GOONDIWINDI
QUEENSLAND
TUESDAY 3 AND
WEDNESDAY 4
MARCH 2020

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

Goondiwindi Cultural Centre

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GRDC 2020 Grains Research Update Welcome

If you are reading this, then chances are you have taken time out from an extraordinarily tough season in our very sunburnt country to hear the latest grains research, development and extension (RD&E) information.

Welcome.

We at the GRDC understand how very challenging the current situation is for growers, advisers, agronomists, researchers and those associated with the grains industry across New South Wales and Queensland.

Drought takes an enormous toll financially, emotionally and physically on those working and living through it daily. We trust that these GRDC Grains Research Updates will offer you new research information to help guide your on-farm decisions this season and to be best placed to take advantage of future seasons. We also hope the Updates provide a chance to connect with your peers and temporarily escape work pressures.

We would like to take this opportunity to thank our many research partners, who, like growers and advisers, have gone over and above in recent years to keep trials alive in rain-deprived environments.

Challenging seasons reinforce the importance of rigorous, innovative research that delivers genuine gains on-farm. For more than a quarter of a century the GRDC has been driving grains research capability and capacity with the understanding that high quality, effective RD&E is vital to the continued viability of the industry.

Sharing the results from this research is a key role of the annual Updates, which are the premier event on the northern grains industry calendar and bring together some of Australia's leading grains research scientists and expert consultants.

To ensure this research answers the most pressing profitability and productivity questions from the paddock, it is critical the GRDC is engaged with and listening to growers, agronomists and advisers.

For the past four years we have been doing that from regional offices across the country. Through the northern region offices in Wagga Wagga and Toowoomba and a team of staff committed to connecting with industry, we are now more closely linked to industry than ever.

Today, GRDC staff and GRDC Northern Panel members are at this Update to listen and engage with you. This is a vital forum for learning, sharing ideas and networking, all of which are critical to effect successful change and progress on-farm.

Regards,
Gillian Meppem
Senior Regional Manager North

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

GRDC
GRAINS RESEARCH
& DEVELOPMENT
CORPORATION

PROGRAM DAY 1 – TUESDAY 3 MARCH 2020

Time	Topic	Speaker (s)
9:00 AM	**Registration, morning tea and trade displays**	
10:00 AM	**Welcome**	***GRDC***
10:15 AM	**Grain production in a changing climate -** impacts & responses to elevated CO_2, heat & moisture stress	***Glenn Fitzgerald*** *(Agriculture Victoria)*
10:45 AM	**Chemical residues/MRL's -** impact, understanding & potential trade issues	***Gerard McMullen*** *(McMullen Consulting)*
11:15 AM	**Hydrogen (from water) as an energy source & the role of ammonia in the process.**	***Chris Munnings*** *(CSIRO)*
11:45 AM	**Advising stressed growers -** signs that someone is suffering & how you can help	***Letitia Cross*** *(RAMHP)*
12:15 PM	Lunch	
1:15 PM	**Concurrent session 1** *(See concurrent sessions for details)*	
3.00 PM	Afternoon tea	
3:30 PM	**Concurrent session 2** *(See concurrent sessions for details)*	
5:15 PM	Close	
5:20 PM	**Emerging Agronomists Networking event - further information and registration can be found at www.seedbedmedia.com.au/agronomists** *Note: Separate registration is required to the Update*	
6:45 PM	**Stand-up networking dinner & drinks at the Royal Hotel,** *48 Marshall Street (Supported by AGT & Syngenta)*	

PROGRAM DAY 2 – WEDNESDAY 4 MARCH 2019

Time	Topic	Speaker (s)
7:30 AM	**Early risers panel session: Using N to feed the farming system - a review of recent research on the efficiency & positioning of fertiliser N, N use & export in pulse crops & implications for N timing. Managing N, P & K in the farming system.** *(Main auditorium)* ***Mike Bell*** *(QAAFI),* ***Richard Daniel*** *(NGA),* ***Bede O'Mara*** *(Incitec Pivot),* ***Jon Baird*** *(NSW DPI) Facilitated by:* ***Paul Gardoll*** *(MCA)*	
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	**Herbicide approval processes - they can be relied on!**	***Jason Lutze/Sheila Logan*** *(APVMA)*
2.00 PM	**New technologies -** observations from a 4 month Fulbright Fellowship study tour of the USA & Germany	***Craig Baille*** *(USQ)*
2:30 PM	**Key decisions for 2020 -** managing costs, crop sequences, nutrition, weeds & disease	***Peter McKenzie*** *(Ag. Consulting & Extension Services),* ***Philip Lockwood*** *(Meremley Ag. Services),* ***Tim Poole*** *(Poole Ag Consulting). Facilitated by* ***Peter Birch*** *(B & W Rural)*
3:00 PM	Close	

LOCATION & TIMING OF CONCURRENT SESSIONS

	Main auditorium	River room	Training & Technology Centre
Day 1 Sessions 1 & 2	Soils	Cereals	Farming systems/Chickpeas
Day 2 Session 3 & 4	Protecting the crop	Soils/Nutrition	Climate & future challenges

CONCURRENT SESSIONS

Soils (Day 1, sessions 1 & 2)

Time session 1	Time session 2	Topic and Speaker (s)
1:15 PM	3:30 PM	**Using plant available water (PAW) to inform decision-making & crop resourcing -** what to do when you do not have a PAWC characterisation on-site? ***Brett Cocks*** *(CSIRO)*
1:45 PM	4:00 PM	**PhD presentation: Linking remote sensing & climate data with variations in crop yield & soil constraints across paddocks** ***Tom Orton*** *(UQ)*
2:10 PM	4:45 PM	**PhD presentation: Predicting & mapping soil properties & their yield impact.** Paddock scale soil mapping to explain yield variability - combining yield data, NDVI, dual EM, gamma radiometrics, elevation, & soil colour to select sampling sites, predict soil properties & their impact on yield potential ***Ed Jones*** *(USyd)*
2:35 PM	4:50 PM	**PhD presentation: A data-based approach to diagnosing & managing constraint based yield variability** ***Stirling Roberton*** *(USQ)* - How many samples & where? - Creating maps - The economics of a targeted response

Cereals (Day 1, sessions 1 & 2)

1:15 PM	3:30 PM	**Optimising cereal grain yield -** utilising physiology & phenology to improve variety adaptation & yield stability ***Darren Aisthorpe*** *(DAF Qld)*
1:45 PM	4:00 PM	**Better wheat germplasm for good seasons/ high inputs** ***Fernanda Dreccer*** *(CSIRO)*
2:15 PM	4:30 PM	**PhD presentation: Using machine vision & learning to rapidly assess crown-rot in wheat** ***Jacob Humpal*** *(NCEA)*
2:35 PM	4:50 PM	**NVT Online -** robust, reliable variety selection decisions ***Laurie Fitzgerald*** *(GRDC)*

Farming systems/Chickpeas (Day 1, sessions 1 & 2)

1:15 PM	3:30 PM	**System profit & commodity price risk -** impact of varying commodity prices on system profit & risk ***Lindsay Bell*** *(CSIRO)*
1:45 PM	4:00 PM	**Nitrogen & water in the farming system -** the multi-year impact of crop sequence ***Andrew Erbacher*** *(DAF Qld)*
2:20 PM	4:45 PM	**PhD presentation: Root lesion nematode *(P. thornei)* -** can wild chickpea germplasm from Turkey help with resistance? ***Roslyn Reen*** *(USQ)*
2:40 PM	4:55 PM	**PhD presentation: Improving Phytophthora root resistance** in chickpeas by breeding for tolerance to waterlogging - implications for diagnosing root health & timing of Predicta®B tests ***Nicole Dron*** *(NSW DPI)*

Protecting the crop (Day 2, sessions 3 & 4)

Time session 3	Time session 4	Topic and Speaker (s)
8:30 AM	10:45 AM	**Cereal pathology after the drought -** evaluating risk after crop & pasture, what's new (seed treatments), Predicta® B for in-crop diagnostics, options for high risk paddocks, Ramularia ***Steven Simpfendorfer*** *(NSW DPI)*
9:00 AM	11:15 AM	**A review of the *Helicoverpa* RMS after two seasons -** what works, what doesn't & making it fit for purpose ***Melina Miles*** *(DAF Qld)*
9:30 AM	11:45 AM	**Farming systems impacts on soil borne disease -** macrophomina, *P. thornei*, Fusarium & others ***Nikki Seymour*** *(DAF Qld)*
9:55 AM	12:10 PM	**Drone weed detection & mapping to drive precision ground spraying** ***Troy Jensen*** *(UQ)*

Soils/Nutrition (Day 2, sessions 3 & 4)

8:30 AM	10:45 AM	**Building soil organic matter -** what the science tells us ***Lynne Macdonald*** *(CSIRO)*
9:00 AM	11:15 AM	**Measuring, using & budgeting P & K soil reserves -** phosphorus buffering index & its role, K interactions with sodium & implications for K management ***Chris Guppy*** *(UNE)*
9:30 AM	11:45 AM	**Reactions in banded P, & P+K fertilizers affecting plant bioavailability** ***Gregor Meyer*** *(UQ)*
9:55 AM	12:10 PM	**PhD presentation:** How urease & nitrification inhibitors perform in bands vs. urea? Will banding limit N use efficiency in grain crops? ***Chelsea Janke*** *(UQ)*

Climate & future challenges (Day 2, sessions 3 & 4)

8:30 AM	10:45 AM	**Climate change, production risk & frost** ***Steven Crimp*** *(ANU)*
9:00 AM	11:15 AM	**Temperature impacts on growth & our use of day degree data -** how different varietal types behave in & adapt to differing thermal environments ***Fernanda Dreccer*** *(CSIRO)*
9:30 AM	11:45 AM	**Maintaining wheat yield & quality under high temperatures -** how do current cultivars compare with what's coming? ***Richard Trethowan*** *(USyd)*
10:00 AM	12:15 PM	**Discussion**

Contents

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General plenary – Day 1

Grain production in a changing climate - elevated CO_2, heat and moisture stress

Glenn J Fitzgerald, Agriculture Victoria

Key words

CO_2, climate change, heat, wheat, drought

GRDC codes

UM00027, DAV00109, DAV00121, DAV00137

Take home messages

- Higher atmospheric CO_2 levels can increase yield, water use efficiency and slow the impacts of rising temperature and drought to crop production
- Because higher levels of CO_2 decrease grain protein in cereals, which lowers bread and market grade quality, new traits/cultivars are needed to overcome this reduction
- Crop management strategies and new traits that help use water more efficiently, especially during grain filling may give an extra boost to yields under future climates
- Because of increased water use efficiency, nodule biomass and more carbon, there may be more N available from legumes, which could make them more attractive in rotations
- Elevated CO_2 is highly likely to increase the incidence of certain pests, thus improved pest management may be needed
- Adaptations to CO_2, heat and drought will require multiple solutions and need to be tuned to local conditions in terms of times of sowing, choice of cultivar and suitable traits (such as WUE, rooting, season length, heat tolerance) and crop, residue and soil management
- Given the increasing speed at which changes are occurring, the sooner we understand what is needed to adapt, the more time we will have to create adapted cropping systems.

Background

Fundamentals

From the perspective of agricultural production, the components of climate change include: increasing and more extreme temperature, more variable rainfall, increasing atmospheric CO_2, changing soil nutrition and interactions between these environments and biotic components, such as pests, diseases and crops. In addition, rainfall distribution and season lengths are changing. These changes are happening simultaneously and there are already many pressures on agricultural systems.

Mean temperatures across Australia are currently about 1°C above those at the beginning of the last century. Importantly, the frequency of extreme temperatures is increasing (Figure 1a). The patterns for rainfall are less clear with high variability for all locations, including eastern Australia (Figure 1b). It is worthwhile noting that the increase in temperature of 1°C may not appear to be very significant. However, as shown in Figure 2, a shift in the mean is really a shift in the distribution of temperatures around the mean. Thus, a relatively small shift to mean temperature translates into a larger change in the number of extreme values, in this case, number or frequency of hot days.

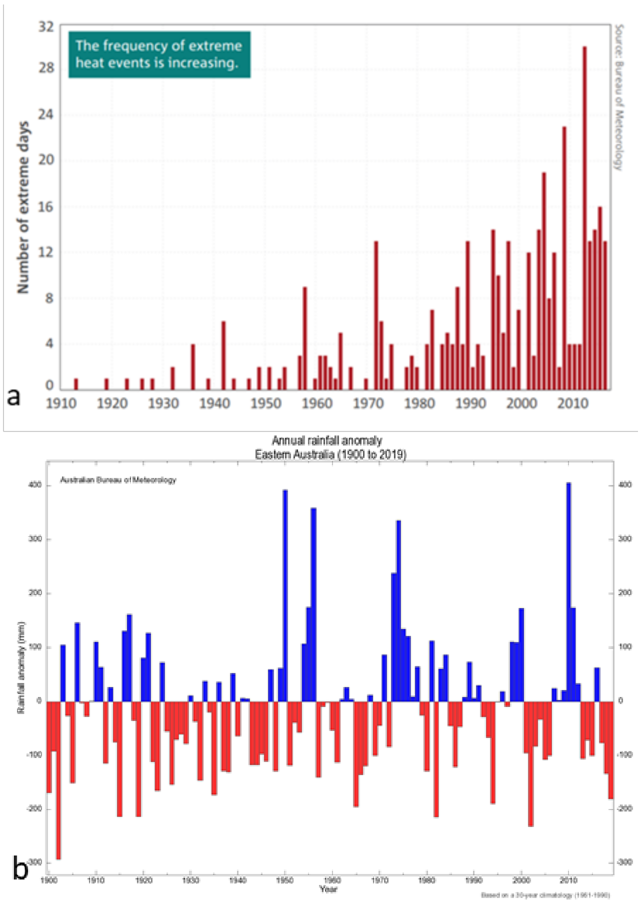


Figure 1. Graphs of (a) increasing frequency of extreme heat events since 1920 and (b) annual mean rainfall deviations in eastern Australia since 1900.

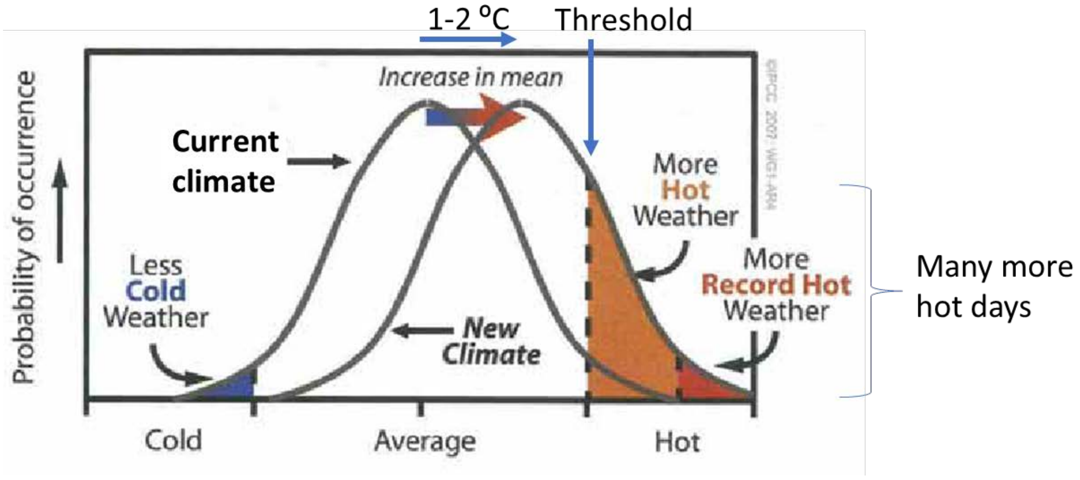
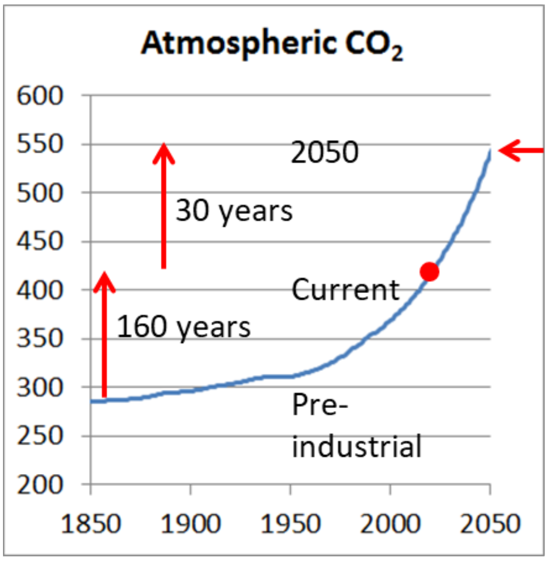


Figure 2. Example of the change in number of extreme heat days due to a shift in the distribution of temperature because of an increase in mean temperature.

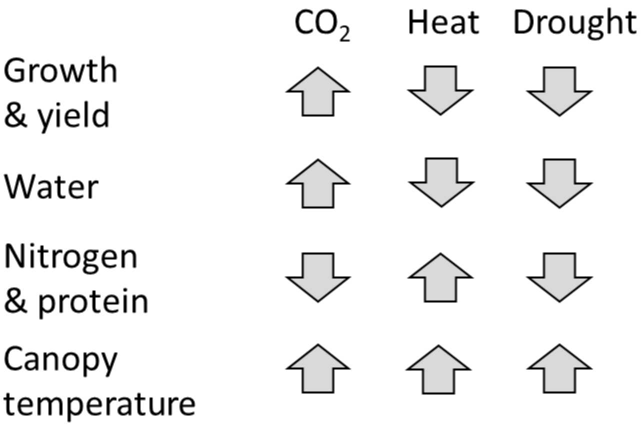
Atmospheric CO_2 has risen from ~280ppm in 1860 to ~410ppm today. It is expected that by 2050 CO_2 concentration will reach 550ppm or as much as a rise in the next 30 years as in the previous 160 years (Figure 3).



NASA 2016

Figure 3. The increase in CO_2 from the beginning of the industrial revolution (~1850 to 2050).

From a fundamental perspective these environmental changes alter carbon, nitrogen and water processes in plants and soil, which, in turn, alter photosynthesis and basic plant and crop growth patterns. In general, for C_3 plants (such as wheat, pulses, canola), increasing CO_2 by itself increases growth, water use efficiency and decreases plant N concentration, while higher temperatures and heat waves tend to do just the opposite, and drought can decrease all three (Figure 4). Elevated CO_2 also causes canopy temperatures to rise due to closing stomata and reduced evaporative cooling. Individually, the effects of these environmental factors on crops are fairly well understood but it is important to understand how they interact.



	CO_2	Heat	Drought
Growth & yield	⇧	⇩	⇩
Water	⇧	⇩	⇩
Nitrogen & protein	⇩	⇧	⇩
Canopy temperature	⇧	⇧	⇧

Figure 4. Impacts of major climate change factors on crops. Up arrows indicate increase or improvement of growth, while down arrows show a negative impact.

Thus, given there are changes in fundamental plant processes from a changing environment, how do these impact agricultural production?

Agriculture under increased CO2, heat and drought

From 2007-2017 the Free Air CO_2 Enrichment (AGFACE) facility operated at Horsham, Victoria (Figure 5a) and for two years (2008-2009) at Walpeup, Victoria. In these facilities, many experiments were run to answer a range of questions relevant to dryland agriculture. Wheat was the predominant crop, but field pea and lentil were also grown. A number of lines and cultivars were grown to test questions around breeding traits for future climates. A sister facility, SoilFACE (Figure 5b) was run from 2009-2015 to answer questions around soils and nutrition in large intact soil cores with three diverse soils.

In each sub-facility (TraitFACE, SoilFACE, Walpeup) half of the plots were kept as ambient controls at current levels of CO_2 (375 - 400ppm) and half of the plots had an octagonal 'ring' from which CO_2 was emitted to raise the concentration around the growing plants to 550 ppm, the concentration expected in 2050. There were always four replications of treatments. Within each plot, small sub-plots (~1.5 x 4m) were sown with different cultivars and N levels, depending on the relevant questions. From 2007 – 2012, there were two levels of irrigation, a rainfed and an irrigated, in other years all plots were rainfed. Ring diameters (Figure 1) varied, depending on location and year, from 4m (SoilFACE and Walpeup) to 12m or 16m at Horsham. The CO_2 emissions were computer controlled according to wind direction and speed to maintain relatively uniform levels across the ring. See Mollah et al. (2009) for complete engineering specifications.

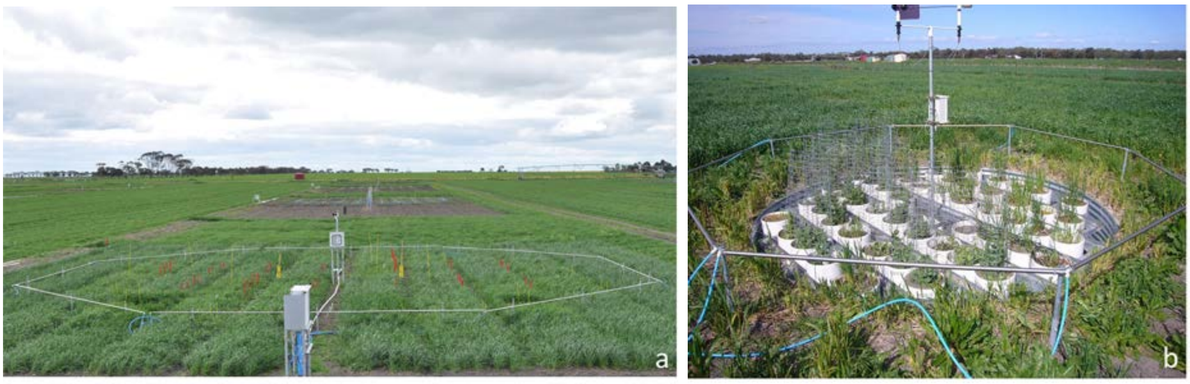


Figure 5. (a) One 12m 'ring' from the main AGFACE and (b) SoilFACE experiments (4m ring) with 30cm soil cores inset.

The strength of using a FACE facility rather than glasshouses, poly tunnels or other enclosures, is that the open nature of the structure allows for multi-factor, dynamic and realistic environments to be tested. This includes allowing variable rainfall, temperature, wind and pests into the growing crops to simulate field conditions as closely as possible. This was critical since the data collected were used to not only to understand agronomic, physiological and soil responses, but were used to validate computer simulation models, which allow us to extrapolate to other locations and into the future. In addition, glasshouses and control environment chambers were also used for more detailed physiological questions, and enclosed chambers in the field were also utilised for studying the impacts of acute heat waves on crops (Figure 6). This type of research is critical to Australian agriculture because climate change may be greatest in semi-arid regions already constrained by marginal growing conditions. Understanding the impacts to crop production will allow us to prepare for the future.

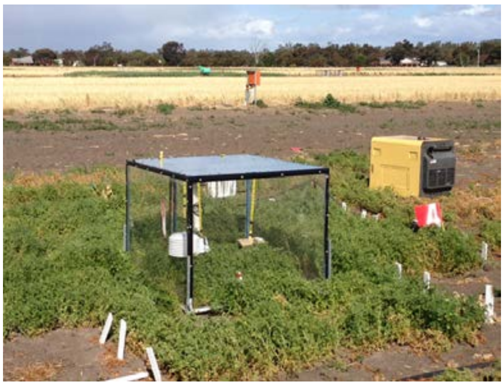


Figure 6. A temperature regulated field enclosure for imposing acute heat stresses on crops.

Results

Agronomy

Yield and grain N

Under elevated levels of atmospheric CO_2 (eCO_2), biomass and yields of C_3 crops generally increase (Kimball, 2016) and this was confirmed in the AGFACE. Under rainfed conditions for wheat, field pea and lentil, yields increased by 21%, 29%, and 58% respectively (Figure 7) on average across the various years of the different experiments. The mean yield increase for wheat under irrigation (extra 76mm water) was 35% at Horsham and 56% at Walpeup. At Walpeup, soils are sandier, temperatures higher and rainfall less than at Horsham, usually resulting in lower yield. Average yields ranged from 1.3 to 3.8 for wheat, field peas and lentils across both sites. Thus, the mean yield increase under eCO_2 for rainfed wheat was 0.7 t/ha, 0.9-1.0 t/ha for field pea and lentil, and 1.2 t/ha for the irrigated wheat. There was greater reduction in wheat grain N at Walpeup (-15%) than at Horsham (-7%). In the pulse crops, there was only a small reduction in grain N (Figure 7, right hand side of graph). Similar experiments conducted with irrigated cotton under eCO_2 in semi-arid Arizona in the U.S. showed boll and lint increases of 40-60% (Kimball, 2006).

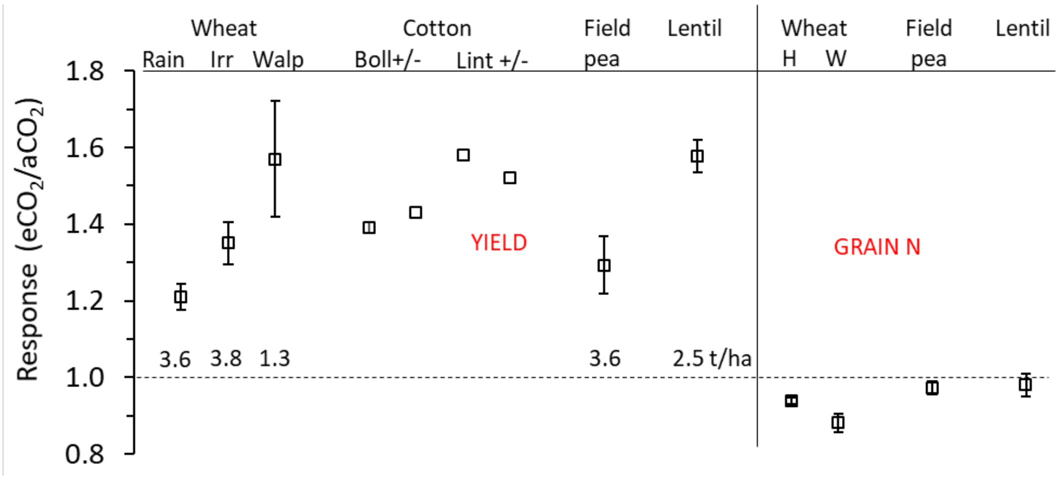


Figure 7. Response of yield and grain/boll/lint and grain N to elevated CO_2 (eCO_2/aCO_2) for wheat, cotton, field pea and lentil. Response (y-axis) is displayed in terms of fractional response compared to ambient (aCO_2) (e.g., 20% increase = 1.2 times increase or 10% decrease = 0.9). Wheat, field pea and lentil data are from the AGFACE. Cotton data is from the Arizona FACE (Kimball, 2006). Yield: Wheat, Rain = rainfed treatments at Horsham, Irr = irrigated treatments at Horsham, Walp = Walpeup site. Cotton: Boll or Lint = boll or lint yield with ample N and H_2O (+) or with ample N but deficit H_2O (-). Grain N: Wheat, H = Horsham, W = Walpeup. Error bars are 95% confidence intervals. Actual yield (t/ha) of the ambient CO_2 treatment for wheat, field pea and lentil are shown above the 1.0 horizontal dotted line (no response to eCO_2).

N uptake

Because eCO_2 increases biomass, more N is required by the crop (Figure 8, wheat). Thus, to take advantage of eCO_2, more fertiliser inputs may be required. This demand for N may be tempered, however, by rising temperatures that will tend to depress yields.

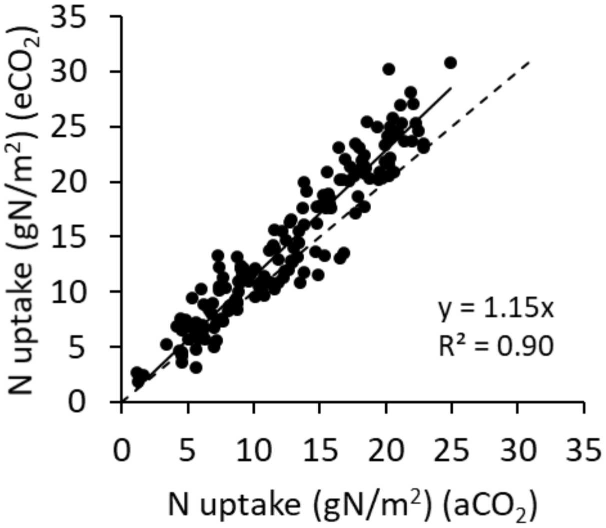


Figure 8. N uptake in above ground biomass at maturity in wheat in AGFACE across all cultivars for ambient and elevated CO_2 (aCO_2 and eCO_2). The solid line represents the increase in N (mean +15%) taken up by crop due to increased biomass under eCO_2. The dashed line is the 1:1 relationship (i.e. no response).

N from legumes

For both field pea and lentil, N_2 fixation (rate and quantity) increased under eCO_2 when there was sufficient soil water to support root rhizobia. In drought-affected field peas, N_2 fixation was partially improved by increased water use efficiency (WUE) under eCO_2, which prolonged nodule activity (Parvin et al., 2019). Because of increases in biomass, nodule activity and WUE, legumes might find a more prominent role in future rotation systems.

Heat

Changes in water dynamics, crop evapotranspiration and canopy temperature suggest that the effects of eCO_2 may interact with heat waves. Because acute heat waves are predicted to increase in frequency, high temperature at critical growth stages was studied in AGFACE by measuring impacts of a natural heat wave and imposing artificial heat using temperature-controlled field chambers (Figure 6). Impacts of heat waves on crops under eCO_2 was mixed. In a natural heat wave during grain fill in 2009, wheat grain size increased and screenings of small seed (<2mm) decreased under eCO_2 (Fitzgerald et al., 2016) suggesting this might buffer heat impacts. But, in controlled chambers, there was no interaction with CO_2 of a imposed heat wave with maximums of 38 - 40 °C on three consecutive days near flowering in wheat (Nuttall et al., 2015) or lentil (Bourgault et al., 2018). In field-grown lentil, eCO_2 helped negate the negative effects of heat on N_2 fixation by improving plant water status (Parvin et al., 2019). These differences show that the impact of acute heat under eCO_2 is complex and timing relative to grain filling is critical.

Quality

Elevated CO_2 lowered grain protein concentration by about 7% across all treatments in the AGFACE experiments (Figure 7 and 9a). Adding N fertiliser did not reverse the loss in grain protein under eCO_2 (Walker et al., 2017). The impact of this was to reduce bread quality (Figure 9b) across all conditions and cultivars tested. Only a small portion of this reduction was due to 'dilution' from increased carbohydrate translocation to grain. It has been suggested that this apparently universal reduction in cereal grain protein is due to a physiological bottleneck in nitrate assimilation and translocation of N to grain (Bloom et al., 2010) and evidence from AGFACE supports this hypothesis (Bahrami et al., 2017). Elevated CO_2 also caused changes in the protein composition of grain (Walker et al., 2019) and reduced grain micronutrient composition of Fe (-5%) and Zn (-11%), which are important in human nutrition (Myers et al., 2014).

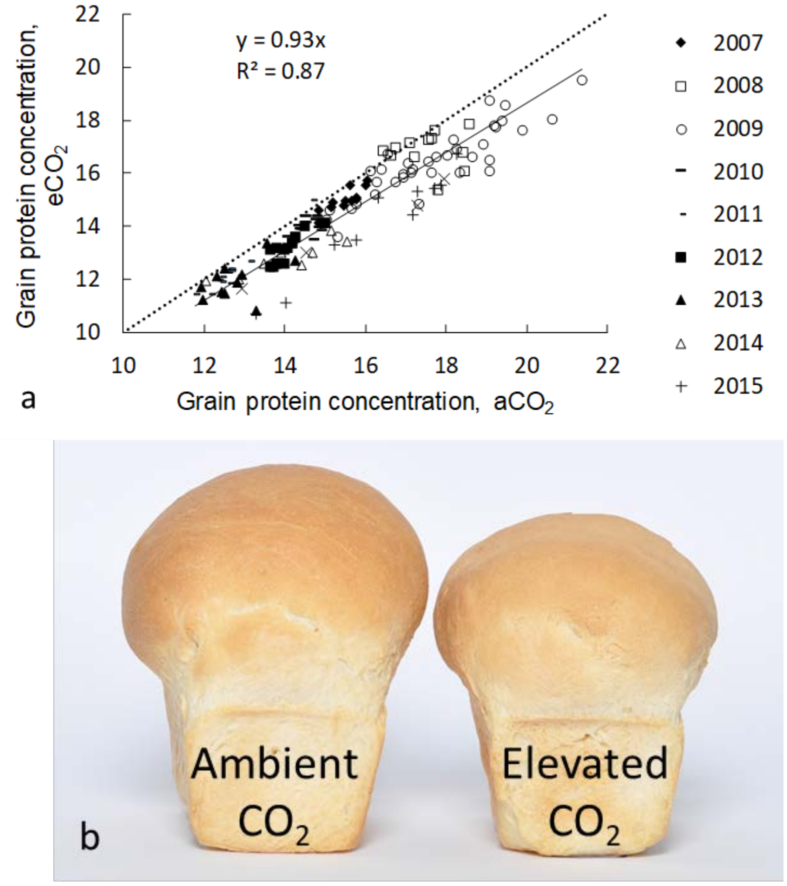


Figure 9. (a) Reduction in wheat grain protein under ambient CO_2 and elevated CO_2 conditions across years and environment for cv Yitpi. Less than 20% of this reduction can be explained by 'dilution' of N by carbohydrate translocation. The dashed line is the 1:1 (i.e. no response) line. (b) Example of reduction in bread quality due to eCO_2.

A crop modelling study using AGFACE data showed that under the expected climate for 2050 (hotter, drier, higher CO_2) the grain protein concentration decrease will vary greatly depending on location, with the Victorian Mallee region showing the largest decrease of 8.2% in grain protein concentration along with a 43% reduction in yield. In the Mallee and Wimmera regions, market grades produced were generally reduced (Figure 10), but not at all sites (see Korte et al., 2019). The net expected result is less grain that meets the standard for bread making (ASW1 grade), although increased yields at most sites will offset any reduction in income due to lowered a quality.

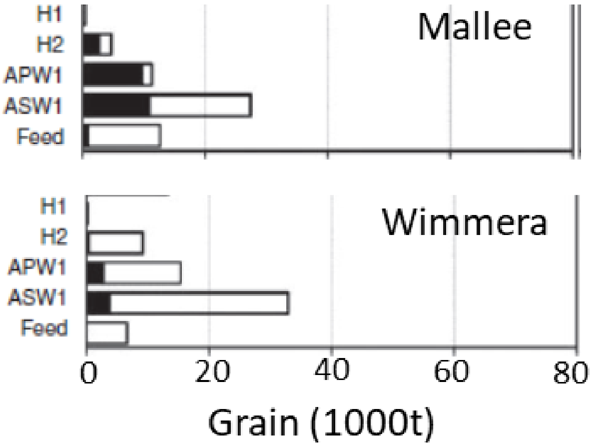


Figure 10. Changes in wheat grain market grades due to eCO_2 levels and climate expected for 2050 for two regions in Victoria. The black bars indicated the amount of grain downgraded from the next higher grade under eCO_2.

Pests

The main pest/vector studied in AGFACE was Barley Yellow Dwarf Virus (BYDV) on wheat. Because the virus is transmitted by the aphid host through phloem feeding, any changes in plant chemistry (e.g., changes in plant N) due to changes in environment could change aphid behaviour or virus virulence. Results from AGFACE showed that under higher temperatures (Nancarrow et al., 2014) the amount of virus in the plants increased under eCO_2 by 11% (Trebicki et al., 2017). In addition, aphids significantly increased sap uptake under eCO_2, increasing feeding damage. Under eCO_2 plants infected by BYDV had relatively greater leaf N concentration than uninfected plants (Figure 11a), which attracts aphids, potentially increasing the spread of virus to other, non-infected plants. Higher virus loads in plants can reduce yields (Figure 11b). There have not been any studies under the combination of eCO_2 and increased temperature, but the fact that both conditions increase virus loads suggests BYDV will become more severe under the future climate.

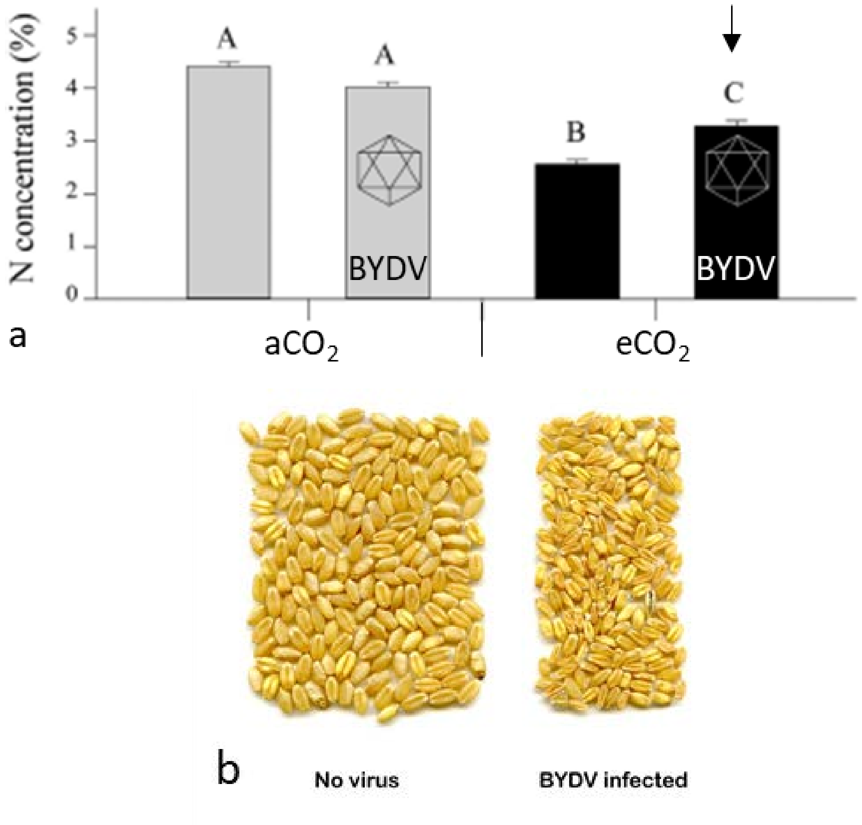


Figure 11. (a) Amount of plant N in wheat plants under ambient and elevated CO_2 with and without BYDV infection (Trebicki et al., 2016). Letters that are different are statistically significant ($p < 0.05$). Under eCO_2 infected plants have relatively higher plant N (arrow), which attracts aphids, potentially increasing infection and virus spread. (b) Example of effect of BYDV infection on wheat grain.

Traits

Transpiration efficiency

Traits that have been used in Australian physiological breeding programs such as increased water-soluble carbohydrates, transpiration efficiency (TE) and reduced tillering were tested in AGFACE to determine if these offer particular advantages under eCO_2. Of these, the TE trait in cv Drysdale was found to increase yields by 19% under eCO_2 above the comparison cv Hartog without TE (Tausz-Posch et al., 2012). In a modelling study across Australia (Christy et al., 2018), the TE trait was predicted to confer an extra 13% average yield advantage over current conditions even with a modelled reduction in rainfall of 20% and a 2°C warming with clear differences across the landscape (Figure 12). Without eCO_2, the yield was reduced by 23% compared to current climate. Thus, there appears to be a clear advantage to a TE trait under future climate.

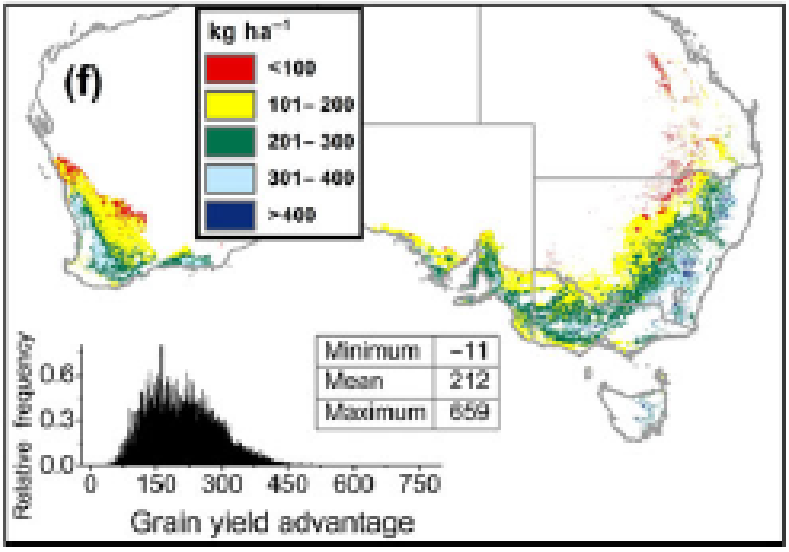


Figure 12. Grain yield advantage of wheat cv Drysdale (+TE trait) over cv Hartog (-TE trait) under eCO_2 in 2050 assuming 20% less rainfall and +2°C of warming over current mean temperature (from Christy et al., 2018).

Roots

Another key trait for adaptation under dryland conditions is root architecture and growth. The impact of CO_2 on root growth was assessed for canola and wheat in both glasshouse and field experiments in AGFACE. It was found that eCO_2 increased root length and biomass at all depths and levels of soil water availability. However, yield was stimulated most when deeper roots had access to more water (Uddin, et al., 2018a, b, c). In addition, deeper rooting cultivars of canola and wheat showed greater stimulation of yield under eCO_2. Thus, under eCO_2 and dryland conditions, roots deeper in the profile allowed crops to take greater advantage of sub-soil water than under current CO_2. The problem with dryland crops in low rainfall areas is that subsoil moisture may rarely be available.

Discussion

There is no denying that CO_2 concentration and mean temperatures are increasing, and extreme temperatures are becoming more frequent. Climate models also predict that rainfall will be more variable and decreasing in the longer term. In terms of grain production, the effect of increasing CO_2 on biomass and yield is expected to be mostly positive, except when soil N and water are scarce. Small amounts of extra water during grain fill and deeper root seem to provide a boost to the CO_2 response for yield. Unfortunately, increasing temperature with reductions in rainfall has the opposite effect by reducing available water and yields. It is also possible higher temperatures reduce yield while increasing grain protein, and this will counteract the protein reductions seen under eCO_2.

Hochman et al. (2017) demonstrated that wheat yields in Australia have stagnated since 1990 (Figure 13). Growers have adapted to drought and hotter conditions, which has maintained production, rather than resulting in decreasing yields. The question is, however, what can be done to adapt and increase yields given all the above-mentioned considerations and changes in climate, as opposed to the flat line in Figure 13b?

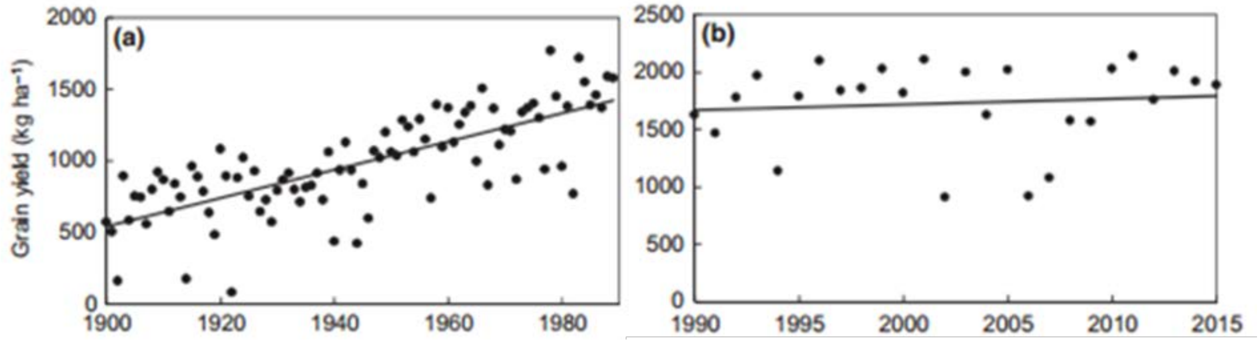


Figure 13. (a) Increasing grain yields in wheat in Australia from 1900 and (b) yield plateau from 1990 to 2015 (Hochman et al., 2017).

We have been able to quantify the impacts of a number of the above factors on production within AGFACE and from international research, but it is not possible to test every combination of environments with all interactions. The complex nature of integrating the impacts of changing environments in agricultural production can be handled through simulation modelling. A good history and summary of modelling in Australian agriculture is presented by Hochman and Lilley, (2019). Field research can provide validation of simulation models, which can then be used to extrapolate to other locations and into the future.

Adaptation

In a recent modelling study using AGFACE and other data, Wang et al. (2018) showed that without adaptation, wheat yields will decline in some parts of Australia (Figure 14a). Two climate scenarios were tested for the years 2050 and 2090. The Relative Concentration Pathway (RCP) 4.5 is a future climate target with lower CO_2 emissions, while RCP 8.5 has the highest emissions, which the world is currently tracking. Without adaptation, Queensland is predicted to be most heavily impacted for all projections, followed by New South Wales. The reasons are that higher temperatures and lower rainfall in the warmer states of QLD and NSW will decrease yields, while in cooler areas, such as Victoria, milder winters and reductions in waterlogging in some areas will benefit crop production.

There are a number of potential changes that can be made to adapt to climate change. In Figure 14a, projected yields are shown (small black rectangles) with earlier sowing (11-18 days) and sowing a longer season cultivar. Shifting the growing season earlier often allows capture of more water, increasing water use efficiency. Sowing a cultivar with a long growth cycle helps resist the shortening of the growing season as temperature rises. Predicting yields nationally on an arable area basis (Figure 14b) showed that by the 2090s, even with the adaptations tested, there is a reduction in yield, which was caused by predicted reductions in the growing area for wheat.

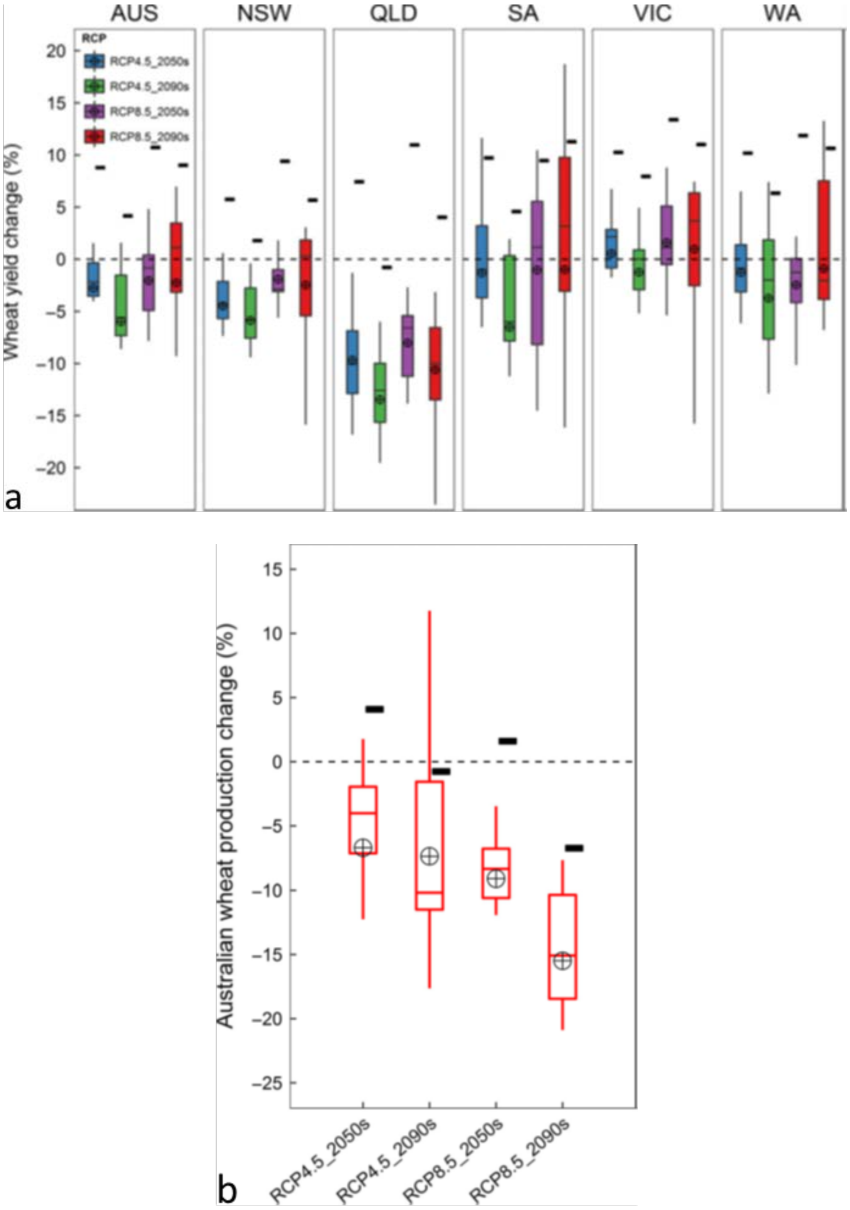
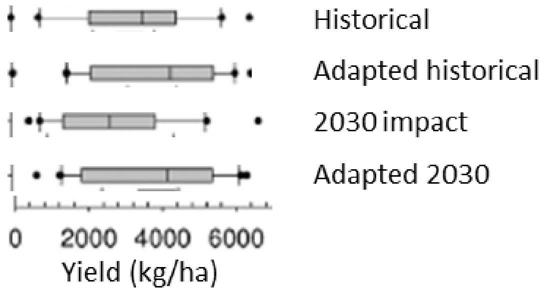


Figure 14. (a) Projected changes in APSIM-modelled wheat yield per hectare with no adaptation (box plots) in Australia and individual states with a moderate (RCP 4.5, blue and green) and business-as-usual (RCP 8.5, purple and red) climate outcome predictions for 2050 and 2090, compared to 1961-2000. Small rectangles represent yield projections with adaptation measures (sowing date shifted to earlier and a longer season cultivar). (b) Australian mean yield response on an area basis (areas climatically suitable for growing wheat). Reductions by 2090 are due to loss of arable land.

An example of local adaptation was shown by Ghahramani et al. (2015) and an excerpt for Goondiwindi is presented in Figure 15. As in Wang et al. (2018), they considered shifting to earlier sowing times and using longer season cultivars as options for the near future, in this case 2030. Their APSIM predictions also showed that despite decreases in yield there are measures that can be taken to adapt cropping systems to hotter, drier and more variable conditions.



Ghahramani et al., 2015

Figure 15. Yields (kg/ha) for 2030 for Goondiwindi for: historical (1980 – 1999), adaptation with historical yields, impact to yields in 2030, and with adaptation measures in 2030. Adaptations considered were earlier sowing and longer season cultivars. Means with error bars are shown.

On a local level, Luo et al. (2018) used modelling to understand how local environment, time of sowing, cultivar selection and phenology (flowering, start and end of grain filling) will impact wheat yields in 2030. Their study included three locations across NSW (Moree, Dubbo, Wagga Wagga), testing five times of sowing and three bread wheat cultivars at each site (Figure 16). The cultivars were of three maturity types: early-mid (Gladius(ϕ)), mid-late (Sunvale) and late (Sunbrook). They found that the rate of wheat development will increase, water use will decrease and WUE will increase in most cases. The combinations of time of sowing with cultivars that produced the highest yields varied by location, and hence, adaptation needs to be targeted to each specific location. Reductions in predicted yields at Moree suggest that other breeding and management solutions may also be needed for adaptation at this site.

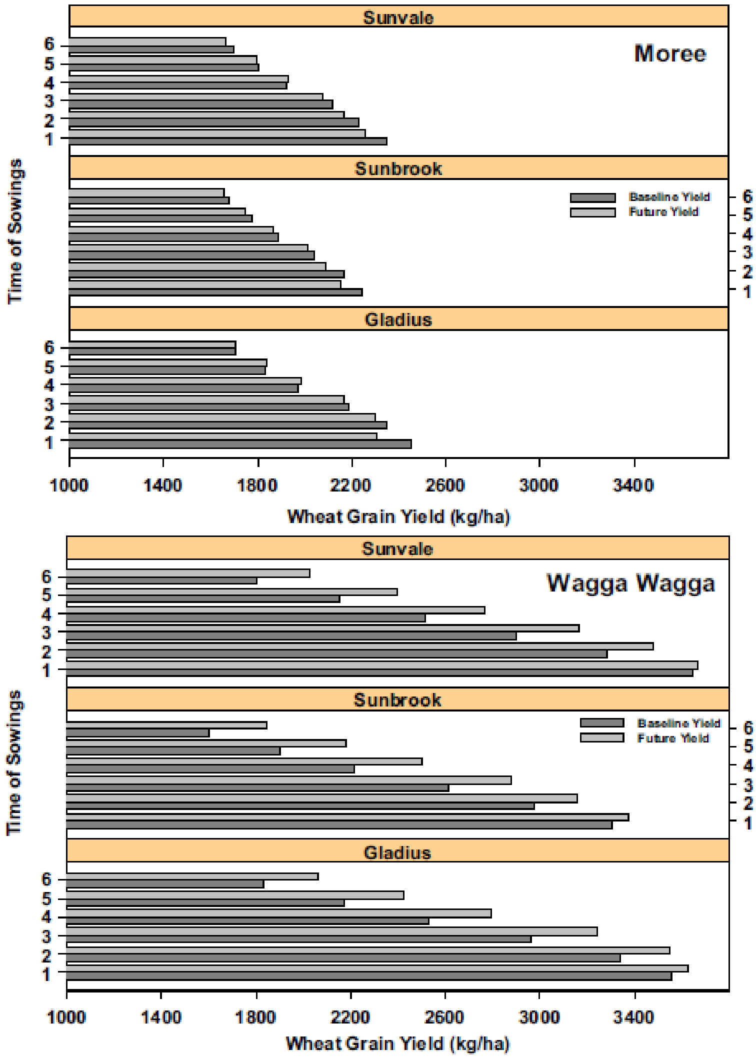


Figure 16. Examples of wheat yields (kg/ha) under baseline (1980-1999) and future 2030 conditions for six times of sowing at (a) Moree and (b) Wagga Wagga. At Moree, 2030 climate (light grey) is predicted to decrease yields. At Wagga, the 2030 climate is expected to increase yields with moderate to later sowings. The yield increase is attributed to eCO_2, the interaction between eCO_2 and soil fertility and more favourable climate (cooler, more rainfall) compared to Moree.

Because climate change involves multiple factors and an ever-shortening time frame, a combination of targeted approaches based on knowledge gained from decades of research could both maximise the positive aspects to crop production and help overcome the negatives. Combining genetics and management for adaptation in a systems approach to a new environment will potentially maintain production in semi-arid regions for longer than if changes are made in a piecemeal fashion.

Conclusion

Much research performed over the last century has underpinned the increases in grain production in Australia. In our dryland environments, this has focused on the impact of changes to water and heat on production using genetic and management tools. Impacts of elevated CO_2 have not been often addressed, possibly in part, because it has been considered ‘positive’ for growth and yield and not something that needs to be overcome. Along with heat, drought, light, soils, nutrition and other factors, elevated CO_2 is now included in most crop models.

To improve our ability to accurately assess climate change impacts to production and therefore to maximise adaptation, there are still a number of issues that need to be addressed in relation to eCO_2:

How do root growth and architecture and access to soil water change under eCO_2, and for legumes, how does this impact rhizobia and ability to fix N?

Does trait expression developed for heat tolerance and water use efficiency (stomata and root architecture) change under eCO_2?

How does the increase in canopy temperature due to stomatal closure affect crop development, C and N translocation and ultimately, grain yield and quality?

Can the bottleneck in N translocation to grain and protein reduction in C_3 crops be overcome?

Only a few pests and diseases have been tested under eCO_2 and interactions with other environments. How will these change and what are the strategies for adaptation?

Crop management practices (e.g., conservation tillage, row spacing, fallow, legume rotation, etc.) have not been well addressed under eCO_2 and greater understanding could help develop better climate-adapted systems.

Thus, a systems approach using all the experimental, analytical and practical tools at our disposal would seem prudent. Given the increasing speed at which changes are occurring, the sooner we understand how to adapt, the more time we will have to create adapted cropping systems.

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Acknowledgements

The research undertaken as part of this project was made possible by the significant contributions of growers through the support of the GRDC, the author would like to thank them for their critical support. Research in the AGFACE program was a joint collaboration between Agriculture Victoria and The University of Melbourne. Research from the CSIRO was also supported in early years of the program. Major research support was also provided by the Australian Commonwealth Department of Agriculture and Water Resources and the Australian Research Council. Student, faculty and fellowship support granted for various individuals is documented in acknowledgements in individual publications. The author gratefully acknowledges the input of international colleagues and students from other FACE facilities and the Agricultural Model Inter Comparison and Improvement Project (AgMIP) consortium and collaborations. Finally the author would like to acknowledge the contribution of members of the AGFACE research team and contributors over the years: Michael Tausz, Garry O'Leary, Roger Armstrong, Joe Panozzo, Piotr Trębicki, Mahabubur Mollah, Sabine Tausz-Posch, Cassandra Walker, James G Nuttall, Maryse Bourgault, Markus Löw, Debra Partington, Clayton R Butterly, Shu Kee Lam, Robert M Norton, Sukumar Chakraborty, Jo Luck, David McNeil, Ivan Mock, Anwar Muhuddin, Marc Nicolas, Saman Seneweera, Alan Yen and others he may have inadvertently left out.

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Chemical residues and maximum residue limits (MRLs) – impact, understanding and potential trade issues

Gerard McMullen, Chair National Working Party on Grain Protection (NWPGP)

Keywords

chemicals, maximum residue limits, MRLs, market access, domestic marketing, export marketing

GRDC code

MCM00003

Take home messages

- It is a legal requirement to follow all label directions when applying any chemical
- There are different perceptions and legal/contractual requirements of key domestic and export markets for chemical residues
- There are market access implications when using chemicals; applying a chemical according to label directions does **not** necessarily mean that grain will meet market requirements
- There is a need for advisers and growers to understand market requirements and seek advice on the MRLs that apply. Talk to your marketer if possible, before you intend to apply chemicals to a crop.

What is a maximum residue limit (MRL)?

A range of different types of chemicals are applied to crops for varying reasons. Chemicals may be used prior to planting, during the crop growth stage or following harvest. Only those chemicals registered in Australia for use on a particular crop may be applied. All chemicals registered in Australia must be used according to label directions (for example; crop type, application rates, withholding periods, etc.). This is a legal requirement in Australia.

When using these chemicals, residues may arise in the harvested grain. Residues may also arise when moving that grain using equipment such as augers and trucks that have previously held grain containing chemical residues.

The nature of residues arising are considered by the Australian Pesticides and Veterinary Medicines Authority (APVMA) and if necessary, an MRL is set for that chemical and crop commodity combination.

An MRL is the maximum concentration of a residue resulting from the registered use of an agricultural chemical which is legally permitted or recognised as acceptable to be present in or on a food, agricultural commodity or animal feed.

What are market requirements?

Chemical residues on imported food and food safety in general are arguably the key focus for markets at present.

When marketing grain in Australia or in an overseas country, residue levels must meet the regulated MRL and customer contract specifications of the destination country. These may differ to the Australian MRL.

Each market, whether it be in Australia or overseas, is responsible for ensuring the food that is imported and subsequently consumed is safe to eat in terms of chemical residues. Each market has their own chemical legislation based on their own particular chemical usage and consumption patterns. Hence different MRLs for the same chemical and commodity may apply in different markets.

There is a trend towards markets developing their own chemical regulations and not relying as previously implied on international standards, such as Codex Alimentarius. There is a trend towards requiring lower (or nil) residues on grain supplied. Markets are also increasing their level of monitoring of imported grain via sampling and testing to check compliance with their needs.

The increase in grain traded internationally may cause a market access issue for Australian grain where:

- The market has no MRL (missing MRL)
- The market doesn't apply a Codex MRL (divergent MRL)
- There is no Codex MRL for those markets that follow or default to Codex
- The market does not have a default policy and hence a zero limit applies
- The market applies a low level of detection (LOD)
- In some instances, contracts do not state the MRLs that apply. It is the responsibility of the supplier or the marketer of the grain to ensure that they know the regulations and that the grain supplied meets those requirements.

Table 1. Some key Australian markets and their chemical MRL regulations.

Market	**Codex**	**Australia**	**China**	**EU**	**Indonesia**	**Japan**	**South Korea**	**Taiwan**	**Thailand**	**Vietnam**
Regulation applied	Not adopted by all markets	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard
Default MRL	No default	No default	No default	Default system	No Default	Default system	Default system	No default	Default system is complex	No default
If no MRL	ZERO	ZERO	ZERO	0.01	CRA / ZERO	0.01	0.01	ZERO	0.01	ZERO
MRL updates	Yearly	Monthly – 6 weeks	Bi-annually	Often	Rarely	Often	Often	Approx. twice/ year	Rarely	Rarely

Note: Above is as at 6 January 2020, variations exist for specific chemicals. MRLs quoted in mg/kg. CRA refers to a Country Recognition Agreement where Indonesia may accept Australian MRLs for some commodities.

Implications for advisers and growers

Even though a grower may apply a chemical correctly and in accordance with label directions, the resulting grain residues may not meet market requirements.

In addition, there is the concern that in many situations the adviser/grower does not know the market requirement before they use the chemical?

All grain trading standards have wording in relation to chemical use that growers must comply with.

An example for the Grain Trade Australia Wheat Trading Standards is outlined as follows:
Chemicals not approved for Wheat – a nil tolerance applies, and this refers to the following:

- Chemicals used on the growing crop in the State or Territory where the wheat was grown in contravention of the label
- Chemicals used on stored wheat in contravention of the label
- Chemicals not registered for use on wheat
- Wheat containing any artificial colouring, pickling compound or marker dye commonly used during crop spraying operations that has stained the wheat
- Wheat treated with or contaminated by carbaryl, organochloride chemicals, or diatomaceous earth
- Chemical residues in excess of Australian Commonwealth, State or Territory legal limits

Residue testing is done either by the marketer or by the National Residue Survey on domestic grain and export grain shipments, the latter funded via a grower levy. If residues arise that exceed the market MRL, price penalties may occur, or the shipment may be rejected and returned to Australia. Costs may be passed from the marketer to the supplier of that grain where there is evidence of chemical misuse or false chemical use declarations. Sampling and testing of future grower loads and shipments may increase or additional segregations may need to be created, which all create extra costs. These increased costs may be passed onto the grower through the purchase price offered for the grain.

The post-farm gate sector expects that growers apply chemicals follow legal requirements. Sampling and testing of all deliveries for all possible chemicals used on-farm is not conducted due to the expense. Rather, targeted sampling and testing is conducted based on market risk. Thus, growers must provide accurate information on chemicals used on that crop. Growers are encouraged to complete Commodity Vendor Declarations correctly when details of chemicals used are sought by the trade. Failure to do so risks the supply of grain that fails to meet market requirements, a loss in reputation of Australian grain and increased costs for all along the supply chain.

Tools to assist with meeting market requirements

On behalf of industry, the NWPGP is the body responsible for providing management and leadership to industry in the areas of chemical use, post-harvest storage, market requirements and monitoring changing chemical regulations and their impact on market access.

The NWPGP is the linkage between government and the industry providing:

- Feedback on issues of concern with chemicals
- Advice on whether government to government submissions are required
- Strategies for dealing with changing market requirements and actions by all in industry to address these.

An annual 2-day conference is held providing participants with the latest research and developments in the area of chemical usage, post-harvest storage and hygiene and outturn tolerances, international and domestic market requirements, and regulations. The outcomes are provided to industry to assist with market access compliance.

A greater focus has been placed in the last two years on providing industry with knowledge of market requirements. This has involved significant communication and liaison with the pre- and post-farm gate sector. The gap between knowledge of the market requirements and what happens on-farm was recognised and communication to the pre-farm gate sector has increased through development of Fact Sheets and presentations to a range of stakeholders throughout Australia. This has occurred via NWPGP, GRDC and various government departments. Further communication with the grower and the adviser sector will continue to benefit all in the industry.

Conclusion

Given the changing nature of market regulations, all stakeholders along the supply chain need to be aware of market requirements in relation to MRLs. Given the implications of incorrect chemical use, there is a need for greater transparency and understanding by growers and advisers of the impact of chemical use on market access.

Going forward there will be a focus on ensuring all supply chain participants understand the risks of non-compliance with label directions and removing the gaps in networking; including chemical registrants, re-sellers, agronomists, growers and their advisers.

Growers need to talk to their adviser/agronomist and storage agent/marketer and where needed other experts, when seeking advice on market requirements.

Acknowledgement

This project is undertaken solely as a GRDC project and is made possible by the significant contribution of growers through the support of the GRDC. The author would like to thank growers and the GRDC for their continued support.

Useful resources

On-farm Stewardship Guide ‘Growing Australian Grain’ http://grainsguide.grainproducers.com.au
National Working Party on Grain Protection www.graintrade.org.au/nwpgp
National Residue Survey https://www.agriculture.gov.au/ag-farm-food/food/nrs
APVMA https://apvma.gov.au

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Hydrogen (from water) as an energy source and the role of ammonia in the process

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Notes

Drought's drain: driving profit through supporting good mental health

Letitia Cross & Camilla Herbig, Rural Adversity Mental Health Program

Key words

farm profitability, mental health, stress management, decision-making

Take home messages

- Even though consultants haven't traditionally seen discussions with growers about stress management and mental health as part of their role it actually makes good business sense
- The 'slow creep' of drought-related stress is detrimental to growers if unaddressed, but supporting growers to understand and manage their stress helps to prevent developing mental health problems, while also supporting future relationships and business outcomes
- Consultants are skilled to support grower's decision-making, and this becomes crucial in adverse times to assist them to understand the facts, their options and ways of making informed decisions
- Recognising mental health concerns for a grower, having conversations and seeking support ensures not only the grower's wellbeing, but as interlinked businesses it also ensures the long-term profitability and viability of both consultants and suppliers.
- Looking after ourselves is essential so as we can cope with day to day stresses and support our families, friends, business and communities.

Background

Creating understanding and awareness of the importance of farmers actively looking after their mental health has not traditionally been a domain of the agriculture service industry. However, because of the co-reliance and linked economic fortunes it makes good business sense for consultants to consider the importance of having conversations with clients about proactively managing their stress and mental health during times of adversity.

Drought is particularly stressful due to the unpredictability and longevity of conditions. In spite of this, if clients are supported to consider their own stress management and mental upkeep as importantly as their equipment, rotational considerations or financial planning, they are positioned to not only survive drought but also to be mentally capable of capitalising on drought-breaking seasonal change. Additionally, this simple approach works to secure both financial and client longevity advantages for the consultant.

Droughts are a natural feature of the Australian environment. But unlike immediate disasters which feature a critical incident or rapid onset (fire, flood etc.), drought has been described as a 'creeping disaster'. This is because by the time a drought is identified, it is usually already well established, with mounting costs, and the opportunity to take proactive action has already been missed (Austin et al., 2018). The unpredictability and longevity of drought results in a cumulative effect, the 'slow creep', where stress which is held for long and unknown periods of time which makes it particularly detrimental. Left unaddressed this continually held stress is associated with negative personal, social, physical health and mental health consequences across time.

Taking action

Consultants, agronomists and broader agriculture service personnel have naturally been focussed on providing advice on the technical or product component of the farming business. There has also been a concern of consultants about overstepping social and personal boundaries to start conversations when living and working in interconnected small communities. However, genuine concern and open discussion is key to overcoming stigma around mental health, empowering people in rural communities to proactively identify, manage and seek help when required.

As consultants and agricultural support services are embedded in rural businesses they are uniquely positioned as independent and reliable sources of advice to support growers and rural communities during adverse times. A particularly important but often overlooked part of this advice is providing mental health and well-being support through general conversation and social connection. Having conversations which encourage clients to manage stress and maintain their mental health not only ensures growers continued productivity through capacity to operate, but as businesses are financially co-dependant it also preserves consultants own long-term profitability and viability.

Consultants with some knowledge and training can be a key contributor to identifying early signs of drought-related stress, through conversations to reduce stigma and encourage help seeking. This can be done in four simple ways:

1. Encourage stress management
2. Support good decision-making
3. Notice changes in clients, have the conversation and encourage help
4. Look after yourself, so you can continue to support others

1. Stress management

Stress is a normal reaction which everyone feels, as it is the physical and emotional response to having demands made upon us. However, the increasing load we carry and how we manage our stress has implications for our mental health, risk of developing an illness, decision-making and consequently operating a successful business.

Practicing stress management techniques in good times and in bad times is key to maintaining good mental health. So, some of the ways that people can be encouraged to better manage their stress includes:

- Try to take some time out and do things that you enjoy – even five minutes of 'putting the whir in our heads down' is beneficial
- Keep in touch with family, friends and neighbours – social connectedness is important
- Reflect on the good stuff – it is easy to fall into the negative in tough times but looking for the good creates balance in our thoughts and actions
- Eat well, sleep well and only use alcohol in moderation – you can't run on an empty tank.

2. Support good decision-making

A number of physical and emotional signs and symptoms of stress can impact wellbeing, concentration, motivation and ultimately decision-making ability. Understandably, when a person's behaviour is being compromised in this manner it is hard to focus on making effective personal and professional decisions.

This becomes particularly problematic in the agricultural industry given the high levels of uncertainty, the need for agility and the ability to make complex decisions associated with agricultural production enterprises. If someone is overstressed or suffering from a period of poor mental health, they have a limited ability to handle complex information; are more likely to make reactionary choices with less information; undertake higher risk options; or make no more decisions, which is still a decision. This type of compromised decision-making can have financial and long-term impacts on both the farming business and the consultant's business, so supporting effective and informed decision-making is critical. Five key ways to support clients in effective decision-making include:

Prioritise decisions – depending on the size, impact and consequences and tackling one at a time

Know your timeframe – understand the level of urgency for a decision to be made

Consider options – laying out the cost, benefits and impacts of different options to make an informed decision

Identify and utilise support network – utilise skills and technological knowledge of supports and professionals to assist

Evaluate, reassess and adapt.

3. Notice changes in clients, have the conversation and encourage help

Notice the change - Sometimes being trusted, independent and reliable, consultants and agricultural service providers are often ideally located to notice a farmer's mental health in decline. Particularly when consultants visit clients regularly over a period of time. Some of the signs and symptoms that someone is struggling with their mental health include:

- Changes in mood or behaviour – e.g. low or flat mood or uncharacteristic anger or irritability
- Social withdrawal
- Feelings of panic, nervousness, being "on-edge", hopelessness and lack of interest in the future – showing signs or making statements to this effect
- Difficulty with usual tasks or activities – trouble concentrating, loss of interest, confidence, or motivation
- Effects on relationships – e.g. family breakdown or arguments
- Loss of interest in usually enjoyable things – e.g. hobbies, social occasions, events
- Low energy levels and unusual physical complaints (e.g. aches and pains)
- Changes in sleeping patterns and appetite
- Changing use of drugs or alcohol – generally increased or becoming more dependant.

A person doesn't have to be exhibiting all of these symptoms, but trust your instincts.

Have the conversation – While it can seem uncomfortable, checking on how someone is travelling and encouraging them to get help is just a conversation, and that's something we do every day. When having a conversation, make sure you have sufficient time, chat to the person in a comfortable place about what you have noticed and why you are concerned. You do not need to fix their problems but listen to their concerns and reassure the person that there is help available. Often just providing an opportunity for the person's concerns to be listened to can be of more value than you realise.

Some examples of ways to start this conversation include:

- "I haven't seen you around much lately… what's been happening?"
- "You look a bit run down, how are you going?"
- "I've noticed…"

Encourage help - If the person is not travelling well, then encourage them to act. There are many different types of help but a GP (General Practitioner) is a great first point of call. They can provide treatment options or a referral to another provider through a Mental Health Treatment Plan. There are also specialised clinicians (counsellor, psychologist & social workers); phone and online resources (Beyond Blue, Black Dog Institute, etc.); the NSW Mental Health Line - 1800 011 511; or for emergencies the Emergency Services (000). Help to source appropriate resources and services can also be gained through your local RAMHP Coordinator, www.ramhp.com.au and www.yougotthismate.com.au.

4. Looking after yourself

Supporting others can take its toll on you so it is important to look after yourself as well. You can:

- Debrief and reach out for support – utilise personal and professional networks to debrief after a difficult conversation or situation. In some workplaces, Employee Assistance Programs (EAP) are available to provide confidential support
- Do things you enjoy, be mindful, take some time out
- Eat well, sleep well and use alcohol in moderation
- Be active – physically, mentally, socially
- Set goals
- Practise gratitude and looking at the positives.

By understanding the impacts of stress in clients and ourselves we can employ stress management strategies, good decision-making practices, have conversations and look after ourselves to support our sector's resilience, maintain our profitability and be ready to jump when seasons turn.

Acknowledgements

The work is undertaken as part of the Rural Adversity Mental Health Program, a collaboration between the Centre for Rural and Remote Mental Health and NSW Health.

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Day 1 concurrent session – Soils

Using plant available water (PAW) to inform decision-making and crop resourcing: What to do when you do not have a PAWC characterisation on-site?

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Key words

Plant Available Water Capacity (PAWC), soil water, APSoil, eSPADE, soil survey, Crop Lower Limit (CLL), subsoil constraints, soil-landscape, yield forecasting, APSIM

GRDC code

CSP00210

Take home messages

- Plant available water (PAW) is a key determinant of potential yield in dryland agriculture. Obtaining a measurement or estimate of PAW can, therefore, inform crop management decisions relating to time of sowing, crop type or the level of fertiliser inputs
- Estimating PAW, whether through soil coring, use of a soil water monitoring device or a push probe, requires knowledge of the plant available water capacity (PAWC) of a soil. PAWC characterisations are publicly available in the APSoil database, which can be viewed in Google Earth and in the 'SoilMapp' application for iPad and Android
- Variation in the observed PAWC is linked to parent material, texture and subsoil constraints. Similarity in soil properties is therefore key, when extrapolating PAWC data
- Recognising how soils are distributed across the landscape, helped by understanding how the soils have been formed, assists with assessing similarity in soil properties. The nearest characterisation is not necessarily the most appropriate one
- Relationships between soil properties, parent material and position in the landscape are reflected in soil-landscape, soil and land resources and land resource area mapping and described in accompanying reports available online through eSPADE (NSW) and the Queensland Globe
- Digital soil maps (DSMs) provide predictions of soil properties at 90 or 100 m resolution and are available through eSPADE for NSW and the Soil and Land Grid (SLGA) for all of Australia
- Predicting PAWC currently requires combining the information from these multiple resources with local observations. Work is currently underway to test and refine the PAWC prediction processes and make them more user-friendly
- In the meantime, exploring the soil differences on your farm using these tools and the provided PAWC information may explain differences in performance between or within paddocks, and help adjust yield expectations and inform management decisions.

Plant available water and crop management decisions

A key determinant of potential yield in dryland agriculture is the amount of water available to the crop, either from rainfall or stored soil water. In the GRDC northern region the contribution of stored soil water to crop productivity for both winter and summer cropping has long been recognised. The amount of stored soil water influences decisions to plant or wait (for the next opportunity or long fallow), to sow earlier or later (and associated crop and variety choices) and the input level of resources such as nitrogen fertiliser. Examples have been presented by others at previous GRDC Updates (e.g. Routley, 2010; Whish, 2014; Dalgliesh, 2014; Fritsch and Wylie 2015; and Bell, 2019).

The amount of stored soil water available to a crop - Plant Available Water (PAW) – is affected by pre-season and in-season rainfall, infiltration, evaporation and transpiration. It also strongly depends on a soil's Plant Available Water Capacity (PAWC), which is the total amount of water a soil can store and release to different crops. The PAWC, or 'bucket size', depends on the soil's physical and chemical characteristics as well as the crop being grown.

The PAWC can be determined in the field following procedures described in the GRDC PAWC Booklet 'Estimating plant available water capacity' (Burk and Dalgliesh, 2013). This method will usually provide the best estimate for a location of interest, although there are some pitfalls and common mischaracterization issues that need to be avoided (Verburg et al., 2017). See below for more details.

Over the past 20 years, CSIRO in collaboration with state agencies, catchment management organisations, consultants and farmers has characterised more than 1100 sites around Australia for PAWC. The data are publicly available in the APSoil database, including via a Google Earth file and in the 'SoilMapp' application for iPad and Android (see Resources section).

But what to do when you are not in the position to do a local field PAWC characterisation and there is no APSoil PAWC characterisation on-site?

The APSoil database provides geo-referenced data (i.e. data linked with locations on a map). The nearest APSoil PAWC characterisation may, however, not be the most appropriate as its soil properties could be quite different. The presence or level of subsoil constraints may vary too. The challenge is, therefore, to find a PAWC characterisation for a soil with similar properties.

The soil properties that affect PAWC (texture, stones and gravel, chemical constraints) change within the landscape as a function of parent material and how the soil formed, or soil material got there. These aspects are reflected in soil-landscape models that underpin soil survey maps produced by state government departments and other research organisations. This information is increasingly becoming available online. Our project tests the hypothesis that soil-landscape information can inform PAWC prediction.

This paper describes the concepts behind PAWC and outlines where to find existing information on PAWC. It discusses findings from research in progress on how you can use the available PAWC characterisation data, along with soil-landscape information and local observations to inform estimation of PAWC on your farm. This is illustrated by examples from the GRDC Northern Region.

Plant Available Water Capacity (PAWC)

To characterise a soil's PAWC, or 'soil water bucket size', we need to determine (Figure 1a):

- Drained upper limit (DUL) or field capacity – the amount of water a soil can hold against gravity
- Crop lower limit (CLL) – the amount of water remaining after a particular crop (wheat, chickpea, cotton, etc.) has extracted all the water available to it from the soil

- Bulk density (BD) – the density of the soil, which is required to convert measurements of gravimetric water content to volumetric.

In addition, chemical data are obtained to provide an indication whether subsoil constraints (e.g. salinity, sodicity, boron and aluminium) may have affected a soil's ability to store water, or the plant's ability to extract water from the soil (e.g. rooting depth).

Plant available water is the difference between the CLL and the current volumetric soil water content (mm water/mm of soil) (Figure 1b). The latter can be assessed by soil coring (gravimetric moisture which is converted into a volumetric water content using the bulk density of the soil) or the use of soil water monitoring devices (requiring calibration to quantitatively report soil water content).

An approximate estimate of PAW can be obtained from knowledge of the PAWC (mm of available water/cm of soil depth down the profile) and the depth of wet soil (push probe or based on a feel of wet and dry limits using an uncalibrated soil water monitoring device).

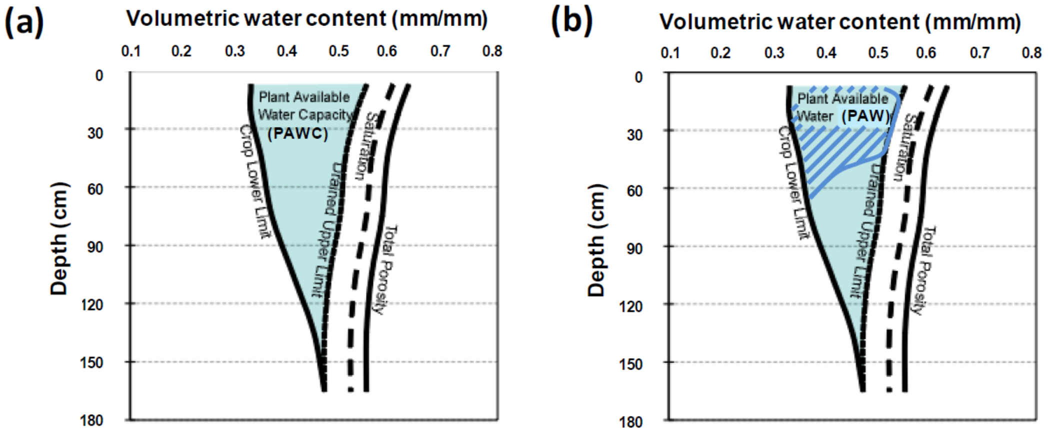


Figure 1. (a) The Plant Available Water Capacity (PAWC) is the total amount of water that each soil type can store and release to different crops and is defined by its Drained Upper Limit (DUL) and its crop specific Crop Lower Limit (CLL); (b) Plant Available Water (PAW) represents the volume of water stored within the soil available to the plant at a point in time. It is defined by the difference between the current volumetric soil water content and the CLL

Field measurement of PAWC

Field measurement of DUL, CLL and BD are described in detail in the GRDC PAWC booklet 'Estimating plant available water capacity' (Burk and Dalgliesh, 2013; see resources section). Briefly, to determine the DUL an area of approximately 4 m x 4 m is slowly wet up using drip tubing that has been laid out in spiral (see Figure 2a). The area is covered with plastic to prevent evaporation and after the slow wetting up it is allowed to drain (see GRDC PAWC booklet for indicative rates of wetting up and drainage times). The soil is then sampled for soil moisture and bulk density.

The CLL is measured either opportunistically at the end of a very dry season or in an area protected by a rainout shelter between anthesis/flowering and time of sampling at harvest (Figure 2b). This method assumes the crop will have explored all available soil water to the maximum extent and it accounts for any subsoil constraints that affect the plant's ability to extract water from the soil.

Pitfalls and common mischaracterization issues have been documented in a report describing APSoil PAWC characterisations in the Liverpool Plains (Verburg et al., 2017; see Resources Section). Key issues affecting the DUL measurement include too little water application or application at rates that cause surface or subsurface runoff and insufficient time for drainage (particularly on clay soils). Those affecting CLL include large rainfall events refilling soil under the rainout shelter via cracks or subsurface flow (especially on slopes) and insufficient wetting of the deep subsoil. The latter issue has been an issue in recent dry years and causes the measured CLL to reflect the water extraction of previous deep-rooted crops.

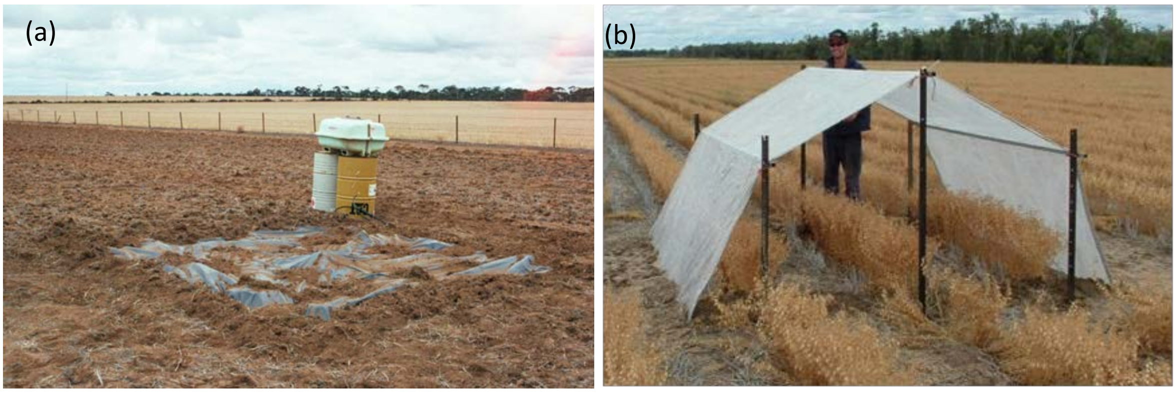


Figure 2. (a) Wetting up for DUL determination and (b) rainout shelter used for CLL determination

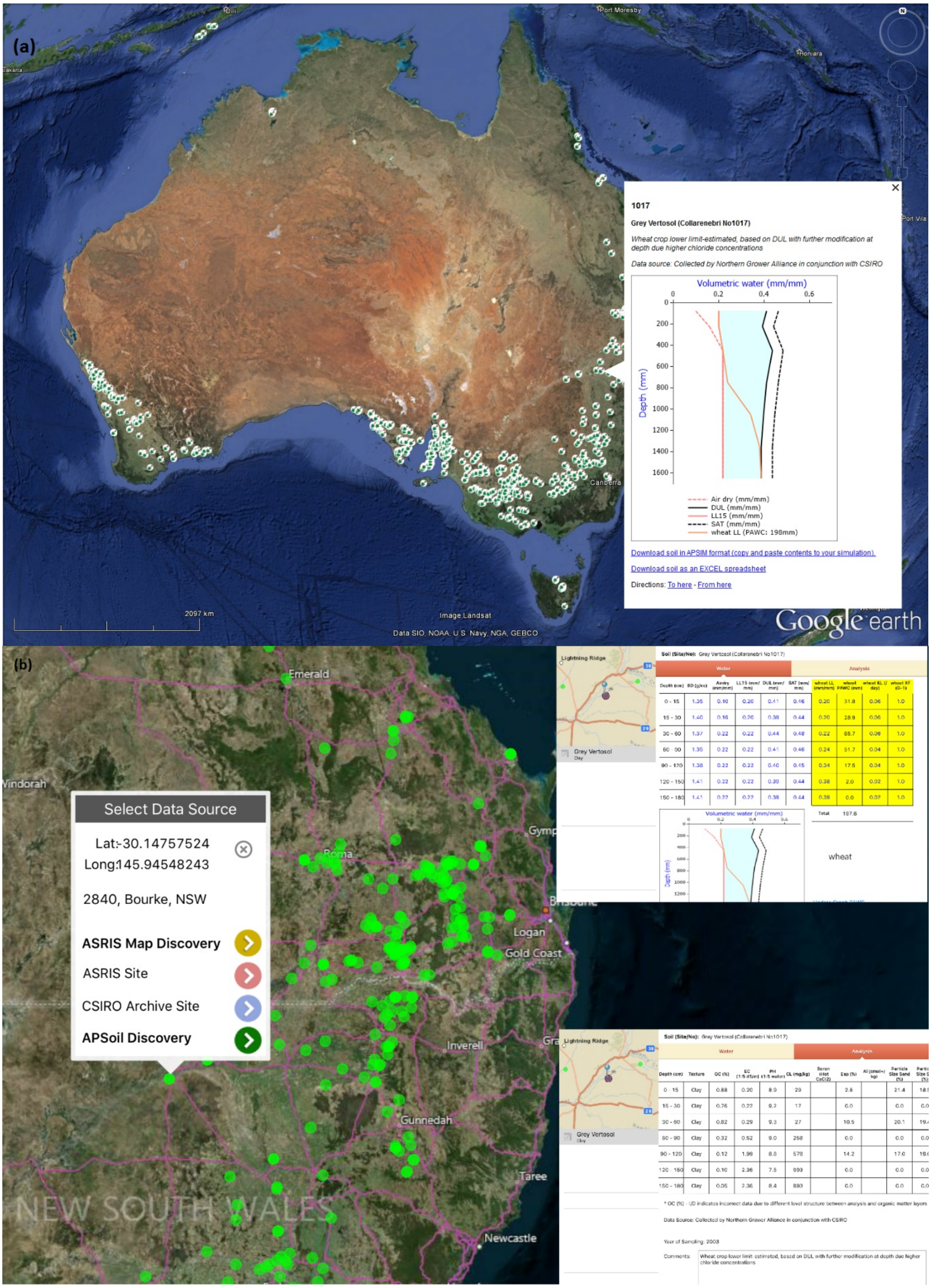
Where to find existing information on PAWC

Characterisations of PAWC for more than 1100 soils across Australia have been collated in the APSoil database and are freely available to farmers, advisors and researchers. The database software and data can be downloaded from https://www.apsim.info/Products/APSoil.aspx. The characterisations can also be accessed via Google Earth (KML file from APSoil website) and in SoilMapp, an application for the iPad and Android. The yield forecasting tool Yield Prophet® also draws on this database.

In Google Earth the APSoil characterisation sites are marked by a shovel symbol (see Figure 3a), with information about the PAWC profile appearing in a pop-up box if one clicks on the site. The pop-up box also provides links to download the data in APSoil database or spreadsheet format.

In SoilMapp the APSoil sites are represented by green dots (see Figure 3b). Tapping on the map results in a pop-up that allows one to 'discover' nearby APSoil sites (tap green arrow) or other soil (survey) characterisations. The discovery screen then shows the PAWC characterisation as well as any other soil physical or chemical analysis data and available descriptive information.

Most of the PAWC data included in the APSoil database has been obtained through the field methodology outlined above, although for some soils, estimates have been used for DUL or CLL. Some generic, estimated profiles are also available. While field measured profiles are mostly geo-referenced to the site of measurement (+/- accuracy of GPS unit), generic soils are identified with the nearest, or regional town.



1017

Grey Vertosol (Collarenebri No1017)

Wheat crop lower limit-estimated, based on DUL with further modification at depth due higher chloride concentrations

Data source: Collected by Northern Grower Alliance in conjunction with CSIRO

Download soil in APSIM format (copy and paste contents to your simulation)

Download soil as an EXCEL spreadsheet

Directions: To here - From here

Select Data Source

Lat:-30.14757524
Long:145.94548243

2840, Bourke, NSW

ASRIS Map Discovery
ASRIS Site
CSIRO Archive Site
APSoil Discovery

Soil (Site/No): Grey Vertosol (Collarenebri No1017)

Water | Analysis

Depth (cm)	BD (g/cc)	Airdry (mm/mm)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	wheat LL (mm/mm)	wheat PAWC (mm)	wheat KL (/day)	wheat XF (0-1)
0 - 15	1.35	0.10	0.20	0.41	0.46	0.20	31.8	0.06	1.0
15 - 30	1.40	0.16	0.20	0.39	0.44	0.20	28.9	0.06	1.0
30 - 60	1.37	0.22	0.22	0.44	0.48	0.22	65.7	0.06	1.0
60 - 90	1.35	0.22	0.22	0.41	0.46	0.24	51.7	0.04	1.0
90 - 120	1.38	0.22	0.22	0.40	0.45	0.34	17.5	0.04	1.0
120 - 150	1.41	0.22	0.22	0.39	0.44	0.38	2.0	0.02	1.0
150 - 180	1.41	0.22	0.22	0.39	0.44	0.39	0.0	0.02	1.0

Total: 197.6

Soil (Site/No): Grey Vertosol (Collarenebri No1017)

Water | Analysis

Depth (cm)	Texture	OC (%)	EC (1:5 dS/m)	PH (1:5 water)	CL (mg/kg)	Boron (Hot CaCl2)	Esp (%)	Al (cmol+/kg)	Particle Size Sand (%)	Partic Size S (%)
0 - 15	Clay	0.88	0.20	8.9	29		2.8		21.4	18.
15 - 30	Clay	0.76	0.22	9.2	17		0.0		0.0	0.0
30 - 60	Clay	0.82	0.29	9.3	27		10.5		20.1	19.
60 - 90	Clay	0.32	0.52	9.0	258		0.0		0.0	0.0
90 - 120	Clay	0.12	1.99	8.8	579		14.2		17.0	19.
120 - 150	Clay	0.10	2.36	7.5	993		0.0		0.0	0.0
150 - 180	Clay	0.05	2.36	8.4	893		0.0		0.0	0.0

* OC (%) - I/D indicates incorrect data due to different level structure between analysis and organic matter layers

Data Source: Collected by Northern Grower Alliance in conjunction with CSIRO

Year of Sampling: 2003

Comments: Wheat crop lower limit estimated, based on DUL with further modification at depth due higher chloride concentrations

Figure 3. Access to geo-referenced soil PAWC characterisations of the APSoil database via (top) Google Earth and (bottom) SoilMapp (APSoil discovery screens as inserts)

Using soil-landscape information to help estimate PAWC

The concept of using soil-landscape information to help estimate PAWC is based on previous work providing soil management advice specific to soil-landscape positions as used in the 'Glovebox Guide to Soil of the Macquarie-Bogan Flood Plain' by Hulme (2003), land management manuals available for several regions in Queensland (e.g. Harris et al. (1999) for the Central Darling Downs) and the on-line mapping and reports for soil-landscapes and soil and land resources in various regions of NSW.

These resources have in common that they draw on a mapping of so-called soil landscape units (SLUs) or land resource areas (LRAs) which identify "broad landscape units that group soils developed from related geology and exhibit recurring patterns of topography and vegetation" (Harris et al., 1999). The maps were produced as part of soil survey programs undertaken by the states and are now available on-line. The Queensland maps can be accessed via the Queensland Globe, whereas the NSW maps are available through the eSPADE tool (see resources section).

As the maps are typically at a 1:100,000 or 1:250,000 mapping scale the map units often include more than one soil and usually do not reflect uniform soil properties or PAWC. Further differentiation within the units is required. The accompanying reports provide guidance on typical sequences of soils and their landscape position or indicate the distinguishing features of different soils. However, local observations on the landscape around the point of interest and specific soil features are still required for PAWC prediction at paddock scale.

Digital soil mapping (DSM) predicts soil properties on a grid using spatial statistical models that describe how site soil data relate to other environmental information layers, called co-variates. These include soil and parent material indicators (e.g. information from gamma radiometrics), climate variables (e.g. rainfall, potential evaporation), existing soil maps and information on vegetation (e.g. land cover, NDVI) and terrain and landscape position (e.g. elevation, slope, orientation of slope). The Soil and Landscape Grid of Australia (SLGA) provides predictions at 90 m resolution and in NSW the eSPADE provides mapping at a 100 m grid (see resources section).

Below we illustrate the use of these resources for two examples from north-western NSW. Previous Update papers provided information on the Liverpool Plains (Verburg et al., 2018) and Central Darling Downs (Thomas et al., 2019).

Macquarie-Bogan floodplain

Detailed SLU mapping has been carried out in this region, but this is not yet available on-line in eSPADE. The Glovebox Guide by Hulme (2003) presents a simplified version of this mapping. The mapping distinguishes four main floodplain formations: Trangie, Carrabear, Bugwah, and Marra Creek (Duncan et al., 2012). These represent different geological times during which the alluvial materials were deposited (~ 1.6 million years to < 5,000 years). As position and stream power of the river system changed over time, the materials were deposited under different energy conditions, affecting their particle size distribution. The particle size distribution is also affected by the relative position within the river systems: high-energy bed-load results in coarser and more variable materials in the meander plains, whereas low energy deposition of clays characterises the backplains (Figure 4). The SLU mapping, therefore, also distinguishes backplain units and meander plain units.

APSoil PAWC characterisations in the area reflect these differences in texture (Table 1). Those representing backplains also show some consistency in PAWC, resulting in a rule-of-thumb that could be used as a first approximation: PAWC of 200-220 mm, unless affected by subsoil salinity which can reduce PAWC by 50 mm or more. Due to their nature, the meander plains are more variable and current work is exploring the use of DSM based predictions and terrain analysis to guide variation within these units. The DSM of electrical conductivity (EC) available in eSPADE also looks promising to identify areas where the presence of salinity limiting the PAWC needs to be considered.

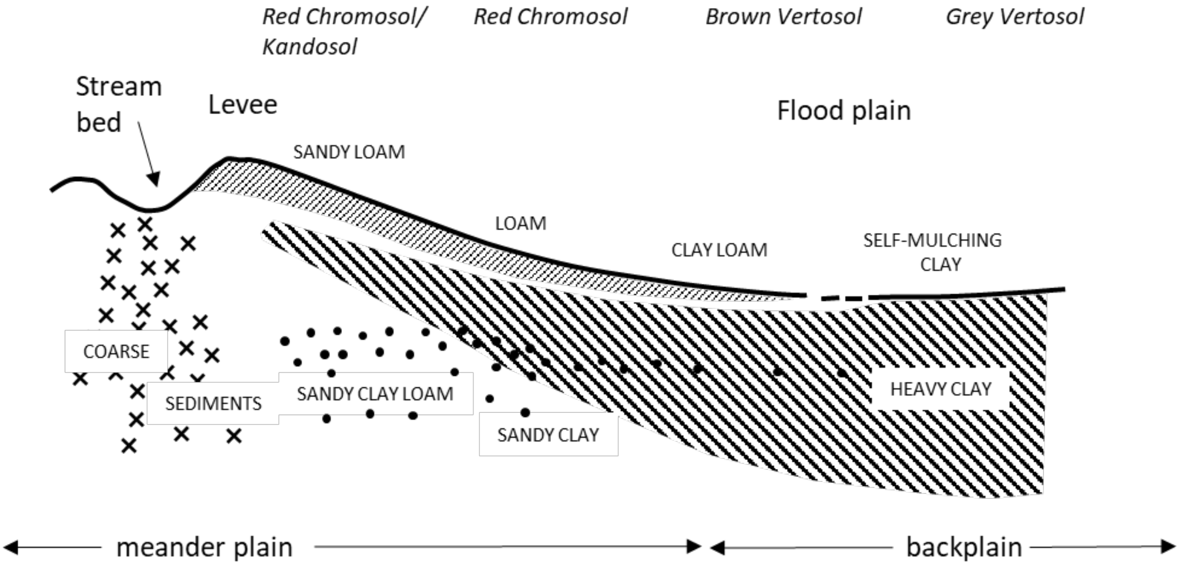


Figure 4. Distribution of materials across the meander plain and backplain; adapted from Butler (1958) with the soil type sequence of one of our transects through the Carrabear Western soil landscape group

Table 1. Select APSoil characterisations in Macquarie-Bogan Floodplain region with PAWC (to 180 cm or rooting depth)

APSoil	Soil-landscape group and unit (SLU)		PAWC (mm)	Soil	Soil Constraints to PAWC
683	Trangie	meander plain	141	Duplex	
684	Trangie	backplain	193	Vertosol	
1161	Carrabear Western	backplain	210	Vertosol	
1156	Carrabear Eastern	backplain	153	Vertosol	Constrained by salinity
248	Carrabear Macquarie	meander plain	148	Duplex	
705	Carrabear Macquarie	backplain	184	Vertosol	
1160	Carrabear Merri	backplain	127	Vertosol	Constrained by salinity
1159	Carrabear Combara	meander plain	215	Gradational	
1158	Carrabear Combara	backplain	213	Vertosol	

Moree Plains

This area has soil and land resources mapping available through eSPADE which covers the alluvial plains and fans of the Namoi, Mehi, Gwydir, Barwon and Macintyre Rivers (NSW OEH, 2016). Our project focussed on the area north of Moree. Most of the agricultural land in this area is mapped as SLUs associated with the floodplains of the different rivers, an SLU representing the gently undulating sandstone hills and rises on the western margin of bedrock-based ranges along the eastern border (e.g. around North Star) or the SLU representing the older alluvial plains and colluvial fans downstream (west) of these bedrock hills (the landscape crossing the Newell Highway) (Figure 5). Clay-rich Vertosols are the dominant soils on the alluvial plains and fans in most of the SLUs. The exceptions are the lighter red duplex (texture contrast) soils in the area around North Star and the mosaics of soils with varying particle size occurring in smaller SLUs representing current or remnant meander plains and levees, not all of which are cropped.

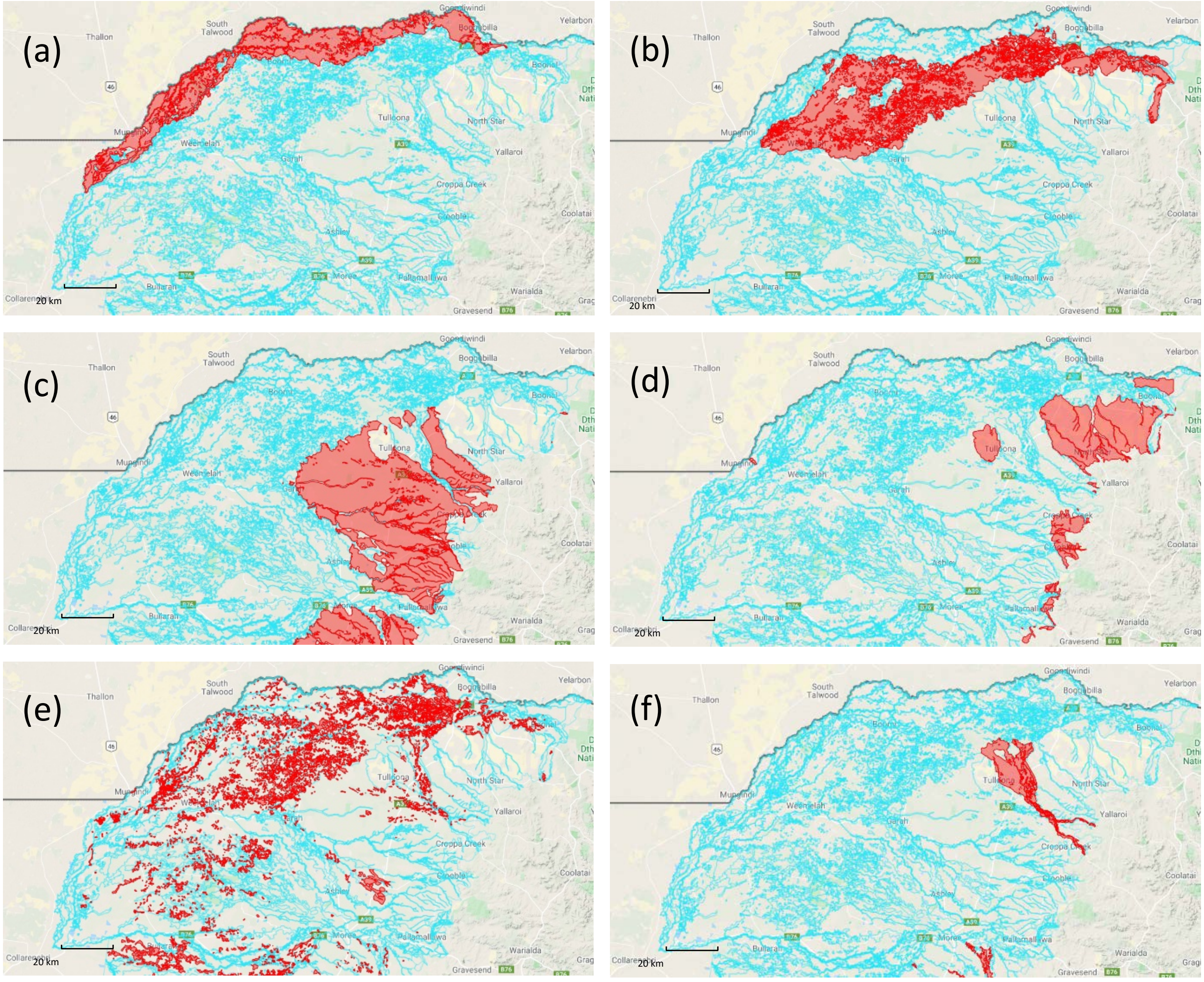


Figure 5. Select Moree Plains soil landscape units (SLUs) highlighted on map using eSPADE; a) Mungindi (backplains and minor meander plains of the Barwon and Macintyre alluvial system), b) Turrawah (floodplains and residual plains of the MacIntyre River fan system), c) Gurley (remnant sheet-flood fan system), d) Mungle (undulating rises to hills mainly on sandstone), e) Boolcarrol (meander plains and levees), and f) Terry Hie Hie (palaeo-levee remnants on fan systems). See eSPADE for more

APSoil characterisations are found in six of the SLUs (Table 2). It is difficult to generalise the nature of soils within the SLUs from these limited data points. For example, the three characterisations in the Turrawah SLU are Black Vertosols whereas the most common soil in this SLU is Grey Vertosol. Nevertheless, the data suggest that Vertosols on the floodplains, plains and fans will have PAWCs in the range of 200 mm (light clay) to 250 mm (heavy clay, clay > 50%) where there are no subsoil limitations. Subsoil salinity constraints can reduce this considerably with the depth of salinity being an important factor. The DSM of EC in eSPADE suggests that salinity subsoil constraint issues are common within most of the alluvial plains and colluvial fan SLUs. Subsoil salinity is usually experienced in soils that are less well drained, e.g. towards the bottom of the slope or in depressions. In flat landscapes like the Moree plains, the local topography plays a role and identification of subsoil salinity may require local assessment.

Due to the lighter texture of the surface soil, the texture contrast soils (e.g. Red Chromosols in Mungle SLU) tend to have lower PAWC (~150 mm, although dependent on texture). The Mungle SLU also has Red Ferrosols, Red and Brown Dermosols (previously called Red-brown Earths), which may have larger PAWC. Non-mapped areas within Mungle SLU representing, for example, drainage lines and depressions, may feature Vertosols and have a larger PAWC, subject to any subsoil constraints.

Table 2. APSoil characterisations in northern Moree Plains region with PAWC (to 180 cm or rooting depth)

APSoil	Soil landscape Unit (SLU)	PAWC (mm)	Soil	Soil constraints to PAWC
1279	Mungindi	204^{W}	Grey Vertosol	Constrained, salinity below 60 cm
1278	Hadleigh Park Road	195^{W}	Grey Vertosol	Unconstrained
1277	Turrawah	224^{W}	Black Vertosol	Unconstrained
1287	Turrawah	227^{W}	Black Vertosol	Unconstrained
1288	Turrawah	182^{W}	Black Vertosol	Unconstrained
55	Gurley	140^{F}	Brown Vertosol	No data, PAWC for fababean which usually extracts less water
59	Gurley	132^{C}	Grey Vertosol	No data, but PAWC profile suggests constraints below 60 cm
101	Gurley	266^{W}	Grey Vertosol	No data, but PAWC profile suggests unconstrained
102	Gurley	203^{C}-239^{W}	Grey Vertosol	No data, but PAWC profiles suggests unconstrained
233	Gurley	188^{C}	Black Vertosol	Constrained, salinity below 60 cm
234	Gurley	114^{C}-117^{W}	Black Vertosol	Constrained, salinity below 30 cm
235	Gurley	196^{C}-238^{W}	Black Vertosol	Unconstrained
238	Gurley	167^{C}-194^{W}	Grey Vertosol	Constrained, salinity below 90 cm
239	Gurley	121^{C}-154^{W}	Grey Vertosol	Constrained, salinity below 60 cm
870	Gurley	216	Vertosol	Constrained, salinity below 90 cm
1286	Gurley	191^{W}	Black Vertosol	Constrained, salinity below 120 cm
236	Mungle	153^{W}-209^{C}	Duplex Red Chromosol	Unconstrained
237	Mungle	103^{C}-139^{W}	Black Vertosol	Constrained, salinity below 60 cm
240	Mungle	147^{C}	Duplex Red Chromosol	Unconstrained
1285	Mungle	245^{W}	Black Vertosol	Unconstrained
68*	Terry Hie Hie	191^{W}	Grey Vertosol	No data, but PAWC profile suggests salinity below 90 cm
865	Terry Hie Hie	221^{W}	Vertosol	Constrained, salinity below 120 cm

*APSoil 68 not georeferenced, ^{W}=wheat, ^{C}=chickpea, ^{F}=fababean.

A chloride concentration of 600 mg/kg was taken as threshold to indicate salinity constraints on the PAWC, but the effects gradually increase with chloride concentration (Dang et al., 2008) and there are some subtle differences between crops (e.g. as shown here for chickpeas versus wheat, see Whish et al., 2007) for more details on the experiments that collected these data.

Reflection

The accessibility of soil landscape information online provides an opportunity to predict PAWC (and other soil properties) where measured data are not available. The information helps explain observed differences and similarities between APSoil PAWC characterisations and the soil at the site of interest. This will provide a first approximation of the PAWC, which will need to be finetuned with local observations of soil, landscape and crop performance over time.

Mixing and matching the information from the available resources (APSoil database, soil and landscape mapping, DSMs) is currently a challenge, as is some of the soil science language in the reports. The soils are described and classified using the highly technical Australian Soil Classification (Isbell et al., 2016) or using local names that are hard to extrapolate elsewhere. The current project is not only testing and refining the PAWC prediction processes, but also looking at how to make them more user-friendly. In the meantime, our advice is to explore some of the available information and maybe seek out soil experts who understand how soils vary across the landscape. In some regions, there are soil and land resource officers in state agencies (usually with a training in pedology) who have the detailed knowledge that can help.

The accumulated knowledge on yield trends and paddock differences (e.g. from yield mapping, farm records) can also be used to understand the inherent qualities of the soils, including PAWC. Under water-limited growing conditions, paddocks or areas within them with subdued yields may indicate PAWC constraining factors. These observations can be used to target further investigations, including into the presence of soil salinity, texture changes or other factors like shallow soil depth.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through cooperation with our PAWC and soil characterisations, their generous time discussing their soils and their support of the GRDC; the authors would like to thank them for their continued support. We also gratefully acknowledge the contributions of CSIRO colleagues and other collaborators involved with the field PAWC characterisations captured in the APSoil database. The information on PAWC presented in this paper heavily draws on the work over many years by Neal Dalgliesh (CSIRO). Discussions with him, Jeremy Whish, and others, including with those involved with soil-landscape mapping (Neil McKenzie, Rob Banks, Brian Murphy, Neroli Brennan, Andrew Biggs and Mark Silburn) helped develop the concepts and ideas presented in this paper. We thank Jeremy Whish and David Deery for their review comments on this paper.

Resources

APSoil database: https://www.apsim.info/apsim-model/apsoil/ (includes link to Google Earth file as well as to various papers and reports)

SoilMapp (soil maps, soil characterisation, archive and APSoil sites): Apple iPad and Android app; documentation: https://confluence.csiro.au/display/soilmappdoc/SoilMapp+Home

GRDC PAWC booklet: https://grdc.com.au/resources-and-publications/all-publications/publications/2013/05/grdc-booklet-plantavailablewater

eSPADE v2.0 (soil-landscape and land systems mapping and reports, reports on soil characterisation sites and DSM predictions): http://www.environment.nsw.gov.au/eSpade2Webapp

(Select 'Soil landscapes' or 'Soil and land resources', 'Soil Profiles', or 'Modelled soil properties' from menu on right and zoom into the area of interest after selecting 'Hybrid' as Base map)

Queensland Globe (LRA maps and more): https://qldglobe.information.qld.gov.au/
(Select 'Add Layers', then choose 'Land resource area mapping' under 'Geoscientific information' and zoom into the area of interest)

Queensland Land resources assessment manuals from:
https://publications.qld.gov.au/dataset?q=land+managament+manual

Soil and Landscape Grid of Australia: http://www.clw.csiro.au/aclep/soillandscapegrid/

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Linking remote sensing and climate data with variations in crop yield and soil constraints across paddocks

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Key words

web-based tool, yield variation, remote sensing, soil constraints

GRDC code

UOQ1803-003RTX. Economics of ameliorating soil constraints in the Northern Region: Spatial soil constraint diagnoses in the northern region

Take-home messages

- There is useful information in historic remote-sensing data, but the data requires considerable processing and analyses
- Data on factors influencing the variation of yields, in particular soil constraints and seasonal rainfall, can help interpret any consistent spatial patterns of within-field yield variation
- We are developing a web-based tool to process the data and make the information easily accessible and interpretable
- The tool should provide growers with better knowledge of past performance and of consistent spatial patterns of yield variation that could be attributable to soil constraints.

Introduction

Better knowledge and understanding of the variation of past crop yields (both spatially across a paddock, and temporally from season to season) can help growers make better management decisions to improve yields in future. Information about the most important drivers of this variation can provide further help. The remote-sensing data compiled from earth-observing satellites provides a valuable information source. In particular, the Landsat series of satellite images (Landsat 5, 7 and 8) provide a consistent set of data dating back to the 1980s. These provide a good opportunity to look at consistent patterns through time – that is, spatial patterns of yield variation that repeat season after season. Such consistent patterns might imply the presence of some kind of soil constraint limiting yields in parts of the field.

For the remote-sensing data to be useful to growers, there is a substantial amount of processing involved:

(i) Accounting for atmospheric effects and the removal of clouds from each image
(ii) The selection of the most relevant images (from a time series of images) and the calculation of an appropriate index to represent the property of interest in any given growing season (yield)
(iii) Statistical analyses of the resulting dataset.

The aim of the work in this project is to develop a web-based tool that growers can use to look at past crop yields in their paddocks and detect any consistent spatial patterns. Along with the processing and analysis of the remote-sensing data, the tool will compile and present past rainfall data and maps of soil constraints. The data on these driving factors could help the user to interpret the variation shown by the remote-sensing data. The tool will aim to make the analysis easy to use and interpret.

Here, we present work towards the development of this tool, and illustrate the type of information it will provide. The illustration is described as a number of steps, some of which the user of the tool will follow, and others which describe the processing and output of the tool.

Illustration

The user inputs the field boundary

The user inputs the field boundary on a map in a web browser. For example, Figure 1 shows the field boundary for a field (called Grandview) at a farm near Biloela, Queensland, which will be used as an illustration.

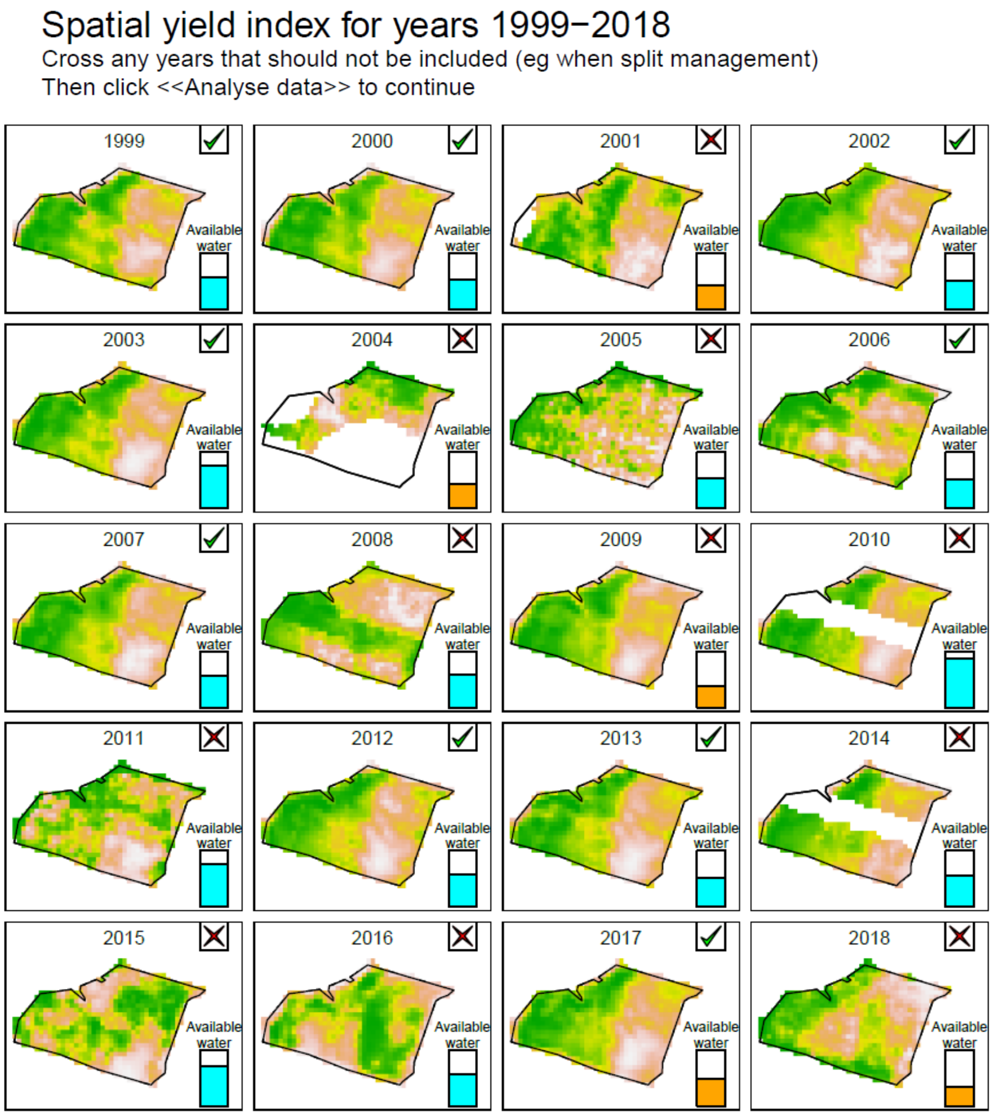
Figure 1. The Grandview field boundary, which will be used as an illustration site; the user will enter this boundary by navigating and clicking the boundary points on a map

Remote-sensing data are collated and analysed to give a yield index for each growing season

When the user has entered the field boundary, the remote-sensing data from within the field boundary are compiled and analysed; maps are presented of a yield index for each growing season dating back to 1999 (Figure 2). To produce each of these maps, time series of images are compiled for each season (not shown here), and images from close to the time of maximum biomass used to calculate a vegetation index, which correlates with yield. For each growing season, the time series is also analysed to determine whether there is enough information to conclude that a winter crop was grown; if so, then a tick is displayed next to the map, else a cross is displayed. The user will have the chance to unselect certain years, for instance years where it is evident that the field was split into different management zones (so that when summarising the long-term results, spatial variation due to management differences within the field does not get confused with spatial variation due to soil constraints). Only maps for the ticked years will be considered in further analysis. It should be noted that the maps show spatial variation within the field in any given season but cannot be used to compare yields across different seasons.

Also shown next to the map for each winter growing season is the growing-season available water, defined here as a third of the preceding summer rainfall plus the current winter rainfall (French and

Schultz, 1984). A recent study (Chen et al., 2019) used this as a variable to summarise climate in a simple model for predicting wheat yield, with peak yields predicted to occur at around 450 mm, and 25% reductions from the peak yield predicted at around 300mm; in the plots, the growing-season available water is shown on a scale of 0-600 mm and is filled light blue or orange, depending on whether the growing-season available water fell above or below 300mm. Although this information is presented here, it is not currently used by the tool, but is something that will be developed further during the course of the project.



Spatial yield index for years 1999−2018
Cross any years that should not be included (eg when split management)
Then click <<Analyse data>> to continue

Figure 2. The yield index based on analysis of the remote-sensing data for the 20 growing seasons from 1999 to 2018. Ticked years indicate when there was sufficient evidence in the remote sensing data to conclude a winter crop was grown, crossed years indicate when the data did not support this conclusion. Available water, defined as a third of the preceding summer rainfall plus the season's winter rainfall, is also shown, on a scale of 0-600mm, and coloured orange when less than 300mm

The produced yield index data for all growing seasons are analysed and any consistent spatial patterns shown

The data from the ticked years are summarised by a map of the mean for each pixel, and a statistical analysis is applied to each pixel to determine whether there is evidence that it has been consistently high or low yielding. This splits the field into three categories; consistently high, consistently low, and moderate (Figure 3).

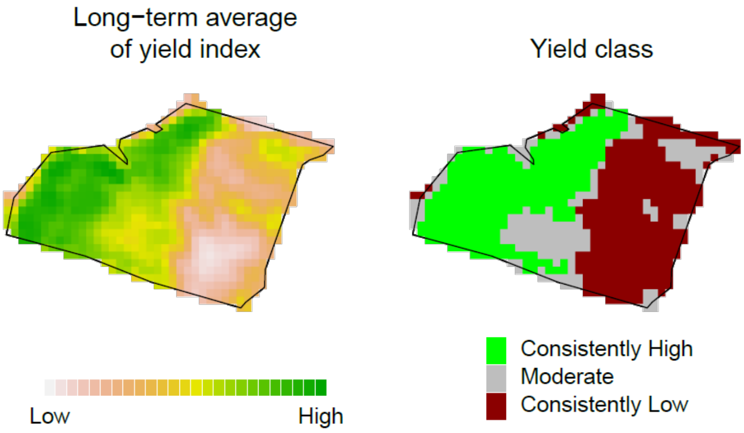


Figure 3. Maps summarising the long-term average of the yield index (over all cropped years) and its classification into consistently high and low yielding areas

Soil maps based on legacy datasets are displayed for comparison

Also shown by the tool are maps of soil constraints (Figure 4; Orton et al., 2020; Lai et al., 2020), produced based on 'legacy' soil data (data collated from state and CSIRO soil databases; Searle, 2014), as well as data on 'environmental covariates' (climate, terrain, radiometric surveys, soil order maps). For illustration, Figure 4 shows predictions of exchangeable sodium percentage (ESP, for soil sodicity) and electrical conductivity (EC, for soil salinity) across the field, although information for other soil constraints will also be available in the tool. The soil maps are shown next to the long-term yield summary maps, to allow comparison. The maps of the soil constraints provide the user with some background information, but because they are produced based on legacy data (perhaps the nearest soil profile measurement being from another farm), it is unlikely that they will provide the grower with new knowledge of the field.

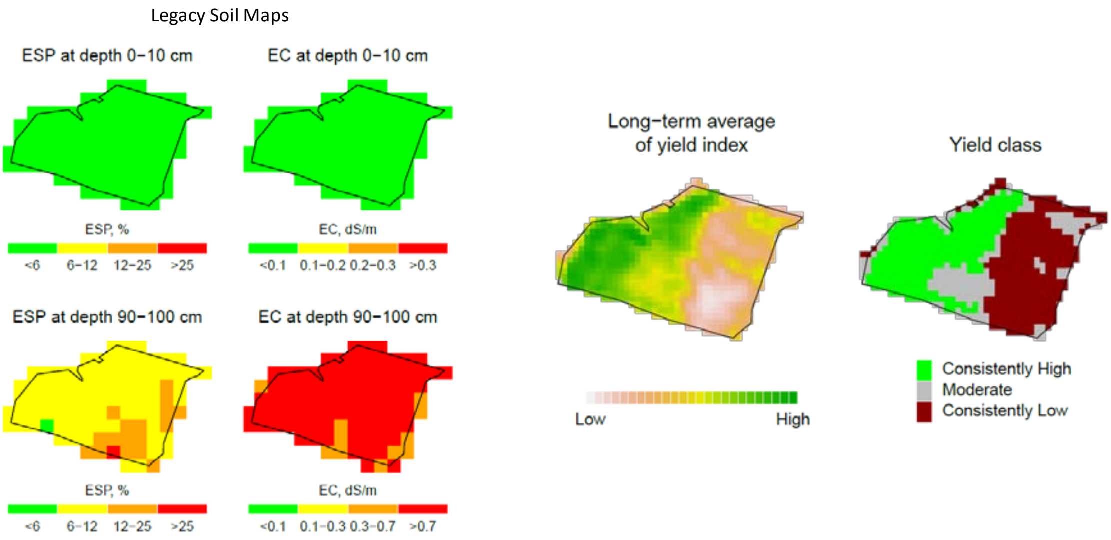


Figure 4. Soil maps for exchangeable sodium percentage (ESP, for soil sodicity) and electrical conductivity (EC, for soil salinity) produced based on the legacy soil data. Maps summarising the yield index are also shown for comparison

The user has the opportunity to input their own local soil data, and the legacy maps are then updated

To provide more useful local information on the spatial variation of soil constraints within the field, the user will have the option of entering their own local soil data, which will be used to update the soil maps that were produced based on the 'legacy' soil datasets. This feature will allow the user to get the most out of all information sources (legacy and local data and the relationships between the soil constraint and the environmental covariates). For the illustration site, the updated maps are shown in Figure 5, again shown next to the long-term yield summary maps. In this example, the maps of both subsoil ESP and subsoil EC show similar spatial patterns to the map of the long-term average of the yield index, suggesting that these soil constraints might be causing the within-field yield variation.

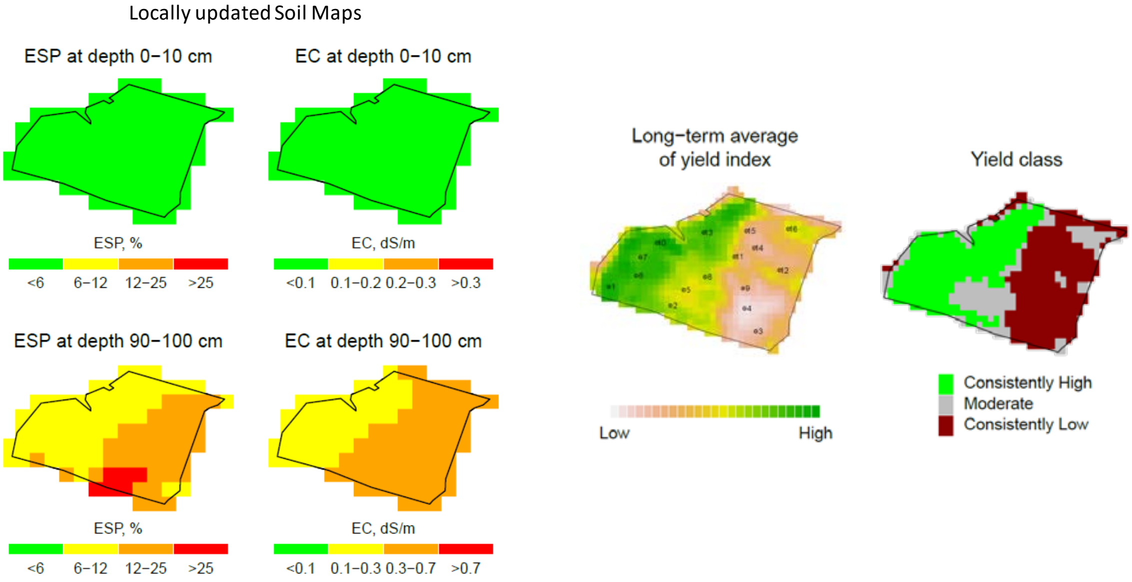


Figure 5. Soil maps for exchangeable sodium percentage (ESP, for soil sodicity) and electrical conductivity (EC, for soil salinity) produced based on the legacy soil data and updated given the local soil data. Maps summarising the yield index and showing the local soil data locations are also shown for comparison

If local data are inputted, the tool also displays and compares soil profiles in high and low yielding areas.

If the user has inputted their own soil data, then the tool will allow comparison of soil profile plots for profiles that fall in the different yield classes. Figure 6 shows the illustration, with local data on ESP, EC and soil chloride (Cl). The most notable differences between the low-yielding and high-yielding areas of the field are below 50cm in the soil profile, with the low-yielding profiles being characterized by higher values of subsoil ESP, EC and Cl.

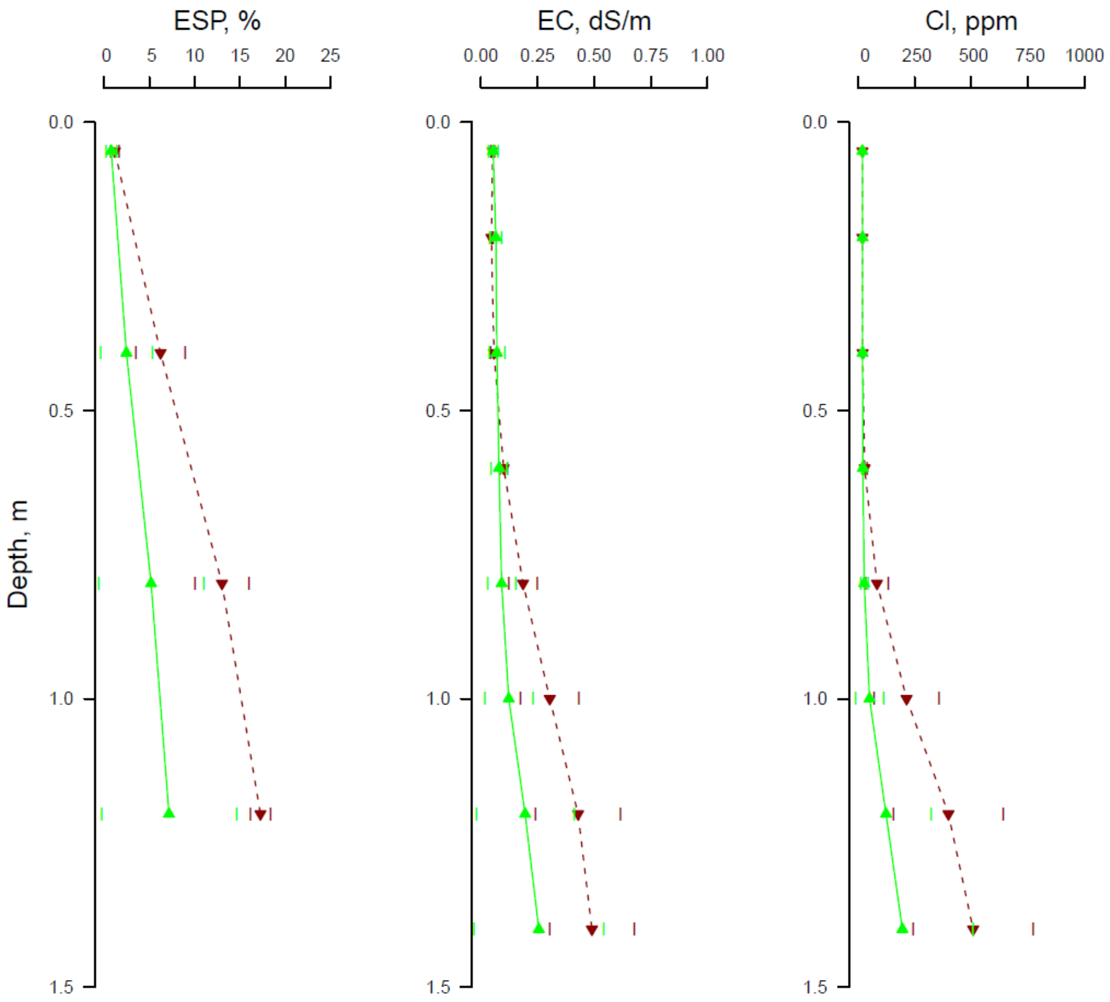


Figure 6. Average soil profile data from within consistently high yielding (green solid lines) and consistently low yielding (dark red dashed lines) areas. Measured soil constraints shown are exchangeable sodium percentage (ESP), electrical conductivity (EC) and soil chloride concentration (Cl)

How can the tool help growers?

Identification of consistently poor yielding areas of a field can help growers to target further soil sampling to better understand the factors causing this yield variation. If local soil data can explain the spatial patterns of yield variation, then appropriate amelioration strategies can be considered, which is the focus of work in another linked GRDC project. In many cases, the tool might only serve to confirm what the grower already knows, while in other cases the tool might provide valuable new insight.

Further work

Over the remainder of the project, we will look at:

- Refining and validating the yield index so that it better represents yield in any given season
- Whether there is evidence that the spatial variation of yield is different in wet and dry years, with less impact of soil constraints being expected in years when there is sufficient in-season rainfall; this feature could be added to the tool in future
- Correlating the remote-sensing data with the soil data and rainfall data statistically, to see if this can provide improved predictions of soil constraints leading to yield loss

- Improving the legacy soil maps by including more recently collected soil data and satellite-based covariates
- Building the computer code into a web-based application.

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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 authors would like to thank them for their continued support. The authors also thank Darren and Tanya Jensen for providing data for use in the illustration. Landsat imagery was supplied by the United States Geological Survey. The support and resources provided by the Queensland Remote Sensing Centre, Department of Environment and Science is also gratefully acknowledged.

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Mapping soil properties and their impact on yield - combining Dual EM, gamma radiometrics, elevation and soil colour to select sampling sites to predict soil properties and investigate their impact on yield across the paddock

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Key words

digital soil mapping, soil constraints, yield analysis, proximal sensing, EM survey

Take home messages

- Although EM surveys are a cost-effective tool to map variation in topsoil and subsoil properties, they do not show which soil properties are causing the variation
- Digital soil mapping can create maps of soil properties that can be used to investigate spatial patterns of yield limiting factors at a resolution as fine as a few hectares in a few thousand hectares
- Experience has shown that only some yield-limiting soil factors can be changed, we believe there is value in understanding whether yield is limited by underlying soil properties or by management
- At this stage soil samples are required to map soil properties.

Glossary

Covariates in digital soil mapping are the spatial properties that are used to predict the pattern of soil properties between the points where the soil is sampled. Covariates include EM survey, soil colour, digital elevation model.

Kriging is a statistical technique used to create surfaces from point data using the variation in the data set to estimate how much to smooth the fitted surface.

Multivariate linear regression is a linear equation in which multiple factors are used to predict a soil property. A general equation is: *prediction= a +b*covariate1 +c*covariate2+…..*

Machine learning builds mathematical models without specific instructions.

Proximal sensing is the collection of soil data using instruments that are close to the soil, but do not rely on soil contact, as opposed to remote sensing where the sensors are metres to kilometres from the site.

Regression kriging predicts soil properties using regression and kriging the difference between measured and predicted values. A general equation is:
prediction = trend predicted using regression + residual predicted using kriging

Surface refers to the spatial pattern of a particular variate across an area. E.g. a map of the depth at which the critical value of 10% exchangeable sodium (ESP) was reached.

Introduction

There have been many improvements in the availability of data and in the statistical techniques used to generate digital soil maps over the past 20 years (Minasny and McBratney, 2015). The data improvements have included relatively widespread availability of measures of landscape variation, such as satellite images and digital elevation models, and on farm measures of variation in the form of electromagnetic induction (EM) and yield variation from yield maps. The statistical techniques have progressed from multivariate linear regression through regression kriging (Odeh et al., 1995) and machine learning with kriging of residuals. These models can be used to make 3d predictions of soil properties. To date, digital soil maps have been produced predominantly by researchers and government agencies (Minasny and McBratney, 2015).

The agronomic value of maps of predicted soil properties can be tested by evaluating the correlation between these predictions and crop yield. The project we conducted was essentially an evaluation of the process of combining covariate data with measured soil properties to create digital maps of soil properties and then evaluating the correlation between the predicted soil properties and crop yield.

Methods

The project was conducted on an approximately 2,000 ha irrigation development on Cubbie Station, a large cotton farm in south western Queensland. The data used were a proximal sensing survey of electromagnetic induction, gamma radiometric and elevation; records of cut and fill, and a bare soil redness index from the Landsat 5 satellite. This data was combined to create a covariate database, and then used to direct the sampling of 70 soil cores at four depths (0-30, 30-60, 60-100, 100-140 cm) which were analysed in the laboratory for pH (1:5 $CaCl_2$), exchangeable cations, EC and texture (sand, silt, clay). Relationships between the laboratory measured properties and the covariate dataset were investigated and used to create continuous surfaces of each property at the four depths across the study area (Figure 1).

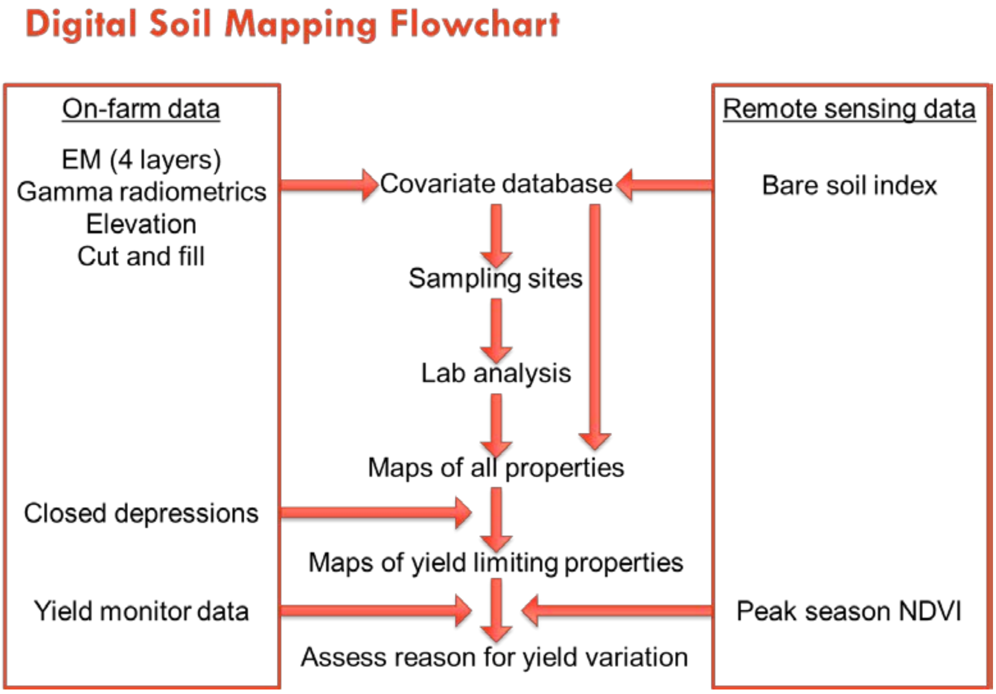

Figure 1. Process used to assess soil reasons for yield variation using digital soil mapping

The potential effect of soil properties on crop growth was assessed by surfaces of the depth to selected critical values. The critical values used were; ESP of 10%; electrical conductivity of saturated extract (ECe) of 10 dS/m; and $pHCaCl_2$ of 8. Correlations between modelled soil properties and cotton lint yield for the 2016- 17 growing season and satellite borne vegetation indices for five years in total were investigated.

Results and discussion

We will describe patterns of 3 of the 9 soil properties that we mapped. These are pH, salinity measured as ECe and sodicity measured as exchangeable sodium percentage (ESP) selected on the basis that there is a body of knowledge indicating a reasonably direct effect of these properties on plant growth. Soil pH was very consistent across the 70 sites assessed (Figure 2). This indicates that soil maps are unlikely to show a spatial effect of pH on crop growth and yield. Salinity measured as ECe was low and uniform in the surface to 30 cm layer and increased and became more variable with depth. This pattern indicates that there may be variation in soil properties that affects plant growth and yield. Average ESP doubled between the 0 to 30 and 30 to 60 cm layer and increased a further 50% to the 60 to 100 cm layer. The coefficient of variation (standard deviation divided by mean) decreased from 33% in the surface to 30 cm layer, to 26% in the 100 to 140 cm layer. The rapid increase in ESP with depth and moderately large variation indicates that there it is a likely contributor to crop yield variability.

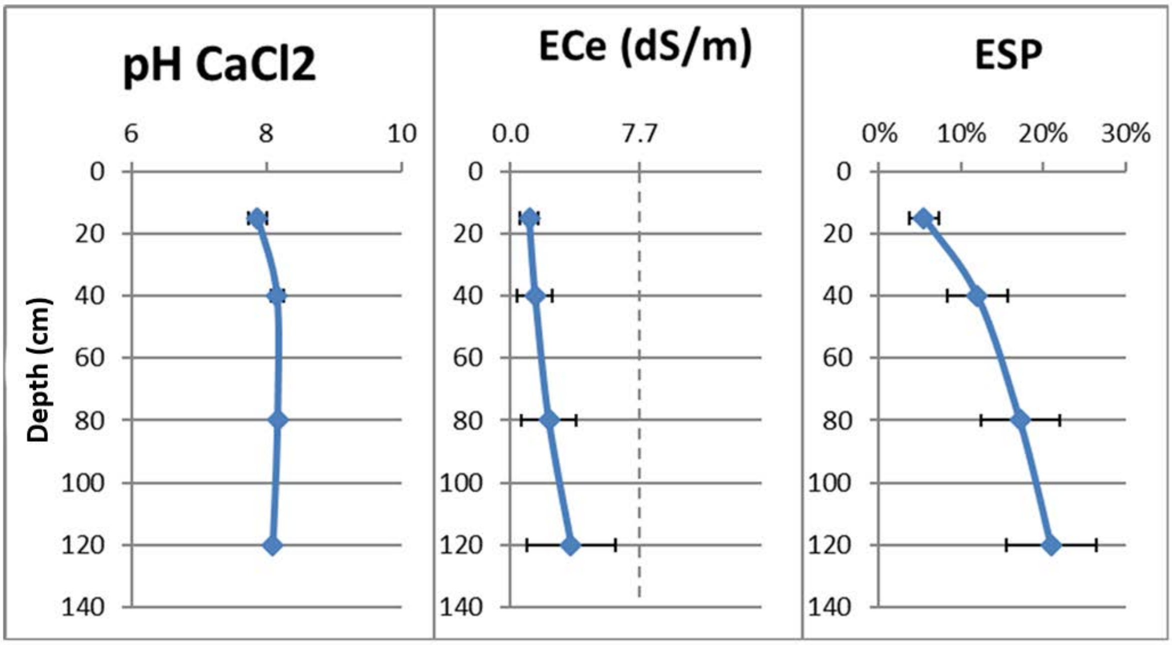

Figure 2. pH ($CaCl_2$), ECe (dS/m) and ESP (%) average and standard deviation of 3 selected properties at 4 depths in 70 sites across more than 2,000 ha of Cubbie Station

The depth to critical soil chemistry values found that the average depth to ECe of 10 dS/m was greater than 140 cm, while the average depth to ESP of 10% was shallower than 50 cm. There was substantial variation over relatively short distances in the depth to critical ESP (Figure 3). A local correlation was used to quantify the relationship between the variation in depth to ESP and yield. In summary, the boxplot in Figure 3 indicates that there was a substantial yield difference between areas where the depth to 10% ESP was shallower than 25 cm and all other depths. This is encouraging in that it indicates that there is potential to increase yield by lowering ESP of the surface 15 cm rather than the whole profile.

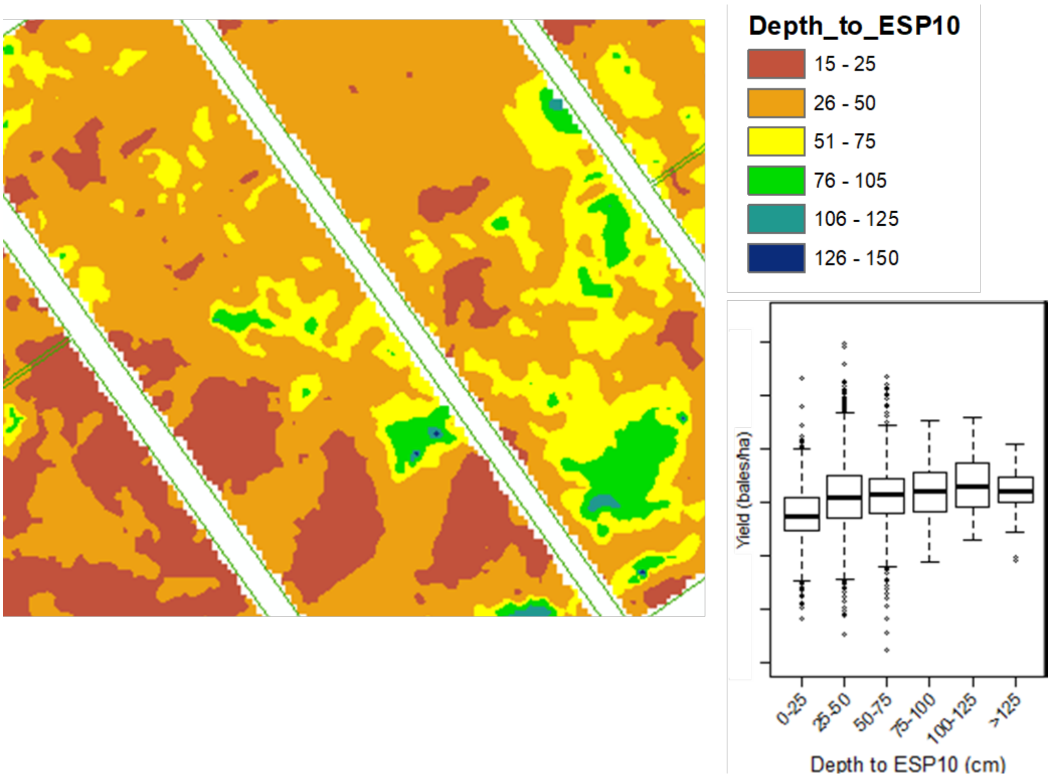

Figure 3. Surface of depth to 10% ESP and boxplot of the correlation between depth to ESP and cotton yield

The correlation between mapped soil properties and crop yield was investigated further by using machine learning to predict the yield of each 20 m by 20 m pixel across the area mapped as dependent on the depth to ESP >10%, depth of ECe >10 dS/m, depth of closed depressions, depth of cut and fill and distance from head ditch. By artificially removing one constraint from the regression we obtained an indication of the yield difference attributed to each constraint. This is demonstrated for closed depressions in Figure 4.

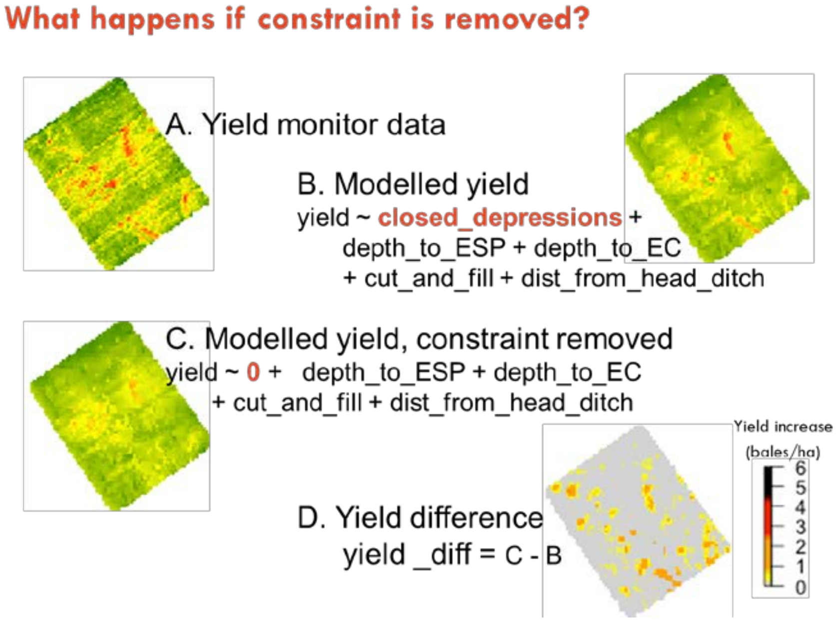

Figure 4. Conceptual model of process to quantify the potential yield benefit of removing yield constraint of closed depressions

Conclusions

- This project demonstrates that while digital soil maps are not an end in themselves, they can be used in association with yield maps to quantify the yield cost of soil constraints.
- Variation in soil properties can affect yield if there is substantial variation in the property, and substantial areas with values that are both lower and higher than the critical value. This occurred most notably with ESP at this site, while the variation in pH $CaCl_2$ and ECe had a smaller impact on yield variability.
- The relationships between covariates and soil properties appear not to be universal, so soil samples are currently required for each survey project, and the covariates vary between sites in their efficacy at predicting soil properties.

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Acknowledgements

The project was undertaken with financial support, encouragement and assistance from Cubbie Agriculture.

Support was also provided by the Sydney Institute of Agriculture & Precision Agriculture Laboratory at The University of Sydney

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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A data-based approach to diagnosing & managing constraint-based yield variability

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Key words

precision agriculture, soil amelioration, variable-rate, soil investment, soil sampling

GRDC code

GRS11002

Take home messages

- Soil sampling is a capital investment, not an operational expense
- We cannot accurately manage multiple constraints using a single set of agronomic soil zones (as opposed to mapping the variation of multiple constraints operating individually or with co-dependence on other constraints)
- It is more beneficial to use soil samples to develop continuous variable-rate soil amelioration maps, not zone maps
- The economically optimum sampling density for soil amelioration is dependent on the inherent variability within a paddock.

Introduction

How many soil samples should be taken within a paddock to provide variable-rate soil amelioration advice? Increasing sampling density will improve the accuracy of the recommendation, however, at some point the cost of taking additional samples will outweigh any economic benefit of an improved recommendation. This body of work aimed to identify the economically optimum sampling density for soil amelioration, taking the amelioration of sodicity as an example. This study also compared the error of blanket-rate application (blanket-rate application is when a single rate is applied across a variable paddock, with the rate often being based on bulked soil sampling) zone-based variable rate and continuous variable rate approaches for amelioration (where error is defined as the estimated cost of under- or over-application of gypsum). (N.B. continuous variable rate maps are not reduced to zones, but instead offer the ability for true precision management, where every 12x12 metre pixel can be managed independently within the paddock). The study investigated the treatment of sodicity to 20 cm and 60 cm depths, with the results for 60 cm treatment presented here. Whilst treatment to 60 cm is not currently possible with commercial equipment (however development in this space is currently occurring), it is crucial to investigate possible yield responses of such treatment to provide an estimated cost-benefit of the equipment investment. Furthermore, the primary focus of this work was to provide indication toward the likely sampling density required for treatment to this depth.

Soil amelioration

Soil amelioration is the process of identifying and alleviating soil constraints (e.g. compaction, salinity, sodicity, acidity and alkalinity). Soil constraints are often highly variable at the sub-paddock scale, and can be interacting or operating independently of each other, meaning their spatial management is extremely difficult without sufficient soil information. Furthermore, amelioration of constraints is expensive, meaning small application errors can be highly economically detrimental, both due to wasted amendment from over-application, and lost yield potential from under-application. Investment in soil amelioration therefore requires significant soil information before making investment decisions.

Method

To identify the economically optimum sampling density for soil amelioration, a 100 ha broadacre site under cereal/pulse rotation was selected. 300 soil cores on a 60x60m grid were collected (3 cores/ha) and analysed for moisture content, bulk density, texture, pH, electrical conductivity, aggregate stability and exchangeable cations (calcium, magnesium, sodium and potassium) at 0–10cm, 10–20cm, 20–40cm and 40–60cm depth increments. This equated to directly measured soil properties and an additional nine environmental covariates (i.e. 4x years of yield data, 4x electrical conductivity (ECa) readings from a DUALEM and 1x elevation layer) at each core location. Using this benchmark dataset, the paddock's 'true' amelioration requirements were identified to a treatment depth of 60 cm. In this case, 'true' was defined as the level of detail obtained by a potential maximum investment for soil analysis at current sampling costs (i.e. 300 cores in 100 ha).

The economically optimum sampling density was subsequently assessed by simulating gypsum recommendations at sampling densities of 0.1–3 samples per ha and comparing them to the original 'true' gypsum requirement maps. This indicated how wrong the gypsum recommendation was (in terms of over- and under-application) at varied sampling densities using either a blanket-rate, zone-based variable-rate or continuous variable-rate approach. The cost of over-application was calculated by multiplying the total over-applied tonnage by the on-farm gypsum price (i.e. $110/t), whereas the cost of under-application was estimated using a site-specific yield model that was developed using the 300 directly measured soil cores and 4 years of yield data. This model was used to estimate the spatial yield response of gypsum application, and subsequently estimate the lost yield potential of under-application. The cost of this under- and over-application error was then compared against the cost of sampling at each density to identify the economically optimum number.

Results/discussion

Application error

For each sampling density (i.e. 0.1–3 cores/ha) and each application method (i.e. blanket-rate, zone-based variable-rate and continuous variable-rate), gypsum recommendations were simulated, and their spatial application error assessed. An example of this is presented in Figure 2. The application error at each density was subsequently quantified for the entire paddock and is presented in Figure 1. For 0–60 cm treatment, marginal application improvements can be observed by increasing sampling density for either blanket-rate or zone-based variable-rate methods. Whilst zone-based variable-rate applications provided improved application accuracy over a blanket-rate approach, the continuous variable-rate method was far superior, particularly at sampling densities ≥ 0.2 cores/ha (1 sample per 5 ha). Furthermore, the accuracy of the continuous variable-rate method improved greatly as sampling density increased. However, marginal improvements were observed when sampling density increased above 0.5 cores/ha, indicating that collecting more soil data provided minimal gains in any spatial prediction accuracy.

The predicted spatial yield response due to the application of gypsum was estimated using a site-specific yield model which was developed using the original 300 soil cores and 4 years of yield data.

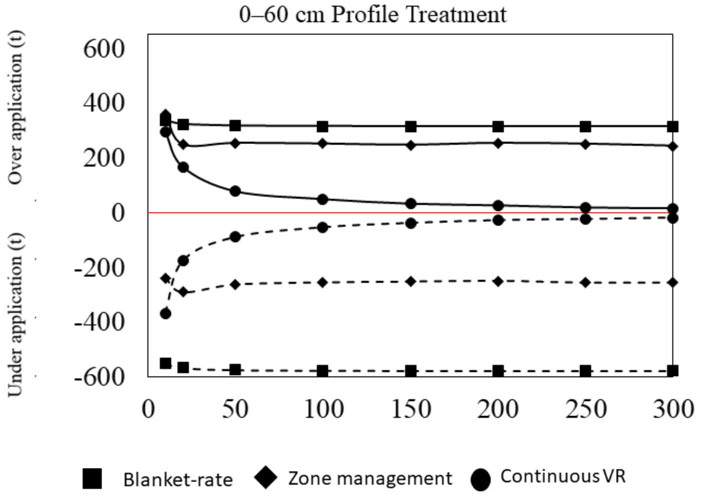


Figure 1. Simulated over- and under-application of gypsum at sampling densities 10–300 cores (i.e. 0.1–3 cores/ha). For each simulated recommendation based on x number of samples, the corresponding over-application error is displayed on the positive y axis (in tonnes), and the under-application is displayed on the negative y axis. As sampling density is increased, the gypsum recommendations generally become more accurate as over- and under-application is reduced

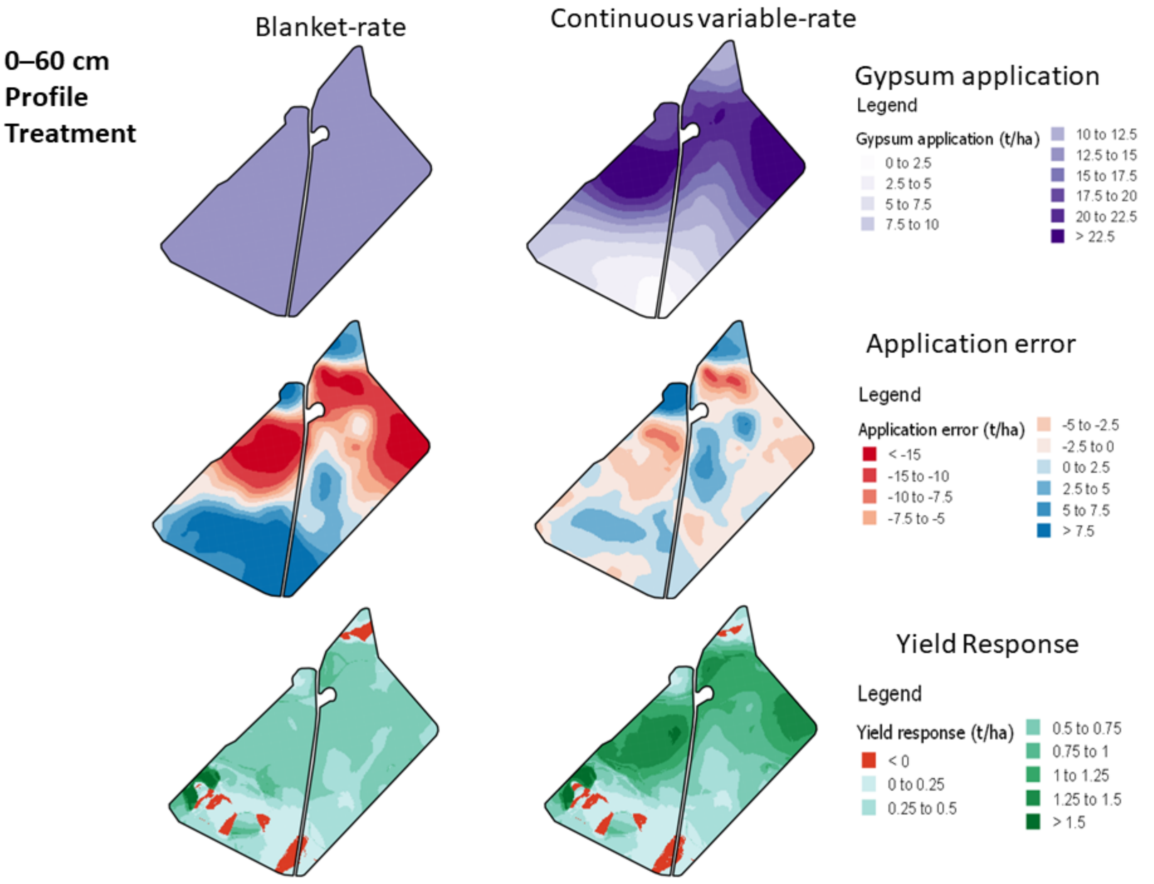


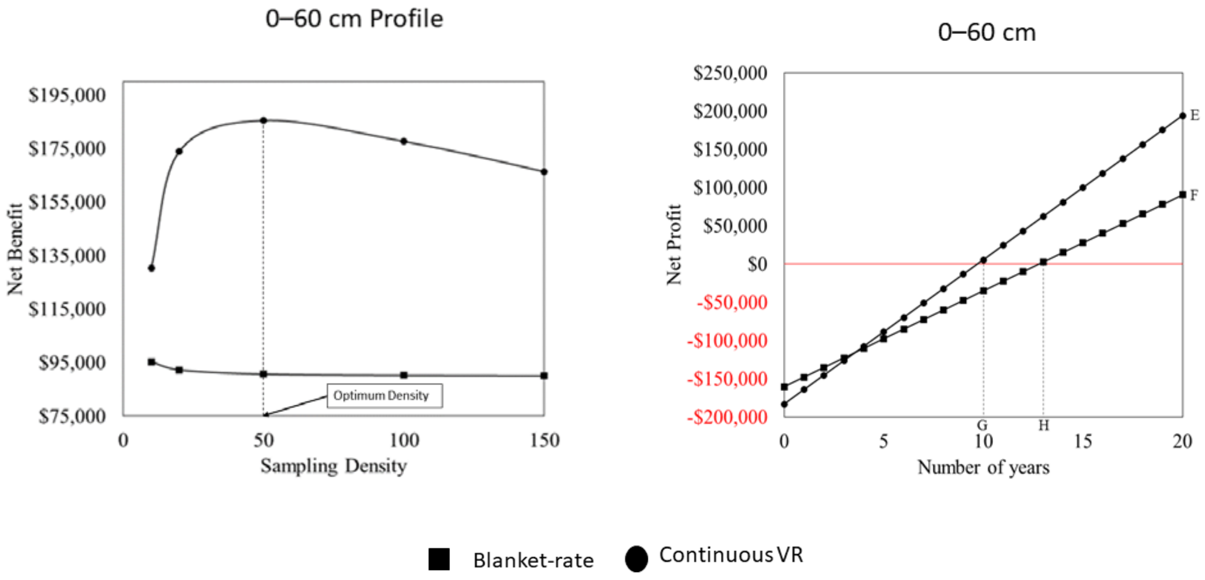
Figure 2. Example of gypsum application based on sampling density of 0.5 cores/ha taking a blanket-rate approach and continuous variable-rate approach for treatment to 60cm. Maps display the

resulting gypsum application, the error of that application and the corresponding predicted yield response of the application

Return on investment

The economically optimum sampling density for the investigated site was identified by assessing the cost-benefit of each simulated gypsum application, both using a blanket-rate approach and continuous variable-rate approach. This was achieved by totalling the predicted annual yield benefit for each simulated gypsum application associated with varied sampling densities over a twenty-year period and comparing against the cost of sampling and amendment (Figure 3a). It can be observed that as sampling density increases to 50 (i.e. 0.5 cores/ha), the largest net benefit of the application can be achieved. At sampling densities below this, the cost of application error exceeds that of the cost of sampling, and at sampling densities above this, the cost of sampling outweighs any benefit of a spatially improved recommendation.

The return on investment of the gypsum application for sodicity amelioration using a continuous-variable rate approach at a sampling density of 0.5 cores/ha was also estimated and is presented in Figure 3b. Whilst at year 0, the cost of taking a continuous variable rate approach was increased, due to an increased sampling requirement, the estimated cost-recovery period of sodicity amelioration was reduced to 10 years, as opposed to 13 years for a blanket-rate approach. Furthermore, the net benefit of the continuous variable-rate approach was estimated to be approximately $100k over the blanket-rate approach, for treatment to 60 cm on this 100ha site over a time period of 20 years.



(a)

(b)

Figure 3 (a). Net benefit of gypsum application based on a blanket-rate approach and continuous variable-rate approach at sampling densities 0.1–3 cores/ha in a 100ha paddock after 20 years (sampling densities >150 omitted from figure). **(b)** Rate of return for gypsum application based on a sampling density of 0.5 cores/ha for blanket-rate and continuous variable-rate approaches

Conclusion

This work estimated the economically optimum sampling density to be approximately 0.5 samples/ha (50 in a 100 ha paddock) for the treatment of sodicity to 60 cm. However, the economically optimum sampling density for any given paddock is site-specific and is dependent on soil formation factors and the inherent variability of that paddock. Therefore, a thorough understanding of the pedology, local geomorphology and underlying geology needs to be linked to these digital soil mapping techniques. Future work aims to integrate this information with other field variability layers to inform the optimum sampling density at an unvisited site. Current work is also investigating the feasibility of gypsum application below surface soil layers, and this should be a consideration for further refinement of optimum sampling densities.

Soil amelioration and the sampling required to undertake it, is a capital investment within the farming business. Cost-recovery of these investments need to be included in medium-long term strategic business development plans.

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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Yield stability across sowing dates: how to pick a winner in variable seasons?

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Keywords

flowering time, adaptation, sowing opportunity

GRDC code

DAN00213 (Grains Agronomy and Pathology Partnership, GRDC and NSW DPI)

Take home messages

- Match optimal flowering period to growing environment to maximise grain yield potential
- One variety doesn't fit all; there are no commercially available varieties that are broadly adapted across a wide range of sowing times or growing environments
- Optimising variety phenology and sowing time combinations achieves grain yield stability across a wide sowing window
- Probability of sowing opportunities will influence variety choice and sowing time decisions.

Background

Across the northern grains region (NGR), wheat is sown across a window from early to late autumn (April–May). There are a range of commercial cultivars which vary in their phenology from slow developing winter types to fast developing spring types, providing growers with flexibility in their sowing window. Field experiments were sown at ten locations in the NGR to determine phenology and yield responses across different environments. The experiments were conducted from 2017 to 2019, and annual rainfall at the ten locations ranged from 184mm to 620mm. The aim of these experiments is to provide growers with regional information about variety adaptation and recommended sowing times.

Aim to target optimal flowering period (OFP) for your growing environment

Across the environments of the NGR, one of the primary drivers of yield and grain quality is flowering time. When considering variety options at sowing, growers should aim to synchronise crop development with seasonal patterns so that flowering occurs at an optimal time. This period is a trade-off between increasing drought and heat threat, and declining frost risk. Across the NGR, the optimal flowering period (OFP) varies from late July in central Queensland to mid-late October in southern NSW. There is no 'perfect' time to flower when there is no risk, rather there is an optimal period based on minimising risks, and maximising grain yield based on probabilities from previous seasons.

Previously, we proposed OFPs from simulations using the APSIM cropping systems for locations across the NGR, based on historical climatic records (1961–2018) according to the parameters outlined by Flohr et al. (2017) for a fast spring genotype (Harris et al., 2019). These OFPs have now been validated using recorded flowering dates and grain yield from field experiments conducted across the NGR from 2017 to 2019. It was determined that the OFP varies significantly in timing and duration, as well as for different yield levels across environments (Figure 1). As flowering time is a function of the interaction between variety, management and environment; the variety x sowing time combinations capable of achieving OFP and maximum grain yield also varied across environments of the NGR (Figure 1).

In very dry seasons, such as 2019, yields are often higher when the crops flower earlier than the OFP; while in wetter seasons, such as 2016, flowering later does not induce the same yield penalties. Despite this, our field data supports the idea that growers should target the OFP for their growing environment to achieve maximum grain yield potential.

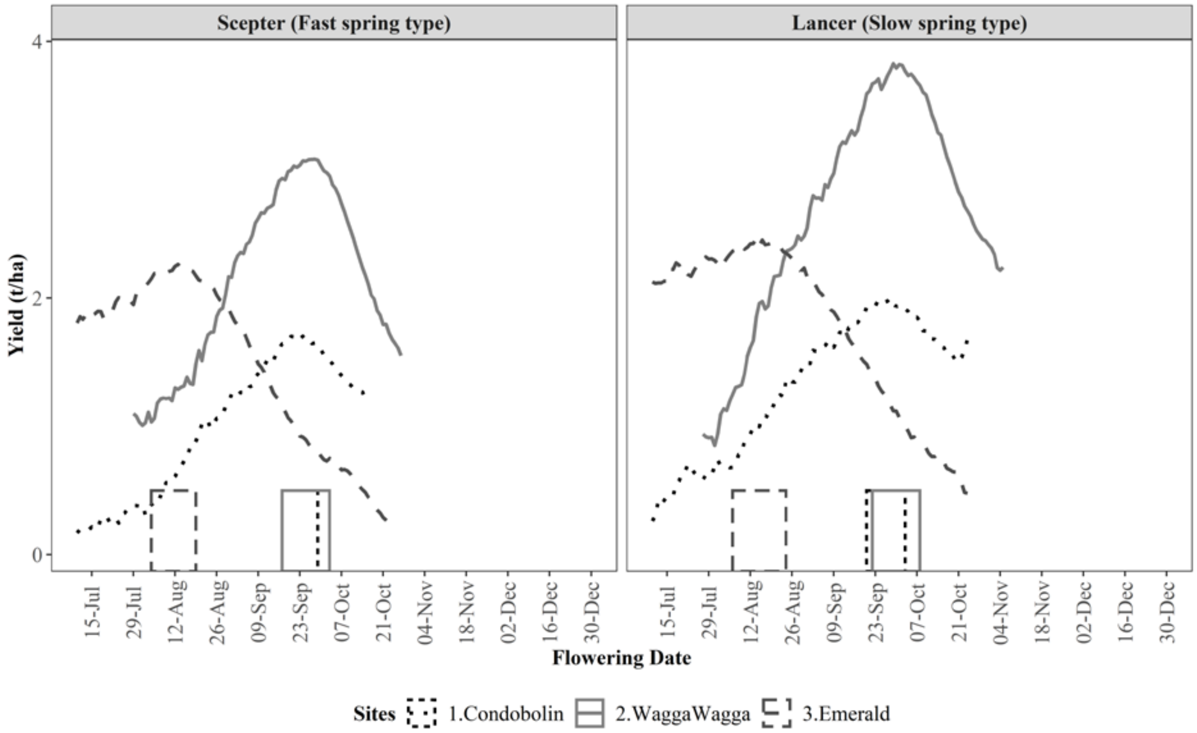

Figure 1. The optimal flowering period (OFP) for a fast spring variety (Scepter⍉) and a slow spring variety (Lancer⍉) determined by combining field data from experiments (2017-2019) and APSIM simulation using methods of Flohr et al. (2017) for Condobolin, Wagga Wagga and Emerald. The lines represent frost and heat limited yield (kg/ha), while the boxes on the x-axis represent the predicted OFP defined as ≥ 95% of the maximum mean yield

One cultivar doesn’t fit all - need to match variety and sowing time

Timing of flowering is influenced by phenology (genotype (G)), location and season (environment (E)) and sowing time (management (M)). Significant G × E × M interactions influencing grain yield responses across environments have been identified. The implication of these findings is that there are no commercially available varieties that are broadly adapted across a wide range of sowing times or growing environments. Differences in seasonal rainfall and temperature extremes imposed during the critical flowering period, which could have been influenced by sowing time, indicated that variety performance is also highly dependent on season. Despite this, there is evidence to suggest that variety choice can be exploited by growers to achieve OFPs and relatively stable yields across a wide sowing window. For example, in Wagga Wagga, southern NSW, winter wheat (for example; LongReach⍉ , Kittyhawk⍉ and Longsword⍉) require earlier sowing to flower within the optimal period, due to their extended phase duration and slower development pattern. Slower developing spring types (for example; Lancer⦶) are suited to late-April, early-May sowing dates, while mid to fast spring types (for example; Beckom⦶ , Condo⦶) are sown mid-late May to synchronise development and target the OFP (Figure 2).

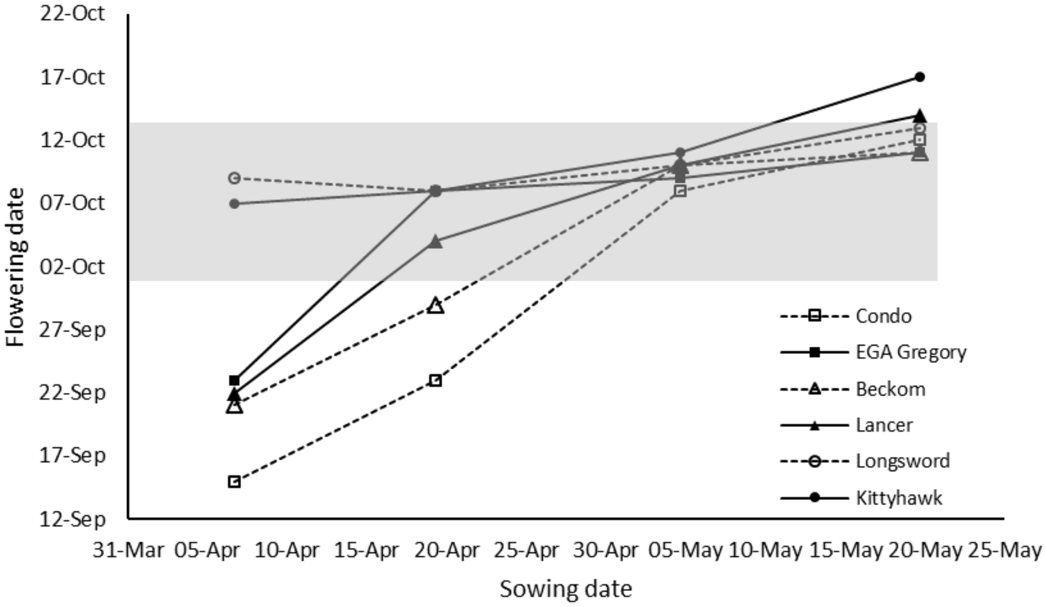

Figure 2. Mean heading date responses from selected winter and spring cultivars at Wagga Wagga (2017-18) and Marrar (2019) across all sowing times. Shaded area represents the optimal flowering period

In southern NSW, when slower developing varieties (for example; winter type EGA Wedgetail⦶) are sown early and achieve OFP, they are capable of higher water-limited yields compared with faster developing spring varieties sown later. However, faster developing varieties (for example; Scepter⦶) are better adapted to regions with shorter growing seasons, and in environments or later sowing scenarios where frost and heat stresses occur in close proximity to each other (Figure 3).

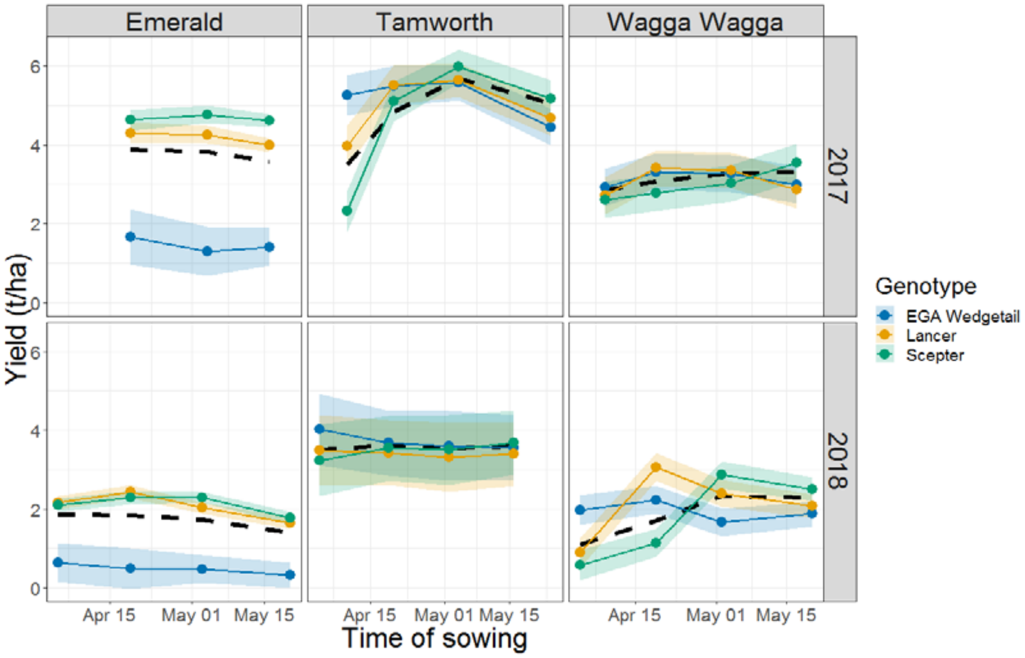

Figure 3. Predicted grain yield responses across sowing dates from early-April to late-May at Emerald, Tamworth and Wagga Wagga sites in 2017 and 2018 for selected genotypes; EGA Wedgetail⦶ (winter type), Lancer⦶ (mid spring type), Scepter⦶ (fast spring type)

Likelihood and timing of sowing opportunities varies across growing environments

Matching flowering date to a growing environment can be a challenge, as the timing of the seasonal break is highly variable. A simulation was conducted to determine the probability of a sowing opportunity occurring across locations of the NGR using methods described in Unkovich (2010). According to this sowing rule, the timing of a sowing opportunity whereby there is sufficient seedbed moisture to establish a wheat crop, differs across environments. Therefore, sowing opportunities will influence variety choice and sowing time decisions also. For example, the probability of a sowing opportunity prior to 25 April was 38% at Condobolin, compared to 65% of years at Yarrawonga (Figure 4). As such, there are limited opportunities to sow a winter wheat at Condobolin, however probability increases to approximately 70% by early-May and the opportunities increase for mid-fast developing varieties. In contrast, growers in Yarrawonga have more flexibility in their sowing window and could consider incorporating slower developing or winter types for earlier sowing in their program.

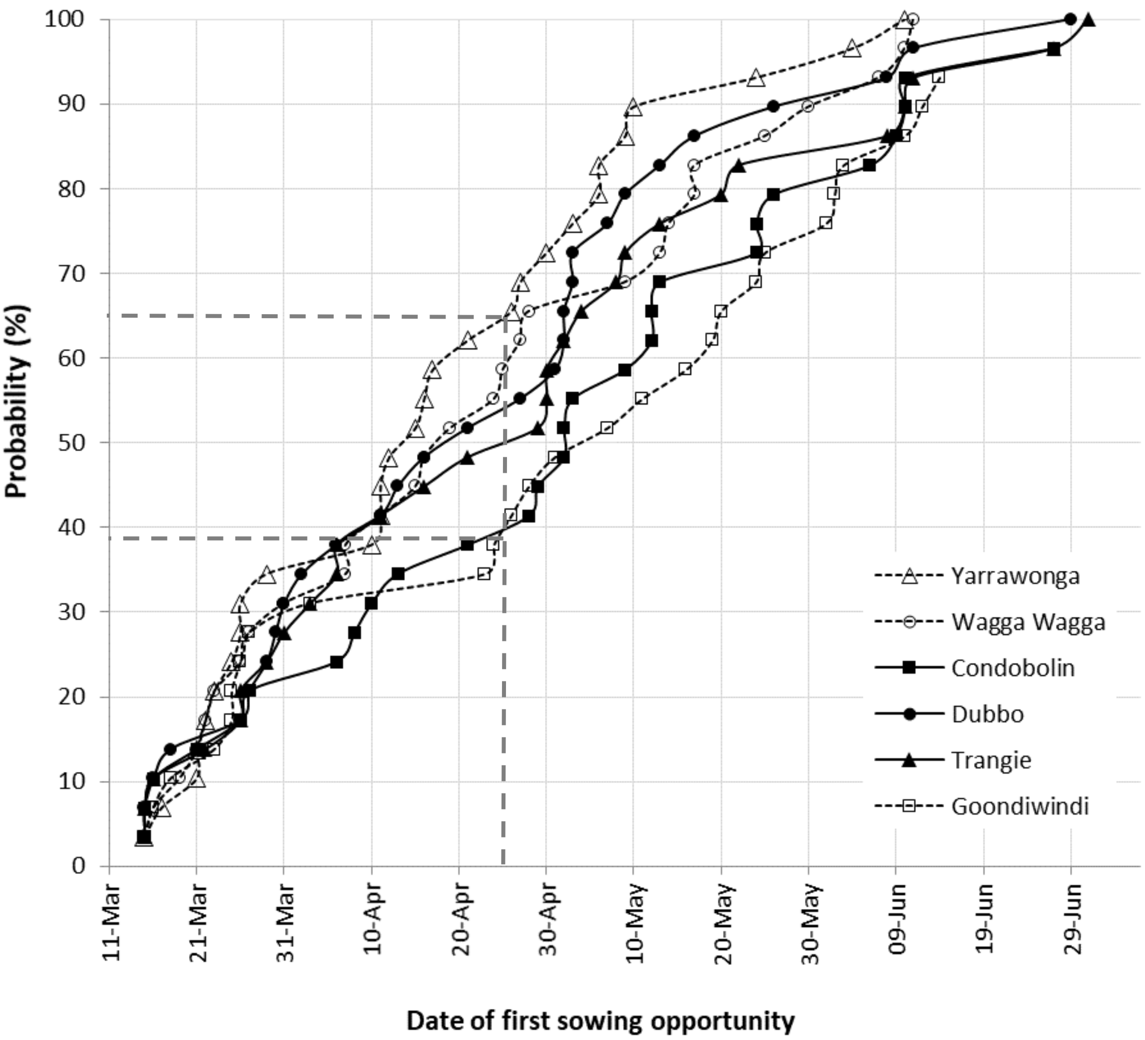

Figure 4. Probability distribution of first sowing opportunity for sites across the Northern grains region from 2000-2018 using the methods of Unkovich (2010). The dashed grey line pinpoints the probability of the sowing opportunity prior to 25 April for Condobolin and Yarrawonga

Conclusion

There were significant interactions between G × E × M, whereby genotypic responses to sowing date varied across sites in the NGR, and within seasons for varieties with varied phenology patterns. These findings indicate that the varieties tested are not broadly adapted to environment or management, and as such there is scope for growers to optimise grain yield through variety selection and management of sowing date by considering phenology responses and target OFPs.

Acknowledgements

This research was a co-investment by GRDC and NSW DPI under the Grains Agronomy and Pathology Partnership (GAPP) project in collaboration with Department of Agriculture and Fisheries, Queensland. The research presented in this paper was 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.

Sincere thank you for the technical assistance of Hugh Kanaley, Cameron Copeland, Dean MacCallum, Mary Matthews, Jessica Simpson, Ian Menz, Bren Wilson and Javier Atayde at the Wagga Wagga, Marrar and Wallendbeen sites; Nick Moody, Braden Donnelly and Daryl Reardon at the Condobolin site; Peter Roberts and Jess Perry at the Cargo site; Jayne Jenkins and Paddy Steele at the Trangie and Wongarbon sites; Stephen Morphett, Michael Dal Santo, Jim Perfrement, Jan Hosking and Bruce Haig at the Tamworth, Breeza and Narrabri sites; John Lehane at the Wellcamp and Pampas sites; Ellie McCosker and Jane Auer at the Emerald site.

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

Better wheat germplasm for good seasons and high inputs

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Key words

wheat, high yield potential, lodging, irrigation, high nitrogen, phenotyping, pre-breeding

GRDC code

CSA00041

Take home messages

New wheat germplasm has been identified that lodges less than Australian cultivars EGA Gregory, Suntop and LRPB Spitfire.

From the favourable genetic markers identified in the new germplasm, only a proportion was present in a database of 502 Australian varieties, suggesting that there is room for improving lodging tolerance in high yielding wheats.

Background

Australian wheat breeding has been largely focused on improving crop yields for dryland environments. Wheat germplasm suited to higher-rainfall environments/years, irrigated systems and high fertility conditions is also needed, with high yield potential and reduced likelihood of lodging.

Lodging due to the permanent displacement of shoots from their upright position, is a common phenomenon in high yielding wheat crops. Lodging counteracts yield gains achieved by breeding and reduces the effectiveness of investment in inputs such as fertilisation and irrigation by reducing yield and quality. Yield is further reduced because fallen plants cannot intercept radiation fully to produce biomass. Direct losses can also occur due to shattering or at harvest, as low-lying spikes are not picked up by the header. The humid environment in a lodged crop can also affect bread-making quality due to higher incidence of pre-harvest sprouting and mycotoxin contamination (fungal infection) if ripening coincides with rainy, humid conditions. Finally, slow harvesting and the need for grain drying also represent additional costs for growers.

Lodging is a complex phenomenon, that depends not only on plant attributes but also soil type, how wet the soil is, wind and crop husbandry. Some of the popular management options, such as delaying N application, managing planting density and the use of plant growth regulators to lower plant height, have variable rates of success and substantial genotype x environment x management interaction (Peake et al., 2016).

Studying the impact of different management practices on lodging, researchers in the UK concluded that the best practice associated with high yields could not avert the damage of moderate to high wind speeds during grain filling, and new wheat genotypes were needed with increased lodging tolerance (Berry et al., 2000).

Two types of lodging have been documented, root or stem lodging. Hence any search for reliable plant traits has to phenotype attributes of the root plate (also known as crown root), the stem and the whole plant, such as height.

The north-eastern part of the Australian cropping belt, ranges from a subtropical climate with summer-dominant rainfall in the north towards a more uniform rainfall distribution in the temperate south. Typically, soils in this area have high clay content and high water-holding capacity. In this region, growers may have access to tactical irrigation around flowering to enhance grain yield. In good seasons or with supplementary water, if crops such as cotton precede wheat in the rotation, a high level of residual nitrogen in the soil is expected, adding to the environmental factors increasing lodging likelihood in crops expected to be high yielding. Occurrence of substantial yield losses due to lodging have been documented in this region for bread wheat and other crops. Hence the need to find better genetic backgrounds for the varieties available for growers.

The overall aim of this project was to provide Australian breeding companies with access to regionally adapted germplasm with stable yields higher than 7 t/ha, with low lodging and deliver information on how to select for low lodging, high yielding wheats, in the form of knowledge about the key traits, phenotypic selection tools and DNA markers.

Methods

The first step was to assemble a highly diverse set of materials, such as local varieties, advanced breeding lines and imported germplasm and identify those that consistently delivered low lodging and high yield across the northern region. Nineteen multi-environment experiments were run over four years in Emerald and Gatton (QLD), Narrabri and Spring Ridge (NSW). The experiments were fertilised with high N doses before sowing (300-350 kgN/ha) and tactical irrigation was used after flowering to induce lodging. Each plot was assessed for yield, height, flowering and percentage of the crop lodged at which angle, border rows were excluded. With the combination of angle and percentage lodged, we built a ‘lodging score’. A lodging score of 0=not lodged and 100=completely lodged (flat on the ground). The benchmark lodging score for the project was 80% of the crop leaning 20° from the vertical and the rest standing, equivalent to ‘17.8’ in terms of lodging score.

A selection of 50 lines was further characterised in detailed phenotyping field experiments for 20-plus traits, mainly attributes related to either root or stem lodging, i.e. root plate spread (RPS), and structural rooting depth, stem strength, diameter and thickness, and components of shoot leverage, such as plant height and height at the centre of gravity.

From the phenotypic characterisation, four donors were selected and were crossed to three recurrent parents chosen by the Australian Plant Breeders Reference Committee – these being EGA Gregoryⓟ, Suntopⓟ and LRPB Spitfireⓟ. Flowering, height and lodging were scored for two consecutive years in the twelve populations; yield data are available for one year only. 288 EGA Gregoryⓟ derived and 63 Suntopⓟ derived lines were genotyped using a 90K Single Nucleotide Polymorphism (SNP) platform. This genetic information was associated with lodging scores from the field to detect relevant DNA markers.

Results and discussion

Extensive field phenotyping using high N fertility and tactical irrigation led to a range of yield and lodging outcomes in multi-environment experiments (Table 1) and highly reproducible rankings for lodging (Figure 1). This means breeders can treat the region as a single target.

Table 1. Mean and range of yield and lodging observed in multi-environment experiments

Year	Locations	Genotype #	Yield (t/ha)		Lodging score	
			Mean	Range	Mean	Range
2012	Emerald	40	5.9	5.2-7.2	-	-
	Gatton	308	5.4	3.4-7.3	39.7	4.3-74.8
2013	Emerald	50	6.7	4.4-8.2	8.2	0.0-28.2
	Gatton	240	4.9	3.0-7.3	12.4	0.6-29.6
	Narrabri	240	6.2	4.0-9.2	5.8	0.0-28.2
	Spring Ridge	50	7.8	6.9-8.6	-	-
2014	Emerald	50	6.0	4.9-7.3	14.2	4.8-23.9
	Gatton	120	5.9	3.6-7.8	11.7	0.0-35.2
	Narrabri	240	6.9	4.6-10.1	16.4	0.0-38.5
	Spring Ridge	51	7.8	4.6-10.2	29.9	1.0-71.6
2015	Emerald	50	7.8	5.5-9.6	8.3	2.2-19.2
	Gatton	50	6.0	4.7-7.7	8.2	0.0-50.4
	Narrabri	50	9.1	7.0-10.3	16.3	1.5-55.9
	Spring Ridge	50	10.0	7.1-11.9	15.8	0.0-70.0
2016	Gatton	51	6.8	4.8-8.4	59.6	12.2-90.2
	Narrabri	54	8.1	6.5-9.6	19.8	0.0-53.1
	Spring Ridge	51	9.6	7.3-10.9	18.8	0.0-67.7

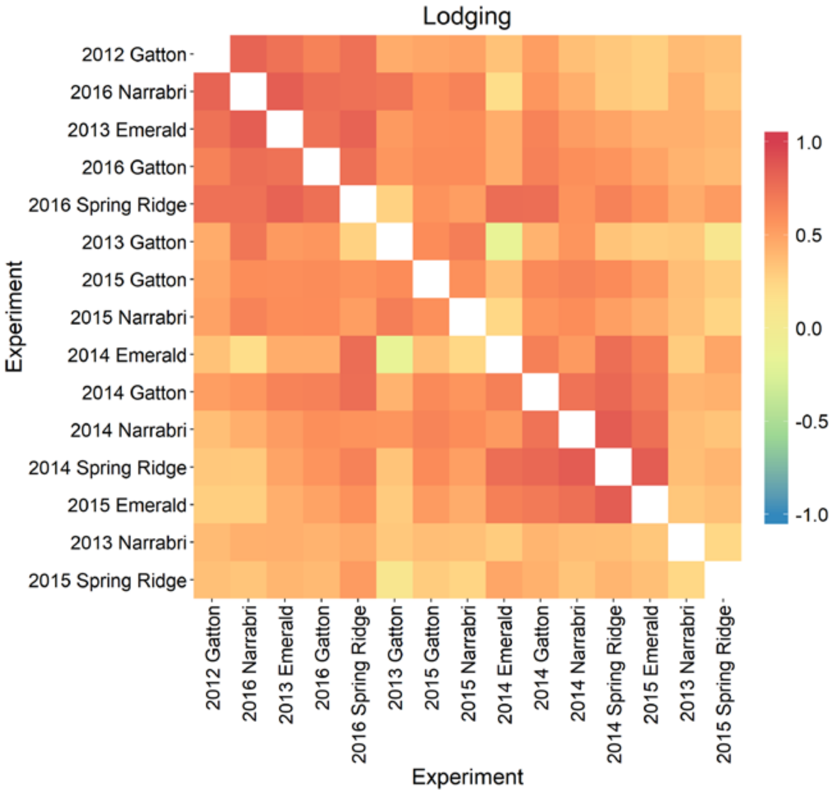

Figure 1. Genotypic correlation matrix for lodging scores between experiments. Scale for genotypic correlation is given as a colour shading denoted in the colour panel at right. A value of 1 indicates a positive and perfect correlation between experiments, i.e. they rank varieties similarly for lodging scores.

A selection of fifty lines underwent a detailed field phenotypic characterisation over two years. Field grown plants were ‘pulled-up’, root plates washed and measured as shown in Figure 2. Root plate spread emerged consistently as a trait able to discriminate low lodging, high yielding germplasm in a classification analysis with a regression tree (Figure 3). If the root plate spread was greater than or equal to 5.5 cm, the lodging scores were small, and yield was high. Stem breaking strength (far right in Figure 2) emerged as an important trait for genotypes with narrower root plates (less than 5.5 cm). Figure 3 shows the regression tree illustrating how trait levels separate groups or nodes of data.

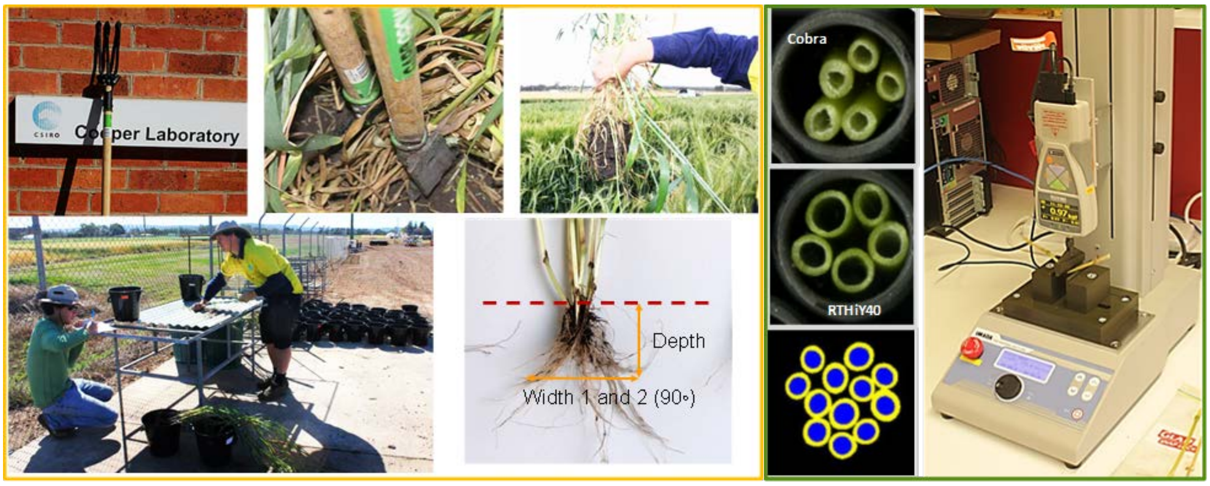

Figure 2. Photos of root sampling, stem breaking and imaging. Images courtesy of Ryan Kearns, Ian Lee Long and Fernanda Dreccer (CSIRO).

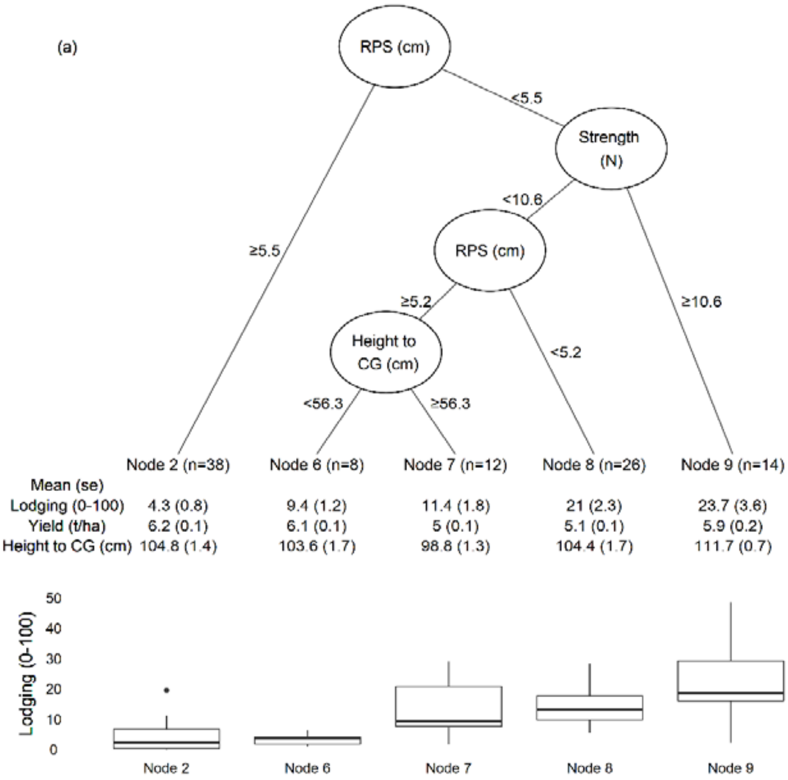

Figure 3. Regression tree. ‘RPS’, root plate spread (cm); ‘strength’, stem breaking strength (N), ‘height to CG’ height to the centre of gravity. Mean and standard error for lodging, yield and height to the centre of gravity indicated below the bubbles. “n” is the number of data in each node. Lodging boxplots for each node shown below.

From this phenotypic characterisation, four donors were selected, one an Australian cultivar (LRPB Cobraⓓ), the other three exotic lines from CIMMYT (RTHiY40, RTHi32, RTHiY57). Donors were low lodging, high yielding, contrasting in height and generally showing wider root plate spread (belonging to Node 2 in Figure 3) than the Australian cultivars parents of the new populations. It is possible that the importance of anchorage characteristics for our conditions is related to the high clay content of the soils in the northern region, typically above 35% clay from the surface (https://aclep.csiro.au/aclep/soilandlandscapegrid/ViewData-QuickView.html) that, when wet, create a very unstable environment for crops to anchor.

Lodging was first evaluated for the new populations in single rows, bordered by the same cultivar to avoid bias. EGA Gregoryⓓ derived lines lodged in a higher proportion and with a higher deviation from the vertical. More than 50% of the EGA Gregoryⓓ derived lines lodged less than EGA Gregoryⓓ, with the tallest donor, RTHiY40 (ca. 107 cm), producing lines as effective as those derived from the shortest donor, LRPB Cobraⓓ (80 cm), in both years. In our experiments, lodging and height were not associated.

Yield was measured in 2018 only in the lodging nursery after heavy rain and ranged from 570 g/m^2 (5700 kg/ha) to 761 g/m^2. Among the EGA Gregoryⓓ populations, 100 lines had a lodging score significantly below the 17.8 benchmark in that year, 12 of which yielded as much as or more than EGA Gregoryⓓ. When LRPB Spitfireⓓ was the recurrent parent, the lines derived from crosses to LRPB Cobraⓓ and RTHiY57 were best at reducing lodging.

DNA markers for lodging were detected both in a biparental population from CIMMYT (Seri x Babax) and the lines from the new populations that were genotyped. These genetic markers do not coincide with known flowering or height genes. Interestingly, the DNA markers that come up in a year of low lodging are dissimilar to those observed in a high lodging year, suggesting that the plant attributes that are important vary with the level of lodging. In 2017, a high lodging year, 4 significant DNA markers were detected for lodging scores. If present in their favourable form, they can reduce the lodging score by approx. 8 points each.

A search for the favourable DNA markers found in the new populations in 502 Australian varieties with known genetic profiles, indicated that no single Australian variety has all the favourable genetic markers. Lodging predictions were generated for the 502 varieties based on the DNA markers detected based on their genetic profile in a high and low lodging year. Amery and Stockade were the only two varieties consistently among the top 25 with lowest predicted lodging score (Figure 4). Further analyses will be carried out in this area to pass the information of the best candidate markers to breeders.

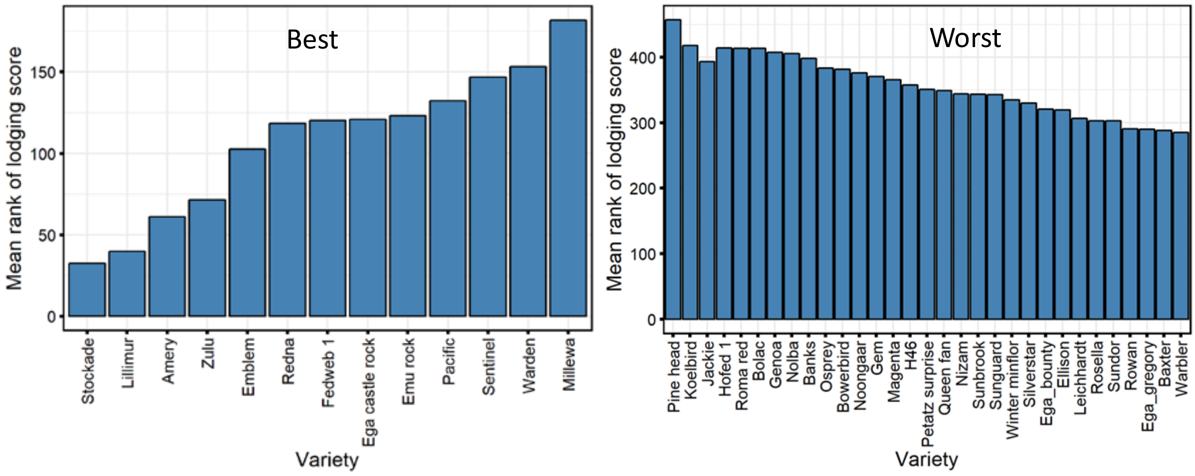

Figure 4. Varieties which have a mean rank of predicted lodging score which falls in the top 25 or the bottom 25 in at least two analyses

Conclusions

This project succeeded at finding genetic diversity for lodging in high yielding wheats and transferring it to new germplasm with known varieties as background. Many of these lines lodge less than their parents and some yield more. The process of selection and investigation of relevant plant attributes succeeded at detecting the traits that were more important to choose donors for our target region, firstly root anchorage, then stem strength.

The findings of this project may not only be beneficial for the northern region but could spill over to wheat varieties designed for the high rainfall zone in the South and high yielding environments of Tasmania or Northern Australia. In addition, the general approach to selection and characterisation of plant attributes is a framework that could be extended to other crops.

Furthermore, as not all favourable genetic markers found in the new populations were present in Australian varieties, there is room to improve lodging tolerance in Australian breeding.

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Acknowledgements

The research undertaken as part of this project was made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC and the cooperation of Australian Plant Breeders. The authors would like to thank them for their continued support.

The technical expertise of Allan Peake, Claire Farnsworth, Mary Anne Awasi, Andy Hundt and Ian Lee Long (CSIRO) is greatly appreciated.

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

NIR sensing and machine learning to rapidly assess crown rot in wheat

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Key words

crop disease, near infrared, proximal sensing, remote sensing, phenotyping

Take home messages

- Non-destructive sensing enables automated early detection of crown rot that previously could only be detected manually after the appearance of visual symptoms
- Machine learning models enhance classification results over traditional analysis techniques
- Near infrared sensing and machine learning models have potential to be deployed as a handheld or drone-based tool for both paddock-level disease detection and phenotyping
- Embracing new sensing technologies presents opportunities for rapid management decisions and site-specific application of inputs where most profitable.

Background

Wheat crown rot occurs in many arid and semi-arid cropping regions around the globe and can be responsible for up to a 40% yield reduction under conducive conditions. In severe cases crown rot can lead to necrosis of the stem, limiting grain production. Visual symptoms are late in the season with the appearance of white heads and stem browning. The lack of readily discernible visible symptoms causes delays in production decision-making, including input selection and timing, and potentially consumes resources in areas of the crop where productivity will be low. Improvements in disease identification, rapid phenotyping and decision making will help growers remain profitable and operations sustainable.

Currently, crown rot assessment involves physical removal of the plant from the soil followed by removal of the leaf sheaths around the lower internodes and visual colour assessment by trained assessors, for example an agronomist or consultant. This process is time consuming, labour intensive, impractical to perform across a field and prone to variation due to human bias and significant environment/pathogen interactions. A machine vision-based sensing system has potential to be used to objectively and rapidly assess disease incidence and severity with high repeatability.

This project aims to develop an automatic sensing system to identify and quantify crown rot in wheat using near infrared spectral signatures and machine learning techniques. The sensing system has intended application for rapid assessment and phenotyping of crown rot in breeding trials and automatic infield detection of diseased areas of crop on farms. Grower benefits are anticipated to be more rapid access to resistant varieties and enhanced ability for resource-saving decisions based on infield detection of crop disease.

A series of experiments were undertaken in glasshouse and field trials in Southern Queensland from 2018 to 2019 to evaluate the ability of non-invasive near infrared crop sensors and machine learning methods to detect and quantify *Fusarium pseudograminearum* in bread wheat.

Methods

Glasshouse trials were conducted at QDAF and USQ facilities in Toowoomba, QLD. In 2018 and 2019, five bread wheat genotypes were observed under positive or null inoculation with *F. pseudograminear*um colonised wheat grain, following the methodology outlined in Percy et al., 2012. Each treatment was replicated 6 times. Pots in the glasshouse trials were configured in randomised block designs and watered to field capacity. The glasshouse temperature was maintained at 20–25 degrees Celsius. Inoculum was applied individually to coleoptiles of each plant at the two-leaf stage.

Two field trials were conducted at the Tosari research station (-27.859964, 151.452766), planted in June of 2018 and 2019. Paired, inoculated and non-inoculated 6 m x 2 m plots were arranged in a strip plot design in a randomised block with three replications. *F. pseudograminear*um colonised millet inoculum was applied into the furrow above the seed at planting. Six randomly selected plants from each plot were chosen, corresponding to each of the five genotypes in the glasshouse trials.

Measurements were taken using a DLP® NIRscan™ Nano near infrared point sensor (Texas Instruments, USA) with a sensitivity of 900–1700 nm once a week throughout the growing season for nine weeks, from three weeks post inoculation. Technical issues caused data from the week 8 assessment of the first glasshouse trial to be lost. The maximum separation between all other measurement dates was 8 days. Sensor measurements were collected from the centre of the newest emerged tiller, the leaf determined to be centre-most and the youngest flag leaf. Calibration reflectance measurements were gathered from a 10% grey, a 60% grey and a 99% white reference Spectralon® panel.

Observed plants in both sets of trials were pulled at maturity and scored manually at the Centre for Crop Health for the presence and severity of *F. pseudograminearum* induced crown rot. Linear regression, clustering and neural net machine learning techniques were evaluated for effectiveness in discriminating and quantifying *F. pseudograminearum* induced crown rot in bread wheat. All analysis and model creation was performed in the Python computing environment (Python version 3.6.8; Python Software Foundation, 2019), using the SciPy ecosystem (Jones & Peterson, 2016) and the Scikit-learn library (Pedregosa et al., 2011).

Results and discussion

Machine learning models were compared for the ability to accurately discriminate crown rot at different timepoints from inoculation. The results achieve crown rot detection ability with accuracies ranging from 55–100%. The top performing machine learning model was an artificial neural network classifier (ANN), which performed with an accuracy of up to 100.00% under optimal glasshouse conditions (Figure 1). Lower classification accuracies were observed in the field trials and may be due to low levels of disease, particularly in genotypes with some resistance. Further analysis is being completed to determine the impact of low disease levels. Differences between the spectral signatures of inoculated and uninoculated treatments indicate that this sensing approach has potential to be scaled to a camera-based system. Further work is being conducted to establish operational requirements for a remote sensing system, for example on a UAV, which is an important step towards large-scale, automated disease discrimination.

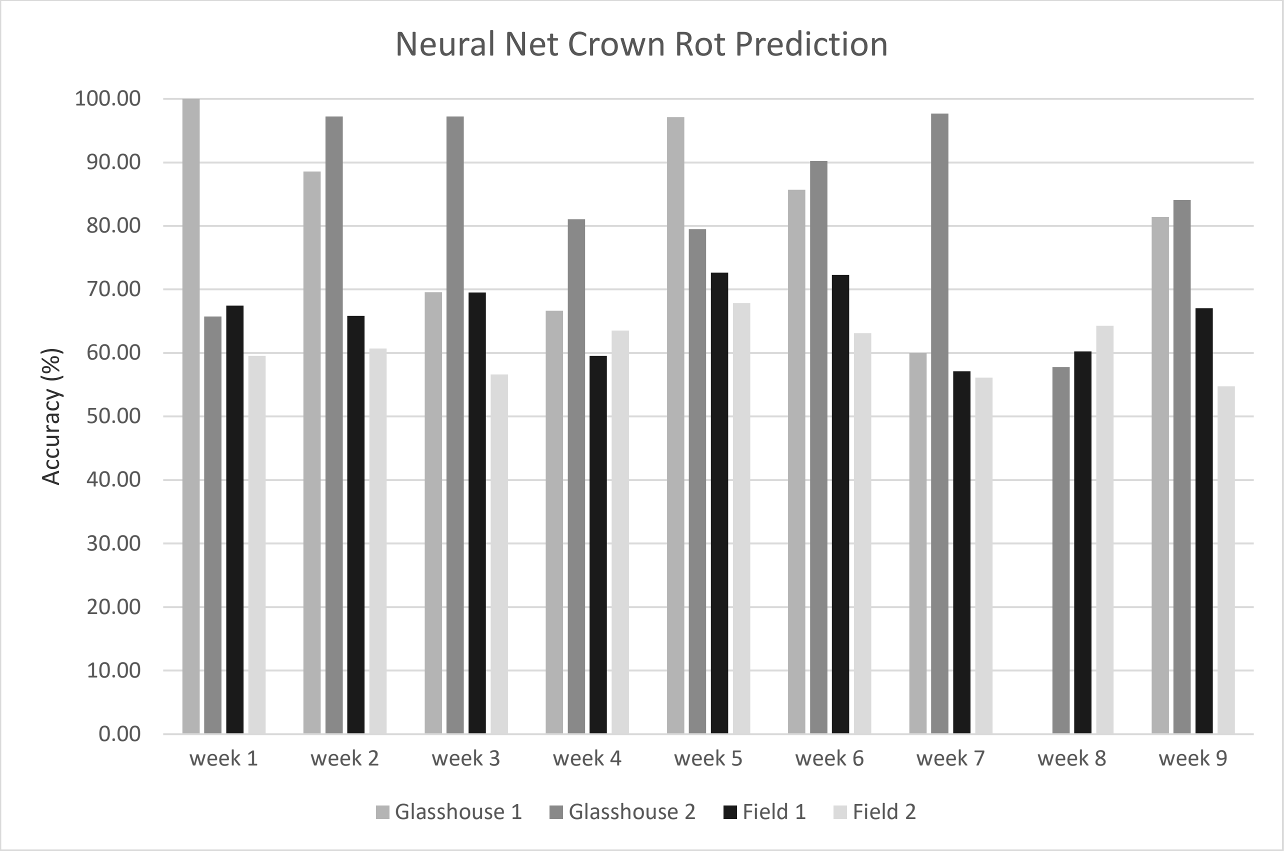

Figure 1. Average classification accuracies of crown rot detection (+ or -) of an optimised artificial neural network for nine weeks, from three weeks post inoculation.

The results of the near infrared-based, machine learning models show detection capability at three weeks post inoculation, allowing time to make production decisions. A near infrared imaging system provides potential for in-crop characterisation on a paddock level automatically and in real-time, where existing characterisation requires manual visual assessment or pre-sowing soil/stubble testing (e.g. PREDICTA®B) which can take days or weeks.

Early detection of crown rot is crucial to optimise operation profits by enabling growers to reduce inputs on affected paddocks and plan future rotations and management strategies. The estimated potential annual yield loss from *F. pseudograminearum* is 22.2% (Murray & Brennan, 2009), as such early detection allows for the reduction of costly inputs, such as foliar fungicides, foliar nitrogen application, or irrigation in dry seasons.

Additional advantages of near infrared sensing of crown rot exist to plant breeders and researchers providing further potential benefits to growers. Rapid phenotypic assessment of crown rot increases breeding company capacity to screen larger numbers of lines more efficiently, delivering improved germplasm to growers in less time.

Summary

Near infrared technology provides rapid, automated and non-destructive detection of crown rot that previously could only be performed manually through destructive methods by trained assessors. Embracing new non-invasive sensing technologies potentially enables rapid management decisions by reducing labour and time costs of disease detection. Further, near infrared technology potentially maximises profit by optimising input timing and restricting input application to the areas where the highest return on investment can be expected. The adoption of near infrared sensing by plant breeders may provide tools to more rapidly release resistant lines, providing further potential benefits to growers. Near infrared technology has the potential to be deployed as a handheld or drone-based sensor for rapid characterisation of paddock disease levels.

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Acknowledgements

This PhD project has been funded by USQ through a Research Training Program stipend and USQ International Fees Research Scholarship. We would like to thank USQ-Centre for Crop Health in collaboration with the Grains Research Development Council for providing access to crown rot field sites and glasshouse trials.

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Notes

Farming system profitability and impacts of commodity price risk

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Key words

gross margin, costs, income, nutrients, crop rotation

GRDC code

DAQ00192, CSA00050

Take home messages

- Large gaps in profitability are possible between the best and worst systems – differences of $92-494/ha 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, but potentially higher crop income wasn't realised over the dry run of seasons and hence has produced lower gross margins than more conservative systems
- Lower crop intensity had lower system gross returns, but because of lower inputs and costs may achieve a more favourable return on investment at lower risk when there are limited planting opportunities. These systems have achieved lower gross margins than the baseline system in all but one comparison
- Increasing legume frequency has the potential to capitalise on favourable legume prices but using long-term prices has rarely exceeded gross margins of baseline systems
- Increasing nutrient supply incurred higher costs and required favourable seasonal conditions to increase grain yields and gross margins – this rarely occurred over the experimental years (excluding Trangie 2016 and Emerald 2017 where significant crop responses were obtained)
- Systems involving crops with higher price variability (e.g. pulses, cotton) had limited downside risk but increased upside opportunities of higher economic returns. Even when comparing recent and long-term grain prices, the relative profitability ranking of systems rarely changed
- Selecting a crop system is a long-term decision with unknown future yield and prices, hence choose systems that maximise system productivity and resilience, rather than responding to current commodity prices.

Introduction

Leading farmers in the Australian northern grains region (NGR) 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. The key factors appear 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:

- Efficiently capture and utilise rainfall particularly for high-value, low-stubble 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
- The price risk of individual crops and the impact on systems' economic returns.

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. This requires quantifying synergies or trade-offs and investigate the impact on whole-of-system productivity, risk, economic performance and sustainability.

As a result, research was initiated in 2014 to identify the key limitations, consequences and economic drivers of farming systems in the NGR. The aim is to assess the impacts of modifying farming system on multiple attributes (e.g. nutrients, water, pathogens, soil health, and economics) across multiple sites. Experiments were established at seven locations and a large factorial experiment at Pampas near Toowoomba with 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 profitability is critical. This paper examines the economic performance of different modifications that we have tested in combination with commodity price risk. This will help quantify the costs or benefits of changing the farming system and the trade-offs for the different cropping intensities and nutrient strategies.

System modifications being tested

We used a set of farming system strategies across our site locations within the NGR. These strategies resulted in different cropping systems per location, based on the environmental (climate & soil) conditions. Below we outline the common set of farming system strategies employed across the farming systems experimental sites over the past 4.5 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 systems implemented. These include:

- **Higher fertility systems** (Billa Billa and Emerald) 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, as well as the economic outcome.
- **Integrated weed management systems** (Emerald). The system has implemented 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.
- Two **low-intensity systems** have been implemented at Mungindi, 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, with the four overarching themes being: mixed opportunity, intensive, summer-cropping, and winter-cropping dominant.

Quantifying system profitability and commodity price risk

Over the 4.5 experimental years we have collected data on crop grain yields, the total inputs of machinery operations, fertilisers, seed, herbicides and other pesticides for each cropping sequence. This allows us to calculate the accumulated income (sum of grain yield x price for all crops in the sequence) and total gross margins (income minus costs) for each of the cropping systems deployed at each location (Table 2 and Table 3). 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. All grain yields were corrected to 12% moisture irrespective of harvest moisture levels. We have used consistent prices for each commodity and inputs across all locations to avoid introducing discrepancies in the data.

In this research we used the key metric of “total gross margins” to compare system profitability per hectare across environments and cropping systems over the whole period (4.5 years). It should be noted that gross margins do not include 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.

Initially we have calculated these system gross margins using 10-year median commodity price over the period 2008-2017 (adjusted for inflation, transportation, grading or bagging costs) (Table 1). However, to explore the impact that variability in commodity prices may play on the relative profitability of different crop sequences we have then calculated the gross margin across a full set of combinations of prices for each crop commodity that may have been received over the past 10 years. We also calculate the specific gross margin for each crop system using commodity prices received over the last 3 years (see Table 1) to see the actual economic outcome during the experimental period and where they fell within the range of possible outcomes.

Table 1. Market commodity prices and farm gate prices used for calculating system gross margins for each crop grown across the farming systems experiments

		Barley	Wheat (APH)	Wheat (Durum)	Canola	Chickpea	Fababean	Fieldpea	Sorghum	Maize	Mungbean	Sunflower	Cotton (Lint + seed – 40% turnout)*
Port Prices ($/t)	10-yr median	258	309	339	543	544	422	375	261	321	950	749	1267
	3-yr average	254	287	317	518	831	419	364	255	325	1151	905	1243
Transportation costs ($/t)		40	40	40	40	40	40	40	40	40	40	40	40
Grading and bagging costs ($/t)		0	0	0	0	0	0	0	0	0	242	0	137
Farm Gate Prices ($/t)	10-yr median	218	269	299	503	504	382	335	221	281	667	709	1090
	3-yr average	214	247	277	478	791	379	324	215	285	869	865	1066

* Cotton price calculated per tonne of bolls harvested assuming 40% is lint and 60% is seed

Commodity prices can be driven by the volatility of local and international demand and supply. Depending on the commodity, annual prices offered can be greatly different to the median price (Figure 1). These price ranges can be used to estimate the future possible range of prices. In figure 1, sorghum, wheat and maize had the lowest median price and lowest variance in price over the ten years. Therefore, even when the price is close to the quartiles (P=0.25 & 0.75 on the y-axis) the price is relatively unchanged (x-axis). Whereas chickpea, mungbean and sunflower median price is high and highly variable. For example, the 3-year average prices are 22-57% higher than the median price.

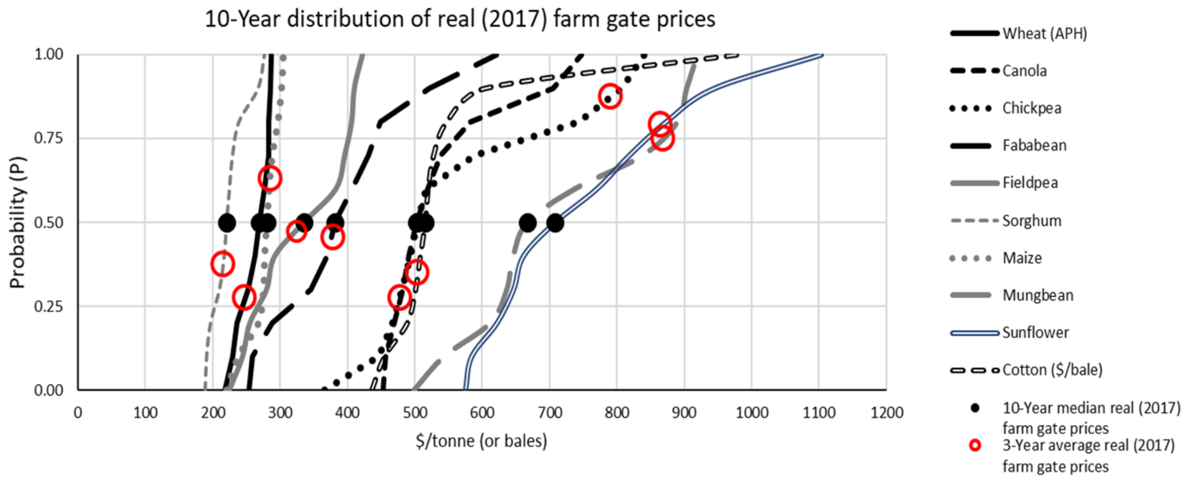

Figure 1. The probability distribution of annual average farm gate price of commodities (2008-2017) in the northern grain production region adjusted for inflation to 2017. The lowest annual price in this ten-year period is shown at P=0 on the y-axis and the highest price is at P=1. We used the 10-year median (P=0.5) prices as the expected price for our long-term economic analysis and compare this to the 3-year average price (2015-2017) (shown in red). Cotton price are given as $/bale (including lint and seed)

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 (Table 2 and Table 3). 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 yield, income and cost differences incurred between sites, due to differences in environmental (climate & soil) conditions, starting nutrient levels and weed status, which greatly influence the gross margin outcome between sites. For this reason, we focus mainly on comparing the economic outcomes between systems at the same site.

The difference between the best and worst system gross margins per location

Within each experimental comparison there was a significant gap between the best and the worst cropping system (Table 2 and Table 3). The difference between the highest grossing and lowest grossing system over the 4.5 experimental years (in $/ha/yr) was $410 at Billa Billa, $359 at Emerald, $269 at Mungindi, $296 at Narrabri, $176 at Spring Ridge, $169 at Trangie on red soil and $232 on grey soil, $285 for the mixed opportunity systems at Pampas, $332 for summer rotation systems at Pampas, and $494 for winter rotation systems at Pampas. The differences amongst rotations have declined over the past year due to the drought conditions limiting planting opportunities and hence total income has remained constant in most systems.

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 fertility systems performed the best, $118/ha/yr higher than the baseline. At Spring Ridge, the higher-legume system was the only system that resulted in higher economic returns of $60/ha/yr. If the lucerne crop had not been successful in the year of planting, then the baseline system would have been the best performing crop on grey soil. Amongst the Pampas systems, the gross margin returns of the baseline systems was exceeded by systems with higher legume frequency or crop diversity by $9 and $31/ha/yr, respectively 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 Billa Billa, Emerald, Spring Ridge and lower crop intensity the lowest GM at Mungindi (grain), Narrabri (ignoring crop diversity), and Pampas (mixed opportunity and winter themes). What this means is that getting cropping intensity wrong for your environment is a major driver of suboptimal system performance.

At Trangie, the ley pasture system resulted in higher returns of $71 and $140/ha/yr than the baseline system for the experimental period for the red and grey soil, respectively. The success of this system was due to good establishment of a lucerne crop in the early wetter years of the experiment, which has survived over the experimental period with periodic harvests. Whereas other cropping systems could not establish crops due to poor soil moisture. Overall, this highlights that there is a significant difference in the profitability of farming systems within a particular situation.

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 (except Emerald and Trangie red soil), this increased system costs and reduced total gross margins by $80-$610 per ha over the crop sequence (or $18-$136 /ha/yr). So far, we have seen few yield or economic responses to this higher nutrient supply approach (except Trangie – red soil and 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 $296 and $1334 less over the whole crop sequence ($66-296/ha/yr lower) than the baseline system. At Pampas diversifying the cropping system has consistently exceeded the returns of the baseline crop sequence by between $138 and $987/ha over the 4.5 years ($31-219/ha/yr higher).
- Higher legume frequency systems have increased the variable costs of production in most cases, mainly due to higher costs for pesticides. While the Emerald and Spring Ridge sites there were marginally higher gross margins ($60-68/ha/yr) than the baseline, because of these higher costs they have a lower return on variable costs (ROVC) (Table 2 and Table 3).
- 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). It would be expected that lower intensity systems would have lower costs and therefore may have higher ROVC than the baseline system, but this was not the case for all regional sites apart from Spring Ridge and Trangie red soil. And it is expected under more favourable conditions the baseline system would have had higher ROVC than the low intensity system. At Pampas, only the summer lower intensity system offered high ROVC, but this was not driven by savings in costs but rather higher income.

- Higher intensity systems did not increase total crop income at any of the sites and typically brought about an increase in costs, so that net returns were generally lower and the ROVC was dramatically lower. This highlights the risks associated with these systems. That is, over the relative dry run of years, these systems were working harder but not smarter than a more conservative cropping system. The high intensity system was up to $410/ha/yr behind the baseline system at Billa Billa, and even at the higher rainfall sites (Pampas, Spring Ridge, and Emerald) it was >100/ha/yr behind the baseline.

Table 2. Total revenue generated, costs of production (fertilisers, seed, operations, chemicals), gross margins (GM), the gap of a system to that the highest system GM per site, returns on variable costs (RVOC, ratio of income to costs), and the maximum cash outlay over the 4.5 years for each farming system tested at each of the 7 regional locations across the northern grains region

Site	**System**	Total income ($/ha)	Total costs ($/ha)	Total GM ($/ha)	Gap from best ($/ha/yr)	ROVC	Max. cash outlay ($/ha)
Billa Billa	**Baseline**	**3901**	**839**	**3062**	**0**	**4.7**	**-317**
	Higher nutrient	3872	1055	2817	-54	3.7	-326
	Higher fertility	3590	1003	2587	-106	3.6	-321
	Higher legume	3597	1017	2581	-107	3.5	-306
	Crop diversity	3010	923	2087	-217	3.3	-352
	Higher intensity	2360	1144	1217	-410	2.1	-513
	Lower intensity	2305	852	1453	-358	2.7	-341
Emerald	**Baseline**	**3787**	**1492**	**2295**	**-118**	**2.5**	**-417**
	Higher nutrient	4090	1534	2556	-60	2.7	-422
	Higher fertility	4352	1528	2824	0	2.8	-417
	Higher legume	4115	1512	2603	-49	2.7	-395
	Higher intensity	2913	1706	1207	-359	1.7	-395
	Integrated Weed man.	4031	1972	2059	-170	2.0	-532
Mungindi	**Baseline**	**1590**	**643**	**947**	**0**	**2.5**	**-290**
	Higher nutrient	1504	909	595	-78	1.7	-313
	Higher legume	1495	727	768	-40	2.1	-290
	Crop diversity	669	537	132	-181	1.2	-351
	Lower intensity (cotton)	1297	752	545	-89	1.7	-297
	Lower intensity (grain)	375	638	-263	-269	0.6	-310
Narrabri	**Baseline**	**2569**	**1023**	**1546**	**0**	**2.5**	**-354**
	Higher nutrient	2265	1329	936	-136	1.7	-486
	Higher legume	2049	928	1121	-94	2.2	-354
	Crop diversity	1439	1227	212	-296	1.2	-633
	Higher intensity	2687	1177	1510	-8	2.3	-507
	Lower intensity	1707	797	910	-141	2.1	-451
Spring Ridge	**Baseline**	**3294**	**2166**	**1128**	**-60**	**1.5**	**-593**
	Higher nutrient	3363	2730	633	-170	1.2	-974
	Higher legume	3403	2006	1398	0	1.7	-712
	Crop diversity	2992	2160	832	-126	1.4	-593
	Higher intensity	2563	1960	604	-176	1.3	-731
	Lower intensity	2525	1480	1045	-78	1.7	-827
Trangie – red	**Baseline**	**1845**	**1021**	**824**	**-16**	**1.8**	**-324**
	Higher nutrient	2337	1444	894	0	1.6	-426
	Higher legume	1853	1049	804	-20	1.8	-363
	Crop diversity	1431	1049	382	-114	1.4	-363
	Lower intensity	1605	737	868	-6	2.2	-442
Trangie-grey	**Baseline**	**1217**	**713**	**504**	**0**	**1.7**	**-251**
	Higher nutrient	963	873	91	-92	1.1	-380
	Higher legume	1119	821	299	-46	1.4	-302
	Crop diversity	953	816	137	-82	1.2	-302
	Lower intensity	761	567	195	-69	1.3	-289

Table 3. Total revenue generated, costs of production (fertilisers, seed, operations, chemicals), gross margins (GM), the gap of a system to that the highest system GM per site, 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 ($/ha)	Gap from best ($/ha/yr)	ROVC	Max. cash outlay ($/ha)
Mixed opportunity	**Baseline**	**4409**	**885**	**3524**	**-31**	**5.0**	-326
	Higher nutrient	4623	1223	3400	-58	3.8	-418
	Higher legume	4678	1032	3647	-3	4.5	-358
	Crop diversity	4665	1003	3662	0	4.7	-314
	Crop div. + nutrient	4371	1394	2977	-152	3.1	-491
	Higher leg. + diversity	4398	978	3420	-54	4.5	-346
	Lower intensity	3382	1002	2380	-285	3.4	-632
Higher intensity	**Baseline**	**4266**	**1218**	**3049**	**-9**	**3.5**	**-308**
	Higher nutrient	4358	1608	2750	-75	2.7	-358
	Higher legume	4105	1332	2773	-70	3.1	-334
	Crop diversity	4085	1081	3004	-19	3.8	-296
	Crop div. + nutrient	3977	1665	2312	-172	2.4	-471
	Higher leg. + diversity	4222	1134	3088	0	3.7	-328
Summer	**Baseline**	**3196**	**724**	**2472**	**-261**	**4.4**	**-382**
	Higher nutrient	3329	938	2392	-278	3.6	-426
	Higher legume	3073	921	2152	-332	3.3	-441
	Crop diversity	4170	906	3264	-85	4.6	-578
	Crop div. + nutrient	4197	1227	2970	-150	3.4	-650
	Higher leg. + diversity	4206	1048	3158	-108	4.0	-593
	Lower intensity	4351	705	3645	0	6.2	-317
Winter	**Baseline**	**3775**	**863**	**2913**	**-219**	**4.4**	**-445**
	Higher nutrient	3570	1064	2506	-310	3.4	-479
	Higher legume	4323	815	3508	-87	5.3	-237
	Crop diversity	4598	698	3900	0	6.6	-237
	Crop div. + nutrient	4252	1162	3090	-180	3.7	-430
	Higher leg. + diversity	4420	739	3680	-49	6.0	-220
	Lower intensity	2444	767	1678	-494	3.2	-441

Cross-site analysis of system profitability

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 total gross margins ($ GM/ha) and the return on variable costs (ROVC) ratio as a proportion of that achieved in the baseline (Figure 2). 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 lower system total gross margin most sites (7 of 10 comparisons), 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 and Trangie red-soil did we observe a positive yield response to additional nutrient supply and hence this is the only location where system gross margins increased. However, the return on investment was similar at 20-30% lower ROVC ratios. At Mungindi the additions of more nutrient reduced grain yield and crop income in one year and added significantly to the costs of this system. We may expect this result under the challenging seasonal conditions we have experienced and with better seasonal conditions it might be expected to realise the benefits of such a strategy.

Increasing legume frequency achieved 20-40% lower total gross margins at Billa Billa, Mungindi, Narrabri, and Trangie red-soil, at other sites gross margins were either higher or similar to system total gross margins in the baseline system. At Pampas the winter-legumes achieved 20% higher and the summer 13% lower gross margins than the baseline system. However, interestingly all ROVC ratios were within ±20% of the baseline system.

Increase crop diversity resulted in 20-80% lower gross margins across all regional sites relative to the baseline system. However, at Pampas, diversity increased the summer and winter legume systems gross margins by 32%; the opportunity system was similar to the baseline. 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 had significantly lower total gross margin at all sites relative to the baseline system, with 20-30% lower total gross margins at Pampas. These systems also have higher costs and hence the return on investment is typically lower.

Lower crop intensity systems have achieved 40-70% lower system total gross margins over the 4.5 years at most locations. However, it also resulted in 47% higher gross margins in the summer system at Pampas and returns were similar to the baseline at the Spring Ridge site.

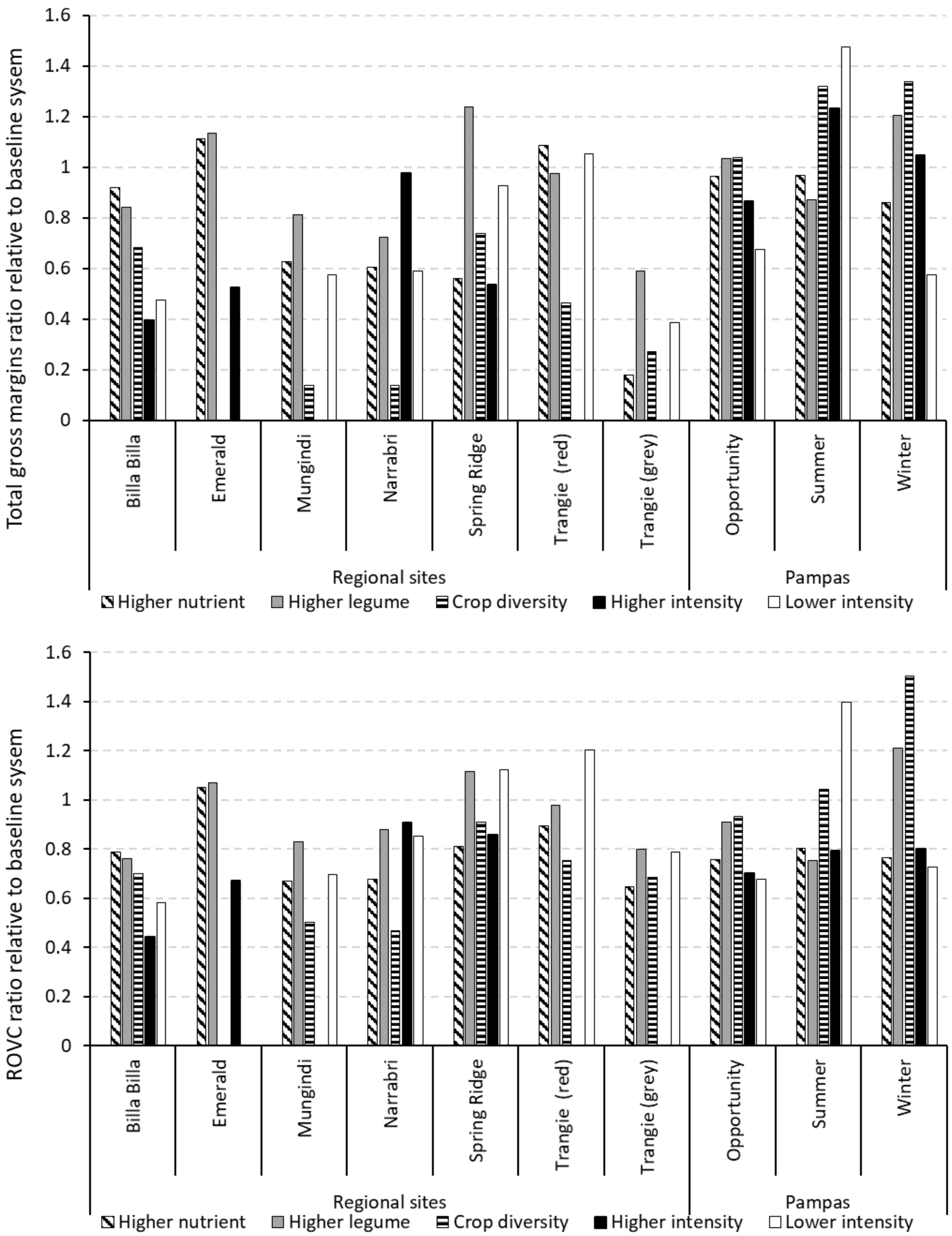

Figure 2. Relative system profitability of different farming systems as a ratio of the baseline system (i.e. 1 equals the baseline, higher is better and lower is worse) at 7 regional sites and under 3 different seasonal crops at the Core site (Pampas). Top shows the gross margin as a proportion of the baseline and the bottom the return on variable costs (ROVC) ratio relative to the baseline system

Impact of commodity price variability

The previous section has been based on the 10-year median commodity prices; however, as indicated by figure 1 some commodity prices can be more volatile than others. Therefore, the possible range of total gross margins for each system will be affected by the combination of commodities it produces. There is little correlation between the prices received for the different commodities here, i.e. the price of wheat does not affect the price of chickpeas.

Figure 3 and figure 4 show the system total gross margins using different combinations of crop grain prices for each of the trial sites and production systems at each site. On these figures, the median (P=0.5) total gross margin values are shown with the black dot and are the same as those presented in the above tables – correlating to 10-year median commodity prices. The values furthest to the left are the lowest probable GM and furthest to the right are the higher GM. The lines show the full range of combinations using the range of grain prices over the past 10 years, and the red dot is the system gross margin using the average price over the past 3 years. For example, at Billa Billa with the 10-year median commodity price for the baseline system total gross margins were $3062/ha (Table 2) and this could be as low as $2490/ha (when all commodity prices of that system are low) and as high as $4092/ha (when all commodity prices are high). Based on the last 3-year average price the returns of the baseline system would have been $3393/ha. Comparing this point, there is a 73% chance of getting lower returns in the future; or 27% chance of higher compared to historical prices. Higher legume prices in recent year has resulted in the baseline and higher legume systems to have above average returns at Billa Billa. Whereas lower sorghum and wheat prices has resulted in the other systems having below average returns.

It is notable that based on total gross margins, the ranking of systems rarely changes when using both the 10-year median commodity price and the actual price over the last 3-years for Billa Billa, Emerald, Mungindi, Narrabri and Trangie red-soil (Figure 3). For Mungindi, even when the higher crop diversity system had high prices (P=0.8) it still did not do better than the lower intensity system with low prices (P=0.2). At Spring Ridge the 10-year median commodity price ranked higher crop diversity ($832/ha; P=0.5) above higher intensity ($604/ha; P=0.5); however, based on the last 3-year average price the higher intensity ($1045/ha; P=0.8) was greater than the higher diversity ($652/ha; P=0.35). The ranking of systems at Trangie red soil also changed slightly with the 3-year pricing, however the baseline, higher legume and lower intensity systems offer similar gross margins and price risk for P=0 to 1.0. This information provides greater understanding of the risk and relative profitability as affected by grain prices associated with different systems.

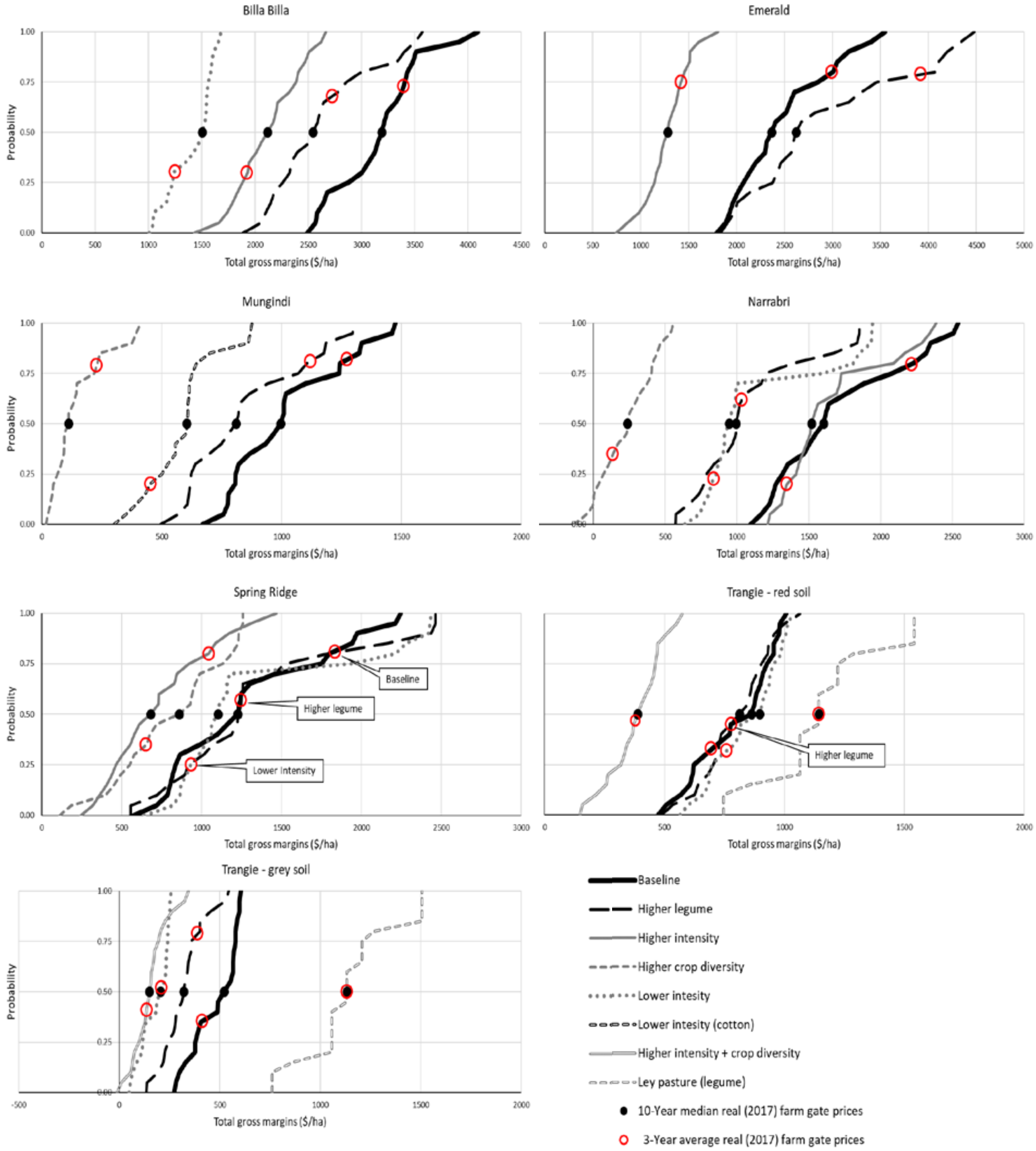

Figure 3. The distribution of total gross margins over 4.5 years calculated using the range of historical commodity prices for each farming system tested at regional locations across the NGR (Figure 1). The total gross margins with the lowest set of grain prices are shown where P=0 on and the highest combination of grain prices is shown where P=1. The median (P=0.5) total gross margins are the equivalent of our median price assumptions (shown in black dot), and the total gross margin using the 3-year average price (2015-2017) is in red

At Pampas, variability in commodity prices would create significant differences in relative profitability amongst the different farming systems. Under the mixed opportunity systems, the higher crop diversity offers the highest expected outcome, and when all commodity prices are down (P=0.0) or high (P=1.0) it is still expected to outperform the other systems by offering higher total gross margins during the experimental period (Figure 4). Therefore, it had the highest returns and least risk of all the systems at that location with those 4.5 year climatic conditions. This was also the case for the winter-dominant cropping theme.

For the summer dominant system, 70% (P=0.7) of the time the lower intensity system benefited from better commodity prices; and 30% (1-0.7) of the time the higher diversity + legume system returned higher total gross margins due to favourable commodity prices. With the higher intensity theme, the median returns and variation of all cropping systems where similar - apart from higher legume. The latter had an 80% chance of offering lower total gross margins 80% of the time, with far lower returns with low prices (P=0.0) and even with high prices (P=1.0) they were only marginally better than the other cropping systems.

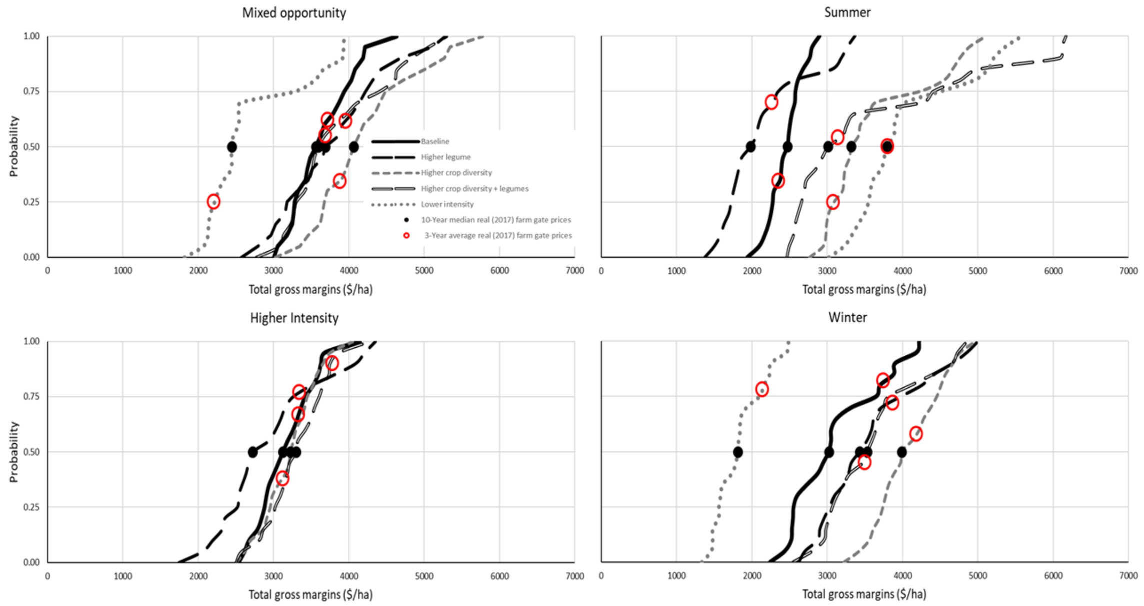

Figure 4. The distribution of total gross margins over 4.5 years calculated using the range of historical commodity prices for each farming system tested at the core experimental site, Pampas (Figure 1). The total gross margins with the lowest set of grain prices are shown where P=0 on and the highest combination of grain prices is shown where P=1. The median (P=0.5) total gross margins are the equivalent of our median price assumptions (shown in black dot), and the total gross margin using the 3-year average price (2015-2017) is in red

Acknowledgements

The research undertaken as part of this project (CSA00050, DAQ00192) 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. We would also specifically like to thank all the farm and field staff contributing to the implementation and management of these experiments, the trial co-operators and host farmers.

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Nitrogen and water dynamics in farming systems – multi-year impact of crop sequences

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Key words

northern farming systems, nitrogen, fallow, water-use-efficiency, soil water

GRDC code

DAQ00192, CSA00050

Take home messages

- Grain legumes have utilised soil mineral nitrogen (N) to the same extent as cereal crops and have higher N export which often offsets N fixation inputs
- Additional applied N reduced the depletion of background soil mineral N status at most sites; we are recovering a high percentage (>50%) in soil mineral pool.
- Application of ~50 t/ha of compost or manure (10 t/ha OC) coupled with N fertiliser rates for 90th percentile yield potential has dramatically increased the soil mineral N in four years
- Decreasing cropping frequency has reduced N export and so stored more N over the longer fallows, which has reduced N fertiliser requirements for following crops
- Long fallows are mineralising N and moving N down the soil profile even under some very dry conditions
- Most excess N is not lost in the system rather it is moved down the soil profile for future crops
- The marginal WUE of crops (i.e. the grain yield increase per extra mm of available water) is lower when crops have less than 100 mm prior to planting. Hence, waiting until soil moisture reaches these levels is critical to maximise conversion of accumulated soil moisture into grain
- The previous crop influences the efficiency of fallow water accumulation with winter cereals > sorghum > pulses. Long fallows are also less efficient than shorter fallows (<8 months). This has implications for assuming how much soil moisture may have accumulated during fallows.

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. Hence, identifying ways to improve crop sequences to make more efficient use of soil water is needed. Growers also 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. Since 2015 experiments have been comparing farming systems and crop sequences designed to meet the emerging challenges. 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)). 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.

Systems with best commercial practices (*Baseline*) at each location were compared to alternative systems with higher and/or lower crop intensity, higher crop diversity, higher legume frequency, higher nutrient supply and higher fertility (with the addition of organic matter).

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 with ongoing soil sampling conducted prior to planting each crop and again after harvest.

Depths of testing:

- soil water; 0 – 10 – 30 – 60 – 90 – 120 – 150 cm
- nitrate and ammonium N; 0 – 10 – 30 – 60 – 90 cm
- comprehensive nutrient analysis; 0 – 10 – 30 – 60 – 90 - 120 – 150 cm

There is a considerable range in soil fertility across the sites 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.

This paper explores five years of data across all geographical locations to compare the nitrogen and soil water dynamics in different farming systems across the northern region, specifically:

- Changes in system nitrogen dynamics due to increasing legume frequency, increasing fertiliser inputs and decreasing crop frequency
- Where the nitrogen is in the soil profile and how it moves over long fallows and different fertiliser regimes
- Dynamics of soil water over different crop sequences demonstrating how these influence crop water extraction and accumulation during fallows
- How soil water availability influences crop water use efficiency and
- How crop type influences fallow efficiency.

How does increasing legume frequency impact on system N dynamics?

Grain legumes are integral in current farming systems. The area and frequency of legumes has consistently increased due to high grain prices and a belief that they improve soil fertility and reduce overall nitrogen (N) fertiliser input costs. The data produced from the Farming Systems project has allowed us to compare the effects of increasing legume frequency on N dynamics over a large geographic area. However, it is important to note here that as the project only has five years of data, all these systems have only planted 1 or 2 extra legume crops compared to the *Baseline*.

To date, results across our sites show that additional legume crops in the crop sequence has had little positive impact on soil mineral N except at Billa Billa (+ leg Figures 1, 2, 3 & 4). The legumes are actually utilising soil mineral N to the same extent as cereal crops and have higher N export which often offsets N fixation inputs. This result is consistent across various starting soil N conditions, from locations with very high starting mineral N status (e.g. Billa Billa - Figure 2 & Pampas – Figure 3) to locations with low mineral N status (Narrabri - Figure 4) where legumes would need to fix N to meet their needs. These results challenge the common assumption that grain legumes reduce N fertiliser needs in the crop sequence. Improved pulse breeding and agronomy has increased harvest index and hence the ratio of N removed in grain to that left in biomass, so residual N has been diminished after the crop.

What is the impact of increasing fertiliser inputs on system N dynamics?

With declining soil fertility across the northern region there is increasing interest in identifying ways to either halt or reverse the trend of increasing fertiliser inputs. 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 phosphorus. 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 by increasing 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*. Another system was also implemented at two of the sites (Emerald and Billa Billa), *Higher fertility,* which also increases nutrient supply budgets to target 90th percentile yield but received an upfront addition of 10 t/ha organic carbon (as ~50 t/ha compost or manure) at the start of the experiment to raise the inherent fertility of the site. This system was designed to determine if a higher fertility level could be sustained with higher nutrient inputs.

The additional N that was applied in the *Higher nutrient* system (+ nut.) reduced the depletion of background soil mineral N status at eight of the ten sites (Emerald, Pampas mixed, Billa Billa & Narrabri shown Figures 1, 2, 3 & 4). The high starting nitrogen levels at Billa Billa has resulted in only one additional application of nitrogen in the *Higher nutrient* system for winter crop 2017, hence all systems have been utilising the original pool of N.

When comparing the *Higher fertility* system (+ fertility) at Emerald and Billa Billa (Figure 1 & 2) the additional organic carbon applied has dramatically increased the mineral N. The last two years has seen this system move ahead of all the systems at both sites. The largest change was seen at the Emerald site with this system holding an additional 150 kg available N/ha than the *Higher nutrition* system. It will be interesting to follow this system over further years to determine if this level of fertility can be maintained through the application of fertiliser rates budgeted for a 90th percentile yield potential.

These results show that applying N fertiliser to aim for a 90th percentile yield potential may reduce the mining of soil available N, and that significant amounts of additional N applied remains in the mineral N pool and hence 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.

What is the impact of decreasing crop intensity on system N dynamics?

The Northern region farming system is centred on growing crops mainly on stored soil moisture. With low fallow efficiencies, the belief is often “use it or lose it”. However, others believe it is more profitable to increase fallow length to reduce the risk to individual crops by increasing soil water at planting. The nitrogen dynamics of this *Lower crop intensity* system (-inten.) are shown below at Pampas (Figure 3) and Narrabri (Figure 4). These systems are storing more N over the longer fallows, which is reducing N fertiliser requirements for following crops. Given the recent dry conditions and enforced long fallows it is interesting to consider the amount and location of available N for the next crop.

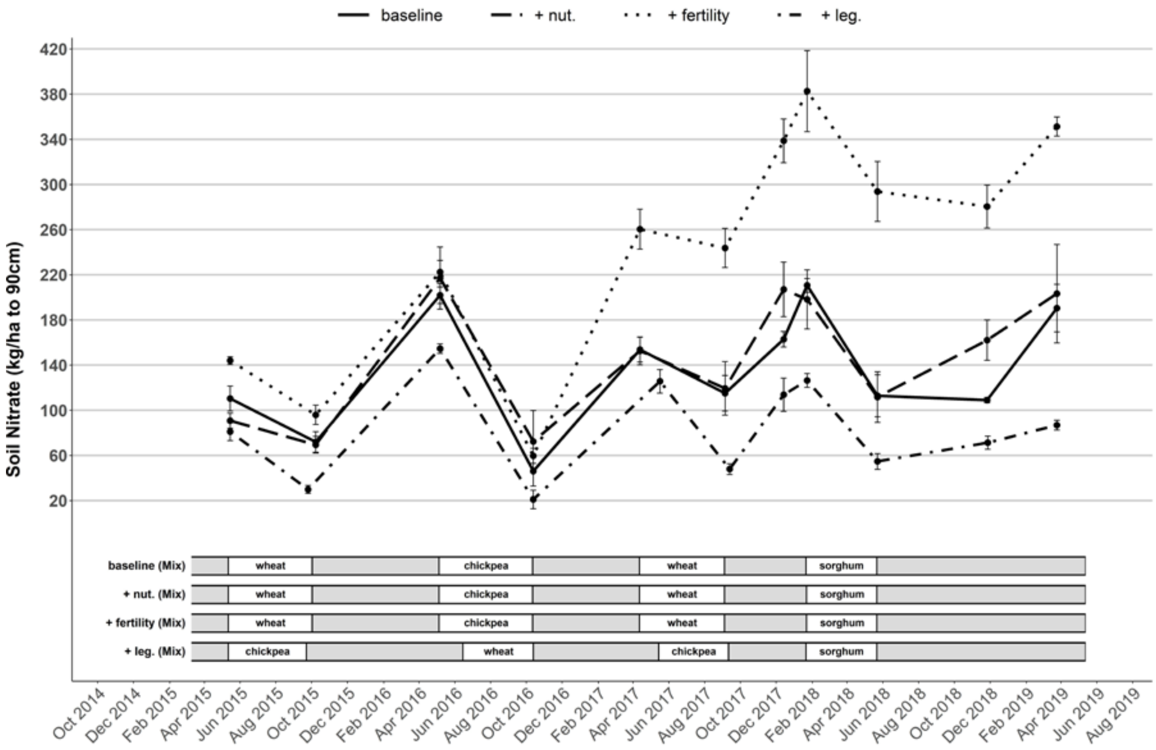

Figure 1. Dynamics of measured plant available soil nitrogen – Emerald

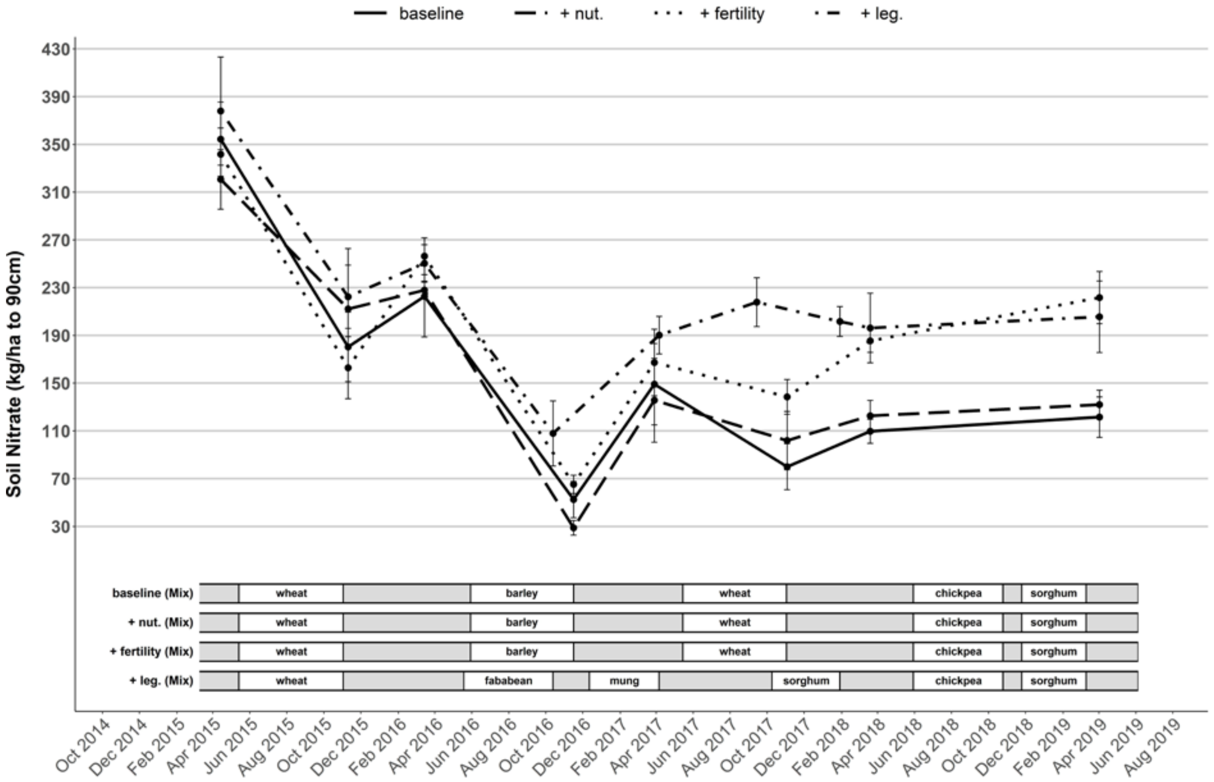

Figure 2. Dynamics of measured plant available soil nitrogen – Billa Billa

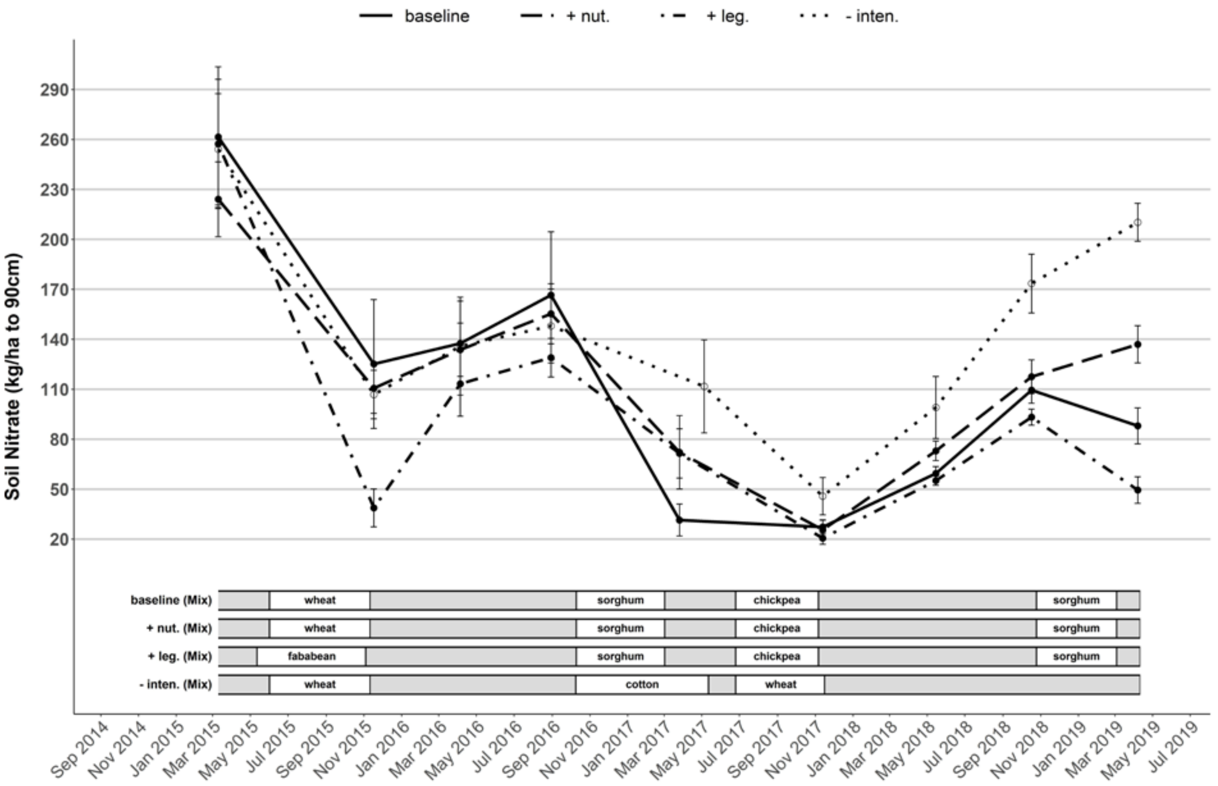

Figure 3. Dynamics of measured plant available soil nitrogen – Pampas mixed

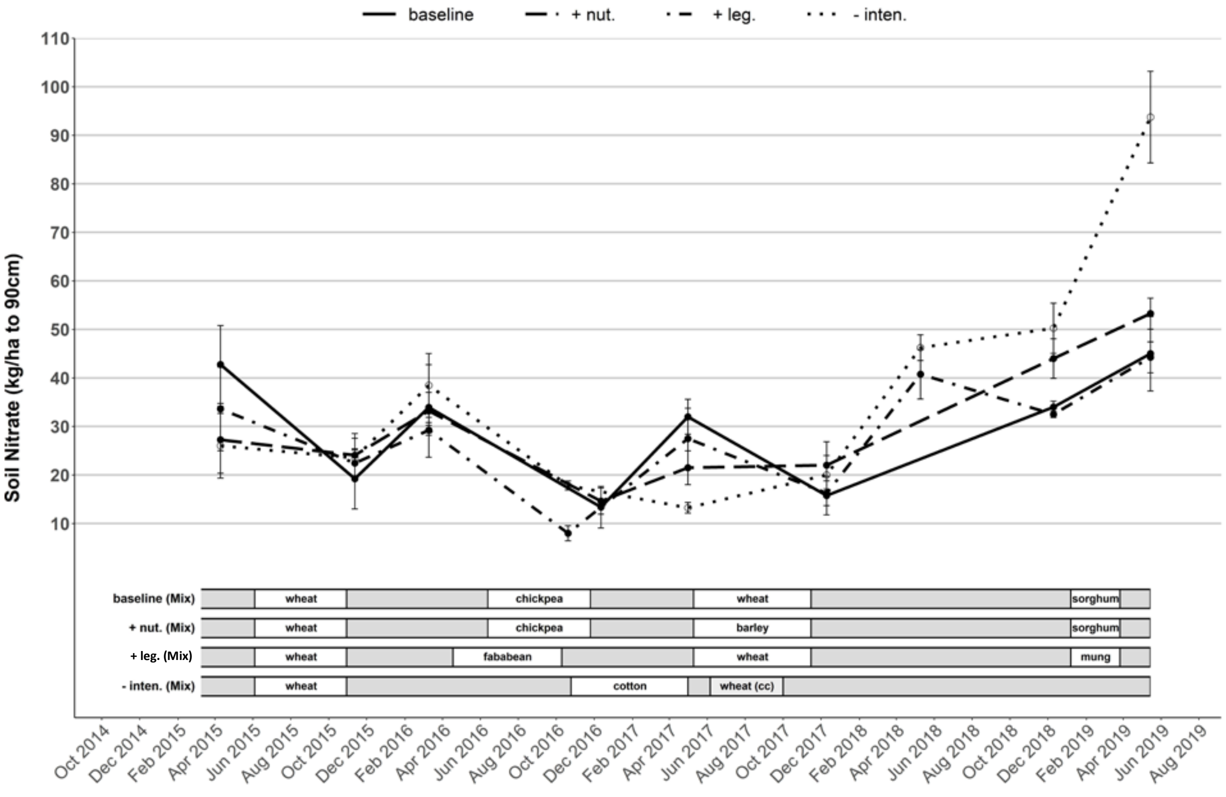

Figure 4. Dynamics of measured plant available soil nitrogen – Narrabri

Where is the nitrogen and how does it move in the soil profile?

When studying N dynamics over time the next question becomes ‘where is the N and how does it move in the profile?’ We have compared the starting available mineral N against that available after four years and where it is positioned in the soil profile at Emerald and Billa Billa (Figure 5). The Billa Billa site with its high starting fertility has seen N throughout the profile decline over time, with the largest change seen in the 0 – 10 cm. However, the Emerald site with its lower starting fertility and use of N fertiliser across all systems, has seen both the *Higher nutrient* and *Higher fertility* systems building N. The majority of this increase was in the 30 – 90 cm layers, indicating that excess N has moved down the profile during this time frame but is still available for future crops.

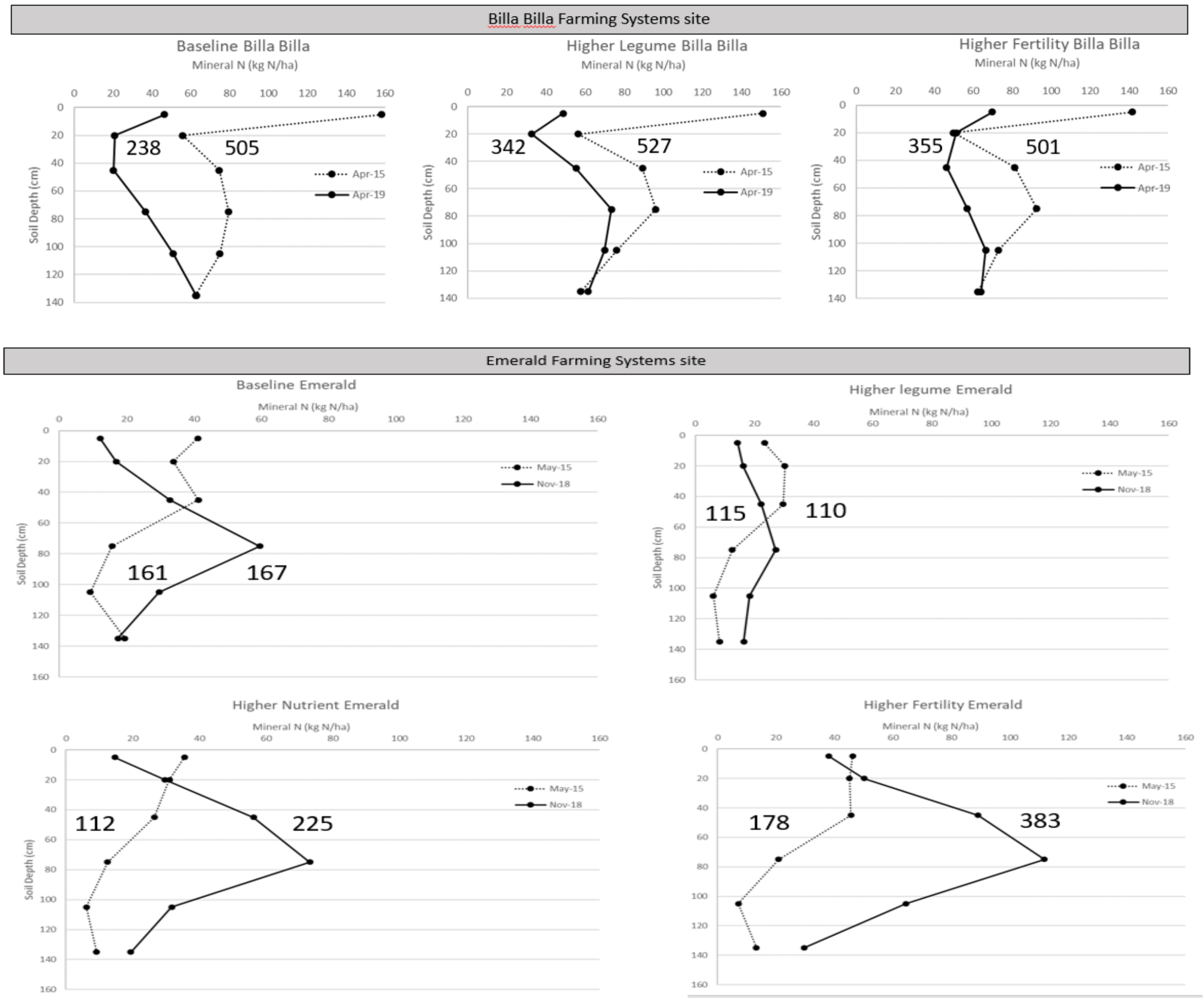

Figure 5. Distribution of mineral N placement within the soil profile from 2015 to 2019 at Billa Billa and Emerald

We know N mineralisation is related to soil type, organic carbon, biomass and rainfall – but what happens during extended dry periods such as the last 18 months across the northern grains region? After the initial increase of mineralised N in the topsoil across several sites, there was a definite movement of mineral N down through the soil profile. For instance, the summer season of 2017/18 saw significant levels of mineralisation within the 0 - 30 cm depth at the northern farming systems sites (Figure 6 - Narrabri and Pampas). This summer recorded below average rainfalls, but there was obviously still sufficient rain to trigger mineralisation. The increase in the 0 – 30 cm corresponds with the location of microbes responsible for the breakdown of organic matter into the plant available form of nitrate and ammonium. Sampling after the winter of 2018 found that the N mineralised during the previous summer, had filtered down the profile into the lower depths (30 - 60 cm). This pattern continued late into the fallow as the accumulated mineral N increased in the 60 - 90 cm depth. These results show that mineralisation can be triggered by even small falls of rain and this N can then move down the soil profile even with lower soil profile moisture levels or when rain does fall. This is important for the next phase of the cropping sequence, as it can be assumed that not only do we have ample mineral N available to maximise grain yields, but the location of the N is within the soil layers where plants require peak N uptake during key growth stages.

The Mungindi site (Figure 7) had preplant N applied for a winter crop that was not planted (2017). The *Baseline* received 20 kg N/ha and the *Higher nutrient* system received 80 kg N/ha in April 2017. The following year soil analysis showed that large amounts of N had mineralised and that this mineralised N and fertiliser N moved into the 10 - 30 and 30 - 60 cm layers during a very dry year. This data shows that if N is applied and not utilised by a crop that it may not be lost from the system but rather move down the profile to support future crop growth and grain production.

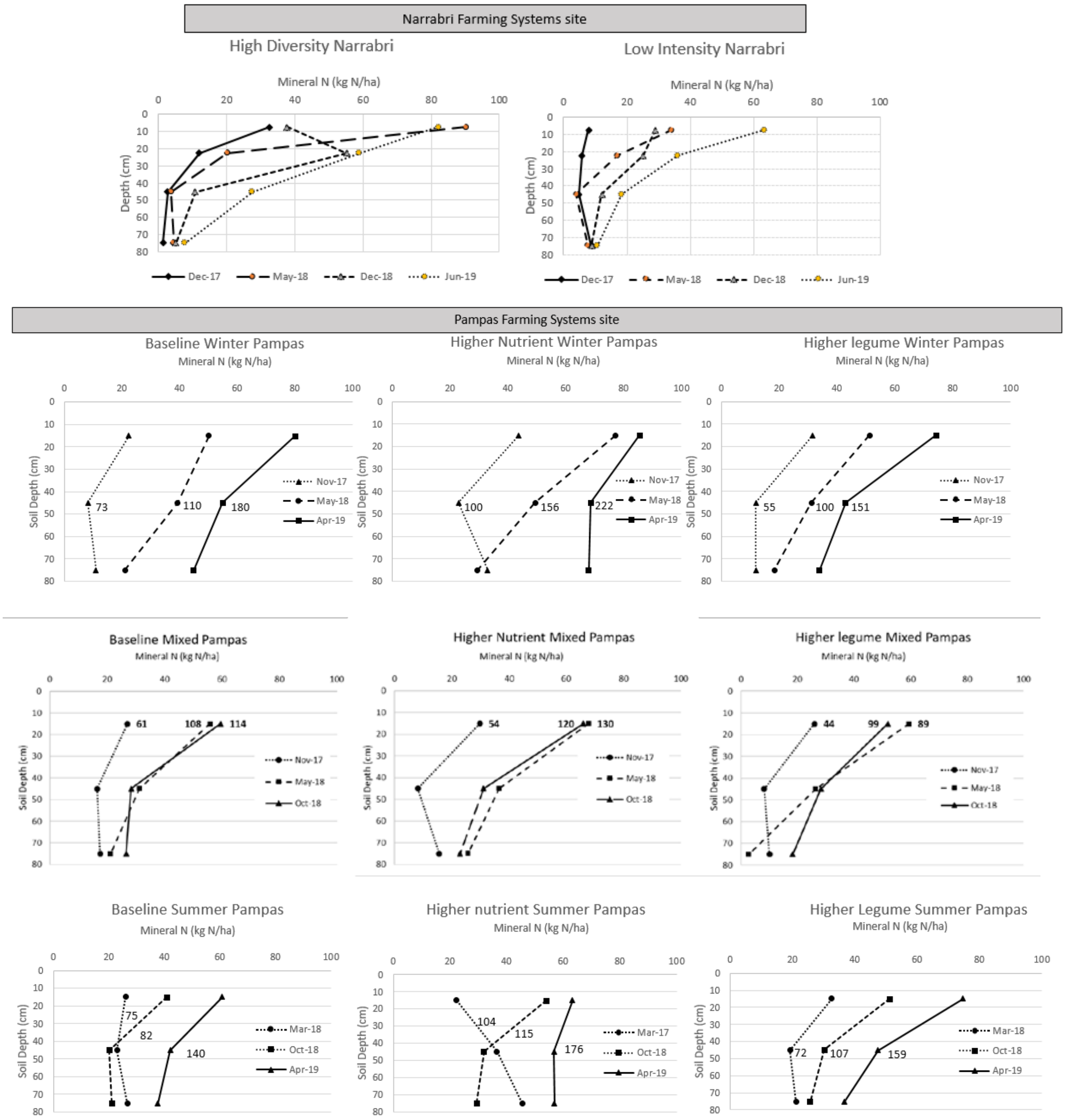

Figure 6. Distribution of mineral N placement within the soil profile over a long fallow period at Narrabri and Pampas

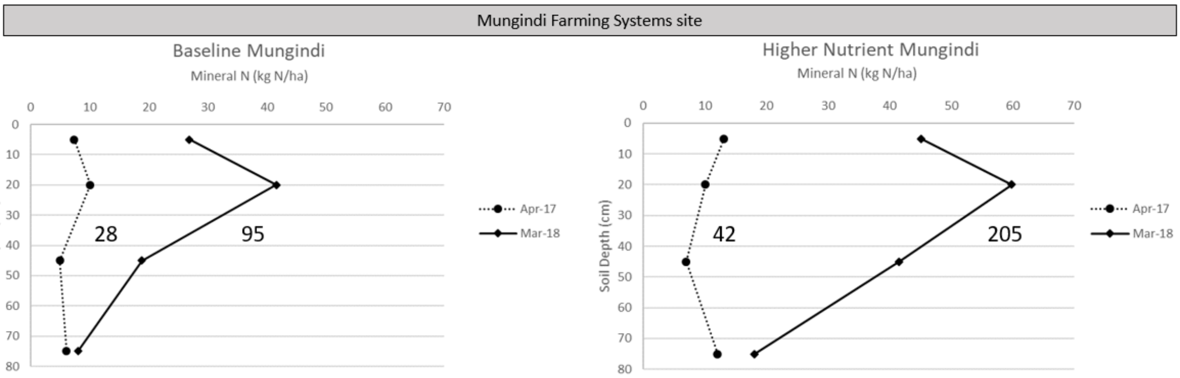

Figure 7. Distribution of mineral N placement within the soil profile over a long fallow period at Mungindi

Untangling the water use efficiency of crop sequences

System water use efficiency of a crop sequence is driven by the efficiency of its fallows (i.e. the proportion of rain falling during the fallow that accumulates in the soil to be available for the next crop) and how efficiently the subsequent crops can convert both the accumulated soil water and in-crop rainfall into grain or product. We have monitored crop water use, water use efficiency and subsequent fallow water accumulation for over 300 different crops to explore how soil water accumulates and is used over different crop sequences.

How does cropping intensity impact on plant available water (PAW) dynamics?

Cropping intensity impacted on the depth of recharge of the soil profile. In the two examples below at Billa Billa (Figure 8) and Pampas (Figure 9) the higher intensity soil profile was never allowed to refill as fully as the *Lower intensity* and *Baseline* systems. While there are implications on yield and WUE (discussed later in this paper) for having less stored water, not allowing the profile to fill may also affect the plants' ability to extract deep nutrients.

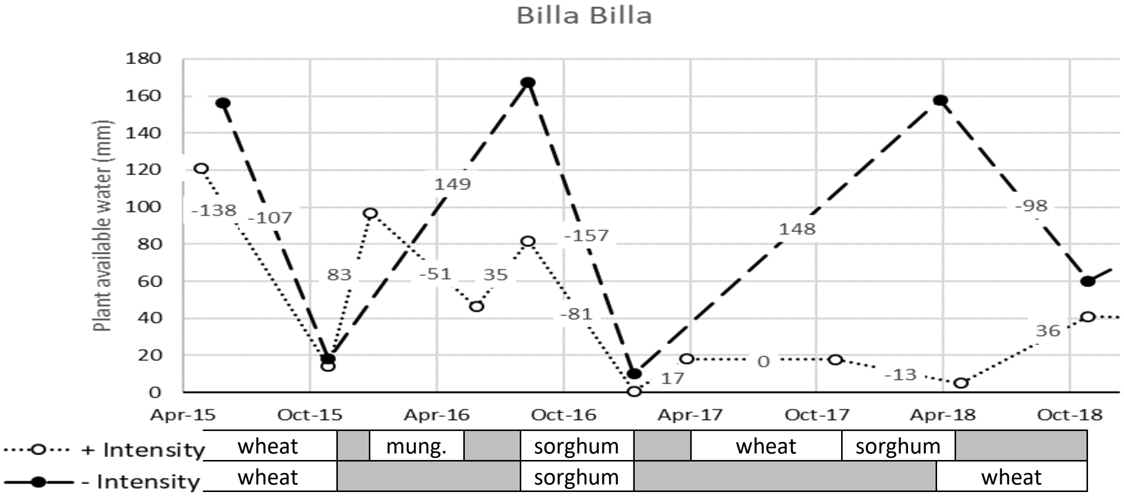

Figure 8. Plant available water (PAW) dynamics of two of the Billa Billa cropping systems. *Nb. Plots were often soil sampled up to 6 weeks prior to planting; crop duration indicated in the chart is from pre-plant soil sample to post-harvest soil sample (not plant to harvest). Numbers show the net change between the two soil water readings

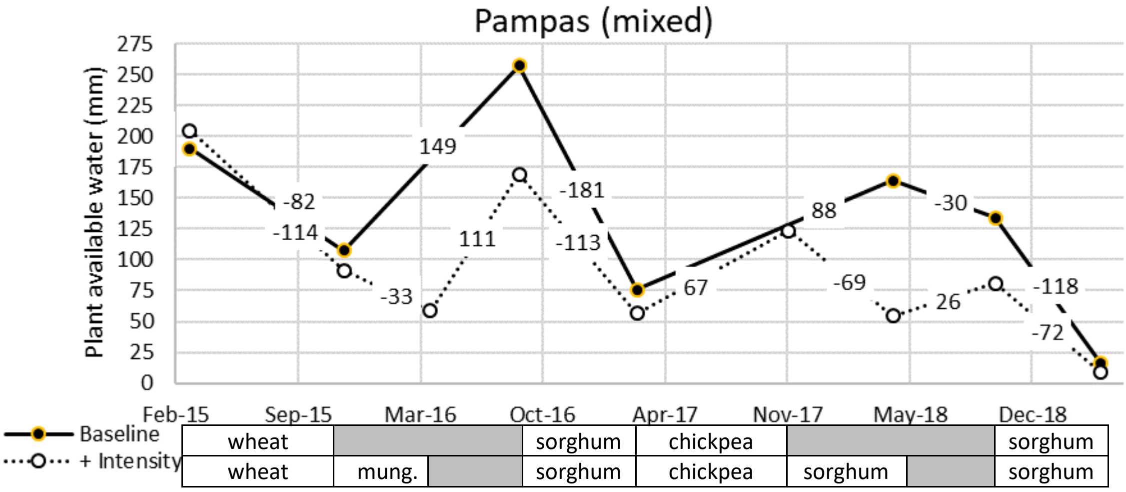

Figure 9. PAW dynamics of two of the Pampas mixed summer/winter cropping systems. *Nb. Plots were often soil sampled up to 6 weeks prior to planting; crop duration indicated in the chart is from pre-plant soil sample to post-harvest soil sample (not plant to harvest). Numbers show the net change between the two soil water readings

How does crop choice impact on PAW dynamics?

The Billa Billa Belah duplex soil is constrained by sodicity at depth, so pulse crops have left water below 50 cm. This deep PAW and rainfall at opportune times has allowed double cropping after pulses – an option that was not available in the systems where cereal crops (or canola) were grown (Figure 10) due to their higher ability than pulse crops to extract water from sodium constrained zones. This has allowed the *Higher legume* system to increase its cropping intensity, with the same PAW planting triggers as the *Baseline*. Similarly at Billa Billa, the *Lower intensity* wheat grown in 2018 reduced the profile by 98 mm (Figure 8) while chickpeas in the *Baseline* and *Higher legume* systems only reduced the profile by 39 and 34 mm respectively (Figure 10), allowing them to double crop to sorghum on the next rainfall event.

On the 'less constrained' black Vertosol at Pampas, the difference in PAW extraction is much less stark. There is still a difference in crop lower limits between the pulse and cereal crops, however the difference is much less. For example, faba beans and wheat were planted in the same season, with similar starting PAW (Figure 11). At harvest the wheat had extracted 14 mm more than the faba bean (compared to 53 mm in the constrained site). After harvest the wheat accumulated an extra 14 mm PAW, so that the two systems had the same PAW again when a winter crop was planted in the winter only systems. However, in the mixed systems the fallow was continued to sorghum in October 2016. With the longer fallow, the wheat stubble continued to provide higher fallow efficiency so had 12 mm more PAW at planting than the faba bean stubble. The extra stored PAW was used by the following sorghum crop, so that the two systems had the same PAW post-harvest and have maintained the same rotation and similar PAW since (Figure 11).

At Mungindi the *Baseline* and *Lower intensity* systems had the 2015 wheat crop in common. However, in 2016 the *Baseline* was planted to chickpea, while the *Lower intensity* was fallowed to cotton in the spring (Figure 12). A large portion of the rain that fell in that season was in the spring, when the chickpea and cotton crops were both in the ground, but with very little rainfall from chickpea harvest to cotton harvest. The cotton crop left the soil 32 mm drier than the chickpea at their respective harvests (chickpea was 19 mm drier at cotton picking), but a combination of residual wheat stubble and dry cracked soil post-cotton, resulted in the lower intensity system having an extra 15 mm PAW when the two systems were planted to wheat in 2018.

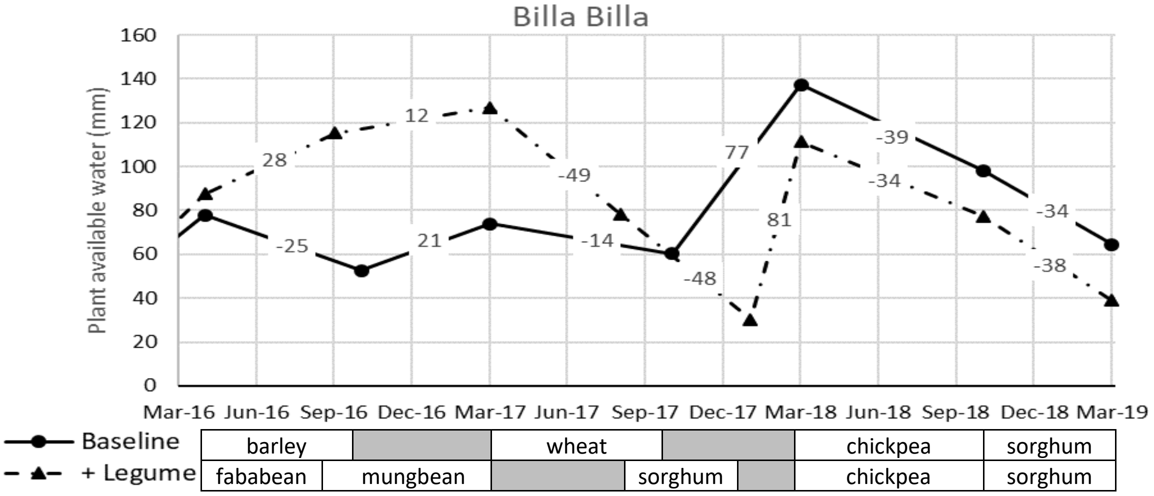

Figure 10. PAW dynamics of two of the Billa Billa cropping systems. *Nb. Plots were often soil sampled up to 6 weeks prior to planting; crop duration indicated in the chart is from pre-plant soil sample to post-harvest soil sample (not plant to harvest). Numbers show the net change between the two soil water readings

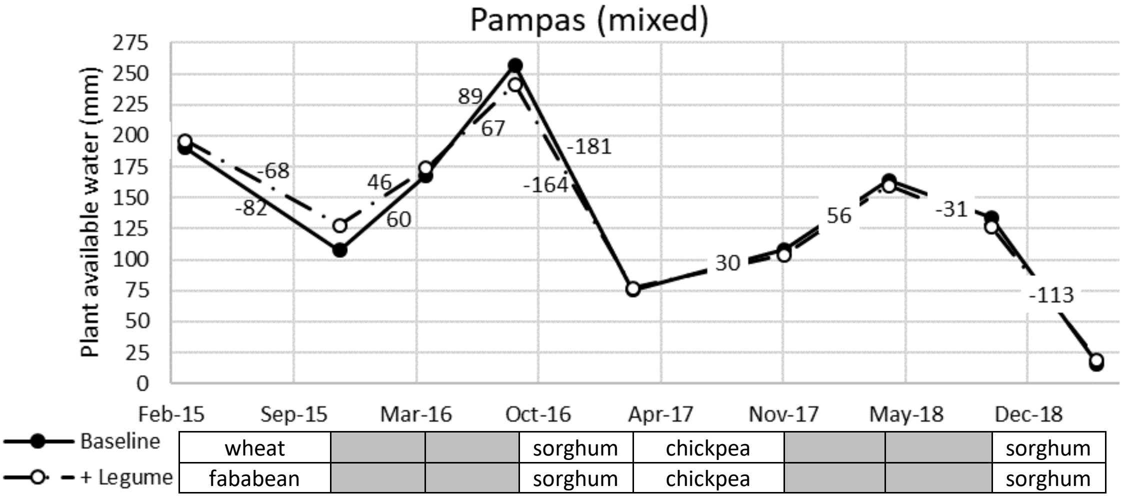

Figure 11. PAW dynamics of two of the Pampas mixed summer/winter cropping systems. *Nb. Plots were often soil sampled up to 6 weeks prior to planting; crop duration indicated in the chart is from pre-plant soil sample to post-harvest soil sample (not plant to harvest). Numbers show the net change between the two soil water readings

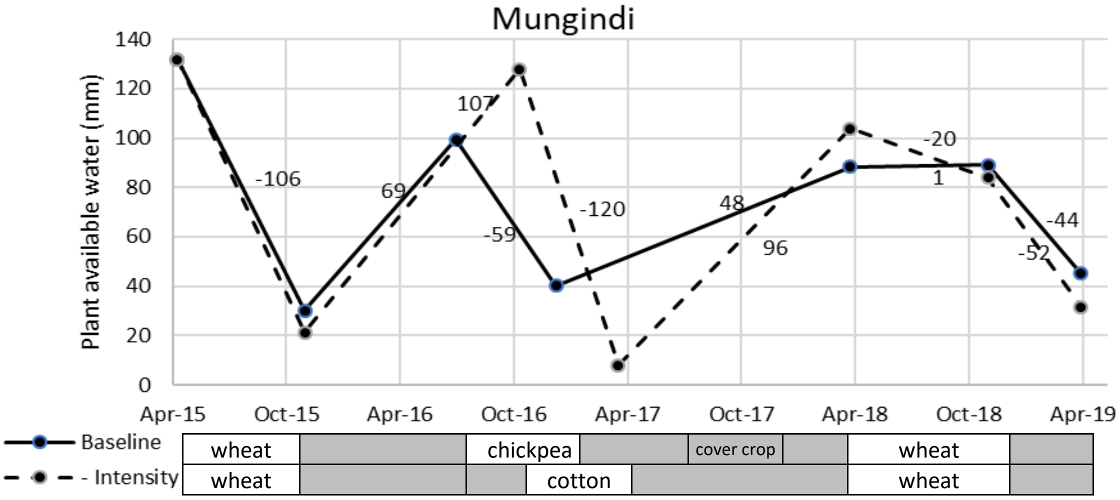

Figure 12. PAW dynamics of two of the Mungindi cropping systems. Numbers show the net change between the two soil water readings

Drivers of crop water use efficiency

The availability of water is a key driver of crop yields in Australian farming systems and hence understanding what drives crop water use efficiency (WUE; the kg of grain produced per mm of crop water use) is critical. A relationship between grain yield and crop water use has been widely used to demonstrate the WUE potential of crops across different environments. In northern farming systems the water available to the crop can come from stored soil water at planting and in-crop rain; In contrast to southern Australia where in-crop rain alone has often been used to calculate crop WUE. Further, the unreliability of in-crop rain can mean that the stored moisture can make up a large proportion of the water available to the crop, and hence has high importance for determining crop yield and crop WUE.

Using the data collected from the farming systems experiments we show that the marginal WUE (kg/mm of additional crop water use) reached its potential at 24 for wheat, 12.5 for chickpea and 18 for grain sorghum. Despite this potential and optimal crop management in these experiments, in most cases the average across all the crops measured was lower; 15.3 for wheat, 8.8 for chickpea and 14.3 for sorghum (Figure 13, TOP). This demonstrates that while WUE is a useful benchmark, there is large season to season variability due to the timing of rainfall events or other stresses that may reduce crop yields.

There is no clear relationship between planting soil water and crop yield across this data, due to large seasonal differences in in-crop rain. Nonetheless, we found some interesting relationships between available soil water at planting for the crop and the marginal WUE that that crop achieved (Figure 13, MIDDLE). This shows that in general, the WUE of crops increases as more soil water is available at planting. Crops of wheat, chickpea and sorghum that had less than 100 mm of plant available water coming into the season, had much less chance of achieving high crop WUE. This is because crops planted on marginal soil moisture are more at risk of depleting the soil profile prior to flowering and the critical grain filling period, unless significant in-crop rainfall occurs. This data suggests that chickpea may be less susceptible than wheat or sorghum to this. We could hypothesize that this is because chickpea has a lower water requirement prior to the start of grain filling and the indeterminate growth habit means that acute water stress at critical phenological times impact less severely on grain yield.

Finally, the gap between the marginal WUE of each crop compared to the potential predicted here (dashed lines) increases significantly in crops with lower soil water prior to planting. Figure 13 (BOTTOM) shows the rate that crop WUE declines per mm of available water across a range of starting soil water conditions. This indicates that the lower the soil water is at planting, the more quickly that WUE will decline. This further demonstrates that crops planted on lower soil water are likely to achieve suboptimal crop WUE and this relationship is not linear. That is, as less soil water is available, the likely reduction in WUE increases further.

In summary, this analysis shows that soil water prior to planting is a critical driver of how efficiently a crop converts the water available to it into grain. It is worth noting however, that this analysis was done using soil water samples prior to planting and hence, in some cases did not include the planting rainfall event itself. Hence, if another 15-20 mm is required to achieve this then this was not included these calculations of soil water at planting.

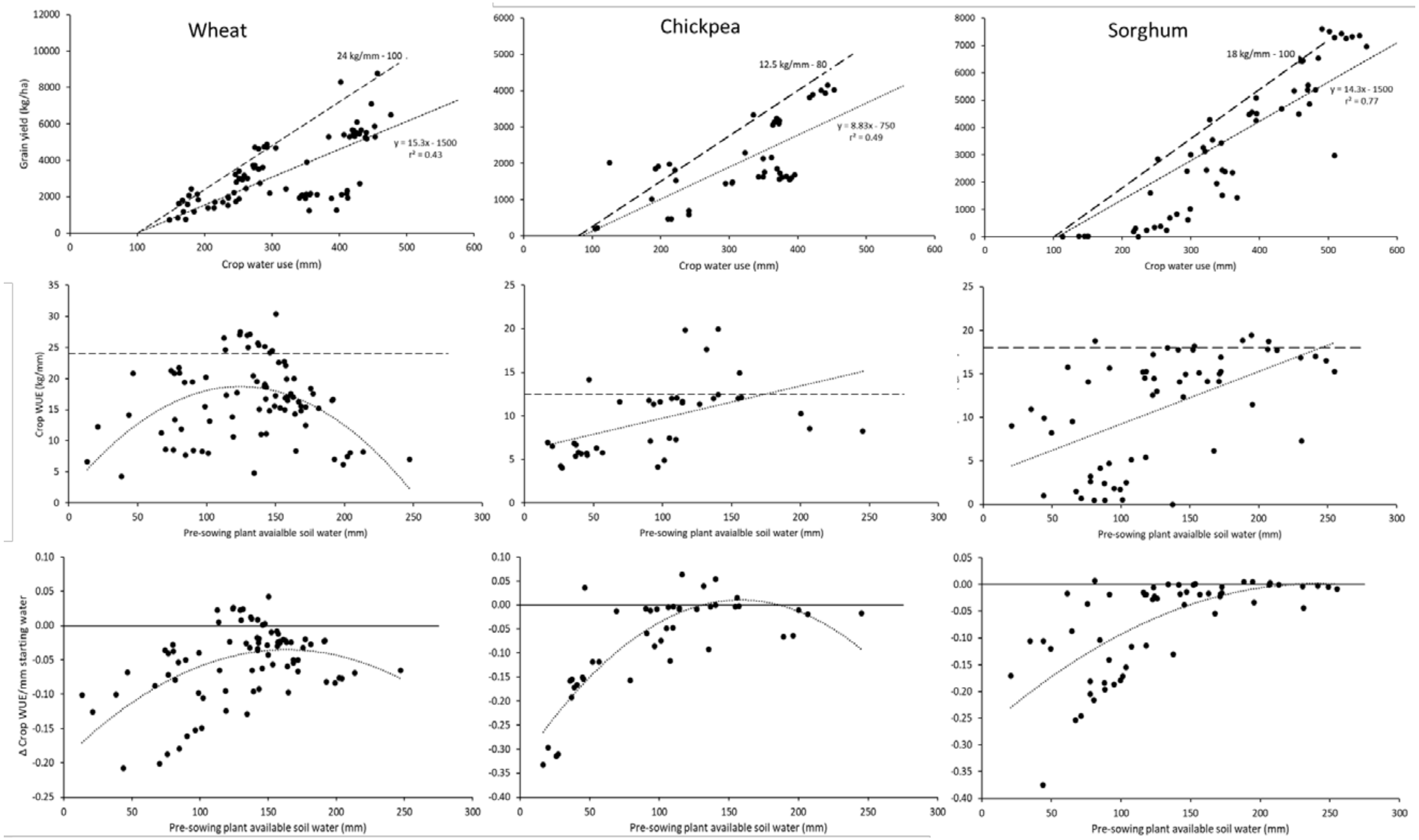

Figure 13. Relationships between water availability and crop yield and water use efficiency (WUE) in wheat, chickpea and grain sorghum collated from data collected across farming systems research sites. TOP –Crop water use (change in soil water plus rainfall) *vs.* grain yield, showing the maximum potential (dashed line) and the average across the dataset (dotted line); MIDDLE – Plant available soil water prior to planting *vs.* crop WUE (as calculated above); and BOTTOM – Plant-available soil water prior to planting vs the difference between the measured crop WUE and the potential WUE per mm of additional water available (dashed lines in above figures)

Crop effects on efficiency of subsequent fallows

Here we have collated this data to compare how different crop types impact on subsequent fallow efficiencies (Table 1). We have removed fallows with little rain (<80 mm) because this distorts the values of FE.

Based on > 20 different fallows we monitored, this quantifies some clear crop effects on subsequent fallow efficiencies – typically related to the ground cover provided and its persistence. Winter cereal crops provide the highest fallow efficiencies while the lower cover after winter pulses results in lower fallow efficiencies. Sorghum is intermediate. With fewer observations, fallow efficiencies after canola were intermediate between the winter pulses and winter cereals. Cotton produced much lower fallow efficiencies. The data also clearly shows that short-fallows are more efficient than longer fallows, because during long-fallows the soil is wetter for longer and hence there is more evaporative losses and residue cover levels are reducing with time.

Table 1. Comparison of efficiencies of fallow water accumulation (i.e. change in soil water/fallow rainfall) following different crops. Data are an average of fallows monitored across the farming systems experiments in northern NSW and southern Qld between 2015 and 2019. Only fallows receiving more than 80 mm of rain are included

Previous crop	**All fallows**	***n.***	**Short fallow (<8 months)**	***n.***	**Long fallows (> 8 months)**	***n.***
Winter cereals (wheat, durum, barley)	30%	*81*	34%	*54*	21%	*27*
Winter pulses (chickpea, fababean, field pea)	20%	*36*	25%	*20*	15%	*16*
Sorghum	22%	*23*	28%	*7*	19%	*16*
Canola	26%	*5*	31%	*4*	6%	*1*
Cotton	16%	*3*			16%	*3*

This means 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 120 mm on average, while the same fallow after a grain legume would have only accumulated 80 mm. This difference could have a significant impact on the opportunity to plant a crop and/or the yield and gross margin of the following crop in the cropping sequence.

Conclusions

Nitrogen

Improved pulse varieties and agronomy has seen greater use of pulses. This has not provided increased nitrogen benefits to following crops as the pulse crops often mine mineral nitrogen from the profile. However, increasing nitrogen budgets to 90th percentile yield potential at planting has meant crops have left nitrogen behind in most seasons, so the nitrogen can move down the profile and accumulate in the deeper soil layers. This effect is accentuated where we also added organic carbon to the system, as the soil is suppling more nitrogen to the mineral pool.

Increasing the time spent in fallow is also allowing the soil to mineralise more N, and the small rainfall events in the recent dry seasons have been sufficient to move N down the profile.

Regardless of the source, excess nitrogen was rarely lost to the system, rather it was moved down the soil profile for future crops, and presumably some has moved into the organic pool. But the only way to be sure how much and where nitrogen is positioned is with a well segmented soil test.

Water

In a northern farming system, grain yield is highly dependent on how much water is stored in the profile during the preceding fallow. The efficiency of capturing and storing fallow rainfall is driven by the stubble left by the previous crops and the duration of the fallow period. Crop type also influences how efficiently crop water use is converted to grain. This research suggests storing more than 100 mm PAW prior to planting increases the likelihood of optimising crop WUE.

Increasing cropping intensity by planting with less stored moisture, reduces the potential to recharge deep soils, which can limit the plants ability to access deep stored nutrients.

Crop choice can dictate the next planting opportunity through the different residual water levels at harvest and fallow efficiency of the stubble left behind. This opportunity could be quite different in the presence versus absence of soil constraints.

Acknowledgements

The research undertaken as part of this project (CSA00050, DAQ00192) 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. We would also specifically like to thank all the farm and field staff contributing to the implementation and management of these experiments, the trial co-operators and host farmers.

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Can wild species of chickpea from Turkey help with resistance to root-lesion nematode (*Pratylenchus thornei*)?

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Key words

chickpea, wild chickpea, *Cicer reticulatum*. *C. echinospermum*, root-lesion nematode, *Pratylenchus thornei*, genetics and disease resistance, tolerance

GRDC code

USQ 00017

Take home messages

- This is the first investigation of a new collection of wild germplasm for nematode resistance. It offers the chance to exploit novel sources of *P. thornei* resistance and untapped genetic diversity, currently not available in cultivated chickpea and will be valuable for national and international chickpea breeding programs
- Accessions of the wild chickpea species (*Cicer reticuatum* and *C. echinospermum*) from Turkey, were on average more resistant to the root-lesion nematode *Pratylenchus thornei* than commercial cultivars of chickpea (*C. arietinum*)
- A total of 53 (30%) wild accessions were found significantly more resistant to *P. thornei* than the least susceptible Australian chickpea cultivar PBA Seamer
- Thirteen of the wild accessions were more resistant than a wild relative of chickpea, *C. echinospermum* ILWC 246 which was identified from earlier studies when only a limited number of wild accessions were available
- Having novel sources of *P. thornei* resistance with possible resistance to multiple diseases and insect pests such as cotton boll worm (*Helicoverpa armigera*), will increase the base of *P. thornei* resistance, and genetic diversity within chickpea for deployment in chickpea breeding programs aimed at developing new varieties with improved yield but possessing *P. thornei* resistance
- Linking the data with genetic diversity studies can provide information on *P. thornei* resistance genes and their locations in the chickpea genome
- Having more effective genes for resistance to *P. thornei* in chickpea cultivars will protect chickpea from yield loss and result in lower *P. thornei* residual populations in the soil. This will benefit other susceptible crops such as wheat, resulting in more flexible rotations with a profitable legume, and allow increased profit for growers.

Background

Wild chickpea and their role in developing cultivars to combat *Pratylenchus thornei* in the Australian grain region.

Crop wild relative (CWR) species are a rich source of genetic disease resistance and diversity and play a major role in meeting disease and environmental challenges in 21st century agriculture. Currently, there is limited genetic diversity within chickpea (*Cicer arietinum*) germplasm, and this hinders further progress in plant breeding worldwide to combat diseases and environmental stresses (Croser et al., 2003). Due to global changes, wild relatives are under threat of disappearing, and wild collections such as the one studied here are economically vital for the future of chickpea breeding and biodiversity in agriculture crops (von Wettberg et al., 2018). The chickpea genus *Cicer* has 43 wild species but only two wild annuals, *Cicer reticulatum* and *C. echinospermum,* can be hybridised with cultivated chickpea. These two wild species occur only in south eastern Turkey where chickpea originated as a domestic crop some 10,000 years ago.

The root-lesion nematode (RLN), *Pratylenchus thornei,* also known as the cereal and legume nematode, is a microscopic eelworm found in 67% of paddocks within the northern grain region of Australia (Thompson et al., 2010). It is the dominant species causing damage in chickpea crops throughout Australia, Europe and Asia with yield losses estimated up to 25% for intolerant Australian chickpea cultivars, and 58% in western Asia (Zwart et al., 2019).

Management for RLN relies on rotation with tolerant and resistant crops, however, *P. thornei* has a wide host range and several seasons of resistant crops are required to reduce soil populations below damaging levels of 2,000 per kg of soil (equivalent to 2 per gram of soil) (Owen et al., 2014). Chemical control is non economical, and inefficient in killing nematodes at depth in the soil profile (Reen et al., 2014). Furthermore, in dry periods, the nematodes are capable of going into a state of anhydrobiosis during slow dehydration of the soil and can become active again once soil moisture is restored. The long term, environmentally sustainable and cost effective solution to the problems with *P. thornei* is to breed and grow crop cultivars with resistance.

The terms resistance and tolerance are often used indiscriminately but both mean two very different things.

- Tolerance is how well a crop yields in the presence of nematodes and growing a tolerant cultivar will help minimise yield loss. However, tolerant cultivars while suffering less yield loss do not reduce nematode soil populations, unless they also possess resistance, and consequently will keep building up soil populations of *P. thornei* thereby limiting rotational options
- Resistance refers to how much a crop cultivar will limit nematode multiplication within the crop roots and soil, thereby limiting the damaging effects on that crop and reducing residual *P. thornei* soil populations to allow more flexible choice of crop rotations.

Crop cultivars can vary in their levels of resistance and tolerance, and breeding programs aim at incorporating a combination of both traits. This has been beneficial in wheat where the combination of resistance and tolerance results in higher yields compared to cultivars being tolerant and susceptible (Sheedy et al., 2012). Chickpea tend to be more tolerant than its main rotational crop wheat, however, current commercial cultivars range from moderately susceptible to very susceptible and will keep building up *P. thornei* populations in the soil.

Previous research seeking *P. thornei* resistance in *C. arietinum* has been extensive, but little resistance was found in cultivated germplasm. The search for useful traits in chickpea has been hindered by the narrow genetic diversity in cultivated chickpea, and a previously limited world collection of wild chickpea that consisted of only 18. *C. reticulatum* and 10 *C. echinospermum* accessions (Berger et al., 2003). Recent collection missions in Turkey in 2013 have boosted the numbers of wild accessions. This new 2013 collection has 100 times more genetic diversity than cultivated chickpea and 12 different genetic population groups were identified within the collection (von Wettberg et al., 2018). This new, larger collection is the focus of this study and the aim was to identify wild accessions with superior *P. thornei* resistance that could be used for breeding Australian cultivars.

Material and methods

The wild chickpea accessions originated from 21 collection sites within five provinces of Turkey and were tested twice for resistance to *P. thornei* over a two year period in controlled glasshouse studies. In order to determine the genetics controlling resistance, it is important to carry out these studies without any environmental influences that can mask the resistance. Extensive research has shown studies carried out in controlled glasshouse environments to assess resistance to *P. thornei* accurately predict field resistance (Thompson et al., 2019).

A total of 174 wild chickpea accessions (133 *C. reticulatum*, 41 *C. echinospermu*m) plus twenty-two reference cultivars that ranged in levels of *P. thornei* resistance were tested. The reference cultivars included 11 Australian desi chickpea cultivars that were moderately susceptible (PBA Boundaryⓓ PBA HatTrickⓓ, PBA Seamerⓓ, PBA Pistolⓓ, Flipper, Howzat and Yorker), susceptible (Jimbour, Sona, and Sonali) and very susceptible (Kyabraⓓ) plus a number of breeding lines with wild relative backgrounds. Four other reference wild *Cicer* accessions were included consisting of one resistant and one susceptible *C. reticulatum* (ILWC 123, ILWC 184 respectively), and one resistant and one moderately susceptible *C. echinospermum* (ILWC 246, ILWC 39 respectively). Plants were grown for 18 weeks and nematodes extracted from the roots and soils and counted under a microscope. There was a high correlation between experiments (0.84%) so data was analysed across the two years to obtain genetic rankings of resistance for the accessions.

Summary of results

On average, the wild species were more resistant than domesticated chickpea cultivars (*C. arietinum* Table 1). While there was a range of resistance within the wild species, neither species appeared more resistant than the other.

Genetic rankings showed (13) 7% wild accessions were more resistant than the most resistant *C. echinospermum* reference ILWC 246 from previous studies (Thompson et al., 2011).

A further 40 accessions (23%) were significantly more resistant than the least susceptible Australian chickpea cultivar PBA Seamerⓓ (Figure 1). This range of resistance for all accessions is illustrated in Figure 2 and shows how the wild accessions are more to the resistant end of the scale. Furthermore two accessions with high *P. thornei* resistance also have promising cotton bollworm resistance (*Helicoverpa armigera*) (Von Wettberg et al., 2018).

Mean *P. thornei* numbers also differed for collection sites and genetic population groups. There were no obvious trends for association of *P. thornei* resistance in terms of elevation and geographic location, as resistant accessions occurred at all elevations and at all sites.

Table 1. Population densities of *Pratylenchus thornei* in relation to *Cicer* species. Means are derived from best linear unbiased estimators (*P. thornei* per kilogram of soil + roots) in Experiments 1 and 2

Experiment	Species	No. Accessions	*P. thornei*/kg of soil + roots^y	
			Log$_e$	Mean *P. thornei*
1	*C. arietinum*	11	10.13 a	25,804
	C. echinospermum	34	8.61 b	5,503
	C. reticulatum	121	8.59 b	5,359
2	*C. arietinum*	12	10.42 a	33,390
	C. reticulatum	135	9.38 b	11,897
	C. echinospermum	43	9.35 b	11,487

Values followed by the same letter within each experiment are not significantly different ($P < 0.05$). Modified from Reen et al 2019.

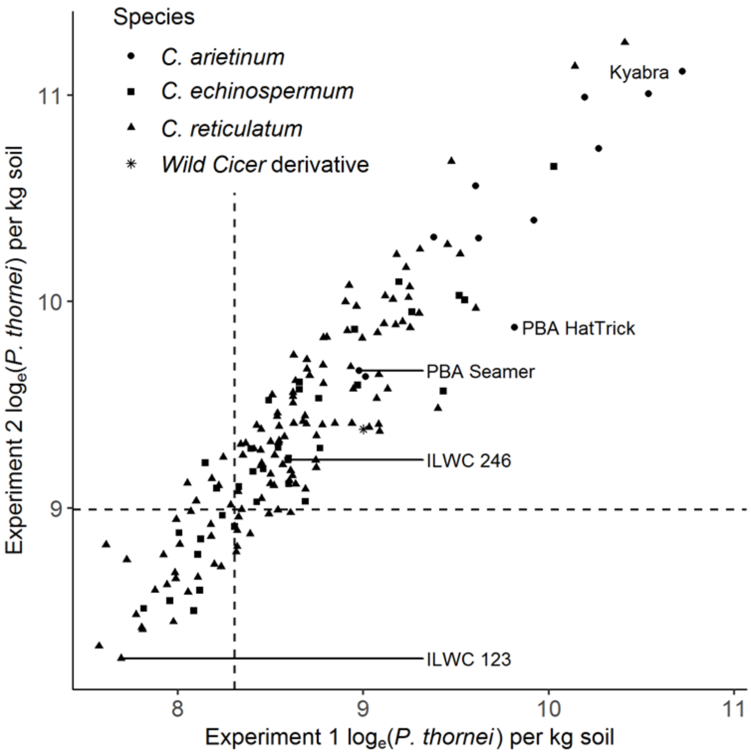

Figure 1. Accession means (best linear unbiased predictors) of *Pratylenchus thornei* population densities for *Cicer* accessions included in both experiments showed a strong genetic correlation between experiments (r = 0.844, n = 167). Vertical and horizontal dashed lines denote the cut-off points for the top 20% accessions for resistance to *P. thornei*. (Source: Reen et al., 2019)

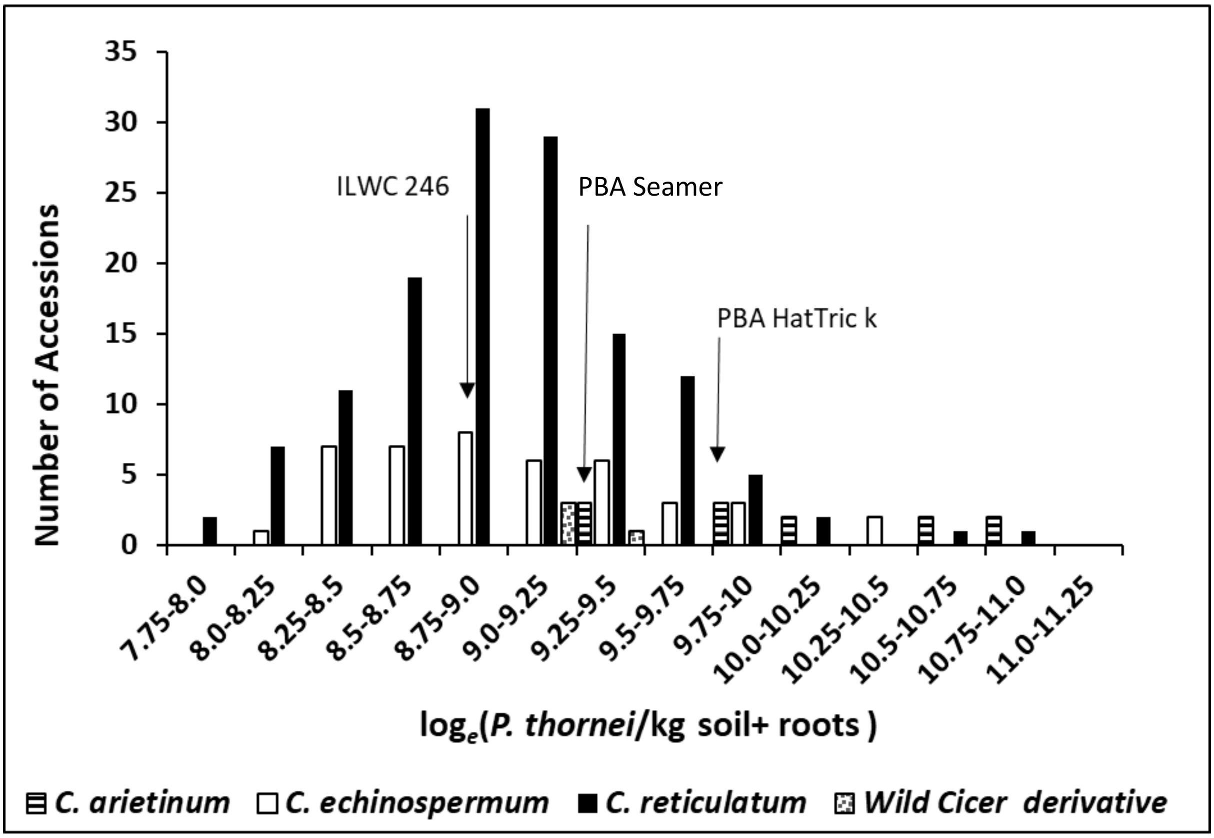

Figure 2. Distribution of accessions showing the spread of resistance to *P. thornei* for domesticated chickpea cultivars (*C. arietinum*) and wild chickpea accessions (*C. echinospermum & C. reticulatum*). Results are expressed in log e (*P. thornei* / kg soil) from combined analysis of two experiments where accessions were tested twice. Accessions left of PBA Seamer have lower values and therefore higher resistance to *P. thornei* than domestic cultivars. (Source from Reen et al 2019)

Discussion

The success of chickpea crop improvement is reliant on the amount of genetic variation available within the germplasm, and investment in new collections such as those studied here are valuable for chickpea breeding worldwide. Wild chickpeas possess a diversity of adaptive genes to disease stresses that have evolved over thousands of years independent of domestication (Berger et al., 2003).

This research is the first worldwide to assess nematode resistance for this new collection of wild relatives of chickpea. The results reveal the collection contains new and diverse sources of *P. thornei* resistance and untapped genetic diversity, valuable for Australian and international chickpea breeding programs to exploit. Furthermore, the identification of *P. thornei* resistance within this collection, highlights the crucial importance of wild species for meeting the challenges in relation to biotic stresses facing the industry today.

Where to from here?

Targeting and exploiting accessions with *Pratylenchus thornei* resistance identified in this research, provides an excellent opportunity to harness this diversity and resistance for chickpea improvement. Within this wild collection, 26 diverse accessions were selected internationally as parents for breeding with elite chickpea cultivars that represent major growing and climatic regions of the world. In Australia, this elite cultivar was PBA HatTrick⚜, and five resulting hybrid populations with improved *P. thornei* resistance have been selected for advancement and mapping studies to identify *P. thornei* resistance genes for future breeding purposes.

It is hoped, future assessment of the resulting progeny combined with genomic resources will facilitate more rapid development of *P. thornei* resistant cultivars with the possibility of combined resistance to multiple diseases. The results also provide the basis for further studies to improve knowledge about the genetic control of *P. thornei* resistance in chickpea. It is anticipated in future research, to pyramid the resistant genes with the combining of multiple resistance to other stresses. The outcome for the chickpea industry will be a reduction in *P. thornei* populations in the soil, which will not only benefit chickpea but other susceptible crops such as wheat, resulting in more flexible crop rotations and increased yields and whole farm profitability.

Acknowledgments

The research undertaken in this project was possible by significant contributions of growers and support of the GRDC, and by DAF Queensland and USQ under the Broad-acre Cropping Initiative. The authors would like to thank them for their continued support.

Furthermore, thanks to AGG for supplying the wild *Cicer* collection and Professor Doug Cook, UC Davis, California, and Dr Jens Berger CSIRO Australia, for collection and importation of the wild *Cicer* accessions into Australia. Special thanks to Hannah Rostad (USQ), for technical assistance, and Kerry Bell in statistical support (QDAF).

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Improving Phytophthora root rot resistance in chickpeas through breeding for waterlogging tolerance - implications for diagnosing root health and PREDICTA®B testing

Nicole Dron, NSW DPI Tamworth

Key words

Chickpea, waterlogging, resistance breeding, Phytophthora root rot, diagnostics, PREDICTA®B

GRDC code

BLG302 - PhD Project: Improving Phytophthora root rot resistance though waterlogging tolerance in chickpea.

Take home messages

- Waterlogging will increase crop damage from Phytophthora root rot (PRR) including a reduction in rooting depth
- Sowing chickpea varieties with higher levels of PRR resistance (PBA HatTrickⓓ & PBA Seamerⓓ) will increase likelihood of survival in the presence of disease and in combination with waterlogging
- Observing chickpea root systems is the best determinant of plant health
- When using PREDICTA®B as an in-crop diagnostic tool, sampling for PRR in chickpea should be conducted approximately 8 days after a waterlogging event when increased levels of *Phytophthora medicaganis* DNA are present in the soil and root tissue.

Background

A link between Phytophthora root rot (PRR) resistance and waterlogging tolerance has been discovered previously in soybean. In chickpea this link has not yet been investigated. In 2010, 2012 and 2016, high in-crop rainfall occurred throughout the season in the PRR affected northern growing region and resulted in observed partial and complete chickpea crop losses. These losses were attributed to a number of issues including: waterlogging, salinity, lodging, Ascochyta blight, Botrytis grey mould and PRR. In undulating paddocks with free draining soil, where regular foliar fungicides could be strategically applied, crops suffered only minor yield penalties. Data collected from PRR yield loss trials (DAN00176, DAQ00186) demonstrated that in the 2016 season, when inoculated treatments were saturated for extended periods, yield loss reached up to 90% of the control in the moderately resistant Australian chickpea cultivar PBA HatTrickⓓ (Table 1). This extent of loss was considerably higher than drier seasons with losses of 33% and 68% in 2014 and 2015, respectively (Table 1). However, it remains unclear as to whether increased yield losses in 2016 can be fully attributed to PRR or occurred in combination with waterlogging. Observations under early and cooler waterlogging events, as seen in 2010, saw extended chickpea survival in the absence of PRR. However, in 2016 extensive damage was recorded which may be related to higher temperatures, later physiological growth stage at the time of waterlogging and/or the presence of the PRR pathogen.

Table 1. Annual rainfall and Phytophthora root rot yield loss trial data from the 2014, 2015 and 2016 seasons for PRR moderately resistant variety PBA HatTrickⓓ*

Season	Total in-crop rainfall (mm)	PBA HatTrickⓓ yield (t/ha) in absence of PRR infection	PBA HatTrickⓓ % yield loss due to PRR infection
2014	137	2.94	33
2015	194	2.50	68
2016	450	4.02	90

*GRDC updates paper - 'Phytophthora in chickpea varieties 2016 and 2017 trials –resistance and yield loss' (Bithell et al., 2018).

The life cycle of most oomycetes, including *Phytophthora medicaginis* which causes PRR in chickpea, consist of two phases each driven by the physical surroundings. The most prolific pathway (outer circle) is induced under high soil moisture (above field capacity) where dormant thick-walled oospore structures produce sac like sporangia containing large numbers of water motile zoospores which are released to infect plants. Zoospores can orientate and move towards the host plant infecting root tissue. The second and direct pathway (inner part of circle) is characterised by the production of a single germ tube from oospores or chlamydospores which also occurs under moist soil conditions. Oospores and chlamydospores are thick walled dormant structures able to survive long periods in adverse soil conditions (highest recorded 10 years). Under waterlogging conditions it is assumed that an influx of zoospores leads to severe PRR disease development. However, germination of Phytophthora spores requires oxygen which is greatly reduced or absent under waterlogging conditions. Oxygen levels are dependent on duration, temperature and soil characteristics. If the waterlogging event is short and water is fast draining, oxygen is not depleted and adequate levels of oxygen remain where Phytophthora species are able to survive and infect host root tissue.

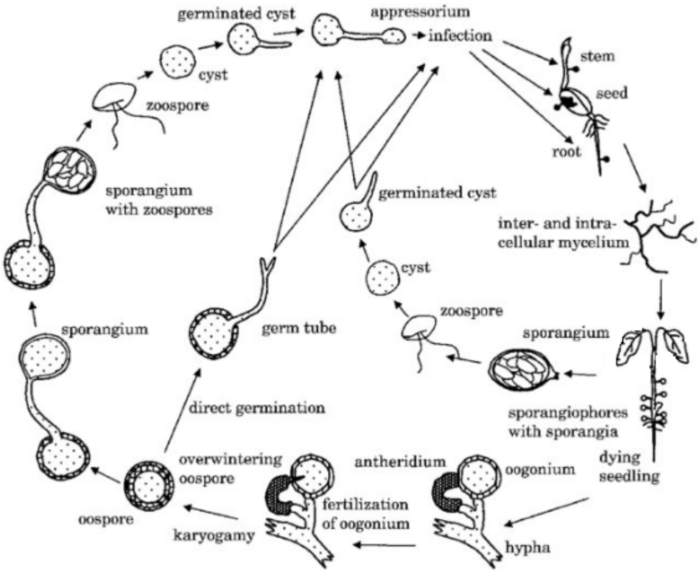

Figure 1. Life cycle of a typical root infecting oomycete *Pythium* and *Phytophthora* species (Van West, Appiah, & Gow, 2003)

Ongoing breeding and pathology efforts aim to understand and improve PRR resistance within Australian chickpea varieties. The specific aim of this PhD project (BLG203) is to investigate the possibility to improve or select for PRR resistance based on variation in waterlogging tolerance; with short term benefits of understanding the interaction between PRR and waterlogging and improved sampling time for in-field molecular diagnostics.

Sources of PRR resistance in commercial chickpea varieties are scarce with the search for novel sources of resistance for incorporation into adapted northern region backgrounds continuing. Older varieties (Kyabraᶲ, Jimbour, Motiᶲ and Yorker) vary with low to moderate levels of PRR resistance. More recent varieties (PBA HatTrickᶲ& PBA Seamerᶲ) are characterised by their moderate resistance to PRR, but have been shown across seasons to still suffer up to 20-70% yield loss from PRR. Wild chickpea has been found to have novel PRR resistance, however it is notoriously poorly adapted, having a prostrate growth habit with low yield and seed quality issues; making genetic lag a major challenge when breeding for PRR resistance. Extensive backcrossing into domestic chickpea material has been required to improve yield, seed quality and adaption whilst maintaining the high level of PRR resistance.

The following results discuss the response of two varieties and one breeding line; the domestic PRR susceptible variety Rupali, and moderately PRR resistant Yorker as well as the wild chickpea interspecific back cross genotype 04067-81-2-1-1 with high PRR resistance. Varieties PBA HatTrickᶲ and PBA Seamerᶲ commonly grown in the Northern region would perform similarly to Yorker with slightly less resistance; and Kyabraᶲ is similar to Rupali in terms of PRR resistance.

Disease symptoms and root characteristics of chickpea in response to waterlogging, PRR and both in combination

In a glasshouse experiment, foliar chlorosis was not observed in PRR resistant 04067-81-2-1-1 and moderately resistant Yorker seedlings in aerated PRR, waterlogging only or waterlogging + PRR treatments (Figure 2, left). However, under aerated PRR and waterlogging + PRR treatments the same entries suffered significant root disease symptoms including lateral root loss and primary root canker (Figure 2, right). The PRR susceptible entry Rupali had significantly increased chlorosis and root disease over 04067-81-2-1-1 and Yorker in both the aerated PRR and waterlogged + PRR treatments (Figure 2). The waterlogging treatment in the absence of PRR did not produce root necrosis or foliar chlorosis in any entry, being similar to the un-inoculated aerated control treatment (Figure 2).

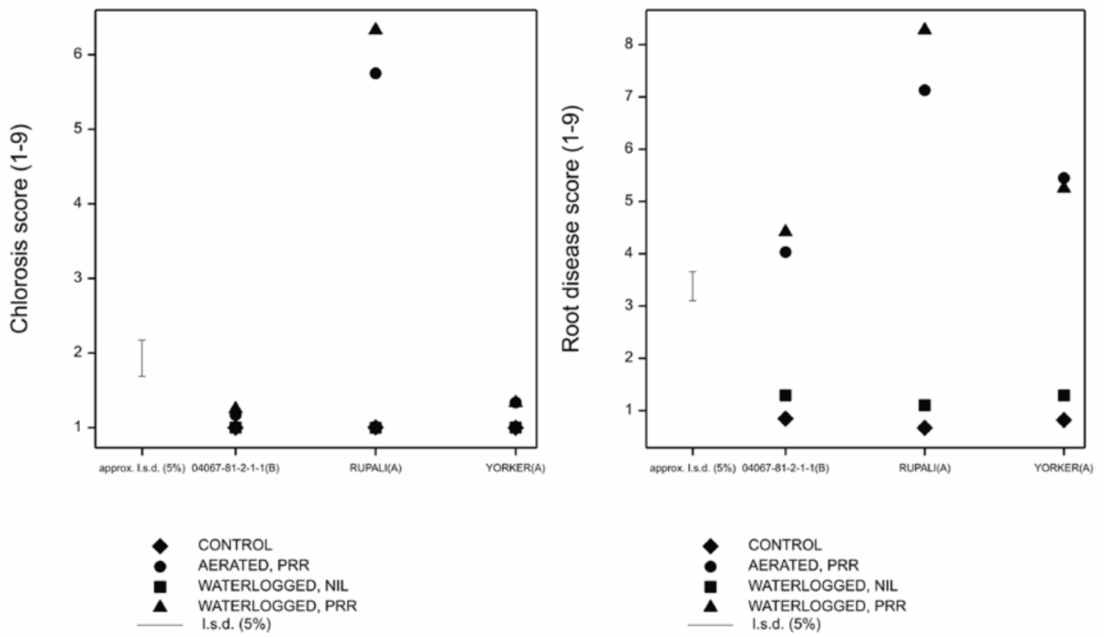

Figure 2. Foliar chlorosis (left) and root disease score (right) for chickpea entries under control conditions, aerated and PRR infected, waterlogged only and waterlogged with PRR infection. Chlorosis and root disease scale 1 =no symptoms, 9 = completely chlorotic foliage or total root loss. Root disease score rated the severity of necrosis in root tissue

04067-82-1-1 has been noted to have an inherently smaller root system compared to cultivated chickpea Yorker and Rupali; and had significantly reduced root volume when infected with PRR under both aerated and waterlogging treatments conditions (Figure 3, left). Yorker had no significant change in root volume across treatments compared with the control treatment, despite having a higher root disease score. Waterlogging alone did not significantly affect the root volume of 04067-82-1-1, Yorker and Rupali (Figure 3, left). Interestingly under the waterlogging only treatment Yorker trended towards having higher root volume than the control treatment. Whilst root length volume remains largely affected by genotype and PRR infection, primary root length was greatly influenced by both waterlogging and PRR treatments (Figure 3, right). Primary root growth appears to be halted in the presence of both PRR and waterlogging. The moderately PRR resistant Yorker and PRR susceptible Rupali however continued to suffer further root length reductions with the combination of waterlogging and PRR infection over the PRR resistant genotype 04067-81-2-1-1 (Figure 3, right).

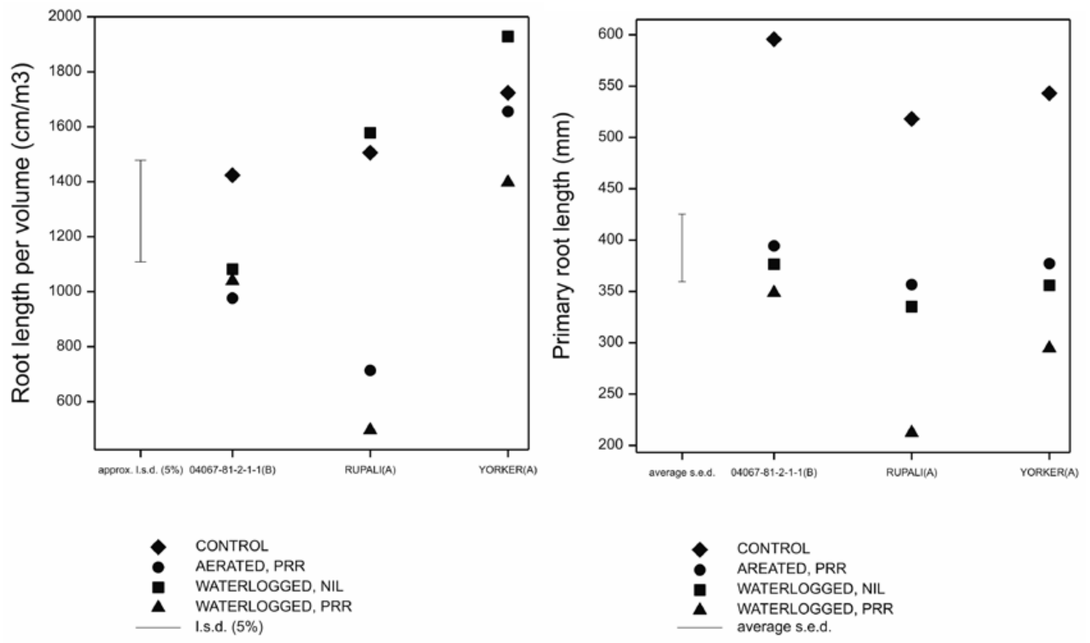

Figure 3. Root length volume (left) and primary root length (right) for chickpea entries under control conditions, aerated and infected with PRR, waterlogged only and waterlogged with PRR infection

What does it mean for growers?

Both waterlogging and PRR can cause advanced root lesions and/or reductions in growth prior to the appearance of chlorosis in leaf tissue, except when a PRR susceptible variety is infected with PRR. The environmental conditions, timing and duration of waterlogging will determine whether plant death or yield losses are attributed to PRR or waterlogging. When diagnosing visually it is important to dig up the roots soon after water receding to identify the presence of brown root lesions which indicate PRR infection. Waterlogged plants will not have initial root lesions and have lateral roots remaining which provide greater resistance when attempting to pull them from the soil compared to PRR infected plants.

Plants may survive waterlogging if it occurs early in the season and plant biomass is low enough for the reduced root volume to maintain plant metabolism. Following flooding, if chickpea plants survive, in the presence of *Phytophthora medicaginis* root lesions will appear after 8-10 days as Phytophthora germinates and infects upon the re-introduction of oxygen to the favourable moist environment. Potting mix and hydroponic experiments (data not shown) as anticipated, showed that under long term waterlogging (11 days) and a lack of oxygen, zoospores were greatly reduced or absent in solution and PREDICTA®B results demonstrated a reduction in the number of Phytophthora DNA copies detected compared to non-waterlogged treatments. These results indicate that when looking to diagnose PRR during a flood season, soil sampling 8 days after waterlogging with the inclusion of suspect chickpea root tissue may provide the best chance to identify the presence or absence of PRR using PREDICTA®B for paddock history purposes.

Losses from PRR infection in chickpeas are increased when they occur in combination with waterlogging; not necessarily because the pathogen is able to proliferate in the favourable conditions, but due to lack of oxygen during waterlogging when root growth is restricted. This limits the chickpea plants ability to compensate for root damage caused by PRR. Initial findings indicate that increased levels of resistance to PRR did reduce damage to chickpea roots under the combination of PRR and waterlogging. Root characteristics under waterlogging did change between the domestic and wild chickpea resistance sources. Understanding the impact of these root traits and usefulness for waterlogging tolerance and/or PRR resistance is ongoing, with a wider search to discover new sources of waterlogging tolerance and PRR resistance.

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Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through the support of the GRDC and the NSW DPI. This work was undertaken as part of project DAN00213: Grains Agronomy & Pathology Partnership (GAPP) - A strategic partnership between GRDC and NSW DPI. The PhD study is enrolled through the University of Adelaide with the support of supervisors Dr. Tim Sutton (SARDI and the University of Adelaide) and Dr. Kristy Hobson (NSW DPI). NSW DPI plant pathologists Sean Bithell, Dr. Steven Simpfendorfer and Dr. Kevin Moore have been instrumental in advising on method development and experience throughout the project. The author would like to thank all involved for their continued support.

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Day 2 early risers session – Nutrition

Notes

Implications of continuing dry conditions on cereal disease management

Steven Simpfendorfer, NSW DPI, Tamworth

Keywords

fusarium crown rot, common root rot, AMF, PREDICTA® B, spot form of net-blotch

GRDC code

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

Take home messages

- Due to a combination of factors there is likely to be increased cereal plantings in 2020, once the opportunity arises
- Failed pastures with decent levels of grass development are potentially high risk scenarios for cereal diseases in 2020 as grasses host many of the causal pathogens
- Unfortunately, prolonged dry conditions increase the risk of cereal diseases including Fusarium crown rot and common root rot
- There has also been a decline in populations of beneficial arbuscular mycorrhizae fungi (AMF)
- However, steps can be taken to minimise impacts which include:
  1. Know before you sow (e.g. PREDICTA®B)
  2. Implementing pre-sowing management options
  3. Sowing quality seed known to have both good germination and vigour
  4. Assessing root health and infection levels around heading – you need to ‘dig deeper’ than just leaf diseases!

Introduction

Unfortunately much of northern NSW and southern Qld experienced a relatively dry winter cropping season again in 2019. These conditions, especially with hotter and drier conditions during grain filling, are ideal for the expression of Fusarium crown rot as whiteheads and resulting yield loss. Fusarium crown rot, caused predominantly by the stubble-borne fungus *Fusarium pseudograminearum*, infects all winter cereal crops (wheat, barley, durum, triticale and oats) and numerous grass weed species also host this pathogen. However, a key point is that dry conditions do not just have implications for Fusarium crown rot management. There are other potential cereal disease implications that need to be considered by growers and management strategies implemented to maximise profitability when recovering from drought.

Potential consequences of dry conditions

Extended dry conditions in 2018 and 2019, possibly longer in some areas, has a range of potential implications on farming systems which can include:

- Reduce stubble cover – increasing wind erosion, reducing fallow efficiency and limiting stored soil moisture levels
- Reduced decomposition of crop residues which can extend inoculum survival to 2 to 4+ years

- Reduced animal stock numbers – extended dry has seen sheep and cattle numbers decline which will take a number of seasons to recover
- Reduced survival of pastures in mixed cropping systems
- Later seasonal breaks reducing opportunities for canola establishment in some districts
- Widespread baling of cereal crops for hay in 2018 and 2019
- Increased pressure on available planting seed for establishing crops in 2020.

Although many of these issues are common across continuous and mixed cropping enterprises, as a general rule those operations that have opted for more intensive broad acre crop production are hopefully more aware of potential pitfalls around limiting cereal diseases and ensuring quality of planting seed. The lack of animal stock, failure of pastures and need for ground cover is likely to see a substantial increase in the area of cereals planted, especially in mixed farming systems once the drought breaks. Grass species and grass weeds tend to dominate as legume species decline in pasture mixes over time and with moisture stress. These are therefore potentially higher risk paddocks for cereal diseases as the grasses serve as alternate hosts for pathogens such as *Fusarium pseudograminearum* (Fusarium crown rot), *Bipolaris sorokiniana* (common root rot), *Rhizoctonia solani* (rhizoctonia root rot), *Gaeumannomyces graminis* var. *tritici* (take-all), root lesion nematodes and some leaf diseases (e.g. barley grass hosts net-blotch pathogen *Pyrenophora teres*).

When the drought does break in impacted regions, hopefully in 2020, growers will be driven by two key factors. The first will be to generate cash flow and the second will be to restore groundcover to bare paddocks through the planting of winter cereals. This will potentially occur with little regard to the risk posed by plant pathogens and the quality of available planting seed. Maximising the profitability of crop production is going to be critical to many farming operations once the drought breaks. The following paper highlights some of the potential issues for consideration by growers and agronomists from a cereal pathology view point. Some practical steps that can be taken to hopefully minimise losses are also outlined.

Step 1: Know before you sow

Although paddock history can be a good guide to potential disease issues, extended dry conditions can allow damaging inoculum levels to still persist from 2-4+ seasons ago (Table 1). Hence, growers need to consider the longer-term sequences within paddocks. How cereal stubble was handled over prolonged dry conditions can also influence the survival and distribution of cereal pathogens. Paddock history is only a guide and provides no quantitative information on the actual level of risk posed by different cereal diseases.

Table 1. Decline in pathogen and beneficial arbuscular mycorrhizae fungi (AMF) levels over 20 months in a replicated cereal variety experiment at Rowena

Pathogen	**13 Dec 2017**	**12 June 2019**	**% decline**	**Risk mid-2019**
Prat. Thornei (no./g soil)	7.7	4.3	44	Medium
Common root rot (pgDNA/g)	58	38	35	Low-medium
Crown rot (phDNA/g)	579	256	56	High
AMF (KDNA copies/g)	90	55	39	Adequate

Consider testing paddocks using PREDICTA®B. This would be especially useful for paddocks coming out of failed pastures which may have become dominated by grasses. PREDICTA®B is a quantitative DNA based soil test which provides relative risk or population levels for a wide range of pathogens that can be used to guide management decisions. However, ensure you are using the latest recommended PREDICTA®B sampling strategy which includes the addition of cereal stubble to soil samples (see useful resources). Addition of cereal stubble (or grass weed residues if present in pasture paddocks) improves detection of stubble-borne pathogens which cause diseases such as Fusarium crown rot, common root rot, yellow spot in wheat and net-blotches in barley. Considerable GRDC co-funded research has been conducted nationally over the last 5 years to improve the recommended sampling strategy, refine risk categories and include additional pathogens or beneficial fungi (AMF) on testing panels. Recent paddock surveys have highlighted that a single pathogen rarely exists in isolation within individual paddocks, but rather multiple pathogens occur in various combinations and at different levels. PREDICTA®B is world leading technology that can quantitatively measure these pathogen combinations within a single soil + stubble sample. Given extended dry conditions the two key cereal diseases of concern for 2020 in northern NSW and southern Qld are likely to be Fusarium crown rot and common root rot. Decline in beneficial AMF populations is also of concern. The risk of both of these diseases and AMF populations can all be determined by PREDICTA®B.

Alternately, cereal stubble or grass weed residues can be collected from paddocks and submitted to NSW DPI laboratories in Tamworth as a ‘no charge’ diagnostic sample (see contact details). Samples are plated for recovery of only two pathogens which cause Fusarium crown rot or common root rot and provide no indication of other potential disease risks.

Step 2: Consider pre-sowing management options

Generic management options are provided with PREDICTA®B test results which are tailored to the actual levels of different key pathogens detected within a sample. Your PREDICTA®B accredited agronomist should also be able to assist with interpretation which can be daunting given the number of pathogens covered by the testing. NSWDPI are also happy to discuss results (PREDICTA®B or stubble testing) and work through potential management options (see contact details).

Fusarium crown rot (Fusarium pseudograminearum)

Assuming the main concern is Fusarium crown rot. Based on the following PREDICTA®B or stubble test results, pre-sowing management options include:

Below detection limit (BDL) or low:
No restrictions, ensure good crop agronomy

Medium:
Consider sowing a non-host pulse or oilseed crop with good grass weed control.

If sowing cereal then:

- Avoid susceptible wheat or barley varieties, durum is higher risk but oats are fine
- Sow at the start of a varieties recommended window for your region
- Consider inter-row sowing (if previous cereal rows are still intact) to limit contact with inoculum
- Do not cultivate - it will spread inoculum more evenly across the paddock and into infection zones below ground
- Be conservative on nitrogen application at sowing (Figure 1) as this can exacerbate infection (e.g. consider split application) but ensure a maintenance level of zinc is applied
- Be aware that current seed treatments registered for Fusarium crown rot suppression provide limited control
- Determine infection levels around heading (see step 4).

High:
Consider sowing a non-host pulse or oilseed crop with good grass weed control.

If sowing cereal then:

- Choose a more tolerant wheat or barley variety for your region to maximise yield and profit (Table 2), durum is very high risk with yield loss >50% are probable in a tough finish but oats are still a decent option
- Sow at the start of a varieties recommended window for your region as this can half the extent of yield loss
- If a late break occurs consider switching to a quicker maturing wheat variety or go with barley to limit exposure to heat stress during grain filling which exacerbates yield loss
- Consider inter-row sowing (if previous cereal rows are still intact) to limit contact with inoculum
- Do not cultivate - it will spread inoculum more evenly across the paddock and into infection zones below ground
- Be conservative on nitrogen application at sowing (Figure 1) as this can exacerbate infection (e.g. consider split application) but ensure a maintenance level of zinc is applied
- Be aware that current seed treatments registered for Fusarium crown rot suppression provide limited control and get to a Syngenta learning centre in 2020
- Determine infection levels around heading (see step 4) and be prepared from sowing to cut for hay or silage if required.

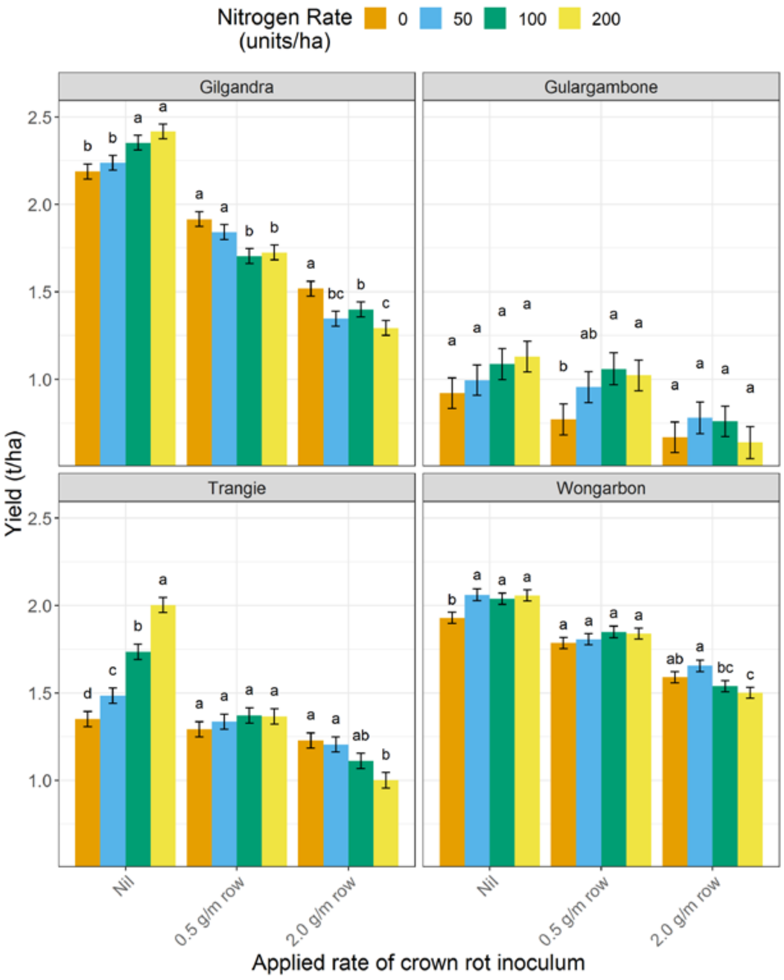

Figure 1. Interaction of nitrogen nutrition and crown rot infection on bread wheat (Suntop⦶ and EGA Gregory⦶) yield across four sites in central NSW in 2018. Note: Nil applied inoculum represents a BDL/low risk, 0.5 g/m row a medium risk and 2.0 g/m row a high risk of crown rot infection.

Table 1. Average yield (t/ha), yield loss from crown rot (%), screenings (%) and lost income from crown rot ($/ha) of four barley, 5 durum and 20 bread wheat entries in the absence (no added CR) and presence (added CR) of crown rot inoculum averaged across 50 sites in central/northern NSW and southern Qld – 2013 to 2017.
Varieties within crop species ordered from highest to lowest yield in added CR treatment. Lost income and income in added CR treatment based solely on reduced yield (t/ha) in added CR treatment or absolute yield (t/ha) in this treatment multiplied by average grain price of $220/t for barley, $240 for AH and $300/t for APH bread wheat and $350/t for durum. Grain quality impacts and variable costs including PBR not considered.

Crop	**Variety**	**Quality Class.**	**Yield (t/ha)**		**Yield loss**	**Screenings (%)**		**Lost income from crown rot**	**Income added CR**
			No added CR	**Added CR**	**(%)**	**No added CR**	**Added CR**	**($/ha)**	**($/ha)**
Barley	**La Trobe**ᶲ		4.17	3.59	14.0	6.5	8.4	128	790
	Spartacusᶲ		4.18	3.58	14.3	2.9	4.6	131	788
	Commanderᶲ		4.09	3.40	16.8	6.1	8.2	151	748
	Compassᶲ		4.20	3.39	19.4	2.1	2.9	179	745
Durum	**Lillaroi**ᶲ		3.79	3.00	20.8	3.2	5.9	275	1050
	Bindaroiᶲ		3.88	2.92	24.7	2.7	5.8	336	1023
	Jandaroiᶲ		3.48	2.64	24.3	4.1	9.2	296	923
	Caparoiᶲ		3.34	2.20	34.1	9.0	16.5	399	770
	AGD043		2.72	1.65	39.1	3.8	13.8	372	579
Bread wheat	**Beckom**ᶲ	**AH**	4.57	3.94	13.9	8.8	12.7	153	944
	Mustangᶲ	**APH**	4.17	3.67	11.9	5.2	7.0	148	1102
	Mitchᶲ	**AH**	4.08	3.51	13.9	7.7	10.2	136	842
	Reliantᶲ	**APH**	4.18	3.50	16.3	5.3	8.1	204	1051
	Suntopᶲ	**APH**	3.99	3.46	13.3	7.3	9.6	160	1037
	Sunguardᶲ	**AH**	3.81	3.35	12.0	6.2	8.7	110	804
	Spitfireᶲ	**APH**	3.86	3.34	13.3	5.8	8.0	154	1003
	Gauntletᶲ	**APH**	3.92	3.29	16.1	4.4	7.0	189	987
	Lancerᶲ	**APH**	3.88	3.27	15.8	4.8	7.1	184	981
	Sunmateᶲ	**APH**	4.02	3.23	19.6	6.4	9.7	237	969
	Coolahᶲ	**APH**	4.03	3.21	20.4	5.8	9.4	247	962
	Flankerᶲ	**APH**	4.04	3.12	22.8	6.0	10.4	277	936
	Dartᶲ	**APH**	3.73	2.99	19.9	9.3	12.8	223	897
	EGA Gregoryᶲ	**APH**	3.90	2.89	25.9	6.7	11.4	303	868
	Vikingᶲ	**APH**	3.48	2.89	17.1	10.9	16.8	179	866
	Lincolnᶲ	**AH**	3.88	2.78	28.3	8.6	12.8	264	668
	Crusaderᶲ	**APH**	3.43	2.76	19.4	8.3	13.4	199	829
	QT15064R	**APH**	3.68	2.73	25.7	8.3	15.1	284	819
	Suntimeᶲ	**APH**	3.43	2.62	23.6	10.6	17.2	243	787
	Strzeleckiᶲ	**AH**	3.03	2.17	28.3	12.0	18.0	206	521
		Lsd (P=0.05)	***max. 0.137***			***max. 1.37***			

Note: The extent of yield loss associated with crown rot infection varied between seasons and sites being 21% in 2013 (range 13% to 55% across nine sites), 22% in 2014 (range 6% to 47% across 12 sites), 18% in 2015 (range 7% to 42% across 12 sites), 13% in 2016 (range 6% to 29% across 11 sites) and 29% in 2017 (range 20% to 45% across six sites) averaged across varieties.

Common root rot (Bipolaris sorokiniaina)

The trend to deeper and earlier sowing of cereals into warmer soils is associated with an increased prevalence of common root rot (CRR) across Australia, especially in the northern region. Deeper sowing lengthens the sub-crown internode in cereals which increases susceptibility to CRR. Soil temperatures greater than 20-30°C, which often occur when sowing earlier, also favour *Bipolaris* infection with yield losses between 7% and 24% reported from CRR in bread wheat. However, delaying sowing to reduce CRR levels is not recommended as the negative impact on yield potential generally outweighs the impact of increased CRR. Note that CRR is also frequently found in association with crown rot, exacerbating yield loss.

Assuming the main concern is common root rot (CRR). Based on the following PREDICTA®B test results pre-sowing management options include:

Below detection or low:
No restrictions, ensure good crop agronomy

Medium or high:
Consider sowing a non-host pulse or oilseed crop with good grass weed control.

If sowing a cereal then:

- Grow partially resistant wheat or barley varieties, oats and triticale may not develop severe infection but act as hosts
- Consider increasing sowing rate to compensate for potential tiller losses
- Consider inter-row sowing (if previous cereal rows are still intact) to slightly reduce infection levels
- If moisture permits, reduce sowing depth to limit the length of the sub-crown internode which is the primary point of infection
- Ensure good phosphorus nutrition which reduces severity
- Ensure good nitrogen nutrition as stunting and lack of vigour is more pronounced in paddocks that are N deficient
- Assess root health coming into Spring (see step 4).

Arbuscular mycorrhizae fungi (AMF)

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. PREDICTA®B has two DNA assays for AMF and 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. It is concerning that AMF DNA was not detected in root systems of 39% of 150 cereal crops surveyed in central/northern NSW and southern Qld in 2018 (Simpfendorfer and McKay 2019). AMF levels are likely to have declined further in the northern region with continued dry conditions in 2019 (Table 1).

Based on the following PREDICTA®B test results (combining the two AMF test results) pre-sowing management options include (Chapter 10: Broadacre Soilborne Disease Manual, SARDI):

Low (<10; long fallow disorder risk high*):*

- Consider growing winter cereals which are a host but have low AMF dependency to increase population
- Avoid sowing highly dependent crops (e.g. chickpea, faba bean, sunflower, mungbean, maize)
- Do not burn stubble.

Medium (10<20):

- Avoid sowing highly dependent crops (e.g. chickpea, faba bean, sunflower, mungbean, maize) if phosphorus levels are low, including at depth
- Avoid burning stubble.

High (>20):

- Crop choice not restricted – be aware canola, lupins and long fallow will reduce AMF levels
- Grow most profitable crop.

Step 3: Ensure quality of planting seed

Seed retained for sowing is a highly valuable asset and the way it was treated at harvest and in on-farm storage during summer, or between seasons, is critical to ensure optimum germination potential and crop establishment in 2020. Retained seed can be tested for vigour, germination, purity/weed seeds and disease pathogens. It is advisable to undertake testing at least two months before sowing so that an alternate seed source can be organised if required. Grading to remove smaller grains which inherently have reduced vigour can also improve the quality of planting seed.

Vigour and germination tests provide an indication of the proportion of seeds that will produce normal seedlings and this helps to determine seeding rates. Particular attention should be given to determining vigour of retained seed for sowing in 2020 due to seasonal conditions in 2018-19. Vigour will be even more important if growers plan to increase sowing depth to capture an earlier sowing opportunity through moisture seeking.

NSW DPI, Tamworth normally provides pathology testing of winter cereal seed for common seed-borne fungal pathogens which will continue in 2020. Germination is also noted but this only tells growers how much of their seed is alive with the main purpose of testing to determine levels of fungal infection present. Testing will be extended for the 2020 pre-season to also provide an indication of vigour and emergence which should be used as a guide only (see contact details).

A comprehensive GRDC fact sheet outlining issues with retaining seed after challenging seasons is available from the GRDC website (see useful resources). The fact sheet outlines how growers can test their own seed. Alternatively, a range of commercially accredited providers of both germination and vigour tests are available.

Seed treatments containing fluquinconazole, flutriafol or triadimenol, can reduce coleoptile length in cereals and cause emergence issues under certain conditions. These active ingredients should be avoided if sowing seed with potentially lower vigour, sowing deeper, sowing into cooler soils, in soils prone to surface crusting or where herbicides such as trifluralin have been applied.

Step 4: Assess infection levels and root health prior to head emergence

Common root rot does not cause distinct symptoms in the paddock. Infected cereal crops may lack vigour and severe infections can lead to stunting of plants and a reduction in tillering. These general symptoms of ‘ill-thrift’ in CRR infected wheat and barley crops can often go undiagnosed. This can be easily identified with the help of a shovel or spade! Simply dig up some plants around heading, wash soil away from roots and inspect the general root health paying particular attention to whether the sub-crown internode (joins seed to the crown) has partial or whole dark brown to black discolouration.

This is a very similar to the situation with Fusarium crown rot, which can also go unnoticed in paddocks until dry and hot conditions during grain filling trigger the expression of conspicuous whiteheads. However, honey-brown discolouration at the base of infected tillers can be used to determine the extent of Fusarium crown rot infection prior to heading. Simply dig up plants (inspect root health at the same time as above), ensure leaf sheathes at the base of tillers are removed and visually inspect for brown discolouration.

Assessing root health and Fusarium crown rot infection levels around heading allows a grower to make an informed decision at this point in time given seasonal predictions (e.g. cutting for hay or silage, reduce further input costs) rather than simply letting the weather dictate the outcome. Although this would be a less than an ideal situation, such tough decisions can still maximise profitability or minimise losses under these scenarios.

Other potential implications of dry conditions – learnings from north NSW in 2019

Dry conditions can also impact on the lifecycle of necrotrophic fungi which cause yellow spot in wheat or net-blotches in barley. We observed this around Croppa Creek in northern NSW in 2019 with spot form of net-blotch (SFNB) in barley crops. Numerous barley crops in a restricted area had decent levels of SFNB lesions on leaves during tillering. This was surprising as the season was relatively dry up to this point with only low rainfall events (<5 mm) since sowing. Rainfall events were accompanied by early morning fogs. These conditions, while not really contributing to yield potential, were enough to meet the 6 hours of high humidity (>80% RH) to initiate SFNB infections on leaves. Interestingly, due to dry conditions the primary infection propagules (pseudothecia) which have a moisture requirement had not matured on 2018 barley stubble. The primary source of infection was mature pseudothecia present on 2017 or even 2016 barley stubble. SFNB was also present in two barley crops sown into wheat stubble which was surprising. However, conidia of the net-blotch fungus *Pyrenophora teres* formed on collected wheat stubble after 4 days in humid chambers. This supports 2018 disease survey findings where the SFNB fungus was found to be saprophytically infecting wheat crops due to late rainfall in October coinciding with senescence of lower wheat leaves.

High levels of SFNB were also present in two barley crops in this same region in 2019 where seed was treated with the fungicide Systiva®. Reduced sensitivity to this SDHI active (fluxapyroxad) was confirmed by the Curtin University fungicide resistance group in net form of net-blotch (NFNB) populations on the Yorke Peninsula of SA in 2019. Pure SFNB isolates collected from these northern NSW barley crops were sent to Curtin University and shown to have **no** reduced sensitivity to fluxapyroxad. In our situation we suspect that dry conditions around the seed prevented Systiva® from dissolving into the surrounding soil, limiting uptake through the roots and movement through the plant into leaves. Seedlings had established well and their root systems had penetrated into deeper soil moisture which was allowing them to progress, but the top 10 cm of soil was very dry with little visual loss of red pigmentation from the seed treatment on seed coats at the time of inspection.

Conclusions

The perpetual risk as a plant pathologist is the perception that we are always the bearer of bad news or 'of the grim reaper mentality'. Elevated risk of stubble- and soil-borne diseases in 2020 is inevitable given continuing dry conditions which have prolonged survival of pathogen inoculum. However, practical steps can be taken to identify the level of risk and strategies implemented to minimise but not necessarily fully eliminate disease impacts on wheat and barley crops in 2020.

Hopefully wet conditions restrict impact of Fusarium crown rot. However, growers and their agronomists need to be prepared to inspect the root health and stem bases of cereal crops around heading to guide some potentially tough but informed decisions. NSW DPI plant pathologists are also available throughout the season to provide support.

Useful resources

https://grdc.com.au/resources-and-publications/groundcover/ground-cover-supplements/groundcover-issue-130-soil-borne-diseases/correct-sampling-a-must-to-accurately-expose-disease-risk

https://grdc.com.au/resources-and-publications/all-publications/factsheets/2011/01/grdc-fs-retainingseed

Simpfendorfer S, McKay A (2019). What pathogens were detected in central and northern cereal crops in 2018? GRDC Update, Goondiwindi. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/03/what-pathogens-were-detected-in-central-and-northern-cereal-crops-in-2018

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. The author would also like to acknowledge the ongoing support for northern pathology capacity by NSW DPI.

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Managing chickpea diseases after the drought

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

Key words

chickpea, disease risk, Ascochyta, Phytophthora, Sclerotinia, root lesion nematode (RLN), management, fungicide rain fastness

GRDC code

Grains Agronomy & Pathology Partnership - A strategic agreement between GRDC and NSW DPI (DAN00213): BLG209 Pulse Integrated Disease Management – Northern NSW/QLD

Take home messages

- Do not underestimate disease risks after a drought – pathogens survive longer and can still threaten your 2020 chickpea crops
- Unless you are in a high risk Ascochyta situation, it is unlikely there will be a cost benefit applying a foliar fungicide to 2020 crops until after the disease is detected
- However, if you are at a high risk of Ascochyta, apply a foliar fungicide before the first post emergent rain event
- High risk situations include planting into paddocks with active Ascochyta inoculum and planting seed that has not been properly treated
- Recent research has shown the Ascochyta fungicides Aviator Xpro and Veritas are rain fast (up to 100 mm rain in 150 minutes)
- Phytophthora and Sclerotinia levels will not have declined much during the drought and pose a medium to high risk in 2020
- Root Lesion Nematodes may have declined during the drought but if numbers at the start of the drought exceeded 10/g soil, it may still be sufficient to cause damage in 2020 chickpea crops.

How drought affects plant diseases

- Drought reduces the breakdown of plant residues. This means that inoculum of some diseases does not decrease as some might expect and will carry over for more than one growing season. The expected benefits of crop rotation may not occur
- Bacterial numbers decline in dry soil. Some bacteria are antagonists of soil borne fungal diseases. These diseases can be more severe after drought
- Abandoned, or drought stressed crops still set seed. Summer/autumn rains can lead to large numbers of volunteers. Low stock numbers make it difficult to control these volunteers, which can host Ascochyta, viruses and virus vectors, and other pathogens
- Weeds that are stressed by drought may be harder to kill and can harbour pathogens
- Soil water and nitrogen may be unbalanced and these are likely to impact diseases in 2020 and beyond.

Chickpea disease risks after the drought and advice for 2020 chickpea farmers

- Ascochyta is unlikely to cause widespread problems in 2020 unless it is wetter than average as inoculum levels have not increased in past two seasons and even if infected with Ascochyta, all varieties recover well during dry conditions. For these reasons, unless you are in a high risk situation, there will be no cost benefit applying Ascochyta fungicides until the disease is detected. High risk situations include planting into paddocks where active inoculum is known to be present (see following examples at Tulloona and Moree) and planting seed of unknown pathogen status that has not been properly treated. In these situations, apply an Ascochyta fungicide before the first post-emergent rain event, then monitor the crop 10-14 days after rain.

- If Ascochyta is detected, apply a registered fungicide before the next rain event. This is especially important during the reproductive stage as Ascochyta on pods causes abortion, seed infection and seed defects. If you miss a spray; fungicides with limited curative activity are now available however they have a limited time of use and tight intervals for application after an infection event occurs. (https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/chickpea-ascochyta-research-what-if-i-miss-a-spray-are-there-salvage-options-with-new-chemistry-how-long-do-fungicides-persist)
- Under drought conditions, some plant pathogens survive longer than normal; Ascochyta inoculum for 2020 chickpea crops may have originated in 2017 or even 2016. In August 2019, volunteer chickpeas in a crop of wheat at Tulloona had Ascochyta lesions. That paddock had grown chickpeas in 2016 (under high Ascochyta pressure); wheat in 2017 and chickpeas in 2018 (crop abandoned due to drought). Rain in Oct/Nov 2018 allowed Ascochyta to develop on abandoned plants, and seed left in the paddock germinated on rain in March 2019 to produce the volunteers that got infected during rain events in May, June and July 2019. Another example of how drought can prolong survival of inoculum was provided in August 2019, when we received chickpea stubble from a paddock at Moree that had grown chickpeas in 2017. The stubble contained fungal fruiting bodies. We soaked the stubble in water for several hours then applied the water suspension to chickpea seedlings; 7 days later symptoms and pycnidia of Ascochyta developed on the seedlings, proving that the inoculum had persisted on the nearly two-year old chickpea residue. Both the Tulloona and Moree paddocks are considered high risk if planted to chickpeas in 2020.
- Remember, the Ascochyta fungus is evolving: In our 2010 Tamworth disease management trial, unprotected PBA HatTrickⓓ (then rated moderately resistant (MR)), lost 37% yield to Ascochyta; while in the 2016 trial, unprotected PBA HatTrickⓓ lost 97% yield to Ascochyta. PBA HatTrickⓓ is now rated moderately susceptible (MS) and will require fungicide under conditions that favour Ascochyta. The good news is that whilst Ascochyta can now cause more damage on unprotected PBA HatTrickⓓ, it is just as easy to manage as when PBA HatTrickⓓ was rated MR.
- Phytophthora root rot (soil borne) and Sclerotinia diseases (soil borne and air borne) are considered moderate to high risk in 2020 because although inoculum loads are unlikely to have increased, their survival will have been prolonged by the drought.
- Botrytis seedling disease (BSD, seed borne) is only likely in crops planted with seed produced in the 2016 (and possibly 2017) crop year. In any case proper seed treatment provides 100% control of BSD.
- Botrytis grey mould (BGM, air borne); the BGM fungus is ubiquitous, has a very wide host range and is a good saprophyte - if conditions favour BGM i.e. dense canopies, warm humid weather, it will occur.
- Root lesion nematodes (RLN, *P. thornei* soil borne) can survive dry periods. Recent research has shown it takes a double break of 40 months free of host plants to reduce numbers to a minimum threshold (2/g soil) so it is unlikely the current drought will have reduced RLN numbers if they started high (40/g) which was likely in the 2016 season. Even starting numbers of 10/g still need a break of 30 months https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/how-long-does-it-take-to-reduce-pratylenchus-thornei-populations-in-the-soil.

- Viruses are an unknown threat after a drought. Most need green plants as reservoirs (some are seed borne) and hosts for their vectors. However, as vectors can fly or be blown in from regions that have not experienced drought, viruses are still a risk to 2020 chickpea crops.

Seed quality

Obtaining good quality seed after a drought may be an issue in 2020. In Nov/Dec 2019, we tested seed from as far back as 2016 and whilst germination of all lots exceeded the Pulse Australia (PA) minimum standard of 70%, some lots were slow getting there, indicating possible loss of vigour. All planting seed should be germination tested and if it meets the PA standard, we recommend it be treated and 'test planted' into paddocks intended for chickpeas in 2020, and the number that emerge counted – this is your best indicator of seed and seedling vigour and may assist identify herbicide residues, but should not be relied on as the sole indicator for this, as symptoms of residual herbicides can in some situations be slow to develop. Paddock emergence tests are best done in March/April.

If you are sourcing seed from outside your region e.g. interstate, be sure the variety is suitable for your farming system and have the seed germination and pathogen tested.

Irrespective of age and origin, all planting seed should be treated with a registered seed dressing – these control seed borne Ascochyta (internal and external), seed borne Botrytis (BSD) and protect seedlings from a range of opportunistic soil organisms that can reduce seedling vigour and establishment under less than favourable conditions e.g. cold or wet soils, deep planting. Planting quality, treated seed is your best bet of healthy seedlings – these will have a rapidly growing root system to obtain nutrient and moisture, be more competitive with weeds and less susceptible to disease.

Predicta®B for assessing Ascochyta risk

The value of Predicta®B as an Ascochyta management tool has not been determined because we do not know what the numbers mean in terms of risk or management. Predicta®B results that are positive for Ascochyta on samples collected after the drought should not be surprising give the persistence of inoculum under drought conditions. On the other hand, a negative result does not mean your Ascochyta risk is nil or low as the test is only as good as the sampling method and inoculum can arrive in your paddock after sampling via wind, machinery, vehicle, animals, surface water flows or untreated seed.

Chickpea Ascochyta Research Update: Is efficacy of Aviator Xpro and Veritas reduced by rain after application?

Previous research (2007) at Tamworth using a rainfall simulator showed that efficacy of the fungicides Barrack720® (720g/L chlorothalonil) and Dithane® Rainshield® (750g/kg mancozeb) on chickpea Ascochyta on cultivar Jimbour was not significantly reduced by 50mm rain in 10 minutes. 150mm in 30 minutes also did not reduce efficacy of Barrack720 but did reduce slightly the efficacy of Dithane. Such rainfall intensities are not common in chickpea crops grown in eastern Australia. From these experiments we concluded that plant tissue sprayed with these fungicides would still be largely protected if rain fell after application (new growth after application would not be protected as both products are protectants only). The 2010 chickpea season (that had frequent rain events) supported this conclusion.

The recent registrations of Aviator Xpro® and Veritas® (both in 2018) for chickpea Ascochyta (with restrictions on number of applications and timing – see labels for details) raised the question of how rain fast are these products.

Two experiments were conducted at Tamworth Ag Institute in December 2019 - January 2020 to determine the effect of simulated rain on the efficacy of Aviator Xpro and Veritas on Ascochyta; Unite®720 (720g/L chlorothalonil) and water were the control treatments. The first experiment (4 reps) was with cv Kyabraⓓ and the second (4 reps) with cvs Kyabraⓓ and PBA Seamerⓓ.

As the results were the same, we report here the second experiment. Plants were sprayed with water, Unite, Aviator Xpro or Veritas using a backpack sprayer with a 1m boom fitted with 110/015 flat fan nozzles at 50cm spacing and a walking pace of approximately 6kph. The fungicide treatments were allowed to air dry for 2hr when the 'rain' plants were placed in the rainfall simulator and exposed to 50mm over 75 minutes or 100mm over 150min (recorded by two rain gauges at each side of the simulator pad). After removal from the simulator, plants were allowed to air dry for 2h, arranged on racks in replicate boxes (55L plastic with clear lids), inoculated to run off with a cocktail (2,000,000 conidia/mL) of 20 Ascochyta isolates obtained from commercial chickpea crops and the boxes placed in a controlled environment facility operating at 12h/12h day/night 15C/20C. Leaf wetness was maintained with ca 50mm depth water in the base of the boxes and firm fitting lids. After 48h the lids were removed and plants were examined for Ascochyta. Five days after inoculation (DAI) first symptoms (petiole wilting) were evident and at 9 DAI, Ascochyta was assessed by counting the numbers of petioles, leaves and stems with symptoms.

The only plants that developed Ascochyta were those sprayed with water; PBA Seamerⓓ had less disease than Kyabraⓓ.

We conclude from this experiment that efficacies of chickpea Ascochyta fungicides Veritas and Aviator Xpro with a 2 hour dry period after spraying and prior to rain occurring, are not affected by simulated rainfall of 50mm in approximately 75min or 100mm in approximately 150min. As such intensities are uncommon during chickpea seasons in areas of Australia where Ascochyta occurs, it is reasonable for growers to be confident that once these fungicides have dried on plant tissues, those tissues will remain protected.

Acknowledgements

This work is part of a major co-investment between NSWDPI & GRDC. The research is possible by the significant contributions of growers through trial cooperation and permission to sample their crops and we thank them for their continued support.

Thanks to Beefwood, Moree; CanBerra, Banana; Woods Seeds, Goondiwindi and Parraweena, Blackville for seed for trials; agronomists for maps and help with crops; Pulse Australia, and chemical companies for products for trials.

Thanks also to Paul Nash and Gail Chiplin for outstanding technical support.

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A review of the Helicoverpa Resistance Management Strategy (RMS) after two seasons: what works, what doesn't, and making it fit for purpose

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[1] DAF Queensland
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Key words

Helicoverpa armigera, insecticide resistance, resistance management strategy

GRDC codes

DAQ00196, DAN1908-005RTX

Take home messages

- The Helicoverpa RMS is designed to extend the life of insecticides through reducing the selection pressure on individual products
- Repeated use in a single crop and cutting rates are two practices that will speed the development of insecticide resistance. Highly efficacious products are at greatest risk of misuse
- In regions where there are sequential plantings of mungbeans and soybeans, e.g. coastal, Burdekin, there are particular challenges in sticking to the RMS.

The Helicoverpa resistance management strategy (Helicoverpa RMS) has been available to the grains industry since June 2018. At the time the strategy was developed, the National Insecticide Resistance Management (NIRM) working group gave an undertaking to stakeholders to review how the strategy was working and make modifications to it if necessary.

Under normal conditions, we would have expected to have had two winter and two summer seasons implementing the Helicoverpa RMS by now. Unfortunately, much of the northern region has not had summer or winter crops during this period, so the opportunities to trial the strategy have been limited largely to central Queensland and the coastal production regions (summer pulses in the Burdekin – Bundaberg).

The review is currently being undertaken through interviews with agronomists in all regions where *H. armigera* is a pest in winter and summer pulses (the focus of the current RMS). At the time of writing this paper, the interviews are not yet completed, so only preliminary impressions can be presented here. The presentation at the Update will include all data and a discussion of the future of the Helicoverpa RMS.

Preliminary findings

It is evident that those agronomists with a 'lived experience' of insecticide resistance, specifically the *H. armigera* resistance in the late 1990s and early 2000, have a heightened awareness of the importance of reducing the risk of resistance development. Communicating the importance of resistance management to the younger agronomists is a key challenge.

The coastal regions are characterised by almost continuous cropping of summer pulses, which presents major challenges for resistance management. The efficacy of Altacor® (chlorantraniliprole) makes it the highly preferred option for the control of Helicoverpa and the product at greatest risk of overuse. In these regions, the current RMS does not appear 'fit for purpose' as it greatly restricts the use of Altacor. However, to be effective, the Helicoverpa RMS must abide by a number of 'rules' or resistance management. Most importantly, the restriction of exposure of successive generations to an individual active. The more generations exposed to an individual active, the higher the risk of resistance developing. This is the basis for the windowing of products. Consequently, there is little option for increasing the window of use, or the number of applications of at risk products without jeopardising the long term efficacy of products like Altacor. Confidence in the effectiveness of alternate products and strategies for targeted use of Altacor during periods of highest helicoverpa risk, are needed in these regions.

Affirm® (emamectin benzoate) and Success Neo® (spinetoram) are not currently windowed. The low pulse area has continued to limit the use of these products to date, and there is no evidence of a change in susceptibility of *H. armigera* to Affirm in testing (L Bird, NSW DPI pers comm). More agronomists reported using Affirm and having increased confidence in it as an option for control of Helicoverpa control. It is proposed that no changes to the windowing of these products be implemented at this stage.

Resources

The Helicoverpa RMS, and a detailed "Science behind" document, are available for download at https://ipmguidelinesforgrains.com.au/ipm-information/resistance-management-strategies/

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.

Julie Ferguson undertook the agronomist interviews and we thank all those who generously gave their time to discuss their experiences and opinions on the Helicoverpa RMS.

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Farming systems impacts on soil borne disease - macrophomina, *P. thornei*, Fusarium & others

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Notes

An automated site-specific fallow weed management system using unmanned aerial vehicles

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Keywords

machine vision, precision agriculture, unmanned aerial vehicle, weed management, section control

Take home messages

While sprayers fitted with camera sensor technology are in wide use for fallow weed management in NSW and Queensland grain growing areas, some growers do not as yet have this technology

- Most modern spray equipment has multiple sections that can be independently operated
- Existing spray technology coupled with georeferenced weed maps generated by current consumer grade UAV technology, has been demonstrated to enable significant reductions in herbicide use
- Techniques have been developed to minimise the size of data files while maintaining system efficiency
- Preliminary testing shows 93% of weeds were sprayed with reductions in herbicide use of 45% in the test field.

There is currently a need to optimise herbicide application technology to minimise herbicide use and resistance. To more fully utilise precision weed spray equipment, a system has been developed implementing the four-step closed loop precision agriculture scheme. The aim being, to create a system that utilises existing precision spray and consumer grade UAV technology. The use of consumer grade UAV technology limited the system being developed to rely on only colour, or red-green-blue (RGB) imagery. Therefore, an algorithm utilising the ‘excess green vegetative’ index was developed. This algorithm has been developed to minimise the detail and number of polygons in the resulting spray maps while maintaining the efficiency of the system. Ground truthing of the system revealed a hit rate on target fallow weeds of 92.6% and a potential herbicide saving of 44.6% when compared to whole of paddock spraying.

Introduction

Unlike the traditional practice of applying a uniform treatment and presuming it to be the ideal, precision agriculture (PA) is a site-specific closed loop scheme used to identify and respond to variability within each management unit. The process steps are illustrated in Figure 1.

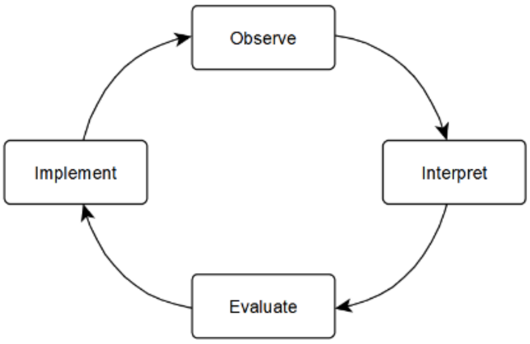

Figure 1. Precision agriculture cyclical process (Cook and Bramley 1998)

Santi, Bona, Lamego et al. (2014) found site-specific weed management based on infestation zones could lead to herbicide reductions ranging from 30% to 70%. These findings are consistent with other studies; Tian, Reid, and Humme et al. (1999) reported a potential herbicide savings of 48%. Timmermann, Gerhards, and Kühbauch (2003) found herbicide reductions differed by crop variety and year, although overall the results showed an average reduction of 54% in herbicides.

Most **contemporary** spray systems manufactured in the past decade have the capacity for section control. However, despite the evidence of herbicide reductions through implementation of site-specific weed management, with the exception of camera based systems where sensors activate individual nozzles and are in widespread use in the GRDC's northern grains region, very few are utilising section control other than for turning off sections upon entering or exiting a field. There is need for an automated pragmatic system to generate targeted herbicide application maps for use with existing precision spray equipment that does not already have camera weed sensor technology. A system under development at the University of Southern Queensland utilises low-cost, unmodified, UAV technology and machine vision to automatically generate prescription spray maps which can be used with contemporary precision spray systems with the aim to provide an pragmatic and inexpensive spray system to reduce herbicide use.

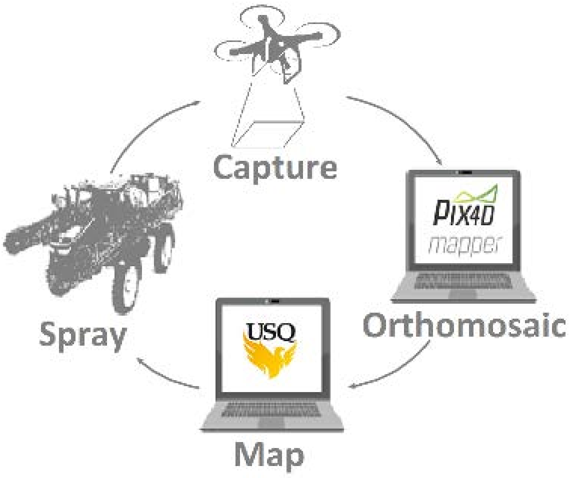

Figure 2. Cyclical precision weed management system

The system depicted in Figure 2, is under development and involves four main processes:

1. Imaging the field using a UAV
2. Processing this RGB imagery to create an orthomosaic
3. Processing this orthomosaic using machine vision to create a spray map and
4. Spraying.

The aim is to implement this in a closed loop fashion based on the four-step precision agriculture scheme and identify persistent weed populations to enable targeted adjustment of herbicides.

The DJI Phantom 4 Pro UAV, a consumer grade UAV, was selected for capturing imagery due to its low cost and high popularity in the Australian market. However, this UAV has several restraints that must be overcome to produce a practical precision weed spray system. The Phantom 4 Pro depends on GPS/GLONASS information to control flight trajectory and to geotag imagery. However, the accuracy of this global positioning system is limited to several meters (DJI, 2019), and far greater precision is required. If not corrected for, this inaccuracy would flow through the rest of the weed spray system and result in spray maps 'misaligned' with weed position.

Contemporary spray equipment utilise guidance. Systems such as the StarFire™ 6000 from John Deere relies on the Real-Time Kinematic (RTK) positioning system and provides +/- 1.2 inch (30mm) pass-to-pass accuracy (Deere & Company, 2019). For the system under development to work efficiently, the spray maps generated must align precisely with the guidance system of the spray equipment. Therefore, a method to correct for the GPS poisoning error of the UAV is required.

To correct for this error and produce accurate orthomosaics, Ground control points (GCPs) were investigated as a solution. GCPs are visual markers with a known precise and accurate geographic location. These targets are positioned in the field and imaged along with the rest of the field under investigation. When the orthomosaic is generated, the location of these GCPs is tagged and the related known accurate geolocation data is assigned to correctly reposition the orthomosaic.

Figure 3. Ground control point

To create an orthomosaic, photogrammetry software is required. There are several software packages available including Agisoft Photoscan Pro, Pix4D, and Microsoft Image Composite Editor (ICE). Gross and Heumann (2016) Evaluated the accuracy of these packages and found Pix4D had the best geometric accuracy with a RMSE of 7.7cm. Therefore, Pix4D was employed to generation of all orthomosaics used in this project. An orthomosaic image is a mosaic of aerial images that has been orthorectified. The orthorectification process removes perceptive distortions from the images and flattens the resulting mosaic using a Digital Surface Model (DSM). The orthomosaic produced is stored as a GeoTIFF, a public domain raster image file format that stores georeferencing information as metadata along with the raster imagery using the “Well-known text” (WKT) markup language. The weed mapping software under development utilises this metadata to translate between the position of the pixels in the GeoTIFF, using the orthogonal coordinate system to create polygons in a vector “shapefile” in the chosen projected coordinate system.

As stated, the aim of the project is to utilise unmodified consumer grade UAV technology. Therefore, the software being developed needs to utilize RGB imagery. Consequently, the software under development uses the green-from-brown colour discrimination technique and is implemented using OpenCV (“OpenCV Library 2019”, 2019) an open-source computer vision library. In order to segment green weeds in the orthomosaic, the vegetation index Excess green (*G_ex)* is used to produce an *G_ex* image, using the following equation (Woebbecke et al., 1995).

$$G\_ex = 2G - R - B$$

Where:
G_ex = Excess Green Image
G = Green Channel
B = Blue Channel
R = Red Channel.

Thresholding this *G_ex* image produces a monochrome raster map of the green weeds. The image relative position of these weed pixels is then translated to the relevant geospatial coordinate system using the Geospatial Data Abstraction Library (GDAL). Initial developments creating zones around each weed using the weeds profile led to the creation of detailed yet excessively large shapefiles. These shapefiles often contained in excess of ten thousand polygons per hectare, which is above the maximum polygon limit of some spray controllers (CNH Global, 2016). Therefore, a method to reduce the number of polygons in these files while maintaining the efficiency and accuracy of the spray maps has been investigated and an algorithm developed. In practice, the algorithm creates zones around the weeds using the minimum number of vertices required and aggregates geographically close weeds within a specified distance.

Figure 4. John Deere 4066R with link sprayer – base station is visible on the left

An evaluation of the developing weed spray system has been undertaken at a test site at Felton, Queensland. The site was first imaged at an altitude of 60 m for the creation of weed maps and then at 30 m for assessment purposes only. A John Deere 4066R with 12m link-sprayer was used for spraying using dye, as seen in Figure 4. The 12 metre boom on this unit was divided into five individually controlled sections. The section behind the tractor was 2.0 m (4 nozzles) with each of the other section being 2.5 m (5 nozzles) with the nozzles on a 50 cm spacing. No RTK base station had been established for guidance at this site; therefore, a mobile base station was employed, as seen in Figure 4. To evaluate the hit rate of the entire system, 200 weeds were numbered and geotagged with a Trimble R2/TSC3 RTK GNSS rover as seen in Figure 6. Paper was placed on each weed to record if it was sprayed as seen in Figure 5. This paper was numbered to correspond to the geotagged information created with the RTK rover.

Figure 5. Sprayed paper used to determine if geotagged weed has been sprayed.

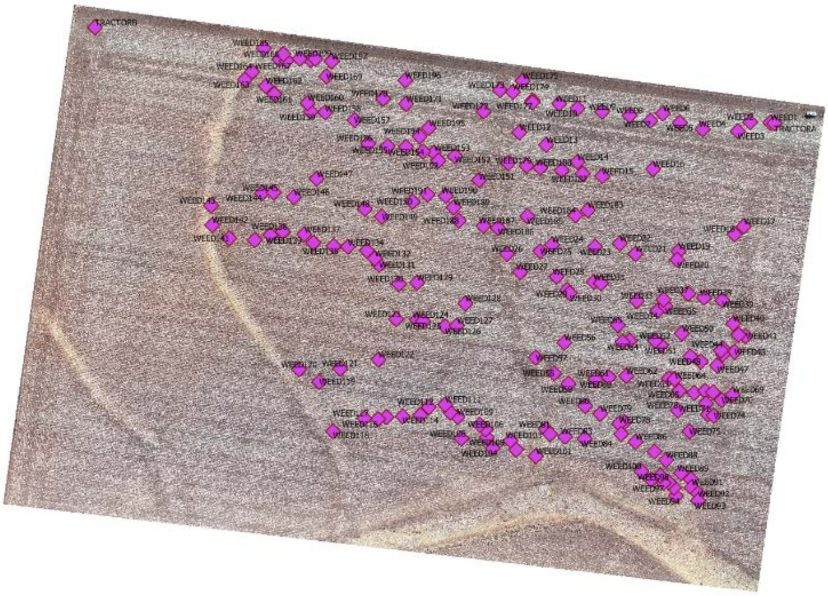

Figure 6. Geotagged weeds

It should be noted that at the time of testing, the weed population was stressed due to cold weather and lack of water. This meant that many of the weeds were less green and some presented a purple tinge as seen in Figure 5. This is significant as the weed detection algorithm uses a green from brown weed identification technique. This also highlights a limitation of using this technique.

The area imaged was ~11.2ha and contained both soybean and sorghum stubble, as seen in Figure 4. The 12m width of the sprayer was inconsistent with spacing of the established tramlines and these tramlines could not be utilized. Therefore, the sprayer speed was limited to 6 km/h due to the uneven surface of the field.

Figure 7. Spray map shown on spray controller

Table 1. Evaluation Results

Evaluation	
Field area imaged	11.2 ha
Sprayed area	6.8 ha
Spray saving	44.6%
Weeds Tagged	200
Hit rate	92.6%
Process	**Time**
Establishment of ground control points in field	0:12
Field imaged at 60 m	0:19
Marking ground control points in Pix4Dmapper	0:11
Orthomosaic creation with Pix4Dmapper	3:57
Spray map creation with USQ software	0:03
Total	4:42

The spray maps generated for this site can be seen in Figure 7 presented on the display in the 4066R. Dye showed well on the paper placed adjacent to each weed as seen in Figure 5. Results from this evaluation can be seen in Table 1. Counting of the dye covered paper revealed the system to have a ~93% hit rate. Of the ~11.2ha field ~6.8ha was sprayed, resulting in a potential herbicide saving of 44.6%. These herbicide reductions are consistent with the before mentioned studies conducted by (Timmermann et al., 2003) and (Santi et al., 2014). The entire process of collecting imagery and producing spray maps took four hours and forty two minutes, ~84% of this time was the time taken to generate the orthomosaic.

Conclusion

A solution has been developed to reduce herbicide usage. This solution couples contemporary UAV and precision spray technology using machine vision and Geographic Information Systems (GIS) technology. Evaluation of the developing system revealed a herbicide saving of 44.6%. Work continues to reduce the time taken to produce these maps. The project is currently in the process of determine the commercial value of the system and developing the technology into other areas.

Acknowledgements

The authors would like to thank the Australian Government's Department of Agriculture and Water Resources and the University of Southern Queensland for funding this project.

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Day 2 concurrent session – Soils/nutrition

Soil organic matter – what the science tells us

Lynne M Macdonald, Mark Farrell & Jeff A. Baldock, CSIRO

Key words

soil organic carbon, soil health, carbon sequestration, carbon accounting, nitrogen supply, nutrient cycling

GRDC codes

CSP00207

Take home messages

- Stocks of soil organic matter (SOM) and the associated carbon and nutrient flows are key to healthy, sustainable, and resilient agricultural systems
- Declining SOM impacts the soil's ability to support key soil functions, including the capacity to deliver N
- Estimates of soil organic carbon (SOC) accumulation rates following relatively modest management changes in Australian cropping and pasture systems typically range from 0.1 to 0.3 tonnes C/ha/yr (also expressed as Mg or Megagram C/ha/yr)
- Building SOM stocks at higher rates is possible through bold management changes that maximise carbon inputs and minimise loss pathways
- Expenditure and opportunity costs need to be evaluated on an individual basis
- A long term (decadal) cyclical approach to management of SOM and nitrogen budgeting will ensure that future productivity is not compromised by short term (annual) approaches that don't capture the value of banking SOM for use in subsequent seasons
- SOM and SOC mean different things and are explained in this paper.

Introduction

Soil organic matter (SOM) is a key component of productive soils and resilient agricultural systems. SOM supports soil structure, moisture and nutrient sorption/retention, and biological processes central to nutrient cycling and to disease suppression. However, it is widely recognised that agricultural production leads to a decline in SOM stocks. For Australian agricultural soils, SOM decline in the top 10 cm is estimated between 20% and 70%, with average SOM stocks about half that of native system soils (Baldock 2019). Declining SOM content can lead to more vulnerable production systems, impairing the ability of the soil to perform key soil functions, including nitrogen supply through the growing season.

There is considerable interest in identifying management practices that build SOM. The principles of conservation agriculture typically align with goals of retaining and building SOM. These include minimising disturbance, maximising crop diversity/rotation, minimising fallow/bare ground, and integrating livestock where possible. Although changes in land-use (e.g. cropping to pasture) are commonly shown to change SOM content, it remains difficult to identify individual practices within a production system that have a consistent effect on SOM across different soil environments.

Accumulation of SOM depends on many factors including climate, soil type, topographic position, land management, and the current SOM equilibrium state. Changes to management are implemented in different ways; different paddocks have varying production constraints that can lead to inconsistent effects of management on input (biomass production) and output (decomposition) pathways.

In this paper we consider:

- The requirements for measuring changes in SOM and the linkages between carbon and nitrogen
- The reported rates of SOC accumulation within the Australian agricultural context and the difficulties in transferring one scenario across a broader context
- How to estimate potential changes in SOC given a change to carbon (crop biomass) inputs; conversely, to estimate the plant biomass production change that would be required to support an aspirational increase in SOC stock.

SOM vs SOC – carbon with or without nutrients

SOM and soil organic carbon (SOC) are often used interchangeably. SOM is not measured directly but calculated following measurement of the SOC content. On average SOM contains 58% carbon (C) and is bound to other essential elements including nitrogen (N), phosphorus (P), and sulphur (S). SOM values are thus on average 1.72 higher than SOC values. Some analytical laboratories report SOC content (mg/g), while others report SOM content. When comparing analytical results, it is important to check what has been reported and to convert data to comparable values if required.

Soil carbon accounting schemes require that changes in SOC content are measured as stocks in the top 30 cm. SOC stocks are expressed as tonnes per hectare (Megagram (Mg) or tonnes/ha), requiring a calculation that accounts for the carbon concentration (g/kg air dried soil <2mm), the depth to 30 cm, soil bulk density (g/cm^3), and accounts for gravel (> 2mm) content.

$$\text{SOC stock} = \left[\begin{matrix}\text{carbon}\\ \text{content}\end{matrix} \;\text{x}\; (1+\theta_m)\right] \;\text{x}\; \text{depth} \;\text{x}\; \begin{matrix}\text{bulk}\\ \text{density}\end{matrix} \;\text{x}\; \left[1 - \begin{matrix}\text{gravel}\\ \text{proportion}\end{matrix}\right] \;\text{x}\; 0.10$$

SOC accumulation rates are expressed as tonnes of C per hectare per year (t C/ha/year). Scientists often express this in SI units, where Megagram (Mg) is the same as a tonne (Mg C/ha/year). These rates can be estimated in two ways:

- **A relative change in SOC stocks:** where measurements are made X years after contrasting management practices have been implemented (Figure 1 e.g. A3-A2). The relative difference between the starting and finishing levels is then divided by the number of years to provide an estimate of the annual difference in carbon stocks under the management practices. A positive difference may be due to a sequestration of carbon, an avoided emission, or a combination of both.
- **A temporal change in SOC stocks:** where a baseline measurement is made prior to management change, and subsequent sampling X years later is used to determine the rate of change (D-C in Figure 1). In this approach a positive difference is due only to a sequestration of carbon in soil (scenario C) and is dependent on the equilibrium state of the soil when the management change was implemented.

The Australian 2018 soil carbon accounting scheme requires temporal measurements with at least two measurement timepoints. Where more temporal measurements are made, the SOC stock change is estimated by basing the rate of change on a regression over time. For carbon accounting, changes in SOC stocks are converted to carbon dioxide equivalents (CO_2e, t/ha), which are 3.67 times the value of the SOC stock (t/ha). It is important to take note of the measurement units when comparing results, and to convert data to comparable units.

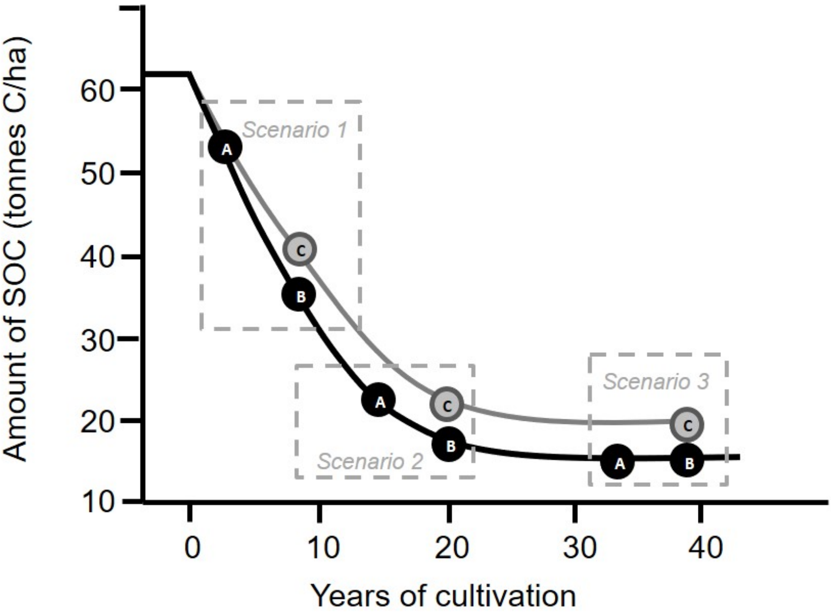

Figure 1. Schematic indicating the differences in SOC stocks (tonnes/ha) under a management change scenario indicating that: relative differences between management practices (C-B) can result from sequestration of carbon (scenario 3) or an avoided emission (scenario 2); temporal differences (C-A) are dependent on equilibrium state of the soil when the management change was implemented, and will only be positive where sequestration has occurred (scenario 3). Graphic modified from Sanderman and Baldock 2010

SOC accumulation in Australian agricultural systems

There remains debate around achievable SOC accumulation rates and the stability/permanence of new SOC in Australian agricultural environments. There are many individual examples of positive, negative, or neutral changes in SOC that result from management. Collating data across the literature, a previous review of SOC sequestration potential for Australian agriculture reports relative gains for a range of management comparisons (Table 1; source Sanderman et al. 2010). For ease of comparison these SOC accumulation rates are reported as both SOC and SOM in Table 1. The data demonstrate the largest relative changes in stocks are achieved where greater management changes are implemented, for example converting cultivated land to permanent pastures (0.3 - 0.6 t C/ha/yr). Where modest management changes are implemented within cropping or pasture systems, the relative changes in SOC stocks are likely to be smaller (0.1 - 0.3 t C/ha/yr). Taking environmental factors into account, these values are broadly in line with rates of SOC change in the broader international literature.

The review does however acknowledge that the available field data captures a narrow range of management options, and that there is limited data to inform SOC change potential under more radical management changes. Recent successes within the Australian government Emissions Reduction Fund (now Climate Solutions Fund) demonstrate that much higher rates of SOC accumulation (~3 t C/ha/yr) can be achieved under the right growing conditions. These individual examples are important in demonstrating the potential to increase SOM and improve overall productivity. However, before investing in management change initiatives it is important to be able to estimate realistic accumulation targets for individual scenarios based on local expert knowledge of the environment, system constraints, and production opportunities.

Table 1. Relative changes in soil organic carbon (SOC) or soil organic matter (SOM) across management comparisons, where: improved cropping practices included enhanced rotation, minimum till, and stubble retention; and improved pasture included additional fertiliser, liming, sowing alternative species, and irrigation. SOC data is sourced from Sanderman et al. (2010) and converted to SOM with a multiplication factor of 1.72

Management comparison	Stock change (t /ha/yr)	
	SOC	SOM
Cropping: improved compared to conventional	0.2 - 0.3	0.34 - 0.52
Pasture: improved compared to current	0.1 - 0.3	0.17 – 0.52
System conversion: cultivated to permanent pasture	0.3 - 0.6	0.52 – 1.03

Soil carbon inputs: visibility and (un)certainty

In order to manage SOM stocks, we need to consider input and output pathways in the carbon cycle. Inputs of organic carbon to soils include plant biomasses and organic amendments, such as manure. Losses include decomposition/mineralisation and erosion. Maximising plant inputs, while minimising erosion loses, represent two of the most important management levers when aiming to build SOM stocks.

Considering both above- and below- ground inputs are important. Inputs from above-ground crop residues can be estimated from yields based on harvest index (HI) data across a range of Australian cropping scenarios (Unkovich et al. 2010). Local expert knowledge of the cropping systems may be useful in fine tuning values.

Although below ground inputs are less frequently measured, they are important drivers contributing to SOM stocks and overall biological fertility. Estimates of root biomass can be made based on general root:shoot ratios, but these numbers tend to be more uncertain compared to shoot biomass inputs. In addition to root biomass that can be readily seen, roots also add a significant amount of carbon in forms that are unseen. Fine root hairs, sloughed root cells and root exudates supply a steady flow of carbon to the rhizosphere through the growing season. These carbon forms are easily used by the microbial community and commonly referred to as rhizodeposits. It is generally considered that the microbial community can be relatively efficient in using rhizodeposits. The microbial community is key to converting these labile carbon forms into more stable carbon that contribute to more persistent soil carbon pools.

Estimating SOC accumulation rates: let’s make some assumptions

A useful cross-check in evaluating target sequestration rates is to consider how much extra crop biomass would be needed to support carbon accumulation in the soil. This provides a tool to question and moderate expectations around rates of SOC change based on local understanding of the extent to which plant biomass inputs can be changed through management. Although this does not account for potential changes in the loss pathways, changing carbon inputs can often be the dominant driver in achieving SOC gains.

A theoretical SOC stock change potential (Figure 2) can be estimated through calculations based on carbon input and loss factors informed by published literature (Table 2). The input factors can be moderated based on local expert knowledge of the farming environment and the changes that can be achieved. Here we estimate the theoretical SOC stock change potential of a cereal system based on changes to carbon inputs including:

1. **plant biomass (roots + shoots):** this approach aligns with input factors used in traditional soil carbon modelling. Shoot biomasses can be approximated based on the yield and harvest index (0.37 for cereals); root biomass approximated based on a root:shoot ratio of 0.5 (cereals); the soil carbon input is estimated using the total plant biomass (shoots plus roots, t/ha) and approximate carbon content (44%); and finally we estimate a retention factor for the biomass-C (RF^{b}) into SOC at approx. 30 %.

$$\textbf{SOC}\ \Delta^{B} = \left[\begin{array}{c}\text{shoot + root}\\ \text{biomass}\end{array}\right] \text{ x } \begin{array}{c}\text{carbon content}\\ \text{(proportion)}\end{array} \text{ x } RF^{b}$$

2. **plant biomass (roots + shoots) plus rhizodeposits**: this approach recognises that traditional soil carbon models don’t explicitly account for labile carbon inputs as a separate pool. Here we include rhizodeposition as equivalent to 50% of root biomass, and that these simple compounds are converted to SOM more efficiently (0.57 retained) by the microbial community compared to plant residues.

$$\textbf{SOC}\ \Delta^{B+R} = \left[\ \text{SOC}\ \Delta^{B}\ \right] + \left[\begin{array}{c}\text{root}\\ \text{biomass}\end{array} \text{ x } \begin{array}{c}\text{rhizodeposition}\\ \text{carbon factor}\end{array} \text{ x } RF^{r}\right]$$

Under these assumptions SOC stock change potential can be estimated for a given increase in plant biomass (Figure 2). Thus, a 0.5 t/ha change in SOC stock can be expected to require an approximate increase in crop biomass in the region of 2.5 t/ha when considering traditionally recognised shoot and root inputs, or 1.4 t/ha where rhizodeposits inputs are also included.

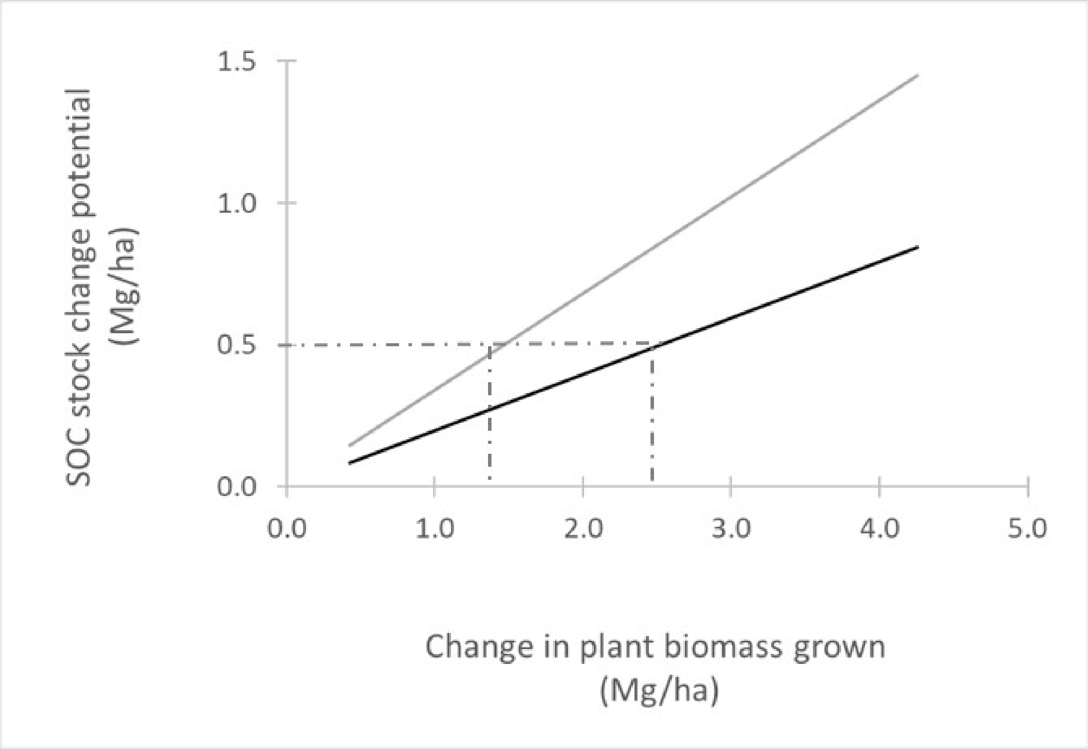

Figure 2. A theoretical SOC stock change potential (t/ha) for a given increase in crop biomass (t/ha) when considering crop biomass inputs (solid black), or crop biomass inputs plus estimated rhizodeposit (solid grey). Assuming steady state equilibrium before the implementation of management change, the calculation factors are listed in Table 2

Table 2. Calculation factors, values, and references used to estimate the theoretical SOC stock change potential based on crop biomass inputs (SOC Δ^{B}) or biomass plus rhizodeposit inputs (SOC Δ^{B+R}) depicted in Figure 2. Factor values* can be updated based on local expert knowledge for a given management scenario

Calculation factor	**Value***	**Reference**
Harvest Index (HI) cereal	0.37	Unkovich et al. (2010)
Root:Shoot (R:S) cereal	0.50	for pasture increase to 1
Carbon content of cereal biomass	0.44	
Retention Factor biomass (RF^{b})	0.30	Ladd et al. (1995)
Rhizodeposition C (proportion of root biomass)	0.50	Jones et al. (2009)
Retention Factor rhizodeposition (RF^{r})	0.57	Pausch and Kuzyakov (2018)

This estimate calculation does not provide a definitive answer on SOC change potential. It provides a tool to consider whether management changes have a big enough impact on plant inputs to support a target SOC stock gain. The harvest index can be updated for different crops with local knowledge or with values reported for a range of crops within Unkovich et al. (2010). It is also useful to consider how close to the water limited yield potential current yields are, and what factors are limiting closing the yield gap. Identifying the constraints in play, what it will take to overcome them, and estimating the gains in crop biomass inputs can be informative in helping to set realistic SOC change targets.

It is important to note the uncertainties and assumptions around this estimate calculation. The calculation assumes that the system is in steady state, not losing or gaining carbon under the current management practice (Figure 1, scenario C). If the system is losing carbon then changed management practices may lead to either a slower rate of SOC loss (avoided emission) but no measurable gain from a baseline (time zero) measuring point, or only a small sequestration gain.

SOM stocks and flows for resilient soil systems: the need for long-term nutrient budgeting

Soil health and fertility benefits from SOM result from decomposition or loss of SOM. Thus, it is equally important to recognise how management changes impact carbon and nutrient flows as much as SOM stocks. Matching fertiliser requirements to a larger yield target is important in ensuring that striving for a larger biomass does not come at the expense of mining the existing SOM for nutrients.

Soil organic carbon contents vary widely. However, the C:N ratio of soil is relatively consistent, commonly reported to be around 12 (12C:1N). For other nutrients, such as phosphorus, the ratio is more variable and less predictable. However, most of the N contained in soil (>95%) is associated with carbon in SOM. Therefore, if we know the SOC content, we can estimate the total N content of the soil. A decline in SOC content will also reduce the soil N stock and the ability of the soil to supply N through mineralisation.

For example, a 0.5% decline in SOC in a 10 cm layer of soil with a bulk density of 1.3 g/cm^{3} (no gravel), equates to a loss of 540 kg N/ha. As SOM content declines, the ability to support N supply through the growing season declines, and the crop becomes more reliant on fertiliser N.

Norton (2016) previously demonstrated that current rates of fertiliser application are likely to result in mining of soil N - mineralisation of SOM that is not replaced through crop residue returns. In the long-term this results in a decline in soil N status over time, a reduction in the ability of the soil to supply N through mineralisation, and a growing dependence on fertiliser N. Part of the benefit of SOM-derived N is that it is made available through the growing season. Mineralisation will occur when the soil is wet and warm providing a certain amount of synchrony with times when crops are actively growing and have a requirement for N.

Baldock (2019) emphasise the importance of conducting N balance calculations over multiple seasons to not only manage soil N status but to manage SOM stocks. A long-term N balance approach allows for phases of building/replenishing SOM, and phases of using SOM so that the crop benefits from stored N. Other than fertiliser application, the main mechanism to enhance N status is a regular legume rotation to contribute to SOM stocks. Baldock (2019) promote the need for longer term (>10 years) economic analyses. The most profitable management approaches in the short-term will maximise the extraction of N from the soil (i.e. mine the soil N reserve) thereby reducing the cost of production. A long-term approach allows the true cost-benefit analysis associated with both building and using SOM in a cyclic manner to benefit crop production.

Conclusions

Productive and resilient agricultural systems require the careful management of SOM stocks and the associated carbon and nutrient flows. Conventional management practices and current rates of fertiliser addition are likely to favour SOM decline, reducing the ability of the soil to supply N through the growing season. Although there is considerable interest in building SOM stocks to support current and future productivity, the potential rates of accumulation are commonly debated.

Scientific literature estimates Australian SOC accumulation rates in cropping and pasture systems to be approximately 0.1 to 0.3 t C/ha/yr, while higher rates (0.3 to 0.6 Mg t C/ha/yr) are estimated when converting from cropping to pasture. It is however acknowledged that there is a lack of data to inform SOC accumulation rates under a broader range of alternative management practices. Building SOM stocks at higher rates is possible through bold management changes that maximise carbon inputs and minimise loss pathways, but expenditure and opportunity costs need to be evaluated on an individual basis. It can be useful to estimate SOM accumulation targets based on local knowledge of the potential changes to plant biomass production. Taking a long term (decadal) view on building and using SOM and the associated nutrient flows is critical to ensuring that future productivity will not be compromised to maximise short term (annual) profits.

Acknowledgements

This research combines knowledge and findings from multiple projects including those funded by the GRDC and the Australian government. This research would not be possible without the significant cooperation and support of Australian farming and agronomy communities to whom we thank for continued support, discussion, and access to land.

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Measuring, using & budgeting P & K soil reserves - phosphorus buffering index & its role, K interactions with sodium & implications for K management

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Notes

Understanding factors affecting the effectiveness of P and P+K fertilisers when deep banded

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Key words

fertiliser band, phosphorus, phosphate fertiliser, potassium co-application, bioavailability

GRDC codes

9175500/UQ00086

Take home messages

- There is increasing interest in periodically applying P and P+K fertilisers in deep bands, but we need to gain a better understanding of the factors which influence their effectiveness. The work reported here supplements and builds upon the existing work being conducted in the field
- It appears that pH is an important factor in influencing availability of banded P. In a calcareous soil, when P is applied as a deep band, much of the P precipitates as calcium-P and is of low availability. For non-alkaline soils, our data indicate that P availability within the band decreases as the pH value within the band decreases. This is because when the soil in the band is more acidic, much of the P can potentially precipitate as unavailable aluminium (Al)-P forms
- Because of the impact of pH on P availability, our data also suggest that the form of P used (DAP, MAP, or monocalcium phosphate/TSP) is likely to be an important factor. This is because the form of P supplied influences the pH within the fertiliser band. Thus, our initial data indicate that DAP has higher availability within the concentrated band than MAP or TSP, although we still need to confirm this
- When K is co-applied with the P, this can potentially decrease the availability of P in certain soils, although we need to conduct further work to understand when this can occur. It is possible that the addition of the K displaces calcium/magnesium from the soil CEC and thereby creates favourable conditions for calcium/magnesium-P precipitation.

Background

The need to place phosphorus (P) and potassium (K) deeper in the soil profile to address nutrient depletion in subsoil layers where prolonged root activity and nutrient acquisition occur has been demonstrated in recent field research activity across the northern region. However, plant responses to deep placement of highly concentrated bands of P fertiliser alone or together with K has been variable, ranging from substantial yield increases in some soils but no observable response in others. The highly soluble P fertilisers triple superphosphate (TSP), mono ammonium (MAP) and di-ammonium phosphate (DAP) are generally considered to be similarly effective sources of plant-available P, but as banding becomes more prevalent, it is necessary to examine how the behaviour of P differs within these concentrated bands compared to other modes of application. Co-application of K-fertilisers in concentrated bands may also potentially have major effects on P availability in some soils, but the underlying reactions and their impact on bioavailable P are not well understood. Developing a mechanistic understanding of fertiliser-soil interactions is therefore required in order to develop effective fertiliser application strategies. The aim of this study was to quantify changes in bioavailable P and to identify what happens to the form of P when P fertilisers are applied as highly concentrated bands, either as P alone or together with co-applied nutrients such as K, and how different nutrient sources and soil types affect these reactions.

Materials

We conducted a soil-fertiliser incubation experiment to identify P reaction products and quantify bioavailable P that forms in concentrated fertiliser bands, as influenced by (i) P source, (ii) co-application of K, and (iii) soil properties. For this, we used six soils representative for the northern region; two Vertosols, one Ferrosol, one Chromosol, one Kandosol and one Tenosol plus a calcareous soil (Calcarosol) from the southern region (Table 1), along with three P forms (mono-calcium phosphate, marketed as TSP; mono-ammonium phosphate, MAP; and di-ammonium phosphate, DAP). The impact of adding K in the form of KCl (muriate of potash) into the P band was explored for the main soil types in the northern region (grey Vertosol, Kandosol, Chromosol), in addition to the calcareous soil. The P rate was 8.2 g P kg soils^{-1} which is the calculated P concentration in the fertosphere (the fertiliser-enriched soil within 10 mm of the band) at a P application rate in the field of 40 kg P ha^{-1} for bands spaced 1 m apart. The KCl was added at a rate of 20 g K kg soil^{-1} being equivalent in the field to 100 kg K ha^{-1}. We have used a range of approaches to estimate how much P remained available to the plant within the band as well as to determine the fate of the P. Specifically, we measured total isotopically exchangeable P to estimate bioavailable P, used X-ray absorption near edge structure (XANES) spectroscopy to identify dominating mineral P species formed in the fertosphere and calculated the saturation index of P minerals in the fertosphere solution to obtain information on theoretically precipitated P species.

Table 1. Selected soil properties

	Unit	Calcarosol	Grey Vertosol	Black Vertosol	Red Ferrosol	Red Kandosol	Red Tenosol	Red Chromosol
pH (1:5 H_2O)		8.5	7.5	7.2	6.1	5.8	5.7	5.6
Total P	mg/kg	463	549	661	744	200	119	283
Clay	g / kg	224	667	543	674	175	65	124
CEC	cmol(+)/kg	33.4	32.8	21.5	7.5	4.4	3.8	3.1
Exch. Ca	cmol(+)/kg	28	22.1	17.5	5.9	2.9	1.7	2.0
Al_{ox}	mg/kg	n.d.	1489	1192	2208	496	381	500
Fe_{ox}	mg/kg	n.d.	3212	1603	2476	913	302	462

Results

Potentially plant-available P within fertiliser bands

The concentrations of potentially plant-available P, measured as isotopically exchangeable P, depended upon soil properties as well as the form of P and ranged from 10 to 85% of total P applied (Figure 1). Among the seven soils, the total isotopically exchangeable P was generally highest in the more acidic Ferrosol, Kandosol, Tenosol and Chromosol (on average 54%), was lower in the two Vertosols (37%) and lowest in the Calcarosol (19%). For the more acidic soils, the isotopically exchangeable P correlated (r= 0.97) with the fertosphere solution pH and soil clay and oxalate extractable aluminium content. Comparing the P sources, the total exchangeable P was consistently lowest with TSP (29%), and generally highest with DAP (54%) and intermediate with MAP (48%). This is because the DAP causes the pH in the fertiliser band to increase, which seemingly decreases the precipitation of P into non-available forms. Thus, excluding the alkaline Calcarosol, increasing acidity of the saturated fertiliser solution resulted in more P precipitated (DAP<MAP<TSP).

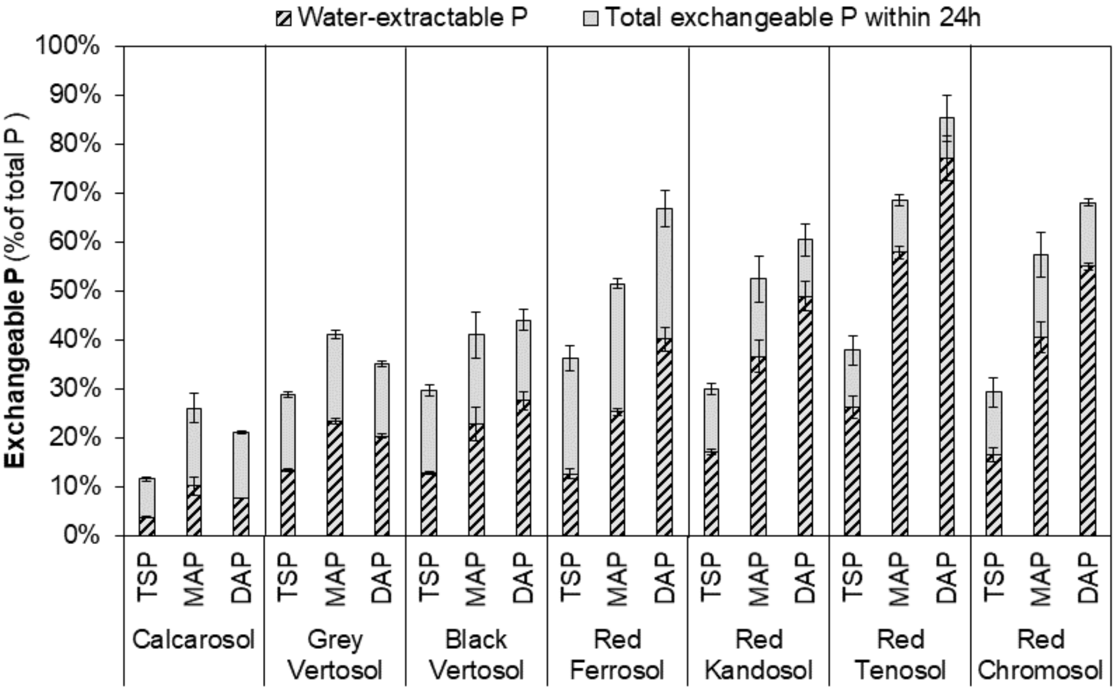

Figure 1. Water-extractable P and total isotopically exchangeable P in the fertosphere at 4 months incubations influenced by P source and soil type. The tested P sources are triple superphosphate (TSP), mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP). Error bars indicate standard deviation (n=3)

The co-application of KCl together with the P fertiliser decreased concentrations of potentially plant-available P to the greatest extent in soils with high exchangeable calcium (i.e. the grey Vertosol and the Calcarosol, Figure 2). The magnitude of this K-induced reduction in exchangeable P depended upon the form of P fertiliser applied. The largest reduction in P availability caused by K was in the Calcarosol fertilised with MAP (-15%). In the grey Vertosol, the K-induced reduction in P availability was smaller (-10%) and was similar for MAP and DAP, but the least impact was with TSP. In the more acidic Kandosol and Chromosol, only the water-extractable P concentration changed but not the total isotopically exchangeable P, suggesting that co-application of K does not affect the potentially bioavailable P in these soils.

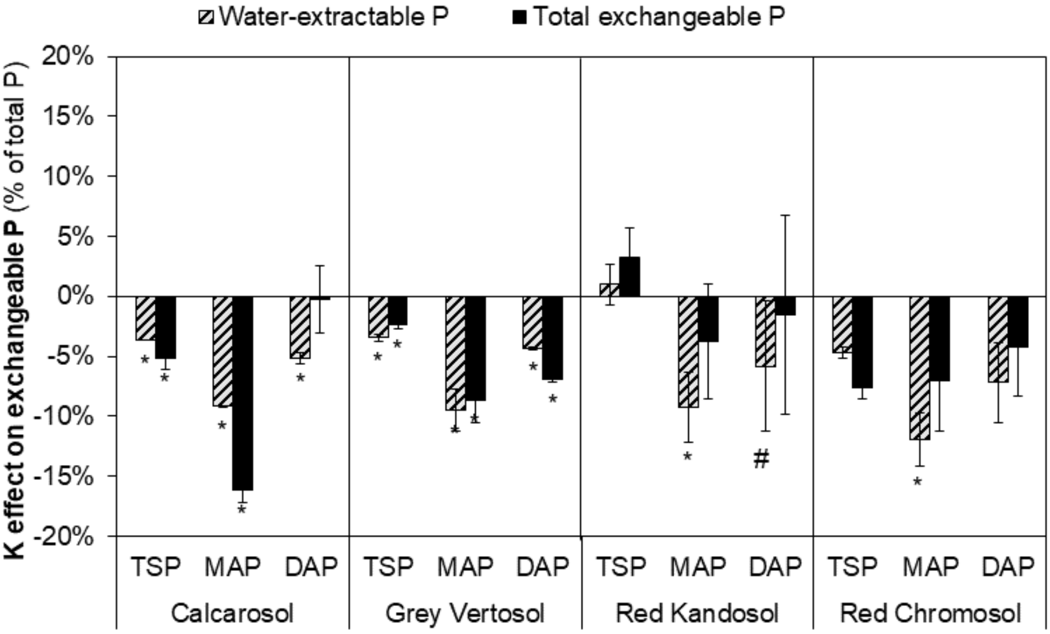

Figure 2. Changes in water-extractable P and total exchangeable P following co-application of K relative to single P treatments of triple superphosphate (TSP), mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP). Bars marked with * (*p*<0.05) and # (*p*<0.1) are significantly different from zero. Error bars indicate standard deviation (n=3)

Transformation of the P fertiliser into non-available forms

When the P fertilisers are applied to soils, some of the P is changed into forms that are non-available or only of low availability – these are called 'reaction products'. For most soils (i.e. all bar the Calcarosol), we found that aluminium-P minerals were the most important reaction products that formed in concentrated P bands. In the Calcarosol, much of the P in the band precipitated as calcium P minerals with little difference recorded among the three P forms.

The importance of aluminium-P reaction products forming in non-calcareous soils and the calcium-P reaction products forming in the calcareous soil was identified using XANES. The P K-edge XANES from the non-calcareous soils receiving only P, exhibited similar spectral features that are characteristic of aluminium-P minerals, most likely taranakite, and adsorbed-P. That precipitation of aluminium-P minerals dominates in the fertosphere of the non-calcareous soils is further supported by modelling, with saturation indices of P minerals calculated based on the elemental concentrations in the fertiliser solution. Again, the highest saturation index in the non-calcareous soils was predicted for aluminium-P minerals, i.e., K- and NH_4-taranakites, regardless of the form of P applied. In contrast, for the Calcarosol the XANES spectra showed a distinct post-edge shoulder (Figure 3) which is a characteristic feature of calcium-P minerals. Again, this interpretation is in line with the predicted saturation indices of calcium-P minerals regardless of the type of P applied.

We also examined what reaction products formed when K was co-applied with the P fertiliser in the band. Co-application of K changed spectral features in the non-calcareous soils, with this effect most apparent for the grey Vertosol supplied with DAP (Figure 3). A small shoulder of low intensity in the post-edge region appeared, which could possibly be due to precipitation of calcium-P. For the Calcarosol, spectral features only changed between P alone and P+K together when TSP was the form of P applied (Figure 3). The spectral feature of soil supplied with TSP+K was very similar to that recorded when MAP or DAP were applied, regardless of K addition. This suggested that in the Calcarosol, the mineral species theoretically precipitating was not affected by K addition.

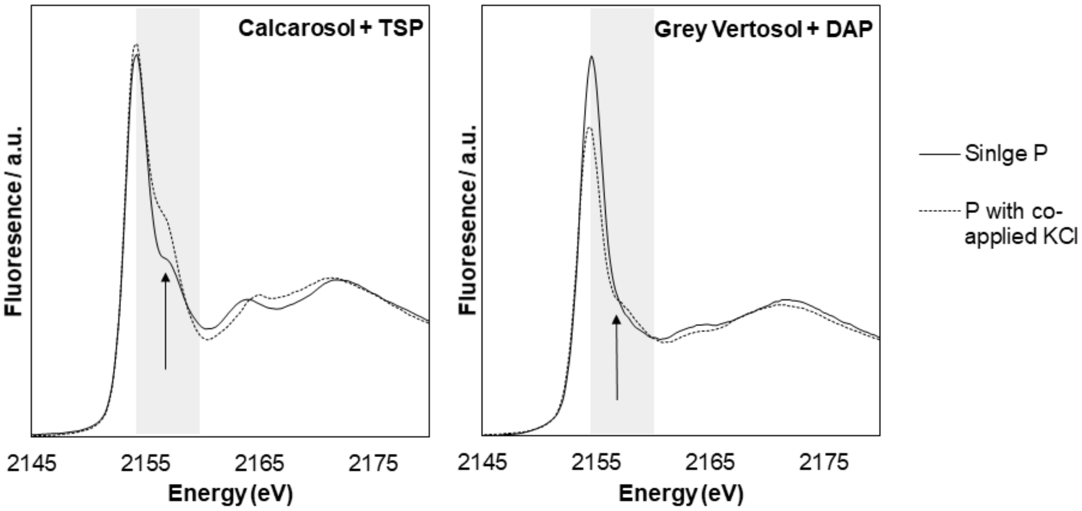

Figure 3. P K-edge XANES spectra from the Calcarosol fertilised with triple superphosphate (TSP) alone or together with KCl (left), and from the grey Vertosol fertilized with di-ammonium phosphate (DAP) alone or together with KCl. Highlighted in grey is the post-edge region. The arrow indicates the energy at which a characteristic shoulder would be seen if calcium P minerals were present

Conclusion

The pH of the fertiliser solution was the most important factor influencing P availability in the band for all soil types except the Calcarosol. Our data indicate that selecting the most appropriate form of P to apply in the band can have a larger impact on potential P availability than does co-application of K fertilisers. For the non-calcareous soils, the potential bioavailable P increased with increasing soil solution pH and decreasing soil clay and soil oxalate-extractable aluminium content. This was due to a reduction in aluminium-P precipitation and specific surface adsorption of the fertiliser P. In the grey and black Vertosols, aluminium-P most likely precipitated because of the high oxalate-extractable aluminium and iron found in these soils, together with apparently low pH buffering capacity of soil solution. The co-applied K is presumed to have displaced exchangeable calcium and possibly magnesium from soil exchangeable sites, leading to precipitation of P with the displaced calcium and a decreasing in the potential bioavailable P. This effect was only recorded in the grey Vertosol and the Calcarosol.

Practical implications

The application of P in concentrated fertiliser bands can have production benefits, but to maximize the return on fertiliser investment it is necessary to better understand the factors that can reduce the effectiveness of these deep-applied P bands in certain soils. The data from this incubation experiment suggest that the effectiveness of banded P will differ between soils and also differ depending upon the form of P used. These differences are because some of the P converts to different forms that have lower availability. The conversion of P to these different forms (reaction products) depends upon the soil properties and the form of P applied. However, the data cannot be interpreted in terms of plant availability under field conditions at this stage, with further work needed.

The experiment was designed to understand the principle chemical reactions and to assess the transformation products within the fertosphere under steady-state conditions. The induced reactions with K are not yet fully understood but the data suggests that the principle mechanisms involve displacement of cations from the exchange surfaces of clay minerals. This results in more P precipitation in soils and is most apparent in soils with high cation exchange capacity. We hope to use the information derived from this ongoing study to prepare recommendations for fertiliser use.

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 (Project 9175500/UQ00086); the author would like to thank them for their continued support.

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Can ‘stabilised’ and controlled-release N deliver improved N use efficiency when applied in concentrated bands?

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Key words

nitrogen, fertiliser band, urease inhibitors, nitrification inhibitors, polymer-coated urea

Take home messages

- New fertiliser technology offers opportunities to reduce environmental losses of N, but achieving better crop N recovery will be the key to its adoption by the grains industry. The fertiliser application method may need to vary for different types of products
- Urease inhibitors can be effective with surface broadcast applications, but offer limited N use efficiency benefits when applied in sub-surface fertiliser bands. Exceptions may be when substantial denitrification losses are expected within 2 – 3 weeks of application
- Nitrification inhibitors applied in banded fertilisers are more likely to be effective in soils with low permeability and high cation exchange capacity. These soils support limited distribution of N (both as urea and ammonium-N) from the fertiliser band and keep the inhibitor and substrate (ammonium-N) closer together
- Polymer-coated urea should only be used to provide a regulated base N supply. Neighbour-granule interactions that occur in banded applications may slow N release to longer than expected time frames, although more work is needed. Further, a relatively high soil moisture content is necessary to enable release of N from granules. If soil moisture is too high, N may release too quickly and be at risk of denitrification and/or leaching losses. Conversely, if soil moisture is very low, N may remain ‘locked-up’ within polymer granules.

Introduction

Declining soil fertility has increased reliance on nitrogen (N) fertiliser inputs to maintain crop yields. However, increasing awareness of the potential impacts of fertiliser N moving off-site has stimulated public concern and discussion about regulation of N-fertiliser use in agricultural industries. The Australian fertiliser industry now offers a range of ‘enhanced efficiency fertilisers’ (EEFs) which aim to improve the timing of N supply relative to crop demand via a suite of technologies that utilize ‘stabilising’ compounds or controlled-release properties. However, many of these products were developed for the highly regulated European market, with soils, climates and agricultural practices not representative of Australian farming conditions. In particular, the practice of broadcasting fertiliser has been increasingly replaced by fertiliser banding in Australia, as a strategy for improving nutrient access by crop roots and for benefits associated with reduced tillage.

This study aimed to investigate several urea-based EEF products in soils and conditions that are representative of QLD agricultural regions to determine if, and in what scenarios, these products may be effective when applied in fertiliser bands. Urea-based products tested included Green Urea NV™ (added urease inhibitor, UI), ENTEC® (added nitrification inhibitor, NI) and Agromaster

Tropical® (polymer-coated urea, PCU), and were compared to granular urea as the industry standard.

Methods

This paper combines results from a laboratory diffusion incubation and a field experiment to provide insight into fertiliser band dynamics that is both mechanistic and indicative of field performance.

Laboratory diffusion incubation

Two soils were collected from the top 10 cm of cropped fields in the Bundaberg region, comprising a yellow Dermosol and black Vertosol. These soils differed in their physico-chemical properties and texture (Table 1), allowing us to investigate the effects of varying soil type on EEF dynamics.

Table 1. Chemical and physical characteristics of soils used in the diffusion incubation. The pH and EC values were derived from a 1:5 (soil:water) measurement, while pHBC refers to the pH buffering capacity, CEC is the cation exchange capacity and concentrations of both ammonium (NH_4^+) and nitrate (NO_3^-) mineral N species are reported.

Soil Order	**pH**	**EC** (dS m^{-1})	**pHBC** (cmol OH-kg^{-1} pH $unit^{-1}$)	**Particle size analysis (%)**				**CEC** Exchangeable cations cmol(+) kg^{-1}	**NH_4-N** (mg kg^{-1})	**NO_3-N** (mg kg^{-1})	**Gravimetric water content** (g g $soil^{-1}$)
				Coarse sand	Fine sand	Silt	Clay				
Dermosol	6.30	0.07	1.32	38	46	9	9	4.5	3.2	6.8	0.12
Vertosol	7.15	0.35	3.51	5	26	21	52	28.5	4.8	8.5	0.32

Approximately 3 kg of air-dry soil (< 2 mm) was placed in round incubation pots (225 mm diameter and 5cm deep). Three cotton wicks (4.5 cm lengths of natural cotton cord) were inserted in an offset pattern at varying distances of 1-3 cm, 3-5 cm, 5-7 cm, 7-9 cm, and 9-11 cm from the fertiliser band (0-1 cm), while a single wick was placed in the fertiliser band. Nitrogen-fertiliser treatments were applied in a vertical 'band' in the centre of the pot at an in-band concentration equivalent to that from N-fertiliser applied at 150 kg N ha^{-1} in bands spaced 1.8 m apart – a rate typical of the sugar industry. The N-fertiliser treatments described in this paper include: (i) standard granular urea; (ii) Green Urea NV, which is granular urea coated with the UI, N-(n-butyl) thiophosphoric triamide (NBPT); (iii) ENTEC, which is granular urea coated with the NI, 3, 4-dimethyl pyrazole phosphate (DMPP); and (iv) Agromaster Tropical, which is a PCU with a reported release period of 90 days. Replicated incubation pots were sealed and maintained at a moisture content equivalent to field capacity (± 5 %) and an ambient temperature of 25°C (±2°C).

Destructive sampling occurred 2, 5, 9 and 16 days after incubation (DAI) for urea and inhibitor treatments and at 2, 10, 20 and 35 DAI for PCU. Soil was sampled in concentric rings 2 cm in diameter out from the central 1 cm band. Each increment was thoroughly mixed and analysed for $pH_{1:5w}$, $EC_{1:5}$ and 2M KCl-extractable ammonium (NH_4^+) and nitrate (NO_3^-). Wicks were removed and bulked for each ring, extracted using ultra-pure water, and analysed for urea, NBPT and DMPP.

Field experiment

The field experiment was conducted at the Gatton Campus research station of the University of Queensland on a black Vertosol (Table 2).

Table 2. Chemical and physical characteristics of the field soil where pH and electrical conductivity (EC) refer to 1:5 (soil:water) measurement; cation exchange capacity (CEC); total organic carbon (TOC); nitrate (NO_3^-) and mineral N species are reported

Soil Order	**pH**	**EC** (dS m^{-1})	**Particle size analysis (%)**				**CEC** ($cmol_c$ kg^{-1} soil)	**Mineral N** (mg kg^{-1})	**NO_3-N** (mg kg^{-1})	**TOC** (%)
			Coarse sand	Fine sand	Silt	Clay				
Vertosol	7.8	0.07	3	16	21	62	49.3	2	<1	1.13

Fertiliser treatments included: (i) granular urea; (ii) Green Urea NV; (iii) ENTEC; and (iv) Agromaster Tropical. These fertiliser treatments were applied at in-band concentrations equivalent to 150 kg N ha^{-1} at row spacing of 1.8 m (27 g N m^{-1}), while additional treatments for urea and ENTEC were included at in-band concentrations equivalent to 50 and 100 kg N ha^{-1}. Fertiliser bands were placed at a depth of 12.5 cm in plots that were 10 m long with 2.5 m between treatments, with four replications.

At each sampling time, a vertical 'face' was excavated at right angles to the fertiliser band to a depth of 30 cm. The resulting slab of soil was sectioned into nine 5×5 cm zones of varying height, depth and lateral distances from the fertiliser band. Zones analysed included: (1) 7.5 – 12.5 cm directly above; (2) 2.5 – 7.5 cm at 45° above; (3) 2.5 – 7.5 cm directly above; (4) 7.5 – 12.5 cm lateral horizontal distance; (5) 2.5 – 7.5 cm lateral horizontal distance; (6) band zone (designated the 'fertosphere'): 0 – 2.5 horizontal and vertical; (7) 2.5 – 7.5 cm at 45° below; (8) 2.5 – 7.5 cm directly below; and (9) 7.5 – 12.5 cm directly below (where cm refers to distance from the centre of the band zone). Individual soil samples (i.e., each segment) were tested using the same analytical procedures as outlined for the diffusion incubation.

Results and discussion

Standard urea (granular)

Rapid hydrolysis of a urea band resulted in significant localized increases in pH (>9.0), electrical conductivity (EC, 1.5 – 2.5 dS m^{-1}) and aqueous ammonia (NH_3, 10 -30 mg L^{-1}), with the magnitude and extent of chemical changes dependent on soil type. These changes resulted in a zone of nitrification inhibition that was observed within and around the fertosphere (soil within 0.01 m of the fertiliser band, Figures 1, 2) in all soils. The impacted zone was greater in coarse-textured, low CEC soils like the Dermosol (Figure 1), that supported greater diffusion of solutes out from the band. In the field, N persisted predominantly as ammonium-N (NH_4-N) from within the fertosphere to 12.5 cm below the band and 7.5 cm horizontally for up to 34 days, although nitrification had commenced by 21 days (Figure 2). It's likely that significant rainfall (139 mm) between 21 and 34 days in the field study leached or denitrified a considerable portion of the existing nitrate–N (NO_3-N). However, renewed nitrification after the heavy rain saw concentrations of NO_3-N increase by the sampling at 49 days, and remain relatively high at approximately 100 mg N kg^{-1} soil by 71 days within the fertosphere and immediately below.

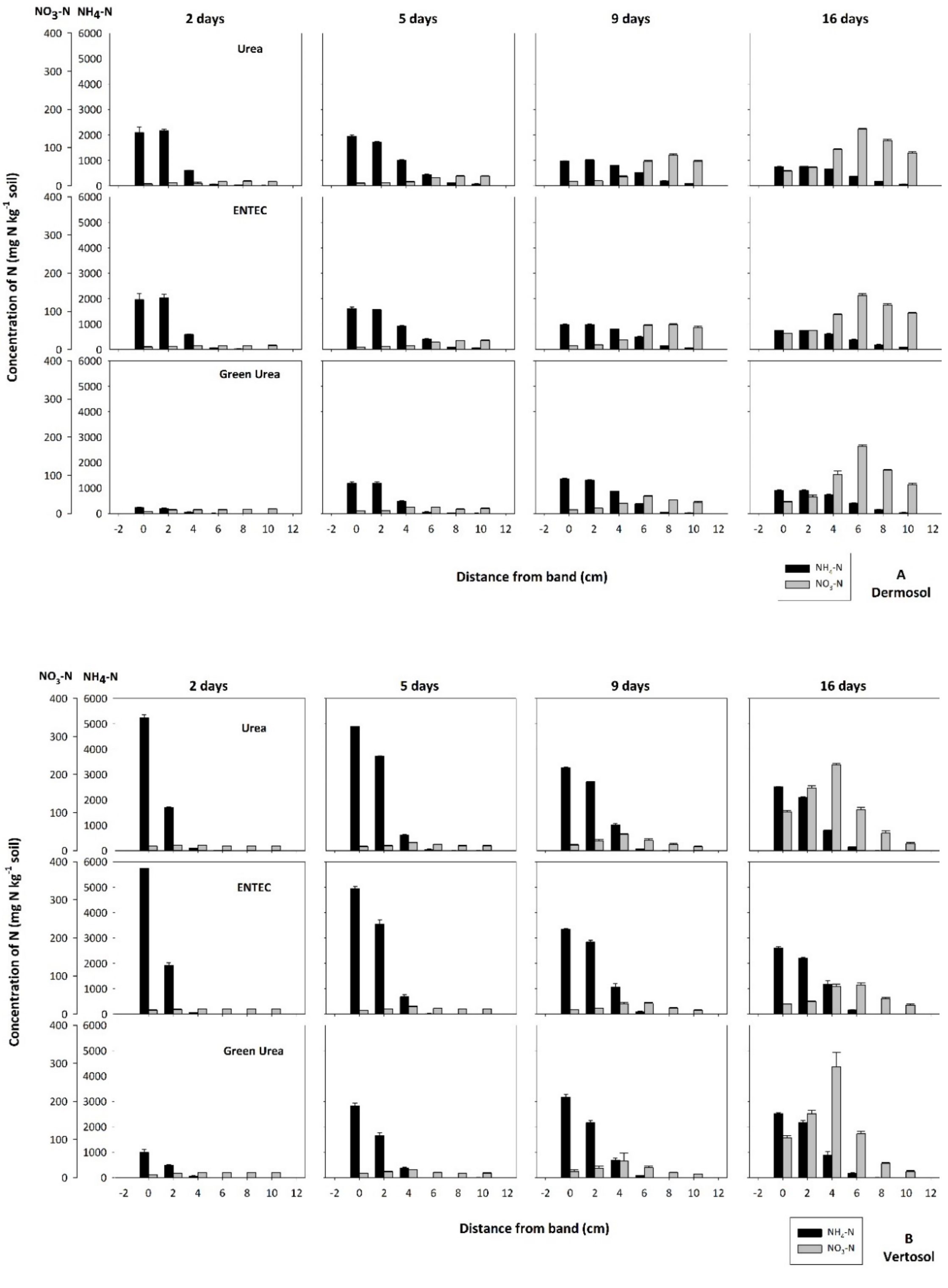

Figure 1. The concentration and distribution of ammonium-N and nitrate-N from bands of urea, ENTEC and Green Urea in the (A) Dermosol and (B) Vertosol of the laboratory diffusion study. Standard error bars of means for each data point are presented.

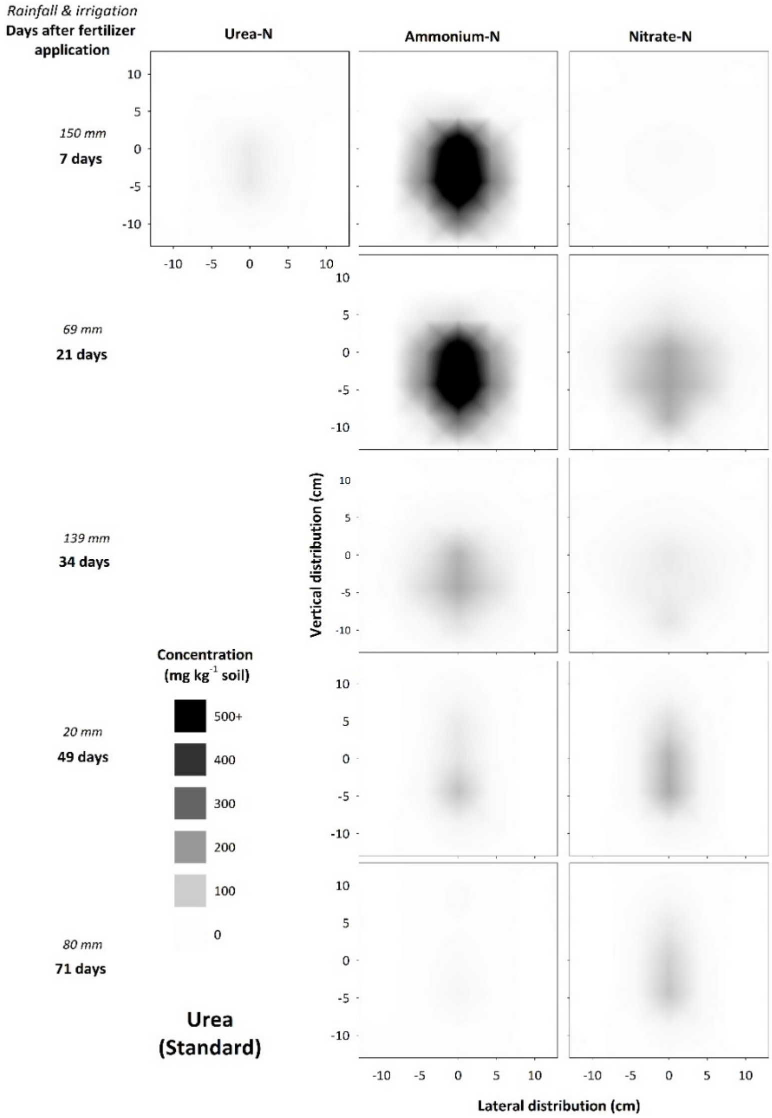

Figure 2. Concentration and distribution of urea-N, ammonium-N and nitrate-N over time in the profile of a Vertosol (field experiment) treated with granular urea.

Urease inhibitor: NBPT

The urease inhibitor (UI) in Green Urea slowed urea hydrolysis for up to 7 – 21 days (Figures 1, 3), with this urea-preservation effect most notable at 7 days in the fertosphere (compare urea heat map in Figure 2 vs Figure 3). This is consistent with studies of broadcast / incorporated application (approximately 7 – 14 days inhibitor efficacy) and indicates UI efficacy is not influenced by banding. Urease inhibitors may therefore prevent denitrification in the event of substantial rainfall within a week following fertiliser application, by preventing transformations of urea to NH_4^+ and then NO_3^-. However, this product will not prevent leaching of N, as even in this Vertosol soil there was evidence of leaching of N deeper into the soil profile with Green Urea (Figure 3 v's urea in Figure 2). This can be due to leaching of preserved urea alone, as well as more rapid nitrification caused by less inhibitory changes in soil chemistry (i.e., pH, EC and aqueous NH_3) in and around the band, enabling rapid nitrification and leaching of NO_3^-.

The use of UIs may therefore be potentially of benefit in regions of the grains industry where more rapid movement of N into deeper soil layers is desirable (e.g., from top-dressed applications during a fallow), but could exacerbate N losses in soils with high leaching potential. Additionally, the delayed urea hydrolysis slowed the formation of aqueous NH_3 so that concentrations in UI treated bands never achieved the same concentration as with standard urea. While these lower aqueous NH_3 concentrations would indicate a reduced risk of volatilization losses from broadcast / surface applied N-fertilisers, reductions in volatilization from buried fertiliser bands are likely to be minimal. Urease inhibitors may provide some benefit when fertiliser is co-applied with NH_3-sensitive seed, although this was not tested in this study.

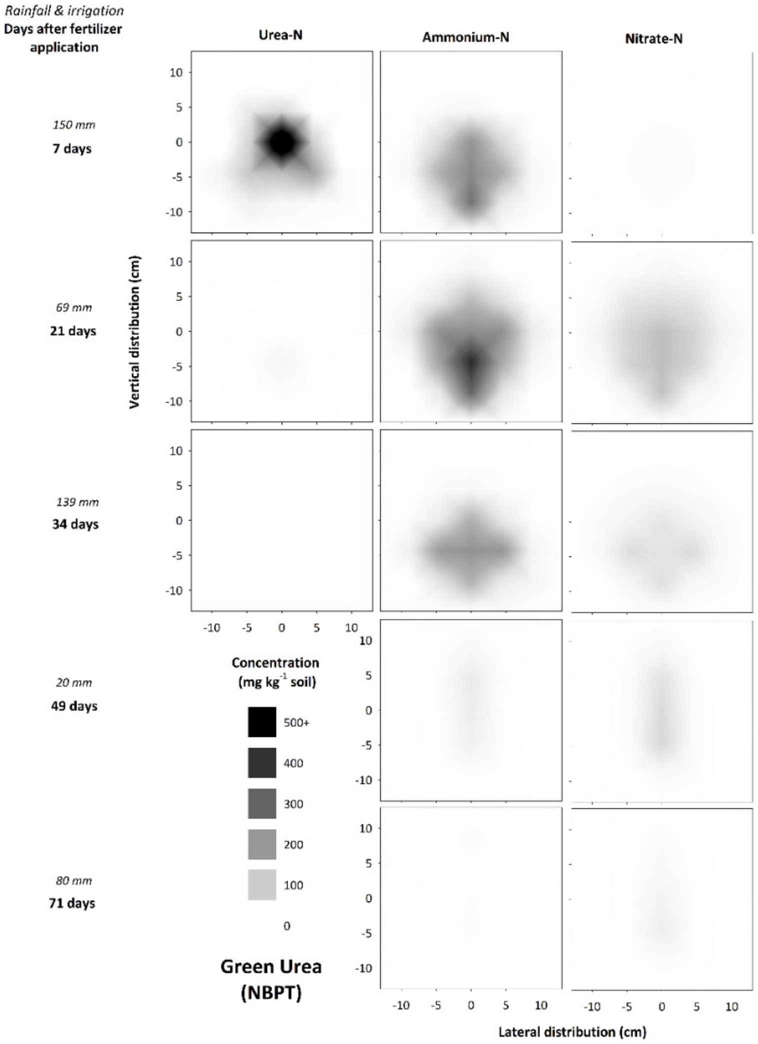

Figure 3. Concentration and distribution of urea-N, ammonium-N and nitrate-N over time in the profile of a Vertosol (field experiment) treated with Green Urea.

Nitrification inhibitor: DMPP

Soil properties which dictate solute movement were the dominant factors influencing nitrogen inhibitor (NI) efficacy. In soils where diffusion is limited (i.e., the Vertosol with low permeability and high CEC), the movement of N out of the fertosphere was restricted (Figure 1). As chemical changes due to urea hydrolysis dissipate, the zone of nitrification is more closely aligned to inhibitor distribution (approximately 1 cm from fertosphere) in these soils than in soils like the Dermosol where greater diffusive movement occurs (Figures 1, 4). Grain-growing regions with soils that are of low permeability and have high CEC (i.e., Vertosols of the northern grains region) will therefore receive the greatest NUE benefits from banded NIs.

In these soils, N is preserved in NH_4^+ form close to the zone of application (Figure 5), reducing the risk of denitrification loss in heavy rainfall events following fertilisation when compared with standard urea. In this N-form leaching losses will also be minimised because of its retention on the cation exchange complex. In contrast, banded NI applications in soils that support rapid diffusion (i.e., coarse-textured soils with low CEC) are not likely to achieve significant NUE benefits due to rapid separation of substrate (NH_4^+) and inhibitor. Interestingly, in the field experiment, inhibitory effects on nitrification in ENTEC-treated soil (Figure 5) were observed for approximately 30 days longer than with standard urea (Figure 2). This is considerably longer than inhibitory effects reported from broadcast / incorporated application. This could be due to the very high inhibitor concentrations found in the band environment (as compared with individual granules mixed through soil, as with broadcast/incorporated applications) and/or preservation of the inhibitor due to hostile band conditions (i.e., alkalinity, salinity and high aqueous NH_3 concentrations) limiting microbial degradation. This is the subject of on-going investigation. Regardless, the net effect was preservation of high NH_4-N concentrations in and around the band for at least 2.5 months under hot, wet summer conditions. This preservation will have large impacts on movement of N into deeper soil layers with rainfall/irrigation, and potentially increase the risk of fertiliser N remaining trapped in the shallow topsoil layers, inaccessible to plant roots once these layers dry.

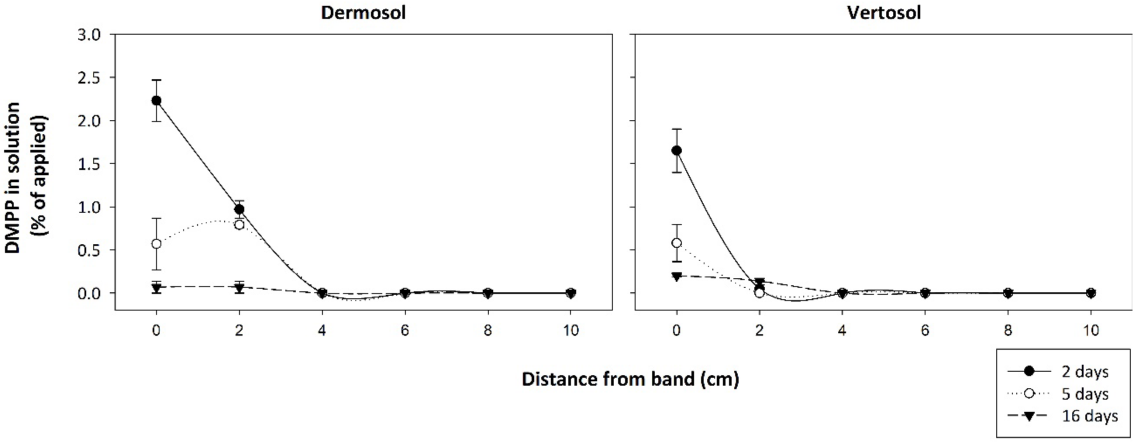

Figure 4. The distribution and recovery (percent of applied) of DMPP from ENTEC in the Dermosol and Vertosol over time. Standard error bars of the mean are shown at each data point.

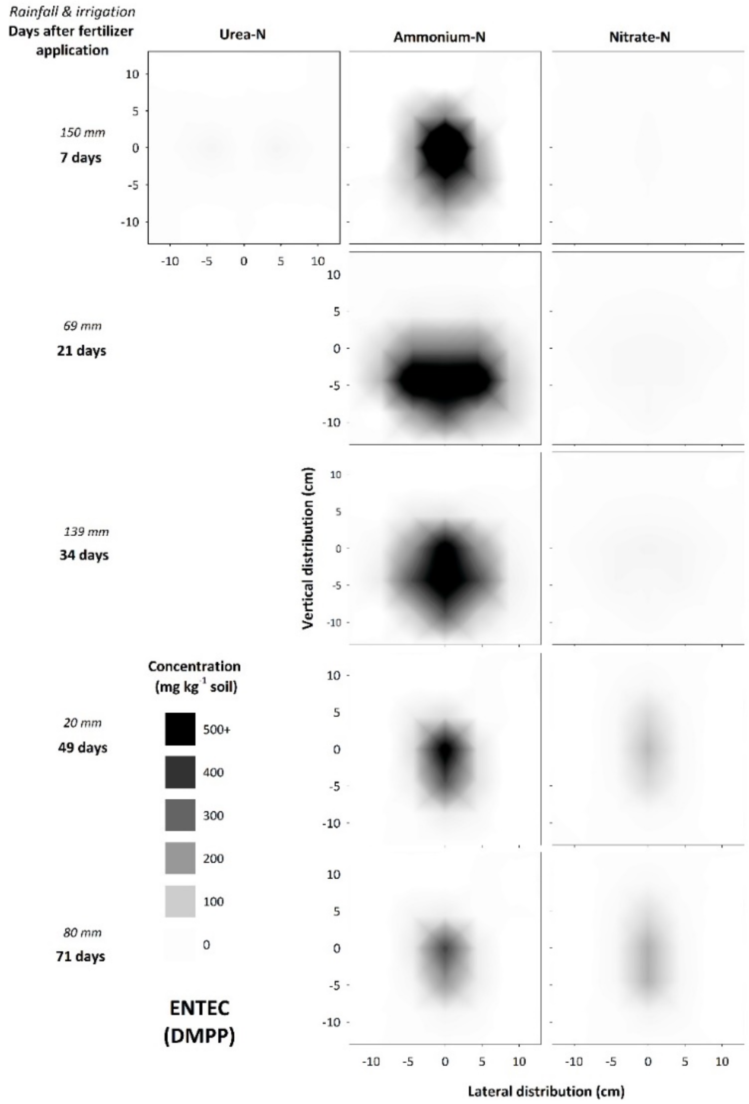

Figure 5. Concentration and distribution of urea-N, ammonium-N and nitrate-N over time in the profile of a Vertosol (field experiment) treated with ENTEC applied at a rate of 150 kg N ha^{-1}.

Lower rates of ENTEC application resulted in lower concentrations and reduced movement of N from bands, and inhibitory effects (both induced by ureolytic activity and conferred by DMPP) were not as persistent (Figure 6). While concentrations of NH_4-N increased with increasing fertiliser application rate, at 7 days NO_3-N concentrations were similar between the application rates (data not shown). This is indicative of inhibitory effects associated with urea hydrolysis but may also be partly due to loss of NO_3-N following rainfall after fertiliser application. By 21 days, the concentration of NH_4-N in urea bands applied at 50 and 100 kg N ha^{-1} had declined but remained high in bands of ENTEC applied at the same rates (Figure 6). This indicates that DMPP had begun to take effect in bands applied at these rates. For ENTEC applied at 50 kg N ha^{-1}, inhibitory effects associated with DMPP were greatest at this time (Figure 6). Similar comparisons of NH_4-N in standard urea bands with that of ENTEC bands applied at the same rates indicated that DMPP was most effective at 34 and 71 or more days for fertiliser rates of 100 and 150 kg N ha^{-1}, respectively (Figure 6).

Interestingly, concentration of NO_3-N and total mineral N (i.e., plant available N) were identified in soil profiles treated with 100 and 150 kg N ha^{-1} from approximately 34 days (Figures 5, 7). This indicates that application rates of ENTEC may be reduced by as much as 50 kg N ha^{-1} without adversely influencing N availability for crops. However, N availability was substantially lower over the initial 34 days in soil treated with ENTEC at 100 kg N ha^{-1} (when compared with 150 kg N ha^{-1}), thereby limiting the suitability of reduced fertiliser rates to crops/scenarios where N supply is not critical for the first month following fertiliser application. This delay in plant N availability with ENTEC may also indicate that in-crop or side-dress applications of ENTEC may not be effective if not applied in advance of anticipated crop N requirements.

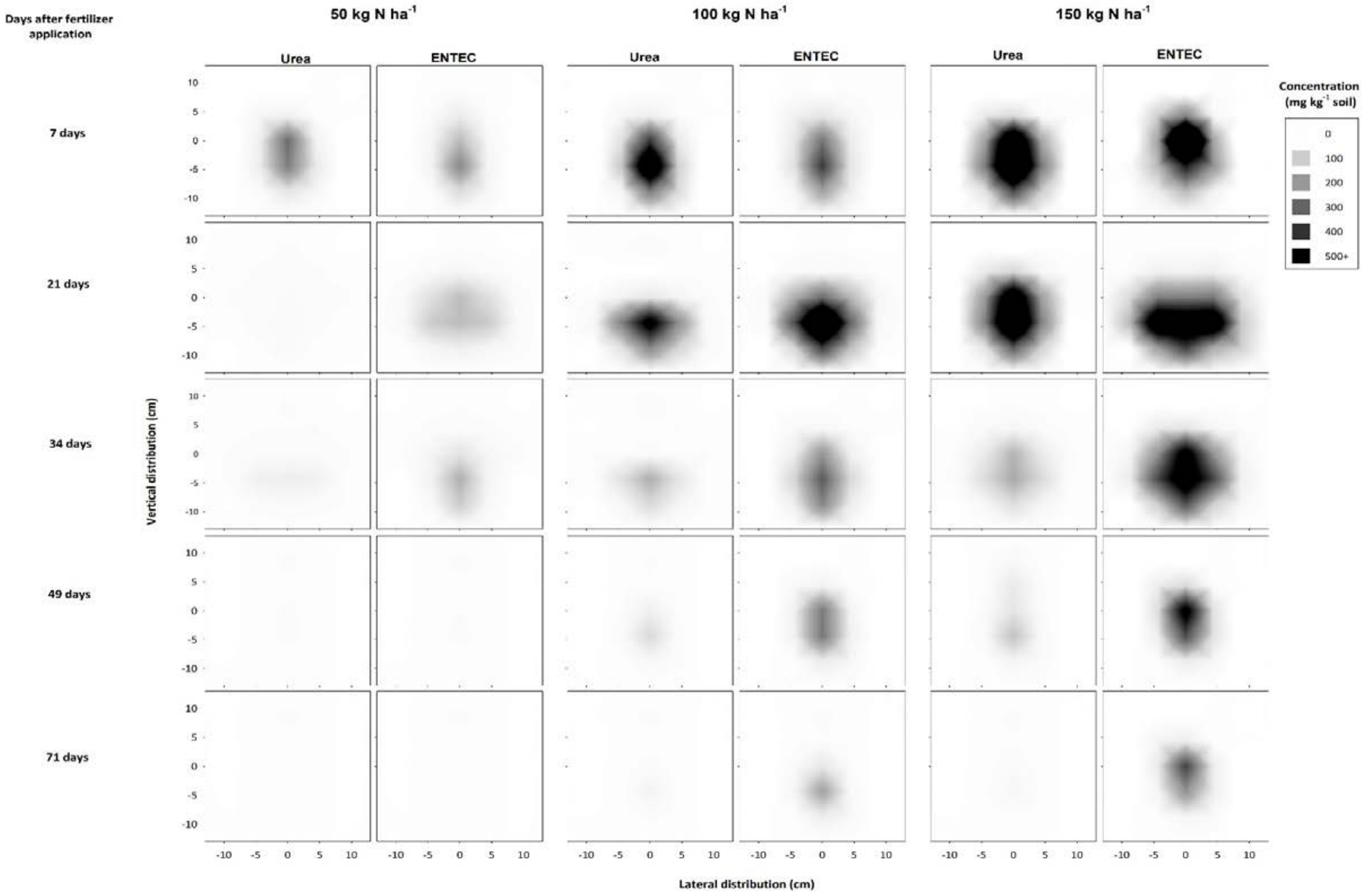

Figure 6. Concentration and distribution of ammonium-N from urea and ENTEC applied at 50, 100, 150 kg N ha^{-1} over time in the profile of a Vertosol (field experiment).

Controlled-release: polymer-coated urea (PCU)

Banding polymer-coated urea (PCU) delayed the release of N into the soil solution as expected (Figures 7, 8), however, N supply appeared to be lower and slower than would be anticipated for a product with a 90-day release. Preliminary laboratory results suggest banding diminishes the concentration gradients between the interior of a granule and the surrounding soil due to the effect of 'neighbour-granules'. As the rate of urea release is driven by this concentration gradient, the slower release when these products are banded seems logical. This contrasts with situations where the same product is broadcast and incorporated, whereby concentration gradients between PCU granules and the surrounding soil solution are maximized and the diffusion-based N-release process is not restricted. Banding PCU granules may therefore extend the predicted release period, resulting in an unpredictable N supply.

Quantification of the effects of banding and in-band concentration (i.e., fertiliser application rate) on delayed release of N from PCU may overcome some possible issues associated with an unpredictable N supply in field conditions. Soil moisture must also be taken into account, as this factor plays a key role in controlling the diffusion-based release mechanisim. In laboratory incubations, more rapid release of N from PCU granules in the Vertosol (Figure 7) was attributed to the greater volumetric water content of this soil at field capacity, which enabled more rapid movement of water into granules and subsequent diffusion of N solutes away from the fertiliser band. Interestingly, the relatively 'benign' chemical conditions of PCU bands, due to the low urea concentrations in soil solution at any given time, resulted in nitrification rates similar to that of standard urea over 71 days (Figures 2, 8). Thus, while relatively moist conditions are necessary for effective release of N, these same conditions represent an elevated risk of leaching or denitrification loss of N released from PCU bands. Soil moisture is therefore a key factor influencing PCU efficacy and delivery of improved NUE. Benefits from banded PCU are therefore most likely in soils with a full (but not saturated) moisture profile and/or are affected by the distribution and amount of seasonal rainfall. Under relatively dry conditions, limited release and distribution of N from PCU may worsen positional unavailability of N, potentially resulting in yield penalties.

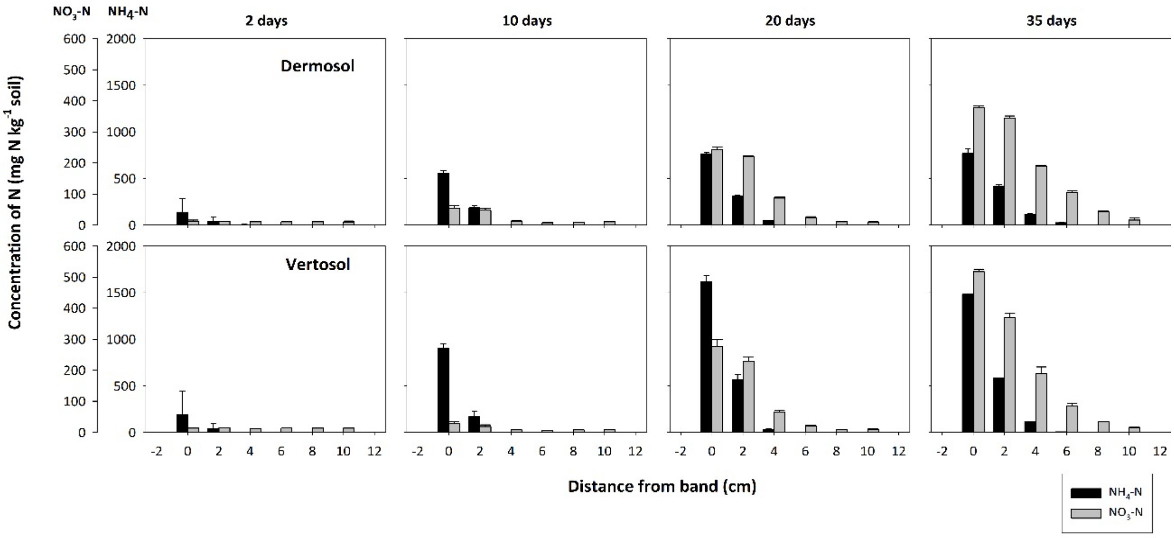

Figure 7. The concentration and distribution of ammonium-N and nitrate-N from Agromaster Tropical bands in the Dermosol and Vertosol of the laboratory diffusion study. Standard error bars of means for each data point are presented.

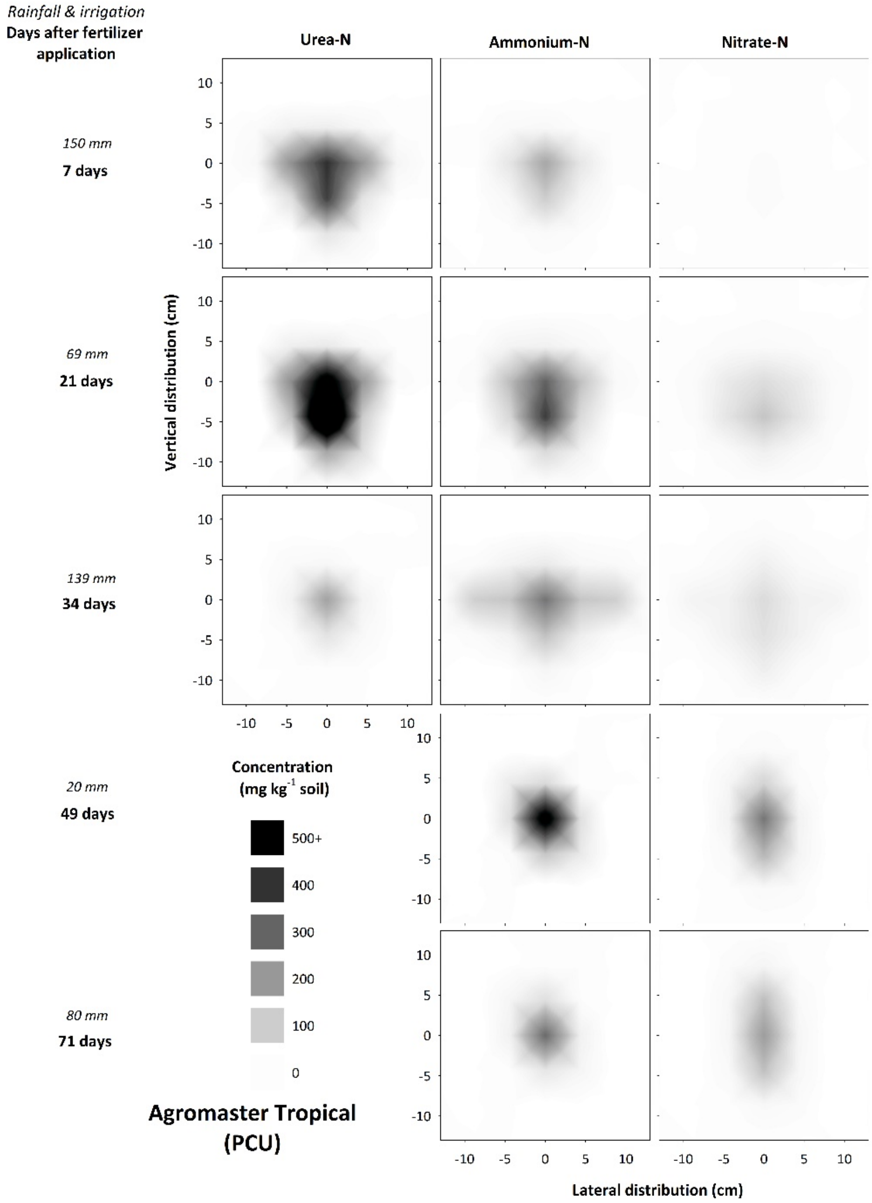

Figure 8. Concentration and distribution of urea-N, ammonium-N and nitrate-N over time in the profile of a Vertosol (field experiment) treated with Agromaster Tropical.

Conclusions

Banding (compared with broadcast/ incorporated application) can have unexpected effects on the efficacy of EEFs. Effective utilization of EEFs in banded application relies on understanding the mechanisms of the differing EEF technologies and the effects and interactions of key factors, such as soil type, soil moisture and/or rainfall. The activity of NIs is likely to be enhanced with banded applications in soil types with low permeability and high CEC, as the inhibitor and substrate (NH_4-N) are better co-located in the soil profile compared to soils in which rates of diffusion and mass flow are much greater. However, the enhanced NI activity may further limit the movement of fertiliser N (NH_4^+ is retained on the soil's high CEC) into deep soil layers with rainfall or irrigation events, and actually increase the risk of fertiliser N being 'marooned' in dry topsoil layers under rain fed conditions. NI-urea application rates, which were reduced by 50 kg N ha^{-1} compared to standard urea, demonstrated similar mineral N concentrations in soil solution, suggesting that there is potential for rates reductions with this EEF without adversely affecting N supply. However, this only occurs after approximately 30 days following fertiliser application, limiting this practice to crops with delayed N requirements.

Polymer coated urea is likely to exhibit slower rates of N release when applied in a band (compared with dispersed application) as 'neighbouring-granules' within the band restrict diffusion out of the granule. The most effective release of N from these granules occurs in moist-wet soil conditions. However, rapid nitrification of released N indicates that once this N is released the risk of leaching and/or denitrification losses is similar to that of urea, and the longer release period may actually represent a similar or greater loss risk profile over a fallow or a full growing season.

The UI product was the exception in that banding did not appear to substantially influence the effectiveness of the EEF technology compared with broadcast/incorporated application. However, the UI was only effective for a maximum of 21 days following fertiliser application, limiting the benefit of this EEF to scenarios where significant denitrification losses might be expected within 2 – 3 weeks of fertiliser application. The UI does not appear to be an effective option for mitigating leaching losses of N.

Acknowledgements

This research was supported by the National Environmental Sciences Program (Tropical Water Quality Hub) project 2.1.8 'Improved Water Quality Outcomes from On-Farm Nitrogen Management'. Scholarship support from the Australian Government Research Training Program (RTP), Howard Memorial Trust, and Sugar Research Australia is gratefully acknowledged.

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Day 2 concurrent session – Climate and future challenges

Changes in northern farming system climate conditions - Goondiwindi

Steven Crimp and Mark Howden, Australian National University

Key words

climate projections, production impacts, adaptation options

Take home messages

- Greenhouse gas (GHG) emissions continue to accumulate in the earth's atmosphere and drive warmer global temperatures. Warming of globally averaged air temperatures of just over 1°C since records began in 1850 has produced national, regional and local changes in environmental conditions. These changes have shifted debate from "Is climate change real?" to "What should we do about it?"
- Adapting agricultural practises will be required to respond to changing environmental conditions and will require all components of the agricultural value chain to work together in order to maintain resilient and profitable food systems.

Historical changes in climate?

Preliminary results suggest that 2019 is likely to be either the second or third warmest year on record, with globally annual averaged air temperatures now 1°C warmer than the long-term average calculated for the period 1961 to 1990. 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 from 208ppm prior to the industrial revolution, to 413.65 ppm as of 4 January 2020 (NOAA, 2020).

In Australia, warming in average temperature (average temperature) has resulted in 2019 being the warmest year on record (1.52°C above the 1961 to 1990 average of 21.8°C) (BoM, 2020). Average daytime maximum temperatures in 2019 of 30.69°C were 2.09°C above the 1961 to 1990 average. In December 2019 more than 40% of the entire country recorded maximum temperatures greater than the 97th percentile i.e. top 3% of temperatures. Examining the shift in the distributions of monthly day and night-time temperature shows that very high monthly maximum temperatures that occurred around 3% 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 1960 to 2019 (length of the temperature record), warming has occurred in both minimum and maximum temperatures with mean temperatures now approximately 1.4°C warmer than in 1960. For the period 1960 to 1991 an annual average maximum temperature of 28°C occurred, on average, 10% of the time. More recently (1992 to 2019) this temperature now occurs on average 19% of the time. Similarly mean annual minimum temperatures have warmed with the frequency of a minimum temperature of 13°C increasing from 25% to 35% of the time (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. Daily minimum temperatures of -2°C now occur 38% of the year as opposed to only 20% of the time over the period 1960 to 1991. When examining the extreme daily maximum temperature values, considerable warming has occurred in Goondiwindi. Extreme maximum temperatures of 43°C occurred on average 18% of the year for the period 1960 to 1991 (Figure 2). During the more recent period (1992 to 2019), this temperature occurred, on average 38% of the year.

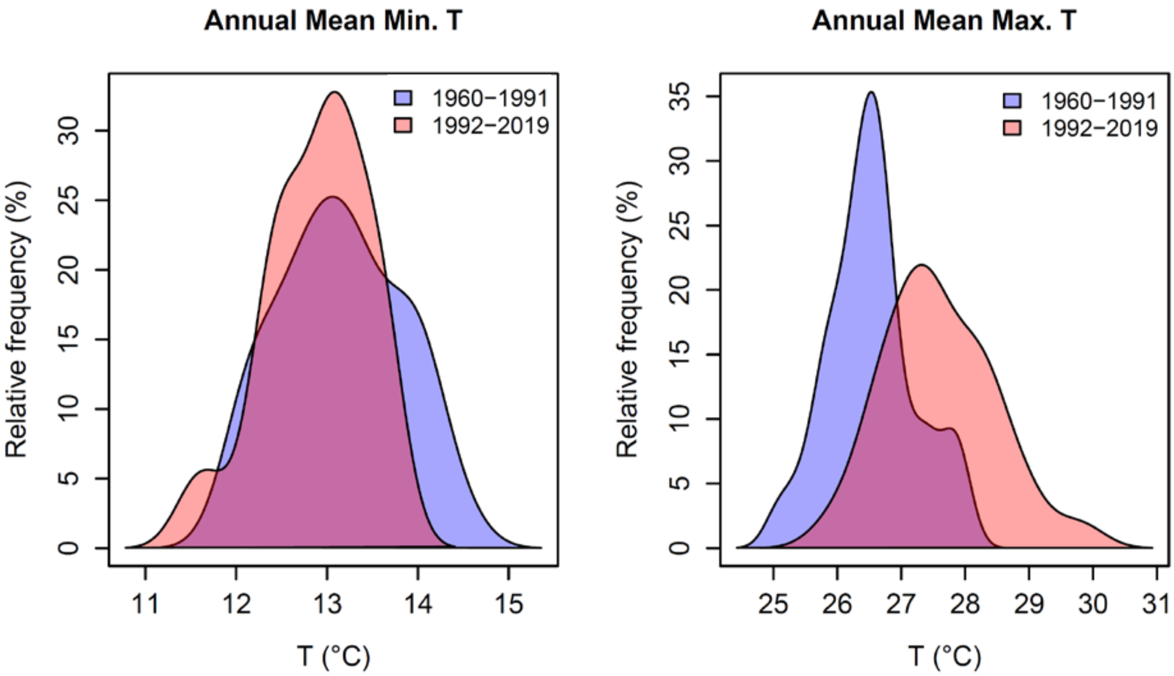

Figure 1. Probability distributions of annual mean maximum temperature (right) and annual mean minimum temperatures (left) for Goondiwindi for two periods, namely 1960 to 1991 and 1992 to 2019

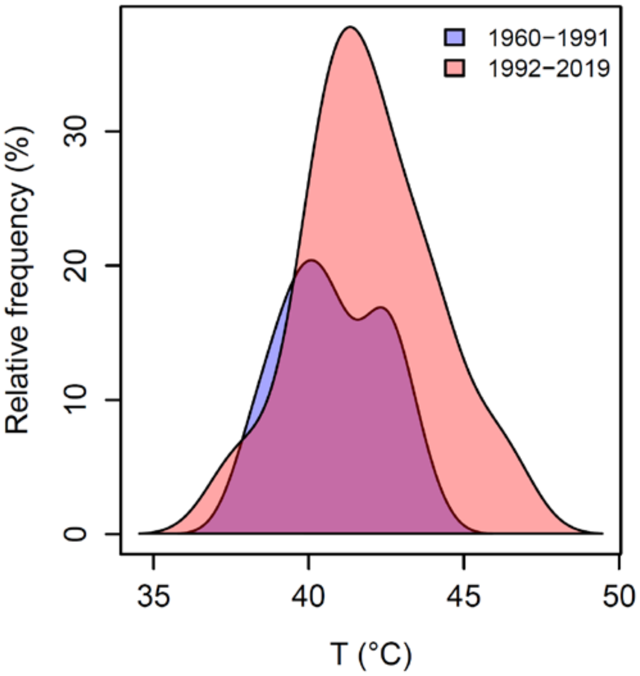

Figure 2. Probability distributions of daily maximum temperature extremes for Goondiwindi for two periods, namely 1960 to 1991 and 1992 to 2019

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 3). 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).

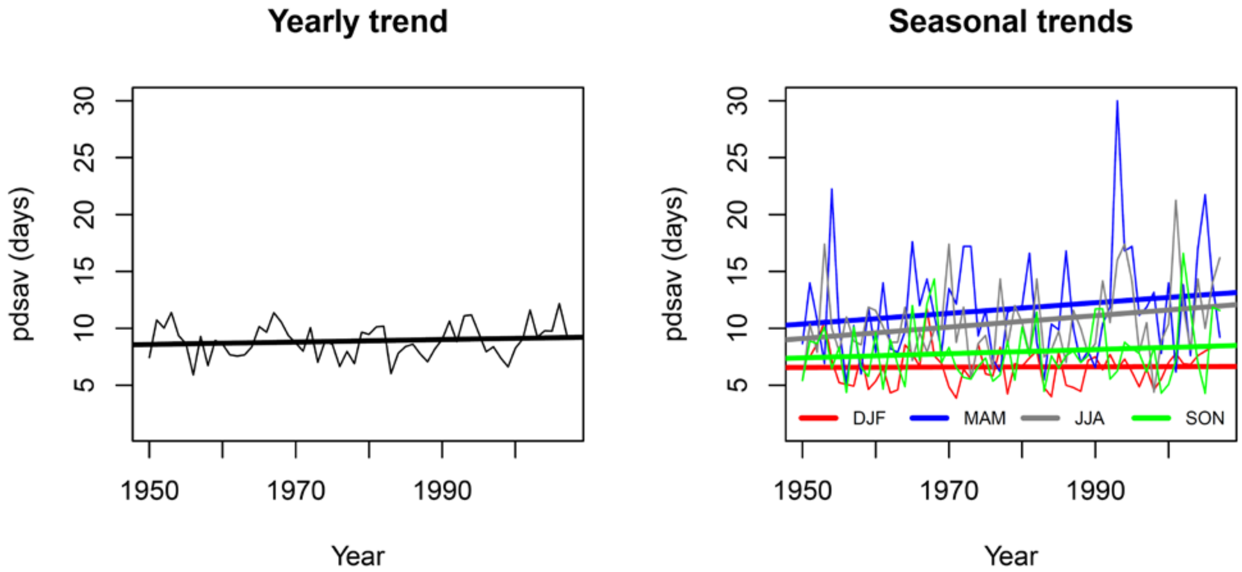

Figure 3. Mean annual dry spell length (left) and seasonal dry spell length for December to January (DJF), March to May (MAM), June to August (JJA) and September to November (SON). Dry spell lengths are expressed in days

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. Recent BoM analyses has shown that from 1960-2018 the ratio of hot records to cold records set across Australia was 6:1 whereas from 1910-2018 the ratio was 9:1 (Blair Trewin pers Comm. 2020). In 2019 the ratio of hot to cold records broken at the state area average level was 34:0 (Blair Trewin pers Comm. 2020). 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.

During the 2018/19 Australian summer more than 206 individual location extreme temperature records were broken in just 90 days (Climate Council, 2019). 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, 2018) 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 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 additional warming of 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 in the south-western parts of Australia by 2090, respectively (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	20.0°C	1.1 (0.5 to 1.6)	1.9 (1.1 to 2.6)	2.9 (2.0 to 3.8)
	Summer	26.4°C	1.1 (0.4 to 1.8)	2.0 (1.0 to 2.9)	3.0 (2.0 to 4.3)
	Autumn	20.4°C	1.0 (0.1 to 1.6)	1.8 (0.9 to 2.6)	2.9 (1.8 to 3.6)
	Winter	12.7°C	1.0 (0.1 to 1.7)	1.9 (1.2 to 2.5)	3.0 (2.1 to 3.8)
	Spring	20.6°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	636mm	-5 (-20 to +7)	-6 (-23 to +14)	-9 (-23 to +13)
	Summer	248mm	0 (-15 to +21)	0 (-23 to +27)	-2 (-21 to +29)
	Autumn	144mm	-3 (-28 to +27)	-4 (-33 to +36)	-8 (-42 to +41)
	Winter	106mm	-1 (-25 to +13)	-14 (-39 to +13)	0 (-49 to +14)
	Spring	139mm	-6 (-22 to +20)	-8 (-34 to +12)	0 (-42 to +21)

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 taking into account 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

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 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 (Howden and Crimp, 2011) via the introduction of improved water-use efficiency options and may mitigate potential yield losses by up to 18% through broader scale adaptation (Ghahramani et al. 2015).

The results suggest a number of adaptation options exist to manage increased future downside risk however the effectiveness of adaptation is driven by the extent of future change. Under conditions of large climate change, tactical adaptation will only have limited effectiveness 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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Acknowledgements

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

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Temperature impacts on growth & our use of day degree data - how different varietal types behave in & adapt to differing thermal environments

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Notes

Maintaining wheat yield under high temperatures - how do current cultivars compare with what's coming?

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Keywords

wheat, heat tolerance, genomic selection, phenotyping, pre-breeding

GRDC code

US00081

Take home message

- Recent Australian wheat cultivars are heat tolerant. However, new materials developed from diverse genetic backgrounds using field-based phenotyping and genomic selection suggest that levels of heat tolerance can be substantially improved.

Introduction

Periods of extreme high-temperature, particularly short periods of heat shock are a major threat to wheat yield and grain quality throughout much of the Australian wheat belt. Current projections of Australian climate change indicate that heat waves and temperature variability will become more frequent and more intense in the coming decades (CSIRO 2011, Climate Change in Australia. http://climatechangeinaustralia.com.au). It is vital that new wheat germplasm with improved high-temperature tolerance and molecular tags linked to this tolerance are developed and introduced into commercial breeding programs.

Genomic selection is a breeding method that requires a reference population of wheat lines that are phenotyped for the trait of interest and genotyped using many DNA markers distributed across the whole genome. Statistical methods are then used to estimate the effect of each DNA marker on the phenotype; the collection of all these DNA marker effects provides a prediction of genomic breeding value. This information can then be used to predict the phenotype of new plants that have known genotypes but not phenotypes. This allows early selection of plants/lines without phenotyping which decreases the breeding cycle leading to increased genetic gain.

Methods

A highly diverse set of agronomically adapted materials were assembled for phenotyping. These included thousands of new lines developed by the University of Sydney, including crosses with synthetic wheat, emmer wheat collected in warm areas, landraces, adapted germplasm with putative tolerance identified in hot wheat growing areas globally, Australian wheat cultivars and other sources of heat tolerance developed by others.

These materials were phenotyped for various traits; including yield, using a three-tiered strategy. Firstly, thousands of lines were evaluated in the field in replicated yield plots at Narrabri in northwestern NSW at different times of sowing. Later, sown materials were exposed to greater heat stress. Subsets of materials, based on performance in the previous year and estimated genetic values, were sown at sites in Western Australia (WA) and Victoria (Vic) to assess the transferability of traits. Each year, high performing lines were retained from the previous year, intolerant materials removed, and new materials added. Materials identified as heat tolerant in the times of sowing experiments were subsequently evaluated in the field during reproductive development using heat chambers to induce heat shock to confirm heat tolerance. Finally, those lines that maintained heat tolerance in the heat chambers were screened in temperature-controlled greenhouses to assess pollen viability under heat stress. Materials surviving all three stages of testing were considered highly heat tolerant.

All materials (>2000 lines) phenotyped in times of sowing experiments were genotyped using a 90K Single Nucleotide Polymorphism (SNP) platform and these formed the reference population for genomic selection from which all DNA marker effects were estimated. A prediction equation was developed and used to calculate genomic estimated breeding values (GEBVs) on selection candidates which were genotyped but not phenotyped. A genomic selection model that incorporated environmental covariates (for example; temperature, radiation and rainfall) directly was developed. This allowed the prediction of line performance under high temperature conditions. Environmental covariates were defined for each plot and growth development phase (vegetative, flowering and grain fill). An in-field validation of GEBV selected lines was then conducted by correlating GEBVs with field trial phenotypes. Various cycles of crosses were made among diverse lines with high GEBVs and progeny subsequently selected for high GEBV. These form the basis of our new elite heat tolerant materials.

Results

Extensive field-based phenotyping over a six-year period identified lines with superior adaptation to terminal heat stress (Figure 1). The tolerance of these materials was then confirmed in field-based heat chambers. The heat chambers were calibrated over a three-year period in replicated, triplicate plots (Table 1). Heat shock at anthesis significantly reduced yield compared to an ambient chamber and the uncovered plot. The ambient and uncovered plot were not significantly different from each other, and therefore, all future screening was conducted as paired plots (with and without heat chambers). The developed genotype-by-environment interaction genomic selection model increased genomic prediction accuracy for yield by up to 19%.

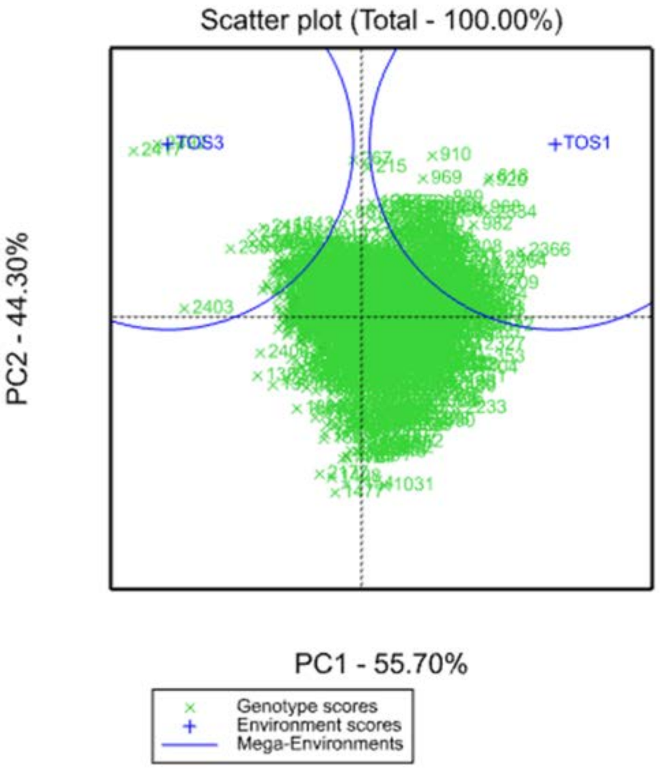


Figure 1. Genotype-by-environment interaction (GGE) biplot of yield in optimal (TOS1) and late (TOS3) sowing at Narrabri, 2013 to 2018

Table 1. The impact of heat chambers on yield, kernel weight, kernel number and other traits, 2013 to 2015

	Treatment			
	Ambient	Heated	No Chamber	Prob.
Yield (kg/ha)	2775 a	2248 b	2849 a	<0.001
TKW (g)	32.5	32.4	32	ns
Height (cm)	82.1	85.5	82.8	ns
Screenings%	4.09	4.89	5.13	ns
Grain number/10 spikes	49.3 a	43.8 b	48.74 a	<0.002

n.b. Means in the same row followed by different letters are significantly different.

The most heat tolerant Australian cultivars evaluated between 2013 to 2018 were the older varieties; Sunco, Annuello, Scoutⓓ, Sunstate and Langⓓ. These cultivars showed little difference in yield between times of sowing over years (Figure 2) but tended to have relatively low yield potential. However, the higher yielding, more recent varieties; EGA Gregoryⓓ, Suntopⓓ and Spitfireⓓ tended to have reduced heat tolerance. Several recently derived pre-breeding lines (PBI09C034-BC-DH38, PBI09C028-BC-DH56, PBI09C026-BC-DH5) have combined both high yield and heat tolerance.

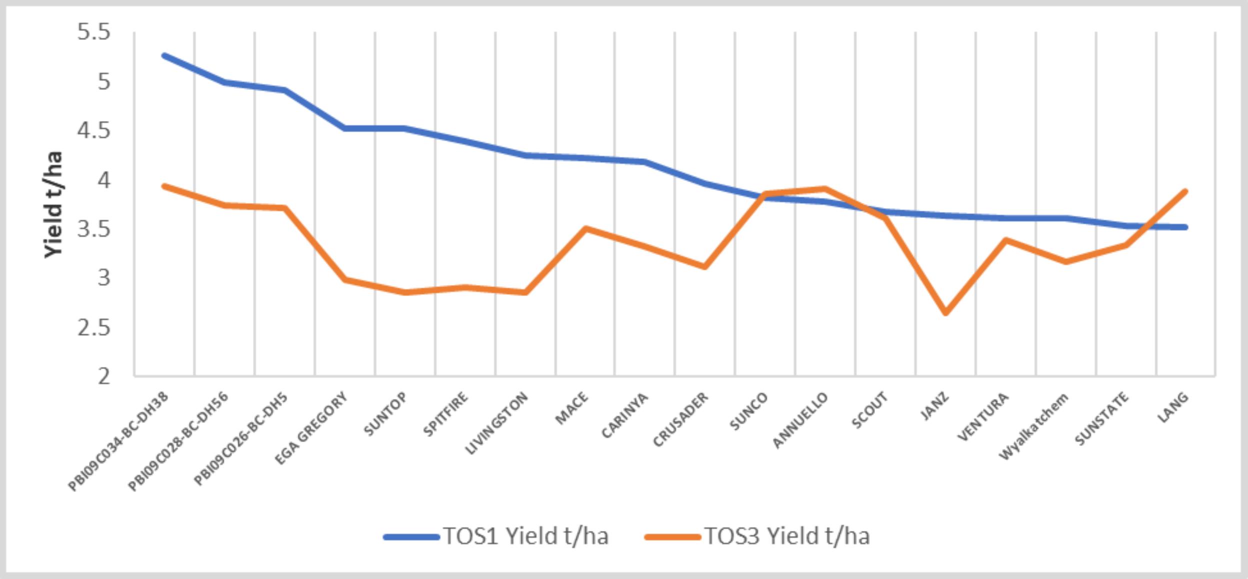


Figure 2. Yield at Narrabri (2013 to 2018) for heat tolerant lines and Australian cultivars for two different times of sowing (TOS1 and TOS2 are optimal and late sowing, respectively)

A wider range of Australia cultivars, including many recent releases, was included in 2019 (Figure 3). Mustang⦶, Scepter⦶, Mace⦶, Sunmate⦶ and Borlaug⦶ all showed relatively high levels of heat tolerance. Mustang⦶ and Scepter⦶ combined this with high yield. The pre-breeding lines PBIC15020-0C-60N-010N and PBIC15022-0C-6N-010N, developed using genomic selection, also combined high yield with heat tolerance. Unlike Mustang⦶, these materials flowered later and did not escape the high temperatures during grain fill.

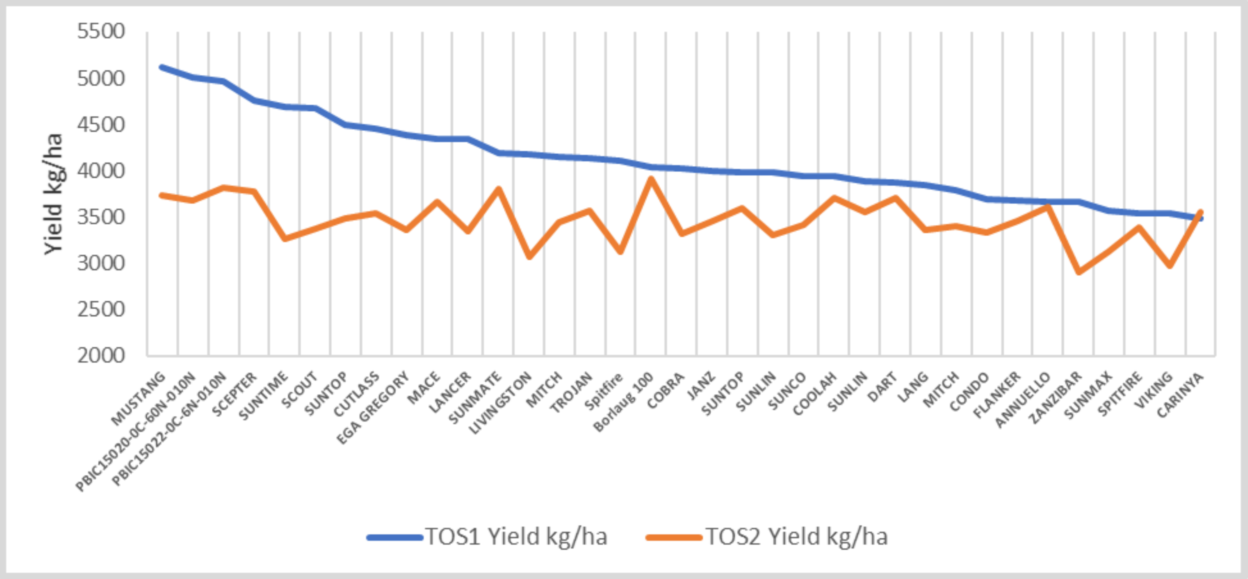
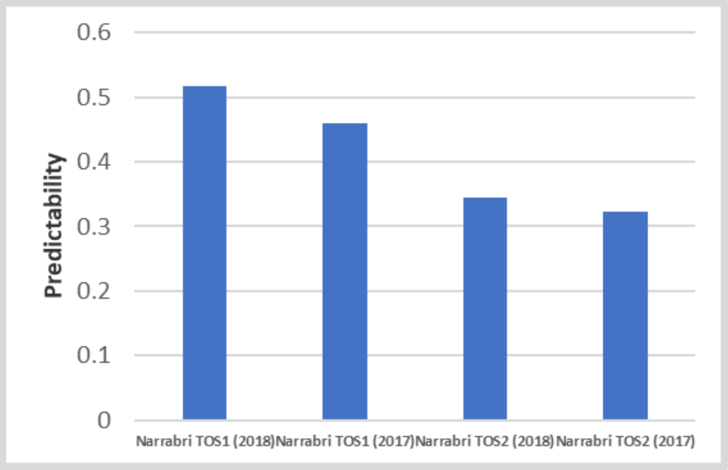


Figure 3. Yield of Australian cultivars and new heat tolerant lines at Narrabri, 2019 for two different times of sowing (TOS1 and TOS2 are optimal and late sowing, respectively)

An important aspect of this work was the transferability of the Narrabri results to other regions of Australia. Subsets of 200 lines, selected for high GEBV, were evaluated at Merredin and Horsham to validate the strategy. A training population was necessary to allow genomic prediction models to calculate GEBVs without the need for phenotyping at other sites. The accuracy of genomic prediction for yield, trained at Narrabri, was evaluated in 2017 and again in 2018 (Figure 4). When the 2018 data were included in the estimations of GEBVs, the predictability exceeded 0.5 for both early and late times of sowing.

A. Merredin



B. Horsham

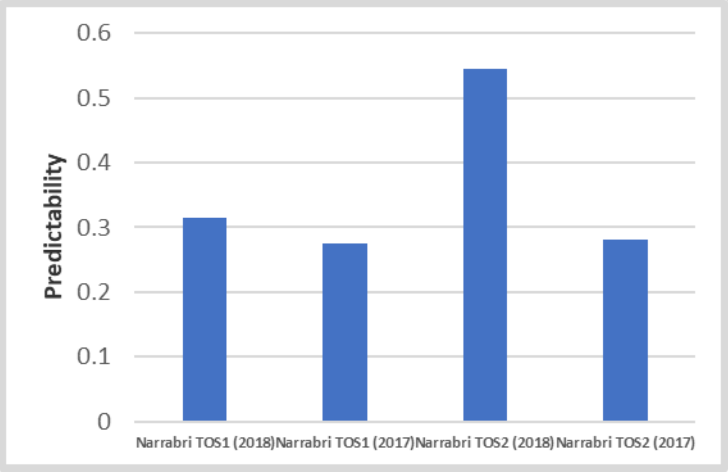


Figure 4. Accuracy of genomic prediction for yield trained at Narrabri (GEBVs calculated from five and six years of data) and validated at Merredin and Horsham in 2017 and 2018. TOS1 and TOS2 are optimal and late sowing, respectively

Conclusion

Some recently released Australian cultivars have both the genetics of high yield and the genetics for heat tolerance. However, new pre-breeding materials developed using genomic selection offer commercial wheat breeders' new sources of diversity for both yield and heat tolerance that can be used to mitigate the effects of a warming environment. The strategy of selecting for heat tolerance at Narrabri for other regions of Australia was validated by the relatively high correlations between GEBVs and yield under heat stress at Merredin and Horsham.

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 authors would like to thank them for their continued support.

The authors would also like to acknowledge the funding support of Agriculture Victoria, and the in-kind contributions of Intergrain and AGT.

References

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

Herbicide approvals: They can be relied on!

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Key words

pesticide regulation, APVMA, safety

Take home messages

- The Australian Pesticides and Veterinary Medicines Authority (APVMA) undertakes a comprehensive risk assessment of all pesticide products prior to registration, addressing risks associated with the product when used according to label directions
- The APVMA also keeps abreast of the developing science and world developments in both science and regulation to ensure that all pesticides are safe.

All pesticides are assessed by the APVMA prior to approval of actives and registration of products. This assessment is risk based, considering both the intrinsic hazard of the pesticide as well as the likely exposure resulting from their use, and is based on internationally accepted guidance. Australian evaluations are consistent with those carried out by other major regulators, as well as international organisations such as the Organisation for Economic Cooperation and Development (OECD), the World Health Organisation (WHO) and the Food and Agriculture Organisation (FAO).

While the APVMA can build on assessments carried out by other regulators and trading partners, such as the EU and the USA, many pesticides are approved in Australia prior to approval elsewhere in the world, and in these cases, other regulators may be utilising the Australian assessment as part of their own considerations. The rigor of the Australian assessment provides confidence that products registered in Australia are fit for purpose and are safe when used according to the label instructions. They are safe for the people who apply them, and for the environment in which they are used. Food crops treated with registered products are safe to eat, and for international sale, provided the label instructions are followed. APVMA also assesses that pesticides will meet label claims and will do the job needed.

The APVMA plays a key role in the National Registration Scheme, and, together with the states and territories, who have responsibility for the control of use of pesticides as well as ensuring compliance with label instructions, ensures that approved herbicides, insecticides and other pesticides can be relied on by users.

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New technologies for the Australian grains industry - observations from a 4 month Fulbright Fellowship study tour of the USA and Germany

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Notes

Desperate or innovative? Key decisions for recovery in 2020 - managing costs, crop sequences, nutrition, weeds & disease

Discussion session

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