 following chickpeas in 2015 (393 kg N/ha). Crop not limited by abiotic or biotic stress.
- Sorghum 2017: Ya>Ysim=Yw. Crop performed better than simulations, APSIM sorghum module needs further development.
- Chickpeas 2018: Ya=Ysim=Yw. Crop not limited by abiotic or biotic stress.

Assessing crop performance: Water Use Efficiency vs modelling

The first paper on Water Use Efficiency (WUE) was published by French and Schultz in 1984. It was a break through at the time, enabling farmers and agronomists to benchmark crop performance against a target and compare performance against other wheat crops. The French and Schultz WUE equation has since been updated by Sadras and Angus, 2006 and Hunt and Kirkegaard, 2012.

Hunt and Kirkegaard, 2012 calculate crop water use as: soil water pre-sowing – soil water post-harvest + rainfall during the same period. WUE is then calculated as yield (kg/ha) / (crop water use - 60). Potential yield is calculated as 22 x (crop water use – 60).

The 2015 to 2017 S Qld and N NSW National Paddock Survey cereal yields are plotted against crop water use in Figure 3. The graph reveals a general tendency for Ya to increase with crop water use with an upper boundary of yield. The upper boundary is reasonably interpreted as Yw for well-managed crops as crop water use increases. The two lines included on the diagram are the Yw lines proposed by French & Schultz, 1984 and Sadras & Angus, 2006 to describe the most efficient use of water. This establishes a common maximum WUE of 22 kg/mm/ha.

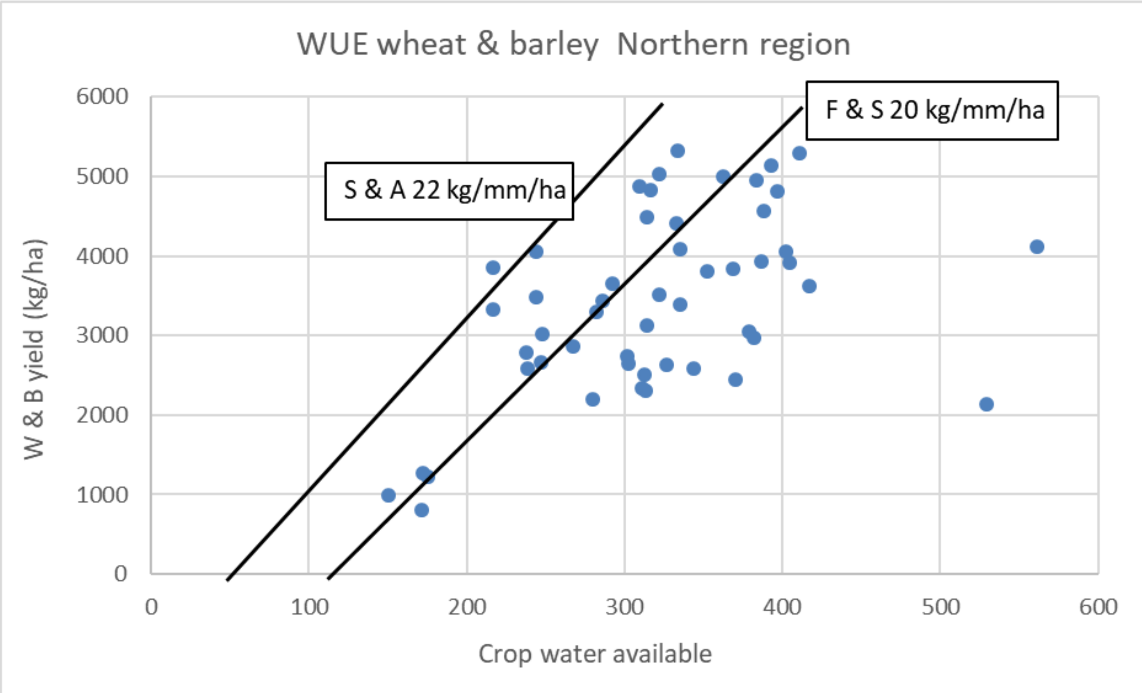

Figure 3. National Paddock Survey S Qld and N NSW wheat yield plotted against crop water available (2015 to 2018)
(crop water available = Starting – Finishing soil water + rainfall over same period).

How useful is WUE compared with computer modelled assessments of potential yield, and what will the future hold?

Figure 3 and other data analysed by French & Schultz (1984) and Sadras & Angus (2006) demonstrate a considerable variation in Ya relative to Yw, i.e. a considerable yield gap in many crops. Key questions for farmers and agronomists are: what is the cause of the yield gap in each individual case and how can it be alleviated?

There are many possible causes that cannot be identified without careful paddock monitoring of abiotic and biotic factors, as attempted in the present project.

We must remember that using WUE to assess yield potential is a bucket approach to a complex system with many interactions. WUE will not explain the causes of a yield gap, nor can it inform on reasons for favourable outcomes. It may identify the presence of a yield gap but not their underlying cause(s). It also cannot be assumed that in all cases Yw (nitrogen unlimited, water limited yield) is at maximum potential as defined by French and Schultz (1984) and Sadras and Angus (2006).

Causes of yield gaps

Abiotic factors

Variability is a feature of farming in Australia and there are several reasons why crop roots cannot access soil water and nutrition such as soil type (texture) and physical and chemical limitations. Chemical and physical constraints to root development can have a large impact on potential yield such as high soil chloride levels in some regions. Frost and heat shock are two other abiotic factors which can have a large impact on crop yield.

Interactions between soil type, available soil water and the amount of water extracted by the growing crop are influenced by crop growth and the distribution and amount of rainfall. If these factors are ignored there is limited predictive capability of yield.

High and low temperatures at critical times of crop development can further cause devastating yield loss.

Crop nutrition appropriate to achieving potential yield (Yw) is relatively well understood and for N, there are many examples of successful tactical responses to fertilisation. But this is not matched for other nutrients such as P, K and micronutrients such as Zn.

Biotic factors

Major infestations of weeds, pests and diseases can cause yield loss and less serious infestations may cause greater losses than is commonly appreciated. The extent of these losses remains unknown without careful paddock monitoring.

The nature of these biotic causes of yield loss vary greatly from site to site, between and within paddocks.

Going forward with crop simulation models

Crop models, such as APSIM used in this study, focus on abiotic factors but include biotic factors such as N nutrition. Their objective is to simulate yield (Ysim) in the absence of biotic factors such as weeds, diseases and pests and to estimate Yw by removing the effect of N shortage. For this, APSIM grows the crop on a daily time step and considers daily solar radiation, rainfall and nitrogen availability. It uses soil-specific information for Crop Lower Limit (CLL) (wilting point) of the soil, defined as the soil water content below which water is not accessible to the crop. CLL is influenced by soil texture (sand, silt, clay content) and subsoil limitations (such as high chloride levels). APSIM also explains the importance of rainfall distribution in terms of growth reductions due to transient water stress. Extreme events of temperature (hot and cold), which may be important at less-than daily time scales need to be further addressed.

Over the last decade our industry has made huge advances in engineering, with precision agriculture enabling mapping of soil types across paddocks, understanding what affects the crops' ability to extract water and most importantly empowering farmers to adopt precision seeding and to apply nutrients as required.

To fully utilise the power of crop models, we need to incorporate on-the-go modelled outputs to field operations such as seeding and nutrient applications. This could well be the next frontier in crop management. Biotic stresses such as weeds, diseases and pests can be included if the appropriate in-field observations are made.

The NPS project has demonstrated that, as crop management becomes more sophisticated, it is essential to understand the reasons why crops fail to perform at their potential. When we understand the reasons why crops do not reach their potential yield, we can better advise the growers we are working with.

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