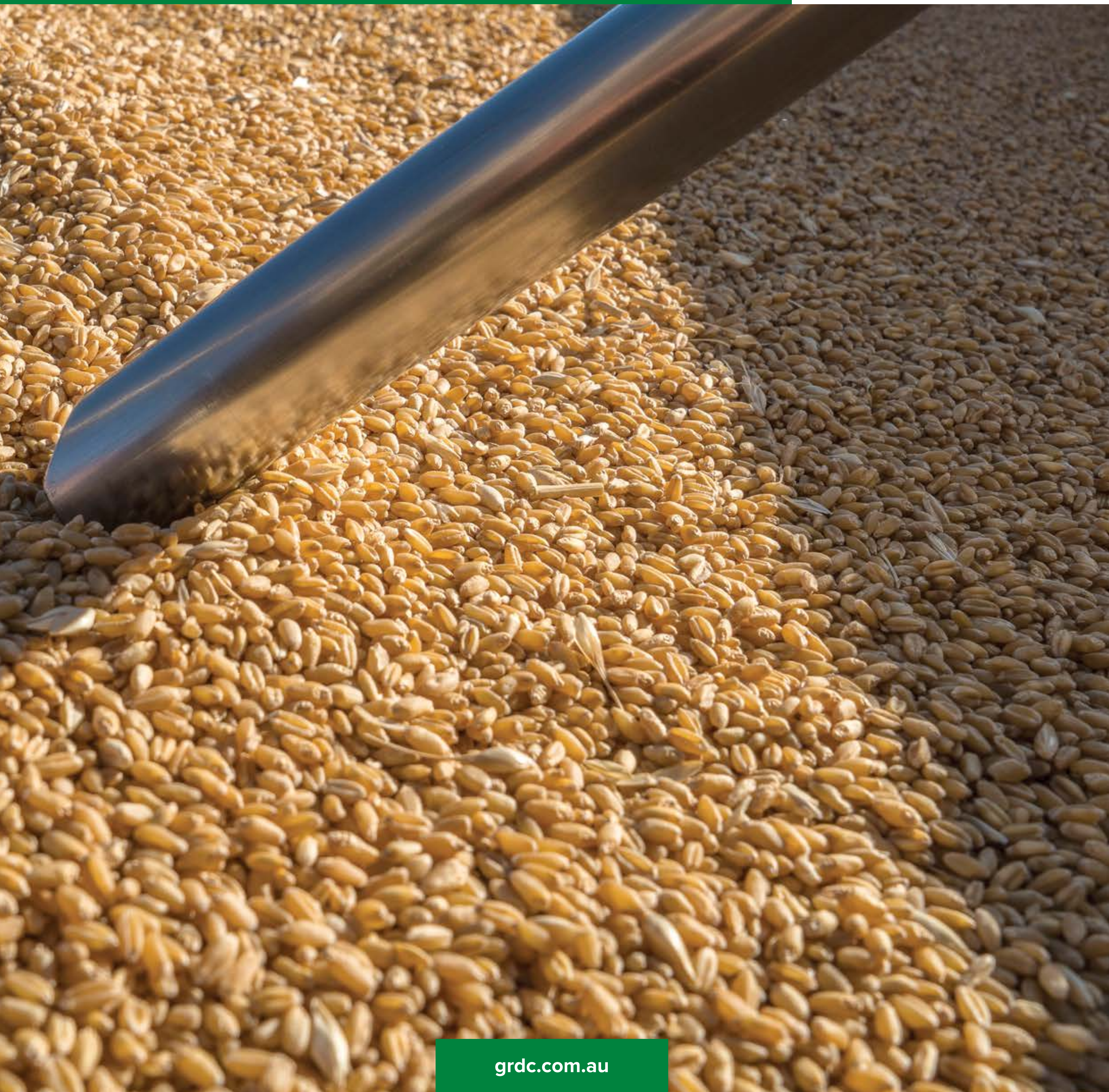
Week 3
NSW/Qld
Tue 1 March 22
Wed 2 March 22
Tues 8 March 22

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION



Agendas for Northern GRDC Grains Research Updates, online
Week 3 – 1, 2 and 8 March 2022

Tuesday 1 March 2022 - Farming system carbon footprints and sequestration options. Also; Satellite imagery for remote crop sensing – Note times are QLD times

Time (AEST, Qld)	Topic	Speaker
8:30 AM	GRDC	John Minogue and Peter Carberry (GRDC)
9:00 AM	How large is the greenhouse gas footprint of grains farming systems and options to reduce this.	Lindsay Bell (CSIRO)
9:40 AM	Carbon sequestration options for grain producers in NSW & Qld - pros, cons and pitfalls.	Peter Grace (Queensland University of Technology)
10:15 AM	Using satellite imagery, smart phones and drones to classify crops and interpret and predict seasonal growth patterns for on farm decision making and supporting variety selection	Scott Chapman (UQ)
10:45 AM	Morning tea	

Tuesday 1 March 2022 - Farming Systems - NNSW & Qld – Note times are QLD times

Time (AEST, Qld)	Topic	Speaker
11:15 AM	Farming system nutrient legacies – impacts on N inputs, cycling and recovery of applied fertilisers(6 years of experiments)	Lindsay Bell (CSIRO)
11:45 AM	Comparing grain and cotton east of the Newell Highway. Impacts on the cropping systems and the advantages of growing summer crops to improve $/mm and as a disease break from winter cereal dominated systems	Jon Baird (NSW DPI) & Geoff Manchee (Grower, Moree)
12:25 PM	How resilient is your farming system strategy for the long haul? Long term simulations of risk and sustainability of various farming systems experiments using APSIM.	Jeremy Whish (CSIRO)
12:45 PM	Discussion	
1:00 PM	Lunch	

GRDC GRAINS RESEARCH UPDATE

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Tuesday 1 March 2022 - Nutrition - NNSW & Qld – Note times are QLD times

Time (AEST, Qld)	Topic	Speaker
2:00 PM	Deep P and K - a call to action! Critical soil indicators, costs, benefits and timing of deep P & K (outcomes from 8 years of research)	David Lester & Doug Sands (DAF Qld)
2:40 PM	P dynamics in vertosols - what factors influence how long deep P lasts and the impact of application method and subsequent tillage on plant response	Nelly Raymond (UQ)
3:00 PM	Root research: What do wheat and sorghum roots do when water is in one part of the profile and P is in another? Root angle and why does it matter?	Frederik van der Bom (UQ)
3:15 PM	Nitrogen release dynamics of Enhanced Efficiency Fertilisers (EEFs): placement, soil factors, plant uptake	Cristina Martinez (UQ) & Chelsea Janke (UQ)
3:45 PM	Close	

Wednesday 2 March 2022 - Ameliorating sodicity - Central & Northern NSW & Qld – Note times are QLD times

Time (AEST, Qld)	Topic	Speaker
8:30 AM	Ameliorating sodicity; what did we learn about ameliorating sodicity constraints with a range of treatments? ESP vs aggregate stability as an indicator of likely response to gypsum	Chris Guppy (UNE) & David Lester (DAF Qld)
9:05 AM	Satellite Sites – Ameliorating spatially variable soil constraints. What did growers try, what was done and how has it worked so far	Stirling Roberton (USQ)
9:30 AM	The economics of ameliorating sodicity with gypsum and lime	David McKenzie (Soil Management Designs)
9:55 AM	Ameliorating sodicity discussion - a consultants perspective	Andrew Ceeney (Pinnacle Agriculture), Graeme Callaghan (Delta Agribusiness), David McKenzie (Soil Management Designs).
10:20 AM	Morning tea	

Wednesday 2 March 2022 - Disease - NNSW & Qld – Note times are QLD times

Time (AEST, Qld)	Topic	Speaker
10:50 AM	Stripe rust outbreaks in 2021 - what did we learn that's helpful to planning for 2022?	Robert Park (University of Sydney)
11:20 AM	Cereal disease issues for 2022. - What did we learn in 2021 and how can we use this to improve management this season? - A new seed treatment for crown-rot - Stripe rust pathotype changes - Netform net blotch management in barley - Fungicide timing - Fungicide resistance	Steven Simpfendorfer (NSW DPI) & Lisle Snyman (DAF Qld)
11:55 AM	Is there a disease downside to stripper fronts? Harvest height implications for crown rot and other stubble borne diseases.	Toni Petronaitis (NSW DPI)
12:15 PM	Nitrogen impacts on crown-rot and implications for management	Mitch Buster (NSW DPI)
12:35 PM	Lunch	

Wednesday 2 March 2022 - Early sown sorghum and SpaceAg – Note times are QLD times

Time (AEST, Qld)	Topic	Speaker
1:35 PM	Early sown sorghum and WUE efficiency	Loretta Serafin (NSW DPI) & Daniel Rodriguez (UQ)
2:20 PM	SpaceAg - Sensors for NASA so astronauts can keep an eye on crops grown in space – developing sensor systems to provide early warnings if something needs attention	Jacob Humpal (USQ)
2:55 PM	Close	

GRDC GRAINS RESEARCH UPDATE

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Tuesday 8 March 2022 - Nutritional decision making for 2022 - NNSW & Qld
Note times AEDT (NSW time)

Time (AEDT)	Topic	Speaker
9:00 AM	Farming system nutrient legacies – impacts on N inputs, cycling and recovery of applied fertilisers (6 years of experiments) - What can we expect after cereals, fabas and chickpeas in 2021?	Lindsay Bell (CSIRO) & Jon Baird (NSW DPI),
9:30 AM	Nitrogen movement, use efficiency and timing of fertiliser application; how much fertiliser are 2022 crops likely to see and utilise?	Richard Daniel (NGA)
9:55 AM	Optimising rate and timing of N not already applied across crop types	James Hagan (DAF Qld)
10:20 AM	Deep P and K - a call to action! Critical soil indicators, costs and benefits of deep P & K and timing	Mike Bell (UQ) & Michael Ledingham (Grower, Moree)
10:55 AM	Panel discussion on N issues and strategies for 2022 after big offtakes in 2021 and high fertiliser prices: How much soil N is there and what are soil tests telling us? Is there inconsistency between N legacy expectation and reality? Issues with crop access to N applied to vertosols late in northern dryland fallows. Discussion of situations and scenarios that growers and agronomists are facing in March 2022	Chair: Chris Dowling (BackPaddock Co)
11:25 AM	Close	

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

Australian grains baseline and mitigation assessment

Maartje Sevenster[1], Lindsay Bell[2], Brook Anderson[2], Hiz Jamali[3], Heidi Horan[4], Aaron Simmons[5], Annette Cowie[6], Zvi Hochman[4]

[1] CSIRO Agriculture and Food, Clunies Ross St, Black Mountain ACT 2601
[2] CSIRO Agriculture and Food, 203 Tor St, Toowoomba City QLD 4350
[3] CSIRO Agriculture and Food, 0 Murray Dwyer Cct, Mayfield West NSW 2304
[4] CSIRO Agriculture and Food, 306 Carmody Rd, St Lucia QLD 4067
[5] New South Wales Department of Primary Industries, Muldoon St, Taree NSW 2430
[6] New South Wales Department of Primary Industries, Armidale NSW 2350

Key words

emission intensity, crop rotation, nitrogen, emissions reductions

Take home messages

- Potential to increase production without significantly increasing overall on-farm emissions, improving emissions intensity by 20%, is possible by optimising N applications based on seasonal conditions and rotations
- Improved N management is a clear option to reduce GHG intensity but by increasing production by 30-40% would result in an industry wide emissions increase
- Monitoring and improving the greenhouse-gas (GHG) intensity of our grain production systems is critical to remain competitive in global markets and provide evidence of Australia's low-emissions credentials
- On-farm emissions (Scope 1) comprise 61% of total emissions, most of which comes from application of lime and fertiliser (26%), denitrification losses (20%) and fuel use (11%)
- Fertiliser is the largest contributor (38%) to GHG emissions both from the production and the use of fertiliser
- The GHG emissions intensity of Australian grains crops is relatively low, producing around 315 kg CO2 equivalent per tonne of grain with regional differences evident
- To achieve reduction in overall absolute emissions, with increasing production, significant reductions of emissions associated with the production of fertilisers and other inputs will be needed.

Introduction

Australian agriculture has defined ambitious climate change objectives, such as in the 2030 Roadmap of the National Farmers' Federation, which aim to contribute to Australia's emissions reductions. Emissions reductions also keep our commodities competitive in export markets that increasingly require evidence of low-GHG emissions credentials. GHG credentials are established using GHG accounting to estimate the GHG's emitted directly or indirectly by a farming enterprise, or emitted in a chain of processes resulting in a particular product. At sector level, establishing GHG baselines provides a reference to estimate GHG emissions reductions associated with climate change mitigation strategies.

Climate change mitigation strategies also need to be assessed for GHG emissions reduction potential to guide the Australian grains industry towards a low GHG emissions future. This is important because it will allow the grains industry to contribute to state/national emissions reduction targets and ensure access to key international markets is maintained.

What we did

GRDC commissioned this study to establish a detailed and robust GHG emissions baseline for the Australian grains sector and explore mitigation pathways that maintain or increase production. An estimate of the GHG emissions associated with grain production in 2005 was developed based on management practices and production statistics for that year (a static baseline) based on 25 leviable crops; wheat, barley, oats, maize, triticale, millets, cereal rye, canary seed, lupins, fieldpeas, chickpeas, faba beans, vetch, peanuts, mungbeans, navy beans, pigeon peas, soybeans, cowpeas, lentils, canola, sunflowers, safflower and linseed. The same approach was used to develop an estimate of current emissions for industry and used data for 2016 because that was the most recent year with the required data available. The study also developed a dynamic baseline that estimated the business-as-usual scenario over the period 1991-2019 using APSIM simulations of common rotations used in grain production systems on a regional basis. The emissions reduction potential of a number of strategies (Table 1) was assessed by either running APSIM models with modified management or by undertaking a static assessment using different emissions factors.

Table 1. Description of GHG mitigation strategies/combinations of strategies that offer the greatest reductions in emissions intensity and whether they were modelled using APSIM or used modified factors

Strategy/combination	Description	APSIM/modified
Best N	N was applied in split-applications, at sowing and GS6. N was only applied at GS6 if adequate moisture for a growth response was present. N rates were pre-determined and not adjusted for available soil moisture. This meant surplus N could remain in the soil after harvest.	APSIM
Max N	N was applied throughout the crop to maintain sufficient N in the soil to ensure that N was not limiting for growth.	APSIM
Rotations	The most optimal crop rotation in terms of the generated economic return per unit of GHG emissions was chosen from amongst 7-10 diverse rotations simulated at each location. This scenario is combined with either “Best N” or “Max N” application.	APSIM
GreenFert	Assumed production of fertiliser occurred using renewable energy and low GHG feedstocks	Modified
Controlled Traffic	Fuel efficiency and yields increased while N_2O emissions associated with fertiliser use declined.	Modified

The study included relevant Scope 1 (i.e. on-farm emissions), Scope 2 (i.e. off-farm emissions from electricity production) and Scope 3 (i.e. emissions associated with the production and transport of inputs other than electricity) emissions associated with crop production. The majority of grain farmers have no control over the end use of crops, so downstream (e.g. post-storage) Scope 3 emissions were excluded from the analysis.

Total emissions and emissions sources

The historic static baseline of the emissions associated with Australian crop production in 2005, so for one year of emissions, showed that GHG emission associated with crop production for that year was 13.75 Mt CO2-e. A breakdown of emissions sources (Figure 1) showed that fertilizer production and use contributed nearly 40% of the total emissions for that year. Emissions derived from N loss from crop residue decomposition were also a key source of emissions, as were emissions from the use of lime, on-farm operations and the production of farm chemicals. When aggregated, on-farm emissions (Scope 1) made the greatest contribution to total emissions (61%) and pre-farm emissions (Scope 2 &3) the remainder.

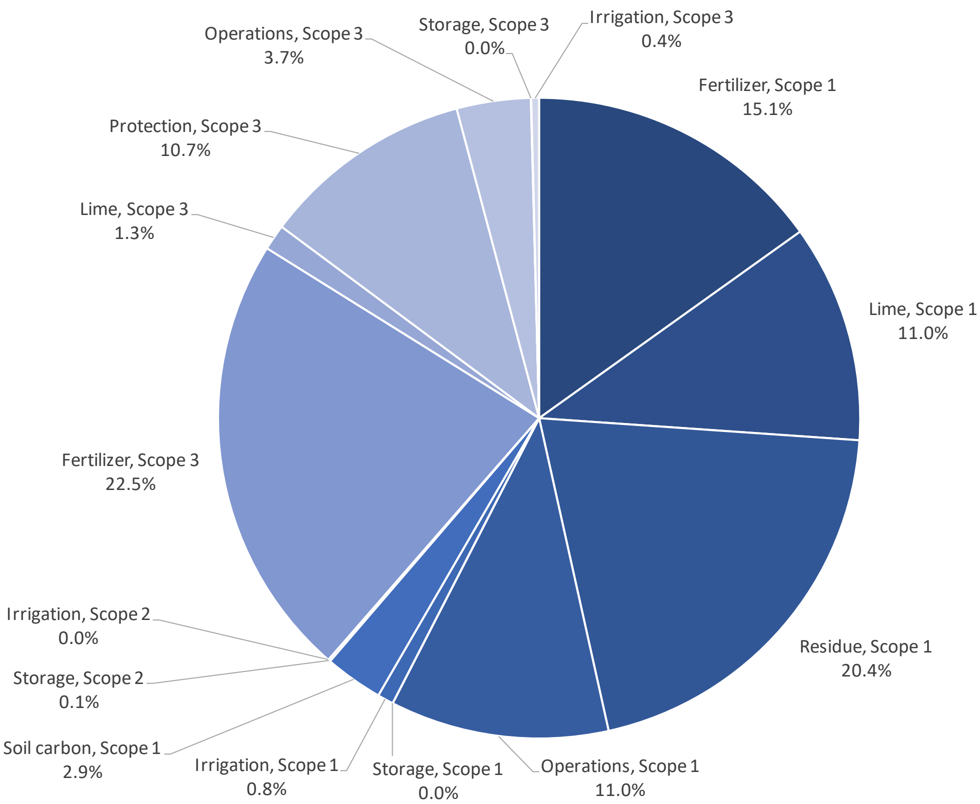

Figure 1. Contributions of emission source categories to the total GHG emissions baseline using 2005 data. Residue emissions are those from the burning and decomposition of crop residue.

Emissions intensity and regional differences

It is also important to assess the GHG emissions intensity of crop production (i.e. the GHG's emitted to produce 1 tonne of crop) because this is the metric on which many decisions are based. Our assessment for the 2005 static baseline showed that 315 kg CO2-e were emitted for each tonne of crop produced. The GHG emissions intensity of crop production is spatially variable as demonstrated by the difference between the GRDC regions (Figure 2) with the emissions intensity greatest for the Western region, lowest in the Southern region and intermediate in the Northern region. The higher emissions intensity for the Western region was primarily due to the use of lime and to lower yields relative to system inputs, which means that per unit of production the emissions were found to be higher.

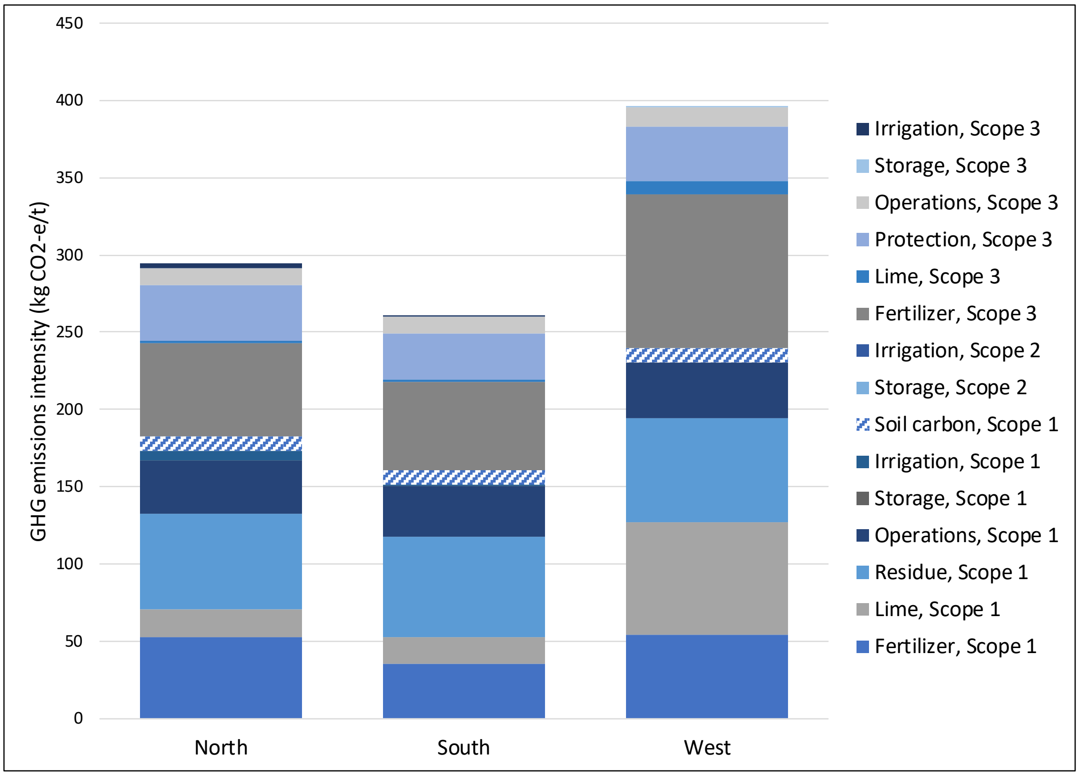

Figure 2. GHG emissions intensity and the contributing sources of emission in 2005 for each GRDC region.

Total emissions for the grain industry also varied significantly on an annual basis, ranging from 6 to 30 Mt CO2-equivalent in any one year (Figure 3). This variability was the result of changes in climate, causing variation in emissions (nitrogen losses) as well as production. The lowest emissions occur in the drought years of 2007 and 2019.

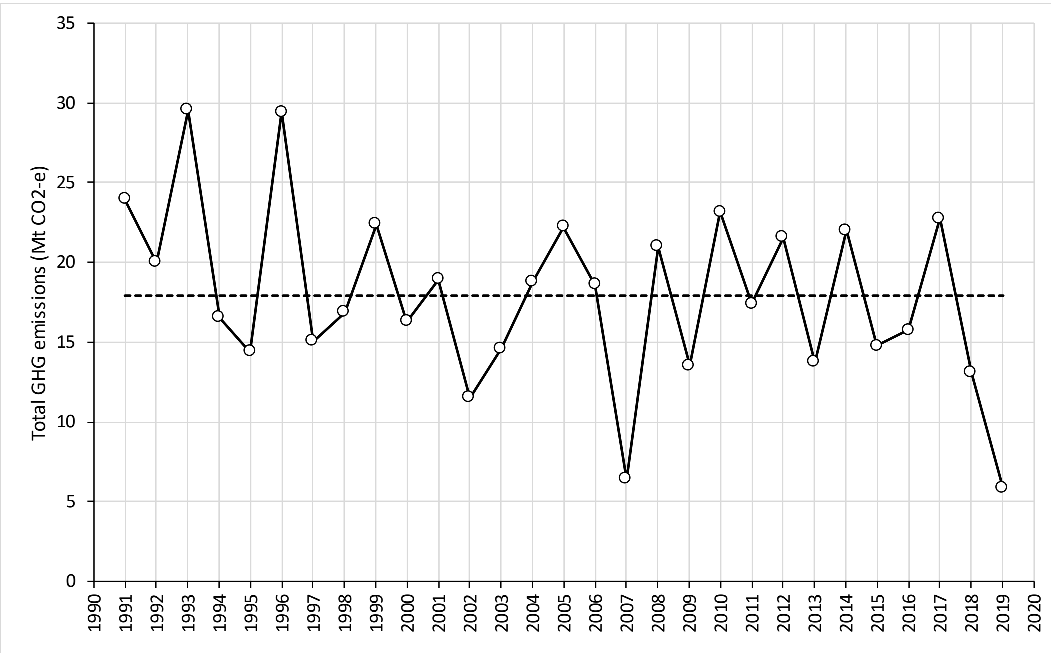

Figure 3. National year-by-year variability in simulated GHG emissions using APSIM (dotted line indicates the 29-year average).

How does Australia compare with other grain producing countries?

Results suggest that the GHG emissions intensity of Australian produced cereals, the majority of which is wheat production, is considerably lower than that estimated by a prominent international database of wheat and barley (Figure 4). With our estimates the emissions intensity of Australian cereal production would be relatively low compared to production in other countries. While the results in Figure 4 for other countries may also be contain inaccuracies, several of the relevant emissions factors deviate from the default values for the Australian environment.

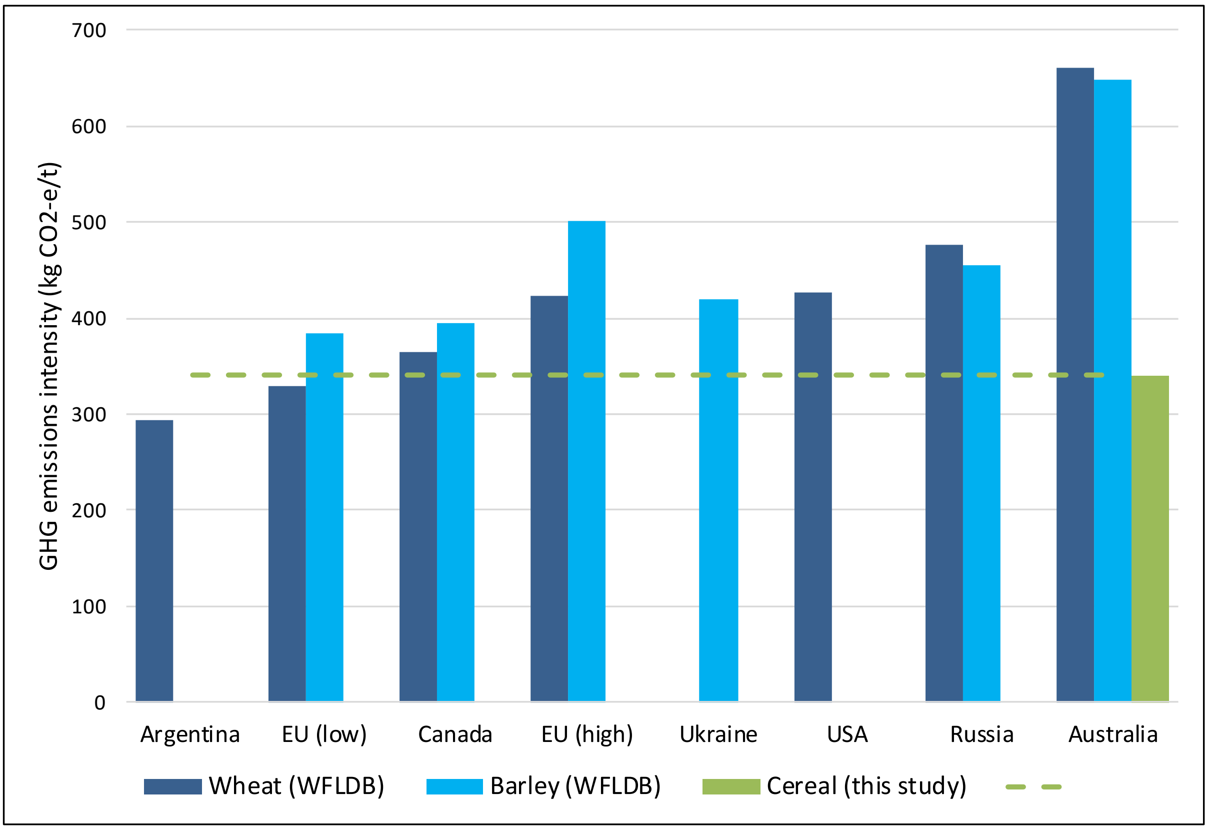

Figure 4. Comparison of GHG intensity results for wheat and barley, by country as available in the World Food Life Cycle Assessment Database (WFLDB), with the result from this baseline assessment for cereals. All data exclude emissions from soil carbon change and land use change.

Options for mitigation – how much can GHG emission intensity be improved?

Our analysis examined several prospective mitigation strategies/combinations on an emissions intensity basis as described in Table 1. The 'MaxN' scenario is not included in this discussion because the 'BestN' scenario is more likely to be achieved. The impact the other scenarios are predicted to have on the emissions intensity of national grain production are presented in Figure 5, along with the emissions for 2015 (Current), relative to the 2005 static baseline (Baseline). Our estimates suggest that the GHG intensity of current systems are 5% higher than those in 2005, due to significant increases in N fertiliser usage and a change in the crop sequences used across the country.

The greatest GHG emissions intensity reductions occurred when the most optimal rotation in each subregion was selected in combination with improved fertiliser N management being implemented. Just implementing improved N management did not reduce GHG emissions intensity to the same extent, but the difference was minimal, suggesting that modifying rotations made a small additional contribution to reducing emissions intensity. Replacing fertiliser produced using conventional manufacturing processes with fertiliser manufactured using low GHG inputs also reduced GHG emissions intensity as did implementing controlled traffic, however these reductions were not as large as those achieved from implementing best N practices.

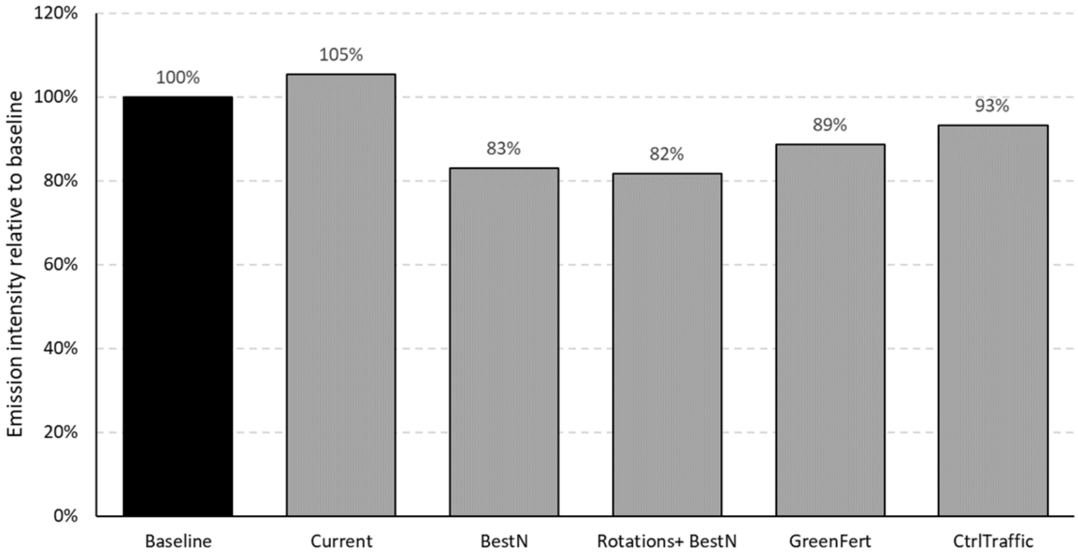

Figure 5. Relative total emission intensity in kg CO_2-equivalent per tonne grain nationally by mitigation scenario modelled compared to the static baseline (2005). The Current (2015) scenario reflects the effects that changes in rotation and nitrogen application rates since 2005 have had. Values for four left-hand columns are the mean over the time series (1991-2019).

Emissions intensity versus total emissions

Results suggest that significant reductions in the GHG emissions intensity of crop production may be possible. However, implementing the Best N and Rotation + Best N strategies that had the greatest reductions (Figure 5) would increase total emissions at a national scale (Figure 6). The increase in total emissions occurs because those strategies involve more use and therefore production of nitrogen. However, because they are also associated with an increase in production (Figure 6) the GHG intensity decreases as shown in Figure 5. The GreenFert and Controlled Traffic strategies had some effect on emissions but only very small to no effect on production so the reduction in total emissions is similar percentage to the reduction in GHG intensity.

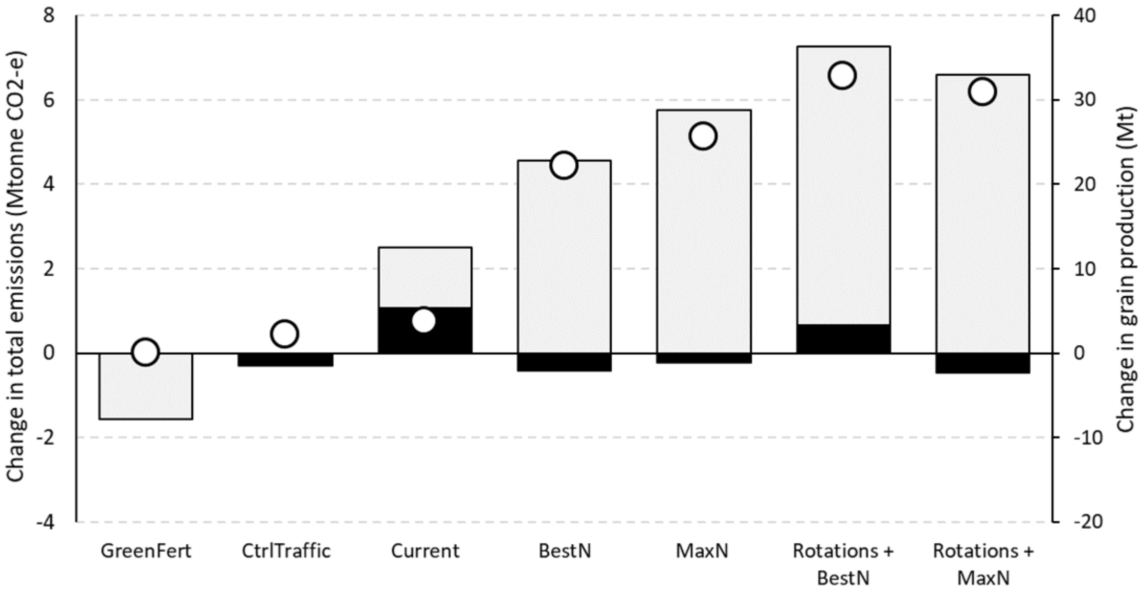

Figure 6. Estimated change in total national GHG emissions (on-farm in black, pre-farm in grey) and total grain production (in Mtonne) relative to the 2005 baseline for mitigation scenarios (see Table 1).

Conclusions

The baseline assessment successfully pulls together data from a wide range of sources with varying levels of spatial resolution into a very detailed GHG inventory for grains with a high level of completeness. This estimates Australia's total GHG emissions associated with grains production in 2005 to be 13.75 Mt CO_2-equivalent or 315 kg CO_2-equivalent/tonne grain. This is much lower than previously calculated for Australia.

On-farm emissions contribute about 60% of this, while about 40% come from emissions associated with agricultural inputs.

Fertilisers were a critical source of GHG emissions both from their production and use on farm. Hence, a clear opportunity is to improve fertiliser application practices that increase production and overall GHG intensity. Further, significant reduction of those emissions can be expected in the longer term via the production of green fertilisers and (other) decarbonisation of energy supply. Offsetting of emissions via reforestation seems the most likely option to reduce absolute emissions and this could be compensated for by increasing production on remaining land.

Absolute GHG mitigation potential in the Australian grains sector is limited due to an intrinsic trade-off between total emissions and production. Given widely supported goals to increase production, it is unrealistic to expect significantly reduced absolute total emissions, given the essential role that carbon and nitrogen play in plant growth, but Scope 1 emissions are shown to reduce in the high-nitrogen scenarios in some regions. Setting targets in terms of GHG intensity, combined with minimum conditions around Scope 1 emissions and production, is the most realistic and in line with recommendations made by the National Farmers' Federation.

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 in collaboration with CSIRO and New South Wales Department of Primary Industries, the authors would like to thank them for their continued support.

We would also like to thank industry organisations GrainGrowers, Grain Producers Australia and GRDC, and their representatives, for their engagement during the project, particularly to identify and discuss mitigation options, as well as many CSIRO experts who were involved in defining mitigation scenarios. We would also like to thank Peter Thorburn, Elizabeth Meier and Neil Huth for their input into the design and implementation of mitigation scenarios and for guidance and review of the GHG modelling. We are gratefully acknowledging contributions to mitigation scenarios by Martin Nolan, Dio Antille and Jeff Tullberg, and contributions throughout the project from Tim Grant, Jenet Austin and Javier Navarro Garcia.

Contact details

Maartje Sevenster
CSIRO Black Mountain
Email: maartje.sevenster@csiro.au

Building soil carbon for your business

Peter Grace[1], Richard Eckard[2] and Warwick Badgery

[1]School of Biology & Environmental Science, Queensland University of Technology
[2]Department of Agriculture and Food, The University of Melbourne
[3]Department of Primary Industries

Keywords

carbon sequestration, soil carbon, soil organic matter.

Take home messages

- Many growers are already employing soil sequestration practices as the norm, but only additional activities are valid for claiming a carbon offset
- Soil carbon sequestration in grains systems is low unless a pasture phase is included
- When estimating carbon credits all greenhouse gases must be included i.e. soil carbon sequestration is potentially negated by nitrous oxide and other emissions
- The long term benefits of increasing soil organic matter for soil health are more profitable and low risk compared to the soil carbon market.

Introduction

Soil organic matter is the backbone of any sustainable farming system. In recent times, there has been significant interest in the role that soils can play in helping Australia meet its greenhouse gas reduction targets. Under the federal government's Australian Emissions Reduction Fund (ERF) which financially rewards carbon offsets, there are two legislated methods which involve soil organic matter or more specifically increases in soil organic carbon. These procedures are very specific and require detailed certified measurements of soil organic carbon and bulk density over nominated time periods. A number of international voluntary soil carbon methods also exist, but their validity as offsets in Australia may be questionable.

To engage in these soil carbon offset markets, farmers must first be able to demonstrate they are undertaking management activities which are in addition to their normal practice. For example, a farmer who changes to zero till practices will be rewarded if they have registered the field (i.e. defined a Carbon Estimation Area) and can show a measurable change in soil organic carbon in the top 30 cm or deeper. A farmer who has employed zero till for many years is unlikely to be rewarded unless there is some additional modification to this practice.

Unfortunately, placing a price on soil carbon has skewed the discussion away from what really matters to farmers, which is soil health and productivity. Soil organic matter, of which only half (~58%) is soil organic carbon has multiple benefits, most notably, maintaining nutrient supply and soil structure. Soil organic carbon is usually only about 1 to 5% of the total soil mass, with the higher concentrations normally under long-term grasslands or crop rotations with significant pasture phases.

What is soil organic carbon?

There is some confusion about what constitutes soil organic carbon. Plant residues on the soil surface, roots and buried plant residues (>2 mm) are not accounted for as soil organic carbon. These first need to be broken down into smaller fractions and decomposed to be considered soil organic carbon, which is why the soils are first sieved to two millimetres before an analysis, to remove all larger fractions. Gravel content and inorganic carbon (or carbonates in alkaline soils) must also be taken into account when accurately quantifying soil organic carbon.

Fractions considered to be part of the soil organic carbon (as per a soil analysis) would be Particulate Organic Carbon (POC; 2.0 – 0.05 mm) or labile C, Humus (<0.05 mm) or stable C, with Resistant Organic Carbon (ROC) being historic charcoal from fires or burning of stubbles. In other words, we must not confuse roots with soil organic carbon.

For sustained productivity, increasing the relative amount of POC is beneficial as this is readily decomposable and a supply of nutrients. To have confidence to sell soil carbon, you want a significant amount of carbon in a more recalcitrant (slowly decomposing) form i.e. stable, so that you have confidence that it will still be there in 25 to 100 years. These permanence time frames are required to engage in carbon markets.

Building soil organic matter

The inherent benefits and the role of soil organic matter for productive and profitable agriculture are well documented (Table 1).

Table 1: Biological, physical and chemical co-benefits that high soil organic matter may confer to an agricultural production system.

Biological roles	Physical roles	Chemical roles
- Reservoir of nutrients	- Water retention	- Cation exchange
- Biochemical energy	- Structural stability	- pH buffering
- Increased resilience	- Thermal properties	- Complex cations
- Biodiversity	- Erosion	

(Source: Jeff Baldock)

Building soil organic carbon is basically an input-output equation; the inputs are crop and pasture residues and roots. The outputs are CO_2 from microbes which are actively decomposing and transforming the carbon fractions, using them as energy but in the process releasing nutrients back to the soil to support plant growth. As much as 90% of the carbon input is lost as CO_2. Soils with a higher clay content have a greater capacity to store carbon per unit of inputs. In a good rainfall year, the inputs increase in response to plant growth with a subsequent increase in outputs and an accumulation of carbon. Carbon inputs exceed outputs. In a drought, carbon inputs drop dramatically in response to reduced plant growth, but the outputs remain because the microbes respond to episodic wetting events and soil carbon decreases. Carbon outputs exceed inputs. Fallow years are good example of significant losses in soil carbon.

In Australia, rainfall determines the majority of soil carbon change in a stable management system (see Meyer *et al.,* 2015). Unless there is a significant change in management, e.g. moving out of conventional cultivation into permanent pasture in a high rainfall zone, the majority of the annual change in soil carbon is a function of rainfall, biomass production and its decomposition. Change in soil carbon in mixed cropping system can often be large and unpredictable, particularly from labile, relatively decomposable carbon (Badgery *et al.,* 2020).

Australia has over 20% more rainfall variability than most countries in the world (Love 2005). Banking on selling soil carbon and its permanence is therefore high risk given the frequency of drought. For example, Badgery *et al.,* (2020) reported that after 12 years of increases in soil carbon, this was reversed in the following 3 years in less than favourable climatic conditions.

In contrast, recent research has demonstrated that just two of the co-benefits of high soil organic matter (i.e. nitrogen mineralisation and water retention) confers as much as $150 per hectare per year productivity value in a pasture system in western Victoria, when the carbon trading value under the same scenario is less than $20 per tonne per hectare year (Meyer *et al.,* 2015). This raises the question, should farmers focus on trading soil carbon, or just bank the inherent productivity benefit of having higher soil organic matter, as there is no paperwork no contracts no liabilities, but all the productivity benefits can be banked? In addition, when the farm needs to demonstrate carbon neutral production in the next decade, this soil carbon will be essential to offset the balance of the farmers greenhouse gas emissions.

How much soil carbon can be accumulated?

The current level of organic carbon in soils across the northern grains zone is well below what can be achieved if we consider the impact of 100 years of conventional agriculture (Figure 1).

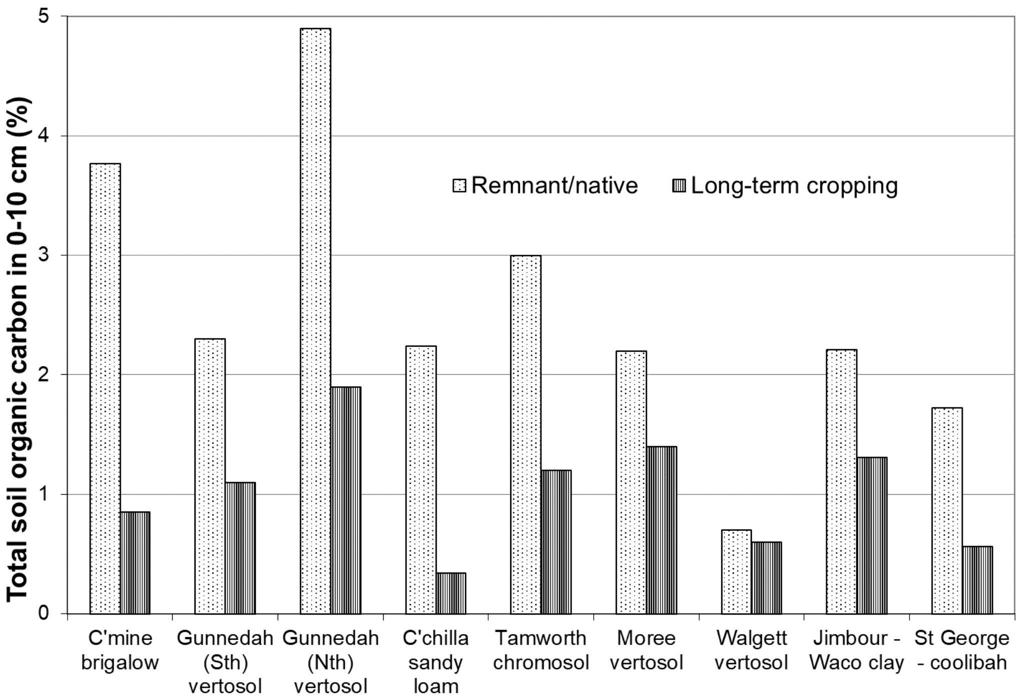

Figure 1. Impact of long-term cropping on soils of the northern grains zone (Lawrence *et al.,* 2017).

The SATWAGL long-term trial at Wagga (Chan *et al.,* 2011) has demonstrated the clear benefits of stubble retention, zero tillage and pasture phases for increasing soil carbon (Table 2). Over a 25-year period, stubble retention compared to burning was 2.2 t C/ha higher, zero tillage compared to conventional cultivation was 3.6 t C/ha higher, and a pasture rotation every second year was between 4.2 and 11.5 t C/ha higher than continuous cropping.

Many of these management practices, as well as reduced fallows, are now commonplace in grains systems of Australia. Soils have potentially reached a new (but low) steady state i.e. little change over time, provided the management does not change. A shift to a pasture-based farming system offers high potential for soil carbon gains (Figure 2) and its benefits, but a major consideration is obviously whether there is enough flexibility on-farm and profitability within the livestock sector to make this transition.

Table 2. Change in soil organic carbon (SOC, kg C/ha over 0–0.30m soil depth) and final stock (t C/ha) under different rotation, tillage, and stubble and pasture management in the SATWAGL long-term field experiment (1979–2004) (adapted from Chan *et al.,* 2011)

Treatment	Tillage	Stubble	Rotation	SOC change (kg C/ha/year)	sig	Final stock (t C/ha)
T1	NT	SR	W/L	-52	n.s.	40.5
T2	CC	SR	W/L	-174	*	38.3
T3	NT	SB	W/L	-98	n.s.	39
T4	CC	SB	W/L	-176	*	35.4
T5	CC	SB	W/W	-278	**	33.6
T6	CC	SB	W/W-N	-193	*	34.6
T7	CC	SR	W/C-G	-2	n.s.	41.7
T8	NT	SR	W/C-M	257	*	48
T9	CC	SR	W/C-M	104	n.s.	43.1

NT, No tillage; CC, 3-pass tillage; SR, stubble retained; SB, stubble burnt; W/L, wheat/lupin rotation; W/C, wheat/clover rotation; W/W, wheat/ wheat; N, N fertiliser; G, grazed; M, mown. *$P < 0.05$; ** $P < 0.01$; n.s., not significant

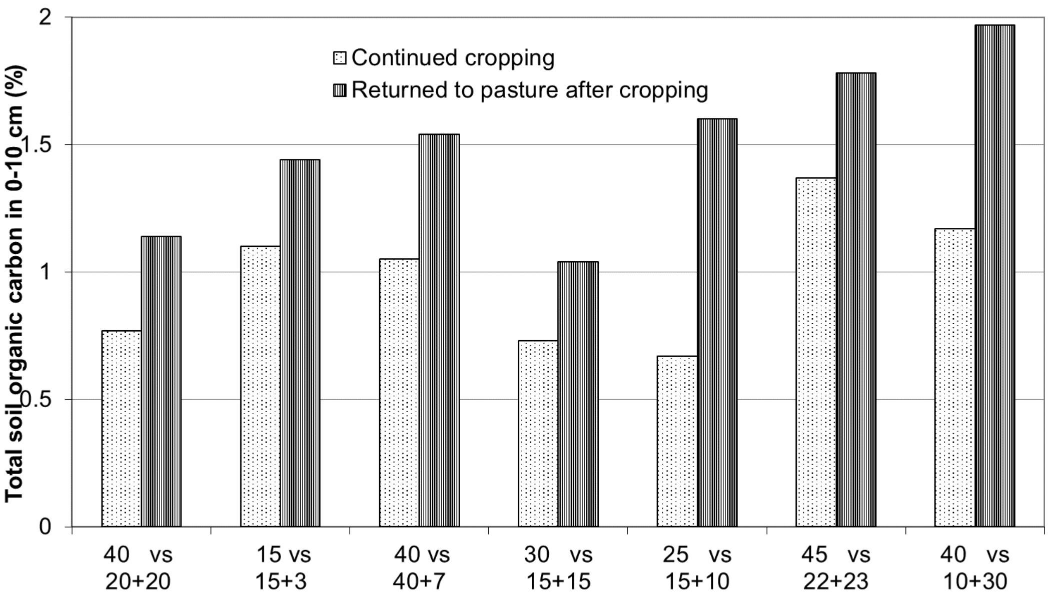

Figure 2. Changes in soil organic carbon levels after shifting from crop to pasture in the northern grains region (Lawrence *et al*., 2017). First value is the total duration of the cropping phase, second value is the duration of the cropping and pasture phases.

Over the past few years there has been an increase in the number of farmers and carbon aggregators making claims of increases in soil carbon that do not align with the published peer-reviewed science. Although conservative, the values presented in Table 3 are those estimated by the

Australian government official carbon model (FullCAM), showing likely increases in soil carbon in response to management. What is also seemingly ignored in claims of soil carbon increase, is the assumption this can continue in perpetuity, which defies the law of diminishing returns. The more carbon you sequester, the more carbon inputs you then require to maintain this level every year.

Table 3: Modelled soil carbon sequestration potential as stipulated and the Australian government ERF Offset method: Estimating Sequestration of Carbon in Soil Using Default Values, Methodology Determination 2015[1]

	Categories of sequestration potential (t C/ha/year)		
Project management activity	Marginal benefit	Some benefit	More Benefit
Sustainable intensification	0.03	0.16	0.45
Stubble retention	0.02	0.08	0.20
Conversion to pasture	0.06	0.12	0.23

[1]https://www.legislation.gov.au/Details/F2018C00126

Where soil has a low organic matter content, but high clay content and good rainfall (i.e. a high potential to increase soil organic matter), it is possible to achieve rates of soil carbon sequestration that exceed those presented in Table 3. The initial high carbon sequestration rates (i.e. the first 5 to 10 years with rates from 0.7 to 1 t C/ha/year in the top 30 cm when converting cropland to pasture; Meyer *et al.,* 2015; Robertson & Nash, 2013) will result in a new steady state after 10 years that matches the rainfall and management imposed. In contrast, the same conditions but with a high soil organic matter starting point, would only vary in direct relation to annual rainfall and distribution.

A new approach to managing soil organic matter in Australia

Perhaps there is a need to consider soil organic matter differently in the Australian context, by managing it more specifically for soil types by farming systems and also managing differently in high versus low rainfall periods. Sandy or granitic soils have very limited capacity to build soil organic matter as carbon is less protected to decomposition by microorganisms in these soil types, whereas clay soils generally have far higher potential to sequester carbon when rainfall is sufficient to maintain carbon inputs from stubble, roots or residual pasture biomass.

The key to building soil carbon, is to understand the capacity for the soil to store carbon in your specific environment (climate x soil type) and management system. This capacity varies considerably even within the same district. Therefore, we should not treat the landscape with a single sequestration potential, but target the areas that are low in carbon but high in sequestration potential e.g. the rehabilitation of degraded lands.

We should also be thinking of El Niño versus La Nina years quite differently, in that we have probably built more soil organic matter in eastern Australia during the recent La Nina, than in the previous three dry years put together. Higher rainfall year should focus on strategies that maximise the sequestration of carbon in our soils, and in low rainfall or drought periods, we focus on minimising the losses. Rather than focus on building soil carbon year by year, a longer-term approach would aim for a net increase in carbon over a 10 year period.

Short-term gain may mean long-term pain

Finally, whilst carbon neutrality is being strongly supported by the agricultural supply chain companies, there is an inevitable point where farmers will need to demonstrate progress towards lower emissions farming systems. Any increase in soil organic carbon you bank as a credit, will be negated by in-field emissions e.g. CO_2 from fuel, N_2O from N fertilisers or CH_4 from grazing livestock. Selling soil or tree carbon means that when the asset **value** leaves your property, you are left with the liability of maintaining what is now someone else's asset for the next 25 to 100 years (short term gain, long term pain). If the soil carbon is sold internationally, it also leaves the industry and the country, making any industry or national carbon sequestration targets increasingly difficult to achieve . Once the soil carbon is sold, the new buyer will be using it against their carbon footprint, which means that the farm will never again be able to use that soil carbon against their future liability, making their carbon neutral target increasingly impossible to achieve. The low risk option is to bank the inherent productivity benefit of improved soil health and don't sell your soil carbon, as you will need this asset for the day when you might need to table it against the balance of your own greenhouse gas emissions to meet supply chain demands.

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Contact details

Peter Grace
Professor of Global Change
Queensland University of Technology
Email: pr.grace@qut.edu.au

INVITA and AGFEML – Monitoring and extending the value of NVT trials

Scott C Chapman[1], Vivi Noviati[1], Andries B Potgieter[1], Swaantje Grunfeld[1], Malini Choudhury[1], Connar MaLaren[1], Daniel Smith[1], Pengcheng Hu[1], Chrisbin James[1], Yanyang Gu[1], Anders Eriksson[1], Bangyou Zheng[2], Fred van Eeuwijk[3], Martin Boer[3], Daniela Bustos-Korts[3], Jip Ramakers[3], Jesse Hemerik[3], Benoit de Solan[4], Frederic Baret[5], Simon Madec[4], Etienne David[4], Wei Guo[6]

[1]The University of Queensland
[2]CSIRO, St Lucia
[3]Wageningen University Research, The Netherlands
[4]Arvalis, Avignon, France
[5]INRAe, Avignon, France
[6]University of Tokyo, Japan

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GRDC code

UOQ2003-011RTX (INVITA) and UOQ2002-008RTX (AGFEML)

Take home message

Utilising digital technologies in national variety trials can be used to

- Provide verifiable records of trials through the season
- Assess trial quality and spatial variability at different stages of the season for different traits
- Improve confidence in estimates of yield performance.

Image analytics applied to phone, drone or 'dashcam' cameras have potential in research and production fields to quantify variation in plant, head count and other metrics and to map spatial variability in these measures across trials and fields.

For growers, we anticipate that these technologies will

- Improve the utility and prediction of variety performance in NVT to help growers choose varieties
- Be more accessible to growers and consultants via services offered by NVT contractors who have been trained via INVITA in use of UAVs and GPS tools
- Support commercial availability of spatial 'counting' methods in consultant and on-tractor imaging systems that will in future augment technologies like scouting, satellite mapping and yield mapping.

Aims

This paper overviews initial results from two complementary projects which started in 2020..

INVITA (**IN**novations in **V**ar**i**ety **T**esting in **A**ustralia - UOQ2003-011RTX), in which UQ partners with CSIRO and WU (Wageningen University, The Netherlands), monitors the quality of national variety trials (through use of drone and phone camera based surveys) and aims to improve the utilisation of environment and observation data (drone imagery, weather data, satellite monitoring) in the process of prediction of variety performance. AGFEML (AGriculture Feature Extraction and Machine Learning - UOQ2002-008RTX) is a project that has worked with Arvalis (France) and the University of Tokyo to develop machine-learning image analysis techniques to accurately count wheat and sorghum heads in research and production fields using images from phone cameras and aerial UAVs (Unpiloted Autonomous Vehicles) . AGFEML is a pilot project in the GRDC Machine Learning program of research that was initiated in 2019 and aims to quantify spatial variation in the field as indicated by the changes in head density measured by imagery. The project has prototyped machine-learning cameras to be able to count heads in real-time, for example on a tractor 'dash-cam' type setup.

Background

The INVITA project was initiated by GRDC to leverage upon the $12M INVITE (**IN**novations in **V**ar**i**ety **T**esting in **E**urope) investment by the EU Commission which began in 2018/19. INVITE involves a series of research activities to improve the process of variety testing across multiple EU countries and is led by INRAe (the French National Institute for Agriculture and Environment). UQ partnered with CSIRO and with Wageningen University (a leading partner in INVITE) to develop INVITA in Australia to build on findings in INVITE and to co-develop measurement and analysis technologies for the GRDC NVT.

Over the last 15 years or so, NVT has developed into one of the largest public variety testing programs in the world and provides Australian growers with timely information about performance which has been assured through investment in high quality experiment design, data cleaning and statistical analysis. INVITE and INVITA both have activities that aim to utilise additional phenotyping information (i.e., plant observations) using drone-based imaging, phone camera data collection, weather monitoring and satellite remote sensing in further improving performance prediction (Smith *et al*., 2021). In Australia, spatial field variation and year-to-year and location-to-location variation in weather have always been major potential sources of uncertainty in research experiments and these technologies aim to partially accommodate and account for spatial and temporal variation effects on crop growth and yield.

NVT and most plant breeding trials typically measure most traits (such as grain yield) at the plot level (i.e., one value per 7 x 2m plot area), and they account for field spatial effects using the methods developed and implemented by SAGI in the annual analyses of NVT. Imaging methods, especially from drones provide sub-plot resolution (<1 to 20cm pixel resolution) and can be used any time in the season. To date, most analytics from UAV images have been based around inferring crop cover and canopy height. In AGFEML we have particularly focused on improving methodologies to be able to 'count' heads of wheat and sorghum using phone and UAV cameras. Hence AGFEML outcomes contribute directly into INVITA in the first instance, with potential applications in other domains.

Methods

INVITA

INVITA data collection began in 2020 using only the main season wheat variety trials. INVITA has three major activities – data augmentation (collecting additional data using satellites, drones, weather stations etc), data analytics (statistical methods) and simulation and machine learning to interpret relationships among sensing and environment measurements and relations to NVT.

In 2020, we

- Established contracts with NVT trial service providers (TSPs) to include extra plots and organise additional data collection including drone training and GPS data collection

- Augmented data collection at up to 100 wheat main season variety trial sites, including satellite data and at 55 sites, additional measurements collected by UAV, high-resolution satellite (<1m res), phone cameras, biomass sampling, Greenseeker measurements, an IoT (internet of things) camera, canopy temperature sensor, as well as estimates of harvest index. We received a total of 344 UAV flights from the service providers, across 84 different sites. A total of 133 229 plot photos were uploaded across 58 sites. Manual observations were recorded in spreadsheets for 43 sites
- Developed data management pipeline for largely automated processing of datasets (including UAV data via commercial partner) and establishment of data checking and filtering protocols
- Coordinated and initiated historical analyses of NVT wheat datasets with research partners (Wageningen University Research) and demonstrated capability to spatially account for variability in grain yield associated with early season scores and/or UAV derived data (e.g., fractional ground cover).

Table 1 shows the types of data and methods used by the INVITA project in NVT sites.

Table 1. Summary of data types, collection and spatial and temporal resolution

Type	Data	Collection	Spatial	Temporal
Images	Field camera image	Static field camera located in SatCal plot at 45°.	A single plot	5 times a day
	Plot photo	3 photos per plot collected by smartphone at nadir.	Plot level	Several times in a season
	RGB/UAV drone images	Drone flight at 25m (resolution <1cm).	Plot and sub-plot level	Several times in a season
	Satellite imagery	GoogleEarth or DataFarming.	Sentinel-2: 10m (trial/site level) Planet: 3m Airbus: 0.5m (plot/trial/site level)	Sentinel-2: every ~5 days Planet: Daily Airbus: Several times in a season
Sensor data	Canopy temperature	GoannaAg sensor located in reference plot. Data access through CSIRO Waterwise API.	Single point	Daily
	Multispectral	Arable mark located in reference plot. Data access through Arable API.	Single point	Hourly
Observations	EM38	Handheld meter or drive-across.	Plot level If KML: sub-plot level	At start of season
	Greenseeker	Handheld device	Plot level If KML: sub-plot level	3 times in a season
	Biomass (dry and fresh weight)	Field collection, drying, weighing.	Plot level	3 times in a season
	Harvest	Dry grain weights.	Plot level	At end of season
MetaData	KML of trial boundaries	Walking around each trial with FieldsAreaMeasure app[1].		
	Field plans			
	GCP location	AeroPoints or RTK GPS equipment		

[1] https://play.google.com/store/apps/details?id=lt.noframe.fieldsareameasure&hl=en_US&gl=US , https://apps.apple.com/gb/app/gps-fields-area-measure/id1123033235

The map (Figure 1) shows the distribution of trials and data collection for the 2021 INVITA measurements, overlaid on NVT trials. Trial outlines were collected using the GPS Fields Area Measure App which allowed us to find trials and extract satellite data as well as to plan UAV flight missions etc. Intensive measurements were taken in 46 wheat main season trial sites (cameras, GoannaAg canopy temp sensors), with at least one UAV flight conducted at approximately 80 sites. See Figure 2 for examples of field camera setup, in-season images and a trial image for NDVI of a reference trial with NVT entries which was grown at UQ Gatton in 2020. The field camera allows us to trace ground cover and phenology (e.g., flowering date) over the season via image analysis. In 2021, another 113 trials of wheat and other crops (barley, canola, chickpea, faba bean, field pea, lentil, lupin, oats) had at least one UAV flight planned. Sentinel-2 satellite data (10m resolution) were collected for all NVT crops at all sites, with approximately 55 sites monitored by high-resolution satellites (~ 30 cm pixel resolution). High-res satellites (Figure 1) may allow us to replace or augment UAV data as we work out how to potentially utilise findings from INVITA into future NVT operations. Regarding historical NVT, we have assembled all Sentinel-2 data back to 2016, as well as LandSat and Planet data as far as available. Due to issues in locating NVT trials, we have also developed a machine-learning assisted approach to 'find' the NVT trials in the satellite imagery.

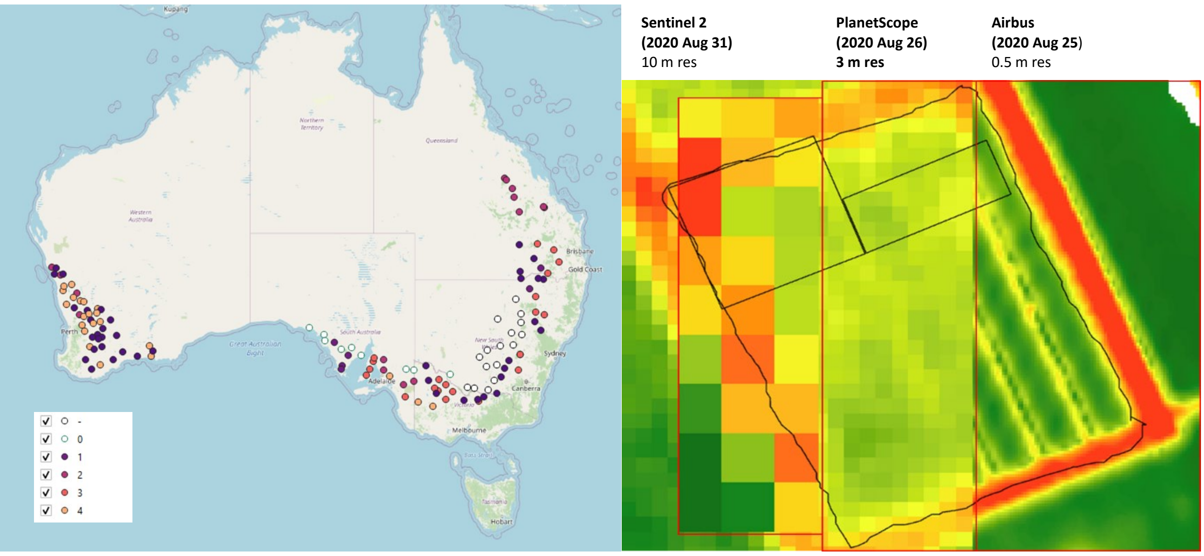

Figure 1. Overview of main wheat trials and (in colour) the level of measurements being collected for INVITA in 2021 winter season. Example of different satellite resolutions in 2020 WMaA20BEVE6

Drone imagery from NVT trials is uploaded to a database and processed to generate images like that in Figure 3 which shows the variation in NDVI signal late in the season. Here the red plots are in grain filling and the later-planted crops are still green.

The UAV and plot imagery have been further processed to estimate crop cover and crop height through the season. The aim is to analyse these data to see what they show about early season spatial variability, as well as whether these types of traits are related to the performance of varieties. We report on some of those outcomes in the results, although the main purpose of this paper is to discuss the way these technologies are being used to improve research trials and their availability to contractors for use in breeding and agronomy applications.

We have also begun developing analyses of simulations that are created from NVT trials. For these we use the APSIM model, measured weather data and satellite imagery. These are used to 'tune' APSIM in order to estimate soil parameters at the NVT site. INVITA has used NVT data to check predictions of flowering date in conjunction with models being developed by the GRDC National Phenology Initiative (ULA00011) and this information will allow us to create seasonal patterns of stress indices for drought, high temperature, frost etc and the occurrence of these in each NVT. Later in the project, such indices will inform statistical models that may be used to predict variety performance in relation to different patterns of stress, but this will take some validation before it would become available in NVT.

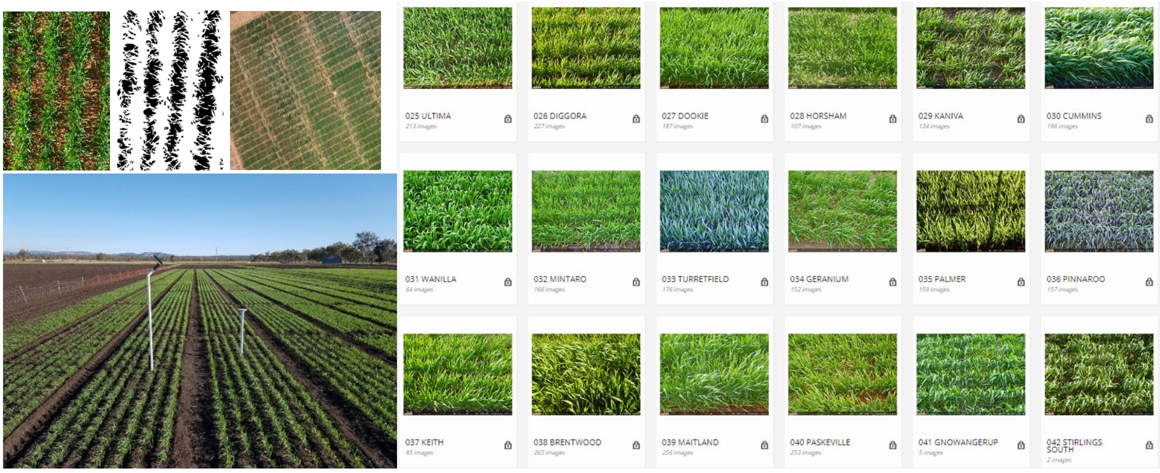

Figure 2. Early season 4G camera images from 2020 NVT with camera and spectral sensor shown on left and an example of camera photo masked to provide an estimate of ground cover from phone, field camera or UAV

Figure 3. Example of NDVI per plot data collected from analysis of a single UAV drone flight at UQ Gatton. This image is stitching together multiple images taken by a drone in a ‘lawnmower’ pattern that takes about 30 minutes per ha at this high resolution.

AGFEML

Machine learning (ML) technologies allow us to do some amazing things. For example, ML methods can now count objects efficiently from imagery and video, e.g. recognising and counting the heads of people in an airport. In this project, we have adapted these types of technologies to count 'heads' of wheat and sorghum. With our partners in Arvalis (France) and U Tokyo, we undertook several activities related to 'head counting'. The first was to work with multiple universities and institutes to create the 'Global Wheat Head Dataset (GWHD)' and establish an online 'competition' (led by U Saskatchewan and coordinated by Arvalis) on the 'Kaggle' website for internet teams to count wheat heads (Figure 4). This had a great response (> 2000 teams) as did another competition in 2021 on the AICrowd (https://www.aicrowd.com/challenges/global-wheat-challenge-2021) website (>2500 teams) and provided rapid insight into what kind of expertise could inform the development of an analytics pipeline for the counting of wheat heads. This pipeline was designed to work using phone or ground images taken by researchers or contractors in NVT trials. There is also the potential to use such images in applications related to scouting for agronomic problems like heat and frost damage to heads.

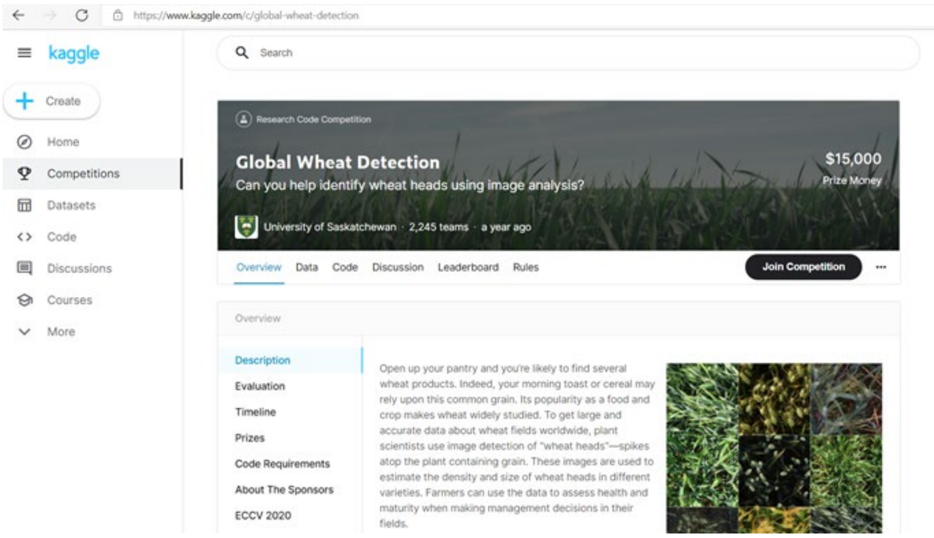

Figure 4. The 1st GWHD competition on Kaggle https://www.kaggle.com/c/global-wheat-detection which attracted 2245 teams

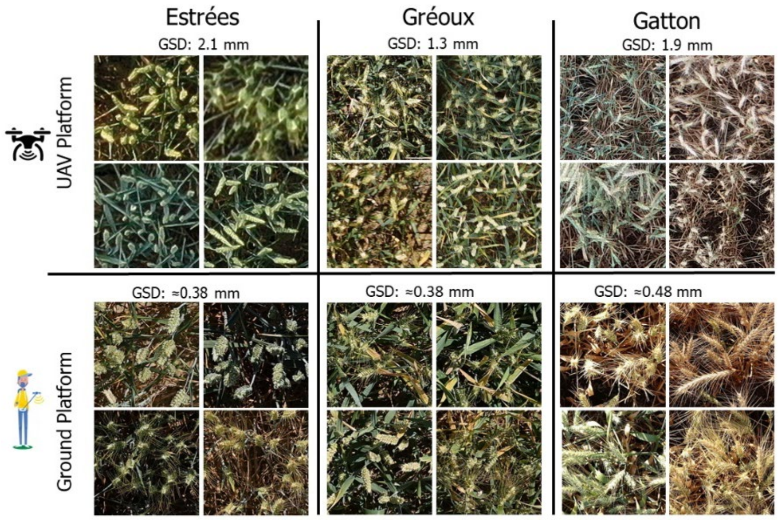

Figure 5. UAV and ground platform photos for testing of wheat head counting. Data from France and from Australia (INVITA trial at Gatton)

The Arvalis team then developed models using the GWHD and applying the best methods and ideas from the competitions. Two contrasting methods (FasterRCNN and SFC2Net) were tested on a set of wheat head images (Figure 5) that had been collected as ground photos in two locations in France and in the INVITA trial at UQ Gatton.

The second major activity was to explore automation of sorghum head counting from UAV images. In this work, we wanted to establish a robust pipeline that would work well in diverse environments (Figure 5). Counting plant heads can be harder than counting human heads in a crowd – images of crops (populations of plants) have a much more uniform 'style' with most of the heads looking similar as well as the background looking similar. Hence, we need to train our system with multiple sets of images from different 'domains' (e.g., taken on different days or different times of development). One method we use for this is called GAN (Generalised Adversarial Networks) which were only invented in about 2014 (see here for some examples https://machinelearningmastery.com/impressive-applications-of-generative-adversarial-networks/). This is the same method that can be used to turn images of one animal into another or to 'replace' a person with a different person in an internet video – sometimes called 'deep fakes'. After developing a robust method of head counting for sorghum, we also tested the method on wheat head datasets that had been collected in ground photo images using a machine-learning camera. In the presentation of this paper, we will show some of the results from the open-source machine-learning camera which we have utilised to demonstrate real-time counting of wheat heads in the field.

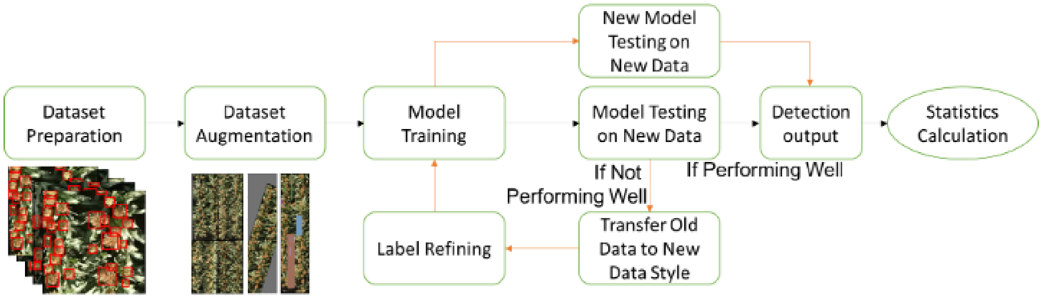

Figure 6. Analysis pipeline for counting sorghum heads from UAV images

Results

INVITA mapping spatial variation

For trials in 2020 and 2021, multiple UAV flights have been analysed to estimate the fraction of ground cover in NVT trials at different times of the season. These data are derived by extracting plot data from UAV data similar to that in Figure 3. Data for each plot are combined with design information and analysed using spatial statistical modelling like ASREML or SPATs (Rodriguez-Alvarez *et al.,* 2020). An example is shown in Figure 7 for a range of ground cover from 0.2 to 0.7 early in season.

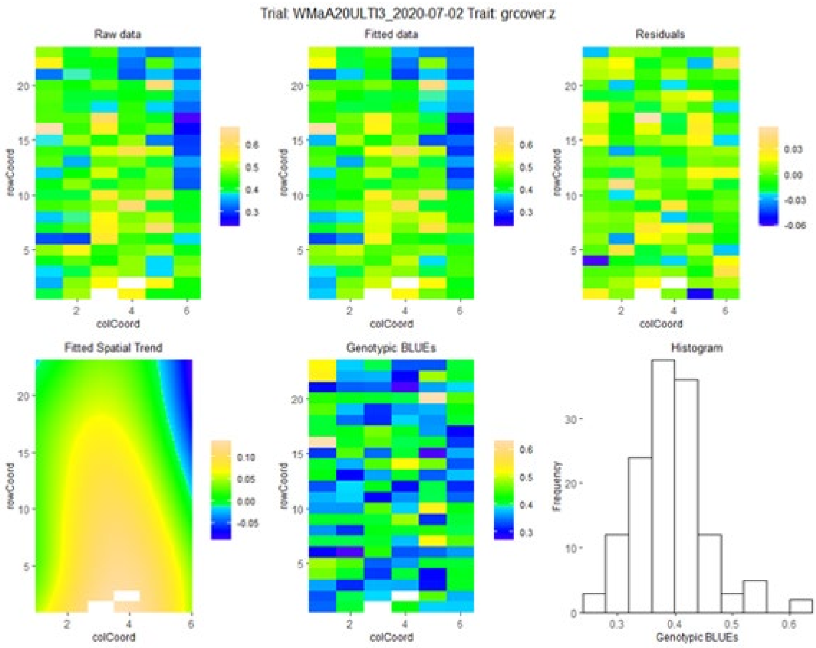

Figure 7. Spatial analysis of ground cover estimate for wheat main season trial, 2 July 2020. The lower left image shows the spatial trend which has been found in the data and has been adjusted in the estimates of the genotype means (the 'BLUEs')

These analyses of ground cover using a UAV provide a more objective measure of the within and between plot variation compared to visual scores, and we have shown that these ground cover estimates are relatively accurate and repeatable. Two questions of interest are:

- Designing criteria to make early-season decisions regarding trial progress, e.g. in situations of extreme spatial variability due to soil issues, rainfall events, crop emergence etc can we utilise these data to inform whether a trial should be abandoned early so that resources can be focused on other higher quality trials?
- Can these measures of ground cover provide an early-season indicator of yield? In Figure 8 we show genetic correlations between early season ground cover and final yield for 30 trials in 2020. In general, these correlations are positive and sometimes neutral, but in several trials the correlations were negative, i.e., early high ground cover was associated with lower final yield. In terms of agronomy, these negative correlations may be related to interactions with seasonal water and nutrient supply e.g., in a situation where rainfall is poor during the season, high early vigour can exhaust soil water supply and result in haying off and reduced grain yield. We are further investigating the seasonal conditions for these contrasting trials to try to better determine why/how negative correlations occur and their relationship to seasonal and soil conditions.

Figure 8. Map of Australia showing the genotypic correlations between yield and early season ground cover (GC1) (DAS < 60) for 30 trials in 2020. Colour shading indicates the strength and direction of the correlation, i.e. positive (blue) genetic correlation of yield and ground cover means that genotypes with better ground cover early in season had a better final yield.

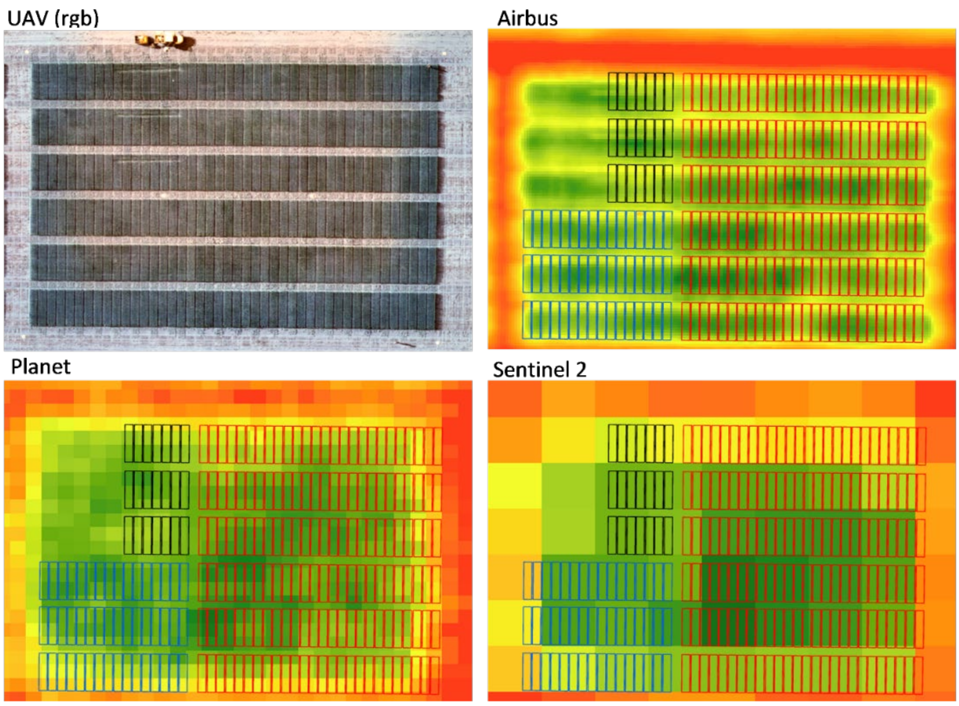

Figure 9. Comparison of UAV (RGB <1cm resolution), Airbus (0.3m), Planet (3m) and Sentinel-2 (10m) images of trial WMaA20BENC6 during the mid-vegetation stage. The plot boundaries overlaid on these images show the limitation of Sentinel-2, in terms of spatial resolution.

Given results from the UAV imaging research, we can initially conclude that spatial analysis offers potential for trial monitoring and identifying sources of error that may impact on estimated of variety performance in trials. A challenge of using UAVs in the NVT is simply the cost and time required to make frequent visits to remotely-located trials. Hence, another aspect of INVITA research is to look at how spatial data from satellites may be utilised, especially to infill changes in spatial patterns between UAV flights. The cost of a seasonal set of higher-resolution satellite images (approx. once/month) is similar to the cost of a single UAV flight and processing. We are currently working on analyses of UAV and satellite data collected on the same dates and rescaling the different images to determine how much of the detailed spatial data in UAV images can be inferred through analysis of satellite images. This will determine how we can best manage the value of using UAV and satellite imaging techniques in the in-season monitoring of NVT trials.

INVITA tracking seasonal variation and weather

The simulation component of INVITA utilises the phenology models of APSIM to estimate the flowering time of trials and genotypes within trials. NVT trials are distributed over an extraordinary range of sites with many being several hours drive from locations of trial contractors (Figure 10). In this part of INVITA we aim to model the flowering time of NVT trials, and especially the genotypes if possible, learning from the outcomes of the GRDC National Phenology Initiative project led by James Hunt at LaTrobe. Our analysis of >21 000 flowering observations (Figure 11) shows that we now have good confidence in being able to predict trial flowering dates using weather data from nearby stations or recorded at NVT sites. This will allow us to characterise the likelihood that frost, heat or drought events were experienced at NVT sites and how these may have interacted with different varieties. The aim here is to have a clearer understanding of when weather events should be informing decisions around the utility of specific trials, e.g., were some genotypes particularly disadvantaged.

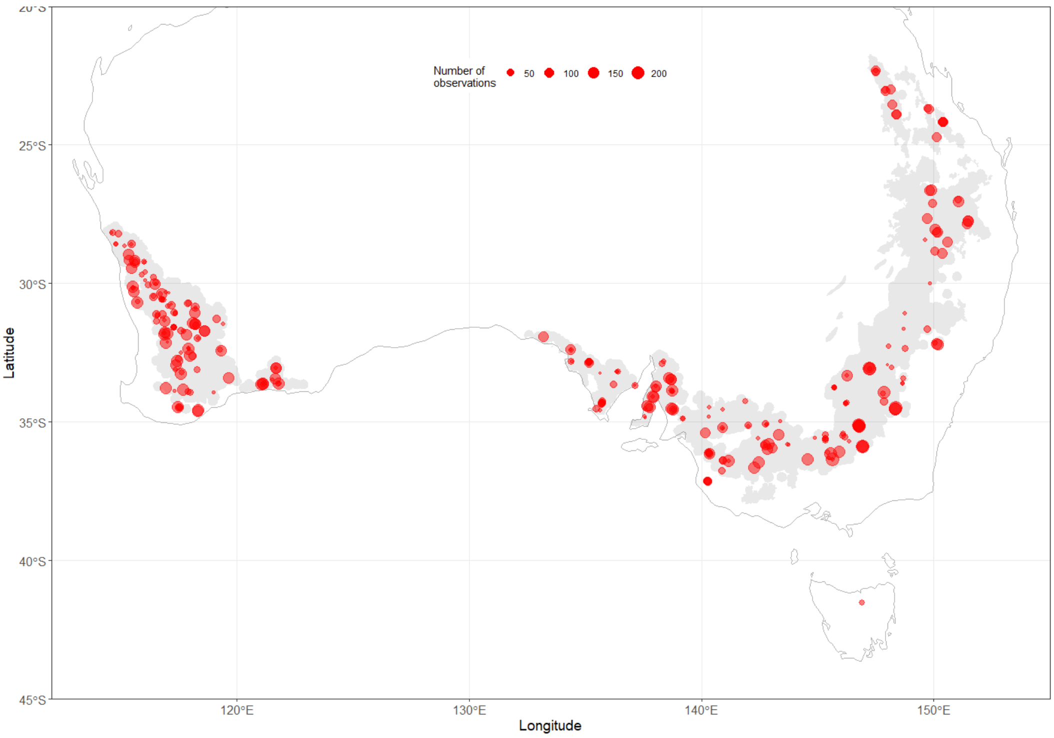

Figure 10. Analysis of 21 000 flowering observations across 2015 to 2020 in 310 trials at 129 locations. Dots show how many observations were used from each historical NVT location

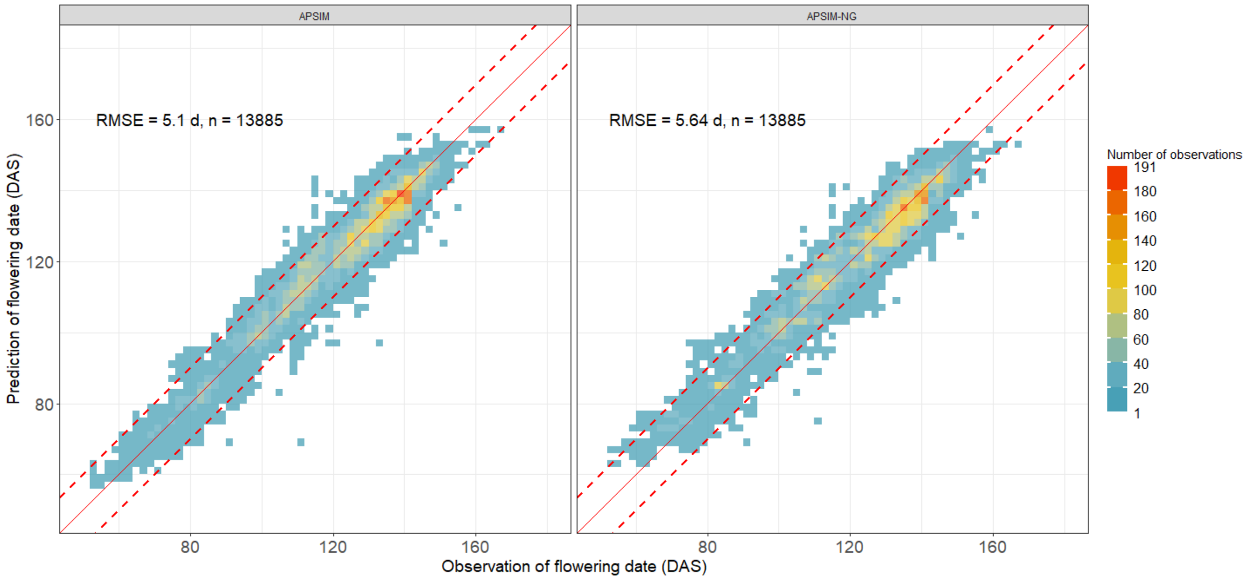

Figure 11. Comparison of prediction of wheat flowering time using parameterisations of two types of APSIM phenology models. This shows we can predict flowering time of most trials and genotypes quite well from weather data alone.

AGFEML wheat head counting from ground images

Of the many activities undertaken in 2021, we report on two significant results here. The first is the result of the application of machine-learning models to count wheat heads in images taken by cameras over the top of field plots. The types of models tested and the image augmentation methods used were inspired by the GWHD competitions described earlier and summarised by David *et al*., 2020 and 2021. The images were taken using the same techniques in sites in France and in Australia (at a copy of the northern NVT which was grown at UQ Gatton). In these images, we had a plastic tubing frame of about 50 x 50 cm that was used as a boundary, and we counted all of the heads we could see, at the time of taking an image above the plants. The Arvalis team then took two models which had been trained on the GWHD (>150 000 labelled wheat heads from many different trials and locations and conditions) and made independent tests.

Table 2. Results from applying two different machine-learning models trained on the GWHD and tested on independent wheat head datasets in France and Australia (Gatton) (Where rRMSE = root mean square deviation; rBIAS = relative bias; and R^2 = the correlation coefficient)

Sites	Faster-RCNN			SFC2Net		
	rRMSE	rBias	R^2	rRMSE	rBias	R^2
Estrées	**9.61**	-6.53	**0.78**	10.54	**0.59**	0.72
Gréoux	19.24	-15.56	-0.13	**12.75**	**1.88**	**0.56**
Gatton	22.04	-16.10	0.71	**15.78**	**4.91**	**0.86**
Overall	19.66	-12.50	0.78	**14.52**	**2.41**	**0.89**

The results in UQ Gatton (Table 2, Figure 12) were good across a large range (20 to 100 heads in the 0.25m^2 image with r2 of 0.71 or 0.86) and demonstrated that we should be able to take such images in NVT trials during early to mid grain-filling and be able to obtain reasonable estimates of head density. The object-based model (Faster-RCNN) tends to under-estimate the head number while the density-based model (SFC2Net) is generally more precise. The research team is working to determine issues around how/when the models are most suitable so that we might be able to automatically process ground photo imagery from NVT to obtain this data. The reason for interest in head number density is that our current yield analysis measures yield and grain size, so we can determine grain number per unit area, but do not have any measure of head number per area. Estimates of head number per unit area can inform us about which situations (soil + weather season) interact with traits like tillering (which increases head number per unit area) and how the balance of crop ‘investment’ in tillers can benefit or penalise potential yield for that situation.

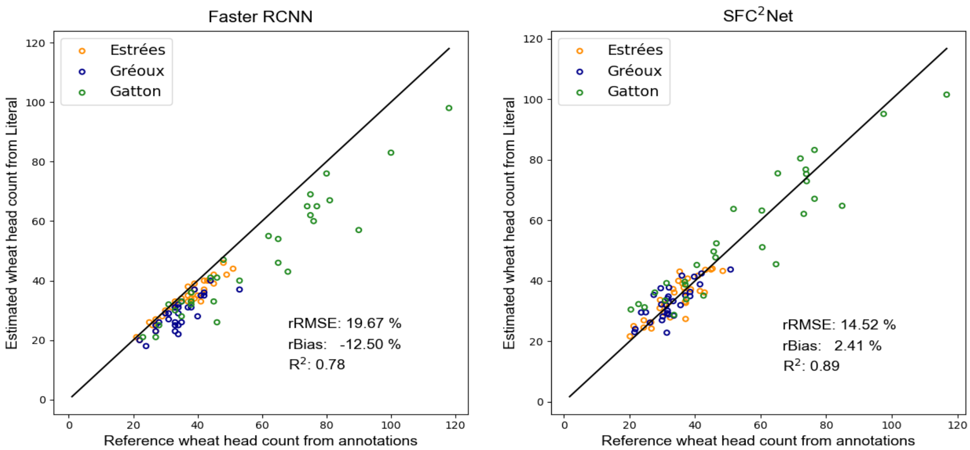

Figure 12. Performance results from independent testing of two head counting algorithms (RCNN and SFC^{2}Net) on quadrat counts of wheat heads in France and Australia (Gatton)

AGFEML sorghum head counting from UAV images

In the sorghum component of AGFEML, we assembled various datasets including those from UQ and from collaborators in a US DoE project based at Purdue University in the USA. These sorghum images all came from UAV datasets (Figure 13). By applying the GAN pipeline we described in Figure 6, we ‘converted’ UQ images into fake images by applying the ‘style’ from Purdue images. In Figure 13, it can be seen that in the ‘fake’ sorghum images in the 2nd column have heads in the same positions as in the ‘real’ images’. We then put these ‘fake’ images back into the machine-learning model and train it to recognise these sorghum heads which look quite different to the originals. This greatly improves the model so that we only have an error of about 2 heads in 50, even when we only use 100 images to train the model (Figure 14). Training the model on both ‘real’ and ‘fake’ images makes it work much better than training only on ‘real’ images.

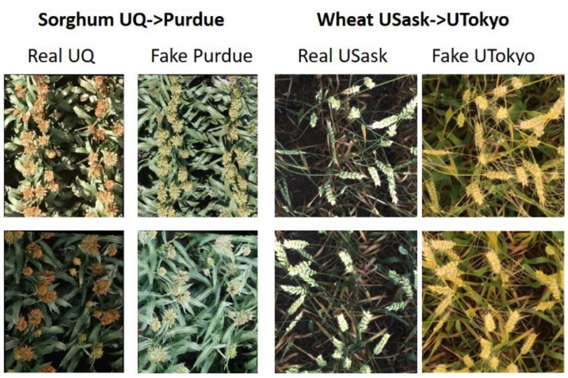

Figure 13. CutGAN 'fake' images generated using UQ image + Purdue ‘style’ (sorghum) and USaskatchewan + UTokyo ‘style’ (wheat). Note how the heads are in the same position in the ‘fake’ images as in the ‘real’ images. So now the ‘fake’ images can retrain the model in a new style.

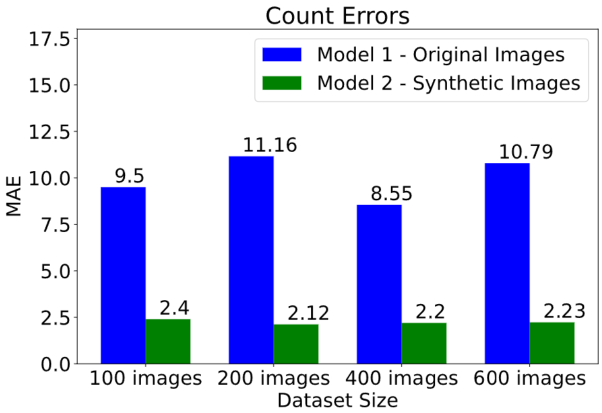

Figure 14. Performance of sorghum head counting model trained on Original or Original+Synthetic images for different size datasets. Use of fake images makes model training work better

Using a modified version of the sorghum head-counting model, we developed a 'rapid' processing pipeline for a drone flight of 90 x 500m in size (Figure 15). In this pipeline, we can process each image from a drone and identify all heads within an image, and then assign automatically detect the rows in the image. This allows mapping of head count for every row and identification of gaps within rows which indicated problems with planter or in-season effects. The result is a detailed head density map and analysis of variation in head density for comparison to soil and yield maps.

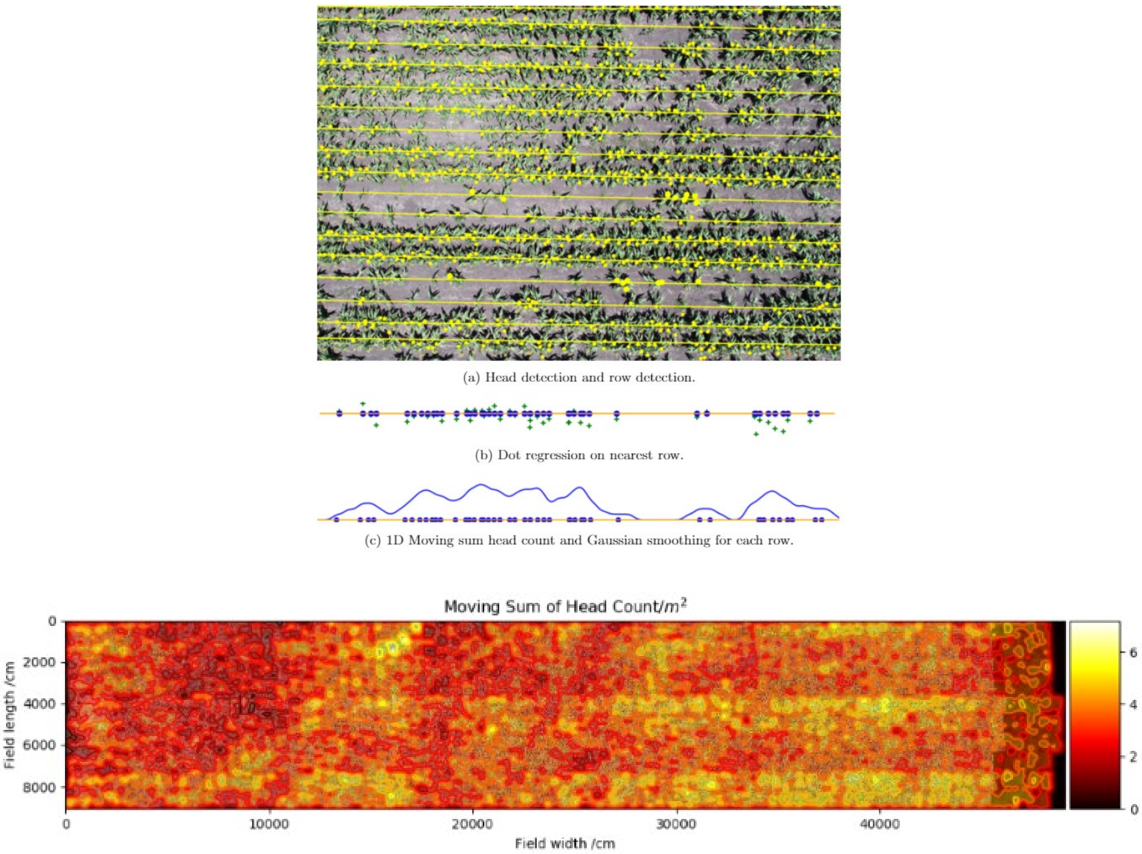

Figure 15. Head and row detection in UAV images (top) and fitted map of head density for entire 90 x 500m field (below). These analyses can be generated from UAV images without full mosaic processing and are viable for computation in the field.

We took our sorghum head-counting model and then applied it to wheat datasets, using the GAN technique again to train the model on both 'real' and 'fake' images like those in Figure 13 (right). When we then implemented this model into a 'machine-learning camera', we could walk through field plots and take photos and obtain counts of all heads in the image as we recorded a 4K video on the camera. This demonstrates that it should be possible to develop a camera system that can be carried by a consultant (e.g., looking at head damage in wheat) or potentially installed on tractors to monitor head density in field conditions (Figure 16).

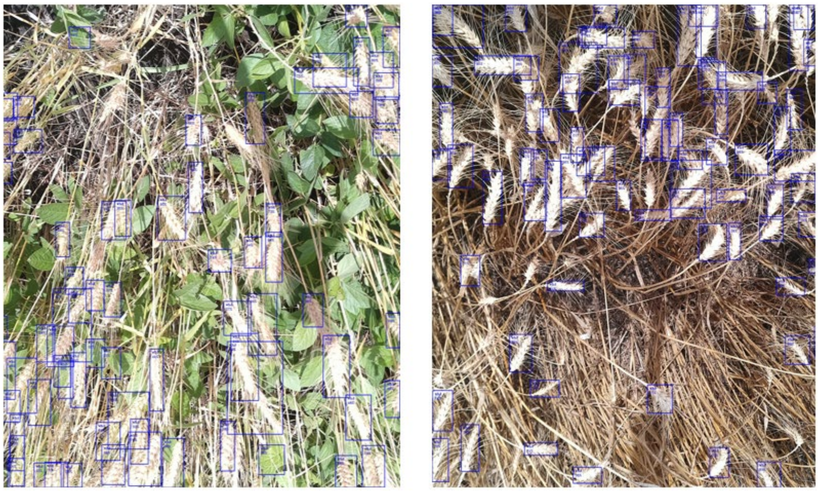

Figure 16. Real time 4K still image processing to count wheat heads using a machine-learning camera

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Contact details

Prof Scott Chapman
The University of Queensland
UQ Gatton Campus, Warrego Highway, Gatton 4343, QLD
Ph: 0417 076 787
Email: scott.chapman@uq.edu.au

Farming system nutrient legacies – impacts of N strategies on N inputs, cycling and recovery over multiple years

Lindsay Bell[1], Jon Baird[2], David Lawrence[3], David Lester[3], Jayne Gentry[3], Darren Aisthorpe[3], Andrew Erbacher[3], Kathi Hertel[2] and Brook Anderson[1]

[1] CSIRO
[2] NSW DPI
[3] DAF Qld

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Take home messages

- Soil mineral N and fertility status has a long-term influence on productivity of a farming system
- Robust N application strategies have legacies of building/maintaining higher soil N status beyond the immediate crop
- Fertilising crops to maximum compared to average yield potential (approx. double N budget) has only required an average of 100 kg of N/ha extra applied over 6 years
- A high proportion of surplus N is recycled or recovered in the soil mineral N pool and is available in subsequent crops
- Robust nutrient strategies have incurred additional costs ($134/ha over 6 years on average), but much of this is 'invested' in soil mineral N stores ($75/ha)
- Only in above median seasons, when crops are responsive to high N rates will economic benefits accrue, but these can be significant.

Introduction

Nitrogen (N) inputs is a major variable cost in most cropping systems and matching the supply to crop demand is critical to maximising water use efficiency and system profitability. Hence, developing a nutrient management strategy that provides sufficient N when crops need it whilst also mitigating the risk of losses to the environment is critical. This problem has been the focus of a plethora of research, with well tested and refined recommendations available to optimise fertiliser applications to individual crops (Angus and Grace 2017). However, nutrient budgeting and evaluation of nutrient use efficiencies has typically taken a crop-by-crop approach, which often overlooks some of the legacy impacts that can occur. For example, a crop provided with N surplus to its requirements often have low NUE and return on investment in that year because the extra N provided was not converted into grain yield; this often occurs in dry seasons. However, the unused N from that crop can contribute significantly to the N supply in subsequent years and may even be used more effectively by the next crop than fertiliser applied in that season (Dowling 2018). Hence, there is a need to take a longer-term more systematic view of N application approaches or strategies.

In the northern farming systems research project, we have been comparing 2 main fertiliser N management approaches over several years. We have tracked the dynamics of N over multiple seasons and how these fertiliser strategies have impacted nutrient input requirements, N utilisation and cycling, and overall system nutrient use efficiency.

System N management strategies deployed

Across the various farming systems experiments we have been deploying two different strategies to apply N fertiliser to crops – a *Baseline* (or standard approach) and a *High Nutrient* system. Both systems have employed the same sequence of crops and have varied only in their fertiliser inputs. A range of yield predictions were generated using APSIM for the specific location, crop sowing date and soil water content at sowing (see Figure 1).

In the *Baseline* system, crops were fertilised to a nutrient budget targeting a predicted yield in the 50th percentile of seasons. That is, adequate N is applied for the crop to reach its yield potential in half of seasons (or an average yield outcome), while in seasons with higher yield potentials it is possible that the crop may not have sufficient N supply to meet its water-limited yield potential.

In the *High Nutrient* systems, crops were fertilised to a nutrient budget targeting a predicted yield in the 90th percentile of seasons. That is, the crops are fertilised so that they should never be limited by nutrient availability in any season, but this means that the crops are 'over-fertilised' in all but the best seasons.

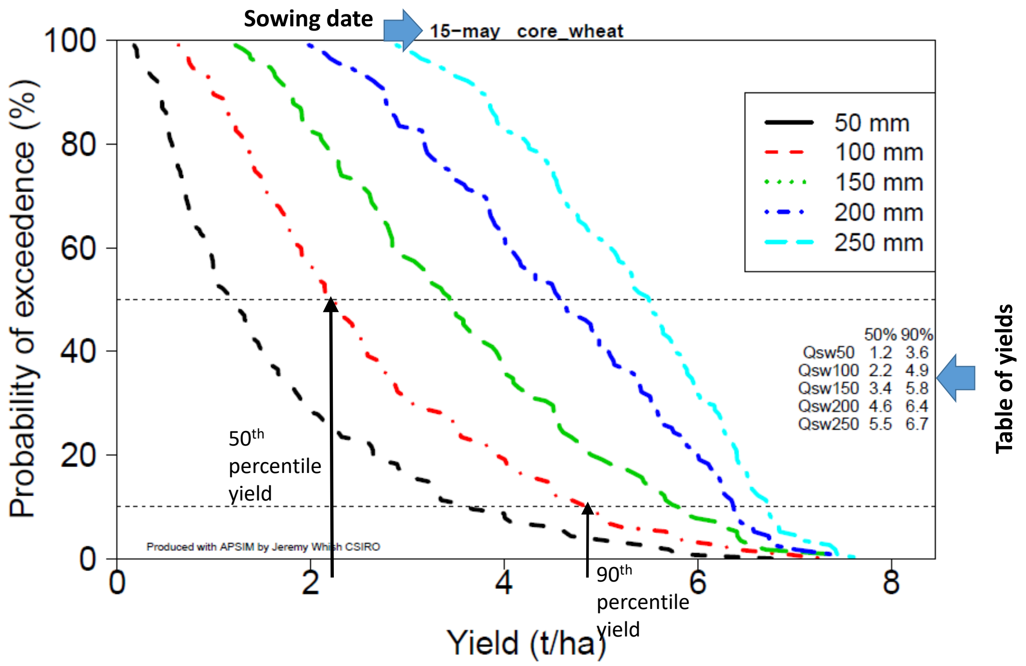

Figure 1. APSIM predictions of wheat yield probabilities with different starting soil water levels (50, 100, 150, 200 and 250 mm plant-available water). For 100 mm PAW at sowing (indicated by red line), the yield predictions for a 50th percentile season and a 90th percentile season are shown; these are used to calculate the N budgets for the crop.

The crop N budgets are determined prior to sowing of every non-legume crop from the predicted yield using well established N requirement calculations. An example for wheat is below (Equation 1). So, for the example crop situation above in Figure 1, this would equate to a crop N fertiliser budget of 83 kg N/ha in the *Baseline* system and 185 kg N/ha in the *High Nutrient* system.

Equation 1 - Wheat $_{N\ budget}$ = Predicted yield (t/ha) x 12 (% protein) x 1.75 x 1.8

Prior to each crop, the amount of fertiliser N to be applied was determined by deducting the amount of soil mineral N available in the top 90 cm of the soil profile from the total crop budget (Equation 2). Hence, if there was sufficient mineral N available in the soil to meet the crop demand, then no synthetic N fertiliser was applied (other than starter to provide other nutrients). This method also did not assume or account for additional in-crop N mineralisation or adjust this based on crop history (e.g., following legumes). In the experimental locations in Queensland, all the fertiliser N was applied at sowing, while in NSW locations a portion (up to 50%) was applied in-crop at the start of stem elongation.

Equation 2 - N to be applied = Crop $_{Nbudget}$ – Soil mineral N (0-90cm)

N inputs and export from systems

Over the various experimental locations there has been a large difference in the amount of applied N fertiliser across the 6 experimental years (Table 1). This is due to significant differences in the natural fertility and background starting N status at the sites. For example, the Billa Billa site was relatively new country and was only recently brought into crop production. This site had over 400 kg of mineral N in the soil profile at the outset of the experiments. No N fertiliser was applied to meet the annual crop budget for the first 5 years while this background N was exploited; only a small amount of N associated with starter fertilisers has been applied. Other sites have received significant N inputs of over 200 kg N/ha over the 6 years, but these application rates are still only 30-40 kg/ha/yr. over the life of the experiment (close to long-term averages nationally).

Despite the significantly different approach to crop N budgeting resulting in typically double the N budget in the *High Nutrient* system compared to the *Baseline*, when balanced over several years and the whole crop sequence this rarely translated into dramatically higher N inputs applied. The extra N applied over the whole 6 years was on average 100 kg/ha of extra N, or only 17 kg N/ha/yr., over the 6 years higher across all sites in the *High Nutrient* strategy. The difference ranged from only an extra 9 kg/ha at Emerald to 260 kg/ha at the Trangie – red soil site, with the larger differences accumulating at sites where the soil fertility or N cycling was lower.

Table 1. Total fertiliser N applied over 6 years of experiments across 11 farming system comparisons spanning the northern region between different N budgeting strategies: *Baseline* (Budget to 50th percentile yield prediction) and the *High Nutrient* (budget to a 90th percentile yield prediction).

Site comparison	Applied N (kg N/ha)			Exported N (kg N/ha)			System N balance		
	Base	High N	Extra	Base	High N	Extra	Base	High N	Diff
Emerald	51	60	9	399	411	12	-348	-351	-3
Billa Billa	17	77	60	344	378	34	-327	-301	26
Narrabri	205	442	237	270	268	-2	-65	174	239
Mungindi	70	154	84	178	193	15	-108	-39	69
Spring Ridge	234	304	70	377	393	16	-143	-89	54
Trangie – Red soil	137	396	259	297	384	87	-160	12	172
Trangie – Grey soil	63	139	76	289	284	-5	-226	-115	111
Pampas Mixed	50	152	102	435	453	18	-385	-301	84
Pampas - Summer	85	127	42	389	379	-10	-304	-252	52
Pampas - Winter	45	104	59	400	396	-4	-355	-292	63
Pampas - High inten.	138	274	136	420	422	2	-282	-148	134
AVERAGE			**103**			**15**			**91**

The *High Nutrient* strategy has not resulted in significantly higher exported N in any of the systems except Trangie on the red soil. This is largely because we have not seen any significant yield increases due to the higher N applications at any of the other sites (discussed further below). However, what can be seen is that across all sites the *Baseline* system is still exporting more N than is being applied. The *High Nutrient* strategy is maintaining a positive or neutral balance at several sites, but at sites with higher natural fertility (e.g., Billa Billa, Emerald or Pampas) the soil continues to meet most crop demand and provide most of the N inputs in the system even under a robust N fertilisation approach.

Crop responses to nutrient strategies

As mentioned above there have been few cases amongst these experiments where the higher nutrient application approach has resulted in a significant yield or protein increases. This is largely because of the below-average seasonal rainfall conditions across most of the seasons in these experiments, and hence the yields and crop demand for N has rarely exceeded the N available in the *Baseline* system. This occurred only at Trangie on a red soil in the wet and high yielding winter of 2016, where we saw a 1.2 t/ha yield increase and a grain protein difference (14.4% vs 11.8%) in the *High Nutrient* system. This highlights that the higher nutrient application approach is only likely to bring about significant yield gains in seasons with high yielding conditions, otherwise the *Baseline* provides sufficient nutrition.

In a couple of situations, we have seen a small reduction in grain yield associated with the *High Nutrient* strategy, where crops produced more vegetative biomass which is likely to have induced more severe water stress during dry grain filling periods. For example, at Mungindi in 2015 we saw a wheat yield reduction of 0.3 t/ha from the *High nutrient* application (50 vs 130 kg of N applied at sowing), but grain protein was higher in the *High nutrient* system (13.1% vs 8.8%).

Recycling and recovery of N

Because in most seasons we have provided N fertiliser in surplus to the requirement of the crop, it is critical to understand the proportion of fertiliser that is still available in the soil. On average across the various cereal crops, we have recovered 80% of the additional N applied at the post-harvest soil sampling after that crop. That is, most of the additional N available at sowing (from both fertiliser applied and starting mineral N) was still present in the soil mineral N pool when soil was sampled after crops were harvested. This value has varied from about 60-100% in most situations but has been lower particularly where crops grew more biomass with the higher nutrient applications but have not converted this to grain yield. In many seasons we have also observed additional N mineralisation in subsequent fallows in the higher nutrient systems.

In Figure 2 we show for 3 different sites the mineral soil N status and the accumulated N applications in the *Baseline* and *High Nutrient* systems. This demonstrates how N applications can have a long legacy in our farming systems. For example, at the Pampas site the legacy of the higher N application in October 2016 can be seen in the subsequent soil mineral N, meaning that the subsequent crop sown did not require additional N fertiliser inputs to satisfy the higher nutrient budget. The additional fertiliser applied in October 2018 sorghum crop is still available in the soil profile 2 years later in 2020. These legacies can take time to become clear, as is shown at Mungindi (Figure 2, bottom). Here, the only additional fertiliser application was made in Jun 2015, and this additional N was taken up by that crop. However, this was not recycled into the system until the fallow between December 2016 and March 2018, after which the difference in soil mineral N has been maintained.

Hence, over the long term a large proportion of the applied N is recovered again in the system, becoming available for use in subsequent crops. This recovery and recycling has been the main reason why the *High Nutrient* system has not required large additional inputs of fertilisers, because residual N from previous applications is contributing to the budget in subsequent years and hence offsetting the need for additional fertilisers.

At the last sampling across almost all sites, the *High Nutrient* system has between 25 and 100 kg of additional mineral N available in the soil profile compared to the *Baseline* system (Table 2). If you account for this current difference in soil mineral N and any additional export of N in grain from the *High Nutrient* systems compared to the *Baseline*, we have recovered on average 85% of the additional fertiliser N applied in the systems (Table 2). At some locations our calculations suggest this value is over 100, which is an indication of other inputs of N, such as from legume fixation, increased mineralisation of soil organic matter in those systems, and/or the variability in measuring soil N. Importantly, these recovery figures do not include the nitrogen in organic form and if there was any increased soil organic matter in those systems.

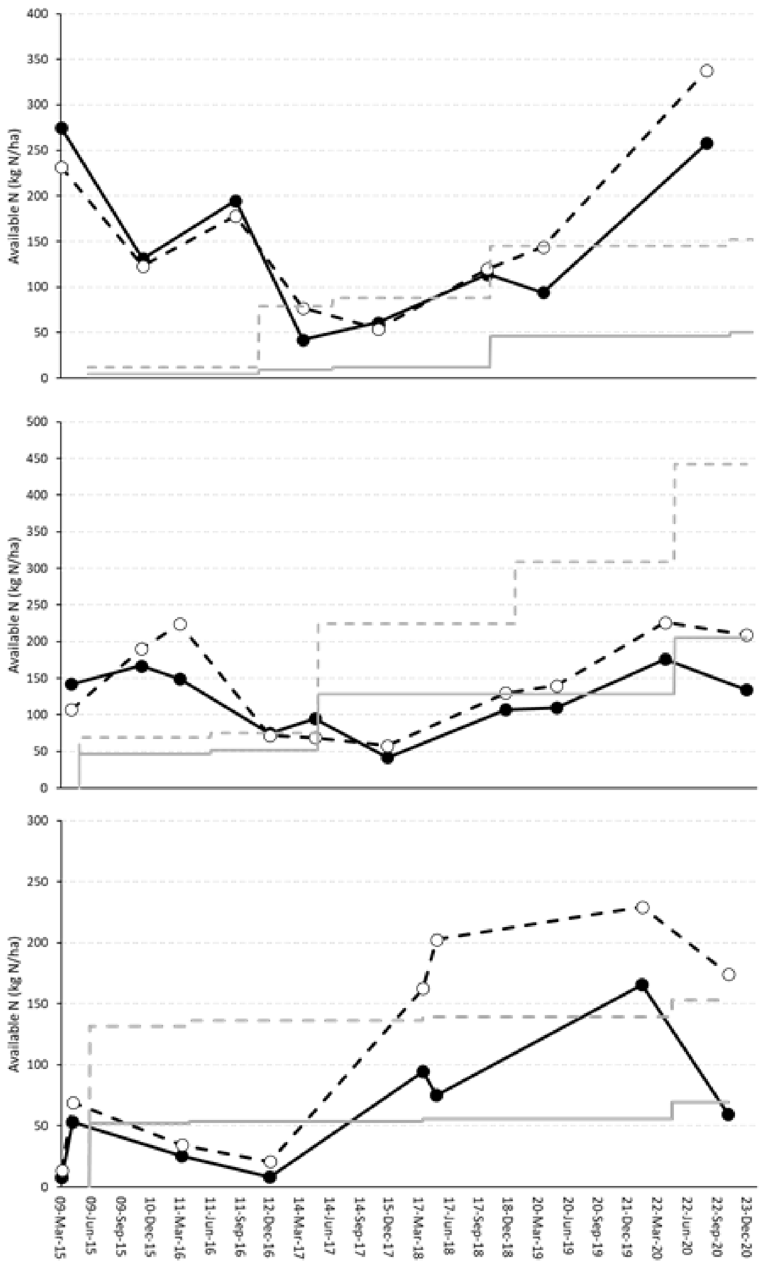

Figure 2. Changes in soil mineral N availability (Black lines - kg N/ha to 90 cm depth) and accumulated fertiliser N applied (grey lines) between *Baseline* (solid) and *High Nutrient* (dotted) systems at Pampas (top), Narrabri (middle) and Mungindi (bottom) over 6 years of experiments.

Table 2. Difference between *High Nutrient* compared to the *Baseline* fertiliser strategy in terms of soil mineral N status (at last sampling), recovery of additional fertiliser N applied (either present in the soil mineral pool or exported by crops), costs of additional fertilisers applied (over 6 years), the total relative economic position of the two systems after 6 years when either excluding or including the differences in most recent soil mineral N status.

Site comparison	Difference in change in soil mineral N at last sampling	Recovery of additional N applied	Cost of extra N fertilisers applied ($/ha)	Net benefit or cost excl. soil N ($/ha)	Net benefit or cost incl. soil N ($/ha)
Emerald	25	na	12	276	309
Billa Billa	47	135%	78	-214	-153
Narrabri	109	45%	308	-703	-561
Mungindi	99	136%	109	-201	-72
Spring Ridge	30	66%	91	-141	-102
Trangie – Red soil	31	46%	337	354	394
Trangie – Grey soil	36	41%	99	-662	-615
Pampas Mixed	123	138%	133	-85	75
Pampas Summer	89	188%	55	-76	40
Pampas Winter	4	0%	77	-442	-437
Pampas High intensity	38	29%	177	-321	-272
AVERAGE	**57**	**82%**	**134**	**-201**	**-127**

Return on investment from N strategies

Over the 6 years, the *High Nutrient* systems have incurred additional costs associated with the higher inputs of N fertilisers applied. While this value has varied between sites, depending on their inherent fertility, on average this has equated to $134/ha, or $22/ha/yr. difference in the costs incurred (noting we have assumed a fertiliser price of $1.30 per kg N). As mentioned earlier, rarely has there been a significant yield increase, and in some cases, some risks of yield penalties occurred. Only at Trangie on the red soil can we see an additional $354/ha has been generated. Across all sites on average the *High Nutrient* systems are around $200/ha behind the *Baseline* in terms of gross margin accumulated over the 6 years. However, if the additional fertiliser that has been invested into the soil mineral N pool is valued in these calculations this net cost is reduced to $127/ha or $21/ha/yr.

Conclusions

Over the experimental years we have been comparing the N strategies in the farming systems we have not had sufficiently favourable conditions to see significant grain yield increases. We have seen crop biomass increases from the additional N inputs, but this has not been converted into grain yield. Only time will tell how the expected higher returns in good seasons will change the long-term profitability and return on investment from this strategy. Regardless, this farming system strategy is likely to play out over the longer-term by maintaining the soils fertility, or lowering the net export of nutrients, and maintaining soil mineral N at a level that ensures crops have the nutrition available to utilise the better years. Ultimately our data shows that the *High Nutrient* strategy does not have a huge cost or risk to the farming system, with a high proportion of the extra N applied being recovered in subsequent years and potentially offsetting subsequent N applications. However, when conducting crop N budgets, it is critical to account for the current mineral N status which accounts for N recycling to avoid wasting unneeded fertiliser.

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Contact details

Lindsay Bell
CSIRO
203 Tor St, Toowoomba
Ph: 0409 881 988
Email: Lindsay.Bell@csiro.au

Comparing grain and cotton in northern NSW. Impacts on the cropping systems and the advantages of growing summer crops to improve $/mm and as a disease break from winter cereal dominated systems

Jon Baird[1], Lindsay Bell[2], David Lawrence[3], Jayne Gentry[3], Andrew Erbacher[3], Kathi Hertel[1], Darren Aisthorpe[3], David Lester[3]

[1] NSW DPI
[2] CSIRO
[3] DAF Qld

Key words

summer cropping, productivity, economics, soil water use, soil-borne disease

GRDC code

CSA00050, DAQ00192

Take home message

- Incorporating summer crops such as sorghum and cotton can improve farming returns in terms of $/ha and $/mm
- The legacy impact of cotton can last a number of subsequent seasons (especially soil water), so productivity needs to account for the whole cropping system, not the one crop
- A sorghum/chickpea double-crop does give similar gross margins as a single cotton crop but there are added risks of planting the second crop compared to cropping after fallows
- Applied fertiliser N was low for summer crops (2-76 kg N/ha) as the dominant source of N was from the residual mineral N and in-crop cycling from organic sources
- Summer crops provided a significant reduction in soil-borne pathogens and nematode numbers, allowing greater choice of crops and cultivars in rotations.

Introduction

The dynamic climate of the northern grains region allows growers to implement diverse cropping systems, from winter dominant to summer cropping including both grain and fibre crops. Hence, there are several options available for grain growers to diversify their crop rotations to help manage disease, weeds, and herbicide options. Summer crops can generate high-value end products (e.g. cotton), make efficient use of spring/summer rainfall, and use nitrogen (N) from mineralisation, which predominately occurs during the warmer months. But there are implications when transitioning into summer crops. Firstly, the length of the pre-plant fallow can elongate when waiting for profile moisture to fill and secondly, the crop legacy impact when returning to winter crops. These implications can decrease the economic gains associated with summer crops and reduce the benefits of a summer cropping transition. On top of these issues there is also the question of how the summer crop will perform, will the forecasted rain be adequate for achieving yields that have high economic returns.

In much of northern NSW and southern Queensland, the pillar summer crops are sorghum and dryland cotton. Dryland cotton requires cropping land to be set aside in a lengthy fallow prior to planting (>10-12 months) to accumulate sufficient moisture to support the long growing season. Post-harvest operations (e.g., pupae busting) can result in further fallow periods prior to the next crop in sequence. In comparison, sorghum can often be double cropped back to chickpea involving a shorter fallow period and easier transition back into winter cropping. Both sequences were investigated within the farming systems project over the last six years at various points in time and locations. In this paper, we compare the performance of crop sequences involving sorghum and cotton compared with those focusing on winter crops grown over a common period at three sites (Narrabri, Spring Ridge and Pampas). This paper looks at the legacy implication of summer cropping, particularly sorghum and cotton and the implications they may have on a farming system in the northern grains region (NGR) and the economic risks of these systems. The paper details the impacts on nitrogen (N), water use and disease/pathogen levels collected from the northern farming systems project over the last six years.

Farming systems research approach and assumptions

The Northern Farming System project was initiated in 2015 and is co-funded by GRDC, CSIRO, QDAF and NSW DPI, with six regional sites (Qld – Emerald, Billa Billa, Mungindi and NSW – Narrabri, Spring Ridge and Trangie), plus a project core site located at Pampas, Qld. Over the last six years, this project has compared over 80 combinations of sites and cropping systems, which provides an opportunity to compare different crop sequences and the legacies effects of crop choice and management over several years in a cropping system on nutrition, disease, weeds and soil water.

This paper will focus on systems where the cropping sequence included crops aligned with the below themes within the same period (2016-2019).

1. Winter – winter only crops with short summer fallows, planting occurring at 50% plant available moisture (PAW). Crops included wheat, chickpea, canola and field pea.
2. Sorghum – sequence containing winter crops (wheat) leading into sorghum with the opportunity of double-crop chickpea.
3. Cotton – cropping sequence focusing on a dryland cotton crop, with rotation crop dependant on available profile moisture. The cotton plant was activated when soil moisture reached 80% PAW to increase yield potential.

Soil moisture and N status were measured at all sites before and post every planted crop or twice annually during fallow years. Crops were managed and sown according to local best management guidelines. For example, relevant to our paper here, cotton was planted on single skip (2 in 1 out) configurations in the higher rainfall regions, and super single or double-skip in the western sites (e.g. Mungindi), and similarly sorghum was sown on 1 m solid in the eastern sites, but on single skip in drier environments.

Across the systems, the inputs required in each system were recorded to calculate the system gross margin return using a 10-year average grain price to Brisbane port minus a set freight charge. Commodity prices per tonne included – chickpea = $504, sorghum = $220, cotton = $1080 (lint and seed), which equates to a cotton price of $480/bale and seed price of $260 per tonne.

Summer crop sequence performance

Firstly, using the farming systems data from Narrabri, Spring Ridge and Pampas we have explored how crop sequences involving a summer pillar crop of sorghum or dryland cotton have performed compared to a winter crop only system. This was done over a 4-year period to account for the differences in fallow periods required both before and after each crop. The common period of comparison was between December 2015 and December 2019. It is worth noting that this period was drier than average at all sites (approximately 1600-1800 mm of rain over this period, or 400-450 mm per year), which induced longer fallow periods across all sequences, and several crops achieved low or negative gross margins owing to very little in-crop rainfall.

Nonetheless, these comparisons show the sequences involving a summer crop of sorghum were superior to the winter-only sequences at all 3 sites in terms of gross margin and system water-use efficiency (i.e. $/mm). Crop sequences targeting dryland cotton were variable, achieving lower GM returns at 2 sites (Narrabri and Pampas). The dryland cotton yields were reduced by hot and dry conditions, achieving yields of 2-2.5 bales per ha (Table 1). On the other hand, the crop sequence targeting dryland cotton at Spring Ridge, achieved a similar total gross margin from this single crop, despite being fallow the remainder of the time.

The winter-only sequence did not plant a crop in the 2018 winter at any of the sites due to lack of accumulated moisture and/or a lack of surface soil moisture to allow sowing.

Table 1. Economic performance and N balance of 4-year crop sequences (2016-2019) comparing the systems based on winter crops including break crops or using a sorghum or cotton crop during at three farming systems experimental sites. The notation for the sequence of crops include: x = 6-8 month fallow, Cp = Chickpea, Wt = Wheat, Fp = field pea, Cn = Canola, Sg = Sorghum, Ct = Cotton.

Location	Pillar crop	Rotation	Total gross margin ($/ha)	WUE ($/ha/mm)	N applied (kg/ha)	N exported (kg/ha)
Narrabri	Winter	x-Fp-x-Cn-x-x-x-Wt	-116	0	154	96
	Sorghum	x-Cp-x-Wt-x-x-Sg-x	1292	0.92	81	137
	Cotton	x-x-Ct-x-x-x-x-x	766	0.64	58	45
Spring Ridge	Winter	x-Fp-x-Wt-x-x-x-Cn	1057	0.83	57	200
	Sorghum	x-Cp-x-Wt-x-x-Sg-x	1487	1.17	86	173
	Cotton	x-x-x-x-Ct-x-x-x	1440	1.14	29	66
Pampas	Winter	x-Cp-x-Wt-x-x-x-x	2195	1.37	41	198
	Sorghum	x-x-Sg-Cp-x-x-Sg-x	2661	1.66	46	239
	Cotton	x-x-Ct-Wt-x-x-x-x	1776	1.11	151	37

Relative returns of summer crop options

The results from the three sites shows that it is crucial to consider the impact or profitability of the sequence of crops rather than individual crops grown in a particular season. When comparing the potential of sorghum and cotton as prospective summer crops, it is important to consider the future crop opportunities and legacies, particularly the opportunity to double crop following sorghum with chickpea which is rarely viable following cotton.

As such our farming systems sites have demonstrated a couple of examples of these two comparisons. Firstly, at Pampas in summer 16/17 both sorghum and cotton crops were sown following a long fallow, but a chickpea crop followed the sorghum crop in 2017. In this comparison, sorghum yielded 7.2 t/ha (GM of $1376) plus chickpeas produced a further 1.6 t/ha (GM of $573), for a total of $1950/ha, while the cotton crop yielded 1.9 t/ha (i.e., 3.8 bales/ha) for a GM of $1468.

The second comparison occurred during a lower yielding 2018/19 summer with grain yields significantly lower for sorghum (4.5 t/ha) with a net return of $710 per ha. There was no opportunity to double crop following the sorghum. By comparison, the cotton crop yielded (1.4 t/ha or 3.0 bales/ha), resulting in a net return of $1175 per ha.

These datasets show that cotton can generate more revenue and a higher return than a sorghum crop in the same season. A similar economic return to dryland cotton can be generated via a sorghum-chickpea double crop, but this opportunity may not be available in all years.

Water and N legacies of sorghum vs cotton

Further to the differences in system economic returns offered by different summer crop options, it is also important to understand and consider their legacies on soil water and nitrogen availability that can impact the performance and input requirements of subsequent crops.

Water use and harvest soil water

Several comparisons where both sorghum and dryland cotton were sown in the same season provide some comparisons of the legacy impacts on PAW and available N (Tabled 2). The data highlighted how low PAW after harvest restricted the potential for double cropping behind either sorghum or cotton. There was only one scenario (Pampas 2016/17) where sorghum was followed by a chickpea double crop. In the same season at Pampas, the cotton was followed by a salvage wheat crop, but there was a large difference in final soil water of over 100 mm. This difference persisted through a long fallow period, where a 60 mm difference in soil water was present at the sowing of the next crop.

The greater PAW after sorghum compared to cotton was also found at Pampas 2018/19, where post-crop PAW was ~0 mm after sorghum and negative 32mm after cotton. Similar levels of soil water extraction occurred at Mungindi (2016/17) and at both locations, the longer-term PAW was higher after sorghum compared to after cotton (range 5-35 mm).

We also note that cotton due to its lower biomass accumulation often left more residual N post-harvest than sorghum. The lower levels of mineral N after sorghum could have implications for N inputs required in subsequent crops

Table 2. Summer cropping impacts on plant available water (mm), water use efficiency (WUE) and residual mineral N

Site	Crop sequence	Pre-sowing PAW (mm)	Final PAW (mm)	Post short fallow PAW (mm)	Post long fallow PAW (mm)	Pre-sowing mineral N (kg N/ha	Final mineral N (kg N/ha)	Applied N fertiliser (kg N/ha)
Mungindi 2016	Sorghum	138	11		110	57	29	2
	Cotton	139	19		105	30	67	11
Pampas 2016/17	Sorghum-chickpea	240	100	155	130	195	55	5
	Cotton-wheat	253	0	80	70	178	100	76
Pampas 2018	Sorghum	120	2	70	150	114	94	34
	Cotton	149	-32	30	115	120	94	2

Note: short fallow = <6 months, Long fallow = >10 months.

Nitrogen use and residual N legacy

A key aspect of dominant summer rainfall areas is the beneficial N mineralisation from soil organic N occurring during the warmer months. The total amount of mineral N from organic sources in northern farming systems has been documented by Baird *et al*., (2018), where fallow periods, especially over the summer months, significantly increased mineral N within the system. Growing summer crops did reduce the mineral N accumulation during the warmer months but applied fertiliser N was low (2-76 kg N/ha) as native N sources from the soil supplied a significant amount of N to the plant. The project found that the longer season growth of cotton had greater use of mineralised N and maintained soil mineral N levels compared to sorghum. As a result, residual N after cotton in all comparisons in Table 3 were greater than the residual N after sorghum crops (the difference ranging from 38-75 kg N/ha).

The legacy impact on rotation crops

The immediate returns of summer crops can be negated by the poor performance of the subsequent winter crop (Table 3). Firstly, when we compare a winter dominant cropping system (chickpea-fallow-wheat) to a summer-winter double crop (cotton-wheat or sorghum-wheat) situation at Narrabri, we demonstrate the significant yield penalty (60%) likely from the reduced soil water prior to planting the subsequent crop.

Second, the longer growing season of cotton had a greater influence on soil water use, decreasing the sowing PAW for the following crops and resulting in a significant reduction in yield compared to the crop grown following sorghum. Consequently, there is a high risk of crop underperformance when cropping after cotton, and generally growers will need to fallow their fields until the soil has been able to restore soil water levels to reduce the risk of lower crop yields.

Table 3. Legacy impact of summer crops on the subsequent crop yield

Site	Crop	Previous crop (season)	Following crop yield (t/ha)
Narrabri 2017	Wheat	Cotton (2016/17)	1.0
	Wheat	Chickpea (2016)	2.2
Pampas 2020	Sorghum	Cotton (2016/17)	2.8
	Sorghum	Sorghum (2016/17)	4.1
	Mungbean	Cotton (2016/17)	1.1
	Mungbean	Sorghum (2016/17)	1.3
Mungindi 2018	Wheat	Cotton (2016/17)	1.2
	Wheat	Chickpea (2016)	0.8

Measured disease and nematode levels

Summer crops provided a break for winter crop disease and nematode loads in our cropping soils. At Narrabri *P. thornei* root lesion nematode numbers were maintained at low levels after a cotton crop within the Low intensity system (Figure 1). At the same time, a winter-based sequence containing wheat and chickpea (Baseline) resulted in a spike for *P. thornei* (8.8 *Pt*/g soil). As a result of this spike in nematode numbers within the Baseline system, management was required to select wheat cultivars with higher nematode tolerance.

The use of summer crop options also reduced moderate to high levels of yellow leaf spot inoculum down to low concentrations at the Spring Ridge site. This break in disease and nematodes allows for a greater diversity of crop choices for future rotations, as the susceptible crops are unlikely to suffer yield loss from the lower pathogen loads in the cropping system (Erbacher, 2019).

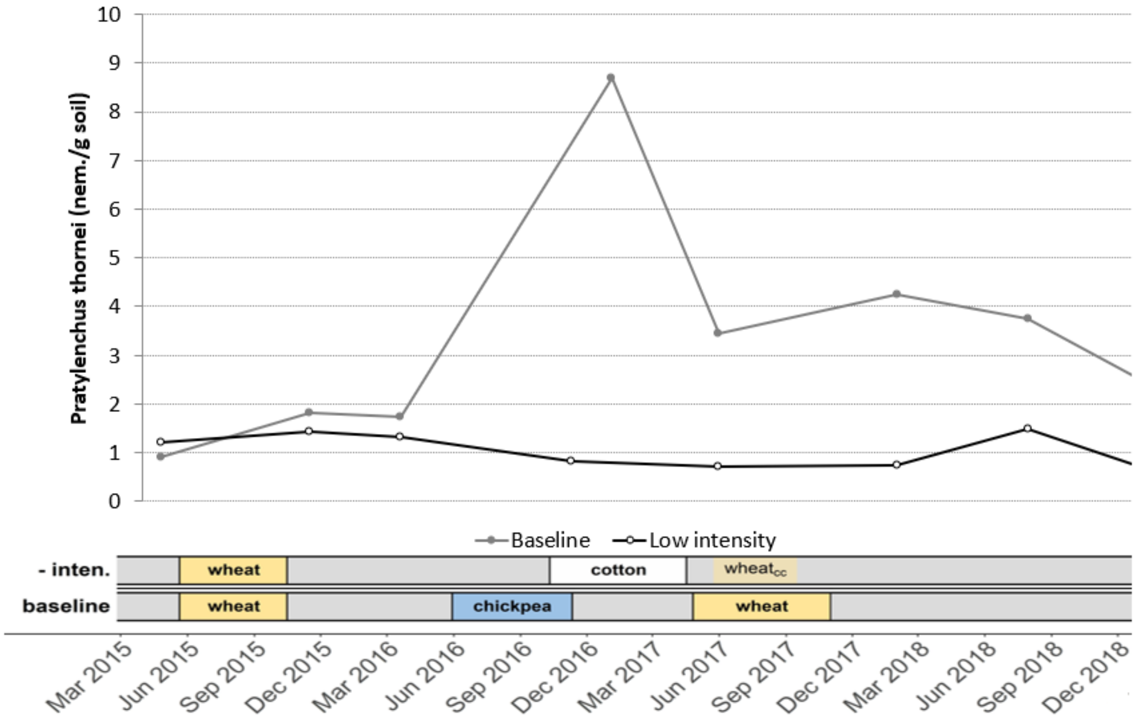

Figure 1. *P thornei* levels at Narrabri between 2015 and 2018. Baseline = Baseline, - inten. = Low intensity.

Conclusion

Summer crops provide a complementary addition to cropping systems in northern NSW and southern Queensland. The improvement in rainfall use efficiency due to the immediate use of summer rainfall can provide growers with greater returns in terms of $/mm compared to waiting for planting a winter crop. Despite the risk of missing crops and the need to either long fallow or double crop in order to return to a winter crop sequence, even under the dry seasonal conditions between 2015-2019 the sequences involving a summer crop have performed better. If rainfall does become limited late in the growing season and the harvest PAW is low, the opportunity for a winter double crop is low and there are likely significant yield penalties (up to 60%) for such crops following a summer crop (especially cotton). However, when conditions are favourable the opportunity to utilise a double crop of chickpea in combination with sorghum can perform favourably compared to other crop sequences and dryland cotton.

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Contact details

Jon Baird
NSW DPI
21888 Kamilaroi Highway, Narrabri
Ph: 0429 136581
Email: jon.baird@dpi.nsw.gov.au

Sorghum and dryland cotton - the pros and cons

Geoff Manchee, Leverton Pastoral Company

Key words

sorghum, cotton, dryland, cropping systems, grower experience, rotation

Take home message

There are benefits and downsides to both crops. They need to fit your farming system and longer term rotational plan.

Background

We have been trying to grow half our summer rotation to sorghum and half to cotton for several years. Our rotation is four or five years based on soil type. Heavier black soils four year and the lighter slope country five years.

- Black soils: wheat, barley, fallow, sorghum/cotton
- Lighter country: wheat, legume, wheat, fallow, sorghum/cotton.

The primary reasons we grow both sorghum and cotton in a planned rotation:

1. Our long-term rotation helps minimise disease, manage weeds and improve nutrition
2. The ability to capture rainfall during different periods of the summer
3. Spreads our workload of farming operations.

Sorghum

Sow in September to take advantage of wet winter harvest period (2021 a classic example).

Pros

- Provides good crown rot and winter weed break
- Early sorghum plant works well with double crop into chickpeas
- Sorghum generally suits our conditions weather and soil conditions, hot dry summers except at flowering
- Sorghum has a strong coleoptile and is good at pushing up out of the ground even in tough conditions. It can be sown relatively deep and pressed firmly
- Sorghum is more attractive now than a few years ago because Chinese buying has improved pricing compared to barley and wheat. China is using the sorghum to make Baijiu known as a Firewater spirit, which is a national drink in China. It is also being used as a gluten free food.
- Relatively simple to grow, generally one insect spray (possibly two), but no disease problems. It just needs rain
- Generally, sorghum is relatively easy to harvest, although we have found ‘stay green’ varieties tricky with spray out timing so have veered away from these.

Cons

- Struggles with heat and dry periods around flowering
- Temperatures over 40 degrees, especially hot winds can cook the grain in the heads, with the result being poor yield or high screenings
- Can be difficult to control grasses if they are not under control at planting, especially on wider row spacing.

Numbers: Sorghum benchmarking past six years not including 20/21

- Average yield 2.6t/ha
- Direct costs $514/ha
- Gross margin: $206/ha

Cotton

Find a good agronomist

Two key decisions:

1. Need to decide early if planning to strip or pick cotton. If stripping, keep the crop short and therefore Pix regularly if the season is good
2. Row configuration super single, single skip or double skip.

Bollgard® and Roundup Ready® has made the management significantly easier, with the agronomist generally able to give a weeks' notice before a spraying for sucking pests, compared to about 6 hours when growing conventional cotton with Heliothis.

The application of glyphosate over the cotton to control weeds especially in dryland has made growing wider row configurations and managing summer grasses significantly easier. Non Roundup Ready cotton was much harder. Shield spray is very time consuming, tricky and there are few registered products.

Pros

- With cotton we try to use tillage to help delay chemical resistance build-up
- Great crop to bolster our regional economy. The average direct growing costs over the past six years were $1,125/ha
- We aim to sow in early November, straight after winter crop harvest to take advantage of summer rains in January and February. This does not always work out. The year before last was too dry to sow and last year too wet, which meant we ended up planting late in mid-December
- Provides a good break for crown rot and winter weeds
- Tap rooted crop is great for helping break up any hard pan you might have. An easy way to tell if a hard pan exists, is to pull some plants out after picking/stripping and see if the main root is straight or has a 90-degree bend
- Cotton positively affects soil performance for subsequent crops. I have found it has given old farming paddocks a new lease of life
- The 748 Bollgard plant can put a large amount of yield on a small bush from a good rain event. Yield potential is very high if it can receive rain at the right times.

Cons

- Cotton has a weak coleoptile especially the new Bollgard varieties and is very tricky to get a good strike. It needs good conditions and ideally a shower of rain after planting, but not heavy rain that would pack the soil down and cause the crop to struggle to push through
- Cotton suffers from long fallow disorder (depleted levels of soil mycorrhiza inoculum that can lead to deficiencies in P and Zn due to poor root uptake) as we found last year after the drought in 2019 with very little stubble cover. The cotton came up but sat there for what seemed like a month and did nothing. Some plants even died for no particular reason. It was very disheartening; the best-looking plants were beside weeds like fleabane. Very strange. Even this year I am seeing similar scenarios
- Expensive crop to grow which increases your risk of a larger loss if things go wrong
- Trying to kill the cotton slashing, mulching and root cutting, then chisel or blade plough
- Cotton marketing can be tricky. The premiums and discounts can be ugly, especially if there is more than one problem like last year where we had colour, leaf and micronaire issues
- Working - this year we are so far behind due to prolonged wet conditions, the paddocks are embarrassing with the cotton out of control over winter harvest. We can't get the chisel plough through it due to blocking up
- In dry years cotton takes a lot of moisture out of soil at depth, it does not leave a lot of stubble cover and it takes a lot of rain to fill the profile back up.

Numbers: Cotton benchmarking for the past six years (not including 20/21)

- Average yield 2.2 bales/ha
- Direct costs $1,125/ha
- Gross margin: $152/ha

Contact details

Geoff Manchee
Moree
Mobile: 0428 548 614

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How resilient is your farming system strategy for the long haul? Long term simulations of risk and sustainability of various farming systems experiments using APSIM.

Jeremy Whish[1], Lindsay Bell[2] and Peter de Voil[3]

[1] CSIRO Agriculture and Food, 306 Carmody Rd, St Lucia, Qld 4067,
[2] CSIRO Agriculture and Food, 203 Tor St, Toowoomba, Qld 4350,
[3] QAAFI, University of Queensland, Gatton Campus Qld 4343

Key words

crop rotation, cropping sequence, crop choice, sowing rules

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Take home message

- Increasing cropping intensity can improve profitability but can increase the risk of a negative gross margin
- An increased cropping intensity removes fallows within the system, reducing the ability to buffer both the biological and logistical complexities of the farming system
- Using long term simulation of management decision rules highlights the limitations of each rule and identifies the long-term consequences of each decision.

Introduction

Deciding what to plant, when and where, is a complex decision that all farmers face. Personal preference, enthusiasm for a crop type and its historic success are often tempered by weed control strategies, disease issues, seasonal outlook, financial outlook, current soil water, summer verses winter split, seed availability and logistics. To reduce the complexity of these decisions, two alternative approaches have emerged. Firstly, the fixed rotation where a sequence of compatible crops are arranged in an agronomically sensible order that helps manage the major constraints, provide logistical certainty, while offering diversity of crop type, sowing date and season. This approach aims to give each crop the best opportunity of success while constraining the populations of pests, weeds or disease. The major criticism of the fixed rotation is its lack of flexibility, which limits the ability to capitalise on high prices of particular crops or respond to particularly good (or bad) seasons. The polar opposite of the fixed rotation would be a purely opportunistic system, where the most suitable crop is planted whenever the opportunity arises. In reality, this is probably a utopian description of a cropping sequence, because good agronomics, availability of seed and personal crop preference will add a degree of structure to all sequences. However, between these two extremes lie reality, most farmers have a degree of structure that they opportunistically vary based on their personal risk profile.

Our previous modelling compared different fixed cropping rotations to see if some are more profitable than others (Whish *et al.,* 2018; Hochman *et al.*, 2020) and how adaptable they are across environments. The conclusion was that increasing crop intensity by reducing or removing the long fallows, used to switch between summer and winter phases of the rotation, increased annual gross margins. The downside to this increased intensity and depending on the environment, was an increase in the number of crops retuning a negative gross margin. In addition, the extra crops reduced the average yields of the existing crops and annual return on investment per crop decreased. In short, increasing intensity had the potential to improve system profitability over the long term, but resulted in extended periods of time generating negative gross margins.

Adding flexibility to the sequence by means of specific sowing rules (such as sow on PAW of 100mm) identified a way these structured rotations could have their intensity increased without significantly increasing risk (Whish *et al.,* 2019). This concept of using rules to develop the cropping sequence has been presented as a series of leavers that can manipulate the farming systems and is being tested within the field experiments of the northern farming systems project. This rule-based approach to crop selection has now run in the field for 6 years, but how will they work over the long term?

The value of modelling has often been stated as taking our experiences from a few years and exploring their performance over many. This has been the case with the original rotation modelling and then the combined flexible modelling, but these both have a specific copping pattern that is followed. To capture the management of the farming systems rule-based field trials has proven a greater challenge.

In this paper we report on the success of simulating some of the farming systems cropping strategy with APSIM. We then present a scenario analysis that uses this new approach to compare the economic returns for Goondiwindi and Pampas from 4 different rotation strategies that use the same four crops.

Modelling the farming systems teams decisions

Method and approach

The farming systems experiments have over 80 crop sequences covering different cropping, nutrition and pasture options across sites. In this paper we will focus only on one of these systems as an example to demonstrate how APSIM modelled the rule-based decisions made by the farming systems team.

Different rules were combined to imitate the complex decisions made when deciding what and when a crop could be sown. Hence, we specified in the model a series of 'decisions' that dictate the timing of crop sowing, and the choice of crops that can be made. This was compared to the actual crop sequence and timings deployed in the experiments.

In all simulations sowing occurred, when the minimum rainfall (e.g. 15mm over 3 days) and plant available water (90mm) triggers were exceeded during the sowing window for that crop. For example, the available water threshold could be varied, i.e. a higher intensity system had a lower plant available water (PAW) requirement (90 mm) compared to the baseline system (150 mm).

Then there were rules that dictated the crop types selected, which were largely driven by the requirement for a break between repeat sowings of that particular crop, the selection of crops available and then crop preferences. Hence, for each crop the break between repeat sowings, (e.g. 2 breaks between each chickpea crop) or how many times a crop could be repeated (e.g. 2 sorghum crops in a row; Table 1) were specified. Higher diversity systems had an increased range of crop options to choose from (up to 13 different crop types) and limitations on what crop type could follow each crop (e.g. no cereal following a cereal, no legumes following a legume; Table 1). Finally, all crops included a pre-determined preference to solve conflict (e.g. if wheat and chickpea could be sown at the same time, chickpea would be selected because it has the higher preference value; Table 1).

Table 1. Decision based rules used to determine if a crop could be sown.

Rule	Variable
Sowing	Sowing window between dates
	Plant available soil water in mm (PAW)
	Amount of rainfall (mm) over a number of days
BlanketRule	Number of breaks (i.e. 6 month periods) between same crop planting
BlanketRule	The maximum number of that crop that can occur in a row
LastNotLegume	Last crop was not a legume
LastNotWinterCereal	Last crop was not a winter cereal
Preference	Scale of 1-5 priority for crop selection (5 Highest, 1-lowest)

Here we examine how well the model-specified rules replicate the crop sequence grown in the W03 system at the Pampas experimental site. The W03 system is a winter-based system that aims to have a high legume frequency and as such has only winter crop options, but includes more legume options to enable every second crop sown to be a legume (Table 2).

Table 2. Decision based rules applied to the winter crop system (W03) simulation and the selection of crops available, their associated rules specifying when the crops could be sown and the soil water trigger used to instigate each sowing event.

System Code	Details	Crops	BlanketRules	Intensity Rule PAW mm	Diversity Rule
W03	Higher Legume Frequency	Wheat	Up to 2 in row	120	LastNotCereal
		Chickpea	2 crop break	120	
		Barley	3 crop break	120	LastNotCereal
		Faba bean	2 crop breaks	120	
		Fieldpea	2 crop breaks	120	

APSIM's Rule-based crop selection vs the farming systems teams crop selection

Some differences were observed between the model output using the rule-based decisions and the crop choices and timing of farming systems team (Table 3). However, in general the model reproduced the decisions of the farming systems team well. Where the model differed highlights the key differences in the way the model selects a crop and the way the team selects a crop.

The differences can be explained by the decision-based sowing rule. APSIM does not have foresight, so only respond to the conditions of the day (rainfall, stored soil water) .

For example: the barley window opens before the wheat window, so once the soil water level is achieved sowing occurs in APSIM. In 2016, the early sowing of barley was missed by the team (due to logistics and a forecast of little follow-up rain) no additional rain fell until late June, when wheat was sown in the experiment. This difference then had a legacy impacting the future crops. In 2018 the model simulated that the early sown barley crop in 2016 had allowed for a longer fallow compared to the later sown wheat crop in that same year. As a result, more water was stored following barley compared to wheat allowing a crop to be sown by the model in 2018, but not the field. This additional wheat crop then caused the difference in crop selection in 2020 in the modelled crop sequence.

Table 3. Results from observed and simulated crop selection rotation W03 at Pampas experiment over the 6 experimental years.

Year	APSIM sowing date	APSIM crop choice	System trial crop choice	System trial sowing date
2015	2/5/15	Fababean	Fababean	13/5/15
2016	16/4/16	Barley	Wheat	1/7/16
2017	14/6/17	Chickpea	Chickpea	26/6/17
2018	3/7/18	Wheat		
2020	22/5/20	Chickpea	Wheat	27/5/20
2021	12/5/21	Fababean	Fababean	23/4/21

Long-term systems scenario analysis

Method and approach

Since the rule-based decisions were shown to be functioning satisfactorily, a long-term scenario analysis was undertaken to extrapolate these over a wider range of seasonal conditions. The scenario analysis compared four crop sequences at Pampas and Goondiwindi over a 64-year period (1957-2021). All sequences included 4 crops (sorghum, chickpea, wheat and mungbean) and had the same rules required to trigger a sowing event.

The first sequence was fixed (Fixed) where every crop was sown every year, four crops in 4 years. If the sowing rules were not met during the sowing window the crop was sown at the end of the window (Table 4). This is described as the must sow rule.

The second sequence was the Flexible (Flex) sequence. This sequence was the same as the fixed rotation with the must sow rule applied to the sorghum, wheat and chickpea crops, but mungbean was only sown if conditions were satisfied.

The third sequence was the free or opportunistic sequence (Free). Here any crop could be sown whenever the rules allowed (Table 4).

The final sequence was the same as the Free sequence but included a rule that prevented two legume crops being sown consecutively (FreeL) (Table 4).

Table 4. Summary of the different management rules applied to the scenario analysis simulations for Goondiwindi and Pampas

System Code	Crops	Must sow	BlanketRules	Intensity Rule PAW mm	Diversity Rule
Fixed	Wheat	yes		90	
	Chickpea	yes		90	
	Sorghum	yes		90	
	Mungbean	yes		60	
Flex	Wheat	yes		90	
	Chickpea	yes		90	
	Sorghum	yes		90	
	Mungbean	no		60	
Free	Wheat	No	2 in row	90	LastNotWinterCereal
	Chickpea	No	2 crop break	90	
	Sorghum	No	2 in row	90	
	Mungbean	No	2 crop breaks	60	
FreeL	Wheat	No	2 in row	90	LastNotWinterCereal
	Chickpea	No	2 crop break	90	LastNotLegume
	Sorghum	No	2 in row	90	
	Mungbean	**No**	**2 crop break**	**60**	**LastNotLegume**

Results

Modelled comparisons between the two sites Pampas and Goondiwindi supported all previous studies. Where by, the higher rainfall site of Pampas can easily sustain a cropping intensity of 1 crop per year or more, with increased cropping intensity in this area not significantly increasing risk (Table 5). For this reason, the remainder of this paper will concentrate on the results from Goondiwindi (Whish *et al*., 2018, Whish *et al*., 2019, Hochman *et al*., 2020).

In contrast at Goondiwindi, the lower annual rainfall increases the risk of experiencing a negative gross margin crop at a rate of 1 crop in ~7 (Table 5). An interesting observation was increasing the intensity by adherence to the rules in the free treatment, increased the intensity to 1.4 crops per year and improved the mean annual gross margin by $79; but did not significantly change the risk. However, an inspection of the cropping sequence showed this result was achieved by regularly planting back-to-back legumes. The inclusion of the legume rule (no legumes following legumes) improve the agronomics of the sequence, but reduced the gross margin to be the same as the flexible system (Table 5). The increased cropping intensity produced the increased annual gross margin in the Free system but individually the returns of each crop were reduced (Table 7). The additional cost of sowing more crops for a reduced value, explains the lower return on investment for these systems.

Table 5. A comparison of the mean annual gross margins for each system after 64 years and an estimate of the risk required to achieve them

Site	Treatment	No. Crops sown	Mean annual gross margin ($/ha/yr)	Percent crops with negative gross margin (%)	Intensity (crops/yr)	Return on investment ($/$)
Goondiwindi	Fixed	65	524	15	1	1.22
Goondiwindi	Flexible	64	533	12	1	1.25
Goondiwindi	Free	87	612	16	1.4	1.11
Goondiwindi	FreeL	78	533	13	1.2	1.05
Pampas	Fixed	65	911	5	1	2.01
Pampas	Flexible	65	911	5	1	2.01
Pampas	Free	107	1143	9	1.7	1.66
Pampas	FreeL	103	1147	8	1.6	1.67

Despite having the same mean annual gross margin, the FreeL system and the Flexible system did not plant the same number of crops or the same crop types at the same time (Table 5). Overall, the 14 additional crops sown in the Free L treatment were predominantly summer crops. This shifted the summer to winter ratio from a potential 50:50 to 66:34. A similar trend towards summer crops was observed in the Free rotation, so it was not exclusively a result of the additional legume rule (Table 6).

Table 6. The difference in summer to winter split within a sequence.

Site	Treatment	Percent summer crops (%)	Percent winter crops (%)
Goondiwindi	Fixed	50	50
Goondiwindi	Flexible	47	53
Goondiwindi	Free	64	36
Goondiwindi	FreeL	66	34
Pampas	Fixed	50	50
Pampas	Flexible	50	50
Pampas	Free	58	42
Pampas	FreeL	57	43

If the individual returns from each crop are examined, the difference between the Flexible sequence and the FreeL sequence becomes more apparent. Despite both sequences having the same mean annual gross margin, they achieve it differently. The FreeL rotation has more sorghum crops and 5 fewer chickpea crops (Table 7), but more importantly the average returns from these chickpea crops are less (Table 8). The increased cropping intensity has reduced the returns from all crops except sorghum. This is due to the rule that allowed 2 sorghum crops to follow each other, allowing a continuous summer cycle of sorghum and mungbean to occur in low rainfall years.

The reduced opportunity to store soil water before winter prevented the switch from a summer crop sequence back to winter crops until a wet season allowed the winter sowing trigger to be satisfied. When the switch did occur, it was usually as a result of a double crop wheat or chickpea crop following a sorghum or mungbean crop. When the switch occurs, the lower initial starting soil water conditions of the double crop meant a lower yield potential from these crops compared to the flexible sequence, where the winter crops were always preceded by a short or long fallow.

Table 7. The number of individual crops sown in each rotation over the 64 years of simulation

Site	Treatment	Chickpea	Mungbean	Sorghum	Wheat
Goondiwindi	Fixed	16	16	17	16
Goondiwindi	Flexible	16	15	17	16
Goondiwindi	Free	16	22	28	21
Goondiwindi	Free L	11	15	32	20
Pampas	Fixed	16	16	17	16
Pampas	Flexible	16	16	17	16
Pampas	Free	23	22	35	27
Pampas	Free L	16	16	39	32

Table 8. Mean crop gross margins from crops grown in the different rotation systems across 64 years

Site	Treatment	Chickpea	Mungbean	Sorghum	Wheat
Goondiwindi	Fixed	874	662	165	386
Goondiwindi	Flexible	874	725	183	384
Goondiwindi	Free	628	416	430	378
Goondiwindi	FreeL	706	397	402	377
Pampas	Fixed	1192	1145	641	625
Pampas	Flexible	1192	1145	641	625
Pampas	Free	858	782	672	470
Pampas	FreeL	916	632	766	588

This reinforces previous results that show improving profitability by increasing cropping intensity within a water limited environment comes at a cost. Overall profits may increase, but each individual crops value may decrease (Table 8). The advantage of a fixed rotation is it allows resources to be prioritised to high value crops. For example, if a high value crop like cotton is included, then it can always be preceded by a long fallow to improve its odds and reduce risk. Similar strategies can be tested in this rule-based simulation. The examples presented all used the same soil water trigger which is quite low for the region, encouraging a high cropping intensity. If the summer crops had a higher trigger compared to the winter crops, then the dynamics between summer and winter would change and an increase in fallows may occur.

Conclusion

The modelling scenarios presented are different to the types of modelling that we have presented over the last 20 years. Historically, we have shown how the models can reproduce yields observed in the field and then used the model to investigate different management scenarios over time with the hope of improving decisions and reducing risk of individual crops.

The focus of the modelling presented here, is not the yield, but the decision to plant a specific crop where and when we did, and the rules that surround or drive that decision. This can be confronting, as the farming systems team discovered. Why was barley not sown on the early sowing opportunity in 2016? Reasons included seed supply, access to machinery and staff availability. Real reasons that are not dissimilar to why many paddocks are not sown at the optimal time and incur a yield gap. This highlighted that logistics and labour are as important to the creation of a yield gap as biological factors such as nematode burdens or under application of nitrogen. Fallows have a real value in northern farming systems by providing disease breaks, refilling profiles and buffering the system from a biological and management perspective.

The modelling presented here is not designed to optimise a range of variables and produce the perfect sequence that can be rolled out across the country. The aim of this work is to look for new opportunities within existing systems. To understand the importance of different environments and assess different rules for their ability to improve economic potential and reduce risk. To that end this work demonstrates the enhanced capability of simulation models like APSIM to aid in testing farm management decisions. The use of APSIM as a boundary object to help consultants, researchers and growers refine and understand the consequences of crop selection decisions is the future for this work and the best way to practically improve the profitability of crop sequences in the northern-grains region.

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Contact details

Jeremy Whish
CSIRO Agriculture and Food
306 Carmody Rd, St Lucia, Qld 4067
Ph: 07 3214 2448
Email: Jeremy.Whish@csiro.au

Deep P and K - Outcomes from 8+ years of research: the good, the bad and the ugly

Dave Lester[1], Doug Sands[1] and Mike Bell[2]

[1] DAF Queensland
[2] University of Qld

Key words

nitrogen, phosphorus, potassium, Subsurface, deep-placement, immobile nutrients, 4R

GRDC codes

DAQ00148, UQ1302, UQ00063, UQ00078, UQ00082, UQ00086, UOQ1805 and UOQ1905

Take home messages

- Stratified soil testing guides fertility and constraint identification. These tests do not need to be conducted annually for immobile nutrients and constraints
- Research experiments with subsurface placement of fertiliser phosphorus (P) at around 20-25 cm on low Colwell P subsoil tests has significantly increased grain yield in central Queensland (CQ) across range of wheat, chickpea and sorghum crops. Winter cereals across southern Qld are generally also positively responding, but chickpeas and sorghum responses in this region have been mixed, ranging from positive to no effect. Data for northwest slopes and plains of NSW is very limited
- The relationships between crop P uptake and grain yield for chickpea, wheat and sorghum are robust. As you get more P into the plant, yields are increasing
- Potassium is an emerging yield constraint, but data sets are not yet as extensive as for P.

Background introduction

Current research into phosphorus (P), potassium (K) and sulfur (S) started in 2009 in DAQ00148 (Bell 2012) with a re-examination of the critical soil test values measuring the fertility status of soils across the northern grains region (NGR). The review established the consistent negative nutrient balance of macronutrients (NPKS) across all the subregions of the NGR confirming a declining fertility base of the soil resource. Observations of consistent depletion of P in the subsoil layers (10-30 and 30-60cm) were also made, and consistent with results of a long-term N x P experiment (Wang *et al.,* 2007), this effect was shown to remain despite fertiliser P additions to the surface layers. These results highlighted the increasing stratification of immobile nutrients in topsoils across the region. The Wang *et al.* (2007) study from Colonsay had shown that approximately 50% of the net P removal occurred from below the top 10cm, with the majority being withdrawn from the 10-30cm depth.

Strategies to assess soil P fertility of both the 0-10 and 10-30cm layers started to evolve. The BSES-P method (a dilute sulfuric acid extractant) was found to provide some indication of a soils capacity to recharge the plant available P pool, as indicated by the Colwell-P test, through dissolution of slower release P minerals (McLaren *et al.,* 2014). Using both the Colwell-P and BSES-P extractions, a preliminary set of critical drivers of P availability by layer was released in 2012 (Table 1) (Guppy *et al.,* 2012). It was suggested from this work that Colwell P, BSES P and PBI (phosphorous buffering index) be used concurrently to determine likely fertiliser P responsiveness, and some guide as to the most effective application strategies (e.g., banding vs. dispersed P). These guidelines, while useful, were also only generalised indicators, with loosely defined ‘critical values’ and a broad grey area between what was considered likely to respond to P applications vs. unresponsive situations.

Table 1. Critical P values to determine likely response or drivers of P availability in northern Vertosols

	Surface (0-10cm)		Subsoil (10-30cm)	
Colwell P	< 25 mg/kg	Likely to get starter response	< 10 mg/kg	Likely to get response to subsurface P placement
	> 60 mg/kg	Ensure good groundcover to limit erosion loss	> 100 mg/kg	Unlikely to see P deficiency
BSES P	< 25 mg/kg	Limited evidence of residual P fertiliser	< 30 mg/kg	Limited reserves of slowly available P. Consider replacement of removed P very 5 years
	> 100 mg/kg	High residual P fertiliser load or natural P fertility	> 100 mg/kg	Potential to slowly replace Colwell P reserves

Values for suggested soil K levels were also estimated with much less certainty (Table 2), with a hypothesis that clay content/clay activity (indicated by CEC) as well as mineralogy were likely to influence potential fertiliser K responsiveness (Guppy *et al.,* 2012).

Table 2. Critical K values used to determine likely response or drivers of K availability in northern Vertosols

	Surface (0-10cm)		Subsoil (10-30cm)	
CEC	ExK (cmol/kg)	High Mg (>30% CEC) or Na (>6% CEC)	ExK (cmol/kg)	High Mg (>30% CEC) or Na (>6% CEC)
<30 cmol/kg	0.2	0.4	0.1	0.2
30-60 cmol/kg	0.4	0.7	0.3	0.5
>60 cmol/kg	0.6	1.0	0.5	0.8

Field work in DAQ00148 included the preliminary proof-of-concept installation of a series of strip-trials on the Darling Downs where P and K fertilisers were applied into the subsoil (Bell 2012). This evolved into a range of nutrition omission experiments examining surface and subsurface addition of P, K and S both singly and in factorial combinations. These omission experiments assisted in validating the suggested ‘responsive’ end of the critical concentrations (Tables 1 & 2), with experiments measuring consistent large, single nutrient responses to applied P in both the surface and subsurface across much of the NGR (Moree to Emerald) (Bell and Lester 2012).

Having consistently generated positive responses to the application of some subsurface nutrition, the research then switched gear with the UQ00063 project into much more regionally spread experiments targeting subsurface P application. K was explored in a more limited number of sites that met the estimated criteria for K responsiveness based on the critical soil test values. For P, the UQ00063 research focussed on plant responses to increasing subsurface fertiliser application rates, typically with or without a starter application. Following the DAQ0048 work, which highlighted the interaction between P and K responses on soils in which low soil concentrations of both nutrients were recorded, K research explored increasing fertiliser K rates (at 20-25cm depth) with a basal P application, and a contrast set of treatments without P to explore a K only effect.

The regional subsurface fertiliser placement in UQ00063 was conducted at a constant band spacing distance (roughly 50cm). Both P and K uptake by roots are diffusion driven processes meaning banding is the most efficient option for applying these less mobile nutrients, as bands create a strong concentration gradient along which nutrients can move to adjacent root systems (Lester *et al.,* 2018a). Derivate research in UQ00078, UQ00086, UOQ1805 and UOQ1905 then explored other factors influencing the effectiveness of subsurface banding of P and K fertiliser applications. This included laboratory, glasshouse and field experiments examining rate by band spacing interactions (varying the band frequency and the in-band concentration), the products and form of fertiliser used to deliver nutrients, the pH of the environment the fertiliser is placed into, and what happens when P and K fertiliser are applied together into the same band (Meyer *et al.,* 2020). Also examined were interactions between root systems, water and P distributions and their impacts on plant P uptake (van der Bom *et al.,* 2022). This research attempted to improve our understanding of the diversity of P dynamics in different Vertosols in the NGR (i.e. the relative importance of absorption/de-sorption typical of acidic pH soils compared to precipitation/dissolution reactions more common on calcareous soils) and incorporating that understanding into APSIM P module parameters (Raymond *et al.,* 2021a).

The following results section attempts to distil this broad history of research projects (led by Prof Bell) into the current understanding on soil and plant P and K nutrition: the good, the bad and the ugly. However, before we discuss this it is worth re-capping how nutrients behave in soil and how soil nutrient supply meets crop demands. While this has been discussed in previous Update presentations (e.g. Bell et al.,2019), it is worth a recap as these characteristics will have a large impact on the effectiveness of any fertiliser program.

How nutrients are acquired by plants

Before we can devise an effective fertiliser application strategy for any nutrient, we need to understand how that nutrient behaves in soil and is acquired by plant roots.

Nutrients are generalised into two groups related to their behaviour in soils, and particularly their response to water movement through soil profiles: mobile and immobile. Plant roots have three main mechanisms to gather nutrient from soils: mass flow, diffusion and root interception (Barber 1995). All three mechanisms are used for every nutrient, but the proportion acquired through each varies.

Nitrogen is predominantly present in soil organic forms that need to be converted to mineral nitrogen (ammonium and nitrate) by microbial activity before plant uptake. Once in those mineral forms, particularly as nitrate, the concentration of N in the soil water increases and N becomes very 'mobile'. Mass flow uptake means as the plant takes up soil water it accumulates nitrate-N dissolved in that water at the same time. As roots deplete the water (and N) close to them, water moves to the root from undepleted soil further away, bringing nitrate with it. So, for the most efficient nitrogen recovery we want the available nitrate distributed with the available water.

Phosphorus is the opposite of N in many ways, with most P in cropped soils present in inorganic forms of varying solubility. The fraction that is readily available for plant uptake is either in the soil water at very low concentrations or held (sorbed) onto clay and organic matter particles. The sorption and desorption processes can occur rapidly, but the net effect is that at any time there is a low concentration of P in the soil water. This means P resupply from water movement from other parts of the soil profile is limited, and P is considered an immobile element in clay soils or 'where you put it is where it stays'. For roots to access P they have to grow into undepleted soil (or be very close to a concentrated P supply like a fertiliser band).

Because of the strong affinity of clays and organic matter for P, roots have to be very close to a P source/high P concentration so that P can diffuse to the root without being sorbed to other particles. Effective P uptake therefore requires either low P concentrations across large soil volumes, with roots always able to grow into soil with available P (perhaps our soils before cropping, in many cases), or concentrated patches of high P availability (bands, slots) which stay moist and where roots can concentrate in large numbers. Once you are relying on P fertilisers, placement is a critical success factor.

Potassium is an interesting blend of these contrasting characteristics. It is still held on clay and organic matter surfaces and occurs in relatively low concentrations in soil water. This means in our high clay soils it also is effectively immobile, although in lighter soils it moves a little further than P. What is challenging, though, is that roots don't congregate around a patch of high K like they do with P, and so it is harder to get rapid uptake of K from a band – unless you put some P with K, to act as an incentive for roots to get interested and congregate in that area.

Deep P and K - the 'good'

One of the strengths in the UQ00063 project was the extensive geographic distribution of experiments, with the majority extending from Moree (NSW slopes) to Kilcummin (CQ) (Figure 1). Approximately 30 experiments were established during the research phase.

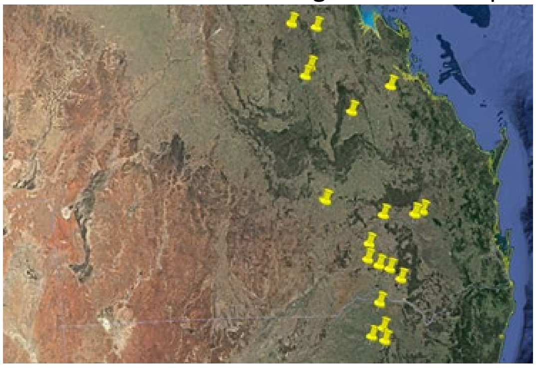


Figure 1. Location of the 30 P trials established from 2012-2017 under UQ00063.

Treatments have generally consisted of rates of P (0 to 40 kg P/ha in CQ or 60 kg P/ha in SQ/NNSW) applied at ~20-25 cm deep in bands spaced roughly 50 cm apart. Sites where K was likely to be marginal based on site soil testing, primarily across CQ, K rates of 0 to 100 kg K/ha on same band spacing as P were made. The K rates were applied with and without P. Most (not all) Qld experiments include an untreated control, acting as a 'Farmer Reference' treatment to gauge baseline production without tillage. Against this benchmark, the effects of ripping and application of basal nutrients (N, S, Zn) or the addition of various rates of fertiliser P and/or K in addition to the basal nutrients, were assessed. Table 1 provides an example of the treatment combinations used in the later years of the experimental program. All main P plots were then split to annual 'with' and 'without' starter P fertiliser applications at planting, to assess whether effects of starter P and deep P were complimentary. Crop choice at each site was dependant on the local rotation and the residual benefit of the different rates of applied P was tracked through subsequent growing seasons.

Table 3. Experimental treatments for Mt Bindango deep placed P sites

Deep P treatment nutrient application rates (kg/ha)							
Trt no	1	2	3	4	5	6	7
P rate (as Mono Ammonium Phosphate)	FR*	0	10	20	30	40	60
N rate (from MAP and Urea)	-	40	40	40	40	40	40
Zn rate (Zinc Chelate)	-	2.0	2.0	2.0	2.0	2.0	2.0

*FR= untreated 'farmer reference'

Field research under UQ00063 concluded in June 2021. Currently the DAF and UQ research teams are compiling the substantial experimental data for final individual site and a broader project meta-analysis of aggregated data sets, so results presented here are still somewhat preliminary in nature. Not every crop responded in every year, and there are some sites with results still perplexing (see more on that later). However, our general conclusions from the starter x deep P rate experiments are that starter applications are beneficial for cereal crops across the region, with P application with seed at sowing ticking the box for early vigour and setting up of the crop. Overall, starter applications on most winter cereal crops increased yields compared to equivalents without starter application, while starter responses in both chickpea and sorghum were more variable.

An area in which further research is needed is the potential role of liquid starter P applications to apply low rates of starter P uniformly – particularly in summer cereals grown in wide rows, where the number of granules/m of crop row is small. Research has shown the P uptake from starter applications is typically small (only 1-2 kg additional crop P uptake), and so there is potential to 'save' on the rate of starter P addition to divert into other parts of the profile where crop recovery is more efficient (e.g., deep bands). Low-rate P applications are sufficient to stimulate root / shoot vigour, set potential grain number and reduce the variability in time to flowering / maturity. This has been observed in wide row sorghum plantings where rates of P application in starter applications are limited by higher in-band concentrations. It is logistically much easier to distribute small amounts of P as a liquid.

Responses to deep P bands

Central Queensland

The grain yield responses to subsurface P banding in Central Queensland for chickpea crops are typically very strong, while wheat and sorghum responses (where N isn't limiting for cereals) are more seasonally and site dependent (Sands *et al.,* 2021a).

The relative yield responses in those sites with relatively high surface P (Figure 2) generally showed a maximum response of ~25%, with a significant amount of variability across the crop years. More than half the yield responses to the 20 kg P/ha and 40 kg P/ha rates represented yield increases of 10% or lower (Figure 2). This contrasts with the relative response to 20 kg P/ha and 40 kg P/ha rates in those sites that had much lower surface P concentrations (Figure 3), in which 75% of the responses produced yield increases of 15% or more. The maximum relative response was also higher, with close to a 40 % increase in grain yield (Figure 3).

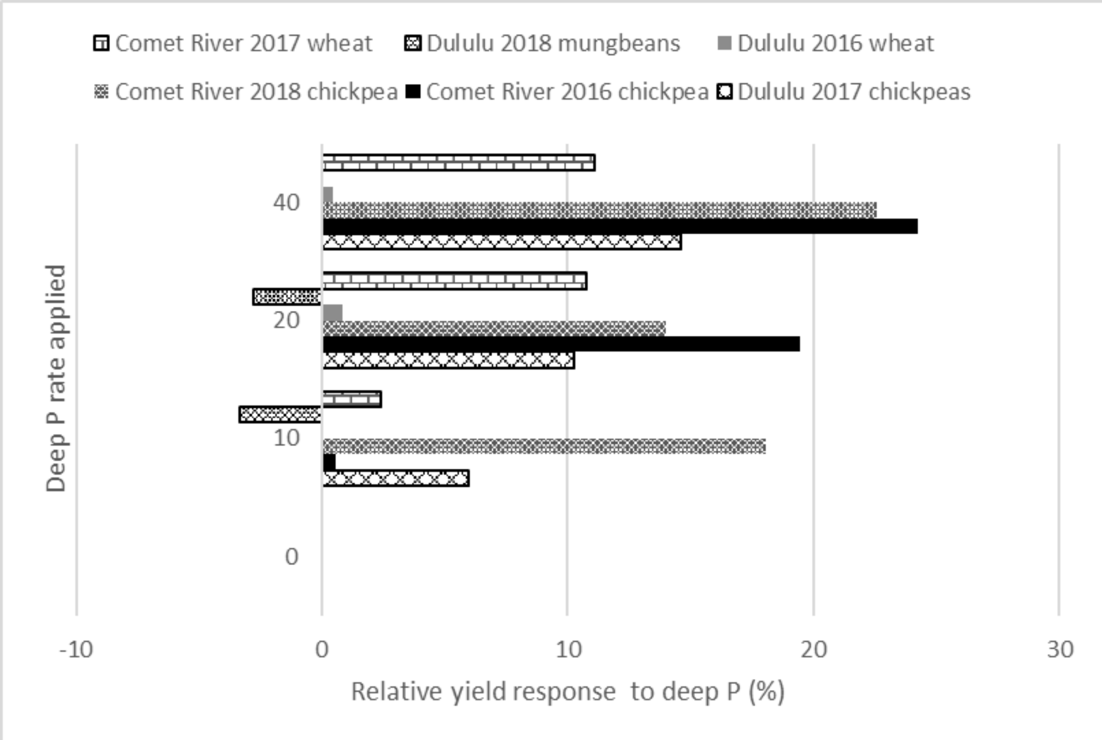


Figure 2. Mean relative grain yield responses to deep applied P treatments as a % of the zero P treatment for those sites that had relatively high Colwell P concentrations (22 mg/kg) in the top 10 cm of soil.

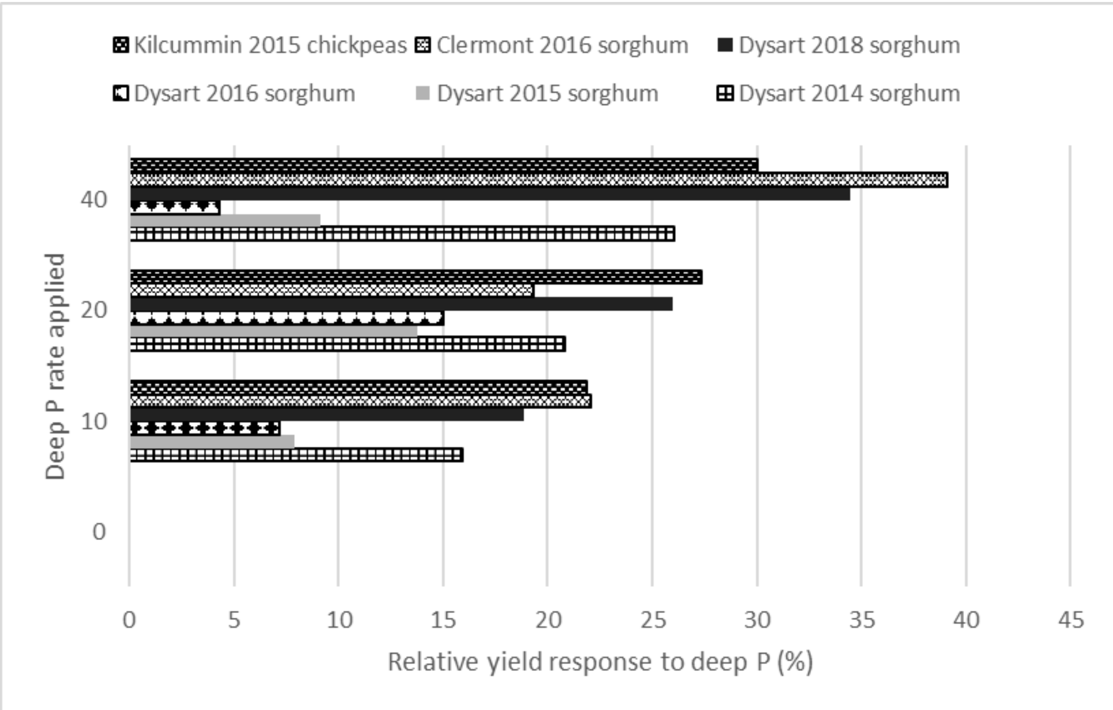


Figure 3. Mean relative grain yield responses to deep applied P treatments as a % of the zero P treatment, for those sites that had low Colwell P concentrations (< 8 mg/kg) in the top 10 cm of soil.

In a very limited set of sites (two sites, one useful) there was even more upside chickpea yield with reapplied P increasing yields further. At the Dysart site (Figure 4) there were similar yields recorded for the FR treatment and the re-ripped 0P treatments with or without extra K and S applications, ranging from 1200-1400 kg/ha. The lack of response to ripping and basal nutrients (N, or N and K) suggest that another factor (P) was the primary nutrient limit to productivity.

There were significant yield increases of 750-1250 kg/ha with the residual deep bands applied at 20 kg P and 40 kg P/ha with background KS, respectively – despite the original application being made back in 2013, and after five crop seasons. If no K had been applied in the original deep bands with the 40 P treatment, yields were reduced by 300 kg/ha – a small but statistically significant drop that suggests availability of K was a secondary limitation to yields at this site, evident only when P availability had been improved first.

The re-application of 30 kg P/ha (as ammonium phosphate plus zinc) prior to the 2019 season saw a further increase in potential yields to 2700-2800 kg/ha without background K, and to 3400-3500 kg/ha when K was also re-applied (Figure 4a). These responses support the primacy of the P limitation but also indicate a growing importance of K limitations once adequate P was available to meet crop demand. The 300-350 kg/ha drop in yields without K seen in the residual P treatments had now increased to 700-800 kg/ha with the improved P availability arising from the fresh re-application (Figure 4b).

The strong P responses at this site were consistent with results from the previous five crops grown on the site (2014, 2015 and 2016 sorghum, 2017 chickpeas and 2018 sorghum), but the magnitude of the response to the re-application was a little surprising given the strong residual effects that were still evident from the original applications – especially the 40P treatment. We have observed that the response to increasing original P rates has changed with time after application. In the first three sorghum crops there was no difference in yields between the 20 and 40 kg P/ha applications, but in subsequent crop years a better relative response was increasingly evident with 40P rather than 20P and yields effectively increased in a linear response to increased P rate. While this linear response is still evident in this 6th crop season, it is clear that crops could respond to more P than was available from the residual bands and that further P from a re-application was needed. The relative increase in yield response in relation to the residual bands raises the question of whether an earlier re-application could have been economically beneficial, and this can only be answered by future research. However, the cost to re-apply 30 kg/ha of P, along with the 50 kg/ha K and 90 kg/ha N in the background fertiliser, was roughly $260/ha. It is very clear that the re-application has paid for itself and delivered a profit in the year of application (assuming $650/t on-farm price).

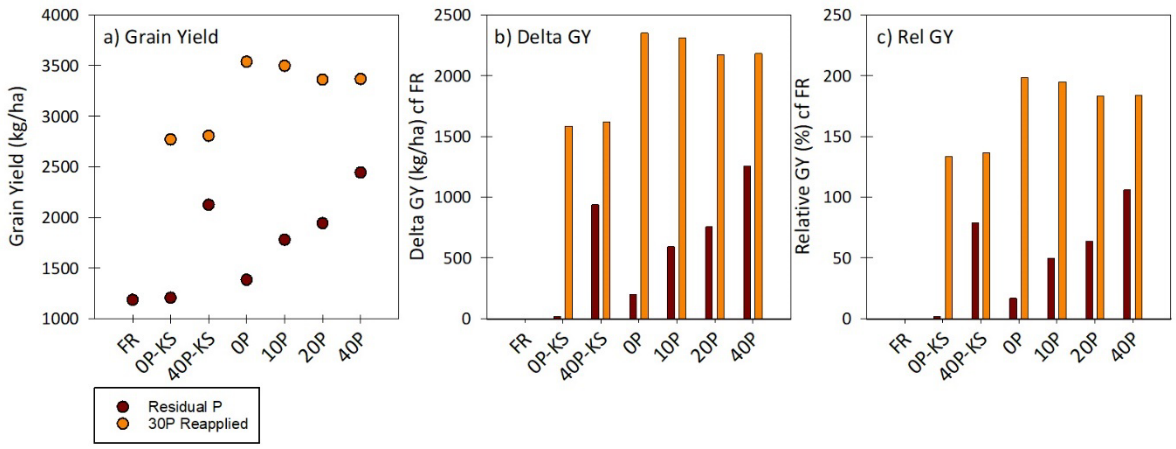


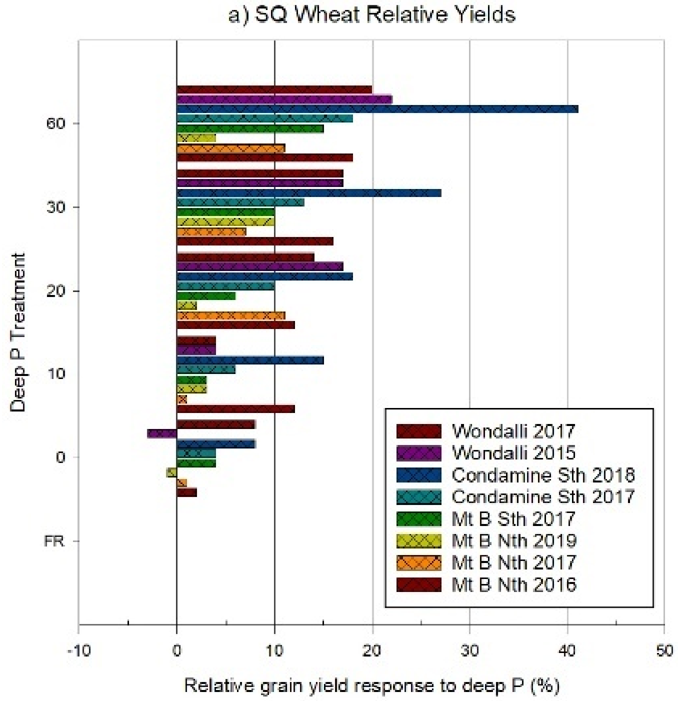
Figure 4. Dysart 2019 chickpea of the 6th crop on residual P vs 1st crop on 30 kg P/ha reapplied for a) grain yield, b) change in yield from the untreated reference, c) change in yield as a relative measure.

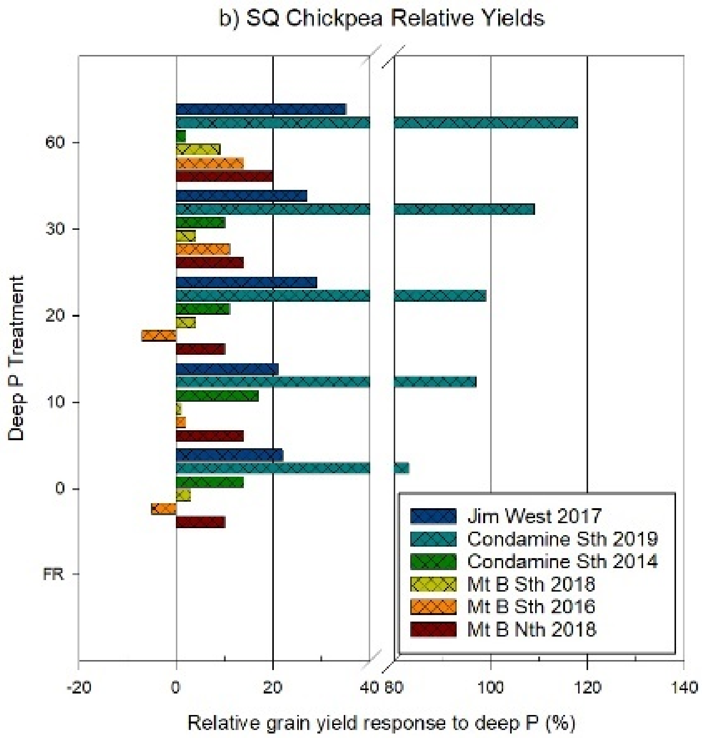
Southern Queensland

Winter cereals through southern Queensland have generally reliably increased grain yields in a range of seasons by about 15% at the 30 kg P/ha treatment (Figure 5a) – although there are exceptions in drought affected years.

Responses with chickpea are mixed with a large scale of effects (Figure 5b). There are usually always significant dry matter increases measured (data not shown) but they do not always translate into increased grain yields. The yield effects appear perhaps muted when the 0P treatment (tillage and basal nutrient) is having about 10% increase without any additional P. Chickpeas did give the largest relative yield increase with nearly 120% increase at Condamine in 2014 (first crop at site). Excluding the huge response, grain yield increased by 13% at 30 kg deep P/ha compared to untreated control.

Sorghum has contrasting yield responses, with rainfall post-flowering likely the major driver of yield (Figure 5c). Two of the five harvested crops have delivered responses >15% in yield, but the remaining three are 4-7%. There is one notable negative effect at the Mt Carmel site in the 0P treatment, possibly due to tillage effects on crop establishment.


a) SQ Wheat Relative Yields
Deep P Treatment
60
30
20
10
0
FR
-10
0
10
20
30
40
50
Relative grain yield response to deep P (%)
Wondalli 2017
Wondalli 2015
Condamine Sth 2018
Condamine Sth 2017
Mt B Sth 2017
Mt B Nth 2019
Mt B Nth 2017
Mt B Nth 2016


b) SQ Chickpea Relative Yields
Deep P Treatment
60
30
20
10
0
FR
-20
0
20
40 80
100
120
140
Relative grain yield response to deep P (%)
Jim West 2017
Condamine Sth 2019
Condamine Sth 2014
Mt B Sth 2018
Mt B Sth 2016
Mt B Nth 2018

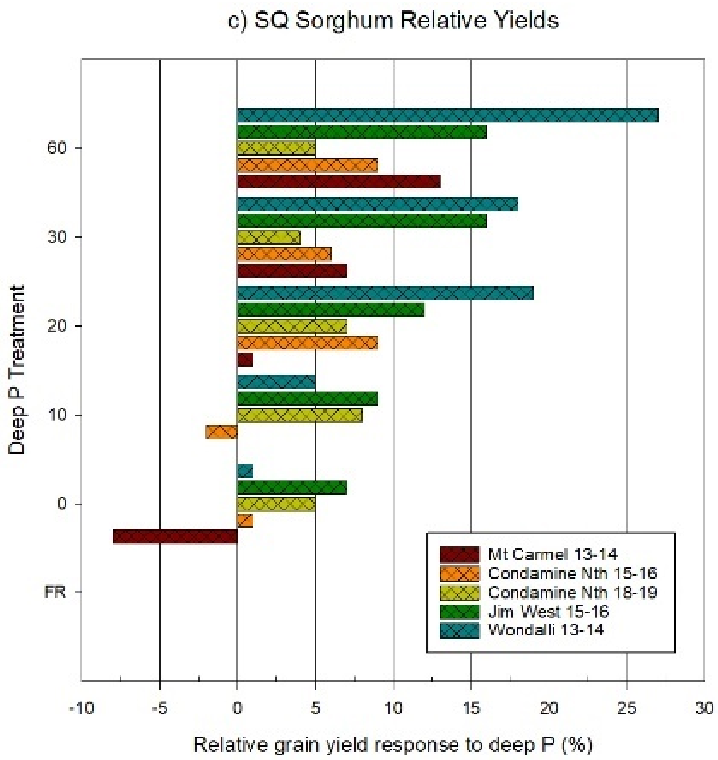


Figure 5. Relative yield responses to deep applied P treatments as a % of the untreated control for a) wheat, b) chickpea and c) sorghum in southern Queensland. Note different scales.

We have confidence in the responses from examining the underlying agronomic drivers measured: dry matter, grain yield and P uptake in each of those studies. Relationships between dry matter (DM) and grain yield (GY) have reasonable correlations (Figure 6 a-c). Subsurface P can increase soil supply of plant available P. That can increase dry matter produced which influences both the P uptake by the plant and concurrently can also influence grain yield. The next question is how to 'best' increase plant P supply?

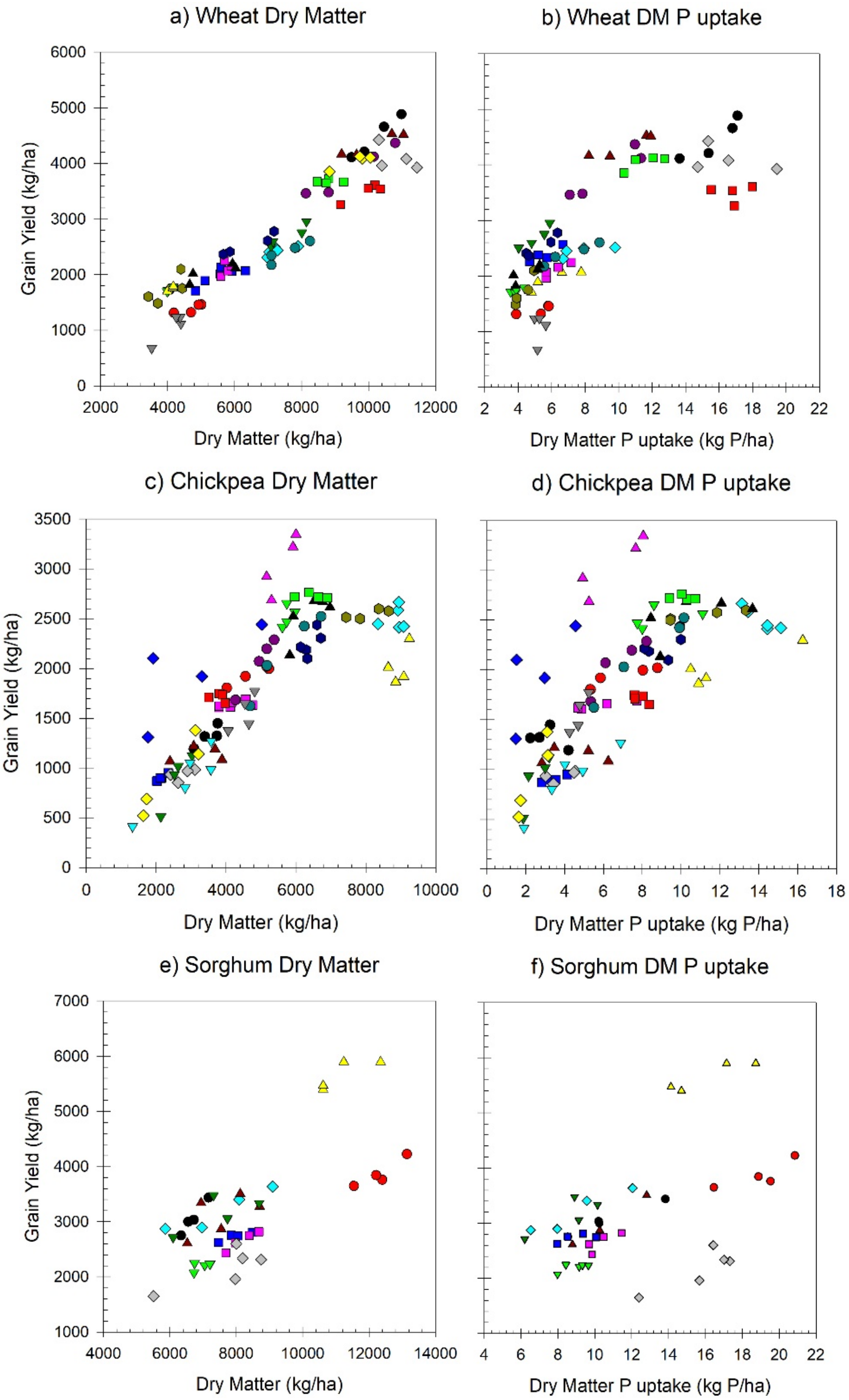


Figure 6. Scatter plot matrices of dry matter versus grain yield, and dry matter (DM) P uptake versus grain yield for a-b) wheat, c-d) chickpea and e-f) sorghum at deep P sites in Queensland.

Responses to deep K bands

Review of the potassium data from experiments is still in a preliminary phase as phosphorus has been a more widespread nutrient across the program. A case study site is presented showing some potential responses, but further investigation of the data will be forthcoming as final reports are prepared.

Central Queensland

Full details are contained in Sands *et al.* (2021b). Briefly, the Dululu trial site had four crops planted and harvested since it was first treated with deep banded fertiliser in November of 2015: Wheat in 2016, Chickpeas in 2017, Mungbean in 2017/18 and Chickpea in 2019. The original soil test from the site indicated adequate levels of P and K in the top 10 cm but a significant change in that analysis in the deeper layers (Table 4).

Table 4. Soil analysis for the Dululu site

Depth (cm)	Nitrate nitrogen (mg/Kg)	Phosphorus Colwell (mg/Kg)	Sulphur (KCl-40) (mg/Kg)	Exchangeable. Potassium (meq/100g)	BSES Phosphorus (mg/Kg)	PBI	ECEC (meq/100g)
0-10	7	17	4	0.23	21	99	22
10-30	22	3	7	0.12	5	109	28
30-60	18	1	18	0.09	4	81	29

Deep K responses at this site were more consistent than for P. Wheat was the only crop out of four that did not respond to the highest rate of K application when background P was applied. Only mungbean responded to the highest rate of K when no background P was applied. It is unclear whether this is a particular characteristic of mungbean, or due to seasonal variation. Accumulated grain yield responses to K were greater than those in the P trial (data not shown). The highest rate of K (100K) provided ~800 kg/ha more than the 0K treatment, while the highest rate of P (40P) in the P trial provided a ~600 kg/ha gain. While the reapplication of 50 kg K/ha to the 25K treatment produced the same accumulated production as the 100K treatment, the 50K treatment was almost 500 kg/ha behind both these treatments. It appears that the K at this site was used at a faster rate than the P, and reapplication will be needed sooner than normally expected for P responsive sites.

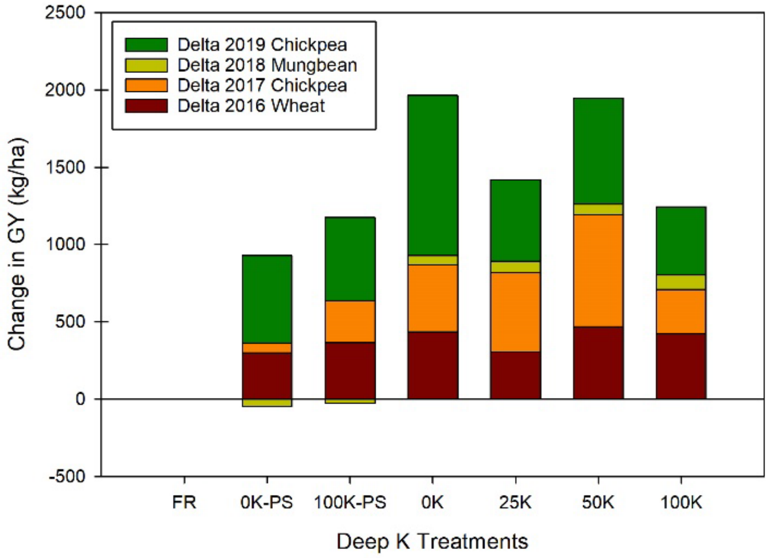


Figure 7. Accumulated grain yield increases over FR treatment for deep K treatments across four crops (25K* this treatment data includes the extra application of 50 kg K/ha in 2019).

This trial site shows the need for subtle differences in management when soils are more restricted by K than P, and perhaps when higher topsoil P accentuates the differences in P supply between wetter and drier seasons. Plant uptake of K (36 kg K/ha) was much higher than P (7 kg P/ha) when the K and P were re-applied for the 2019 season. This five-fold difference presents a challenge of how much K should be applied and how long it will last. In the K trial in 2019, the re-applied treatment used up 15 kg of K more per hectare then the 100K residual treatment. This means that of the 50 kg K/ha that was re-applied in 2019, almost a third of it has been taken up by the 2019 chickpea crop.

Increasing plant nutrient uptake from fertilisers, including P and K

Acquisition of immobile nutrients applied into the subsurface by plant roots is an exercise in probability – fertiliser needs to be placed such that the roots are more likely to find those nutrients early enough in the plant life cycle to make a difference in growth, and that placement zone has to be wet enough for long enough for roots to be active and acquire enough nutrient to make a difference.

During two projects we have attempted to explore the placement effects of P and K fertiliser applications on crop uptake and yield responses through some field experiments. Early research in DAQ00148 compared applying into the surface, or subsurface or both on three band spacings (Figure 7), but this was all at one constant application rate of 40 kg P/ha as MAP. Research in UQ00078 evolved to explore the diffusion gradients created by a range of P rates (0, 10, 20, 40 or 80 kg P/ha) or K rates (0, 25, 50 or 100 kg K/ha) at each of the three band spacings at depth.

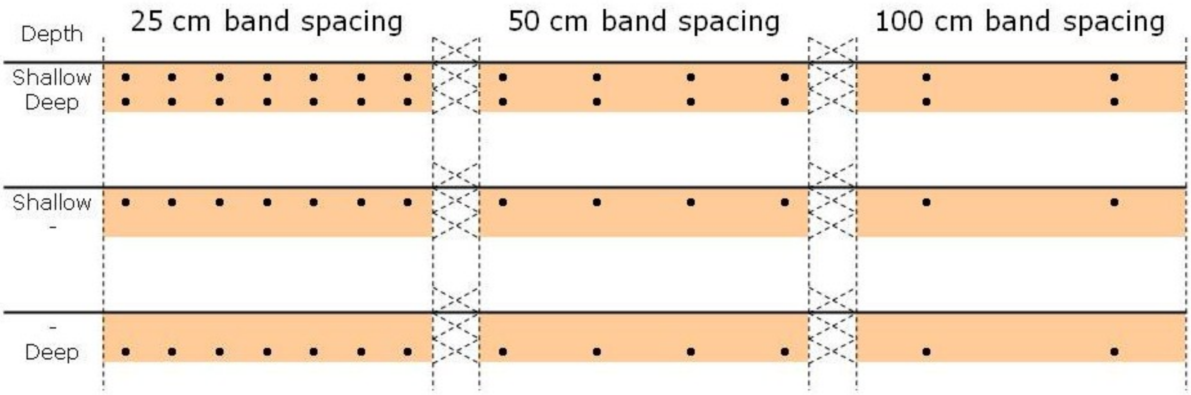


Figure 8. Fertiliser band and depth placement strategies for P and K application in DAQ00148.

The research outcome suggests that while band spacings are important (narrower is better – 25cm & 50cm give better nutrient access than 100 cm), it is the rate of application that has the greatest impact on crop recovery.

Above ground dry matter at maturity was increased with increasing P rate in 3 of 6 seasons across the two sites (data not shown). Briefly, responses were approximately 10% greater than the 0P treatment, with the effect not really detectable until application rates were > 20 kg P/ha. In several years, distinct visual growth responses were observed in the stages up to flowering (photos not shown). Full details are reported in Lester, Weir et al. (2018b) and Lester and Bell (2020).

Crops grown in 2017 (chickpea) and 2018-19 (sorghum in two fields) allowed drone platforms to capture NDVI for assessment of relative influence that application rate and band spacing had. In general, the rate of P applied appeared to be a more dominant contributor to NDVI than band spacing (Figure 8). These effects are very difficult to precisely capture through dry matter cuts. Challenges also exist in homogenising whole plant samples for analysis to calculate nutrient uptake.

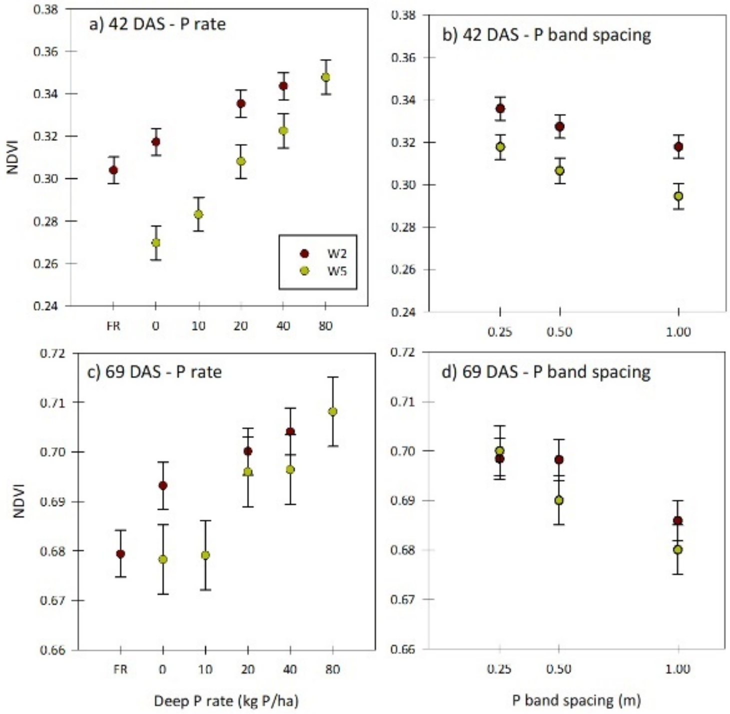


Figure 9. NDVI of sorghum at 42 and 69 DAS for deep P rate x band spacing experiments conducted in W2 and W5 fields growing sorghum in 2018-19

In northern region cropping soils, granular ammonium phosphates should be the first product choice for application in a subsurface program. Field experiments in UQ00078 at two sites in Qld over several growing seasons compared no P application with applying rates of ammonium phosphates as granular and fluid forms (MAP, DAP, FlowPhos) or calcium phosphates (TSP) without any clear cut result (Lester *et al.* 2018b), due to the inherent variability in field sites and challenging seasonal conditions where a lack of water/heat stress limit potential yields.

Research conducted through laboratory and glasshouse experiments at University of Queensland (Meyer *et al.,* 2020) examined P products and the interaction with coapplied K on fertiliser bands in a variety of soils. Findings suggest for non-calcareous soils, the pH of the soil and the pH of the P product as it dissolved influenced soil P availability. In general, ammonium phosphate fertilisers are the preferred delivery mechanism for band applications, but there was little evidence of any advantage of MAP over DAP, with similar findings reported in Raymond et al. (these proceedings) for dispersed P.

We have regularly seen increased crop growth on sites comparing the untreated control to the 0 kg P/ha plots, particularly in the initial crop seasons after application. This suggests that tillage associated with subsurface nutrient placement is providing some benefit, although these trials were not designed to separate tillage effects from the added background nutrients that were added at the time. The soil disturbance needs to be disruptive enough to break up legacy compaction, and early enough to allow reconsolidation of soil to allow successful establishment of the next crop.

Economic ROI from deep P and/or K

Deep P and K are long term decisions, with significant upfront costs (Table 4) and returns expected to be recouped over 5 years or more. Analysis of the 8 longest running trial sites spread across southern and central Queensland, where P was applied as MAP, show promising returns from deep P application, with cumulative yield benefits ranging from 1% to 42% at 20kg P/ha (Table 5).

Table 5. Treatment cost by P rate with basal N

Treatment (P kg/ha)	Application ($/ha)	Urea ($/ha)	MAP ($/ha)	P treatment cost ($/ha)
0	$30	$69	$0.00	$99
10	$30	$61	$73	$164
20	$30	$57	$109	$196
40	$30	$52	$145	$227
60	$30	$43	$218	$291

Note: Using long term average MAP ($800/t) and Urea ($450/t) prices

Table 6. Cumulative yield benefit vs farmer reference

	Central Queensland				Southern Queensland			
P rate (kg/ha)	Comet River (4)	Emerald (5)	Dysart (6)	Dululu (4)	Mt Bindago (4)	Warra (4)	Condamine South (5)	Jimbour West (6)
0	21%	7%	13%	12%	1%	-8%	6%	9%
20	36%	5%	42%	19%	10%	1%	14%	18%
30					13%	0%	16%	19%
40	39%	7%	41%	19%				
60					14%	4%	19%	24%
Colwell-P (mg/kg at 10-30cm)	6	6	1	3	3	3	4	8

Note: numbers in brackets following site names are the number of crops that have been harvested at these sites. It is expected that the benefits of higher rates of P will become more pronounced the longer each site is cropped.

Using 5-year average prices these yield benefits have largely transferred through to significantly improved profitability, with 20kg/ha P generating up to $1586/ha in additional gross margin above farmer reference treatments (Table 6). Return on Investment (ROI), averages 2.7 across the 8 sites, meaning for every $1 spent on deep-P, profit has increased by $2.70.

Table 7. Cumulative gross margin benefit and ROI of 20P vs FR ($/ha) (ROI expressed as $ return/$ invested)

	Central Queensland				Southern Queensland			
	Comet River (4)	Emerald (5)	Dysart (6)	Dululu (4)	Mt Bindago (4)	Warra (4)	Condamine South (5)	Jimbour West (6)
Gross Margin Benefit	$770	$27	$1586	$767	$60	-$94	$392	$673
Return on Investment	3.9	0.1	8.1	3.9	0.3	-0.5	2.0	3.4

Sites which have not been responsive highlight some of the uncertainty still surrounding the practice of deep P and K. For example, the Warra site suffered a significant yield penalty due to deep placement in the year 1 sorghum crop (presumably due to lingering tillage effects on soil moisture), which was not able to be overcome by deep P addition due to a strong K deficiency that was observed across the site. This occurred despite soil tests suggesting K was marginal-adequate at the site. Following a background K application all subsequent (grain) crops showed positive responses to deep-P, but these benefits were not enough to offset the treatment costs and the first year yield penalty in the high value chickpea crop to break even.

Where Colwell P concentrations in subsoils are low (<10mg/kg), deep-P appears to offer strong economic returns in many situations, although there were several sites where other constraints, particularly N and K deficiencies, have limited P responses across the trial program. This means growers need to take into account all-nutrient requirements of crops, as well as the constraint status of their soils, and apply nutrition in line with the improved 'non-P-limited' yield potentials.

Deep P and K banding - the 'bad'

There are a number of not so positive results from this program.

- There is a 'Goldilocks' soil moisture for putting treatments in. Too dry and you break your gear trying to work hard ground and you can't get your bands deep enough. Too wet and you don't get the disturbance needed to break up the upper 20-25cm profile
- Doing deep placement without sufficient rainfall for reconsolidation doesn't allow successful crop establishment and/or good access to the deep bands. There needs to be good soil-band contact in moist soil for roots to access these nutrients, and fertiliser sitting in air gaps/voids created by tillage will not result in nutrient uptake. The solution is timing deep banding earlier in the fallow once there has been enough rainfall to soften the profile in the tilled zone. The longer the period post-ripping, the more rainfall events (hopefully) and the better the profile reconsolidation
- Growing season conditions will influence the crop response to subsurface applied nutrients – especially when the topsoil layers are quite fertile. The length of time the crop root system has access to different soil layers (i.e. the top 10cm v the subsoil), how enriched each layer is for the nutrient in question and how often each layer rewets during a growing season, will all influence the response to deep banded nutrients. This uncertainty is overcome to some extent by the good residual value obtained from these deep bands, especially for deep P, so

a lack of response in a good season can see responses deferred to subsequent growing seasons
- Meaningful data from northern New South Wales is sparse, due to a combination of extended very adverse drought conditions and logistical challenges associated with operating over a large geographic area from a single research base
- Translation from research experiments to grower practice is mixed. There are reports deep P bands are not always working for every grower who does it. A more thorough investigation of these situations (soil characteristics, application method, timing, and rate, seasonal conditions etc) is needed to determine whether these effects are related to soil types or other factors.

Deep P and K - the 'ugly'

There are still a number of unknowns relating to deep P banding.

- We can't track uptake directly from fertiliser P bands over multiple crop sequences. The estimates of P uptake are based on the difference between P uptake from untreated and treated plots, with an assumption the change in P uptake is all that is being acquired from the fertiliser band. There may well be greater P uptake from the deep P bands and some sparing of background P from the rest of the soil profile; but we don't know if this occurring, and if so, how big these effects may be
- It has been challenging to get good estimates of differences in nutrient uptake by crops using the differences between banded treatments. This is due to variability in measurement of the above ground dry matter from a small sample area, and the homogenising of bulky plant samples containing both vegetative material and immature grains into a representative plant sample of < 1 g for acid digestion. Grain yields and grain nutrient concentrations provide a more robust estimate of P/K leaving the paddock, but this fraction varies with crop nutrient status and indeed the nutrient itself. A lack of grain nutrient removal may still mean a lot of the deep-banded nutrient has been taken up by the plant but returned to the relatively enriched topsoil, which is particularly the case for K
- Understanding of P behaviour across diverse cropping soils is limited. There are sites (e.g., Emerald Ag College) where crops are obtaining substantially more phosphorus than current soil tests suggest they should. We still don't know where that P is coming from, which highlights that our understanding of P dynamics in vertosols still has a way to go
- The longevity of P from undisturbed fertiliser P bands (the 'fertosphere') in soils is variable, with work being conducted in UQ00063 by Chelsea Janke following up the banding studies reported by Meyer at al. (2020; 2021) over longer aging periods. Other lab work is being undertaken to assess behaviour of P dispersed through the soil (Raymond *et al.,* 2021b), with this work linked to field studies in Qld and NNSW conducted in UQ00082. The laboratory studies show that for the same rate of P application, some soils allow a much greater proportion of applied P to enter the plant available soil P pools measured by Colwell P than others (Raymond *et al.,* 2022). This is consistent with results from field sites at Gindie, Hopelands and Ningadoo, with the reasons for this still being assessed
- Our knowledge of interactions between soil moisture, root activity and P acquisition for different species is limited (van der Bom *et al.,* 2020). These interactions have significant implications for plant growth and phenology; as well as for breeding programs selecting for specific root morphologies to improve deep water extraction
- The interaction between plant P uptake, growth and phenology responses, soil water extraction and transpiration are also an area of uncertainty. Are crops extracting more water because they have larger root systems, or respiring more efficiently because of better P status?

- Lastly, potassium is a major nutritional challenge emerging in the cropped vertosols and, given the relative immobility of K and the amounts taken up by crops, it is going to provide a significant long-term challenge to fertiliser management programs. There has been less research on K management in clay soils nationally and internationally, as K infertility has not traditionally been a problem due to adequate initial reserves. As those reserves are eroded, the imperative to better understand K dynamics in vertosols is increasing and research in this space is breaking new ground.

Concluding remarks

There is a strong likelihood of having to manage P and K simultaneously in many broad acre cropping sites across the NGR in coming years, to optimise the efficient use of available water. This is already a reality in significant areas of CQ (especially on open downs soils) and we are approaching these conditions in the northwest slopes of NSW and on some box/upland soils in southern Queensland.

Grain yield increases in response to fertiliser K applications in vertosols have been limited to sites in CQ and the inland Burnett, where subsoil K reserves are very low. We have also run trials on soils with marginal K status in southern Qld that have been able to provide insights into crop K acquisition from fertilisers, but at this stage yield responses have been small and inconsistent. This situation will change as the crop removal continues, and so we need to continue to develop both short- and long-term responses to K decline.

Most of the research reported here has involved a single application of deep P/K bands into low P subsoils. Data suggests that while responses are profitable in most situations, these single bands are not completely overcoming the problem of P/K infertility. The strong residual value of banded P in particular, combined with periodic reapplications enriching 'new' soil on each occasion, are a way to slowly rebuild soil fertility banks.

An important consideration is how often these re-applications are needed, with our data suggesting there will be a need to reapply subsurface K much sooner than subsurface P. Crop K uptakes are typically ten times greater than P, so the residual amount of deep K after consecutive cereal/sorghum crops will rapidly decline. Most of this K won't be leaving field in grain, but it won't be where you put it in the subsoil as it will instead be released from stubbles into the topsoil. How long deep K applications last, and how you manage subsoil P and K will be important, as deep K bands alone are not effectively utilised by plants - an 'entrée' of P with the K is needed to give roots a reason to proliferate around the bands. Identifying appropriate P/K blends for different situations and application frequencies will occupy nutrition researchers for some time to come.

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Contact details

David Lester
Queensland Department of Agriculture and Fisheries
13 Holberton Street, Toowoomba Qld 4350
Ph: 0428 100 538
Email: david.lester@daf.qld.gov.au

Doug Sands
Queensland Department of Agriculture and Fisheries
99 Hospital Road, Emerald
Ph: 0749 910 811
Email: douglas.sands@daf.qld.gov.au

Mike Bell
University of Queensland, Gatton Campus
Ph: 0429 600 730
Email: m.bell4@uq.edu.au

P dynamics in vertosols – which soil properties affect declines in P availability over time? Are there differences between MAP and DAP?

Nelly S. Raymond, Peter M. Kopittke, Frederik van der Bom, Michael J. Bell,
The University Queensland, School of Agriculture and Food Sciences, St. Lucia, QLD 4072

Key words

fertiliser, phosphorus availability, soil test, modelling, vertosol

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Take home message

- Vertosols vary greatly in their physical and chemical properties which affect the dynamics of P availability after fertiliser addition
- The degree of P saturation (a product of original P fertility, crop removal and fertiliser inputs) is one of the key soil properties that affects both the initial increase in P-availability after fertiliser addition and the longer-term residual P availability
- DAP application can result in initially greater P availability compared with MAP in some specific vertosols, although those benefits are short-lived
- The type of P fertiliser has very minor impacts on the longer-term P-availability in vertosols compared to soil properties that influence the initial sorption and re-release of applied P.

Why the focus on phosphorus fertiliser availability in vertosols?

Grain production in northern NSW and southern and central Qld is based primarily on alkaline clay soils which had relatively high fertility prior to the commencement of cropping. In these systems there has been limited, or in some cases no phosphate fertiliser applied, with crop phosphorus (P) demands primarily met from indigenous soil P (Dalal, 1997; Wang *et al*., 2007). Over time, the P removal in harvested grains or forages has therefore exceeded the amount applied in fertilisers or soil amendments, and this has led to a decrease in soil P reserves. It has now become increasingly common to observe crop responses to the addition of P fertilisers (Bell *et al*., 2012) (Figure 1), and particularly when P fertilisers are applied into depleted subsoils. This means that while fertiliser budgets used to be dominated by nitrogen (N), there is now a need to accommodate additional P inputs. Similarly, while low rates of starter P in the seeding trench may have been adequate to meet past demands, application strategies that can ensure larger amounts of fertiliser P uptake are becoming increasingly important. The impact of these increased fertiliser requirements on grower profitability has been further accentuated by the current spike in fertiliser prices which have seen costs/kg of most inputs effectively double within a short period of time. There is therefore an increasing need to understand how, where and when to apply P fertiliser to maximise the benefits of this investment.

There is a long history of P research in southern and western cropping regions, particularly on acidic and lighter textured soils, or on highly calcareous soils in SA. However, the applicability of those findings to our northern systems on (largely) alkaline, often non-calcareous clays is limited. Key differences include

1. The strongly depleted soil P reserves;
2. The alkaline soil pH and resulting soil-fertiliser P reactions that determine availability;
3. The high clay contents in the vertosols, that limit internal P redistribution, and that provide a large number of potential P sorption sites that could limit fertiliser P availability to plants;
4. The widespread lack of tillage and profile mixing, combined with a large reliance on water (and nutrients) extracted from subsoils during dry periods.
5. Fewer growing season rain days and associated greater reliance on deep stored soil water and thus greater capacity for nutrients to become stratified and unavailable to the crop.

These points are all significant in terms of how they may impact on P management in the cropping system. Southern and western Australian cropping regions started with very low P soils, but regular applications of P fertilisers for many decades, often at rates greater than those needed to meet crop demand, have been able to build a 'bank' of soil P fertility in many situations. This has resulted in P deficiencies now being much less common and growers and advisers are questioning whether future strategies should change to a soil P maintenance strategy, or even an occasional P mining event when fertiliser prices are high. The northern vertosols are heading in the opposite direction on the soil P decline curve, with previously adequate P concentrations now suboptimal, and those effects often most significant in subsoils. While deep banding has been proposed as a strategy to address this subsoil P decline and has shown some strong productivity and profitability impacts in trials in many areas, research is also showing that reliance on those deep bands can be very seasonally dependent and is limited in what it can provide to a crop due to drying out of the soil around the band (e.g., see van der Bom *et al.* these proceedings). Indeed, researchers are suggesting a much greater emphasis on timing and placement of any fertiliser P inputs such that the soil volume and profile distribution of P-enriched soil is increased (i.e., to some extent, attempting to rebuild a broader soil P bank).

However, to improve the P fertility of vertosols and the ability of crops to acquire the P they need to optimise crop performance under variable seasonal rainfall, there needs to be a fundamental understanding of what happens to fertiliser P that is either banded or mixed into different profile layers in these soils. Due to the historical lack of an imperative for P application in these soils, this understanding is limited to specific combinations of sites and seasonal conditions – not always with no till cropping management (Hibberd *et al.,* 1991; Strong *et al.,* 1997; Dorahy *et al.,* 2005). Recent research has started to explore the P dynamics that occur in concentrated fertiliser bands in different soils and with different P (and K) fertilisers (Meyer *et al.* 2020), with a particular focus on deep banded applications. However, not all P is applied at high rates in concentrated bands in subsoils, and crop residues and unused starter P are returned, and often mixed into, topsoil layers. Interactions between soil type and bioavailable P fractions, the volume of soil enriched during fertiliser application, seasonal moisture availability and crop root system dynamics are all expected to be key factors driving fertiliser P dynamics in vertosol soils and will influence how readily crops can access these inputs over a crop rotation.

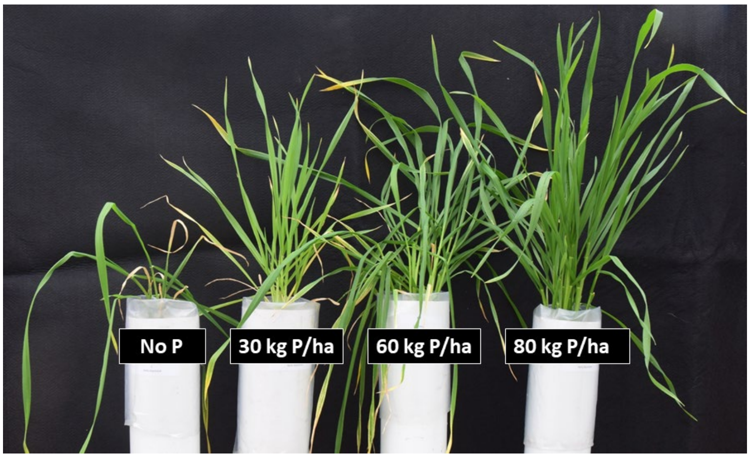

Figure 1. Effect of MAP addition on wheat growth in a long-term cropped Central Queensland (CQ) soil

Objectives of the research

The research reported here was conducted to provide a better understanding of P behaviour in alkaline clay soils from the northern grains region (NGR) with a longer-term objective of being able to predict the behaviour and residual value of different P fertiliser strategies in grains cropping systems. The work has focussed on vertosols, which vary greatly in their physical and chemical properties that are likely to affect soil P dynamics. While other research has focussed on banded P, these studies have focussed on fertiliser P applications that involve a greater degree of fertiliser mixing and exposure to the surrounding soil particles, equivalent to incorporation of fertilisers or crop residues with tillage.

The project initially focussed on the evaluation of crop models to simulate soil P dynamics and crop responses to historic long term fertiliser trials run by Strong *et al.* (1997) and Hibberd *et al.* (1991) and found that these models have struggled to predict soil P dynamics, and hence residual P value in crop sequences (Raymond *et al.,* 2021). This has necessitated a fresh look at P behaviour in these soils, focussing on the initial interaction between soil and fresh fertiliser (dominated by P sorption reactions) and the subsequent residual value of added fertiliser P with increasing times after application. The soil assays used the most common commercial P fertilisers mono-ammonium-P (MAP) and di-ammonium P (DAP). These fertiliser products cause different pH in the soil solution as they dissolve, with MAP producing an acidic pH in solution (pH 3.5) whilst DAP produces an alkaline pH in solution (pH 7.5-8). These differences in pH reaction are expected to influence P behaviour and dynamics within the soil.

The work reported here focuses on P dynamics and recovery from soil using a variety of laboratory analyses. The project is also undertaking glasshouse studies to extend the findings to include plant P uptake using wheat or chickpeas grown in soils supplied from sites established in UQ00082, and while these are nearing completion, results are not reported here.

Our specific objectives were:

1. Determine the variability in sorption and desorption reactions that occur when fertiliser P is applied to different vertosols in the period immediately following application
2. Examine the changes in indices of soil P availability determined shortly after P application, and then how those changes persist or decline with increasing time in the soil.

These two objectives will provide insights into the impact of P fertiliser type (ammonium phosphates with either acidic or alkaline reactions) on the dynamics and availability of P in a range of vertosols from the NGR, and will determine the extent to which these differences in P dynamics and availability can be explained by differences in key soil properties

Large gradient in physical and chemical properties in vertosols

Vertosols vary greatly in their physical and chemical properties, although it is not clear which of these soil properties will contribute to differences in crop P availability. We collected vertosols from nine sites across the NGR (Figure 2) to study the dynamics of added fertiliser P in response to the variation in soil characteristics they provided. All the soils came from fields with a long-term cropping history with limited or no P fertiliser application, so total P contents were low and soil P tests (e.g., Colwell-P and BSES-P) indicated a likelihood of crop fertiliser response. While low P availability was common to all the soils, they differed markedly in other properties likely to affect the dynamics of added fertiliser P. As an example, soil pH_w varied from 5.7 to 8.8, there was a large variation in clay content (24 – 58 %) and the likely number of P sorption sites (indicated by characteristics such as the presence of iron and aluminium oxides and free calcium carbonate) differed greatly. This variability in intrinsic properties related to plant P supply highlight the fact that vertosols cannot be consider as one unique soil type and that the fate of applied P fertiliser is likely to differ from one vertosol to the other.

Soils	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**
pH_{water}	8.2	8.8	8.7	8.7	6.5	8.7	7	7.3	8.8
Clay *(%)*	58	53	41	41	28	35	52	56	45
CEC *(cmol_c kg⁻¹)*	69	61	49	26	16.3	24	23	65.6	53
P_{total} *(mg P kg^{-1})*	329	972	295	157	138	193	134	161	132
Colwell-P *(mg P kg^{-1})*	8	4	7	13	9	7	3	15	<2
BSES-P *(mg P kg^{-1})*	59	22	67	15	12	44	<2	5	7
$PBI_{ColwellP}$	163	245	165	110	52	101	211	161	149
$Al+Fe_{oxides}$ *(%)*	1.1	1.1	0.8	1.2	0.5	0.6	4.1	4	1.5

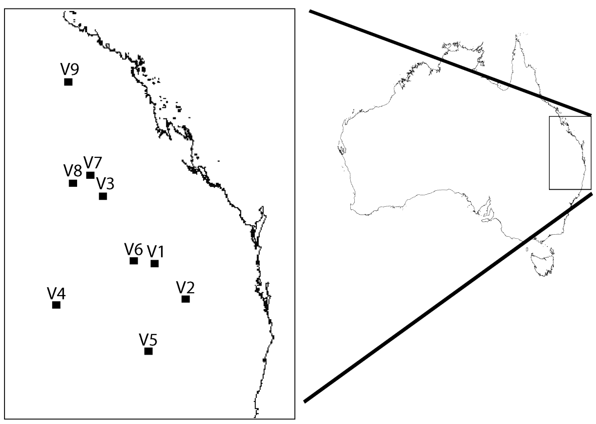

Figure 2. Locations of Soil sampling site locations V1: basaltic vertosol from Jimbour; V2: basaltic vertosol from Felton; V3: basaltic/alluvial vertosol from Rolleston; V4: alluvial vertosol from St George; V5: alluvial vertosol from Biniguy; V6: basaltic/alluvial vertosol from Hopeland; V7: basaltic vertosol from Comet River; V8: basaltic vertosol from Gindie: V9: basaltic vertosol from Kilcummin.

Variability in sorption and desorption reactions with fertiliser P addition

The use of sorption and desorption curves can provide insights on P application strategies to optimise plant P acquisition and are also considered a useful tool to describe the short-term behaviour of added P. Sorption curves are generated by the addition of graded amounts of P to soil (Rayment & Lyons, 2011), and determine the extent to which that P is retained (sorbed) onto the soil matrix. The present study showed that vertosols drastically differed in their short-term P sorption behaviour (Figure 3), which was reflective of the wide range of soil properties within this soil type. The PBI criteria defined by Moody (2007) classified these soils as having low (V5 – PBI 52) to moderate (V1, V2, V9 - 150 to 250) sorption capacities, and while the relative ranking of the maximum amounts of sorbed P were consistent with this index (i.e. V5 < V1 and V9 < V2), these differences reflected large differences in the capacity of each of these soils to sorb P.

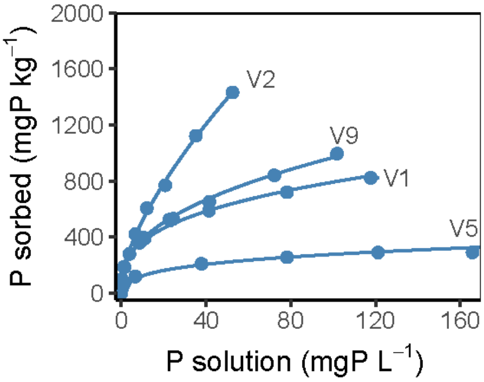

Figure 3. Sorption curves for selected vertosols fitted using a non-linear regression model based on a Freundlich equation.

The variability between soils was even more substantial when the subsequent desorption process (release of sorbed P back into solution) was studied. The desorbability of the previously sorbed P varied substantially between vertosols, and with the amount of added P that had been sorbed in each soil (Figure 4). At low concentrations of sorbed P (LH panel), analogous to low (commercial) rates of P fertiliser broadcast and mixed through the soil volume with conventional tillage, only small fractions of the sorbed P could be desorbed and that release differed substantially between vertosols (between 2 and 10 % of the previously sorbed P). This suggests that low rates of dispersed P may have limited plant availability in many low P vertosols, even shortly after fertiliser application. Conversely, larger fractions of sorbed P were readily desorbable when high concentrations of P had been sorbed, which would be analogous to the situation after a long history of P fertiliser use, or in close proximity to a fertiliser band. This suggests that P in and around fertiliser bands should result in higher relative P availability (up to 75 % of sorbed P), compared to dispersed P that has reacted with larger soil volumes, and is therefore retained more strongly on the soil matrix. Additionally, at high concentrations of sorbed P, the desorption of P was 'relatively' similar across the soil types, especially for those with 'similar' PBI values (see High P example in Figure 4b, where PBI ranges between 101 and 211). Collectively, these sorption and desorption curves on vertosols with low P and little history of fertiliser P application showed that even in the vertosols in which P was more readily desorbable, mixing P fertiliser through large soil volumes is likely to be a less efficient way of improving plant P uptake.

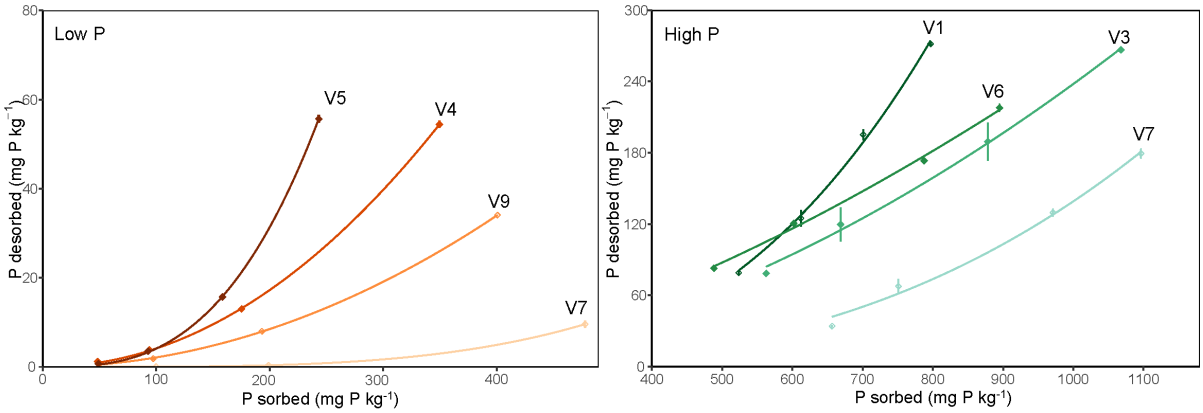

Figure 4. Phosphorus desorption curves for four vertosols differing in their P release at left (a): low concentration of P initially sorbed (< 500 mgP kg^{-1}; Low P) and right (b) at high concentration of P initially sorbed (> 500 mgP kg^{-1}; High P).

Effect of soil properties on longer-term P availability

Sorption and desorption curves are useful to describe P behaviour in the very short-term, but time is likely to further affect the amount of P sorbed and the extent to which it is either 'fixed' or only slowly available. Formation of more stable calcium phosphates and increasing occlusion of adsorbed P will both reduce the long-term availability of P (Lindsay *et al.,* 1989). These factors, combined with a low proportion of applied P typically recovered in the year of application in many cropping systems, highlight the need to understand the longer-term soil P dynamics in relation to specific soil properties that will ultimately determine the residual value of applied fertiliser P.

To determine the soil properties affecting the decline in P availability over time after P fertiliser addition, we set up an incubation with the nine contrasting vertosols. The soils were incubated with P fertiliser applied mixed through the soil volume. Two fertiliser types were used: MAP and DAP at a rate of 50 mg P kg^{-1} (~ 55-60 kg P ha^{-1}). Soil P-availability was assessed using Colwell-P and BSES-P measured after 10, 30, 90 and 365 days of incubation. Similar trends were reported with both extracts, so only the Colwell P data are reported here.

The application of P fertiliser significantly increased P availability measured with Colwell-P in all soils (Figure 5). However, it was clear that the initial net increase in P-availability 10 days after P addition was highly variable between soils, with the increase in Colwell P in response to the same amount of P fertiliser addition ranging from the equivalent of 12 and > 80 % of the applied P. As an example, the fertiliser-induced increase in P availability measured using Colwell P in V7 was very marginal (e.g., net increase of only 6.3 mg P kg^{-1} with MAP and 7.5 mg P kg^{-1} with DAP). On the other hand, the net increase in Colwell-P in V5 was 30 mg P kg^{-1} with MAP and 44 mg P kg^{-1} with DAP. These results correlate with the sorption and desorption behaviour previously observed for low rates of added P and they again emphasise the variable responses to incorporated P in different vertosols.

As the time in the incubation increased, the Colwell extractable P decreased, with the sharpest decrease occurring relatively quickly after P fertiliser addition (between day 10 and day 30 of the incubation (Figure 5)). After 30 days incubation, subsequent changes in Colwell-P were negligible or indicated only a marginal loss of P-availability. The decline in P-availability differed considerably between soils, with net recovery of the added P in the Colwell-P extract falling by between 6 and 44%. One year after P fertiliser addition, soil differences were more pronounced, with V1, V3, V4, V5 and V6 showing much higher residual effects on Colwell-P than V2, V7, V8 and V9. For the former ‘high residual P’ group, the residual increase in Colwell-P was at least twice as high at 1 year (~20 mg P kg^{-1}) than in the low response group of soils (~10 mg P kg^{-1}).

The initial value of Colwell-P 10 days after P fertiliser addition was correlated to the degree of P saturation (DPS) of the soils in their pre-incubated condition, with this index calculated as the soil background Colwell-P (before P fertiliser addition) divided by the phosphorus buffering index ($PBI_{Colwell-P}$)(DPS = Colwell-P/$PBI_{Colwell-P}$). This showed that the number of P sorption sites (indicated by the $PBI_{Colwell-P}$) and their relative saturation (indicated by the desorbable P measured by the Colwell P extract) were key determinants of the decline of P availability over time. While the number of sorption sites is likely to be influenced by the clay content and mineralogy of the soils themselves, the degree of P saturation will be strongly influenced by cropping duration and the previous applications of P fertiliser.

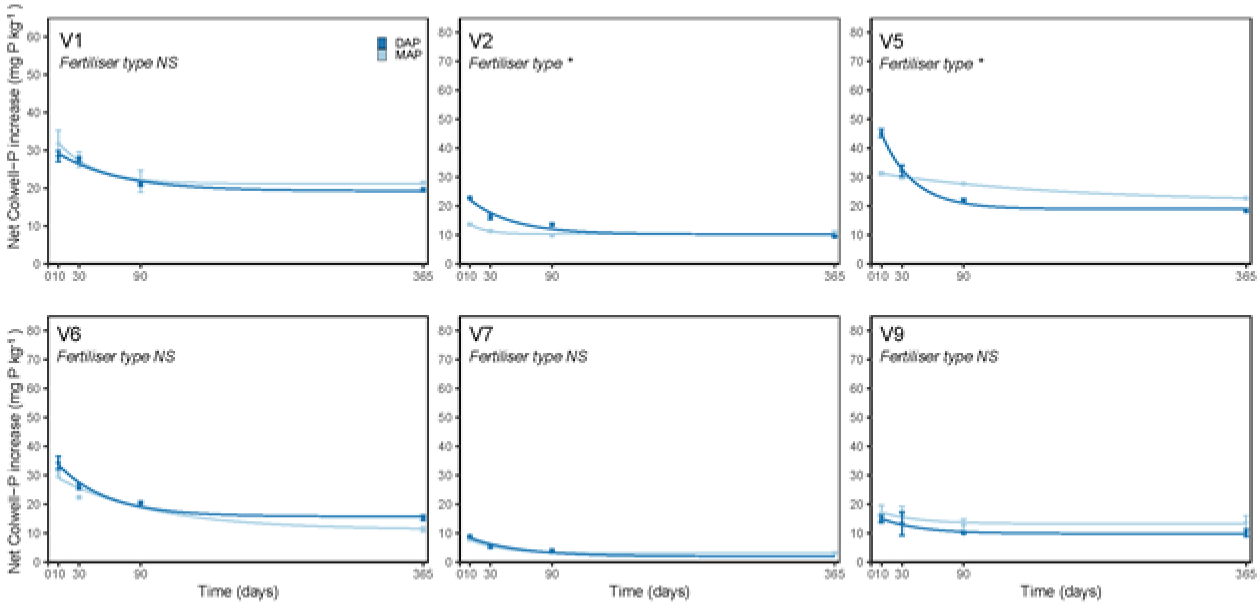

Figure 5. Phosphorus availability decline over time in Colwell-P after the addition of 50 mg P kg^{-1} (~ 60 kg P ha^{-1}) applied as MAP or DAP. The star after ’Fertiliser type’ indicates that the type of fertiliser has a significant effect on Colwell-P decline over time while ’NS’ indicates no significant differences between the fertiliser types.

Does the type of fertiliser matter when broadcast and mixed throughout the soil profile?

Differences in the granule dissolution pH have been hypothesised to influence P-availability in soil. Therefore, because the difference in the fertiliser granule dissolution pH between MAP (pH 3.5) and DAP (pH 7.5-8) were so marked, MAP has often been preferred for alkaline soils (e.g., vertosols) while DAP has been preferred in more acidic soils (e.g., Ferrosols). In our incubation, the type of fertiliser used had only marginal effects on the Colwell-P test value 10 days after application. The addition of 50 mg P kg^{-1} as MAP or DAP increased the average Colwell-P test result across all soils by 28.1 and 30.6 mg P kg^{-1}, respectively, with DAP addition resulting in slightly greater P availability in some vertosols (e.g., V2 and V5). Although DAP resulted in higher initial P-availability in some specific soils, it was clear that over time, most differences in P availability between MAP and DAP disappeared. The initial higher P availability measured with DAP correlated with higher P availability observed in the concentrated P bands of this product (Meyer, 2020), and can be explained by the initial change in soil solution pH after P fertiliser application. The greater acidification by MAP is likely to result in more precipitation reactions, leading to a greater reduction in P availability shortly after P mixing through soil. However, in contrast to P banded applications, the soil solution is likely to be less saturated and can quickly be buffered by the surrounding (unfertilised) soil, which is consistent with the lack of differences in P availability between MAP and DAP over longer periods. While there is no clear long-term benefit of using MAP or DAP on P-availability, it is clear that soil characteristics rather than the fertiliser type seem to determine the increase in soil test P after fertiliser application, and their residual benefits in the longer-term.

Practical implications

- This research suggests that the further the native soil P reserves in cropped vertosols are run down before starting fertilising to halt or reverse this trend, the harder it is going to be to return to a system that can meet crop P demands – both in terms of investment in P fertiliser to make a difference, and in the flexibility of application strategies than can be employed
- When dealing with low P vertosols, and particularly in soil layers that have not received much/any P fertiliser (e.g., depleted subsoils), banding is clearly the most reliable application strategy. Smaller, less concentrated bands that collectively enrich more of the soil volume (i.e., narrower band spacings, or more frequent, lower rate applications in different positions) are likely to minimise the precipitation reactions previously seen in narrow concentrated bands, but also reduce the strong P sorption observed when P is mixed throughout large soil volumes
- This research has demonstrated that the choice of fertiliser product has little impact on either the short- or longer-term fate of applied P, with soil properties a more important determinant of the effectiveness of applied P in increasing soil P availability to plants
- Identification of the specific soil properties that drive these dynamics, and the extent to which any such indicators can form part of routine soil test diagnostics (e.g., like PBI) will have a large impact on the fertiliser strategy recommended to rebuild soil P reserves and cropping systems resilience
- These results require further research to confirm the correlation between these laboratory soil assessments of P availability and increased plant recovery of applied P.

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Contact details

Dr. Nelly Raymond
The University of Queensland
St Lucia Campus
Ph: 04049 18489
Email: n.raymond@uq.edu.au

Prof Mike Bell
University of Queensland
Gatton Campus
Ph: 0429 600730
Email: m.bell4@uq.edu.au

Root research: What do wheat and sorghum roots do when water is in one part of the profile and phosphorus is in another? Root angle and why does it matter?

Frederik van der Bom, Alwyn Williams, Nelly Raymond, Mike Bell,
University of Queensland

Key words

root distribution, root angle, drought, soil heterogeneity, phosphorus stratification

GRDC code

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Take home messages

- Over the past 3 years, we have conducted a series of controlled and semi-controlled experiments with wheat and sorghum genotypes with contrasting root angle, focussed on quantifying the productivity advantages of root architecture in soils with stratified and banded phosphorus (P) reserves
- Root angle was related to deeper exploration of the soil profile (narrow) and scavenging for P in the topsoil (wide), particularly early in the season. A narrow root system may access deep banded P slightly earlier than a wide root system, but it may also be at risk of 'missing' the bands completely, given the very small, enriched soil volumes. In contrast, a wide root angle could improve (early) exploration of the topsoil layer and crop growth if no P is available in deeper layers
- Access to surface-stratified P can quickly be reduced by the soil drying out, providing the crop with only a limited window of opportunity to take up P from this layer, and diminishing the potential benefits of shallow roots for improved P uptake. However, there may still be benefits of wide root angle genotypes through an ability to exploit rewetting events, but these would be highly dependent on in-season rainfall distribution
- Adequate crop nutrition is a critical success factor for root growth in general, and for root architecture to be reliably expressed. Severe P scarcity can eliminate the benefits of plant genetic selection, so the importance of placement and timing of P applications to optimise the performance of 'designer' root systems cannot be overlooked.

Introduction

This paper is based on results from a series of experiments supported by GRDC in the northern grains region, focussed on improving crop and agronomy/nutrition management. The specific aim of this research was to provide a better understanding of how genotypes with selected root angles will confer benefits in the growing conditions of the northern region.

A lot of investment is currently being made in breeding of genotypes with deeper root systems with the expectation that these will enhance exploitation of deep soil water reserves and enhance performance in environments with terminal drought. These genotypes are selected for specific root traits such as narrow root angle, which has been found to correlate to a deep root architecture in glasshouse studies. Selection for these traits generally occurs using rapid, high-throughput screening tools on juvenile plants (e.g. 5 day old seedlings, in the case of root angle). This approach offers advantages over evaluating rooting depth in the field, which is difficult, slow, and often gives variable results. However, evidence of relationships between root angle and rooting depth and field performance is limited. In part, this is likely because the conditions in the field are very different from those in which selection takes place. Therefore, it is important to understand how genotypes selected for contrasting traits like narrower root angle function in realistic production environments where moisture availability and distribution fluctuates during the season and less mobile nutrients are typically concentrated in the topsoil layers (stratified) or in narrow fertiliser bands. Both conditions have become increasingly common in the northern region.

Our aim was to quantify the impact of spatially separate distributions of water and immobile nutrients on the productivity of winter and summer cereals, with particular attention to how root traits (root angle) affect productivity in soils with stratified/banded nutrient reserves.

Water and phosphorus (P) distribution and implications for crop resource uptake

Before we discuss the role of crop genotypes and root architecture, it is worth noting how the soils in our cropping systems are managed, and what this means for crop resource availability and the crop root system. Historically, the productivity of grain systems in the northern region has been governed by the efficient capture, storage and extraction of water from the soil profile, with agronomic practices focused on

1) Achieving a uniform and deep profile refill during a fallow to allow stored water to support crop growth during dry periods and
2) Synchronising crop water use with key yield-determining growth stages.

However, many of the soils in the northern region are changing as a result of chronic under-fertilisation that has depleted native soil fertility, which has led to greater reliance on annual fertiliser inputs to meet crop nutrient demand.

Widespread adoption of conservation agricultural principles with minimal tillage have delivered important benefits, but also mean that P input from crop residues, manures or fertilisers tend to be applied onto the soil surface and/or in infrequent relatively wide bands with very little mixing through the soil layers. This has led to increased surface stratification of P (relatively high concentrations in the topsoil, but very much lower/depleted concentrations in deeper soil layers), which has a low mobility in these clay soils. As a result, P and water reserves can often become spatially separated in all but the wettest years, meaning root systems face major trade-offs for the exploration for P versus uptake of water. For example, genotypes with a narrow root angle may have deeper roots systems and the capacity to explore and take up water from deep subsoil layers, but may do so at the expense of topsoil exploration and uptake of stratified P, or be less efficient at finding and exploiting banded P fertiliser.

'Deep banding' (0.15-0.3 m depth) of P fertiliser is becoming an increasingly common management practice to provide more consistent crop access to P. This approach relies on the placement of P in layers that stay moist for longer, and on roots proliferating in and taking up P from the small, highly enriched soil volumes around the concentrated bands. Because the topsoil tends to dry rapidly, 'deep bands' can elicit significant crop responses, even in soils with relatively high topsoil P availability. The substantial responses to deep P bands across the northern region where subsoil P is low have been detailed in a number of recent publications (Lester *et al.* 2019, Sands *et al.* 2018).

How crop root systems respond to this heterogeneous distribution of P in the soil profile and its spatial separation with water will determine productivity in any given set of seasonal conditions. In other words, the exact benefit of root system architecture will depend on efficient capture of both resources that are in short supply.

Root angle and why does it matter?

Breeding for root architecture is thought to have a great potential for producing crops with 'designer root systems' better adapted to capturing soil resources such as water, or P. The big difference with traditional breeding is the focus on improving productivity by focusing on below-ground root traits and targeted development of varieties with phenotypes that include combinations of root traits that are presumed to be suited to specific environments. For example, selecting genotypes with a narrower angle should lead to a steeper root architecture enabling crops to access otherwise out-of-reach soil water, allowing prolonged growth and yield accumulation during grain filling, even under terminal drought conditions. In contrast, a wide root angle should lead to more shallow soil exploration, allowing a crop to more efficiently forage for resources from the top part of the soil profile. Although some evidence exists for these developments to work in environments with a single target constraint (i.e. either water or P limited), crops in the northern region are frequently exposed to multiple soil constraints simultaneously, with trade-offs such as described above (van der Bom *et al.,* 2020).

Experimental approaches

During the past 3 years we have used lines defined by contrasting seminal or nodal root angles (i.e. wide vs narrow) from durum wheat and sorghum breeders to conduct a series of short-term (early-season), medium-term (anthesis) and full season experiments. These have been conducted in either rhizoboxes (short term) or in an automated lysimeter system with 60 cm × 30cm diameter soil cores (medium and long term) and have involved exposing these genotypes to different P distributions and soil water dynamics. Responses have been assessed on the basis of both aboveground and belowground growth. In assessing responses to P distribution, we used soils with low or high background P fertility and contrasted this to different zones and methods of fertiliser P placement (No P, starter P banded adjacent to the seed row, P mixed through the top 10 cm layer, and deep bands at 25cm. Rates of starter P (~6 kg P/ha) were much lower than those used to supply P for growth (~45 kg P/ha in the topsoil and banded P treatments). These P distributions were interacted with different soil water dynamics that would impact on root distributions and water/nutrient acquisition. These included constant watering to maintain the soil close to field capacity ('wet'); allowing the topsoil to dry out ('dry'); or allowing the soil to dry and then rewet ('rewet').

In all the experiments the soil was a P responsive grey vertosol from Hopeland (near Chinchilla), which received all other nutrients except P as a basal application in all experiments. The applications of P fertiliser were in the form of MAP.

For brevity, we primarily focus on the results from the experiments with durum wheat, but similar experiments have been conducted for sorghum lines. Generally, the sorghum data have provided a similar picture to that from durum wheat and suggest that same principles apply to both species.

Trial results

Early season growth responses to phosphorus placement

Durum wheat biomass showed clear positive growth responses to P placement, particularly to enriched topsoil P (Figure 1). The amounts of P supplied in the topsoil-P and the P-band treatments were equal, but for banded treatments roots had to grow through the very low background P layer first to reach the deep P band, whereas ample P would have been available close to the seed for the topsoil-P treatment. Secondly, the P band was applied as a concentrated row which would have reduced the probability of root to P fertiliser contact compared with the P that was distributed in the 10cm topsoil layer.

For both genotypes root intensity in the topsoil was largest when P was placed in this zone, and this fertilisation effect also improved root growth in deeper layers (Figure 2). In other words, a greater crop access to P was associated with more roots in medium to deep zones.

When P was banded at 25cm, the narrow genotype tended to grow larger and take up more P than the wide genotype. Its root growth intensity increased in the 20-30 cm layer where the band was located, but this was not the case for the wide genotype. Thus, the narrow genotype was quicker to develop roots in the layer with the P band, though visual observations at time of harvest (38 days) indicate that local root development close to the location of the P band was also beginning for the wide genotype. This suggests that the main driver of the treatment response was one of timing of access to the deep P band.

Overall, the narrow genotype had greater root intensity at depth than the wide genotype, whereas the wide genotype had a greater root intensity in the topsoil for all treatments. Thus, the genotypes expressed deep and shallow rooting patterns in agreement with their selection for root angle. However, the difference in deep roots between the two genotypes was marginal for the control treatment, and differences between P applications were far greater than those between genotypes. In particular, both genotypes had the greatest root intensity at any depth when they also had the greatest access to P (topsoil P). This emphasises the importance of early P nutrition 1) to improve early root growth in general, and 2) as a requirement to achieve the intended root architecture for which selection took place.

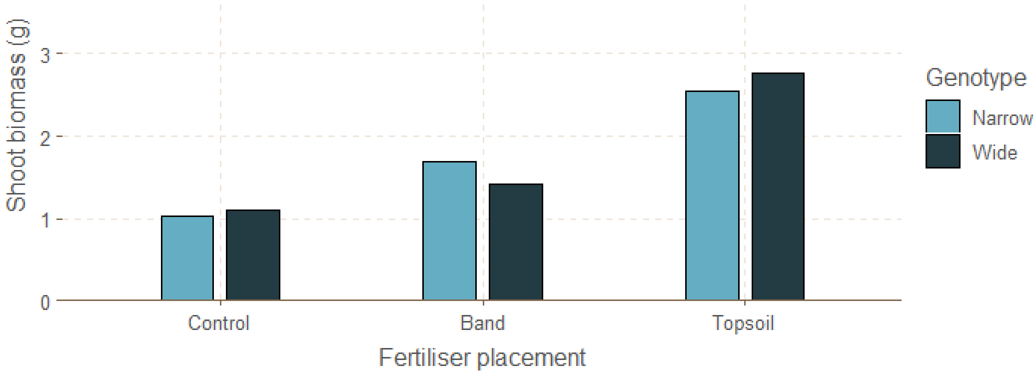


Figure 1. Early growth responses (up to late tillering) to P placement by two durum wheat genotypes with contrasting root angle

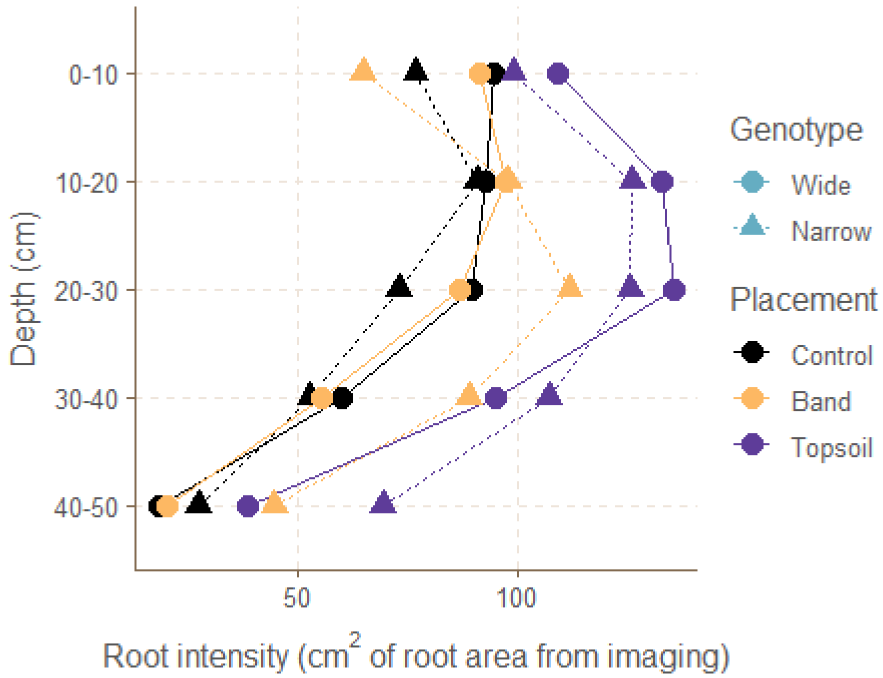


Figure 2. Root intensity (root area) of two durum wheat genotypes with contrasting root angle at late tillering

Early growth responses – the role of starter P

In a second early growth study, we evaluated the functioning of selected genotypes with different combinations of starter-P and deep P bands. Across the northern region the traditional P fertiliser application method is starter P. Bell *et al.* (2020) reported early growth responses to starter P were consistent with crop uptake of around 1-1.5 kg P/ha from starter P application, but very low P reserves elsewhere in the soil profile limited the ability of crops to find enough P to grow any additional biomass and fill grains. In these environments responses to deep P bands have been quite consistent irrespective of variability in seasonal conditions, with uptake from deep P bands often observed to be additive to starter P (Lester *et al.* 2019, Sands *et al.* 2018).

The effect of starter P on early crop growth and root growth was clear, with durum genotypes that received starter P growing larger than those with only deep P bands (Figure 3). Similar to the topsoil P treatments in the first experiment, starter P would have supplied the crop with P early on, whereas roots had to grow through low P soil to reach the deep P band. The response in both experiments thus emphasizes the benefit of ensuring ample P close to the seed, to improve early P uptake and plant growth. Noteworthy is the increase of biomass of the narrow genotype when starter P and a deep P band were combined, with the application of starter P boosting early root development (Figure 4, right) and allowing quicker exploration of the subsoil with the deep P bands. Note that the methodology in this experiment means the root responses to the deep bands are assumed to represent both the 20-30 cm and the 30-40 cm layers.

For sorghum (Figure 3, bottom) the difference between starter P and a deep P-band was particularly pronounced for the wide genotype, which agrees with the notion that a narrow root system is quicker to explore the subsoil. Here, the addition of starter P on top of a deep P band had a clear additive effect and substantially boosted early growth of the wide genotype.

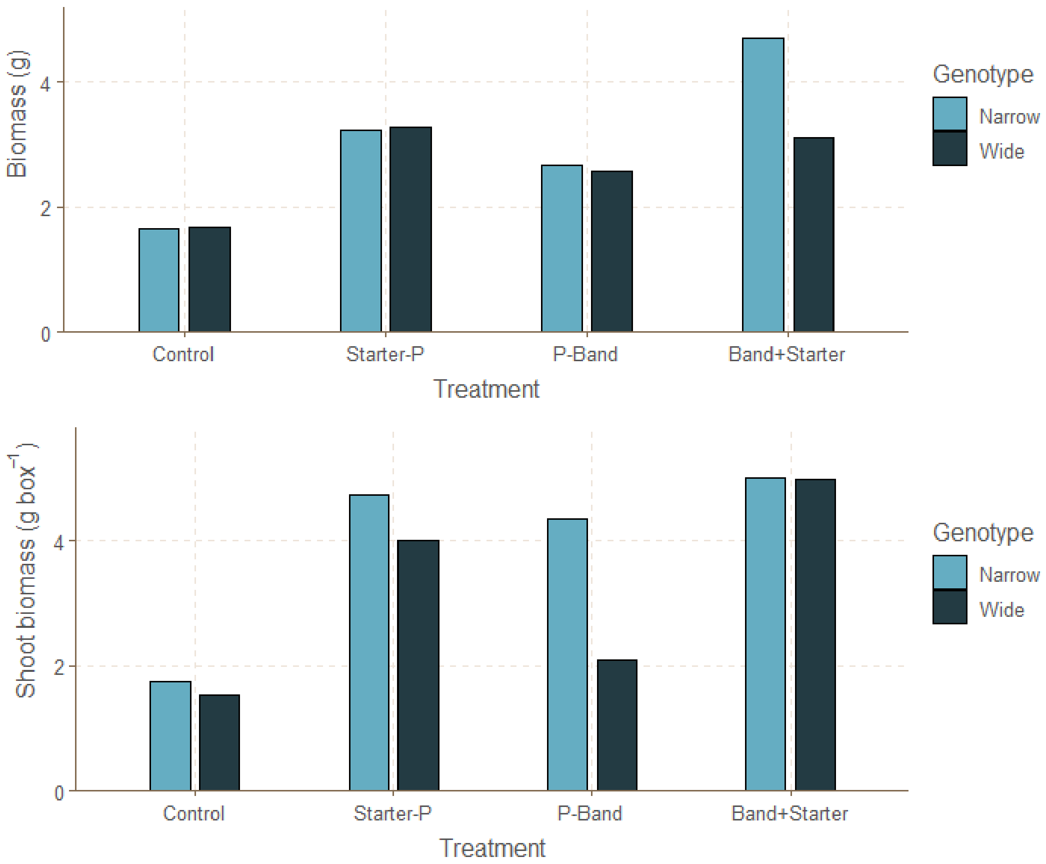


Figure 3. Early growth responses to P placement by genotypes with contrasting root angle, considering starter-P. Top: durum wheat; Bottom: Sorghum. Plants grown for approx. 7 weeks

Both genotypes generally expressed deep and shallow rooting patterns in agreement with their selected root angles (Figure 4). The root responses to the placement of P are characterised by very local plastic changes of root architecture, which are thought to be triggered by the root tip sensing a locally higher P concentration and responding by proliferating lateral roots in this zone. For these responses to occur, the root tip needs to be in a relatively close proximity to the applied granules. This is very easily achieved for starter P as this is applied close to where roots are initiated from the seed, but the probability of roots encountering P fertiliser granules becomes smaller as the distance of application from the seed increases i.e. for deep P bands. Indeed, we have observed considerable variability in the response of narrow genotypes of both durum wheat and sorghum to deep P bands (Figure 1, 3), indicating that solely relying on the genotype for quick subsoil exploration may be a 'hit and miss' strategy in terms of accessing deep P bands. In contrast, starter P and/or maintaining topsoil P concentrations seem a more reliable strategy to boost early root growth and improve the capacity and likelihood to find and make use of deep P bands.

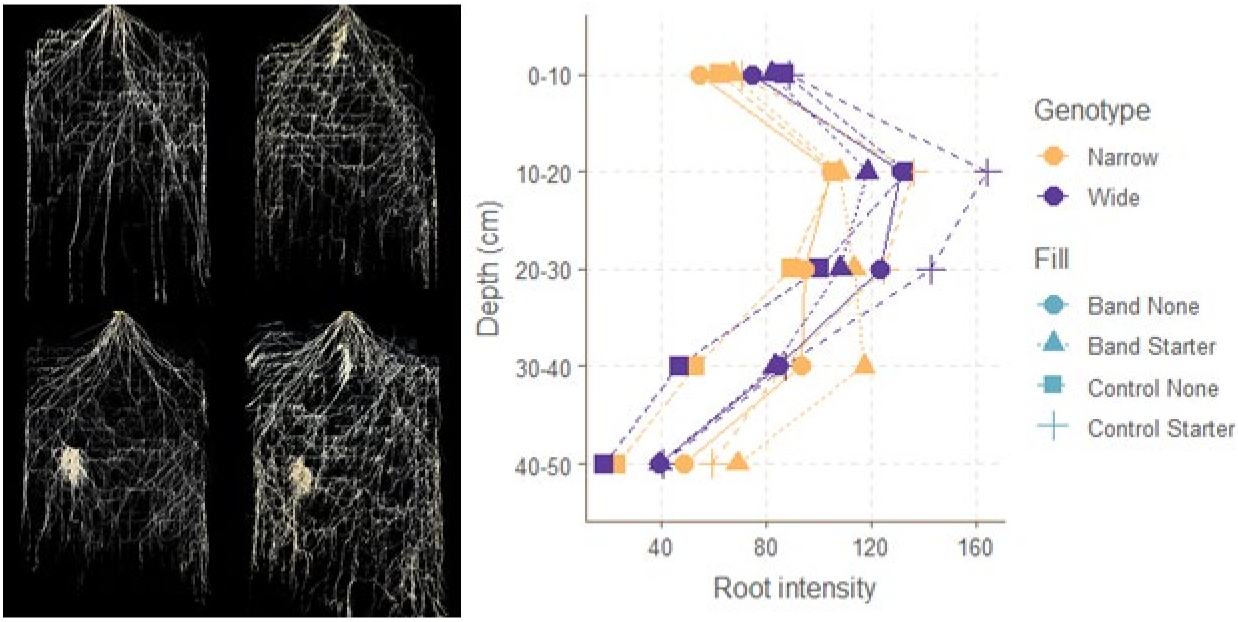


Figure 4.7 Left: Root proliferation around the band is a highly localized response of fine roots. (clockwise) low-P control, starter P, banded P+starter P, banded P alone. Right: root intensity of two contrasting durum wheat lines in response to starter P and deep P bands.

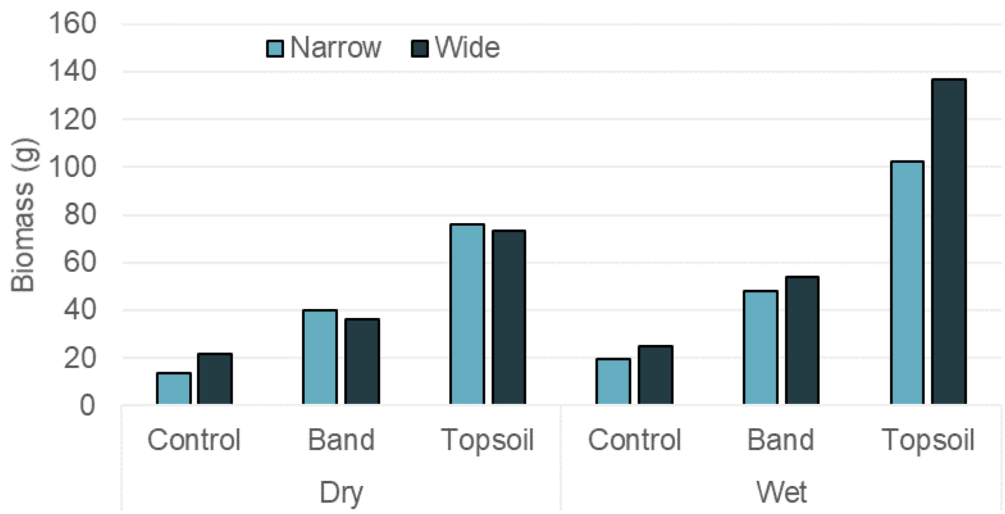
Effects of phosphorus placement and water dynamics at anthesis

In the absence of starter P, the placement of P fertiliser increased biomass at anthesis of both genotypes in the order of Control < P-Band < Topsoil P (Figure 5), which also corresponded to greater tiller numbers (not shown). These results complement the observations of the short-term experiment and illustrate that deep bands can deliver additional P uptake and crop growth, but unless there is access to some P during the early stages of growth, this cannot fully compensate for low P in the topsoil layers.

Under well-watered conditions, the wide genotype could take advantage of its greater ability to explore the topsoil compared to the narrow one (Figure5, bottom). However, a drying topsoil strongly reduced shoot and root growth, tiller production, and P uptake for this P placement, as it would have made the P located in this zone unavailable. Proportionally this resulted in a greater growth reduction in response to a drying topsoil in the wide genotype, and subsequently, no differences in the average performance between the two genotypes. In contrast, the effect of topsoil drying was very limited where deep P was banded, as this deeper layer did not dry out and continued to support P uptake. This agrees with field observations that show quite consistent responses to deep P bands in a variety of seasonal conditions (Lester *et al.* 2019, Sands *et al.* 2018).

When P was deep banded, both genotypes took up similar amounts of P and produced a similar amount of biomass. This seems contradictory to the short-term experiments in which the narrow genotype seemed better able to use a P band. One possibility is that the limited volume of enriched soil and highly local root response (Figure 4) means there is a maximum achievable root density, after which there is no more benefit of increasing root mass. Indeed, we observed no important differences in root length density between the two genotypes around the P bands (Figure 5). Another possibility is that at the extreme root density around the bands, P uptake is limited by other factors such as competition between roots of the same plant, or rapid drying of the band as a result of root activity.

Despite no apparent difference in shoot and root biomass, the wide genotype showed delayed crop phenology, suggesting P deficits while the plant slowly developed enough roots around the band to acquire P. This slower crop development may have positive or negative effects, depending on seasonal demand for water in relation to the available supply. More time to accumulate biomass may generate greater yields in a relatively wet year, but in a dry year a longer time to flowering may deplete more of the available water reserves and leave less available during grain-filling.



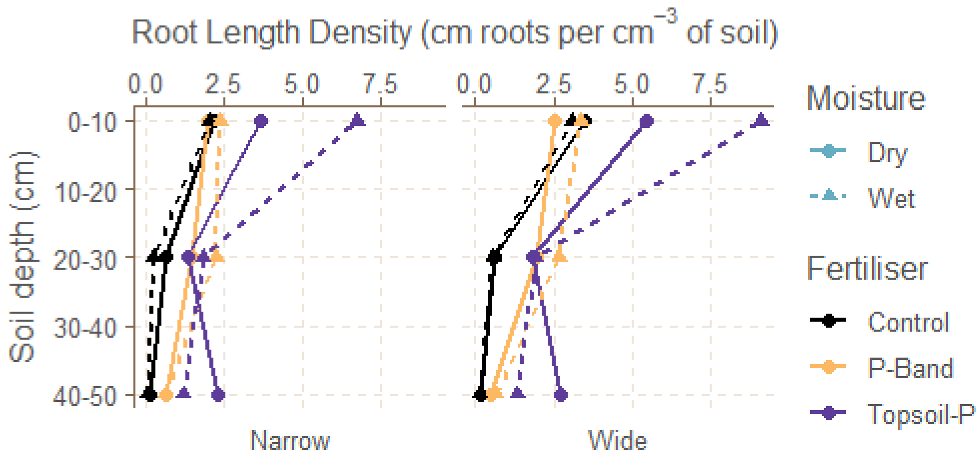


Figure 5. Growth responses to P placement and soil water by durum wheat genotypes with contrasting root angle (anthesis). Top: aboveground biomass, bottom: root length density

Effects of phosphorus placement and water dynamics on grain yields

In the final study we evaluated the responses of the contrasting genotypes to deep P bands and drying/rewetting, in a soil profile that was characterised by a 5cm stratified P topsoil layer and a starter-P application. In this environment, the deep P bands provided an important source of P in the subsoil (Figure 6), regardless of the soil water treatments, though the effect was proportionally more important as water availability was reduced. Similar responses to deep P bands have previously been observed on soils with a high topsoil P availability, with these responses often being more pronounced in seasons with sparse or irregular rainfall (Bell *et al.*, 2012). This illustrates the loss of crop access to stratified P as the topsoil layer dries out. Deep P bands that are placed in layers that stay moist for longer can thus sustain crop P uptake when access to the topsoil is limited, though the difference between the wet stratified P soil and the dry soil with a deep band make it clear that a single deep band cannot fully compensate for the loss. This is also further illustrated by the increased P uptake when the topsoil was allowed to rewet after it had dried out.

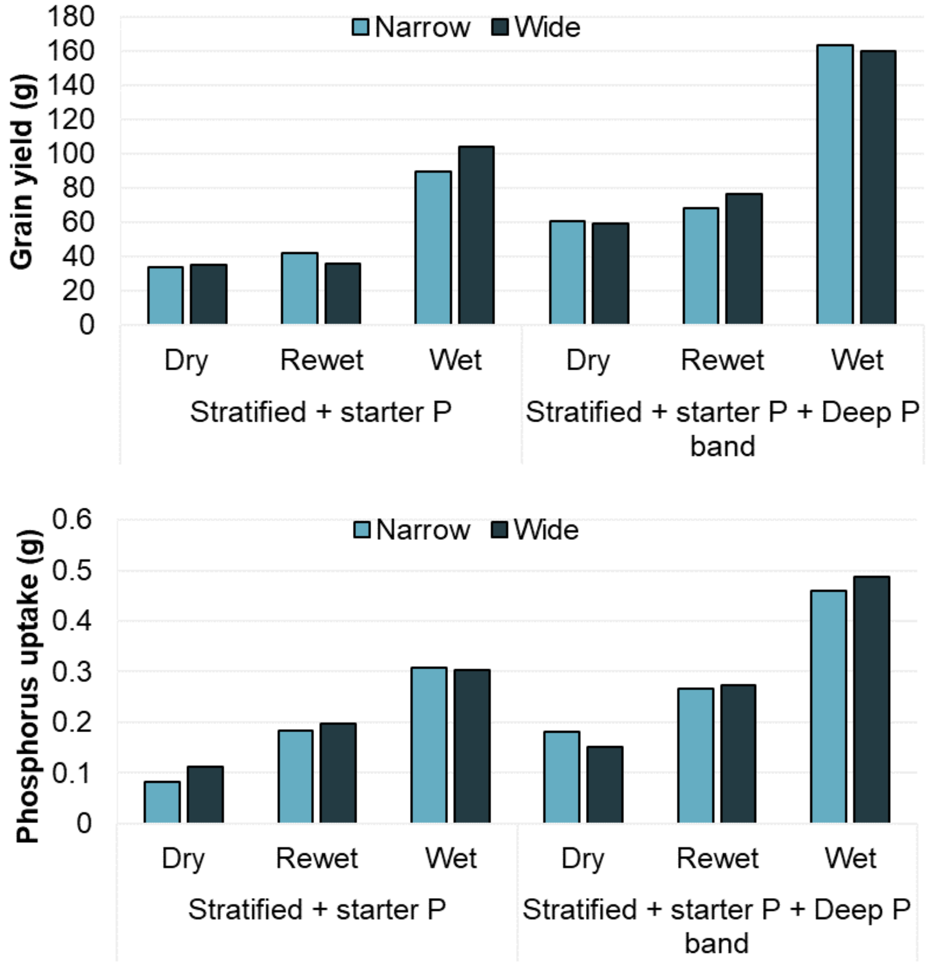


Figure 6. Durum wheat grain yield. In all treatments a 5cm stratified phosphorus layer and a starter-P application was included.

Future nutrient management opportunities

- Narrow root systems may be slightly quicker to reach down to a deep P band but are also at greater risk of 'missing' them entirely, especially at wider band spacings. Slower access of Wide root systems to deep bands may be compensated by a delayed phenology, but this may be a risk or a benefit depending on seasonal conditions (rainfall)
- Shallow roots systems have the capacity to improve (early) uptake of phosphorus from the topsoil, but a drying topsoil diminishes this advantage
- Phosphorus access is critical for 'designer' root architecture to be expressed
- Get P into the crop as early as possible. Starter fertilizers are therefore really important, but also be aware that they are not an effective solution to meeting crop P demand in most seasons. Starter P has an important role to play in early season growth and establishing yield potential. While the amount of P acquired from the starter P band is quite small, it can have valuable additive effect and improve deep band use
- Early P access (whether stratified P or starter P) is especially important in very dry seasonal conditions in which access to topsoil P is rapidly reduced

- Deep P provides an important source of P in the subsoil, but it cannot completely compensate for a general lack of soil P availability.

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Contact details

Frederik van der Bom
University of Queensland
St Lucia Campus
Ph: 07 3443 2604
Email: f.vanderbom@uq.edu.au

Mike Bell
University of Queensland
Gatton Campus
Ph: 0429 600730
Email: m.bell4@uq.edu.au

Nitrogen release dynamics of enhanced efficiency fertilisers (EEFs): placement, soil factors and plant uptake

Cristina Martinez[1], Chelsea Janke[1], Yash Dang[1] and Mike Bell[1,2]

[1] School of Agriculture and Food Sciences, The University of Queensland
[2] Centre for Crop Science, Queensland Alliance for Agriculture and Food Innovation, The University of Queensland

Key words

nitrogen, granular urea, enhanced efficiency fertilisers, inhibitors, controlled release fertilisers

Take home message

Enhanced efficiency nitrogen fertilisers (EEFs) control and delay the release of nitrogen (N) into soil, potentially leading to improved crop uptake and reduced environmental losses. However, in these studies we found that banded application of EEFs did not demonstrate any improvements in maize grain yields relative to conventional urea fertiliser.

The main responses to EEFs were as follows:

- Nitrification inhibitors (NIs) significantly reduced N_2O emissions compared to urea and delayed nitrification but did not increase crop N uptake. Residual N in the soil was generally shallower (≤ 0.3m) than from urea and provided no additional N to a subsequent maize crop
- Urease inhibitors (UIs) did not improve N uptake by the initial maize crop and did not have any greater residual benefit than urea. UIs increased the depth of NO_3^- movement compared to urea, with most residual N located > 0.3m in the profile
- Polymer coated urea (PCUs) delayed N release, then provided a low and continuous supply of N throughout the season. This N was not effectively captured by the maize crop, with either no yield advantages or in some cases poorer yields compared to urea

Despite EEFs performing as designed, no clear productivity or yield advantages were found relative to conventional N fertilisers (i.e., urea) in banded applications. The slower rate of N release and / or availability appears to be poorly synchronised with crop N demand.

Introduction

Improved nitrogen use efficiency (NUE) in Australia’s cropping industries is critical for

(a) Reducing fertiliser costs to growers

(b) Improving agronomic efficiency and crop yields and

(c) Reducing environmental impacts (e.g., nitrous oxide [N_2O] emissions, leaching & runoff losses).

Enhanced efficiency fertilizer (EEF) technology (i.e., inhibitors and controlled-release products) are potential tools for improving NUE in cropping environments. However, the effective use of EEFs is hampered by a poor understanding of how these technologies behave in soil and how this translates to agronomic outcomes in the field. Furthermore, most EEF products have been developed and tested in temperate environments where they are broadcast or incorporated with conventional tillage. Thus, a better understanding of the mechanisms at work when different EEF technologies are band-applied under Australian field conditions is required.

This study evaluated several urea-based EEFs, including urease inhibitors (UI - Green Urea NV™), nitrification inhibitors (NI - ENTEC®) and 90 day controlled-release polymer coated urea (PCU - N90®), benchmarking their performance against granular urea under field conditions on Vertosol soils. The N release dynamics of these products were quantified and their potential to increase crop production and reduce N_2O emissions were investigated.

Methods

This paper presents data from a series of field experiments (2018-2020) established at The University of Queensland Gatton campus. These experiments provide an integrated assessment of EEF performance benchmarked against granular urea under irrigated field conditions in southern Queensland, with maize as the test crop.

Maize production

In September 2017, a forage sorghum crop (cv. Pioneer® Super Sweet Sudan) was planted, and sequentially cut and baled twice, to deplete the indigenous soil-N prior to the start of the experiments. The first experiment examined EEFs (UI, NI and PCU) applied to maize at rates of 125 kg N ha^{-1} (sub-optimal relative to crop N demand) and 250 kg N ha^{-1} (optimal or supra-optimal). To confirm these rates were sub/supra optimal for the maize crop, six rates of urea (0, 62.5, 125, 175, 250 and 300 kg N ha^{-1}) were tested to develop a reference N response curve, against which EEFs were benchmarked. A second experiment in the same season (adjacent to the first experiment block) compared N_2O emissions from NI and PCU against those from urea at an intermediate rate of 150 kg N ha^{-1}. Treatments in both experiments were replicated four times in randomised block designs.

Fertilisers were band-applied at a soil depth of 10cm with a spacing of 75cm, immediately prior to sowing of the maize crop. Maize hybrid PAC 606IT was planted at a rate of 70,000 plants ha^{-1} at a depth of 6cm, adjacent to fertiliser bands.

N_2O emissions

Nitrous oxide emissions were measured over the entire maize crop season using a fully-automated chamber measuring system (see Grace *et al*. 2020). Chambers were positioned next to plant rows to account for N_2O emissions integrated across the fertiliser band and adjacent row. Grain yield at 14% moisture was determined at time of harvest, after which soil samples were collected from fertiliser treatments (250 kg N ha^{-1}) to quantify mineral N remaining in the soil. Soil samples were carefully taken to represent the band, near-band and inter-band locations (see Dang *et al*. 2021).

Residual N

Soil samples were collected using a 50mm diameter tube pushed by a hydraulic sampling rig and partitioned into 0–0.1, 0.1–0.3, 0.3–0.6 and 0.6–0.9m increments. Samples were dried at 40^oC, ground and analysed for concentrations of nitrate (NO_3^-) and ammonium (NH_4^+). The total mass of NO_3^- and NH_4^+ was calculated by multiplying concentrations with bulk density and the depth of the soil layer.

In 2019, the same maize hybrid PAC 606IT was planted over the treatment plots without application of N fertiliser, to assess the residual value of fertiliser N applied during the previous season. The crop was sown at a rate of 65,000 plants ha^{-1} at a depth of 6cm into the space between the rows from the previous maize crop. Grain yield at 14% moisture was obtained at time of harvest.

Three-dimensional soil dynamics

Following the maize crop harvest in June 2019, wheat was sown to further draw down the soil N. An experiment was then established in January 2020 to investigate the release and distribution dynamics of N from banded fertilisers (urea, NI and PCU).

Fertiliser products were band-applied at a soil depth of 10cm with a spacing of 75cm on 8 January 2020 at a rate of 150 kg N ha^{-1}. Soil samples were collected 7, 19, 46, 78 and 145 days after the onset of N release (i.e., once fertiliser bands were wet). During sampling, a profile (approx. 0.4m deep, 0.3m wide) perpendicular to the fertiliser band was exposed in each plot in central bands. Once the fertiliser band was located, a 5cm diameter soil coring tube was inserted into the face of the soil profile, such that the fertiliser band was in the centre of the tube. Additional tubes were then inserted directly above (5cm) and below (10cm) the fertiliser band on all sampling times, with two additional samples collected adjacent to the band for the first three samplings (see Martinez *et al*. 2021). After field sampling, soils were stored at 4°C until processing was completed within 48 hours of collection. Samples were manually mixed to ensure homogeneity and analysed for NO_3^-, NH_4^+, and soil pH. Samples collected on the fertiliser band were also analysed for urea-N.

Results

Maize production

Prior to the 2018 maize crop, NO_3^- (< 1 mg kg^{-1}) and NH_4^+ (2-4 mg kg^{-1}) concentrations were low at all soil depths. Maize yield and grain N content was therefore highly responsive to N fertilisation (Table 1). Grain yield increased significantly with increasing rates of applied urea up to 175 kg N ha^{-1}, after which only very small increases were observed. A Mitscherlich equation provided the best model fit for the relationship between N rate and yield, with maximum potential yield of 11.9 t ha^{-1} and 90% relative yield of 10.7 t ha^{-1} at 175 kg N ha^{-1} (Fig. 1).

Grain yields from EEF treatments did not improve compared to urea (Figure 1 and Table 1). While an average yield increase of 19% was recorded as N rates increased from 125 to 250 kg N ha^{-1}, increases were not statistically significant for the NI treatment. Furthermore, the PCU produced significantly lower yields at both the low (8.1 t ha^{-1}) and high (10.3 t ha^{-1}) application rates compared to urea (9.7 and 11.4 t ha^{-1}, respectively; Figure 1).

Table 1. Grain yield for maize grown in 2018 and 2019 at increasing rates of urea (0, 62.5, 125, 175, 250 and 300 kg N ha^{-1}) and EEFs (UI, NI, PCU) applied at 125 and 250 kg N ha^{-1}.

Urea rate kg ha^{-1}	2018 (*year of fertiliser N application*)		2019 (*residual fertiliser N*)	
	N response curve (urea N, kg N ha^{-1})			
0	1.7[a]		3.7[a]	
62.5	7.2[b]		4.0[a]	
125	9.7[c]		4.4[a]	
175	11.2[d]		5.1[b]	
250	11.4[d]		6.4[c]	
300	11.9[d]		8.2[d]	
	Relative performance of EEFs			
N type	*125 kg N ha^{-1}*	*250 kg N ha^{-1}*	*125 kg N ha^{-1}*	*250 kg N ha^{-1}*
Urea	9.7	11.4	4.4	6.4
UI	9.7	11.0	4.0	6.6
NI	9.9	10.7	3.7	6.7
PCU	8.1	10.3	3.2	5.9
l.s.d (p<0.05)	2018		2019	
N products	0.9		0.6	
N rate	0.4		0.3	
Interaction	1.3		0.8	

Values within a column followed by the same letter are not significantly different at *p*=0.05. UI = urease inhibitor; NI = nitrification inhibitor; PCU = polymer coated urea

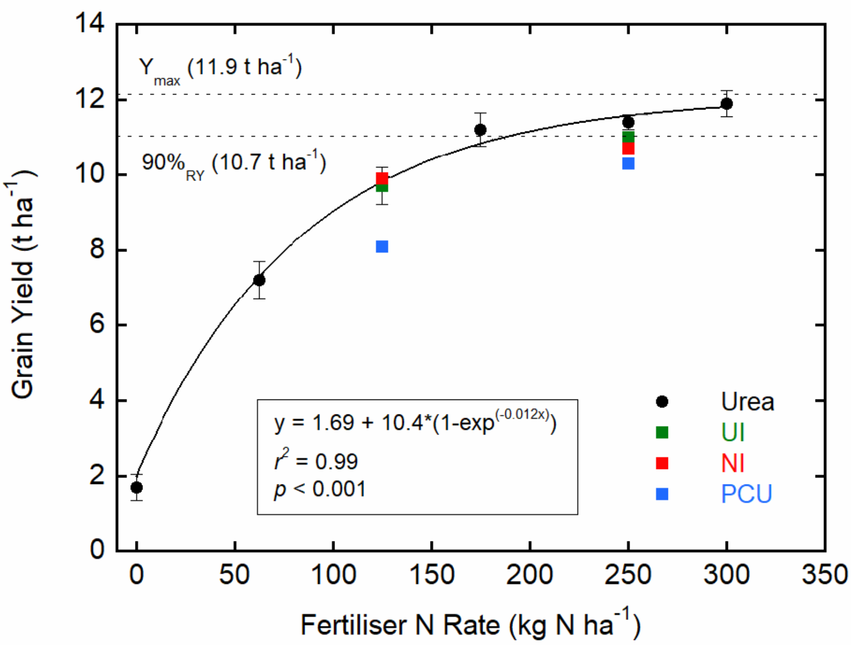

Figure 1. Maize grain yield (2018) response to increasing rates of urea fertiliser application and relative performance of EEFs at application rates of 125 and 250 kg N ha^{-1}.

N_2O emissions

The majority of N_2O emissions occurred in the first two months after sowing / fertiliser application, when soil mineral N was highest. The highest daily N_2O fluxes from all treatments occurred after an

80mm rainfall event in February, with a smaller peak also occurring in response to a 50mm irrigation event that was applied to the emission trial area during the postharvest fallow period (Figure 2a). The EEFs produced significantly lower cumulative N_2O fluxes than urea, but differences between urea and PCU were not significant (Figure 2b). The PCU product continued to produce spikes in emissions in response to rainfall events later in the growing season (Figure 2a). Conversely, the NI produced significantly lower cumulative N_2O fluxes than urea and the PCU (Figure 2b). The calculated N_2O emissions factors ranged between a high of 1.2% of applied urea-N to a low of 0.2% for the NI. The PCU had an emission factor of 1.0%, indicative of little improvement compared to the urea.

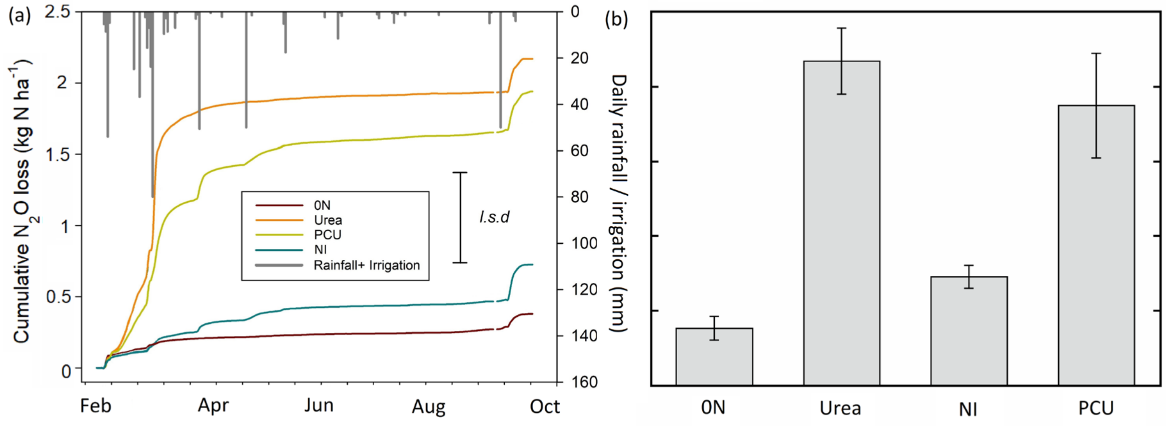

Figure 8. N_2O emissions from EEFs and urea-N, both applied at 150 kg N ha^{-1} during the 2018 growing season (a) pattern and (b) cumulative. 0N = nil N applied; NI = nitrification inhibitor; PCU = polymer coated urea

Residual N

Soil samples collected after the 2018 maize harvest revealed increasing amounts of residual NO_3^- in the soil as fertiliser N rates increased above 125 kg N ha^{-1} (Figure 3). Interestingly, while increasing rates of applied urea significantly ($p < 0.001$) increased the residual mass of NO_3^- in the soil, the mass of NH_4^+ remained largely unchanged (Figure 3a). The mass of residual NO_3^- in soil was statistically similar for all EEFs except the UI, which had more NO_3^- than urea at an application rate of 250 kg N ha^{-1} (Figure 3b). At 250 kg N ha^{-1}, NH_4^+ concentrations were greater for the PCU treatment compared to urea.

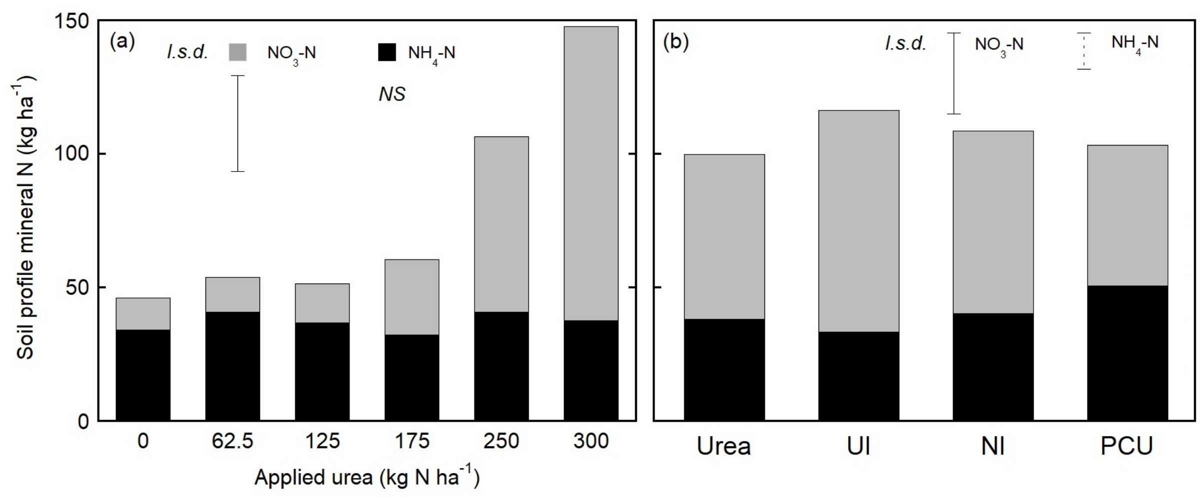

Figure 9. Residual soil profile mineral N (kg N ha^{-1}) for (a) increasing rates of applied urea (0-300 kg N ha^{-1}) and (b) EEFs applied at 250 kg N ha^{-1}. Vertical bars represent *l.s.d.* at 5% significance: NO_3-N (solid), NH_4-N (dashed), NS (not significant). UI = urease inhibitor; NI = nitrification inhibitor; PCU = polymer coated urea

Despite wet seasonal conditions (419mm of rainfall and irrigation), NO_3^- was largely confined to the band and near-band (0.05–0.10m) positions, with relatively small amounts found in the mid-row positions (i.e., 0.35–0.40m from the nearest band), with similar patterns observed for urea and EEFs (data not shown). There were noteworthy differences in the depth distribution of NO_3^- for the different N fertilisers (Figure 4), with the mass of NO_3^- in the 0–0.3m for PCU (85%) > NI (70%) > urea (55%) > UI (30%). Relative NO_3^- mass in the 0–0.1m soil depth followed similar patterns, with PCU (33%) > NI (23%) > urea (15%) > UI (10%). Movement of NO_3^- below 0.3m was highest for the UI (70%), with relatively lower NO_3^- mass observed for urea (45%), NI (30%) and PCU (15%).

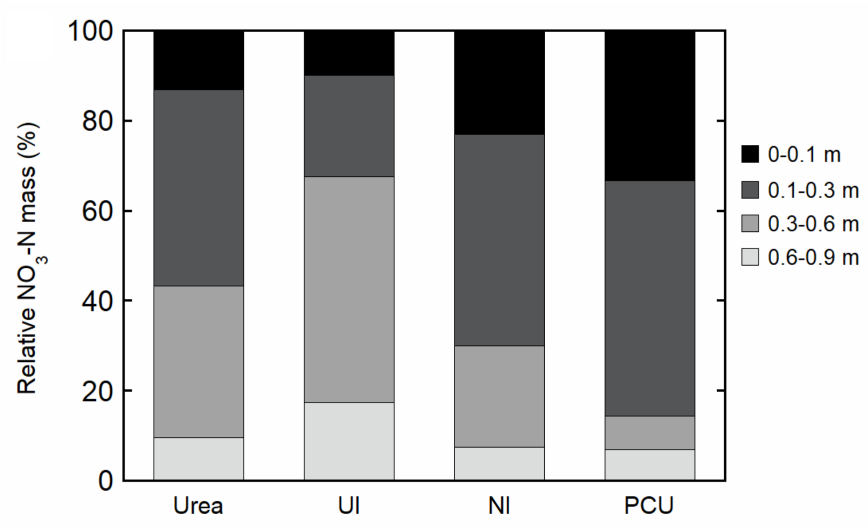

Figure 4. Relative NO_3^- mass (%) depth distribution for urea in comparison to EEFs (UI, NI and PCU). UI = urease inhibitor; NI = nitrification inhibitor; PCU = polymer coated urea

In the subsequent maize crop grown in 2019, there was no grain yield response to residual N in plots treated with rates up to 125 kg N ha^{-1} (applied in 2018; Table 1), which was consistent with the lack of residual N seen in the soil profiles (Fig. 3). However, significant improvements in grain yield were observed as the initial N application rate (2018) increased to 175 kg N ha^{-1} and above. Consistent with this, grain yield and N content responses from EEF products was greater at an initial N application rate of 250 kg N ha^{-1} compared to the lower rate of application (125 kg N ha^{-1}). Nevertheless, none of the EEF products resulted in significantly higher grain yields or N contents relative to urea at either low (125 kg N ha^{-1}) or high (250 kg N ha^{-1}) rates of application. Notably, the PCU yielded 28.1% lower than urea when both were applied at a rate of 125 kg N ha^{-1}.

Three-dimensional soil N dynamics around N bands

Irrespective of fertiliser type, NH_4^+ was the predominant soil mineral N species at 7 days after onset of N release, after which the proportion of mineral N found as NO_3^- increased for both the urea and PCU treatments (Figure 5). Over the first 46 days, the concentration of NH_4^+ in the PCU treatment was relatively low (compared to urea and NI) and was distributed over a much smaller zone around the fertiliser band. In the NI treatment, a greater proportion of mineral N in the soil remained as NH_4^+ for the first 46 days, after which NO_3^- became the predominant N form, peaking at 78 days. Nitrate concentrations peaked at 46 days in the urea and PCU treatments and declined considerably after this time (Figure 5).

In-band soil pH was significantly higher in all fertiliser treatments relative to the unfertilised control at 7 days, although that of the PCU was significantly lower than the urea and NI treatments (Figure 5). Soil pH continued to increase for PCU until 19 days, while only minor changes were evident for granular urea and the NI between 7 and 19 days. Subsequently, the pH of soil for the urea treatment declined up to 46 days, after which no further change was recorded. For the NI treatment, the pH remained higher than the urea and PCU treatments at 46 days, with this difference being significant compared to urea. A minimum pH of 6.5 was reached at 78 days for this N-fertiliser treatment. In comparison, the pH of soil treated with PCU demonstrated a continuing decline from 19 days until at least 145 days. The acidification of soil resulting from nitrification in and around N-fertiliser bands was substantially greater in the PCU treatment compared to urea, with the PCU treatment recording a significantly lower in-band pH (5.0) by 145 days relative to granular urea (pH 6.9; Figure 5).

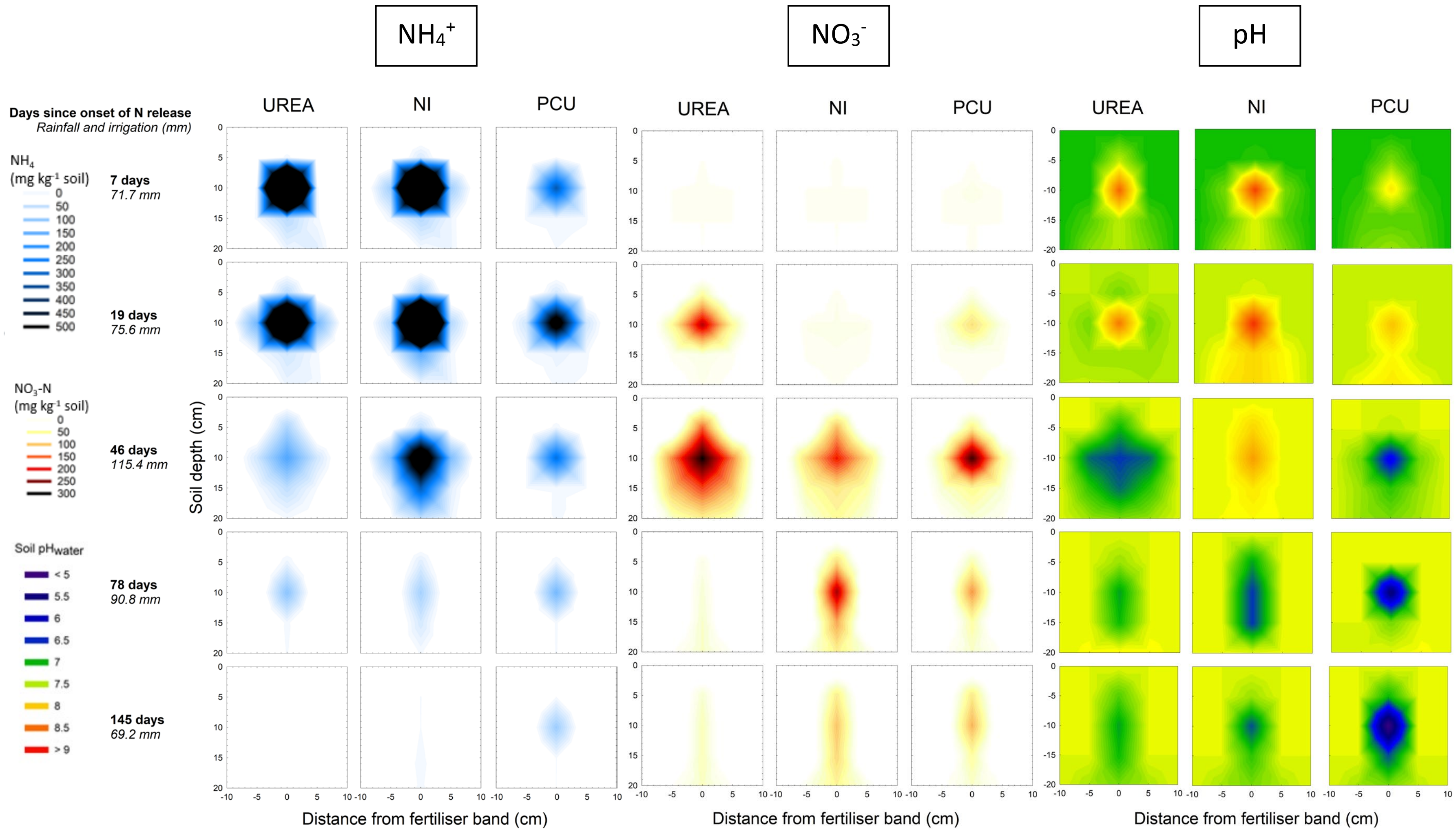

Figure 5. Vertical and lateral distribution of NH_4^+ and NO_3^- (mg N kg^{-1}) and changes in soil pH in and around fertiliser bands of urea and EEFs at 7, 19, 46, 78 and 145 days after onset of N release. The total amount of incident rainfall and irrigation (mm) between sampling occasions is shown.

Discussion

Nitrification inhibitors reduce N_2O emissions but do not improve crop N acquisition

The preservation of N as NH_4^+ for an extended period (Figure 5) provided the driver for the NI to significantly reduce N_2O emissions (Figure 2) relative to those from urea fertiliser. However, the net N 'saved' by reduced N_2O emissions was low (*ca*. 1.5 kg N ha^{-1}; Figure 2b) and not surprisingly did not translate to improvements in maize grain yield (compared to urea; Figure 1) or greater end-of-season soil mineral N concentrations (Figure 3b).

Controlled release of N is poorly matched to maize demand and does not reduce N_2O emissions

Release of N from PCU granules was slow and controlled, and the relatively benign chemical conditions around the fertiliser band (compared to urea; see Janke *et al*. 2020, Martinez *et al*. 2021, Figure 5) meant N was rapidly converted to NO_3^-. The limited N available during early growth stages was likely well below crop demand and contributed to the poorer productivity of maize (compared to urea; Table 1). A large proportion of N from PCUs remained in smaller zones of N distribution (Fig. 5) that were closer to the soil surface (Figure 4) and so inaccessible for uptake in dry(er) topsoil layers later in the growing season. This likely contributed to yield penalties, as crop roots followed water down the soil profile, leaving N released from the PCU more susceptible to N_2O emissions.

Urease inhibitors may be useful for deeper incorporation of N into soil profile

Urease inhibitors target NH_3 volatilisation, however, this loss pathway is effectively minimised by sub-surface fertiliser application. The most significant impact on N dynamics from this EEF is the maintenance of N in the form of urea-N, which increases the rate of N movement down the soil profile as rainfall or irrigation water drain through the fertiliser band (Janke *et al*. 2020). Deeper distribution of N following fertilization with a UI (compared to urea) has been observed both in-season (Janke *et al*. 2020) and as residual N in this study (Figures 3, 4). However, UI treatments did not deliver any improvement in maize yield (Figure 1), suggesting that this N at depth at the end of the initial growing season was either no longer available the following year, or was not available at a time that matched crop N demand. The reasons for this lack of residual benefit could not be determined.

Banded urea may behave like a 'slow-release' fertiliser

Whilst EEFs performed true to their stated mode-of-action (e.g., controlled release from PCU, nitrification inhibition by NIs, etc.), the timing and distribution of available N appeared to limit the efficacy of these products for improved crop productivity. It is well established that restricted N availability before the V8 stage (around 30 days after emergence) will significantly reduce yield. Accordingly, if release is too slow (i.e., PCU) or N is preserved in a largely unavailable form or in very constrained soil volumes (i.e., NIs), then early N supply may be insufficient and consequently limit final grain yield. In extreme cases, this mismatch may be so great that EEFs may perform worse relative to conventional N fertilisers (i.e., PCU). Compared to EEFs, the volume of soil enriched with N in banded urea treatments is greater, potentially enabling better coincidence with a larger proportion of growing crop roots. Furthermore, a greater proportion of N is available earlier from urea bands, better coinciding with maize demand. These dynamics may explain why no yield penalties were observed for maize treated with conventional urea (compared to EEFs) even though urea did result in much greater N_2O emissions. Urea bands may therefore act as a short term 'slow-release' N source in terms of N availability in clay soils such as the Vertosols.

Conclusions

Despite differences in N release dynamics and some reduction of N losses, we saw no clear agronomic advantages for EEF use relative to conventional N fertilisers when band applied. This was largely due to asynchrony of N availability with crop demand and / or poor co-location of N with crop root activity. From an agronomic perspective, conventional urea delivers grain yields which are similar or better than that of EEFs, and at lower cost for each kg of N applied. The NIs were effective at greatly reducing N_2O emissions without any adverse impacts on crop productivity. Polymer-coated urea and UIs did not demonstrate either agronomic or environmental benefits in this study. It's possible that under different environmental conditions or soil types, the efficacy of these technologies compared to urea may improve. Furthermore, crops with differing patterns of N demand may demonstrate different responses to EFF application.

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Contact details

Cristina Martinez & Chelsea Janke
School of Agriculture and Food Sciences,
The University of Queensland, St Lucia, QLD 4072
Email: cristina.martinez@uq.edu.au and c.stroppiana@uq.edu.au

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Ameliorating sodicity - Central & Northern NSW & Qld

Ameliorating sodicity; what did we learn about ameliorating sodicity constraints with a range of treatments? Yield responses to ripping, gypsum and OM placement in constrained soils.

David Lester[1], Cameron Silburn[2], Craig Birchall[3], Richard Flavel[3], Chris Guppy[3], John Maclean Bennett[4], Stirling Roberton[4], David McKenzie[5]

[1] Department of Agriculture and Fisheries Queensland, Toowoomba
[2] Department of Agriculture and Fisheries Queensland, Goondiwindi
[3] University of New England, Armidale
[4] University of Southern Queensland, Toowoomba
[5] Soil Management Designs, Orange

Key words

soil testing, ConstraintID, aggregate stability, nitrogen, phosphorus, tillage, ripping

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Take home message

- In Qld, it appears a yield gap does exist for cereal grains with substantial positive yield increases generally from combinations of tillage and subsurface nutrient placements
- In the early phases of the experiment, there has been no yield difference between organic and inorganic nutrient application but the input rates are very high. These might diverge in future as Nitrogen supply from the organic treatment might provide a longer release pattern
- With generally high levels of growing season rainfall in crops grown since soil ameliorants were applied, there has not yet been the opportunity for the soil water benefits expected from amelioration of soil sodicity with gypsum to be fully expressed as yield increases.

Background

Model analyses suggest a yield gap between water-limited potential yield and currently achieved production exists across northern Australian grain regions (Hochman and Horan 2018). This yield gap is a function of physical, chemical, and biological factors in each soil, including the capacity of soil to store and release water for efficient plant use. Many regions where yield is constrained contain dispersive soil within the surface 50cm and deeper. Sodicity (a high exchangeable sodium percentage) is a major cause of aggregate dispersion and may compromise soil structure. Dispersive behaviour decreases both soil water availability and nutrient acquisition, increases risk of runoff and erosion, and impairs biological (soil microbial and plant root) activity. Acidity, salinity (presence AND absence) and compaction further constrain yield potentials. However this project focuses on sodicity as the major constraint with often related constraints considered as compounding and/or interacting factors.

Amelioration of subsoil constraints is an expensive process. The engineering challenges and energy requirements are significant. It is important to acknowledge that production benefits from subsoil amendment are more likely to be observed in poorer seasons. In good seasons, root function and activity, and soil moisture, will be able to sustain yield from surface activity and extraction where soils are often less constrained. However in poorer seasons, where subsoil moisture is required to finish a crop, subsoil amelioration may have a proportionately larger impact on yield. Hence a positive return from investments in subsoil amelioration are less likely to be seen in better growing seasons than in drier growing seasons.

A series of linked investments is assessing the economics of ameliorating constrained surface and sub-surface soils in the northern region. The program has four areas covering: (i) spatial soil constraint identification, (ii) amelioration and management of soil constraints, (iii) economics of adoption, and (iv) an overarching communications and extension program. The research into soil amelioration and management has two components led by University of Southern Queensland (USQ). First is a set of six small-plot core experiments exploring detailed amelioration research. There are three sites in northern and central New South Wales (NSW) managed by the University of New England (UNE) located at Forbes, Armatree and Spring Ridge, and three sites in southern Qld managed by the Department of Agriculture and Fisheries (DAF) at Talwood, Millmerran and Dulacca.

This paper briefly describes the treatments being studied and reports on the field trial grain yield results to-date.

Core sites characteristics

All sites were generally alkaline in the upper profile and have an exchangeable sodium percentage (ESP) well over the 6% nominal threshold for classification as sodic (Isbell and National Committee on Soil and Terrain 2021). Profile chloride (Cl) values were generally low, indicating that sodicity was likely to be the primary restriction. The soil chemical characteristics at the six core experiments are below:

Location: Armatree

Soil type: Brown Sodosol, not dispersive (0-10cm) to dispersive (10-20) surface, to strongly alkaline and dispersive at depth, compact surface layers

Depth	pH	pH	EC	Ca	Mg	Na	K	ECEC	ESP	Cl	P
(cm)	(H_2O)	($CaCl_2$)	(1:5)	(cmol/kg)					%	(mg/kg)	(mg/kg)
0-10	6.0	5.3	0.20	3.7	3.4	0.91	1.00	9.0	10		58
10-20	7.8	6.8	0.20	8.5	7.9	2.63	0.83	19.9	13		7
30-40	9.3	8.3	0.45	13.1	12.6	5.78	0.81	32.3	18		8
60-70	9.4	8.4	0.58	12.3	13.4	6.35	0.96	33.0	19		6

Location: Forbes

Soil type: Brown Vertosol, not dispersive (0-10cm) to dispersive (10-20) surface, to strongly alkaline and dispersive at depth

Depth	pH	pH	EC	Ca	Mg	Na	K	ECEC	ESP	Cl	P
(cm)	(H_2O)	($CaCl_2$)	(1:5)	(cmol/kg)					%	(mg/kg)	(mg/kg)
0-10	6.3	6.1	0.39	8.7	7.7	2.13	0.77	19.3	11		89
10-20	7.9	6.9	0.30	15.4	10.2	4.76	0.55	30.9	15		12
30-40	9.1	8.2	0.64	12.5	11.3	8.14	0.49	32.5	25		4
60-70	9.1	8.3	0.85	11.3	10.4	9.57	0.56	31.9	30		1

Location: Spring Ridge

Soil type: Black Vertosol, moderate ESP and salinity in surface, increasing to high ESP and salinity at depth, but both are non-dispersive due to the salinity

Depth	pH	pH	EC	Ca	Mg	Na	K	ECEC	ESP	Cl	P
(cm)	(H_2O)	($CaCl_2$)	(1:5)	(cmol/kg)					%	(mg/kg)	(mg/kg)
0-10	8.2		0.54	31.7	41.7	3.3	2.4	79.1	4		100
10-20	8.2		0.62	37.2	43.5	5.2	1.4	87.3	6		
30-40	8.3		1.94	31.0	51.5	13.9	1.0	97.4	14		
60-70	8.3		2.52	28.7	56.7	19.5	1.1	106	18		

Location: Dulacca

Soil type: Grey/Brown Vertosol, surface soils not spontaneously dispersive but subsurface highly dispersive.

Depth	pH	pH	EC	Ca	Mg	Na	K	ECEC	ESP	Cl	P
(cm)	(H_2O)	($CaCl_2$)	(1:5)	(cmol/kg)					%	(mg/kg)	(mg/kg)
0-10	8.5	7.7	0.21	18.1	8.0	2.73	0.93	29.8	9	43	9
10-20	8.8	7.8	0.25	15.8	9.8	3.99	0.61	30.3	13	53	14
30-40	8.1	7.3	0.46	15.4	12.3	7.10	0.45	35.3	20	102	4
60-70	6.8	6.7	0.66	12.0	12.8	8.83	0.48	34.1	26	275	8

Location: Millmerran

Soil type: Grey/Brown Vertosol, surface and subsurface soils not spontaneously dispersive, very compact soil through the profile.

Depth	pH	pH	EC	Ca	Mg	Na	K	ECEC	ESP	Cl	P
(cm)	(H_2O)	($CaCl_2$)	(1:5)	(cmol/kg)					%	(mg/kg)	(mg/kg)
0-10	6.6	6.3	0.15	8.4	6.6	2.37	0.31	17.7	13	153	38
10-20	8.7	7.4	0.24	10.6	9.0	3.36	0.20	23.2	14	330	5
30-40	6.9	6.2	0.38	9.5	15.	6.82	0.14	31.4	22	428	3
60-70	6.4	5.5	0.43	10.2	16.4	8.79	0.18	35.5	25	457	2

Location: Talwood

Soil type: Red/Brown Vertosol with surface soils not spontaneously dispersive, subsurface highly dispersive at 60-70cm.

Depth	pH	pH	EC	Ca	Mg	Na	K	ECEC	ESP	Cl	P
(cm)	(H_2O)	($CaCl_2$)	(1:5)	(cmol/kg)					%	(mg/kg)	(mg/kg)
0-10	8.3	7.6	0.17	27.5	4.7	1.8	1.3	35.5	11	22	18
10-20	8.7	7.9	0.23	27.8	7.0	3.8	0.7	39.3	10	26	3
30-40	8.9	7.8	0.36	22.5	9.4	7.0	0.4	39.4	18	73	2
60-70	9.2	7.9	0.44	20.3	9.9	9.9	0.5	40.7	24	163	2

Experiment treatments

This research focussed on eliminating sodium as a constraint for the upper 50 cm of a soil profile. It was 'proof-of-concept' research, intended to explore effects of different strategies on soil water storage and grain yields. Gypsum application rates were designed to remediate the ESP to ≤ 3% in either or both of the top 20 cm of soil and half (a quarter in NSW) of the soil volume in bands from 20 cm down to 50 cm depth.

Similar treatment structures are used in both NSW and Qld, with both physical and chemical ameliorants, a range of options exploring impacts and/or interactions between tillage (shallow and deep), deep placement of nutrients (as inorganic or organic forms), surface and subsurface applications of gypsum to reduce ESP to < 3%, incorporating organic amendments (lucerne pellets in NSW and composted feedlot manure in Qld), and applying elemental sulfur (ES) to decrease soil pH (Table 1). For subsoil amelioration, gypsum rates were compared against an organic amendment compost (Qld)/lucerne pellet (NSW), and ES to reduce pH and dissolve calcium carbonate to produce gypsum in-situ. Organic matter also acts to limit aggregate dispersion (as well as providing nutrients at depth) and, whilst not reducing ESP, may act to improve water holding capacity and pore stability.

Table 1. Treatment structure for core soil constraints sites in southern Queensland

Trt	Synopsis
1	Untreated control – typically managed as rest of field by the grower
2	Ripping to 20-25 cm
3	Ripping to 20-25 cm with application of 50 kg N/ha, 30 kg P/ha (50 kg K/ha) +Zn in bands
4	Surface spread gypsum, then ripping to 20-25 cm with application of NP(K)Zn in bands
5	Ripping to 20-25 cm with application of NP(K)Zn in bands, then re-rip to ≈35 cm
6	Ripping to 20-25 cm with application of NP(K)Zn and subsurface gypsum in bands
7	Surface spread gypsum, then ripping to 20-25 cm with application of NP(K)Zn and subsurface gypsum in bands
8	Surface spread gypsum, then ripping to 20-25 cm with application of NP(K)Zn in bands, then re-rip to ≈35 cm
9	Surface spread gypsum, then ripping to 20-25 cm with application of NP(K)Zn and subsurface elemental sulfur (ES) in bands
10	Ripping to 20-25 cm with application of high-rate 280N 100P (K) +Zn equivalent to N and P additional from organic matter (OM) treatment in bands, then re-rip to ≈35 cm
11	Ripping to 20-25 cm with application of OM in bands, then re-rip to ≈35 cm
12	Ripping to 20-25 cm with application of OM and ES in bands, then re-rip to ≈35 cm
13	Surface spread gypsum, ripping to 20-25 cm with application of OM and ES and subsurface gypsum in bands, then re-rip to ≈35 cm

The applied gypsum rate for subsurface placement was 50% (25% in NSW) of the total needed for the whole 20 to 50 cm layer of soil: if a total of 20 t/ha of gypsum was theoretically needed to remediate the 20 to 50 cm layer in this initial application 10 t/ha was applied in Qld and 5 t/ha in NSW.

Agronomic timings of crop years are outlined in Table 2.

Table 2. Agronomic information for crops across Qld soil constraints core sites.

Site	Crop	Sown	DM	GSR	Harvest
Millmerran	Sorghum 19-20	21-Jan-2020	05-May-2020	201	10-Jun-2020
	Sorghum 20-21	01-Nov-2020	02-Feb-2021	236	NR
	Barley 2021	20-May-2021	21-Sep-2021	141	01-Nov-2021
Dulacca	Wheat 2020	15-May-2020	16-Sep-2020	72	15-Oct-2020
	Wheat 2021	05-Jul-2021	04-Nov-2021	*245	Hand harvest
Talwood	Sorghum 20-21	06-Jan-2021	08-Jun-2021	321	21-Jun-2021

Results and discussion

Queensland results

Three core sites in Qld have had six crops grown but only grain yield from five, with the 2020-21 sorghum crop at Millmerran unable to be harvested due to rain and mice damage. Growing season conditions for most crops have been very favourable from in-crop rainfall events. The first wheat crop at Dulacca had lowest in-crop rain with 72 mm received between sowing and dry matter maturity sampling.

Visual crop responses have been seen across several site years, e.g. Millmerran in April 2020 (Figure 1). Treatment effects can be observed but also some underlying site variability.

Figure 1. Image across the Millmerran core site looking west 27 April 2020

Generally NDVI measurements have been increased in plots with higher nutrition applications, typically Trts 10-13 (Table 1) e.g. Dulacca wheat in 2020 (Figure 2) the dark blue plots are those.

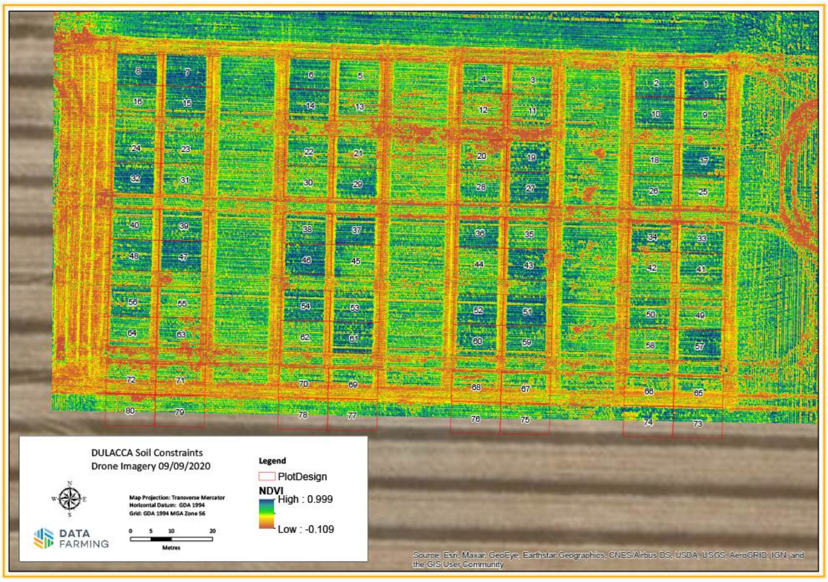
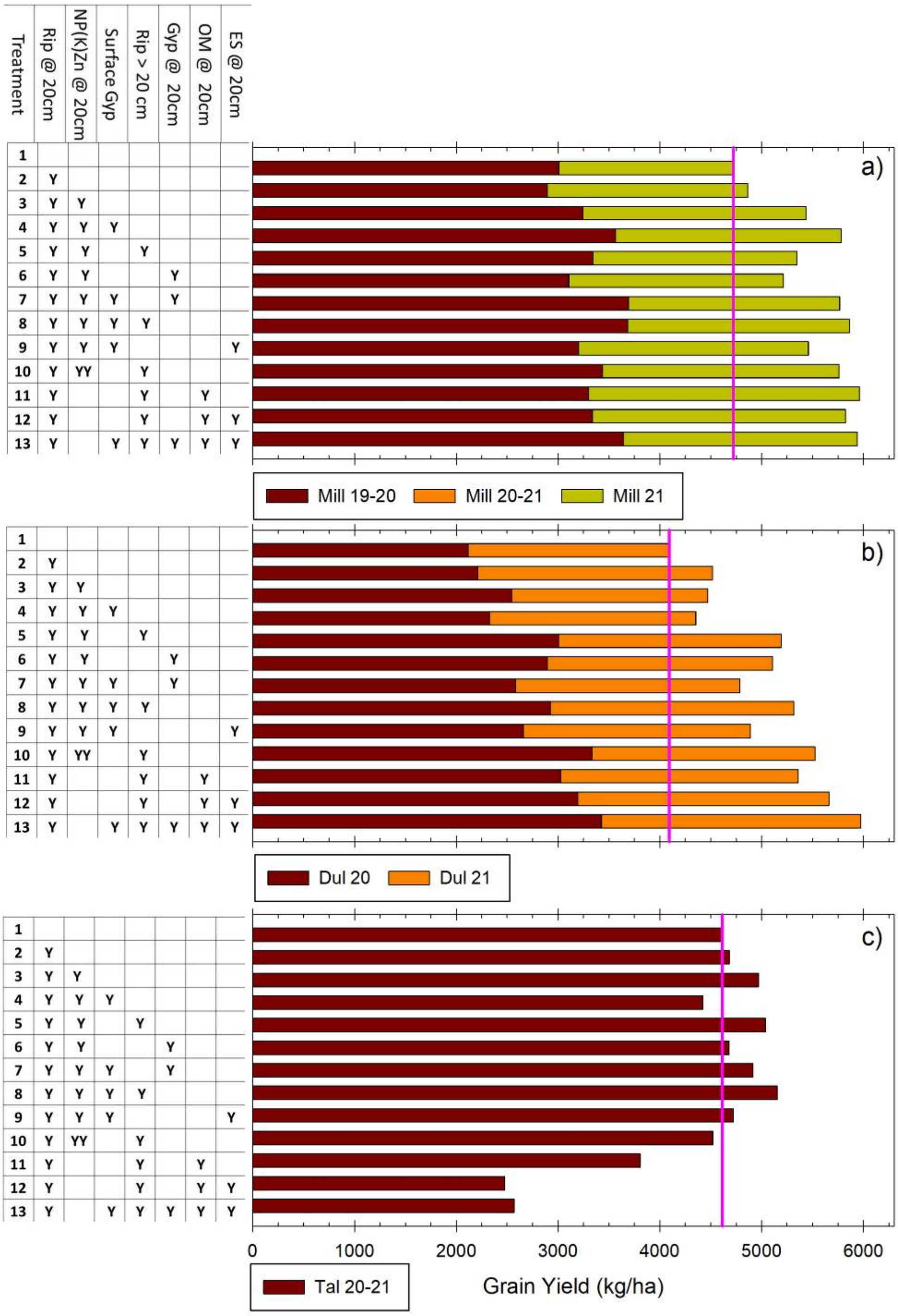


Figure 2. NDVI image of Dulacca site September 2020.

Apart from Talwood (Fig 3c) cumulative grain yields are generally increased through experimental treatments compared to current farmer practice.

Growing season rainfall at Talwood for the single-skip sorghum crop was >300 mm, so subsoil water was not really needed. Some soil water measures indicate the site was wetter after the sorghum crop than when it was planted (data not shown). The negative impact of the OM treatments (11-13) was related to crop phenology, those plots flowered 10-7 days in-front of the remainder of the experiment. Early flowering treatments received more damage from midge and other insects resulting in negative yield effects compared to later flowering treatments. Maturity dry matter measurements of those treatments were slightly less than the remainder of the trial, but the grain harvest index values highlight the grain yield impact (data not shown).



Treatment	Rip @ 20cm	NP(K)Zn @ 20cm	Surface Gyp	Rip > 20 cm	Gyp @ 20cm	OM @ 20cm	ES @ 20cm
1							
2	Y						
3	Y	Y					
4	Y	Y	Y				
5	Y	Y		Y			
6	Y	Y			Y		
7	Y	Y	Y		Y		
8	Y	Y	Y	Y			
9	Y	Y	Y				Y
10	Y	YY		Y			
11	Y			Y		Y	
12	Y			Y		Y	Y
13	Y		Y	Y	Y	Y	Y

Figure 3. Cumulative grain yield vs treatment for a) Millmerran, b) Dulacca and c) Talwood experiments. Pink reference line equals the untreated control yield.

At Millmerran and Dulacca, the yield increases varied in scale but have some common features being a combination of tillage and nutrition. At Millmerran (Figure 4), treatments 3-13 all have tillage to at least 20-25 cm (some deeper) and a subsurface nutrient application of either inorganic or organic sources. The average yield increase across all those treatments is 945 kg/ha or a 20% gain in yield.

Treatment	Rip @ 20cm	NP(K)Zn @ 20cm	Surface Gyp	Rip > 20 cm	Gyp @ 20cm	OM @ 20cm	ES @ 20cm
1							
2	Y						
3	Y	Y					
4	Y	Y	Y				
5	Y	Y		Y			
6	Y	Y			Y		
7	Y	Y	Y		Y		
8	Y	Y	Y	Y			
9	Y	Y	Y				Y
10	Y	YY		Y			
11	Y			Y		Y	
12	Y			Y		Y	Y
13	Y		Y	Y	Y	Y	Y

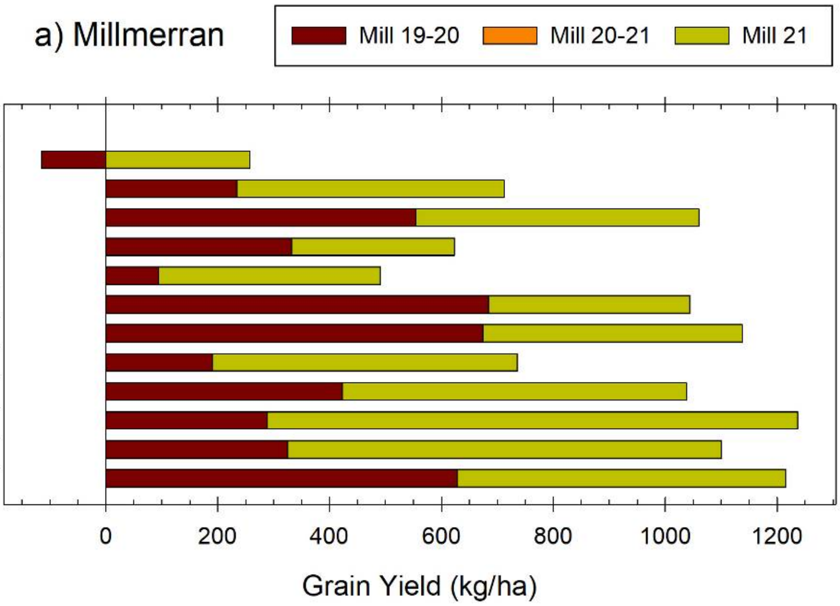


Figure 4. Change in grain yield vs untreated control at Millmerran for sorghum in 19-20 and barley in 2021

For Dulacca (Figure 5), the tillage treatments all appear to be contributing to increased yield particularly the deeper ripping (treatments 5, 8, 10-13). A nutrient response is also evident, more prominent with the high nutrient applications (treatment 10-13). Treatment 5 (ripping > 20 cm and subsurface nutrient) had cumulative yield gain of 1100 kg/ha (27%). Aggregating all the deep tillage treatments together (treatment 5, 8, 10-13) the increase is 1410 kg/ha (34%).

Treatment	Rip @ 20cm	NP(K)Zn @ 20cm	Surface Gyp	Rip > 20 cm	Gyp @ 20cm	OM @ 20cm	ES @ 20cm
1							
2	Y						
3	Y	Y					
4	Y	Y	Y				
5	Y	Y		Y			
6	Y	Y			Y		
7	Y	Y	Y		Y		
8	Y	Y	Y	Y			
9	Y	Y	Y				Y
10	Y	YY		Y			
11	Y			Y		Y	
12	Y			Y		Y	Y
13	Y		Y	Y	Y	Y	Y

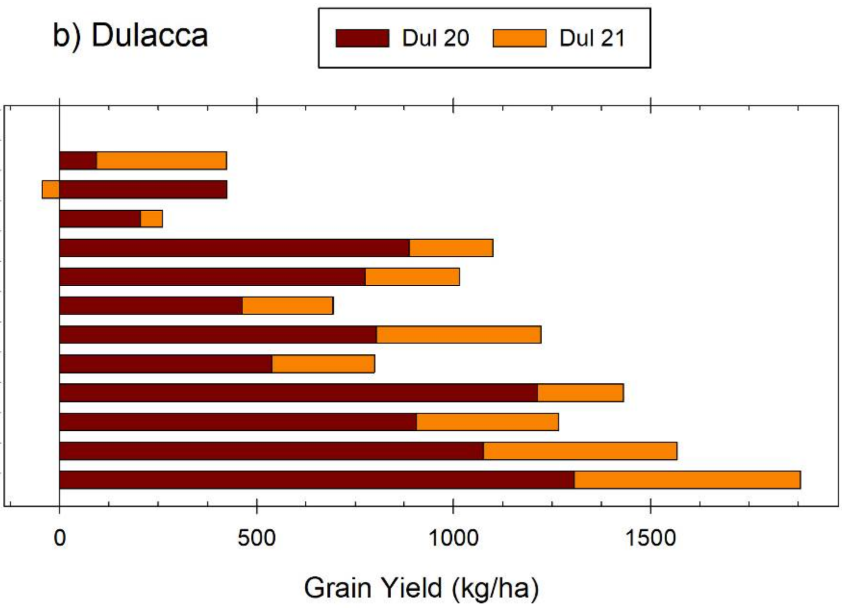


Figure 5. Change in grain yield vs untreated control at Dulacca for wheat in 2020 and 2021

While gypsum has been applied in significant quantities at the three experiments, contributions to increasing yield under the better seasonal conditions across the sites to-date are not evident at this stage of the experiment life.

NSW results

The NSW sites had one winter crop each in 2020, followed in 2021 by a winter crop at Forbes and Armatree, and a sorghum crop at Spring Ridge sown in October. All sites and crops have had wet to very wet fallows and growing seasons. In 2021, they used little of the available soil water during grain filling, but in 2020 Armatree and Spring Ridge used most of the profile, with roots and cracking to at least 1m depth.

Armatree: wheat then canola

In the 2020 wheat crop at this site, growing conditions were wet during winter and spring, but dried out as the crops were filling. The OM treatments had the highest biomass production at flowering, but ran out of moisture during grain fill and finished with yields similar to the controls. Otherwise, deep ripping treatments generally increased yield by ~20% compared to the controls.

2021 was a wet year, with the canola crop waterlogged in comparison to the large crops grown locally in the previous year. The highest yields came off the 3 treatments containing OM, and they outperformed the controls by ~0.7t/ha (30%), with the OM+ES being the most obvious visually between flowering and harvest. Deep ripping treatments (± gypsum) also gave an increase in yield (~0.15t/ha) compared to the control. The shallow rip treatments (treatment 2-4) had very little effect in the second year, producing similar yields to the control treatment, in comparison to 2020 where even shallow rips gave a yield increase.

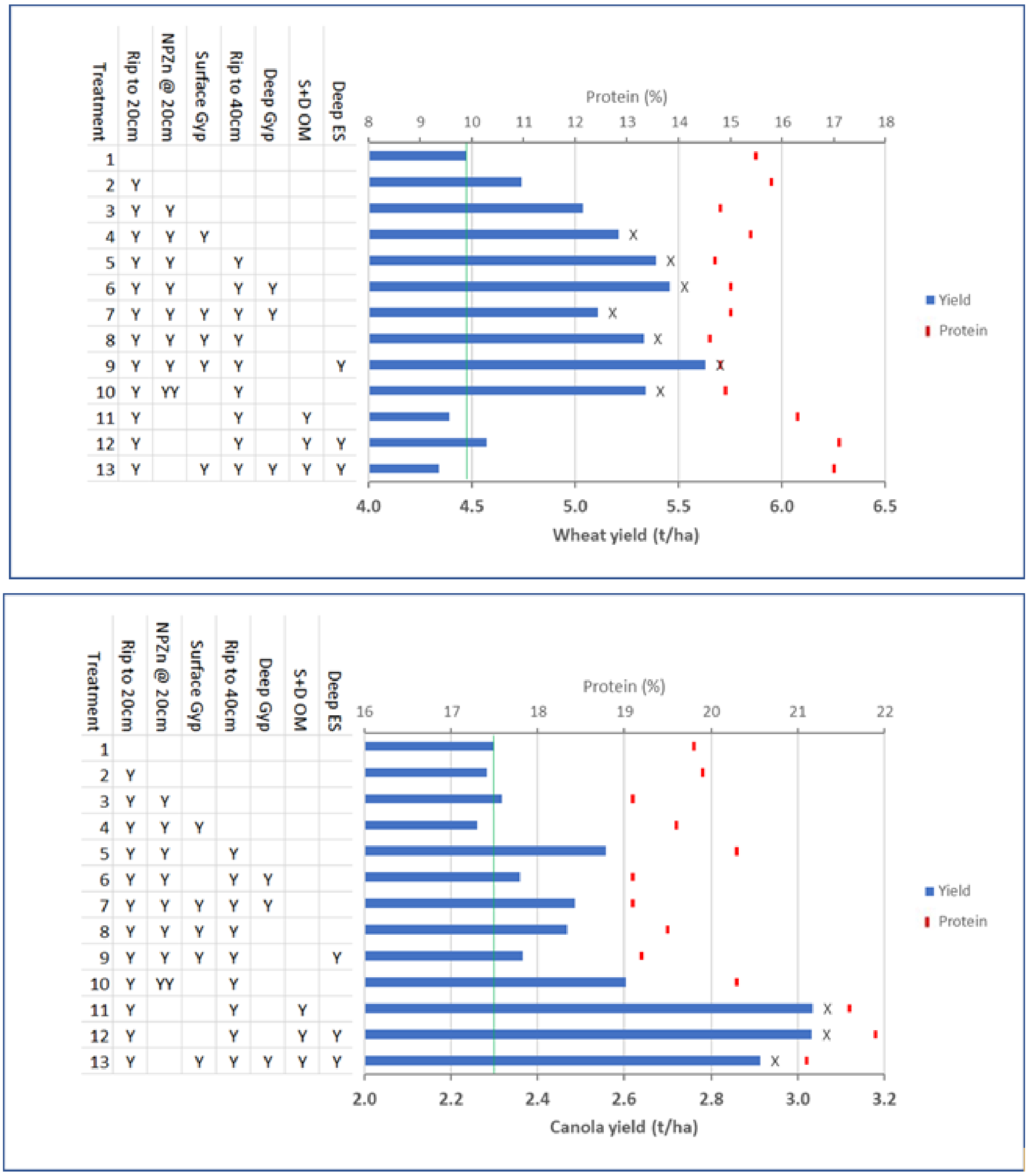


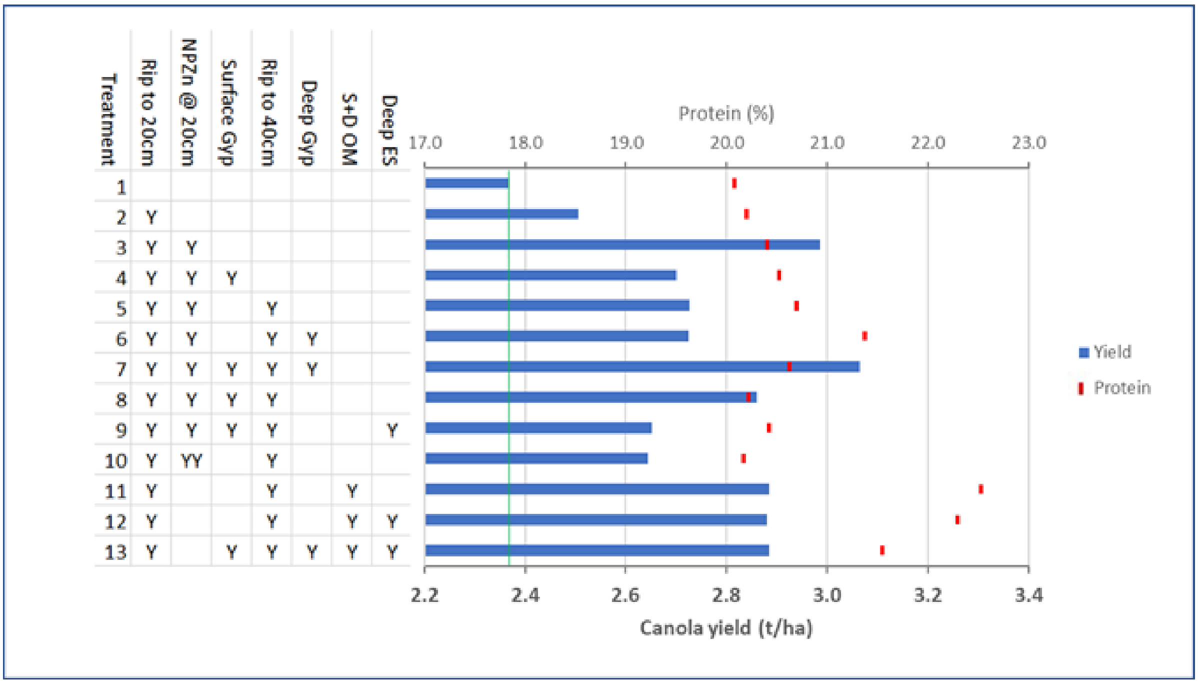
Figure 6. Armatree yield and protein data for wheat in 2020 and canola in 2021. Treatments topped with an X are significantly different to the control treatment.

Forbes: canola then barley

The site was waterlogged for most of winter 2020, and still had moisture in the profile at harvest, so provided little information on changes in soil structure and PAWC as a result of amendments. There was no significant difference in yield between treatments, partly due to a variable plant population and waterlogging, and partly to harvester losses in the higher biomass plots. The higher protein content in the OM treatments suggests that these plots did yield higher.

The site was even wetter in 2021, with water in the wheel tracks for most of the season and areas of the trial lost to waterlogging. Again, there was considerable moisture left in the profile when the barley reached maturity. The controls averaged ~4.5t/ha with 9% protein.

There was a large and significant increase in yield in most of the deep ripping treatments this year, with the increase averaging 1.9t/ha (42% increase) compared to the control. There was little difference between the amendments applied to the deep ripped plots, and even the deep ripped plots with no amendments added. However, we are expecting that the plots with gypsum, OM or elemental sulfur should have better structure for longer than the unamended deep ripped plots.



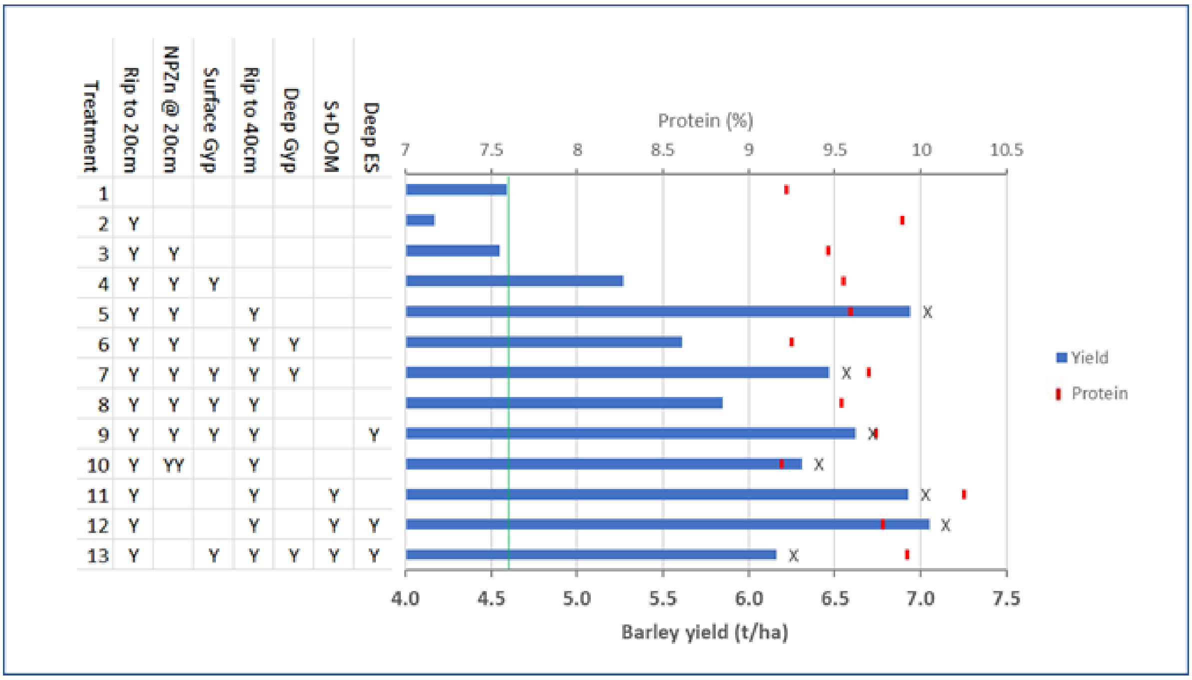


Figure 7. Forbes yield and protein data for canola in 2020 and barley in 2021. Treatments topped with an X are significantly different to the control treatment.

Spring Ridge

Yield outcomes from the current sorghum crop will be available later in the year. In 2020, the barley crop was very high yielding (over 6t/ha) across the whole site, but there were no differences between treatments. While the site is sodic and saline, the lack of difference and overall high yields suggests that the site is not as constrained as first thought, at least in a wet season.

Effect of amendments on soil structure

The Armatree site has also provided information on the effect of the treatments on soil structure two years after application. An RTK GPS used at sowing found that the height of the soil surface of the plots containing ES, and the treatment with both surface and deep gypsum, had the most elevated surface height, being 3-5cm higher than the unripped control.

Treatment	Rip to 20cm	NPZn @ 20cm	Surface Gyp	Rip to 40cm	Deep Gyp	S+D OM	Deep ES
1							
2	Y						
3	Y	Y					
4	Y	Y	Y				
5	Y	Y		Y			
6	Y	Y		Y	Y		
7	Y	Y	Y	Y	Y		
8	Y	Y	Y	Y			
9	Y	Y	Y	Y			Y
10	Y	YY		Y			
11	Y			Y		Y	
12	Y			Y		Y	Y
13	Y		Y	Y	Y	Y	Y

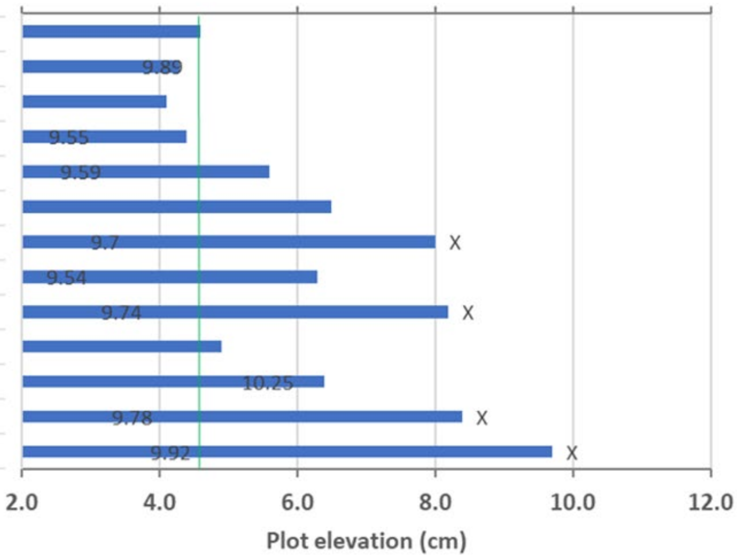


Figure 8. Elevation of treatment plots at Armatree.

Discussion

In the majority of sites tillage alone was beneficial in the first two seasons. Yield responses, even in good to wet seasons across eastern Australia, were still observed to ripping alone. These yield responses, in the order of 20-40%, were recorded in seasons where we considered responses were less likely to be observed as a result of generally high levels of growing season rainfall. These results interact with nutrition in a number of ways at each of the locations. We believe that in locations where deep ripping alone has yielded as much as tillage with nutrition, that at least part of that response may be associated with opening up root access to layers of soil that may have accumulated nutrition. In the seasons we have observed so far, the extra aeration and oxygen in the root system following tillage may have been reduced by waterlogging and hence not allowed the extra nutrition to fully express as yield in those treatments.

The differences in N source between NSW and Qld sites may also have interacted with the wetter seasons in NSW and resulted in interesting nitrogen use efficiency observations. The total N supplied in NSW (20t/ha as lucerne) amounted to nearly 800 kg N/ha or labile (low C:N) organic material. In Qld, the N source was applied at half the rate and as a 'pre-mineralised' product. Hence the magnitude of the responses to nutrition in NSW are commensurately greater and warrant further investigation. In good seasons where biomass production is not constrained by either water or nitrogen, and nitrogen release is high, conversion to both biomass and yield is efficient and root systems from season to season may redistribute this high 'slug' of organic N more evenly through the profile. Soil cores at the end of this season may identify if N redistribution and N loading of the profile, may occur in these circumstances.

Overall, wet conditions have meant that the full impact of amendments on improving soil structure and particularly increasing PAWC, were not observed. Where water is relatively non-limiting, benefits from gypsum improving structure and porosity with the impact of increasing plant available water are less likely to be observed. However, it should have allowed the gypsum, and possibly elemental sulfur, to spread through a larger volume of soil than would have occurred in dry years – soil cation results will confirm this later this year. Therefore, despite the absence of any significant gypsum effect in these two seasons at any site, (relative to the nutrition benefits), this does not preclude gypsum having improved soil structure and those benefits being observed in subsequent years. Evidence that gypsum has improved structure, if not yet yield, is found in the surface elevation observations at Armatree. Ripping effects are potentially declining after 15 months with above average rainfall. This is 'as expected' if ripping effects are not stabilised in some way. However, where gypsum was applied at both surface and depth and where it was supplied with OM and/or generated in situ with ES, then plots had not slumped back to their original levels.

One surprising aspect of the soil pits dug between the seasons was evidence that elemental S had oxidised. The window of time when the ES was present and oxygen and water were both available was quite small at most of these sites given the depth at which it was placed and the amount of water in the profiles. As ES usually has a lag period while the micro-organisms that use it as an energy source multiply up enough to oxidise the ES, it is fascinating that this occurred at all. This suggests that given the absence of ES in the profile, populations of S oxidising bacteria in the subsoil may be greater than expected.

Conclusions

Yield gaps exist in the Qld core sites with treatments at two sites delivering substantial increases in cereal grain yield. There have been no pulse crops in the Qld sites to-date.

Apart from the Talwood site which had an exceptional rainfall year, tillage and nutrition appear to be the consistent keys to yield increases in Qld sites. Possibly the removal of legacy compaction from farming practices prior to establishment of current controlled traffic, or just loosening of the soil volume to allow more water, air and root access are mechanisms. There are no substantial differences in the form of nutrient delivery, between inorganic or organic materials in Qld. This may evolve over time as N supply in OM treatments is likely to have a release pattern that persists over an extended period.

So far, the gypsum applications on the non-dispersive surface soils haven't appeared to have any influence on yield. No additional measurement of structural changes on site has occurred yet. Subsurface gypsum applications potentially have been ameliorating the soil profile during the period since application, but seasonal conditions with high rainfall in-crop probably has not required any substantial use of additional subsoil water made available as a result of amelioration.

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Contact details

David Lester
Department of Agriculture and Fisheries Queensland, Toowoomba
PO Box 2282, Toowoomba, Qld 4350
Ph: 07 4529 1386
Email: david.lester@daf.qld.edu.au

Chris Guppy
University of New England, Armidale
Agronomy and Soil Science
Ph: 02 6773 3567
Email: cguppy@une.edu.au

Satellite sites – ameliorating spatially variable soil constraints. What did growers try, what was done and how has it worked so far?

Stirling Roberton, University of Southern Queensland

Key words

soil amelioration, soil constraints, variable-rate, paddock variability, return-on-investment

GRDC code

USQ1803-002RTX

Take home message

- Soil constraints are highly spatially variable
- Crop response to soil amelioration is complex and soil specific, meaning it is difficult to predict which soils will provide the biggest crop response for a specific farm (which soils should I invest in?)
- Installation of strip trials can be used to identify the farm-specific soils which offer the greatest economic potential for improvement
- The presented methodology offers an approach to develop a business case to guide investment into soil amelioration.

Introduction

Soil constraints are prevalent across the northern grains region, with very few farms displaying unconstrained conditions. These constraints (acidity, alkalinity, compaction, salinity, dispersion, sodicity and nutrition) limit crop yield by reducing the soil's ability to store water and nutrients and provide them to the plant when they are needed. Soil constraints are overcome by the implementation of various soil amelioration strategies*,* which are largely focussed on improving soil structure, chemical stability and nutrient availability within the soil which in turn improves the storage and movement of water and nutrients. Consequently, soil amelioration is largely focused on strategies such as deep ripping, manuring, applications of lime and gypsum, fertilisers and elemental sulphur and combinations of all, both in the surface (0–20 cm) and sub-surface (20–80 cm). Implementation of these strategies are intended to have a permanent, or at least semi-permanent improvement in soil structure/soil health which will ultimately increase the long-term production value of the soil resource. Whilst the long-term economic significance of this is large, the investment required to make these changes is often substantial ($200–$2000/ha). Hence, when making these capital investments, we want to be confident that they are only being applied to areas of the paddock where they are needed, and there is some indication on what the likely Return-On-Investment (ROI) will be before expenditure is made.

Unfortunately, there is no crop model which can accommodate changes in soil chemistry or soil structure to simulate crop yield response due to soil amelioration for a specific soil. Whilst our six regional core soil amelioration trials are invaluable in providing a broad indication of what crop responses are achievable, they are limited by two factors:

1. Soil constraints and their severity is highly spatially variable
2. Crop response due to amelioration is complex, non-linear and soil specific. This means we can have 2 soils which share similar soil constraints within the same paddock (e.g. an acidic-

dispersive soil), require the same application rate, yet they may have different crop responses due to amelioration.

This means within a single paddock, a variety of soil amelioration strategies may be considered, all on a variable-rate basis. Furthermore, even if we get the diagnosis correct, there is still no indication of what the likely ROI may be. Are you better off investing in areas of the paddock which require 6 t/ha of gypsum, or the areas that only require 2 t/ha? Which will provide the best return? Which soils should you invest in?

To answer these questions, we developed a new methodology which involves the installation of on-farm soil amelioration strip trials to guide farm-specific investment decisions. Whilst results from these trials remain in the infant stages (i.e., currently only 1–2 years' worth of data), this paper demonstrates how the installation of soil amelioration trials may be used to estimate what the likely ROI may be for soil amelioration on any farm and identify how these trials can be used to guide investment in other areas of the paddock/farm

Developed methodology

The methodology described below has been deployed to install a total of 18 strip trial sites at the time of writing, out of a total of 61 farms across the Northern Grains Region where some preliminary work has been undertaken. The key point of difference of the methodology is the spatial analysis which is undertaken along each trial strip, where crop responses are measured down the strip as opposed to simply comparing strip totals or averages. This provides the ability to firstly identify where the biggest crop responses are being observed, and secondly, to identify which soil types/soil constraints the largest crop responses are being achieved from. Once obtained, this information can be combined with a more extensive paddock/farm mapping exercise to determine where similar constraints exist across the rest of the paddock/farm. Soil amelioration investment can then be targeted to those areas where the largest crop response is likely.

This paper uses an example trial located in central NSW, where only a single years' worth of yield data is currently available. Practical deployment of this methodology should rely on multi-year data, so this example exists only for illustrative purposes only.

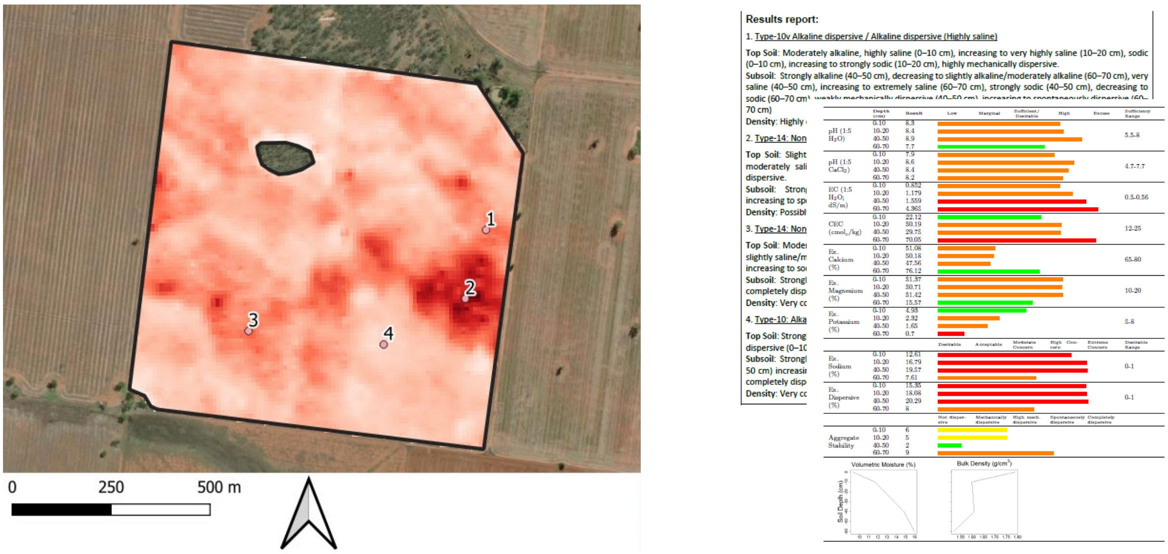
The implemented methodology takes the following steps:

Step 1 – Initial sampling constraint diagnosis

This step seeks to broadly identify the main constraints and their spatial variability across the paddock. Here we utilised EMI data, elevation data, yield data, gamma radiometric data, long-term NDVI information and grower experience information to select 4x sampling locations aimed at identifying the broad constraints and their spatial variability across the paddock (Figure 1A).

Step 2 – Constraint diagnosis

The second step requires the accurate diagnosis of soil constraints from laboratory analysis of the 4 extracted soil cores at multiple depths through the profile (0–10 cm, 10–20 cm, 40–50 cm and 60–70 cm for each soil core). Soil analysis included; soil pH, soil EC, exchangeable sodium percentage (ESP), texture, aggregate stability, bulk density and nutrient analysis. Given what we know about the spatial variability of soil constraints across a paddock, using a sample size of only 4 cores is not sufficient to accurately diagnose the extent of the constraints, nor is it sufficient to design variable-rate management plans. It merely provides an indication of the range of issues the grower is dealing with and informs which amelioration strategies may be considered. Figure 1B displays an example of the laboratory and soil constraint reports developed for each site.



(A) (B)

Figure 1. Soil sampling for initial constraint diagnosis (A) paired with the soil analysis, constraint diagnosis and amelioration recommendation reports (B).

Step 3 – Trial design, implementation and benchmark sampling

Once constraints have been diagnosed, treatments are designed according to the most severe constraint and positioned in a location which is both representative of this constraint and which considers paddock variability. This will help ensure adequate investigation of treatment responses across the paddock variability. In this approach, we accept that there will be areas where treatment application will likely be over-applied, and areas where it will be under-applied. The only way to avoid this is to increase sampling density to design a variable-rate trial plan prior to implementation. Whilst this is possible, a more cost-effective initial solution is to initially blanket-apply the treatment strip, and then back-calculate where over- and under-application was achieved. A key component of the methodology is the intensive benchmark soil sampling which is taken along each treatment strip (Figure 2). These samples are used in the latter steps to identify which soil constraint types are providing the largest yield response. Examples of treatment installation is displayed in Figure 3.

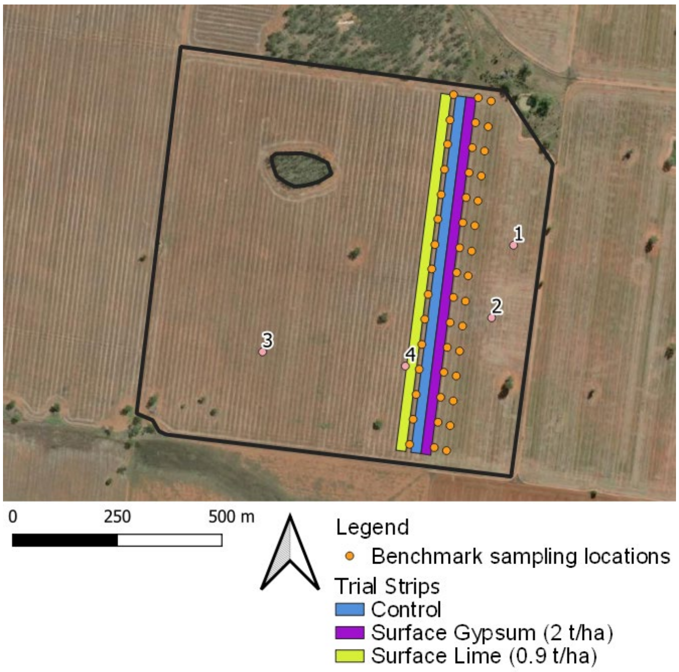


Figure 2. Trial design and benchmark soil sampling locations

(A)

(B)

Figure 3. Trial implementation for surface lime (A) and deep rip + deep placed gypsum (B). Note that deep placed gypsum was not undertaken at the site in this example but is shown here for reference.

Step 4 – Observe and map yield response

Over several seasons, yield data (obtained from the header) should be collected and analysed across the trial site. Yield analysis should not stop at calculating strip totals/strip averages, but instead should involve a yield response calculation, where every harvested point along each strip is compared directly to its closest control point in the nil strip. Undertaking this style of spatial analysis identifies which parts of the strip are contributing the biggest yield responses. Figure 4 displays an example of this type of analysis in practice. When only observing the entire yield map in Figure 4B, no visual responses in the treatment strips can be observed. However, after undertaking spatial analysis of the strips and comparing each point to its closest control point, it is apparent that there are areas of each strip contributing an ~0.8t/ha yield increase, which may be considered significant. Whilst this is only observed in small areas of the strip, these soil constraints/soil types may represent larger area across the paddock/farm. Hence, using this approach, it is possible to identify which soils offer the greatest potential to benefit from soil amelioration. The final step is to identify where else these conditions exist (Step 5).

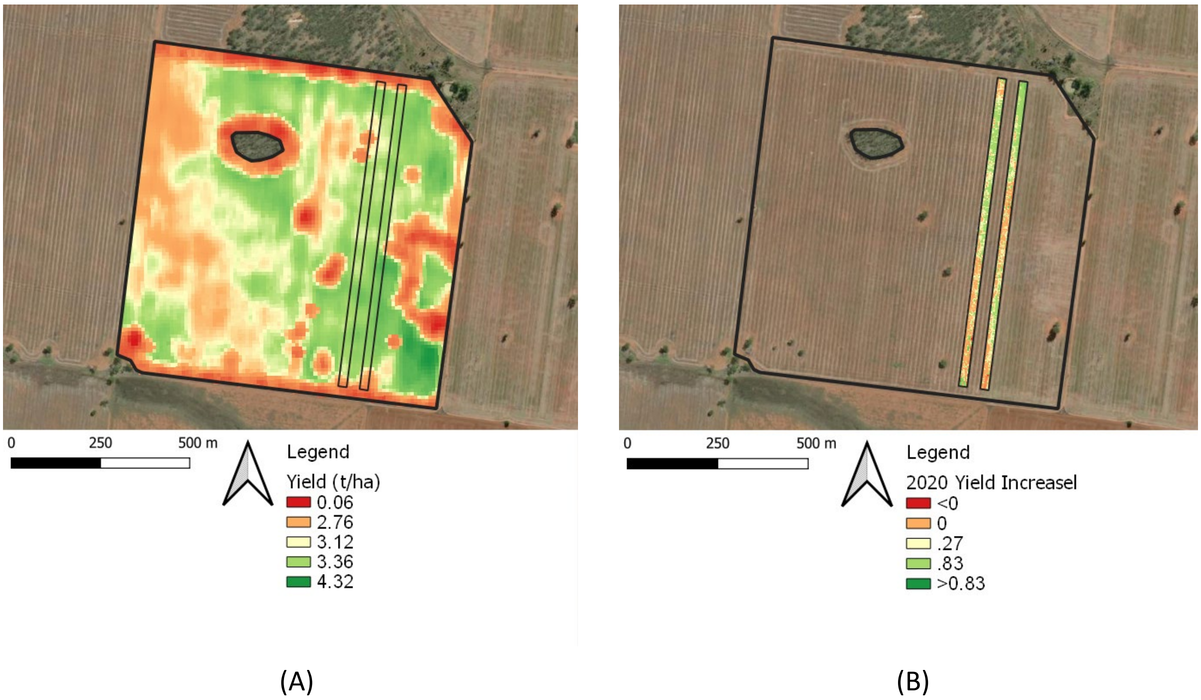


Figure 4. Paddock yield map (A) compared with yield response map (B) where points in each treatment strip are compared against their closes control nil strip.

Step 5 – Paddock and farm analysis (future work)

The final step extrapolates the yield responses observed along the trial strips to estimate which other areas of the paddock/farm will likely produce a similar yield response if amelioration was attempted. Achieving this requires two sub-steps: 1) laboratory analysis of the benchmark soil samples which were taken along the length of each strip at treatment installation; and 2) an intensive soil survey taken across the remainder of the paddock/farm to map soil constraints at fine scale. Whilst this second step will require increased investment in soil sampling, the dataset will be valuable in identifying the areas across the paddock/farm which will provide the largest yield responses if amelioration was attempted. This sampling investment may be considered as a due diligence step prior to making a substantial soil amelioration investment. In doing so, soil amelioration can not only be targeted to the areas where required, but targeted to the areas which will provide the largest yield response and subsequently, ROI from the amelioration. This analysis may be used to build amelioration investment reports which can be used to justify investment in soil amelioration, whether it be for internal budgeting purposes or external financing requests. Figure 5 provides an example of how the yield responses obtained from the treatment strips can be coupled with paddock maps of constraints to identify areas which are likely to provide a similar response.

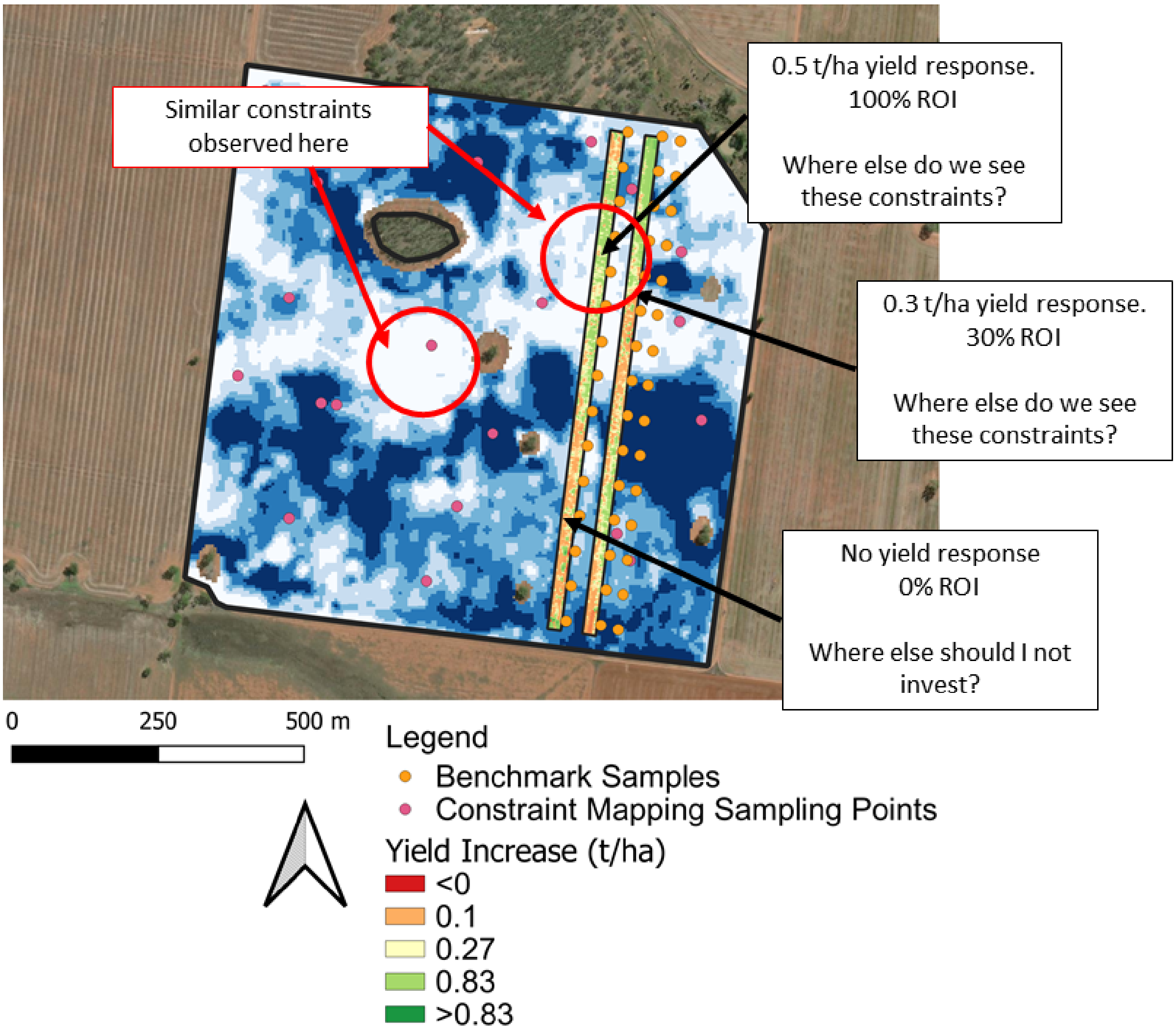


Figure 5. Illustrative example of how tracking the yield responses down the strip can be used to infer where similar yield responses may be achieved in other areas of the paddock/farm.

Conclusion

This paper has presented a methodology which can be deployed to estimate the likely yield response and ROI of soil amelioration before wide-scale investment is attempted. This step-based approach relies on implementing site-specific strip trials (tailored to each site) to tell us which soils offer the greatest potential for improved crop response. Coupled with soil amelioration cost data, it also becomes possible to map ROI of soil amelioration. Using multi-year yield data, this methodology may be used to develop whole-farm soil amelioration investment plans which may be used for internal budgeting purposes, or to access external financing to achieve large-scale amelioration. Achieving this remains a goal of future work.

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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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Contact details

Stirling Roberton
University of Southern Queensland
West St, Toowoomba, QLD, 4350
Ph: 0417 138 503
Email: Stirling.roberton@usq.edu.au

The economics of ameliorating sodicity with gypsum and lime

David C McKenzie

Key words

sodic soil, dispersion, gypsum, lime, organic matter, deep ploughing, yield gap costs.

GRDC code

David is a contributor to GRDC Projects B and C, 'Economics of Ameliorating Soil Constraints in the Northern Region' (Grant numbers: USQ1803-002RTX, USQ1803-003RTX).

Take home messages

- Soil scientists from UQ have highlighted the magnitude of grain yield constraints associated with sodic soil in the Northern Region. Sodicity is a problem for grain growers when it causes the soil to be dispersive. Vertosols and Sodosols are the main cropping soil types with this problem. An over-reliance on EM surveys and topsoil nutrient testing means that most grain farms in eastern Australia have a serious lack of accurate and comprehensive soil profile data to guide productivity improvements and the provision of soil-related ecosystem services
- A team from USQ, UNE, QDAF and NSW DPI (GRDC funded) is evaluating diverse and novel treatments for both topsoil and subsoil sodicity. But so far there are only two years of yield data (2020-21) for most of the study sites. Two years of yield response data are inadequate for meaningful economic analysis; at least five years of measured yield response data are required
- In the meantime, while waiting for additional data sets from this initiative, we have to make the most of previous studies. Very little historical data is available apart from a study initiated by a Moree farmer and UNE Armidale student, Bill Yates, in the early 1970s and data generated by the widely reported GRDC SIP08 soils project some 13 years ago
- The two main study sites used by Bill Yates were near Gurley and Garah; they were Grey Vertosols with dispersive/sodic surface soil, minimal deep vehicle compaction and no serious nutritional limitations. Some of the treatments were persistent and continued to give impressive yield gains up to five wheat growing seasons (1973-77) following amelioration, particularly gypsum 12.5 t/ha. All of the gypsum treatments were profitable, particularly at near-zero interest rates and at a rate of 2.5 t/ha. Deep ploughing (discing) also was profitable, despite poor persistence at 'Delvin', but financial losses followed application of 12.5 t/ha chopped straw
- Lime is much less soluble than gypsum and was slow to give suppression of dispersion, but significant yield benefits were eventually observed at both 'Gurley Station' and 'Delvin'.
- Yields close to potential were achieved in some years, e.g. gypsum 12.5 t/ha treatment at 'Gurley Station' in 1977, and at 'Delvin' in 1974. The annual cost of the estimated yield gap on the sodic soil without amelioration at these study sites exceeded $500 per hectare.
- Specialist soil assessment and management services are needed to assist growers and their agronomists to map and plan for the economic improvement of sodic/dispersive soil, in conjunction with integrated assessment and management of associated soil constraints such as compaction, pH imbalance, excessive flatness, salinity and nutrient deficiencies. If done professionally, this type of assessment allows soil constraints to be viewed as economic

opportunities, when managed in conjunction with the use of 'true variable rate' precision agriculture techniques.

Introduction

Orton *et al.* (2018) have estimated that of the 11.34 million ha of cropping land in NSW and Qld, 69% is affected by sodicity and that observed grain yield gaps can at least partially be attributed to soil constraints, not just agronomic factors (suboptimal management of pests and diseases, weeds, nutrient uptake, time of sowing, crop density and variety choice). Across the wheat growing land of Australia, the total potential annual economic benefit of sodic soil amelioration using gypsum was estimated to be A$1.15 billion per annum.

With support from the Grains Research and Development Corporation (GRDC), leading grain farmers and their advisers are re-assessing management inputs to reduce significant soil related yield gaps, where economic feasibility can be demonstrated. Very little new land is available for development (Heard 2021). Soil amelioration options for dryland grain production on sodic soil prone to dispersion in eastern Australia include gypsum, lime, organic matter and deep ripping. But there is uncertainty about effectiveness and persistence of treatments and the associated economic risks.

An ambitious new study of amelioration on dryland sodic cropping soil is described by Lester *et al.* (2022). The core site studies (and associated demonstration site; Roberton 2022) in southern Qld and northern NSW are evaluating diverse and novel treatments to address sodicity constraints in both topsoil and subsoil. Vertosols and Sodosols are the main soil types (as described using the Australian Soil Classification; Isbell 2016) with sodicity limitations in these regions. But so far there are only two years of yield data (2020-21) for most of the study sites. Two years of yield response data is inadequate for meaningful economic analysis; at least five years of measured yield response data are required covering a broad range of rainfall outcomes.

While waiting for additional data sets from core research sites, the only available option for farmers and their advisors requiring urgent advice about soil improvement techniques is to make the most of previous studies. This includes data generated by the widely reported GRDC SIP08 soils project some 13 years ago (Dang *et al.* 2006). Of particular value is the pioneering UNE-DPI work initiated by a Moree farmer and UNE Armidale student, Bill Yates, in the early 1970s (Yates 1972) and reported by Doyle *et al*. (1979) and Yates and McGarity (1984). The two main study sites were at 'Gurley Station', Gurley and 'Delvin', Garah; Grey Vertosols were present with inherently dispersive/sodic surface soil, minimal deep vehicle compaction and no serious nutritional limitations at that time. So and Onus (1984) estimated that 38% of cropping soil in the lower Gwydir Valley had a suppression of dryland wheat yield because of topsoil instability (dispersion index in the range 9 to 12).

Monitoring of the yield of dryland wheat grain occurred over five years (1973-77) following surface applications of gypsum (by-product phosphogypsum; calcium sulfate), lime (calcium carbonate) and organic matter. Deep ploughing (discing to 25 cm) also was evaluated, with the objective being to

a) Physically lift calcium carbonate nodules closer to the surface (nodules are frequently present in these soils at depths of approximately 15 cm) to improve surface soil structural stability and
b) Break any sub-surface compaction pans. Yates (1972) found that structural instability was not a problem in the Moree district where soil carbonate levels exceeded 0.28%.

The aim of this paper – 45 years after the field work was undertaken by Bill Yates, David Doyle and their colleagues – is to re-examine the economic performance of these treatments in relation to yield gaps. An important issue is the performance of lime as a possible substitute for gypsum when ameliorating dispersive/sodic soil. Also, challenges associated with extension of this information to grain growers via soil science specialists are discussed.

Gypsum-lime grain yield responses, 1973-77, in relation to estimated yield potential

Yield response data are shown in Table 1. Treatment details have been presented by Doyle *et al.* (1979). The economic data in Table 2 provide an overview of ameliorant profitability over the five years of the experiments. A more refined version of this analysis is being developed by colleagues associated with GRDC Project C, 'Economics of Ameliorating Soil Constraints in the Northern Region' at USQ.

Table 1. Grain yields of ameliorative treatments at 'Gurley Station' and 'Delvin' (Doyle *et al.* 1979). The modelled potential (rain limited) wheat grain yields were calculated using the equation of French and Schultz (1984) and rainfall data from the study sites.

Treatment	**'Gurley Station'**					**'Delvin'**			
A Series Experiments: Wheat grain yield, t/ha (Gypsum surface application was in January 1973)									
	1973	**1974**	**1975**	**1976**	**1977**	**1973**	**1974**	**1975**	**1977**
Control	1.1	0.8	1.7	0.7	1.0	0.2	1.1	1.4	1.8
Chopped straw (12 t/ha)	0.8	0.9	2.1	0.9	-	1.5	2.5	1.3	2.0
Deep plough (DP) 25 cm	1.0	1.1	2.1	1.0	1.2	-	2.3	1.2	1.7
Gypsum (12.5 t/ha)	1.8	1.0	2.6	1.5	2.0	1.4	3.3	1.7	2.6
Gypsum (12.5) + DP	1.5	1.8	2.6	1.7	1.8	0.6	3.5	2.0	2.8
LSD (p = 0.05)	*0.5*	*0.6*	*0.6*	*0.3*	-	*0.3*	*0.5*	*0.4*	*0.3*
B Series Experiments: Wheat grain yield, t/ha (Gypsum and lime surface application was in April 1974)									
Control		0.5	1.0	0.7	1.0		0.7	1.5	1.5
Gypsum (1.25 t/ha)		0.5	1.6	1.0	1.3		1.5	1.5	1.9
Gypsum (2.5 t/ha)		0.9	2.1	1.1	1.5		1.7	2.1	1.8
Lime (5 t/ha) + S		0.7	1.9	1.0	1.5		0.7	1.9	1.9
LSD (p = 0.05)		*ns*	*0.5*	*0.3*	*ns*		*0.7*	*0.4*	*0.4*
Potential yield, t/ha (French & Schultz 1984)	4.3	3.3	5.3	4.3	2.2	3.0	3.5	3.3	6.4

Yields close to potential were achieved in two from nine 'site years'; gypsum 12.5 t/ha treatment at 'Gurley Station' in 1977, and at 'Delvin' in 1974. But the usual outcome was yield outcomes far short of potential, even though amelioration had occurred.

The 12.5 t/ha gypsum treatment gave permanent displacement of sodium in topsoil and part of the subsoil (to a depth of 45 cm at 'Gurley Station'; McKenzie 1982). The 1.25 t/ha and 2.5 t/ha gypsum treatments, however, only provided a temporary electrolyte improvement (Loveday 1976) in the topsoil.

Some treatments were persistent and gave impressive yield gains that were still present after five wheat growing seasons (1973-77), particularly gypsum 12.5 t/ha (Table 1). The gypsum treatments were profitable (Table 2), particularly at near-zero interest rates. Of the rates under consideration, gypsum (2.5 t/ha) was the most profitable. Despite poor persistence at ‘Delvin’, deep ploughing also was profitable; but financial losses were associated with applications of 12.5 t/ha chopped straw.

Table 2. Net Present Value (NPV) of wheat grain yield improvements following soil amelioration at 'Gurley Station' and 'Delvin' (A series experiment 1973-77, B series experiment 1974-77). Economic assumptions are: Wheat price = $250/t, 2021 ameliorant costs (D-A An-Vo *pers. comm.*) and three interest rates (0%, 5%, 10%). In 1976 at 'Delvin' there was no crop due to failure of sowing rains.

Treatment	Ameliorant Cost ($/ha)*	'Gurley Station' NPV ($/ha)			'Delvin' NPV ($/ha)		
		0%	5%	10%	0%	5%	10%
A. Control	$0						
A. Chopped hay (12 t/ha)	$1,800	-1700	-1721	-1738	-1100	-1155	-1203
A. Deep plough (DP) (25 cm)	$60	215	171	137	165	149	135
A. Gypsum (12.5 t/ha)	$875	25	-108	-214	250	131	33
A. Gypsum (12.5) + DP	$925	100	-46	-163	175	40	-70
B. Control	$0						
B. Gypsum (1.25 t/ha)	$88	212	175	144	212	185	162
B. Gypsum (2.5 t/ha)	$176	424	358	303	299	260	226
B. Lime (5 t/ha), S (120 kg/ha)	$340	135	79	33	-140	-167	-189

* Gypsum $70/t, Lime $50/t, chopped hay $150/t, deep ploughing $60/ha

Lime is much less soluble than gypsum and was slow to suppress soil dispersion, but significant yield benefits were eventually observed at both 'Gurley Station' and 'Delvin'. In many parts of the Northern Region, lime provides a lower-cost source of calcium than gypsum. For example, where gypsum costs $70 per tonne and lime is $50/t, the cost of calcium from gypsum is $265/t, but only $125/t when derived from lime. Because many grain farms are closer to lime quarries than to gypsum sources, the use of lime as a sodic soil ameliorant can also provide transport savings. Sodic soil has in the past been assumed by many as being too alkaline for added lime to be effective, but the topsoil pH ($CaCl_2$) values at 'Gurley Station' and 'Delvin' were below the threshold of ~6.6 nominated by Richards (1954) for adequate dissolution of lime to improve sodic soil. Emerson (1977) noted that calcium carbonate could be used instead of gypsum, provided time is given for the carbonate to be reprecipitated as clay sized particles so as to increase its solubility.

Assuming a wheat price of $250 per tonne, the annual cost of the yield gap on the sodic soil without amelioration at these study sites (1973-77) averaged $725 per hectare at 'Gurley Station' and $619 per hectare at 'Delvin'. Without intervention, this is a cost that recurs year after year and adds up to a significant total over several decades where sodicity/dispersion is widespread across a farm. It should be noted however that yield gap numbers are theoretical and to be realised; successful management must be implemented, and yield gains realised to bridge this gap.

In a nearby follow-up experiment described by So and McKenzie (1984), it was shown that the deep movement of rain water was increased greatly by 7.5 t/ha gypsum – see Figure 1. Rainfall following the application of gypsum (by-product phosphogypsum) in March 1978 was well above average. The deeply infiltrating water on the gypsum treated soil had an elevated electrolyte concentration because of dissolved gypsum, but profile chloride concentrations were reduced (McKenzie 1982). Under these circumstances, losses of nitrate-N via deep leaching can be significant and may result in crop growth restrictions because of N deficiency.

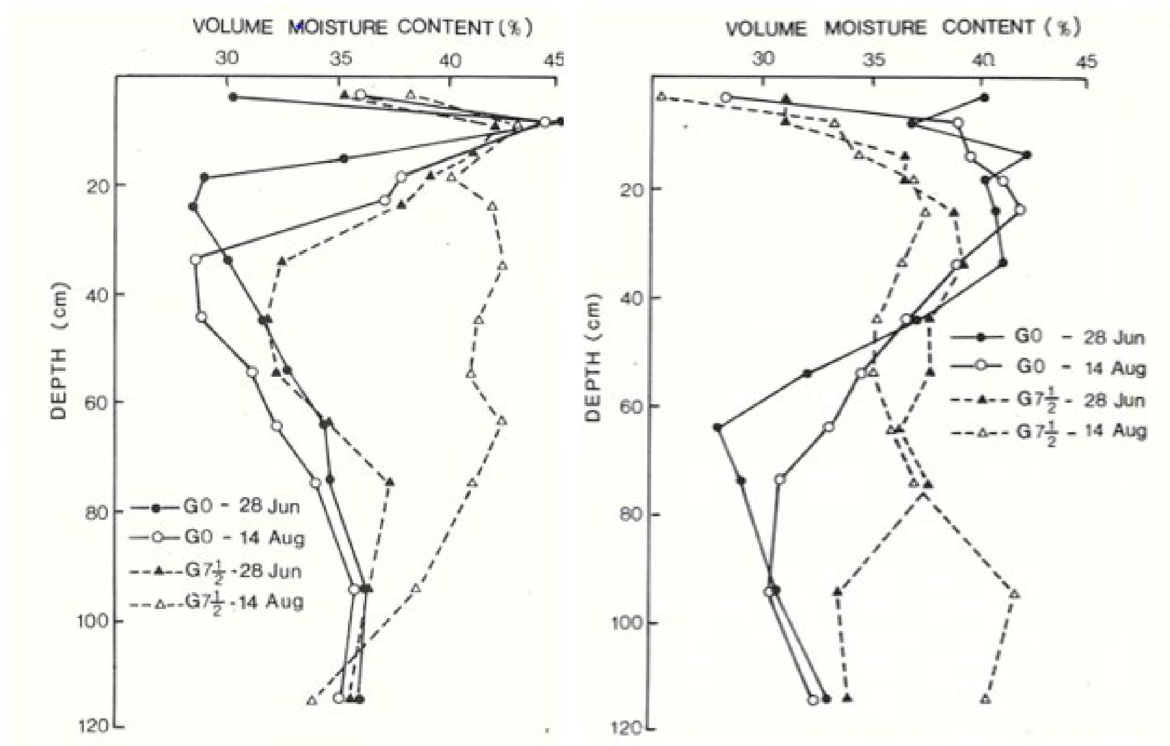

Figure 1. Volumetric water content as a function of depth on poor-yielding sodic soil at 'Delvin' Garah and 'Wyndella' Gurley in the winter of 1978, with and without gypsum (7.5 t/ha) at two times 6 weeks apart (So and McKenzie 1984).

The Doyle *et al.* (1979) study did have several shortcomings:

- The study needed to be >5 years duration, especially for the evaluation of lime which appears likely to have a greater persistence in sodic soil than gypsum following a series of wet years
- No split applications of gypsum were included in the experimental design. Loveday (1976) has noted the importance of adding follow-up split applications of gypsum to maintain the beneficial electrolyte effect until permanent displacement of exchangeable sodium by calcium has been achieved
- Gypsum-lime blends and subsoil applications were not assessed
- Alternatives to the by-product gypsum (phosphogypsum) used by Doyle *et al.* (1979) need to be assessed, e.g. coarse mined gypsum with relatively low solubility (Abbott and McKenzie 1996).

The nature of soil constraints at 'Delvin' and 'Gurley Station', in relation to soil limitations across other parts of the Northern Region

Dispersion associated with sodicity must not be considered in isolation from other soil factors that adversely affect crop growth. Table 3 provides a comprehensive framework for the planning of sodic soil amelioration. The main circumstance under consideration by Doyle *et al.* (1979) was '1. Surface dispersion/sodicity with neutral pH' (Dispersive Vertosols; Tight budget).

GRDC Projects B and C are studying a broad range of Northern Region grain paddocks where several other constraint scenarios exist (Lester *et al.* 2022).

The following notes explain the assumptions used when creating Table 3.

a) For the amelioration strategy with a 'tight budget', the focus is on topsoil improvement. This will work well in years with favourable rainfall patterns but won't be so good in dry years when crop roots have to grow deeply into untreated subsoil.
b) For the more expensive amelioration strategy with 'credit not limiting', both topsoil and subsoil are improved. This allows crop roots to grow deeply and function well in both wet and dry years.
c) However, it should be noted that a Grey Vertosol or Brown Sodosol, ameliorated to a depth of say 60cm, will still be moderately constrained when compared with a soil such as a low-salinity Black Vertosol that can allow root penetration to at least 2m deep.
d) The aim of the 'Gypsum - split dose' approach (gypsum costs spread over several years) is to overcome dispersion via the electrolyte effect of dissolved gypsum (Loveday 1976), and to eventually achieve permanent replacement of exchangeable sodium by exchangeable calcium (target ESP = 3). Shainberg *et al*. (1980) noted that in distilled water, clay dispersion and hydraulic conductivity decrease at ESP values as low as 1 to 2%.
e) The Oster and Jayawardane (1998) equation is used to calculate gypsum requirement for permanent replacement of exchangeable sodium by calcium.
f) Where the pH ($CaCl_2$) is less than 6.6, the soil is considered to be sufficiently acidic for applied lime instead of gypsum when overcoming sodicity constraints (Richards 1954).
g) It is assumed here that split application of gypsum for overcoming subsoil dispersion is not feasible because of the high cost of the associated repeated deep ripping.
h) Large additions of organic matter to the subsoil (both natural and synthetic, e.g. PAM) is not yet a proven cost-effective soil amelioration option (Doyle *et al.* 1979), so at this stage is not included on the ameliorant list.
i) There also is economic uncertainty about the use of elemental sulfur to lower pH and produce gypsum *in situ* in soil containing $CaCO_3$ nodules; the best option for strongly alkaline zones may be selection of crop varieties with natural adaptation to high pH.
j) The up-front cost of intensive and comprehensive soil assessment (soil sampling, analysis and mapping) will be similar for both 'tight budget' and 'credit not limiting' amelioration scenarios. The importance of considering these soil testing costs as capital expenditure rather than annual expenditure in farm budgets is emphasised by Bennett *et al.* (2021). A favourable development is the refinement of proximal soil sensing methods with potential to greatly reduce the cost of soil analysis.

Table 3. 'Soil Amelioration Options' to consider for constrained soil in the GRDC Northern Region.

Soil Types (Australian Soil Classification)	**Dispersive Vertosols & Sodosols**		**Self-mulching Vertosols (sodic subsoil)**	
The Main Constraint Combinations	Soil amelioration strategies to focus on: Not to be ranked - they all are important for each paddock/soil/yield gap zone under consideration (Liebig's 'Law of the Minimum' is assumed to apply whereby crop growth is restricted by the most limiting factor influencing plant performance).			
	Tight budget	***Credit not limiting***	***Tight budget***	***Credit not limiting***
1. Surface dispersion/sodicity (if pH is neutral or acidic, use gypsum-lime blend)	Gypsum - Split dose	Gypsum - All at once	n/a	n/a
2. Subsoil dispersion/sodicity	**DELAY**	Gypsum - All at once	**DELAY**	Gypsum - All at once
3. Surface compaction	Ripping if possible + Controlled Traffic (CTF)		Ripping (if compaction is severe) + CTF	
4. Subsoil compaction	Deep ripping if possible + CTF		Deep ripping (if compaction is severe) + CTF	
5. Surface dispersion & surface compaction combined	Gypsum (Split) + Rip	Gypsum (All) + Rip	n/a	
6. Surface dispersion & subsoil compaction combined	Gypsum (Split) + Rip	Gypsum (All) + Rip	n/a	
7. Subsoil dispersion & surface compaction combined	**DELAY**	Gypsum (All) + Rip	**DELAY**	Gypsum (All) + Rip
8. Subsoil dispersion & subsoil compaction combined	**DELAY**	Gypsum (All) + Rip	**DELAY**	Gypsum (All) + Rip
9. Acidic surface pH	Lime		n/a	
10. Acidic subsoil pH	**DELAY**	Lime	n/a	
11. Acidic surface pH + (5)	Lime + Gypsum (Split) + Rip	Lime + Gypsum (All) + Rip	n/a	
12. Acidic surface pH + (6)	Lime + Gypsum (Split) + Rip	Lime + Gypsum (All) + Rip	n/a	
13. Acidic surface pH + (7)	**DELAY**	Lime + Gypsum (All) + Rip	n/a	Lime + Gypsum (All) + Rip
14. Acidic surface pH + (8)	**DELAY**	Lime + Gypsum (All) + Rip	n/a	Lime + Gypsum (All) + Rip
15. Alkaline surface pH	Elemental sulfur (ES) ??		Elemental sulfur (ES) ??	
16. Alkaline subsoil pH	**DELAY**	ES ??	**DELAY**	ES ??
17. Alkaline surface pH + (5)	ES + Gypsum (Split) + Rip	ES + Gypsum (All) + Rip	n/a	
18. Alkaline surface pH + (6)	ES + Gypsum (Split) + Rip	ES + Gypsum (All) + Rip	n/a	
19. Alkaline surface pH + (7)	**DELAY**	ES + Gypsum (All) + Rip	**DELAY**	ES + Gypsum (All) + Rip
20. Alkaline surface pH + (8)	**DELAY**	ES + Gypsum (All) + Rip	**DELAY**	ES + Gypsum (All) + Rip
21. Nutrient deficiency - in addition to any of the above scenarios	Fertiliser		Fertiliser	
22. Paddock too flat - in addition to any of the above scenarios	Earthworks to improve surface drainage		n/a	
23. Paddock erodible - in addition to any of the above scenarios	Erosion control earthworks &/or stubble		Erosion control earthworks &/or stubble	
24. Saline subsoil - in addition to any of the above scenarios	*Select salt tolerant crop varieties*			
OVERCOMING MISTAKES				
24. Subsoil remains compacted because of ineffective ripping	Repeat deep ripping; do it effectively		Repeat deep ripping; do it effectively	
25. Re-compaction of soil following CTF failure	Repeat deep ripping; improve CTF		Repeat deep ripping; improve CTF	

26. Soil returns to being dispersive because of split doses being overlooked	Gypsum - Split dose	n/a	n/a

Specialist soil assessment and management services are needed to assist growers and their agronomists (soil management 'general practitioners') with the accurate mapping and improvement of sodic/dispersive soil, in conjunction with integrated assessment and management of associated soil constraints such as compaction, excessive paddock flatness, pH imbalance and subsoil salinity.

If done professionally, this type of assessment allows soil constraints to be viewed as economic opportunities. Large improvements in farm returns on investment and land values are possible (Bennett *et al.* 2021) via this approach, in conjunction with the use of 'true variable rate' precision agriculture techniques. It is important, when developing improved soil management strategies, to think critically when selecting soil survey methods of relevance to the soil landscapes under consideration. Unless soil sampling sites are chosen sensibly, the maps of key soil factors such as poor aggregate stability in water usually lack accuracy, which often results in economic losses because of the application of ameliorants in the wrong locations and/or at inappropriate rates. EM survey data, for example, often correlate poorly with maps of soil instability in water (dispersion).

Conclusions

The pioneering work of Moree farmer and UNE student, Bill Yates, in the 1970s on naturally sodic/dispersive soil under dryland wheat has been underestimated and overlooked by many soil managers in the Australian grains industry. An outstanding feature of the work by Yates and his colleagues (including David Doyle, NSW DPI, Tamworth) was the duration of time (5 years) over which the amelioration impacts were monitored.

Gypsum benefits were shown to persist for at least 5 years, and sometimes the improved yields were close to the modelled potential yields, i.e. a substantial narrowing of the yield gap. The annual cost of the modelled yield gap on the sodic soil without amelioration at these study sites exceeded $500 per hectare during the period 1973-77.

All of the gypsum treatments were profitable, particularly when interest rates are close to zero and at a rate of 2.5 t/ha. Deep ploughing also was profitable, despite poor persistence at 'Delvin', but financial losses were associated with applications of 12.5 t/ha chopped straw.,

Lime is much less soluble than gypsum and was slow to suppress soil dispersion, but significant yield benefits were eventually observed at both 'Gurley Station' and 'Delvin'. In many parts of the Northern Region, lime provides a lower-cost source of calcium than gypsum. For example, where gypsum costs $70 per tonne and lime is $50/t, the cost of calcium from gypsum is $265/t, but only $125/t when derived from lime.

However, the work by Yates, Doyle and colleagues only dealt with a single soil constraint scenario. The circumstance under consideration by Doyle *et al.* (1979) was '1. Surface dispersion/sodicity with neutral pH' (Dispersive Vertosols; Tight budget). It appears that compaction damage was not a severe constraint. GRDC Projects B and C are studying a broad range of Northern Region grain paddocks where several other constraint scenarios exist (Lester *et al.* 2022).

A list of 'Soil amelioration options' to consider for constrained soil in the GRDC Northern Region has been presented. No two paddocks are exactly the same in terms of the 3D spatial variations of key soil factors influencing crop growth (not just sodicity/dispersion, but also problems such as compaction, excessive paddock flatness, pH imbalance and subsoil salinity), and the changes in soil health over time. On all farms, specialist soil science input is required to help farmers and agronomists develop the most cost-effective way of collecting the required soil data (in conjunction with other layers of information such as yield data and remote sensing information) with adequate accuracy, and to then select an appropriate variable-rate soil amelioration strategy to maximise return on investment. An over-reliance on EM surveys and topsoil nutrient testing means that most grain farms in eastern Australia have a serious lack of accurate and comprehensive soil profile data to guide productivity improvements and the provision of soil-related ecosystem services. A vital step is consideration of the expense of accurately measured soil survey data, and the soil amelioration inputs that follow, as capital expenditure instead of annual costs (Bennett *et al.* 2021).

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Contact details

Dr David McKenzie
Soil Management Designs
Orange NSW 2800
Ph: 0458 497 574
Email: david.mckenzie@soilmgt.com.au

Ameliorating sodicity discussion - a consultants perspective

Contact details

Andrew Ceeney
Pinnacle Agriculture
Ph: 0447 421 485
Email: aceeney@pinnacleag.net.au

Graeme Callaghan
Delta Agribusiness
Ph: 0458 472 363
Email: gcallaghan@deltaag.com.au

David McKenzie
Soil Management Designs
Ph: 0458 497 574
Email: david.mckenzie@soilmgt.com.au

Notes

Northern region wheat stripe rust epidemic in 2021 – learnings for 2022

Steven Simpfendorfer[1], Robert Park[2], Mumta Chhetri[2]

[1] NSW DPI Tamworth
[2] The University of Sydney

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Take home messages

- A significant stripe rust epidemic occurred in 2021 across much of northern grains region
- Good cropping years are usually also good for rust infection. The green bridge, an early start to stripe rust infections and mild conditions allowed additional rust lifecycles, which all led to higher inoculum and infection in 2021
- Slow crop development in mild conditions left some crops unprotected between typical management growth stages and delayed onset of adult plant resistance
- Varietal resistance can vary considerably between the key pathotypes (strains) of stripe rust and there was an increased distribution of the 239 pathotype in 2021, which resulted in some unexpected varietal responses
- Predicted La Niña conditions, on the back of 2021 seasonal conditions, is likely to support another stripe rust epidemic in 2022 but steps can be taken to reduce risk and improve management.

Why was there a problem in 2021?

Good cropping years are usually 'good' (i.e., bad) rust years! These pathogens make a living off live plant tissue, so the more vigorous plant growth is, the better the substrate for rust pathogens. Typically, vigorous plant growth occurs in years with good moisture, which is also conducive to rust infection.

At least six hours of leaf wetness is needed for a stripe rust spore to germinate and infect the leaf blade. Once established, further disease progression is purely dependent on temperature. The optimum temperature range for stripe rust development is 12-20°C. At these temperatures it will take 10-14 days for a fresh batch of spores to emerge from infected leaves. This is called the latent period, during which time stripe rust infection within leaves is not visible. Temperatures above or below this optimum range DO NOT kill the pathogen. Rather the fungus slows and can become dormant outside these temperatures, but importantly will continue to develop once temperatures return to the optimal range. Hence, the more time in a 24-hour period between these optimum temperatures, the shorter the latent period. Conversely, as temperatures normally warm in spring the stripe rust fungus stops developing during the day once above 22°C but continues again overnight as temperatures drop. In these circumstances, the latent period extends to a 20+ day cycle time.

Consequently, the frequent rainfall and extended mild temperatures well into spring across much of the northern grains region in 2021, favoured infection and multiple lifecycles of stripe rust. These conditions created an extremely high pressure season for stripe rust across this region.

Did slow crop development change disease impact and does nutrition play a role?

Seasonal conditions not only affect the stripe rust pathogen, they also affect crop development and expression of resistance genes in different wheat varieties. Most varieties rely on adult plant resistance (APR) genes for protection from stripe rust, which as the name implies, become active as the plant ages. Consequently, all varieties, unless rated resistant (R), are susceptible as seedlings and move towards increasing resistance as they develop and APR genes become active. The growth stage at which APR becomes active differs between wheat varieties and relates to their resistance rating. An MR variety would generally have APR active by growth stage (GS) 30-32 (early stem elongation), MR-MS by GS37-39 (flag leaf emergence), MS by GS49-60 (awn peep-start of flowering) and MSS by GS61-75 (flowering to mid-milk). Varieties rated S or worse have relatively weak levels of resistance that are generally of limited value in disease management. Note that a variety can have a higher or lower resistance rating to individual pathotypes (aka strains) of the pathogen, depending on its resistance genes and the corresponding virulence of different stripe rust pathotypes.

Mild temperatures during 2021 that extended well into spring slowed crop development, which consequently delayed the expression of APR genes whilst also favouring multiple lifecycles of stripe rust infections. This extended time between growth stages also affected management strategies, which in more susceptible varieties is based around early protection with fungicides until APR within a variety is reliably expressed.

For example, in MS varieties a two-fungicide input strategy normally provides effective management of stripe rust, with flutriafol on starter fertiliser or in-crop fungicide application at GS30-31 being the first input, followed by a second fungicide application at GS39. This strategy relies on extended control of in-furrow flutriafol (normally out to GS37-39) or approximately three-weeks leaf protection from a foliar fungicide applied at GS30-31. With a two-spray strategy the GS30-31, application provides three weeks protection of the flag-2 leaf and lower leaves to limit stripe rust development in the canopy. Over the next four to five weeks, the flag-1 and flag leaf will emerge and be unprotected (but should also be under reduced risk of disease due to the first fungicide application). A second application at full flag emergence (GS39) then provides a further three weeks protection of the top three leaves, so that when the heads emerge in four to five weeks and APR becomes active, there has been little opportunity for stripe rust development in the canopy. However, in the milder 2021 season, gaps between key growth stages became extended as crop development slowed resulting in longer periods where the leaves were exposed to stripe rust infection using this traditional two-fungicide input strategy. In milder seasons, more susceptible varieties potentially require a third fungicide input to provide full overlap of protection across susceptible growth stages.

Higher levels of nitrogen nutrition can also delay crop maturity and expression of APR genes within varieties whilst also being more conducive to stripe rust infection (thicker canopy and leaf nitrate food source for pathogen). Differences in nitrogen nutrition can relate to rotation history (pulse vs cereal/canola in previous season) and rate and timing of fertiliser application (pre-sowing, at sowing or in-crop). However, under higher levels of N nutrition the resistance level of a variety only ever drops by one category; it does not for instance make a MRMS variety an S. Under high levels of N nutrition growers need to manage a variety as one category lower in resistance (i.e. manage a MRMS as an MS).

Did the rust in 2020 contribute to the problem in 2021?

All rusts, including stripe rust, are biotrophic pathogens. This simply means they need a living host in order to survive, including between cropping seasons. Volunteer wheat over summer and into autumn provides this living host for stripe rust survival and is often referred to as a 'green bridge.'

A number of factors dictate the extent and importance of green bridge carry-over between seasons. Firstly, the amount of stripe rust within a season increases the probability and likely level of infection in volunteer wheat plants in the following non-cropping phase. Hence, elevated stripe rust levels in 2020 increased green bridge risk in 2020-21. Summer rainfall is also important for the germination and infection of volunteer wheat plants over summer and into early autumn. The actual resistance of the variety grown also contributes to its importance as a green bridge host, with only a few volunteer plants of a susceptible variety required to survive over summer to produce millions of stripe rust spores, which can then infect autumn sown wheat in the next season.

In eastern Australia in 2021, stripe rust was detected on May 25. This is significantly earlier than the 40 year average of July 13 and was a good indicator of significant green bridge survival. The years in which we have experienced early disease onset have generally been the worst for stripe rust, emphasizing the importance of green bridge control.

Has the stripe rust pathogen changed again in 2021?

Work at the University of Sydney's Plant Breeding Institute Camden revealed the emergence of three new wheat stripe rust pathotypes in 2021, all involving mutations of the 198 pathotype. Extensive comparative greenhouse testing with these new pathotypes has shown that they pose no greater threat to current wheat cultivars than the existing 198 and 239 pathotypes.

Differences in stripe rust levels between various production areas in 2020 and 2021 and in the reaction of varieties between seasons can largely be explained through the varying distribution of existing stripe rust pathotypes in each season. For example, the 239 pathotype was an exotic introduction to Australia, likely from Europe, and was first detected in 2017 at two locations in Victoria. 239 was not detected at all in 2018, at one site in Victoria in 2019 and at 15 sites across NSW in 2020 (7.6% of isolates).

However, there was a large increase in the frequency and distribution of 239 across the northern region in 2021, with 44% of isolates identified as the 239 pathotype. Hence, a variety (Vixen$^{\phi}$ for example) that is MSS to the 239 pathotype but MRMS to the other two main pathotypes (198 and 134) appears more susceptible to growers in 2021 than it did in 2020.

In these cases, the variety itself has not changed – it is simply that the 239 pathotype of stripe rust, which can cause significant levels of disease in Vixen$^{\phi}$, has increased prevalence and distribution this season. Additionally, the limited distribution of the 239 pathotype until 2021 means that data on the vulnerability of wheat varieties to it have been limited. The more common occurrence of 239 in 2021 has enabled better data on varietal response to be captured, and so the resistance ratings of a number of varieties are likely to now change. It is important to use the most recent disease ratings when making variety decisions.

How do I know if I'm growing a suitable variety and where do I find the most recent resistance ratings?

NVT online (nvt.grdc.com.au) has a Disease Ratings tool (top right). This is an excellent source of the most current variety ratings to the various pathotypes of stripe rust and a wide range of other diseases. The tool allows users to filter by crop, variety and disease with the disease rating results presented in an easy to read comparative colour coded table. The data in this on-line tool is updated by March each year to ensure that varietal responses from the previous season have been incorporated. Growers should be careful when accessing resistance rating data as publications from previous seasons can quickly become outdated and potentially misleading.

There are multiple stripe rust pathotype ratings in the NVT Online disease rating tool – which one do I use?

Multiple pathotypes circulating across the northern grains region in the past two seasons have certainly complicated varietal resistance ratings to stripe rust. The four dominant pathotypes have differing virulence to various resistance genes within wheat varieties. Hence, a wheat variety can have a vastly different reaction to different pathotypes and therefore the management strategy employed by growers should reflect this.

The challenge for growers and agronomists is knowing which pathotype occurs in their region. The 198 (46% of isolates), 239 (44%) and 134 pathotypes (8% 134 Yr17+ and 1% 134 Yr17+27+) were widely distributed in 2021, whereas only two isolates of the 64 pathotype were identified in 2021, one from northern NSW and one from Qld. Knowing this may influence how much emphasis is placed on individual pathotype ratings.

Rust pressure from different stripe rust pathotypes can be quite localised, which is why some agronomists and growers have valued the additional information provided by having access to resistance ratings to the various common pathotypes. For example, the early sown winter wheat variety DS Bennett⸙ is particularly susceptible to the 198 pathotype. Hence, in areas where DS Bennett⸙ is commonly grown, volunteers over summer and early sowing of this variety potentially selects for early dominance of the 198 pathotype.

If the area sown to DS Bennett⸙ decreases over time, then the dominance of the 198 pathotype early in the season may also be reduced. Equally, good early season management of stripe rust in DS Bennett⸙, such as widespread adoption of flutriafol on starter fertiliser, will also assist in reducing early pressure from the 198 pathotype.

Given the widespread distribution of the 239 pathotype in 2021, greater emphasis should be placed on varietal resistance to this pathotype in 2022. Although these newer 198 and 239 exotic pathotypes have dominated in 2021, varietal reaction to the older 134 pathotypes should not be ignored as they were still detected, albeit at low frequencies, in 2021. Pathotype distribution is mapped by the Australian Cereal Rust Laboratory throughout the season (Australian Cereal Rust Survey 2021 Sample Map - Google My Maps), which can be used to tweak in-crop management decisions. Equally, growers and agronomists should seek in-season intelligence of which varieties are developing rust in their local area. This information is a valuable guide as to which pathotype(s) are likely circulating and will potentially impact their crops. The Cereal Rust Lab also publishes periodic Cereal Rust Reports that include information on varietal responses to all three rust diseases along with information on the rust resistance genes each carry.

My Winter Crop Sowing Guide has 2022 East Coast ratings? What is this?

Long-term monitoring of cereal rust pathotypes in Australia has shown that while rust pathotypes migrate periodically between the western and eastern cereal growing regions, there are many pathotypes that occur in the east that do not occur in the west. This means that a variety that is rust resistant in the west could be rust susceptible in the east depending on the resistance genes it carries. For example, currently any variety with the resistance gene Yr17 will be resistant in WA, but vulnerable in eastern Australia. The same situation applies with the leaf rust resistance gene Lr24, which is effective in WA but not in eastern Australia.

The 2022 East Coast stripe rust rating represents the in-field disease response shown by a variety (as measured by pathologists) to naturally occurring stripe rust infection across multiple field sites in eastern Australia in previous seasons. Hence, this rating is influenced by the most abundant pathotypes in the preceding 2021 season, where there was a dominance of 198, 239 and 134 pathotypes. Due to the low frequency (0.6%) of the 64 pathotype it is excluded from this combined East Coast rating.

The unexpected increase in prevalence of the 239 pathotype in 2021 resulted in the 2021 East Coast rating (which was based on 2020 field reactions), not being a good indicator of field performance for some varieties with greater susceptibility to this pathotype.

The 2022 East Coast ratings will reflect the change in distribution of pathotypes in 2021 and as a result the East Coast rating of some varieties has changed. It is for this reason that pathologists always recommend consulting current disease guides, which are updated annually.

What crop stage do these disease ratings relate to?

Varietal ratings relate to the combination of seedling (all stage) and adult plant resistance genes. The ratings are based on a variety's visual reaction to different pathotypes in replicated field experiments conducted across Australia annually under the NVT pathology system. This GRDC invested project then provides a national consensus rating each year. So, in essence, the disease rating relates to how a variety will react to stripe rust throughout the growing season.

How does varietal resistance work and what is seedling resistance versus adult plant resistance?

Like animals, plants have evolved an immune system that protects them against invading pathogens. COVID-19 has taught us that animals (humans) can develop this immunity through exposure and vaccination. In plants however, this immunity is determined at 'birth' and broadly speaking is based on genes that either:

- Detect the presence of a pathogen and trigger a defence pathway (so called immune receptors). This resistance is usually effective at all growth stages and is known as all stage resistance (ASR; also referred to as 'seedling' or 'major' resistance). While very effective, ASR genes are those that are usually overcome by new rust pathotypes acquiring virulence.
- Slow pathogen growth by 'starving' it. This resistance is effective at adult plant growth stages only and is known as adult plant resistance (APR; also referred to as minor gene resistance). APR is often durable, but incomplete in the protection it provides.

Where a variety only carries an ASR gene and this is overcome by a new rust pathotype, its resistance rating may change from resistant to very susceptible.

Adding another dimension of complexity, many wheat varieties carry a combination of ASR and APR genes. Having both ASR and APR genes means a pathotype change can result in a slight increase in susceptibility when the ASR gene is overcome by a new pathotype, but the APR gene(s) is still effective in providing 'back-up' resistance.

New varieties have been impacted by stripe rust - has resistance broken down?

When a variety becomes more susceptible to stripe rust than previously experienced, it should be remembered that nothing has changed with the plants themselves. It is the pathogen that has changed. Either it has mutated to overcome a resistance gene, or a new exotic pathogen has been introduced. There is currently no evidence to indicate that what we have seen in 2021 is due to mutating or new pathotypes overcoming varietal resistances. Unexpected responses to stripe rust observed in some varieties this season is likely the result of a change in pathotype distribution (particularly an increase in 239) and climatic conditions (persistence of green bridge, earlier infections, multiple pathogen life cycles and slowed crop development). These factors are described in more detail in the other questions.

Why have varieties with the same rating been impacted to a different extent?

The pathotype infecting individual crops can have a significant impact on the level of stripe rust development. For example, when comparing Beckomⓓ, Scepterⓓ and Vixenⓓ (table below) if sown as strips in an individual paddock they will behave quite differently depending on the pathotype present within the paddock. If the 134 17+ pathotype is present, then Scepterⓓ (MSS) will have more stripe rust development than Vixenⓓ (MS) with an even lower level in Beckomⓓ (MRMS).

However, if the 239 pathotype is present, then Vixenⓓ (S) will be impacted the most, followed by Scepterⓓ (MRMS), whilst Beckomⓓ (MR) will appear quite clean. If the 198 pathotype is present, then all three varieties will have quite similar low levels of infection, as all are MR to this pathotype. More than one pathotype can infect an individual crop throughout the growing season with the 198 pathotype dominating early in both 2020 and in 2021, while the 239 and 134 pathotypes generally infected later in the season.

Table 1. Stripe rust rating for Beckomⓓ, Scepterⓓ and Vixenⓓ depending on the pathotype present

Variety	Origin	Year of release	Resistances and tolerances			
			Rust			
			Stripe Rust (2021 east coast) Resistance	Stripe Rust (Yr_134 17+ Pathotype) Resistance	Stripe Rust (Yr_198 Pathotype) Resistance	Stripe Rust (Yr_239 Pathotype) Resistance
Beckomⓓ	Australian Grain Technologies	2015	MRMS	MRMS	MR	MR
Scepterⓓ	Australian Grain Technologies	2015	MSS	MSS	MR	MRMS
Vixenⓓ	InterGrain	2018	S	MS	MR	S

Stripe rust management

Is it possible to see where stripe rust has been found?

Rust and pathotype distribution is mapped by the Australian Cereal Rust Laboratory throughout the season (Australian Cereal Rust Survey 2021 Sample Map - Google My Maps). There are a few weeks lag in identifying the pathotype, but locations with variety details are mapped weekly after submission to the Australian Cereal Rust Survey and listed as 'result pending' until pathotype information is available.

Does knowing the pathotype change my in-season management?

This depends on your individual approach, as to whether you will take a worse-case scenario approach to stripe rust management based on a variety's reaction to dominant pathotypes in the previous season, or you wish to be more responsive in-season to timing and differential appearance of pathotypes in your area.

Will APR be enough?

Generally, if a variety has a level of stripe rust resistance below an MR rating then fungicide application is required to minimise stripe rust infection at earlier growth stages until APR is expressed. However, note that all varieties unless rated R are still susceptible to stripe rust infection as seedlings, which normally only occurs in seasons such as 2021 with early high disease pressure.

APR is a very useful control mechanism but if significant stripe rust infection exists within a crop when APR becomes active, this mechanism can strip significant green leaf area killing these existing infections. This is not the best way to use APR within varieties. Fungicide application is required at earlier growth stages to minimise infection levels around the time that APR is expressed so that this genetic protection becomes active without stripping out green leaf area.

When do I pull the trigger on fungicide applications?

There are a number of factors to consider when planning fungicide management strategies, but the aim remains to maximise retention of green leaf area on the top three leaves (flag (f), f-1 and f-2) throughout the season to protect yield potential. Considerations when planning fungicide strategies include:

- Observed level or predicted level of stripe rust pressure in crop or region
- Seasonal conditions in terms of recent/predicted rainfall and temperature which dictates infection events and disease cycle time
- Level of genetic resistance within a variety to different pathotypes and the corresponding need for protection at earlier growth stages (e.g. MRMS likely only requires a single fungicide at GS30 whilst MS requires fungicide at GS30 + GS39)
- Nitrogen status of crop with high N crops having delayed APR expression and more conducive to infection
- Growth stage of crop and whether APR visually active
- Yield potential of crop as fungicide application is always an economic decision.

Like many crop inputs, predictions are that fungicide supplies may be tight or uncertain in 2022. This places more emphasis on variety selection for the 2022 season and growers should consider reducing the areas sown to stripe rust susceptible varieties which are reliant on fungicide intervention to protect yield potential. Increasing the area sown to more resistant varieties that are less reliant on multiple fungicide inputs appears worthy of consideration. This will be even more important if the 2021/22 summer is wet which will favour elevated green bridge carry-over of inoculum leading into the 2022 season.

Is the aim for the plant to be rust free?

Ideally, crops should be managed to avoid significant development of spores within canopies so that fungicides are being used more in a preventative rather than curative approach to disease management. However, it is often impractical in high pressure seasons to expect every leaf to be totally clean. More important is whether the infections appear fresh (yellow and fluffy) or old (orange and drier) as spores can be visible and viable on leaves for 2-3 weeks until they desiccate. Is tissue death evident behind the pustules and is there flecking in leaves adjacent to hotspots or more heavily infected plants? This indicates that APR is active and infections although evident will not progress further. Low levels of infection can still occur in MRMS or even MR varieties, but these will not significantly impact on yield so chasing totally rust free crops may not always be economical.

Grass weeds seem to be covered in rust – do they contribute to the problem?

Potentially yes. Barley grass in particular was infected across most of the northern region with stripe rust in 2021. Barley grass can be infected by two types of stripe rust. This can be either:

- Barley grass stripe rust, which does not infect wheat but can cause mild infection in some commercial barley varieties or
- Pathotypes of wheat stripe rust, which can contribute to additional disease pressure in wheat crops.

Rust came in late to the heads - does this impact yield or quality, and carry over in the seed?

Stripe rust can infect individual spikelets within heads when spores enter through a gap created when the anthers (flowers) are exuded from the head. Hence, it is a fairly narrow period of infection that is unrelated to the level of genetic resistance within a variety. Head (glume) infection does not cause abortion of flowers but spores accumulate at the top of the developing grain and compete for resources. Glume infection can therefore reduce grain size within individual infected spikelets, while the rest of the grain within a head develops normally.

The impact on grain size is dependent on the amount of resources that the seed and stripe rust fungus are competing for during grain filling. In a softer prolonged grain fill period, both the seed and pathogen are likely to obtain the resources they need, with minimal or no impact on grain size. Head infection does not carry over in the seed and spores will die or be less visible as the heads dry down into harvest, with any remaining spores blowing away during the harvest process.

In some situations, despite multiple fungicide applications, the disease seemed to keep progressing – is there fungicide resistance in stripe rust?

The University of Sydney Cereal Rust laboratory periodically conducts fungicide insensitivity testing of bulked up isolates from grower paddocks of the dominant pathotypes. There has been no evidence of fungicide insensitivity in stripe rust in the last three years, but bulk testing of 2021 pathotypes will be conducted in early 2022 to confirm this is still the situation. There are a range of other potential explanations for the situation that was observed in 2021, including:

- Fungicide applications being outside the curative activity phase (if applied more than ~five days from infection, necrosis and pustule formation still occurs)
- Vast difference between preventative vs curative approaches
- Rapid reinfection of crops from spores surviving 2-3+ weeks in hotspots
- Pure quantity of spores blowing freely in the wind, and/or
- Mild temperatures extending the time between growth stages and therefore increasing the length of time that leaves were unprotected by fungicide in traditional fungicide strategies.

Many paddocks were too wet to use a ground rig. Does the application method make much difference to the level of control?

Potentially. As the saying goes ‘coverage is king’ when it comes to fungicide protection. Ground rigs allow higher water rates to be used and generally provide greater canopy penetration than aerial applications. Aerial applications are also inhibited by structures within paddocks such as trees and power lines, which can result in some areas simply not being able to receive coverage. Stripe rust can continue to cycle within these unsprayed areas and potentially provide a source of inoculum for more rapid reinfection of the crop once the fungicide protection wanes. Ground rigs generally do a better job of even application across all areas sown within a paddock.

Am I likely to see stripe rust again in 2022, and if so, what do I do?

The amount of inoculum in the landscape and predictions of a wet summer (La Niña conditions) suggest that stripe rust could be a problem again in 2022. Minimise early infections by managing green bridge over the summer and autumn period. Understand the level of resistance associated with the varieties you are growing and seek advice on appropriate fungicide strategies to ensure pathogen loads are kept low until such time as APR can be fully expressed. Growers and agronomists can assist in on-going rust surveillance and research by being vigilant with paddock monitoring and submitting samples to the University of Sydney Australian Cereal Rust Survey.

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Contact details

Steven Simpfendorfer
NSW DPI, 4 Marsden Park Rd, Tamworth, NSW 2340
Ph: 0439 581 672
Email: steven.simpfendorfer@dpi.nsw.gov.au
Twitter: @s_simpfendorfer or @NSWDPI_AGRONOMY

Robert Park
The University of Sydney, Plant Breeding Institute, Camden, NSW 2006
Ph: 0414 430 341
Email: Robert.park@sydney.edu.au
Twitter: @PbiCobbitty

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Cereal disease management: using learnings from 2021 to improve management in 2022

Brad Baxter[1], Steven Simpfendorfer[2] and Andrew Milgate[1]

[1] NSW DPI Wagga Wagga
[2] NSW DPI Tamworth

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Take home messages

- Favourable climatic conditions in 2021 resulted in the increased prevalence of a range of cereal diseases across NSW, especially the wheat leaf diseases: stripe rust, Septoria tritici blotch (STB) and yellow leaf spot
- In combination with increased cereal stubble loads produced in 2021, pathogen levels are likely to be elevated again in 2022
- Predicted La Niña conditions over summer will maintain or increase the risk of stripe rust in 2022
- Multiple stripe rust pathotypes were prevalent across NSW in 2021. Keep up to date with latest varietal resistance ratings
- STB pathogen (*Zymoseptoria tritici*) can grow saprophytically on senescent wheat plants regardless of their resistance status
- Minimise disease impacts in 2022 by using an integrated approach to management
- NSW DPI plant pathologists can assist with correct diagnosis and advice on appropriate management options.

Introduction

A cereal diagnostic service is provided to NSW cereal growers and their advisers under projects BLG207 and BLG208 as part of a NSW DPI and GRDC co-investment, Grains Agronomy & Pathology Partnership (GAPP), at no charge. Evidence based methods are used to confirm diagnosis which includes a combination of visual symptoms, crop management history, paddock distribution and recovery/identification of the causal pathogens (microscopy, humid chamber or plating). Any suspect virus samples are confirmed using ELISA antibody testing at the NSW DPI Elizabeth Macarthur Agricultural Institute at Menangle.

Wheat, barley and oat rust samples (stripe, leaf and stem) are sent to the Australia Cereal Rust Control Program (ACRCP). The submission of samples to ACRCP facilitates the tracking of pathotype populations and distribution across the cropping belt of NSW and Australia. This includes a new interactive map (Australian Cereal Rust Survey 2021 Sample Map - Google My Maps) which is regularly updated throughout the growing season by the ACRCP. Growers can access this resource to see which pathotypes dominate in their region. This can be very important to guide in-crop management decisions given five different stripe rust pathotypes were present at varying levels across NSW in 2021. Individual wheat varieties can have vastly different reactions to these pathotypes, so identification of the dominant pathotype for a particular region and time provides useful guidance for development of appropriate seasonal in-crop management.

The project also records disease enquiries received from growers and advisers throughout each season. These project activities support NSW cereal producers to obtain correct in-crop diagnosis of diseases and independent management advice. Correct diagnosis limits adverse economic impacts via minimisation of unnecessary application of in-crop fungicides.

Collation of this data across NSW provides an annual 'snapshot' of the key biotic and abiotic constraints to cereal production (Table 1).

Table 1. Cereal diagnostics and enquiries processed across NSW between 2019 and 2021. Disease/issues are ranked in order of frequency in 2021

Disease/issue	2021	2020	2019
Stripe rust (wheat)	343	194	13
Fusarium crown rot	99	61	14
Septoria tritici blotch	56	17	13
Yellow leaf spot	56	10	4
Other non-disease (e.g. soil constraint, leaf blotching/mottling)	53	34	24
Spot form of net blotch	50	65	32
Leaf rust (wheat)	37	35	2
Take-all	33	16	1
Common root rot	26	2	3
Frost damage	24	45	4
Rusts crown and stem (oats)	24	29	4
Wheat streak mosaic virus	23	3	1
Net form of net blotch	20	23	0
Physiological/melanism	20	65	10
Fusarium head blight	18	10	0
Nutrition	18	16	2
Wheat powdery mildew	17	53	1
Seedling root disease complex (Pythium, crown rot, Rhizoctonia, take-all)	13	8	2
Loose smut	11	9	1
Rhizoctonia	9	12	7
Barley powdery mildew	8	12	0
Herbicide	7	28	6
Scald	7	65	4
Bacterial blight (other cereals)	4	30	0
Barley yellow dwarf virus	4	19	1
Leaf rust (barley)	3	0	0
Red leather leaf	3	1	7
Septoria oats	3	3	2
Oat leaf blotch	2	0	0
Other minor diseases	2	5	2
Ring spot	2	0	1
Barley grass stripe rust	2	20	1
Bacterial blight (oats)	1	22	3
Total	**998**	**912**	**165**

Individual seasons have a strong influence on the demand for cereal diagnostic support provided to NSW growers/advisers, with over five-times the number of activities in the wetter 2020 and 2021 seasons compared with much drier conditions experienced in 2019 (Table 1). These increases were primarily due to more conducive conditions for the development of a range of cereal leaf diseases.

For 2021, wheat stripe rust maintained top ranking as the most diagnosed and queried cereal disease with 34% of the total activities. Fusarium crown rot in winter cereals was in second place in 2021 followed by Septoria tritici blotch (STB) and yellow leaf spot (YLS) tied for third place. In fourth spot were other 'non-disease' related issues which emphasises the on-going importance of correct diagnosis.

Are you getting a correct diagnosis?

Importantly, 13% of activities in 2021, 21% in 2020 and 28% in 2019 were not related to disease. These samples were either diagnosed as being plant physiological responses to stress, frost damage, herbicide injury, related to crop nutritional issues or other non-disease issues. All 132 samples in 2021 were submitted as suspected of having disease issues. This highlights the ongoing importance of the diagnostic service provided by these projects to NSW growers and their advisers to support correct identification and implementation of appropriate management strategies.

A second opinion from a plant pathologist can ensure the correct diagnosis – (see contact details below)

What we saw in 2021

Wheat stripe rust

Wheat stripe rust made up 34% of activities in 2021, far exceeding 21% in 2020 and 8% in 2019. The conducive 2020 season enabled the build-up of stripe rust inoculum which was then hosted by wheat volunteers over the wet 2020/2021 summer. Resultant high inoculum levels combined with early opportunity for sowing grazing wheat kickstarted the epidemic for the 2021 cropping season.

There were two predominate pathotypes identified in NSW in 2021, along with three other pathotypes with reduced incidence. The predominate pathotypes identified by the Australian Cereal Rust Survey in 2021 were 198 E16 A+ J+ T+ 17+ (198) and 239 E237 A- 17+ 33+ (239), making up around 90% of the samples submitted (pers comm, R. Park) The other pathotypes identified to a lesser extent than 198 and 239 in 2021 included 134E16A+17+, 134E16A+17+ 27+ and 64E0A-.

Each of these pathotypes may affect a particular variety (host) differently. This is due to the genetic makeup of the host plant i.e. the resistance genes within the plant and the individual pathotypes virulence or avirulence status on those genes. It is important to keep up to date with the latest variety resistance ratings because the ratings can change from year to year. Disease resistance ratings are developed through the National Variety Trial (NVT) pathology screening project. These ratings are released annually on the GRDC website and in state based sowing guides, such as the NSW DPI Sowing Guide. There have been some significant reductions (more than one resistance level) to the ratings of varieties for the 2022 season, these include Astuteⓟ (triticale), Boreeⓟ, Catapultⓟ, Coolahⓟ, Cootaⓟ, Devilⓟ, Fusion (Triticale), KM10 (Triticale), LRPB Oryxⓟ, Rockstarⓟ, Sheriff CL Plusⓟ, Stingⓟ, Valiant CL Plusⓟ, Vixenⓟ and Yitpiⓟ.

Minor reductions (one resistance level only) to the ratings of varieties including Ascotⓟ, Caparoi ⓟ, Chief CL Plusⓟ, Corackⓟ, Cutlassⓟ, Denisonⓟ, DS Tullⓟ, Emu Rockⓟ, Illaboⓟ, Kinseiⓟ , LRPB Flankerⓟ LRPB Havocⓟ, LRBP Impalaⓟ, LRPB Kittyhawkⓟ, LRPB Mustangⓟ, LRPB Nighthawkⓟ, LRPB Nyalaⓟ, Mitchⓟ, RGT Ivoryⓟ, SEA Condamineⓟ, Sunblade CL Plusⓟ, Suncentralⓟ and Sunmasterⓟ.

Septoria tritici blotch (STB)

On the back of a conducive 2020 season and heavy residual wheat stubble loads, the stubble-borne wheat disease STB ranked equal third in 2021 (Table 1). STB has a fungal structure produced on wheat stubble (perithecia) which releases airborne spores (ascospores) under ideal environmental conditions. The ascospores produced can spread long distances (>km's) to infect susceptible wheat, durum and triticale crops. Even after a non-host break crop (e.g. canola) is sown in a paddock, any remaining stubble residues from preceding wheat crops can still be a source of inoculum and infect newly emerging wheat crop.

After an infection event, lesions will appear up to 28 days later and produce pycnidia (small black structures inside tan leaf lesions that give a speckled appearance). The pycnidia produce a different type of spore called conidia which are then splash dispersed by rainfall within the wheat canopy causing new infections and further driving STB infections.

Preliminary stubble spore release research conducted at Wagga Wagga Agricultural Institute (WWAI) has shown that the resistance rating of the wheat variety grown has little influence on inoculum levels produced, i.e. the number of spores released in the following season. This indicates that the STB pathogen (*Zymoseptoria tritici*) can grow saprophytically on senescent wheat plants regardless of their resistance status. Which means stubble management to reduce inoculum loads is important in wheat on wheat paddocks for 2022 when STB is prevalent across the southern NSW region.

The first instance of the G143A mutation in STB in Australia was confirmed at Millicent in South Australia in 2021. Mutation G143A is linked to resistance to the Group 11 fungicides (QoIs), known as strobilurins. Reduced sensitivity to demethylase inhibitor fungicides (DMI, Group 3) also known as triazoles has been well documented in NSW and more widely throughout Australia in the past. However, the triazole 'epoxiconazole' at label rates is still effective against STB. Many fungicides use mixtures of both Group 3 and Group 11 modes of action (MOA) Any grower who suspects reduced sensitivity after the application of one of these products should contact a state based pathologist for details about submitting a sample to Curtin University's Centre of Cereal Disease Management (CCDM) for resistance testing (see contact details below). Submission of samples due to spray failure also applies to other diseases such as powdery mildew in both wheat and barley, net-form of net blotch (NFNB) and SFNB, which have known reduced sensitivities to fungicides.

Wheat streak mosaic virus (WSMV)

Wheat streak mosaic virus was more prevalent in 2021 with 23 confirmed cases, up from three in 2020 and one in 2019. The majority of these came from the high rainfall, mixed farming regions of southern NSW around the Young, Harden and Cootamundra regions. However, cases were reported as far north as Cumnock in central NSW. WSMV is transmitted by the wheat curl mites (WCM) which host on cereal volunteers and grass weeds, which were favoured by the mild wet 2020/2021 summer in cropping paddocks or nearby pasture paddocks. WCM migrate or are windblown into newly emerging crops where they transmit WSMV as they feed on seedling wheat plants. The earlier the infection occurs, the more severe the yield penalty. Early infection in young plants can cause death and as the season progresses, expression can include sterile empty heads, heads trapped in the boot due to leaf curling and pinched grain. Early infections can be devastating as seen in 2005, with up to 80% loss observed in infected paddocks.

WSMV can be seed-borne at low infection (<1%) levels. On a paddock scale, this can still result in a considerable number of plants infected in the newly emerged wheat crop. Seed ideally should not be retained from crops or areas of crops known to be infected with WSMV in 2021. Seed-borne transmission is a distinct risk for spreading WSMV into other paddocks or regions. It is expected the risk of WSMV will be further elevated for 2022.

Disease risk in 2022

On the back of conducive weather conditions in 2020 and 2021, inoculum and disease risk levels for the 2022 season are elevated. Diseases require a susceptible host, a source of inoculum and conducive environmental conditions to develop.

Climatic conditions (rainfall, temperature and humidity) play a significant role in initiating and driving disease epidemics. Individual pathogens each have a specific set of climatic conditions that must be met to promote initial infection and favour disease development.

If 2022 is mild and wet, there is a higher risk of foliar disease epidemics. These include biotrophic diseases such as rusts and necrotrophic diseases such as STB and YLS in wheat and SFNB, NFNB and scald in barley. These conditions will also favour soil borne diseases take-all and Pythium. If the 2022 season is drier, there will likely be a reduction of foliar diseases and increase in root diseases, such as Fusarium crown rot and Rhizoctonia where expression is favoured by the drier conditions.

The outlook for the 2021/2022 summer is wet and mild conditions, much like 2020/2021. If the forecast is correct and summer cereal volunteers and weeds are not controlled, the 'green bridge' will provide the ideal platform for biotrophs such as wheat stripe rust epidemics to initiate early on in the 2022 season.

The final inoculum consideration is from seed borne diseases and virus such as bacterial blight, smuts, bunts, Fusarium infected grain and WSMV. Sourcing clean seed for sowing in 2022, that is, not from crops infected in 2021, is important to reduce risk of these diseases.

Integrated disease management for 2022

There are integrated management strategies that growers can use to assist reduction in disease pressure from foliar, soil and stubble-borne diseases.

1. Risk identification prior to sowing

Be proactive instead of reactive. Consult paddock notes, management plans and rotation sequences from previous years to identify known and potential disease issues. Gain an understanding of your underlying inoculum levels through PreDicta®B DNA based testing method. PreDicta B quantifies a wide range of pathogen levels in your paddock and provides an associated risk level. Alternatively, 2021 cereal stubble can be submitted to the NSW DPI Tamworth laboratory for free plating of Fusarium crown rot, common root rot and take-all risk (contact Steven Simpfendorfer, details below). This provides information necessary to develop management plans and identify changes if the associated risk is unacceptable. It is recommended that growers and advisors review extension materials and disease bulletins as well as assess stubble for disease indicators such as formation of yellow leaf spot or net blotch fruiting bodies (raised small black lumps on outside of stubble).

Assess the 'green bridge' risk!!

2. Crop rotation

Sow break crops for one or more years between cereal crops. Break crops include pulses, canola and grass free pasture legumes (e.g. lucerne). This will facilitate the breakdown of cereal pathogen inoculum present. Grass weed control is vital in break crops as most grass weeds are alternative hosts of winter cereal pathogens.

As inoculum levels in 2022 are likely to be elevated, sowing cereal-on-cereal will have increased risk of yield loss. If there is a perceived or known disease issue in a paddock, switch out to a break crop to eliminate yield loss and drive inoculum pressure down.

3. Variety selection

Select varieties that provide the best resistance ratings to known or likely disease issues. This gives wheat crops the best chance of optimising yield in the presence of a pathogen. If there are multiple known disease issues, select the variety with the best resistance rating to the potentially most damaging disease.

This is particularly important for wheat stripe rust in 2022 as many widely grown wheat varieties have seen a reduction in their levels of resistance to new pathotypes and therefore will require more intensive management. Effective varietal selection will reduce the likelihood of requiring repeated in-crop fungicide applications, which will be a benefit in 2022 with potential tight fungicide supply, much like the 2021 cropping season.

4. Stubble management

Retained stubble systems are driving the prevalence of soil and stubble-borne diseases in NSW farming systems. On the back of successive high yielding years in 2020 and 2021, heavy cereal stubble loads exist in many paddocks across NSW. The stubble provides a source of inoculum for necrotrophic foliar diseases such as STB, YLS in wheat and SFNB, NFNB and scald in barley. Cutting height at harvest can affect the physical amount of stubble left standing in the paddock for pathogens such as Fusarium to further vertically colonise post-harvest. Other reduction management options for stubble-borne diseases include burning, mulching, grazing, baling stubble or soil incorporation of stubble.

Burning may have minimal effect on the inoculum levels of Fusarium crown rot, common root rot and take-all, as most of the inoculum is in the crown or root system below ground. The decision to burn cereal stubble should be weighed up against disadvantages such as nutrient loss, reduced storage of fallow moisture and increased erosion risk.

Lowering harvest cut height, mulching and incorporating stubble can reduce the amount of standing stubble but can potentially also spread pathogen inoculum more uniformly across a paddock. The risk and benefits must be weighed up before undertaking these operations.

Inter-row sowing is another effective stubble management technique. This physically distances the plant from the previous stubble row, reducing contact with pathogens that cause soil and stubble borne root diseases.

5. Volunteer cereals and grass weed control- the 'green bridge'

Chemical or mechanical control of cereal volunteers and weeds during the summer fallow period is critical to reducing the survival of rusts and insect virus vectors such as aphids or WCM. Controlling the green bridge reduces or breaks the inoculum cycle of diseases or lifecycle of virus vectors. Control of volunteer cereals and grasses in non-crop areas such as fence lines, around dams, creek lines and silos, is also important.

Controlling the green bridge is vital as a management tool for all cereal rusts. Stripe rust (especially 198 pathotype) developed early in grazing wheats in 2021, particularly in DS Bennett[A.] The disease survived on wheat volunteers over summer and infected these crops early, kick starting what was a high-pressure stripe rust season which then spread onto main season plantings. The 2022 season is potentially shaping up to be similar to 2021 so if sowing grazing crops early in 2022, spray out volunteers and weeds well in advance (4 weeks) of sowing to delay the onset of stripe rust infections. As wheat stripe rust is highly wind dispersed, this approach is much more effective if adopted across a whole region. Note that the more susceptible a wheat variety is to stripe rust, the greater the importance to control the green bridge.

Green bridge control will also reduce your risk of WSMV. This is critical as there are no effective in-crop management options for WCM such as insecticides. Early sown grazing wheat crops are generally sown in high rainfall, mixed farming regions of NSW which are the same locations in which WSMV was prevalent in 2021. The WCM hosts on cereal volunteers and grass weeds and under ideal conditions can survive for 2 weeks without a host. One contributing factor of WSMV infections in 2021 was the knock down herbicide spray being applied to paddocks just in front of sowing operations. The WCM was hosting on the green bridge (mainly volunteer wheat) in these paddocks, which by the time the herbicide spray had taken affect, the new wheat crop was emerging. The WCM moved off the senescing green bridge and straight onto emerging wheat plants, infecting large numbers of plants and continuing the cycle.

For this same reason, it is advised to spray out volunteers in any adjoining wheat paddocks from 2021 or fallow paddocks well in advance of sowing to avoid the same WCM migration pattern onto emerging wheat crops in 2022.

6. Grazing

Grazing can be a technique to reduce the incidence and severity of cereal foliar diseases. By grazing the crop, green leaf area is removed along with infected tissue present at the time. Grazing also reduces humidity within the crop by opening up the canopy and allowing airflow, thus creating an environment which is less conducive to development of leaf diseases.

Early crash grazing can be an option to reduce wheat stripe rust pressure. However, be mindful of grazing withholding periods if flutriafol was applied to starter fertiliser at sowing. If taking the grazing crop through to grain harvest, stock must be removed from the crop by GS31 to avoid yield penalties. Note that grazing is not as effective as a management strategy if infection is patchy, or stripe rust hotspots are already present in a crop.

7. Fungicide use

Due to the evolution of fungicide resistance in some cereal pathogens, such as *Zymoseptoria tritici* (STB) and *Blumeria graminis f. sp. tritici* (wheat powdery mildew- WPM) and the risk of further resistance development, it is essential that fungicide MOA's are rotated if there is to be more than one fungicide application per year. This reduces the risk of resistance development in target and non-target pathogens.

Moving forward into 2022, due to the changes in resistance ratings of widely grown varieties showing increased susceptibility to the 198 and 239 stripe rust pathotypes, fungicide management will have to change to suit. Widely grown varieties such as Catapultⓟ, Coolahⓟ, Cootaⓟ, Rockstarⓟ and Vixenⓟ have seen their ratings drop by two or more levels. What this means is that a previously rated moderately resistant to moderately susceptible (MRMS) variety is now classed as susceptible (S) and will require a more robust fungicide management package to what was employed on that variety in previous years.

Due to the high inoculum pressure expected in the 2022 cropping season, the recommended fungicide regime for an S or worse rated variety to stripe rust should include an up-front fungicide such as flutriafol on starter fertiliser at sowing, followed by a GS31 and GS39 in-crop fungicide application.

Alternatively, if an up-front fungicide is not used, a minimum of two in-crop fungicide applications should be planned, timed at GS31 and GS39. Earlier in-crop invention may be needed if stripe rust appears prior to GS31.

Fungicide applications can be altered to suit another key growth stage such as flowering, seasonal conditions and outlook along with yield potential. Fungicide resistance management through rotation of MOA and individual triazole actives within season should also be considered (see AFREN- https://afren.com.au/).

8. Adequate nutrition

Ensure adequate nutrition is applied to optimise crop health and yield potential which is balanced to meet seasonal conditions. Application of too much nitrogen can cause the development of excessive canopy biomass exacerbating foliar diseases. Increased nitrogen application can also increase moisture stress during anthesis and grain filling if in crop rainfall or stored soil water supply is limited. Late season water stress can also exacerbate the expression of Fusarium crown rot in infected crops.

9. In-crop monitoring

Inspection of cereal crops for the presence and extent of disease development and the resulting management decisions are vital to economic performance. Missed fungicide spray timings on susceptible varieties can have significant yield penalties in conducive seasons.

Wheat stripe rust can cycle every 10-14 days at optimum average daily temperatures of around 15°C (max + min temp/2). Due to changes in resistance ratings of widely grown wheat varieties to stripe rust, regular monitoring is required to identify early infections as fungicides are considerably more effective when used in a preventative rather than curative strategy.

Early disease detection through regular monitoring is therefore important. Irregular inspections may miss the expression of disease after an infection event.

Conclusions

Overall cereal crop production was above average across a large proportion of NSW in 2021 even though late rain impacted on quality in some areas. The 2022 season is already shaping as another favourable year for crop production with high soil moisture levels already accumulating. Cereal disease risk is likely to be higher due to pathogen build-up in 2020 and 2021. Well-planned integrated management strategies in the face of higher input costs and potential tight fungicide availability in 2022 will assist minimisation of disease levels whilst maximising profitability. NSW DPI is here to support correct diagnosis and discuss management options prior to sowing and as required throughout the season.

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Contact details

Brad Baxter
NSW DPI, Pine Gully Rd, Wagga Wagga, NSW 2650
Ph: 0428 294 121
Email: brad.baxter@dpi.nsw.gov.au
Twitter: @BradBaxter1985 or @NSWDPI_AGRONOMY

Steven Simpfendorfer
NSW DPI, 4 Marsden Park Rd, Tamworth, NSW 2340
Ph: 0439 581 672
Email: steven.simpfendorfer@dpi.nsw.gov.au
Twitter: @s_simpfendorfer or @NSWDPI_AGRONOMY

Andrew Milgate
NSW DPI, Pine Gully Rd, Wagga Wagga, NSW 2650
Ph: 02 6938 1990
Email: andrew.milgate@dpi.nsw.gov.au

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Fungicide resistance in wheat powdery mildew in NSW and northern Victoria in 2020-2021

Steven Simpfendorfer[1], *Kejal Dodhia*[2], *Steven Chang*[2] and *Fran Lopez-Ruiz*[2]

[1] NSW DPI Tamworth
[2] Centre for Crop Disease Management, Curtin University Perth

Keywords

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GRDC code

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Take home messages

- The wheat powdery mildew pathogen has a very high risk of developing fungicide resistance
- Resistance to Group 11 (QoI) fungicides has been detected across most of the southern growing region and was detected in parts of NSW in 2020 and 2021
- Widespread resistance or reduced sensitivity to Group 3 DMIs is considered a high risk and a DMI 'gateway' mutation was detected at very high frequency across NSW and northern Victoria in 2020/21
- Careful use and rotation of available fungicide actives will help control the spread of resistance in wheat powdery mildew
- Agronomic practices that minimise disease pressure reduce the need to apply fungicides
- Good management will help protect the long-term efficacy of current fungicides.

Introduction

A key challenge in 2020 winter cropping season was the level of wheat powdery mildew (WPM), caused by *Blumeria graminis* f. sp. *tritici* (*Bgt*), across much of NSW and northern Victoria. High mineralised soil nitrogen levels following 2-3 years of drought favoured thick canopies and elevated leaf nitrate levels which favour WPM infection. WPM infections progressed into heads late in the season in some regions. Infection occurred in a range of bread wheat and durum varieties, especially Scepter⦸ and Vixen⦸ (Table 1) which are susceptible-very susceptible (SVS) to WPM and grown widely across the affected regions. WPM occurred predominantly in high-value, irrigated cropping regions, which create ideal conditions for disease development but was also prevalent in a number of dryland crops in the wet 2020 season. Lower levels of WPM were observed again in some crops in 2021. There were concerns around fungicide management with less than desirable control achieved. Factors contributing included:

- Potentially reduced fungicide sensitivity and/or resistance in the pathogen
- Application timing - i.e., too much time between stripe rust fungicide timings to cope with the quicker cycle time and rapid infection that occurs with WPM and/or
- Spray coverage, especially of heads, which are a horizontal target.

Many crops in 2020 had 2-4 in-crop fungicide applications during the season, yet WPM continued to progress. The WPM pathogen '*Bgt'* has a remarkable ability to adapt to fungicide treatments and is at high risk for the development of fungicide resistance.

In response, a collaboration with the Centre for Crop Disease Management (CCDM) based at Curtin University in WA was established to collect and analyse WPM samples for levels of fungicide resistance.

Wheat powdery mildew is favoured by susceptible wheat varieties growing in mild and humid weather (15° to 22°C, relative humidity > 70%), with a dense crop canopy, high nitrogen levels, good soil moisture profiles and extended periods of damp, humid conditions under the canopy. *Bgt* survives on wheat stubble and volunteer wheat plants. Spores can be spread to crops by the wind over moderate distances (kilometres). The pathogen is crop specific and only infects wheat, not barley or other grain crops.

What we did

WPM samples were collected by collaborating agronomists, sent to Tamworth for processing to help ensure viability in transit and sent to CCDM for molecular analysis of frequency of mutations for DMI (F136 'gateway' mutation, triazoles) and Qol (A143 mutation, strobilurins) resistance within the WPM population in each sample. In 2020, nineteen viable WPM samples were analysed by CCDM from across NSW and northern Victoria, with sample distribution being; NE Vic (4), SE NSW (5), SW NSW (8), NE NSW (1) and NW NSW (1)(Table 1). In 2021, three WPM samples collected from NSW were sent to CCDM for investigation. Further laboratory and glasshouse testing is ongoing with CCDM to determine the relative sensitivity of these WPM populations to various DMI actives.

What we found

The F136 mutation, also known as a 'gateway', has been previously associated with reduced sensitivity to some DMI (Group 3, triazole) fungicides. This mutation is normally found together with other mutations that are ultimately responsible for the resistant phenotype observed in the field. Once the frequency of the F136 and other mutations in a WPM pathogen population reach moderate levels, then reduced sensitivity to DMI fungicides is possible under field conditions. Very high frequencies may result in resistance to WPM and spray failure under field conditions with some DMI actives. The F136 'gateway' mutation itself does not necessarily mean field failure. It is however an initial warning that issues with continued DMI fungicide use exist. Field efficacy of different DMI fungicides in the presence of this 'gateway mutation,' can vary considerably, depending on what other mutations exist once this 'gateway' mutation occurs within a WPM population.

All 22 NSW/Vic WPM samples from 2020/21 had a F136 frequency of between 62 to 100% (Table 1). Such a high frequency of DMI resistance across NSW/Vic was surprising but not unexpected given the lack of field control in these crops in 2020. A lower frequency of the Qol A143 mutation was detected which ranged from 3 to 98% (Table 1). Presence of the Qol A143 mutation in the WPM pathogen population is associated with complete resistance to strobilurin fungicides (e.g., azoxystrobin), with the strobilurin fungicides becoming ineffective under field conditions at pathotype resistance frequencies above 50%. This is alarming; as four of the WPM samples tested (3 in 2020 and 1 in 2021) showed high or very high levels of resistance mutations to DMI (Group 3) and QoI (Group 11) modes of action (MoA), which could potentially result in dual resistance to fungicides from both of these MoA groups. The strobilurins are known to rapidly succumb to fungicide resistance, which is why they are always mixed with another MoA fungicide group (usually DMIs, Group 3). The high frequency of DMI F136 in NSW/Vic WPM pathogen populations is likely increasing the rate of selection for Qol resistance.

A concerning aspect in relationship to the Qol A143 resistance gene, is that it confers cross resistance to all fungicides within the group 11 mode of action group (strobilurins).

Table 1. Location of 19 wheat powdery mildew samples collected across NSW in 2020 and 3 in 2021 along with frequency of DMI (triazole) gateway and QoI (strobilurin) mutations

Location	Year	Region	Variety	DMI F136	QoI A143
Katamatite	2020	NE Vic	Scepterᶲ	100%	90%
Katamatite	2020	NE Vic	Scepterᶲ	100%	90%
Cobram	2020	NE Vic	Scepterᶲ	100%	46%
Cobram	2020	NE Vic	Scepterᶲ	100%	28%
Balldale	2020	SE NSW	Scepterᶲ	100%	98%
Walbundrie	2020	SE NSW	Scepterᶲ	100%	5%
Rennie	2020	SE NSW	Suntopᶲ	85%	27%
Rennie	2020	SE NSW	Scepterᶲ	85%	20%
Deniliquin	2020	SW NSW	Scepterᶲ	99%	35%
Deniliquin	2020	SW NSW	Scepterᶲ	99%	20%
Deniliquin	2020	SW NSW	Scepterᶲ	83%	20%
Jerilderie	2020	SE NSW	Scepterᶲ	100%	37%
Hillston	2020	SW NSW	Vittaroiᶲ	96%	21%
Hillston	2020	SW NSW	Vixenᶲ	94%	3%
Hillston	2020	SW NSW	Vixenᶲ	85%	6%
Yenda	2020	SW NSW	Cobraᶲ	100%	44%
Yenda	2020	SW NSW	Vixenᶲ	100%	12%
Edgeroi	2020	NE NSW	Lillaroiᶲ	82%	29%
Wee Waa	2020	NW NSW	Bindaroiᶲ	62%	51%
Corowa	2021	SE NSW	Scepterᶲ	100%	94%
Wee Waa	2021	NW NSW	Auroraᶲ	100%	20%
Finley	2021	SW NSW	Scepterᶲ	100%	38%

Fungicide resistance terminology

To address the ‘shades of grey’ surrounding fungicide resistance and how it is expressed as a field fungicide failure, some very specific terminology has been developed.
When a pathogen is effectively controlled by a fungicide, it is defined as sensitive to that fungicide. As fungicide resistance develops, that sensitive status can change to:

- **Reduced sensitivity**
  When a fungicide application does not work optimally but does not completely fail.

This may not be noticeable at field level, or the grower may find previously experienced levels of control require higher chemical concentrations up to the maximum label rate. Reduced sensitivity must be confirmed through specialised laboratory testing.

- **Resistance**
  When a fungicide fails to provide disease control in the field at the maximum label rate.

  Resistance must be confirmed by laboratory testing and be clearly linked to a loss of control when using the fungicide correctly in the field.

- **Lab detection**
  A measurable loss of sensitivity can often be detected in laboratory *in vitro* tests before or independent of any loss of fungicide efficacy in the field. Laboratory testing can indicate a high risk of resistance or reduced sensitivity developing in the field.

The Australian grains crop protection market is dominated by only three major mode of action (MoA) groups to combat diseases of grain crops; the DMIs (Group 3), SDHIs (Group 7) and strobilurins (or quinone outside inhibitors, QoIs, Group 11). Having so few MoA groups available for use increases the risk of fungicide resistance developing, as growers have very few alternatives to rotate in order to reduce selection pressure for these fungicide groups.

With two of the three fungicide MoA groups now compromised in some paddocks in New South Wales and Victoria, all growers and advisers need to take care to implement fungicide resistance management strategies to maximise their chances of effective and long-term disease control.

The Australian Fungicide Resistance Extension Network (AFREN), a GRDC investment, suggests an integrated approach tailored to local growing conditions. AFREN has identified the following five key actions, 'The Fungicide Resistance Five', to help growers maintain control over fungicide resistance, regardless of their crop or growing region:

1. Avoid susceptible crop varieties
2. Rotate crops – use time and distance to reduce disease carry-over
3. Use non-chemical control methods to reduce disease pressure
4. Spray only if necessary and apply strategically
5. Rotate and mix fungicides/MoA groups.

Managing fungicide resistance

It is important to recognise that fungicide use and the development of fungicide resistance, is a numbers game. That is, as the pathogen population increases, so does the likelihood and frequency of naturally resistant strains being present. A compromised fungicide will only control susceptible individuals while the resistant strains within the population continue to flourish.

As a result, it is best if fungicides are used infrequently and against small pathogen populations. That way, only a smaller number of resistant individuals will be present to survive the fungicide application, with many of these remaining vulnerable to other competitive pressures in the agro-ecosystem.

Keeping the pathogen population low can be achieved by taking all possible agronomic steps to minimise disease pressure and by applying fungicide at the first sign of infection once the crop has reached key growth stages. In cereals, the leaves that contribute most to crop yield are not present until growth stage 30 (GS30/start of stem elongation.) Foliar fungicides applied prior to this are more often than not a waste of money and unnecessarily place at risk the longevity of our cost-effective fungicide resources by applying an unneeded selection pressure on fungal pathogens for resistance.

Integrated management strategies

Management practices to help reduce disease pressure and spread include:

- **Planting less susceptible wheat varieties**
  Any level of genetic resistance to WPM slows the rate of pathogen and disease development within a crop and reduces the reliance on fungicides to manage the disease. Avoid growing SVS and VS wheat varieties in disease-prone areas.

- **Inoculum management**
  Killing volunteer wheat plants during fallow periods and reducing infected wheat stubble loads will reduce the volume of spores spreading into an adjacent or subsequent wheat crop.

- **Practicing good crop rotation**
  A program of crop rotation creates a dynamic host environment that helps reduce inoculum levels from year to year. Rotating non-susceptible wheat varieties can also provide a more dynamic host environment, forcing the pathogen to adapt rather than prosper.

- **Disease levels can be higher with early planting**
  Later planting can delay plant growth until after the initial warm and damp period of early winter that favours WPM. This is important as infection of young plants can lead to increased losses at maturity. Later sown crops also tend to develop smaller canopies which are less conducive to powdery mildew infection. However, delayed sowing can have an associated cost of reduced yield potential in some environments which should be carefully considered by growers.

- **Careful nitrogen management**
  As excess nitrogen favours disease development, nitrogen application should be budgeted to measured soil N levels and target yield so as to be optimised to suit the growing purpose.

- **Encouraging air circulation**
  Actions that help increase airflow into the crop canopy can help lower the relative humidity. This can include wider row spacing, reduced plant populations (note yield potential should still be maximised). In mixed farming systems grazing by livestock can be used to reduce and open up the early season crop canopy, with potential to reduce the level of disease inoculum present at commencement of stem elongation when the ‘money leaves’ start to appear.

Fungicide recommendations for wheat

Planning of fungicide rotations needs to consider all fungal pathogens that may be present in the crop. Otherwise the fungicide treatment for one pathogen may select for resistance in another. For example, whilst there is little evidence of the development of fungicide resistance in rust populations globally, growing S-VS rust varieties means the only control option is fungicides. This can potentially have off-target selection pressure on the development of other fungal pathogens such as *Bgt* which is very prone to developing fungicide resistance.

Careful fungicide use will minimise the risk of fungicide resistance developing in WPM in Australia and help ensure the longevity of fungicides.

Advice to NSW and Victorian wheat growers includes:

- **Avoid using Group 11** fungicides in areas where resistance to QoIs has been reported.

- **Minimise** use of the **Group 3** fungicides that are known to have compromised resistance.
- **Monitor Group 3** fungicides closely, especially where the gateway mutation has been detected.
- **Rotate Group 3** fungicide actives within and across seasons. In other words, do not use the same Group 3 product twice in succession.
- **Avoid** more than three applications of fungicides containing a **Group 3** active in a growing season.
- **Group 11** fungicides should be used as a preventive, rather than for curative control and should be rotated with effective **Group 3** products.
- **Avoid** applying **Group 7** and **Group 11** products more than once per growing season, either alone or in mixtures. This includes in-furrow or seed treatments that have substantial activity on foliar diseases, as well as subsequent foliar sprays. Combined seed and in-furrow treatments count as one application.

Growers and agronomists who suspect DMI reduced sensitivity or resistance should contact the CCDM's Fungicide Resistance Group at frg@curtin.edu.au. Alternatively, contact a local regional plant pathologist or fungicide resistance expert to discuss the situation. A list of contacts is on the AFREN website at grdc.com.au/afren.

Further information on fungicide resistance and its management in Australian grains crops is available at the AFREN website at grdc.com.au/afren.

Conclusions

NSW and Victorian growers need to be aware that issues with fungicide resistance already exist with WPM which could result in reduced fungicide sensitivity or potentially spray failures with DMI (triazoles) and QoI (strobilurin) fungicides. Further testing by CCDM is ongoing as to the level of reduced sensitivity to different DMI actives in these WPM pathogen populations, which will be communicated to growers and their advisers once available. Fungicide resistance is real and needs to be managed using an integrated approach to limit further development of fungicide resistance within WPM pathogen populations and in other at-risk fungal pathogens (e.g., net-blotches in barley and yellow spot or Septoria tritici blotch in wheat).

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Contact details

Steven Simpfendorfer
NSW DPI, 4 Marsden Park Rd, Tamworth, NSW 2340
Ph: 0439 581 672
Email: steven.simpfendorfer@dpi.nsw.gov.au
Twitter: @s_simpfendorfer or @NSWDPI_AGRONOMY

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Learnings from 2021 – how to improve barley disease management in 2022?

Lislé Snyman, Dept. Agriculture and Fisheries Queensland

Key words

barley, net blotch, leaf rust, smut, fungicide resistance, disease management

GRDC code

National Variety Disease Screening (NVT)

UOA2003-008: Program 2: Minimizing the impact of major barley foliar pathogens on yield and profit – surveillance and monitoring of pathogen populations.

DAQ2106-007: Disease surveillance and related diagnostics for the Australian grains industry within the northern region.

Take home messages

- High levels of net form net blotch (NFNB) infection were present in 2021 barley crops
- Continuous barley cropping increases the risk of stubble-borne diseases such as net blotch
- Management strategies for foliar diseases includes resistant varieties, crop rotation, seed treatment, regular crop monitoring and timely fungicide application
- Managing the green bridge will limit disease load of rust diseases early in the season
- Resistance to fungicides have been reported in powdery mildew, NFNB and spot form net blotch (SFNB) in Australia
- Fungicide resistance development can be managed by using an Integrated Disease Management (IDM) strategy.

Background

Above average rainfall from May to July delayed planting of many barley crops in SE QLD in 2021. Despite higher-than-normal annual rainfall, disease incidence was not as prolific as anticipated. Dry conditions during August and September were unfavourable for disease development and most likely limited disease incidence, particularly in the late planted crops. Despite that, some crops were severely impacted by disease during 2021. Net form of net blotch (NFNB) was the most widespread disease observed during the season, with leaf rust and smut present in many crops.

Net form net blotch is covered in the paper 'Net form net blotch management in barley' and will not be discussed here.

Leaf rust

Leaf rust of barley is widely distributed and occurs regularly in the northern region. It is considered one of the five major barley diseases in Australia and can significantly reduce yield and quality. Barley leaf rust was widespread in Queensland in 2016, but due to the drought conditions, was only present at very low levels until 2021. Samples submitted from Qld crops during 2021 to the Plant Breeding Institute, Sydney University, were collected from varieties Compass⫯, Laperouse⫯ and Leabrook⫯. These varieties are rated as susceptible to very susceptible (SVS) to very susceptible (VS) in Qld.

The disease is caused by the obligate parasite, *Puccinia hordei.* It spreads by means of airborne spores, able to travel long distances. The pathogen spreads rapidly when conditions are favourable and large areas are planted to susceptible varieties, resulting in the development of epidemics. In the presence of a green bridge, the pathogen can survive over summer and be present at high levels early in the growing season. High inoculum levels put pressure on major resistance genes and can lead to the development of new, more virulent pathotypes.

Large areas sown to S to VS varieties across a range of environments almost ensures that leaf rust will be a problem in some areas contributing to high inoculum levels causing epidemics whilst adding selection pressure on the pathogen to mutate and acquire new virulences.

Smut

The presence of smut in barley crops seems to be on the increase in recent years, with both forms detected in crops annually. Varieties of the Hindmarsh⟨Ⓓ⟩ lineage e.g., Hindmarsh⟨Ⓓ⟩, La Trobe⟨Ⓓ⟩ and Rosalind⟨Ⓓ⟩, are particularly prone to loose smut infection.

Barley is impacted by two species of smut – loose smut and covered smut, caused by *Ustilago nuda* and *Ustilago hordei*, respectively. In both, grain is replaced by black spore masses. These are encased in a membrane. This membrane is quite fragile in loose smut and ruptures soon after head emergence, releasing the spores. In covered smut, the membrane is much more persistent, breaking during harvesting.

Loose smut is most often observed around flowering when infected heads, bearing a mass of dark brown to black sooty spores, are visible. In plants infected with loose smut, the membrane ruptures soon after head emergence, releasing airborne spores which infect surrounding florets. Infection occurs under moist conditions at temperatures around 16 – 22°C. Florets are susceptible to infection from flowering to about one week after pollination. Germinating spores infect the ovary and the fungus survives as mycelium within the embryo of the infected seed. Once infected seed is sown, it germinates and carries the fungus in the growing point of the plant, becoming visible as a black spore mass at head emergence. Loose smut is well adapted for survival with infected plants usually being slightly earlier than healthy plants, ensuring an adequate supply of inoculum when the bulk of the crop is flowering.

Heads infected with covered smut frequently emerge later than healthy heads and tend to be shorter, hence may go unnoticed. As with loose smut, grains are replaced with a mass of black powdery spores. The membrane however remains intact and only breaks during the harvesting process, contaminating healthy grain. The spores germinate after planting, infecting emerging seedlings, growing through the plants where they eventually replace the grain with spores. The fungus is favoured by temperatures of 14 – 25°C.

Loose smut is exclusively internally seed-borne, while covered smut is either externally seed-borne or survives in the soil. The life cycle of loose smut in barley is the same as in wheat; however barley loose smut will not infect wheat and vice versa.

Since seed treatment has been effective for so long, smut is not a breeding priority. There are various seed-treatment products available, however it is important to ensure that it is applied properly, and that seed is appropriately covered. If left untreated smut will result in yield and quality loss. If smut is detected in a crop, growers are advised to source new, clean seed for sowing.

Fungicides - resistance risk and timing

Fungicides are essential in maintaining healthy crops and are applied routinely in most barley crops. The choice of fungicide is determined by registration, efficacy, availability and price. Fungicide efficacy varies with disease. When conditions are favourable for disease development, a repeat application may be required for effective disease control.

The efficacy of some fungicides has been impacted by the development of resistance in pathogens. Thus, a previously effective fungicide fails to control disease, despite correct application. Without intervention, more fungicides are likely to become ineffective.

Repeated use of fungicides with the same mode of action (MoA), selects for individuals in the fungal population with reduced sensitivity to the fungicide. The risk of developing fungicide resistance varies between different MoA groups, different fungal pathogens and different environments.

Higher disease pressure indicates larger pathogen populations and increased probability of developing resistance to fungicides.

In Australia, fungicide resistance in barley pathogens have been identified to date in powdery mildew, spot form net blotch (SFNB) and net form net blotch (NFNB) (Table 1).

Table 1. Fungicide resistance and reduced sensitivity identified in pathogens of Australian barley crops since 2010. X = resistance, # = reduced sensitivity, ● = lab detections. Source: Fungicide resistance management guide (AFREN).

Fungicide group	Compounds affected	Resistance status						Industry implications
		NSW	Qld	SA	Tas	Vic	WA	
Barley powdery mildew - *Blumeria graminis* f. sp. *hordei*								
3 (DMI)	Tebuconazole, propiconazole, flutriafol	●	●		●	●	X #	Field resistance and reduced sensitivity to some Group 3 fungicides.
Net form net blotch (NFNB) - *Pyrenophora teres* f. *teres*								
3	Tebuconazole, propiconazole, prothioconazole, epoxiconazole			#		#	X #	Field resistance and reduced sensitivity to some Group 3 fungicides.
7 (SDHI)	Fluxapyroxad			X #				Field resistance to fluxapyroxad.
3 + 7	Tebuconazole (3), fluxapyroxad (7)			X #				Risk of field resistance and reduced sensitivity to both Group 3 and Group 7 fungicides due to the existence of double mutants.
Spot form net blotch (SFNB) - *Pyrenophora teres* f. *maculata*								
3	Tebuconazole, propiconazole, prothioconazole, epoxiconazole					●	X #	Field resistance and reduced sensitivity to some Group 3 fungicides.
7	Fluxapyroxad						X #	Field resistance and reduced sensitivity to Group 7 fungicides.
3 + 7	Tebuconazole (3), fluxapyroxad (7)						●	Risk of field resistance and reduced sensitivity to both Group 3 and Group 7 fungicides due to the existence of double mutants.
Hybrid net/spot form net blotch – caused by *Pyrenophora teres* f. teres x f. *maculata*								
3	Tebuconazole, propiconazole, epoxiconazole						X	Field resistance to some Group 3 fungicides.

Fungicide resistance can be managed through the use of an integrated disease management (IDM) strategy to reduce disease pressure and reliance on fungicides. Relying on:

- Resistant varieties
- Crop rotation
- Clean seed
- Green bridge management
- Stubble management
- Use fungicides only when necessary and apply strategically
- Rotate and mix fungicide MoA groups
- Monitor regularly for disease - fungicides are more effective at lower disease levels.

Conclusion

Barley foliar pathogens cause devastating yield and quality loss worldwide. Research has proven that the more susceptible a variety, the bigger the yield and quality loss resulting from disease. Thus, growing a susceptible variety increases risk and requires dedicated effort towards persistent monitoring and decision making. The presence of a green bridge will present an opportunity for many pathogens to survive over summer (e.g. rusts which require a green host for survival) and be present at high levels early in the growing season. Thus, the green bridge will need to be carefully monitored and appropriate measures taken to reduce inoculum load at the start of the season. Planting barley on barley will increase the risk and disease pressure of stubble-borne pathogens and may aid the survival of fungicide resistant individuals.

The epidemiology of the pathogen, the biology of the host and environmental conditions all impact disease management. The use of a proper IDM approach will not only limit the development of fungicide resistance, but will also reduce economic input and support sustainable farming.

Further reading

Australian Fungicide Resistance Extension Network (AFREN): https://afren.com.au/resources.

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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.

Contact details

Lislé Snyman
DAF QLD
Hermitage Research Facility, 604 Yangan Rd, Warwick, Qld
Ph: 0428 324 932
Email: lisle.snyman@daf.qld.gov.au

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Net Form Net Blotch management in barley

Lislé Snyman, Dept. Agriculture and Fisheries Queensland

Key words

barley, net form net blotch, pathotypes, varieties, management

GRDC code

National Variety Disease Screening (NVT)

UOA2003-008: Program 2: Minimizing the impact of major barley foliar pathogens on yield and profit – surveillance and monitoring of pathogen populations.

DAQ2106-007: Disease surveillance and related diagnostics for the Australian grains industry within the northern region.

Take home messages

- High levels of net form net blotch (NFNB) infection were observed in 2021 barley crops
- Continuous barley cropping increases the risk of stubble-borne diseases such as net blotch
- The NFNB pathogen is both seed and stubble-borne
- Virulence's are dynamic and fluctuate in response to available host genotypes
- Management strategies for foliar diseases include resistant varieties, crop rotation, seed treatment, regular crop monitoring and timely fungicide application
- Resistance to fungicides have been reported in both NFNB and SFNB in Australia
- Limit fungicide application by spraying only when necessary, rotate fungicides with different modes of action and use recommended rates.

Background – Net form net blotch

Net blotch in barley is caused by one of two forms of *Pyrenophora teres* (*P. teres*). Net form net blotch (NFNB) is caused by *P. teres* f. *teres* (*Ptt*) and spot form net blotch (SFNB) is caused by *P. teres* f. *maculata* (*Ptm*). The two forms are morphologically identical and can only be distinguished by symptoms and molecular characterisation.

Symptoms of the net blotches are initially very similar, looking like small dark spots. They then develop into lesions with varying amounts of necrosis and chlorosis, determined by climatic conditions and resistance/susceptibility of the host. NFNB are characterised by net like dark brown necrotic lesions, whereas SFNB symptoms are characterised by dark circular or elliptic brown spots surrounded by a yellow chlorotic area.

Both forms are stubble-borne and survive from one season to the next on crop stubble or residue. The pathogen can also infect and survive on other cereals such as wheat and oats and can infect a wide range of other grasses (*Agropyron, Bromus*, etc). These are however regarded as minor hosts.

The net form net blotch pathogen is diverse, ever-changing and able to overcome the resistance in barley varieties. Virulence changes result from increased selection pressure on the pathogen by continuous barley cropping, no-till farming practices and widespread cultivation of genetically homogeneous crops.

Environmental conditions play a major role in the development of NFNB. Disease development and infection is favoured by frequent wet periods and mild temperatures.

Variation in the virulence of the pathogen is studied using differential sets. These sets include a number of lines or varieties with known resistances. For the set to be of local benefit, the inclusion of regional varieties is required and in order to identify changes in virulence, needs to be updated to include genotypes representing new sources of resistance.

Plant pathologists and breeders can use the knowledge on virulence in the pathogen population to identify and deploy sources of resistance effective against local pathotypes. Pathotype studies in Australia identified populations of *Ptt* to be quite unique to each state and reflect the cultivation of locally adapted varieties.

Net form net blotch in 2021

Net form net blotch occurs regularly in the northern region and samples are collected from crops throughout the season. In 2021, 14 samples of NFNB were collected from Qld barley crops. These were mostly collected from varieties Commander⦹, Spartacus⦹ and RGT Planet⦹ with very high levels of disease observed in some crops.

Despite above average rainfall in the 2021 season, disease incidence was not as prolific as anticipated. The wet spell in July delayed planting of many crops. The dry spell in August and September most likely restricted disease onset and progress in late planted crops (Fig. 1). However, some crops were severely impacted by high disease levels, particularly in varieties mentioned above and in barley-on-barley crops.

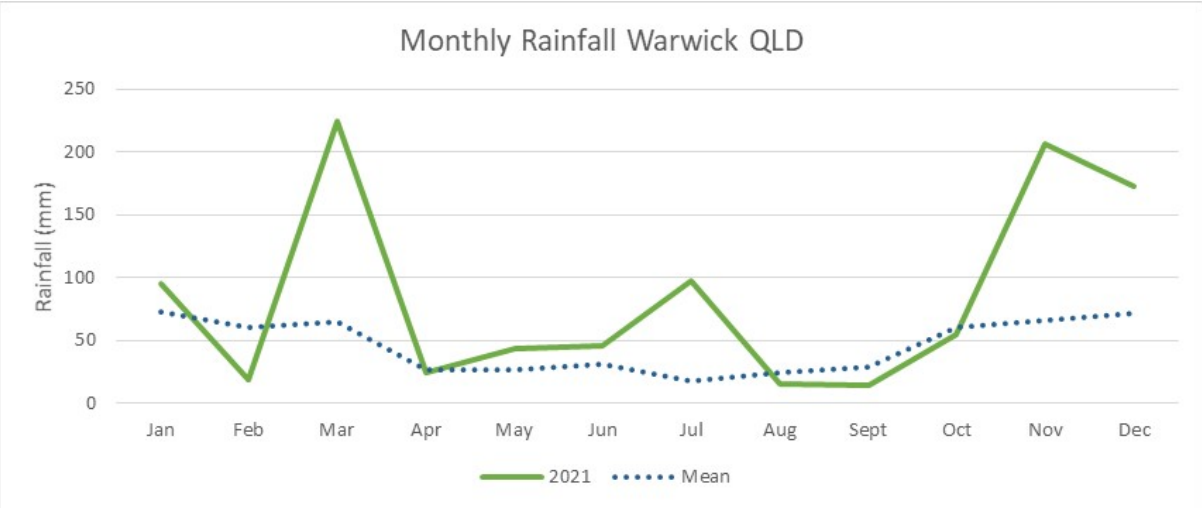

Figure 1. Monthly rainfall for the Hermitage Research Station, Warwick.

Disease management

Barley foliar pathogens are a significant challenge to the grains industry and a major constraint to profitable barley production, affecting both yield and quality. Many of these pathogens are genetically and pathogenically diverse, able to reproduce sexually and can rapidly develop new virulence's and overcome genetic resistance.

The adoption of stubble retention practices has led to an increase in the incidence of stubble-borne diseases such as the net-blotches. Planting successive barley crops in the same paddock increases pathogen incidence.

Growing a high yielding, well adapted, resistant variety provides the most economic and environmentally friendly means of disease control. Genetic resistances need to be durable to provide long-term protection. Net form net blotch is best controlled by sowing varieties rated MS or better in combination with cultural practices that reduce inoculum load.

All current barley varieties and varieties considered for release are rated for resistance to a suite of diseases and pathogens through the National Variety Trial disease screening process. They are categorised in 9 resistance categories rating from resistant (R) to very susceptible (VS). These genotypes are screened annually in nationwide disease nurseries, with disease ratings assigned and reviewed on a yearly basis. The most up to date information on resistance ratings are available on the NVT website (https://nvt.grdc.com.au/nvt-disease-ratings).

The NFNB pathogen persists on plant residue. Cultivation of the same variety will lead to an increase in the presence of pathotypes virulent on that particular variety and put increased pressure on effective resistance genes. Best practice includes crop rotation with non-host crops such as wheat, canola and chickpea. NFNB is also seed-borne and can spread with infected seed. Various seed treatment products are registered for NFNB control. Systemic fungicides applied as a seed-treatment will provide protection against seed-borne diseases.

In susceptible varieties where yield potential is high, fungicidal control can be justified. Foliar fungicides should be aimed at protecting the key leaf solar panels present during grain filling – namely; the flag leaf sheath, the flag leaf (f), flag -1 (f-1), and f-2.

Resistance to Group 7 (SDHI) and Group 3 (DMI) fungicides has been identified in NFNB populations in SA and WA, respectively, with reduced sensitivity identified to other Group 3 fungicides in WA and Vic and both Groups 3 and 7 in SA.

To ensure that fungicides remain effective, it is important to limit fungicide application by spraying only when necessary, rotate fungicides with different modes of action and use fungicides at recommended rates. Avoid using tebuconazole as a stand-alone product in barley to avoid indirect fungicide resistance selection. By applying it for powdery mildew control, you can indirectly select for NFNB or SFNB isolates resistant to tebuconazole without the intention of controlling those diseases. Isolates resistant to fungicides can be spread through infected seed. It is beneficial to all to ensure that we use fungicides in such a way that we protect their longevity.

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

Conclusion and 2022 planning

The absence and/or low incidence of many diseases in 2021 in the northern region does not mean that we can get complacent. With favourable environmental conditions, pathogens will continue to cause yield and quality loss and we have to make the right decisions to ensure that we can stay ahead of disease development and the evolution of the pathogen.

Continuous monitoring of the NFNB pathogen populations provides information on the virulence's in Australia and aid in the identification of effective resistance for use in the development of resistant varieties.

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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.

Contact details

Lislé Snyman
DAF QLD
Hermitage Research Facility, 604 Yangan Rd, Warwick, Qld
Ph: 0428 324 932
Email: lisle.snyman@daf.qld.gov.au

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Fusarium crown rot seed fungicides: independent field evaluation 2018-2021

Steven Simpfendorfer, NSW DPI Tamworth

Keywords

fungicide seed treatments, yield loss, wheat, barley, durum, disease

GRDC code

DAN00213: Grains Agronomy & Pathology Partnership (GAPP) - A strategic partnership between GRDC and NSW DPI (Project BLG208) and DAN00175: National crown rot epidemiology and management program.

Take home messages

- Current fungicide seed treatments registered for the suppression of Fusarium crown rot (FCR) inconsistently reduce the extent of yield loss from FCR
- Victrato® had consistent and stronger activity on limiting yield loss from FCR
- However, under high infection levels, significant yield loss may still occur in drier seasons
- Fungicide seed treatments, including Victrato®, should not be considered standalone control options for FCR
- Seed treatments should be used as an additional tool within existing integrated disease management strategies for FCR.

Introduction

Fusarium crown rot (FCR), caused predominantly by the fungal pathogen *Fusarium pseudograminearum* (*Fp*), is a major constraint to winter cereal production across Australia. A range of integrated management strategies including crop rotation, varietal selection, inter-row sowing, sowing time, stubble and fallow management are required to minimise losses. A number of fungicide seed treatments have been registered for the suppression of FCR in recent years with a further product Victrato® from Syngenta likely to be available to Australian growers prior to sowing in 2024. Although chemical companies conduct their own widespread field evaluation across Australia, growers and their advisers value independent evaluation of the potential relative fit of these fungicide seed treatments within integrated management strategies for FCR.

What we did

A total of 15 replicated plot experiments (generally 2 x 10 m with minimum of 3 replicates) were conducted across NSW from 2018-2021 with one additional field experiment conducted in Victoria (Horsham) and two in WA (Merredin and Wongan Hills) in 2018 only (Table 1). The winter cereal crop and number of varieties differed between experiments with wheat (W), barley (B) and/or durum (D) evaluated in each experiment (Table 1).

Six fungicide seed treatments: Nil, Vibrance® (difenoconazole + metalaxyl-M + sedaxane at 360 mL/100 kg seed), Rancona® Dimension (ipconazole + metalaxyl at 320 mL/100 kg seed), EverGol®Energy (prothioconazole + metalaxyl + penflufen at 260 mL/100 kg seed) and Victrato® (Tymirium™ technology based on cyclobutrifluram at 40 and/or 80 g active ingredient/100 kg seed). All fungicide seed treatments were applied in 1 to 3 kg batches using a small seed treating unit to ensure good even coverage of seed. Note that not all six seed treatments were examined in 2020 and 2021.

All field experiments used an inoculated vs uninoculated randomised complete block design with inoculated plots infected by *Fp* inoculum grown on sterilised wheat grain added at 2.0 g/m of row at sowing. This ensures high (>80%) FCR infection in inoculated plots with uninoculated plots only exposed to background levels of *Fp* inoculum naturally present across a site. This design allows comparison between the yield effects of the various fungicide seed treatments in the presence and absence (background levels) of FCR. Yield loss from this disease is measured as the difference between inoculated and uninoculated treatments.

What did we find?

Averaged across all cereal entries

Lower levels of in-crop rainfall between March and September generally lowered the yield potential at each site in each season, but also increased the extent of FCR yield loss. This was highlighted in the nil seed treatments where yield loss ranged from 11 to 48% in 2018, 14 to 20% in 2019, 11 to 37% in 2020 and 9 to 11% in 2021 (Table 1).

Table 1. Effect of various fungicide seed treatments on yield loss (%) associated with Fusarium crown rot infection in 18 replicated inoculated vs uninoculated field experiments – 2018 to 2021

Year	Location	Crop[A]	Rainfall[B] (mm)	Yield[c] (t/ha)	%Yield loss from Fusarium crown rot[D]					
					Nil	Vibrance	Rancona Dimension	EverGol Energy	Victrato 40 gai[E]	Victrato 80 gai[E]
2018	Merriwagga, NSW	2W	63	1.44	44	nd[F]	nd	32	25	18
	Mallowa, NSW	2W	73	1.73	48	nd	nd	nd	26	24
	Gilgandra, NSW	2W	93	2.14	42	35	27	28	16	9
	Merredin, WA	2W	182	2.66	35	nd	nd	nd	23	13
	Horsham, Vic	2W	185	2.56	21	nd	nd	nd	+2[I]	+5
	Wongan Hills, WA	2W	291	3.27	11	nd	nd	nd	1	0
2019	Gulargambone, NSW	W/B	141	3.12	20	2	5	9	-[G]	+2
	Narrabri, NSW	W/B	200[H]	4.01	14	10	9	7	-[G]	6
2020	Boomi, NSW	3W/D	202	4.91	37	nd	28	nd	24	18
	Gurley, NSW	W/B	234	6.50	13	nd	nd	nd	-[G]	1
	Rowena, NSW	W/B	247	6.21	12	7	nd	4	-[G]	2
	Trangie, NSW	3W/D	412	4.13	26	20	23	19	4	2
	Gilgandra, NSW	3W/D	420	4.07	12	6	7	7	3	0
	Armatree, NSW	3W/D	425	4.37	11	nd	nd	7	3	+1
2021	Boomi, NSW	3W/D	349	5.74	10	-[G]	-[G]	-[G]	2	+1
	Armatree, NSW	3W/D	404	6.67	11	-[G]	-[G]	-[G]	2	1
	Wongarbon, NSW	3W/D	424	5.68	9	-[G]	-[G]	-[G]	6	4
	Rowena, NSW	3W/D	454	6.80	11	-[G]	-[G]	-[G]	1	0

[A] Winter crop type variety numbers where W = wheat variety, B = barley variety and D = durum variety.
[B] Rainfall in-crop from March to September at each site. Critical time for fungicide uptake off seed and expression of FCR.
[C] Yield in uninoculated treatment (average of varieties) with nil seed treatment.
[D] Average percentage yield loss from FCR for each seed treatment (averaged across varieties) compared with the uninoculated/nil seed treatment.
[E] gai = grams of active ingredient.
[F] nd = no difference, %yield loss from FCR with fungicide seed treatment not significantly different from the nil seed treatment. . Values only presented when reduction in %yield loss from FCR significantly lower than the nil seed treatment.
[G] All treatments not included at these sites.
[H] Included two irrigations at GS30 and GS39 of 40 mm and 30 mm respectively due to drought conditions.

[I] Results with a plus in front of them show that the treatment yielded higher than the uninoculated nil treatment (i.e. the treatment reduced impact from both the added FCR inoculum as well as natural background levels of fusarium present at that site.

Vibrance and Rancona Dimension significantly reduced the extent of yield loss from FCR in 6 of 14 experiments whilst EverGol Energy reduced FCR yield loss in 8 of 14 field trials (Table 1). However, the Victrato significantly reduced yield loss from FCR in 14 of 14 trials at the 40 gai rate and 18 of 18 field experiments at the 80 gai rate (Table 1). The reduction in yield loss was also generally stronger with this product compared with the other fungicide seed treatments and better at the 80 gai than 40 gai rate (Table 1).

Significant yield loss (9 to 26%) still occurred with Victrato at drier sites. These dry conditions increased the yield loss from FCR (>35% in nil seed treatment). However, the 80 gai rate at these disease conducive sites, at least halved the yield loss compared with the nil seed treatment (Table 1). Yield loss from FCR was lower at the wetter sites (<26%). Victrato reduced yield loss to <6%, with increased yields at some sites due the effects of background levels of FCR infection being reduced (Table 1). Moisture stress during grain filling exacerbates yield loss from FCR and favours the growth of *Fp* within the base of infected plants. Dry soil conditions throughout the season at the seeding depth, is likely to restrict the movement of fungicide actives off the seed coat and into surrounding soil and uptake by root systems. This would reduce movement of the fungicides into the sub-crown internode, crown and tiller bases where FCR infection is concentrated. It is currently not clear if reduced efficacy under drier conditions may be related to one or both of these factors.

What about durum?

Durum wheat is known to have increased susceptibility to FCR compared with many wheat and barley varieties. The increased prevalence of FCR in farming systems aided by the adoption of conservation cropping practices, including retention of cereal stubble, has seen durum removed from rotations due to this risk. The durum variety DBA Lillaroiⓓ was compared with three bread wheat varieties at four sites in 2020 (Table 1).

Table 2. Effect of Victrato seed treatment at two rates on the extent of yield loss[A] (%) from Fusarium crown rot in three bread wheat (W) and one durum (D) variety at three sites in 2020

Variety	Boomi 2020			Trangie 2020			Gilgandra 2020			Armatree 2020		
	Nil[B]	Victrato 40 gai	Victrato 80 gai	Nil	Victrato 40 gai	Victrato 80 gai	Nil	Victrato 40 gai	Victrato 80 gai	Nil	Victrato 40 gai	Victrato 80 gai
Lancerⓓ (W)	29	23	20	30	10	8	13	2	0	9	4	+7[C]
Mitchⓓ (W)	39	18	11	13	+2	+5	9	2	1	5	0	0
Trojanⓓ (W)	34	22	18	20	4	2	12	1	0	14	2	2
Lillaroiⓓ (D)	48	32	24	45	11	6	16	5	+2	14	6	+2

[A] Average percentage yield loss from FCR for each seed treatment compared with the uninoculated/nil seed treatment for that variety.
[B] Nil = no seed treatment.
[C] Results with a plus in front of them show that the treatment yielded higher than the uninoculated nil treatment (i.e. the treatment reduced impact from both the added FCR inoculum as well as natural background levels of fusarium present at that site.

The extent of yield loss from FCR with nil seed treatment was generally higher in the durum variety (14 to 48%) compared with the three bread wheat varieties (5 to 39%). The bread wheat variety Mitchⓓ tended to have reduced yield loss from FCR compared with the other entries, apart from the

Boomi site (Table 2). Yield loss from FCR was reduced with Victrato in both the bread wheat and durum varieties (Table 2). Even in the higher loss site at Boomi in 2020, the 80 gai rate halved the extent of yield loss in the durum variety Lillaroi⊕ with better efficacy in the other three sites.

Conclusions

Current fungicide seed treatments registered for the suppression of FCR can inconsistently reduce the extent of yield loss from this disease. Victrato appears to have more consistent and stronger activity on limiting FCR yield loss. In the absence of fungicide seed treatments, average yield loss from FCR infection across the 18 sites over three seasons was 21.5%. The 80 gai rate of Victrato significantly reduced the level of yield loss from FCR down to an average of 4.9% across these 18 field experiments. Under high infection levels, as created with artificial inoculation in these experiments, significant yield loss may still occur (up to 24% measured), particularly in drier seasons.

Dry soil conditions around the seeding depth throughout a season may reduce the uptake of fungicides applied to the seed coat. Drier seasons also exacerbate FCR expression, which would place additional pressure on fungicide seed treatments. However, even under these conditions Victrato at the 80 gai rate still at least halved the level of yield loss from FCR.

Fungicide seed treatments, including Victrato, should not be considered standalone control options for FCR. Rather, they should be used as an additional tool within existing integrated disease management strategies for FCR.

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Contact details

Steven Simpfendorfer
NSW DPI, 4 Marsden Park Rd, Tamworth, NSW 2340
Ph: 0439 581 672
Email: steven.simpfendorfer@dpi.nsw.gov.au
Twitter: @s_simpfendorfer or @NSWDPI_AGRONOMY

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Is there a disease downside to stripper fronts?
Harvest height implications for Fusarium crown rot management

Toni Petronaitis[1,2], Clayton Forknall[3], Steven Simpfendorfer[1], Richard Flavel[2] and David Backhouse[2]

[1] NSW Department of Primary Industries, Tamworth, NSW
[2] University of New England, Armidale, NSW
[3] Department of Agriculture and Fisheries, Leslie Research Facility, Toowoomba, QLD

Key words

cereal stubble, stubble management, integrated disease management, Kelly-chain, post-harvest, chickpea, wheat, barley

GRDC codes

DAN00213: Grains Agronomy & Pathology Partnership (GAPP) - A strategic partnership between GRDC and NSW DPI. Projects BLG211 and BLG304 GAPP PhD
DAQ00208 – Statistics for the Australian Grains Industry – North

Take home messages

- Taller standing stubble allowed vertical progression of the Fusarium crown rot fungus within the stubble after harvest, whilst short stubble prevented further growth (i.e. vertical growth was limited to the height of the cut stubble).
- Stripper fronts, which leave higher standing stubble, may increase stubble-borne disease inoculum after harvest of an infected crop, especially if wet fallow conditions are experienced.
- In high-risk situations, such as an infected crop with high biomass, cutting the crop shorter at harvest will limit further inoculum development within the stubble after harvest (beyond the levels already present at harvest).
- Cutting infected cereal stubble shorter prior to rotation with shorter-stature crops such as chickpea or lentils also prevents the dispersal of infected stubble when harvesting these shorter break crops.

Introduction

Despite continuous research and the development of crop protection strategies, the impacts of Fusarium crown rot (FCR), caused by the fungus *Fusarium pseudograminearum* (*Fp*), have increased in Australia over the past four decades. The adoption of conservation-agriculture practices such as cereal stubble retention helps to offset the risk of low in-crop rainfall but promotes the carry-over of *Fp* inoculum to successive cereal crops (Simpfendorfer and McKay, 2019). Despite the yield penalties associated with FCR, the benefits of cereal stubble retention on soil structure, moisture and fertility are considered a necessity in the northern grain's region (NGR, northern New South Wales and Queensland). Finding ways to limit the negative effects of disease whilst retaining cereal stubble is therefore important to crop production in the NGR.

The adoption of higher harvest-heights (stripper-fronts), light tillage (Kelly-chaining) and rotations with shorter stature break crops such as chickpea (*Cicer arietinum*) are becoming common in the NGR. Stripper front harvesting systems improve harvest efficiency through the rapid 'stripping' of heads during harvest, but also increases retained standing stubble biomass by increasing standing stubble height i.e., ~50-60 cm compared to ~30 cm with a combine harvester. It is unknown how such an increase in vertical cereal stubble height will affect the survival and/or growth of *Fp*.

Fusarium pseudograminearum is capable of surviving in post-harvest cereal stubble for ~3 years (Summerell and Burgess 1988) and can also continue to colonise (grow) in post-harvest cereal stubble (Petronaitis *et al.* 2020) by a process known as saprotrophic colonisation. Additional cereal stubble remaining from stripper front-harvests may increase the opportunity for saprotrophic colonisation, as there is more cereal stubble to vertically colonise, compared to the extent of growth possible in stubble remaining from conventional or shorter harvest-heights. This has the potential to increase inoculum levels and inoculum dispersal. As such, lowering of the harvest-height of a cereal crop infected with *Fp* may restrict saprotrophic colonisation of standing cereal stubble after harvest. If true, reducing or modifying harvest-heights of cereals infected with FCR could be beneficial for preventing further increases in *Fp* inoculum levels during fallow or non-host periods.

What did we do?

Field experiments were conducted at Breeza and Narrabri in northern New South Wales, spanning the 2019, 2020 and 2021 winter crop growing seasons. Cereal stubble (from durum wheat of the variety DBA Lillaroi⦹) with extensive *Fp* colonisation was established at both sites in 2019 and a range of target harvest-height (low, medium or high) and harvest-trash (trash returned to plot or trash removed off plot) treatments were imposed at harvest in 2019. Prior to sowing in 2020, an additional stubble management treatment (Kelly-chain) was imposed on a selection of plots. This treatment was applied in combination with the harvest-height treatments, to plots that had previously had trash retained. A chickpea break crop (PBA Seamer⦹) was subsequently sown across both field experiments in 2020.

Chickpea plant populations (plants/m^2) of variety PBA Seamer⦹ were counted in each plot 30 days after planting. Lowest pod heights were measured on two random plants per plot prior to harvest as the distance from ground level to lowest pod. Grain yield was determined from machine harvested grain samples taken from 2 × 10 m plots.

Soil moisture content (SMC) was measured in November 2019, May 2020 and November 2020. One 1.2 metre soil core was sampled per plot and cut into 0-30 cm, 30-60 cm, 60-90 cm and 90-120 cm segments. The wet weight and dry (dried for 48 hours at 105 °C) weight of each soil segment was measured to calculate gravimetric SMC.

Durum stubble from 30 plants were collected at random across each plot in November 2019 (durum harvest), May 2020 (chickpea sowing) and November 2020 (chickpea harvest). Stubble was separated into individual tillers and twenty tillers were then selected randomly for culturing. Starting at the stem base (crown), a 1.5 cm segment was removed from the tiller every 5 cm along the entire tiller length. Stem portions were surface sterilised (5 mL sodium hypochlorite solution, 45 mL deionised water, 50 mL >98% ethanol) for 1 minute then washed with sterile water. Samples were dried overnight and plated on 1/4 strength potato dextrose agar (PDA) + novobiocin (10 g PDA, 15 g technical agar plus 0.1 g novobiocin/L water) and incubated under alternating ultra-violet light (12 h light/12 h dark) for 7 days at 25 °C. Pathogen incidence was recorded as the number of segments producing typical *Fp* colonies based on morphology. Maximum colonisation was defined as the maximum height at which *Fp* was detected in each sample.

The nine stubble management treatments (factorial combination of harvest-height and harvest-trash, plus Kelly-chain treatments), were randomly assigned to plots in each experiment according to a randomised block design, with three replicate blocks. The response variable, length of maximum colonisation, was analysed across sampling times, for each experiment separately using a linear mixed model framework, whereby treatments, sampling time and their interaction were fit as fixed effects while structural terms were fit as random. The analysis of SMC used a similar modelling approach with the treatment structure expanded to include a fixed effect corresponding to the depth of sampling, and the subsequent interaction effects between depth, treatments and sampling time. Response variables related to chickpea crop performance were analysed separately for each experiment. All models were fit using the ASReml-R package in the R statistical computing environment.

What did we find?

Saprotrophic colonisation of cereal stubble by Fp was restricted in shorter stubble

The maximum colonisation height of *Fp* in the post-harvest cereal stubble increased significantly over the 2019-20 fallow in the medium (32 or 25 cm) and tall (48 or 38 cm) stubble at both sites (P < 0.001, Figure 1). *Fp* height did not change in the short (17 or 13 cm) stubble because the fungus had already reached the observed (cut) height at harvest (Nov 2019). At Breeza, maximum colonisation height increased significantly in medium (+11.1 cm) and tall (+22.2 cm) stubble over the fallow period from Nov 2019 to May 2020 (Figure 1). Similarly, at Narrabri, *Fp* progressed significantly in medium (+15.2 cm) and tall (+21.4 cm) stubble over the same period (Figure 1). Maximum colonisation then decreased slightly over the chickpea break crop period (from May 2020 to Nov 2020) but was still elevated significantly in the medium and tall stubble compared with the shorter stubble heights at both sites (Figure 1).

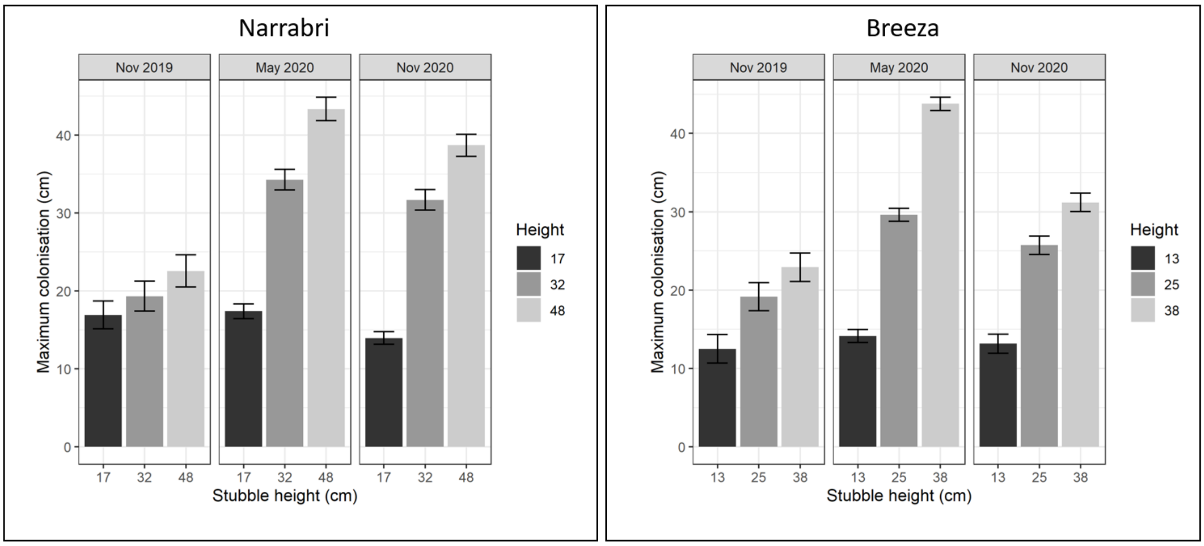

Figure 1. Maximum vertical colonisation by *Fusarium pseudograminearum* in cereal stubble of different heights (mean observed height, in cm) from harvest of the infected crop (Nov 2019), a summer fallow (May 2020) and a chickpea break crop (Nov 2020) at Breeza and Narrabri in NSW. Note harvest-heights were unique to each site due to differences in final crop height in 2019, with slight variability in actual height achieved between and across plots for each target height treatment. Error bars represent the approximate back-transformed standard error of the mean.

Maximum colonisation of short stubble at Breeza in November 2019 was significantly lower than medium and tall stubble, but this was possibly a reflection of the shorter stubble treatment imposed (stubble was sampled after harvest), given that maximum colonisation at the Narrabri site was more uniform (Figure 1). Maximum colonisation measurements above the mean observed height (e.g., Breeza in May 2020), was due to variation in individual tiller lengths within a harvest-height treatment (Figure 1). There was no effect of cereal trash treatment (retained, removed or Kelly-chained) on maximum colonisation at each time of sampling for both sites (P > 0.1).

These results demonstrate that *Fp* can continue to saprotrophically colonise cereal stubble after harvest. Specifically, if stubble is left longer, *Fp* can colonise to the cut height of cereal stubble in the first six months after harvest and persist high within the stem for at least another six months (compared with levels at harvest in November 2019). These findings support the concept that lower cereal harvest-heights are effective at preventing the vertical progression of *Fp* in infected standing stubble post-harvest.

Cereal stubble treatments did not compromise soil moisture

There were no detrimental effects of the cereal stubble treatments on soil moisture levels after the 2019 summer fallow (May 2020) and after harvest of the chickpea crop (November 2020) ($P > 0.2$) (data not shown). There was good fallow rainfall at both sites: 324 mm at Narrabri and 439 mm at Breeza (from 01/12/19 to 31/05/20), significantly increasing soil moisture over the fallow period (for depths 0 to 90 cm, $P < 0.03$). So although the stubble treatments didn't affect fallow efficiency at these sites, the different stubble treatments may have had a more profound impact on soil moisture levels if drier conditions had persisted over summer and autumn.

Chickpea crop performance was not affected by cereal stubble treatments

Overall, the cereal stubble treatments did not have any meaningful impact on chickpea performance in these experiments, with no differences in yield, and only minor differences in chickpea establishment. There was no significant effect on chickpea yield of standing stubble height ($P > 0.96$), trash treatment ($P > 0.19$) or the interaction of harvest-height and trash treatments ($P > 0.14$) at both sites (data not shown). At Breeza, the Kelly-chained treatment resulted in slightly higher chickpea establishment (+4 plants per m^2) compared to the trash retained treatment ($P = 0.05$), possibly due to better seed-soil contact when using a disc seeder in Kelly-chained plots. Lowest pod height was not affected by cereal stubble treatments at either site ($P > 0.32$).

Implications for stripper front harvest adoption

The present study confirms that *Fp* can saprotrophically colonise the full length of cereal stubble in the field, given sufficient fallow rainfall. Harvesting higher with a stripper front may therefore increase risk of higher *Fp* inoculum levels compared harvesting at a lower height with a conventional combine header. Given that *Fp* is detected in 100% of cereal crops in New South Wales (with majority in the 'high' category) (Milgate and Simpfendorfer, 2020), the widespread use of stripper fronts could result in further increases in disease incidence and severity in this region. Planning for stubble management (including stubble/harvest heights) prior to harvest, based on the infection status of the cereal crop to be harvested and future crop sequence, is therefore recommended.

In cereal crops infected with *Fp*, reducing stubble height by harvesting lower would be a useful strategy to limit saprotrophic colonisation after harvest. Ideally, harvest height would be above the height at which the stubble has already been colonised by *Fp*, as this means that less infected stubble is spread into the inter-row spaces, thus optimising inter-row sowing strategies to minimise disease in subsequent cereal crops. This approach could still be used with stripper-fronts by stripping grain, if desired, then following up with a shorter harvest height. The cut fraction (free of pathogen) could be left between rows as mulch or baled and removed. If saprotrophic colonisation has occurred during a wet summer period, cutting low, baling and removing the infected stubble prior to sowing the next crop is preferred to burning stubble. This way there is still a proportion of ground cover to protect the soil surface, but the bulk of inoculum that may infect the next crop has been removed.

Restricting movement of *Fp* vertically within standing cereal stubble may provide two-fold benefits. Firstly, it can prevent inoculum build-up within the standing stubble fraction, beyond the inoculum levels present at harvest. Secondly, it may stop the spread of inoculum across a paddock during harvest of short-stature crops such as chickpea, improving the efficacy of inoculum avoidance strategies like inter-row sowing. Harvesting cereals above the height of *Fp* colonisation could prevent the non-colonised stubble fraction from becoming saprotrophically colonised. Although the cereal harvest-height modification for FCR management appears promising, the implications on FCR risk in a subsequent cereal crop are still to be determined in these field experiments in 2021 (results not available at time of writing).

Stripper fronts offer faster and more efficient crop harvest but could potentially create future issues in cereal crops infected with *Fp*. Even if only low levels of infection are experienced during the growing season, or disease expression is restricted (stem browning/whiteheads) by favourable seasonal conditions or plant tolerance, rapid colonisation of stubble may still occur after plant senescence (Petronaitis *et al*. 2020). So, be vigilant about checking your cereal crops for disease symptoms and consider confirmation of inoculum levels and hence risk through diagnostic services if necessary.

Testing using PREDICTA® B is effective in determining disease risk (following the up-to-date protocol of adding cereal stubble to the sample). If your paddock/s have returned a below detection limit or low risk PREDICTA® B test for cereal disease, then you can continue following best practise agronomy for your next cereal crop.

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 and the authors would like to thank them for their continued support. Ms Petronaitis would like to thank the GRDC and NSW DPI for co-funding her GAPP PhD scholarship (BLG211). Technical support provided by Chrystal Fensbo, Alana Johnson, Luke Neale, Finn Fensbo, Jason McCulloch, Stephen Morphett, Michael Dal Santo and Jim Perfrement is gratefully acknowledged.

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Contact details

Toni Petronaitis
NSW DPI
4 Marsden Park Road, Tamworth NSW 2340
Ph. 02 6763 1219
Email: toni.petronaitis@dpi.nsw.gov.au
Twitter: @ToniPetronaitis

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New insights into nitrogen and water interactions with Fusarium crown rot

Mitch Buster[1,2], Richard Flavel[2], Steven Simpfendorfer[1] Christopher Guppy[2], Mike Sissons[1]

[1] NSW Department of Primary Industries, Tamworth

[2] University of New England, Armidale

Key words

nitrogen management, high protein, durum, bread wheat

GRDC code

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Take home messages

- Deep banded nitrogen can have a significant effect on grain protein under low in-crop rainfall conditions
- Fusarium crown rot had no significant effect on grain protein levels
- Soil nitrogen availability appears to be a driver of Fusarium crown rot (FCR) severity in-crop
- Durum variety DBA Lillaroi⦸ suffered a significant yield penalty (25%) in the presence of additional FCR inoculum in a wet finish and 36% in a dry finish
- Test to ensure your paddock is clean of FCR inoculum before considering durum as an option
- LRPB Lancer⦸ had improved tolerance to FCR with 8% yield loss in a wet finish and 9% in a dry finish and could be considered in moderate risk paddocks to limit disease impacts.

Introduction

Fusarium crown rot (FCR), caused by the stubble-borne fungus *Fusarium pseudograminearum* (*Fp*), produces significant yield penalties over much of northern NSW and southern Qld. This is primarily due to the fungus' ability to restrict the plants vascular system. When coupled with typical low in-crop rainfall during grain filling, the resulting moisture stress exacerbates the impact of FCR on grain yield.

Historically, nitrogen (N) interactions with the FCR fungus have not been well studied or understood. With current record high N fertiliser costs, it is imperative to ensure that financial returns are maximised through well-informed N fertiliser decisions. This controlled study explored interactions between spatially available soil N, FCR and available soil moisture during flowering and grain filling in a high protein bread and durum wheat variety.

Methods

Soil, tube design and FCR treatments

Polyvinyl chloride (PVC) soil tubes 150 mm diameter x 1200 mm length were used to simulate a field soil profile. The soil used was a grey Dermosol with a PAWC of 202 mm/m and starting N of 36.4 mg nitrate N/kg and 3.8 mg ammonium N/kg soil. The upper topsoil (top 350 mm) was compacted to a bulk density of 1.2 g cm^{-3} and the lower subsoil (bottom 780 mm) was packed to a bulk density of 1.3 g cm^{-3}. Two FCR treatments were used, background and background plus *Fp* inoculation. The background plus inoculation treatment contained a band of 20 mm of inoculated soil. This was prepared by adding ground *Fp* infected seed (0.5 - 2 mm fraction) evenly mixed throughout soil at rates of 1 g inoculum / 100 g of soil (Forknall *et al.,* 2019). The background treatment had 20 mm of soil mixed with sterilised grain in a similar manner. A further 10 mm of soil was then added to both treatments to minimise colonisation of the fungus across the soil surface during the experiment.

Plant materials and growing conditions

One bread wheat, LPRB Lancer⟮D⟯ and one durum, DBA Lillaroi⟮D⟯ were grown over a six-month period. Seed was treated with Vibrance® and Emerge® at rates of 360 mL/100 kg and 240 mL/100 kg, respectively for standard bunt and smut control and early protection against aphids. Six seeds of each cultivar were sown below the inoculum layer approximately 3 cm below soil surface and thinned to four plants per pot upon establishment. There were five replicates of each cultivar and treatment. The experiment was conducted in an air-conditioned polyhouse complex at Tamworth Agricultural Institute (TAI) with a 25°C day and external ambient night temperature regime.

Fertiliser

At planting, soil tubes were treated with KNO_3 equivalent to 50 kg K/ha, which was evenly mixed in the top 350 mm of soil to rectify K deficiency. The banded treatment received urea in solution equivalent to 80 kg N/ha at 350 mm below the surface. The surface treatment received the same solution at 50 mm below the surface.

Watering

Soil tubes were individually weighed and watered to field capacity each week until flowering. Post flowering, the dry finish treatments were managed to 40% of field capacity (-100 kPa matric potential), whilst the wet finish treatment maintained the original field capacity watering regime. Water was administered through a 25mm PVC pipe located in the soil column which had three watering points vertically throughout the profile at 35 cm, 55 cm and 75 cm below the soil surface. This method sought to mimic dryland growing conditions in northern NSW with minimal in-crop rainfall during grain filling with crops growing predominantly on stored soil moisture.

In crop measurements

Plants were visually scored for the severity of FCR infection based on a 0-3 scale at GS31 and at harvest. This determined whether all the FCR inoculated treatments physically displayed signs of infection and the severity of disease at these growth stages. Scores were averaged across plants within each growth tube prior to conversion to a 0-100 FCR index (Forknall *et al.* 2019). Immediately prior to harvest, counts were taken of plants, tillers and heads. Heads on main stems from each plant were removed, followed by the stems that were first measured for height and then cut 5 mm above the soil surface. The remainder of the heads and stems were then collected. Both heads and stems were dried at 40°C for 72 hrs prior to threshing and weighing. Grain was threshed from the collected heads from the four main stems of plants in each soil tube. Grain weights and counts for mainstems and other heads were recorded separately. NIR spectroscopy was then conducted on all samples to determine grain protein levels. The main stem was cut at 5 cm intervals starting at the base. The lower 1 cm of these pieces was kept for laboratory FCR testing of vertical *Fp* recovery and the upper 4 cm for nutritional analysis. The 4 cm nutritional analysis sections were grouped by tube, then trimmed to 5 mm lengths and scanned using NIR for N tissue estimations. A calibration curve was constructed using LECO on a sub-set of tissue samples to correlate estimated tissue N for the remaining samples.

Results

Deep banding of N decreased FCR severity scores early in season at GS31 compared to surface applied N in both the background plus inoculation treatments of LRPB Lancer and in the background treatment of DBA Lillaroi (Figure 1). However, deep banding of N increased FCR severity scores at harvest in the background treatment in both cultivars (Figure 1). These results demonstrate that FCR severity potentially has a relationship with the relative availability of N to the crop.

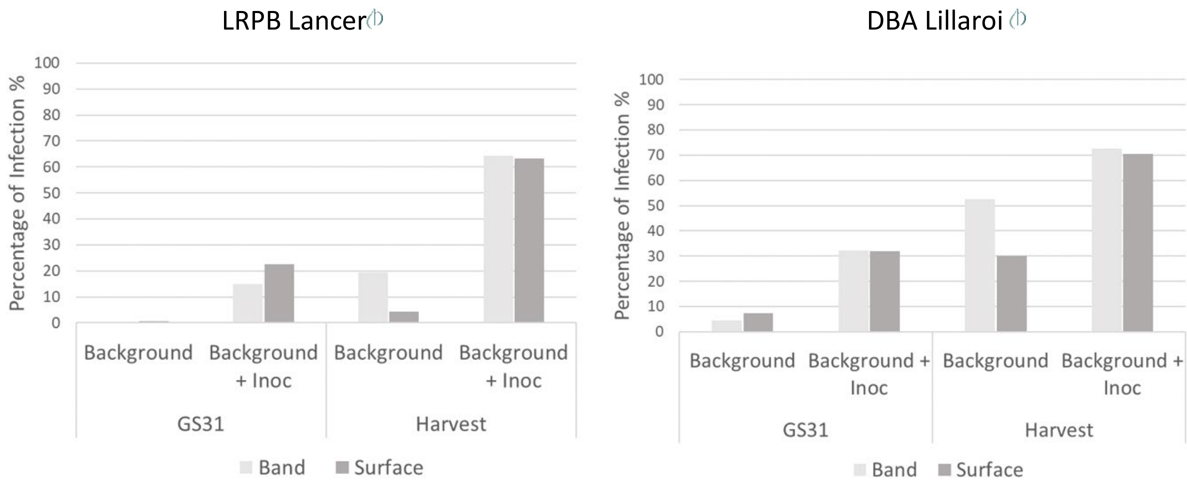

Figure 1. Effect of banded (35 cm) and surface (5 cm) nitrogen application on FCR severity (FCR index 0-100) conducted at GS31 and harvest of LRPB Lancer (left) and DBA Lillaroi (right) in the presence of background or background plus inoculation infection by *Fp*. Data averaged across water treatments.

Nitrogen placement had no significant effect on yield (Figure 2, left). Banding of N resulted in a significant increase in grain protein compared to surface application of N in both durum and bread wheat (Figure 2, right). Increased levels of FCR infection had no significant effect on grain protein (Figure 2) and tiller count (data not shown).

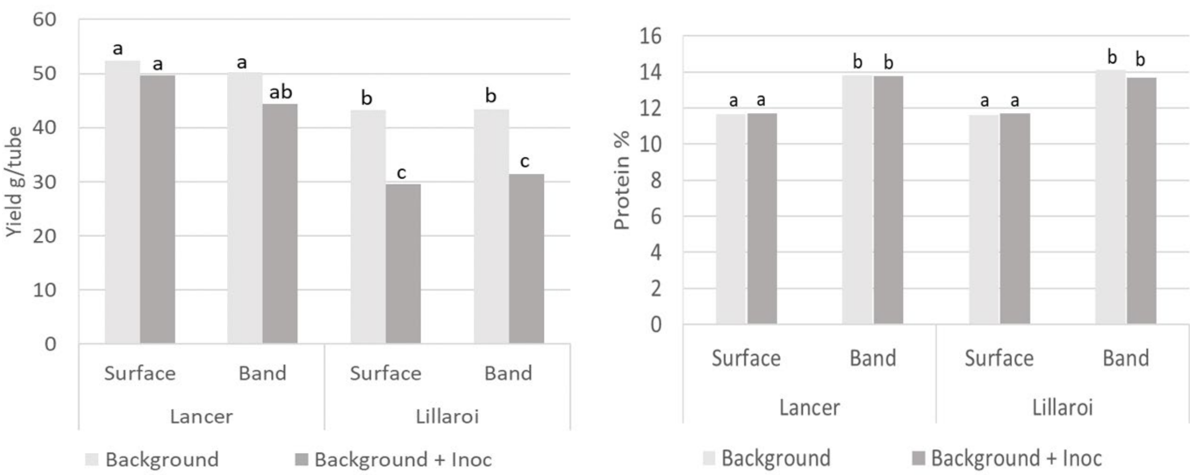

Figure 2. Average yield (left) and protein responses (right) of LPRB Lancer and DBA Lillaroi under banded and surface applications of urea with background and background plus inoculation FCR treatments. Significance letters indicate 95% confidence (p>0.05).

Infection levels of *Fp* recovered from laboratory plating demonstrated a significant increase in vertical colonisation of main stems in both cultivars with the background plus inoculum treatment compared to background only (Figures 3 & 4). The vertical height intercept where 50% of tillers were colonised for LRPB Lancer⦶ was a height of 27.5 cm in the background plus inoculation treatment, but only 10 cm in the background only treatment (Figure 3). Whilst for DBA Lillaroi⦶ the 50% vertical colonisation was 33 cm in background plus inoculation and 27 cm in background (Figure 4). Recovered tissue N post-harvest was significantly higher in the background plus inoculation FCR treatment compared to background alone with LPRB Lancer⦶ (Figure 3) but was not significantly different with DBA Lillaroi⦶ (Figure 4). This is likely due to the increased susceptibility of DBA Lillaroi⦶ to FCR resulting in a smaller separation between FCR treatments which limited ability to detect differences in N tissue recovery. The increase in tissue N relative to FCR severity indicates that fungus is increasing the plants demand for N (Figure 3, 4) but not transferring into protein (Figure 2), suggesting a decrease in nitrogen use efficiency (NUE).

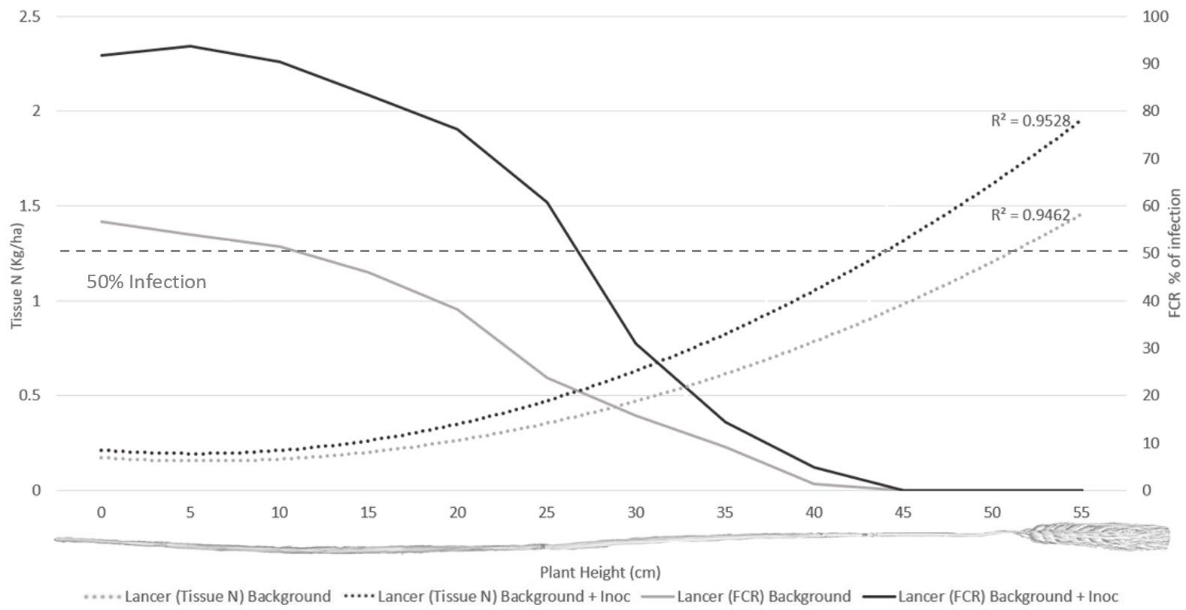

Figure 3. Tissue N (Kg/ha) and percentage of FCR infection as sampled vertically up the main stem of LRPB Lancer⦶. Data averaged across nitrogen and water treatments.

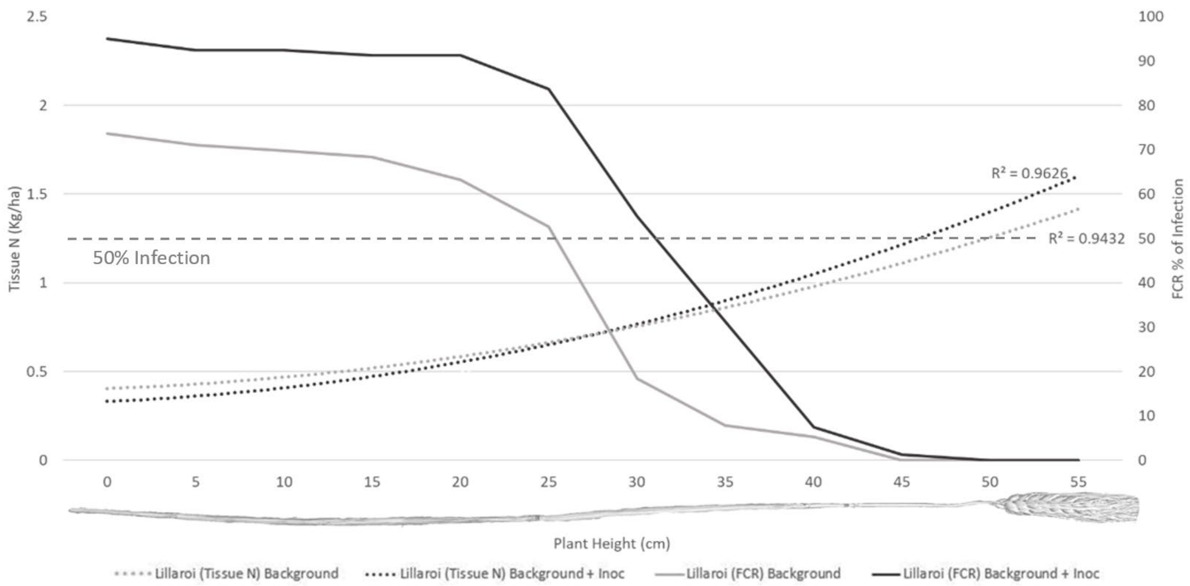

Figure 4. Tissue N (Kg/ha) and percentage of FCR infection as sampled vertically up the main stem of DBA Lillaroi⦸. Data averaged across nitrogen and water treatments.

Increased levels of FCR infection (inoculated treatment) decreased yield in DBA Lillaroi⦸ by 25% under wet finish conditions and 36% under dry finish conditions relative to the background levels of inoculum (Figure 5). There was a trend towards LPRB Lancer⦸ being 8% lower yielding under wet finish conditions and 9% lower under dry finish conditions due to increased FCR infection but these differences were only significant at the 90% level as opposed to the 95% level shown in Figure 5 below.

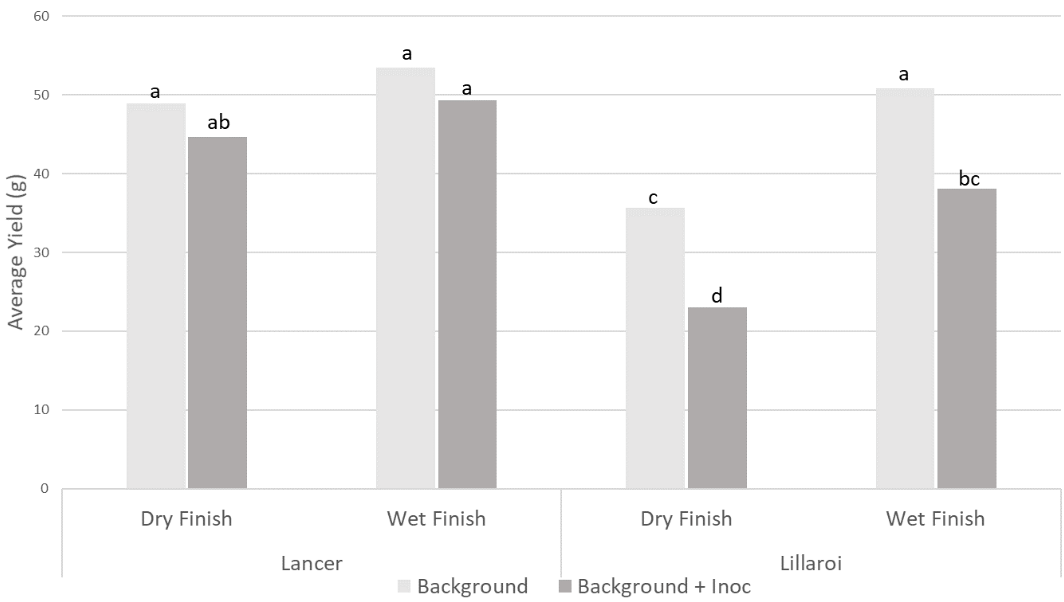

Figure 5. Average yield response of LPRB Lancer⦸ and DBA Lillaroi⦸ under dry and wet finishes to the growing period post flowering with varying levels of FCR infection. Significance letters indicate 95% confidence (p>0.05)

Summary

Nitrogen availability was demonstrated as a likely driver for FCR severity in-crop with surface N applications resulting in an increase in FCR severity (compared to banded N) under certain treatments at the early GS31 assessment. However, as the season progressed under low simulated in-crop rainfall, the topsoil dried and hence crop access to surface applied N decreased. At harvest, banded N treatments resulted in the highest severity of FCR but produced higher grain protein levels compared to surface N applications. Logistically banding fertiliser at 35 cm is not easily achieved, however practices such as applying N early in the fallow and allowing it to move down the profile with rainfall events may achieve a similar N location outcome.

Residual tissue N concentrations within stems at harvest increased with greater severity of FCR infection. This N was not translocated to the grain, and it is suspected that an increased demand for N is placed on the plant by the fungus, potentially mining more N out of the soil profile and decreasing NUE. At the time of writing of this paper soil N analysis was not complete but these results will confirm the fate of N in the presence of varying levels of FCR infection. Even so, N availability in wheat stems did not appear to be a driver of FCR colonisation.

Fusarium crown rot did not influence grain protein, however yield penalties were significant especially in the durum variety. This was not a result of decreased tiller number but a combination of reduced grain size and whitehead expression (data not presented). Yield penalties in the durum variety were exacerbated under a dry finish, which frequently occurs in northern NSW and southern QLD cropping systems. The prevalence of FCR in these regions combined with historically dry/hot seasonal finishes has made durum production inherently higher risk than growing bread wheat varieties, such as LRPB Lancer, which has improved tolerance to this disease. To manage this risk, growers should consider PREDICTA®B or NSW DPI stubble testing of paddocks planned for durum production in 2022 prior to sowing.

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 and the NSW DPI. This work was undertaken as part of project DAN00213: Grains Agronomy & Pathology Partnership-A strategic partnership between GRDC and NSW DPI. The PhD study is enrolled through the University of New England with the support of supervisors Dr. Richard Flavel (UNE), Dr. Steven Simpfendorfer (NSW DPI) Dr. Christopher Guppy (UNE) and Dr. Mike Sissons (NSW DPI). The author would like to thank them for their continued support.

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Contact details

Mitch Buster
NSW Department of Primary Industries
4 Marsden Park Rd, Tamworth 2340
Ph: 0428 306 914 Email: mitch.buster@dpi.nsw.gov.au

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Optimising sorghum agronomy & winter sown sorghum: water use and water use efficiency

Daniel Rodriguez[1], Loretta Serafin[2], Joseph Eyre[1], Darren Aisthorpe[3] and Dongxue Zhao[1]

[1] Centre for Crop Sciences, QAAFI The University of Queensland
[2] New South Wales Department of Primary Industries
[3] Queensland Department of Primary Industries and Fisheries

Key words

early sorghum, water use, water use efficiency

GRDC code

UOQ 1808-001RTX

Take home message

- Sowing early in late winter or early spring reduced the likelihood of heat stresses around flowering across most sites, at a very low risk of frost damage (after 7 leaves or floral initiation). Sowing sorghum in late summer also reduces the risk of heat stress, though at the expense of no double cropping, and an increased risk of frost damage in the southern sites
- Across all sites the yield of winter (very early) sown sorghum was similar or higher than sowing in spring and summer
- A winter sown sorghum will have a lower likelihood of a dry finish (terminal water stresses), which will reduce the potential for high screenings and minimise or eliminate lodging
- At the cropping system level there is an increased likelihood of double cropping after a winter sown sorghum
- Results from the analysis of two seasons of trials (2018-2020) across 15 sites from the Liverpool Plains in NSW to Emerald in Qld, showed that at each site the combination of hybrid, planting time and plant population created up to a 66% difference in grain yield and 8-fold differences in water use efficiency. This indicates that matching hybrid and agronomic management to site conditions should be important to farmers and consultants
- There are large gains to be made from informing optimum combinations of hybrid and agronomic management to site and expected seasonal conditions. DigitalAg applications that integrate information from multiple sources (e.g., networks of soil moisture sensors and seasonal climate forecasts that inform crop simulation models) need to be developed to better characterise site and expected seasonal conditions to inform the optimum combinations of hybrid and management within and across fields.

Summary

Early sowing of grain sorghum offers farmers the opportunity to increase; crop water use efficiency, the number of sowing opportunities cropping intensity and profits. Early sowing also reduces the risk of heat stress at flowering and terminal drought stress, reducing screenings and lodging.

Background

The main challenges of growing a profitable sorghum crop include avoiding periods of extreme heat around flowering and reducing the likelihood of water stress between flowering and grain filling. Australia's climate has warmed by about 1.4 °C since 1910, and an increase in the frequency and intensity of extreme heat and water stress can be expected. Extreme heat at flowering causes pollen sterility that reduces grain numbers, the main determinant of final yield. In addition, water stresses during grain filling will increase screenings affecting grain quality. It may induce lodging. Options to 'de-risk' sorghum cropping involve avoiding the overlap of crop sensitive growth stages with the hottest and driest times of the year. We propose that sowing sorghum in late winter or early spring, can contribute to de-risking the impact of heat stresses around flowering and reduce the likelihood of terminal water stresses during grain fill. Benefits are likely to include an increased number of sowing opportunities, higher and more stable grain yields in some sites and seasons, improved grain quality and an increased cropping intensity by increasing the opportunity for double cropping of a winter crop after a short summer fallow.

However, for the practice to be promoted and adopted we needed to answer the question: 'How cold is too cold to sow sorghum?' Here we present the results from a winter sown sorghum program funded by GRDC and led by UQ-QAAFI, in collaboration with NSW DPI, QDAF and farmers from the Liverpool Plains in NSW to Central Queensland.

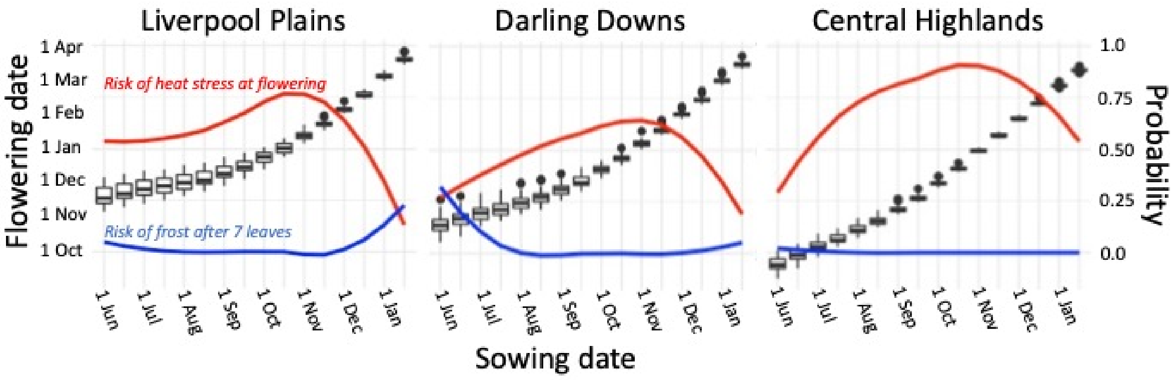

Figure 1. Flowering date for a range of sowing dates (black boxplots) at Breeza, Liverpool Plains NSW (a); Dalby, Darling Downs Qld (b); and Emerald, Central Queensland (c). The red lines show the probability of a heat stress event at flowering, defined as a maximum temperature higher than 36°C around a 7-day window centred at flowering. The blue line shows the probability of a damaging frost, defined as air temperature lower than 0°C after the sorghum crop has 7 leaves (floral initiation) and becomes sensitive to frosts. Climate records are 1980-2021.

What have we learnt so far?

Early (winter) sown sorghum is unlikely to be damaged by late frosts in the Liverpool Plains or the Central Highlands. Sowing early in late winter or early spring reduces the likelihood of heat stresses around flowering across most sites, at a very low risk of frost damage i.e., frosts after 7 leaves or floral initiation. Sowing sorghum in late summer also reduces the risk of heat stress, though at the expense of no double cropping, and an increased risk of frost damage in the southern sites.

The yield of early (winter) sown sorghum was similar or higher than that of later sowing dates (Figure 2). This was associated to higher values of seed set due to a reduced incidence of heat stresses around flowering; and improved grain size (reduced screenings) due to increased availability of soil water later in the season.

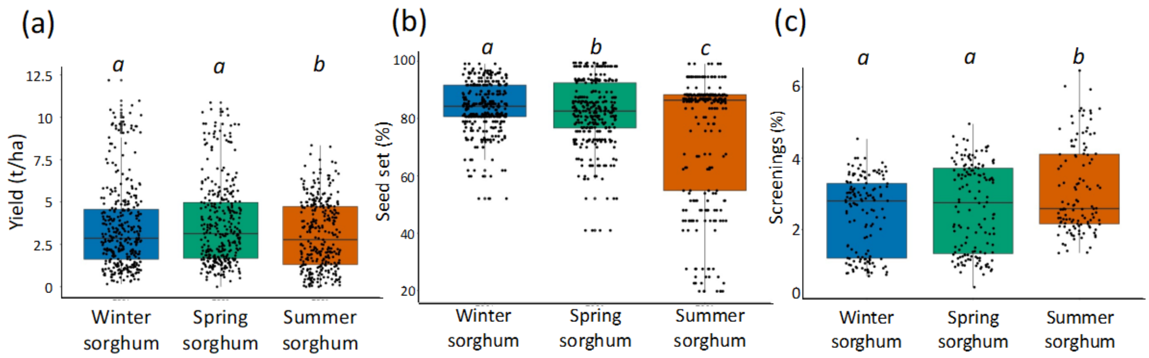

Figure 2. Outcomes from 15 trials sown across the Liverpool Plains, Northern NSW, Darling Downs, Western Downs and Central Queensland for the 2018/19 and 2019/20 seasons. (a) Mean yields for the three tested times of sowing (winter, spring, and summer); (b) the estimated seed set from the incidence of extreme air temperature events around flowering; and (c) percent screenings. Different italic letters on top of the boxplots indicate statistically significant differences (p<0.05).

The median total water use (emergence to maturity) of winter sown sorghum crops (324mm) tended to be like that of spring sown crops (326mm), though higher than that of summer sown crops (300 mm) (Figure 3). However, winter and spring sown crops tended to use more water later in the season between flowering and maturity, i.e., 120, 93 and 80mm, respectively (Figure 3).

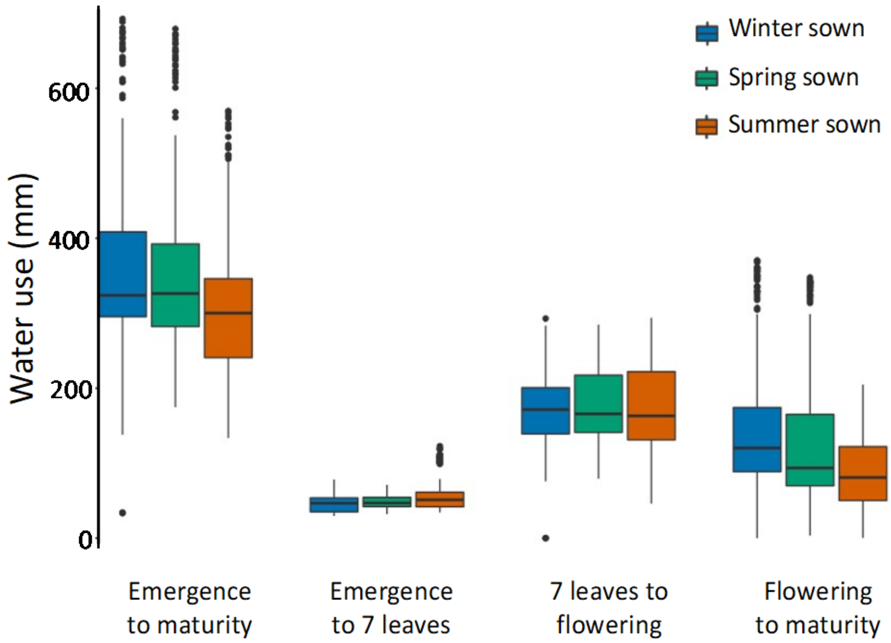

Figure 3. Modelled crop water use (mm) for three tested times of sowing (winter, spring, and summer) from crop emergence to maturity, emergence to 7 leaves (or floral initiation), 7 leaves to flowering, and flowering to maturity. Results are APSIM simulations for the 15 sites and combined three times of sowing, six commercial hybrids and four plant populations, sown across the Liverpool Plains, Northern NSW, Darling Downs, Western Downs and Central Queensland for the 2018/19 and 2019/20 seasons.

The values of crop water use efficiency of winter sown sorghum tended also to be higher than those crops sown in spring and summer (Figure 4).

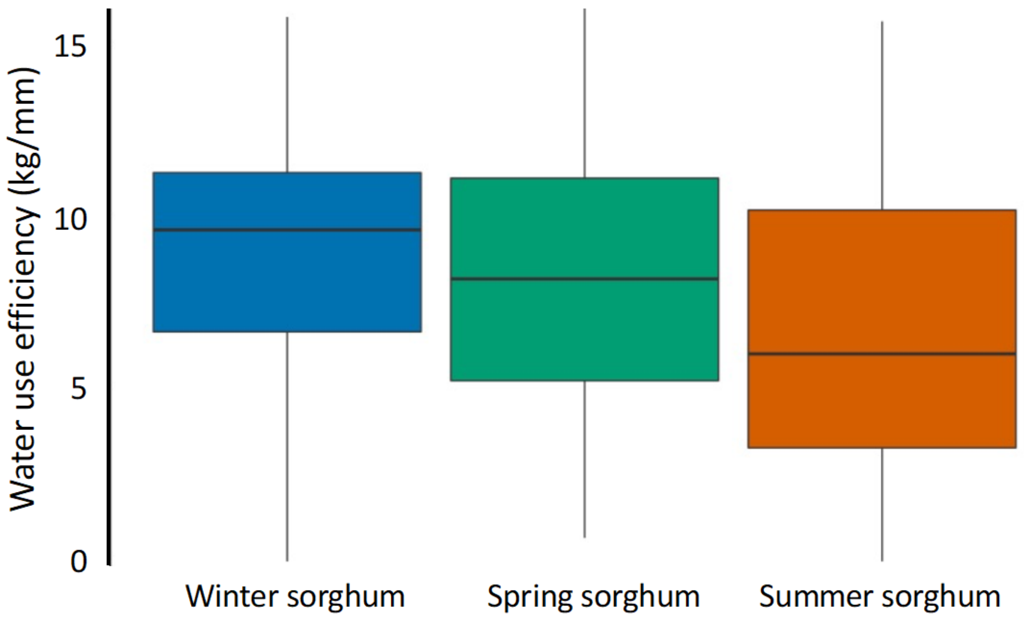

Figure 4. Modelled water use efficiency (kg/mm) for the three tested times of sowing (winter, spring, and summer). Results are APSIM simulations for the 15 sites and combined three times of sowing, six commercial hybrids and four plant populations, sown across the Liverpool Plains, Northern NSW, Darling Downs, Western Downs and Central Queensland for the 2018/19 and 2019/20 seasons.

The higher water use efficiency of the winter sown sorghum crop was explained by the crop growing during a cooler time of the year (i.e., lower atmospheric demand), and a relatively smaller canopy size at flowering. Compared to the spring sown crop, this resulted in an additional 30mm of water used between flowering and maturity. This additional ~30mm of crop water use was responsible for the reduction in screenings observed in the winter sown crop (Figure 2).

Conclusions

In conclusion, the yield of winter (very early) sown sorghum can be similar or higher than sowing in spring and summer. A winter sown sorghum will have a lower likelihood of a dry finish (terminal water stresses), which will reduce screenings and minimise or eliminate lodging.

The increased water use efficiency of the winter sown sorghum means that additional water will be available during the grain fill stages, compared to spring or summer sown crops. However overall modelled water use was also slightly higher for winter sown crops, probably due to the extended growing season.

Acknowledgements

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Contact details

Daniel Rodriguez
QAAFI The University of Queensland
Ph: 0434 075 094
Email: d.rodriguez@uq.edu.au

Loretta Serafin
NSW DPI
Ph: 0427 3118 19
Email: loretta.serafin@dpi.nsw.gov.au

Space agriculture: sensing crops in space

Jacob Humpal[1], Cheryl McCarthy[1], Craig Baillie[1], Cassy Percy[2], Peter Brett[1]

[1] USQ Centre for Agricultural Engineering
[2] USQ Centre for Crop Health

Key words

proximal sensing, food production, machine vision, leafy greens

Take home messages

- Basic metabolic and nutrient requirements of space crew members are required to be met to successfully support deep space missions
- Research is needed into the identification and development of solutions for 'smarter' monitoring of plants to create a sustainable food supply on space missions
- Automated detection of plant stress will enable rapid remediation efforts and provide increased food safety and security.

Background

To successfully support long flight or deep space missions such as those planned through the Artemis series of missions (NASA 2020) the basic metabolic and nutrient requirements of space crew members are required to be met. Currently, astronauts are supported through resupply missions, which have been used on all manned missions to date (Niederwieser 2018). Resupply missions are difficult to support in deep space so manufactured solutions such as mass-produced food bars have been proposed. However, there are no long-term studies on what impacts such a diet would have on astronauts' health. Fresh plant crops, particularly leafy green vegetables provide for both the basic metabolic needs as well as a contributing to a diverse micronutrient balance. Plants rich in antioxidants may also provide some protection from the detrimental but not fully understood effects of deep space radiation. In recent years growing plant crops as a staple component of astronauts' diets has been dismissed for proximal missions. For proximal missions the break-even point favours resupply launches. While adding life support systems for food production increases initial launch mass, it decreases resupply requirements. A break-even calculation for these hybrid systems suggests they would be feasible after a 3-year, 6-crew member mission. This is approximately the duration of the planned Mars missions.

Research is needed into the identification and development of sensing and algorithm solutions for 'smarter' monitoring of plants to create a sustainable food supply on space missions. Currently, NASA has three controlled plant habitats, two vegetable production system (Veggie) units and the larger Advanced Plant Habitat which are currently onboard the International Space Station (ISS). The Veggie units were developed to be simple, low resource systems designed to produce fresh vegetables on board the International Space Station (ISS). The Advanced Plant Habitat provides hundreds of calibrated sensors for monitoring and automating plant growth experiments in microgravity to inform decisions around the development of future space agriculture systems. There is a wall mounted plant growth chamber 'Lada' which has been in use since 2002 in Zvezda, the Russian module of the ISS. The plant habitats are intended to facilitate plant experiments in space however the plant habitats currently do not contain autonomous decision support to assess performance of plants in experiments. Currently, experiments are monitored by experts on the ground for the purpose of reducing additional workload of the astronauts. However, as communication lag increases with increased distance from the Earth, software needs to be developed to accompany existing and new plant sensors to interpret plant stress signals automatically. Automated detection of plant stress will enable rapid remediation efforts and reduce the need for the post-harvest sanitation that is currently used, which will provide increased food safety and security.

A project team at the University of Southern Queensland's Centre for Agricultural Engineering (CAE) is developing new machine vision-based plant sensing solutions, through a Moon to Mars Feasibility Grant provided by the Australian Space Agency (ASA). The team is developing launch-ready software, associated algorithms and the specification of accompanying machine vision cameras and/or sensors for the early quantification of plant induced stress by examining water, nutrient and plant disease interactions. This paper outlines a brief history of growing plants in space, current plant monitoring approaches for space and Earth, and new approaches for plant monitoring with machine vision.

A brief history of plants in space

The successful growth of plants in space promote not only food production and sustainability, but also oxygen regeneration and water recycling (Stankovic 2018). However, plants in space are exposed to increased levels of electromagnetic and particle radiation and reduced gravity. These extremes affect plant biological responses including the mechanisms necessary for plant growth and development (Morrow 2014; Stankovic 2018). As such, research is needed to understand the impacts of space on plant systems to aid in the development of sustainable plant production onboard spacecraft.

The first plant experiments to be successfully deployed into orbit were onboard the Biosatellite II which flew in orbit for three days before returning to Earth in 1967 (Morrow 2014). The first plant grown through a full life cycle in space was *Arabidopsis thaliana*, flown on the Soviet Salyut-7 low orbit space station. Some viable seed resulted, but most was unviable. Differences were observed between space and Earth grown plants (Stankovic 2018). The first successful seed-to-seed plant growth experiment (*Arabidopsis thaliana*) in space was completed in 2001 (Stankovic 2018). Recent plant experiments have focused on better understanding the biological mechanisms which may allow plant adaptation to space (Morrow 2014; Stankovic 2018).

Plant growth habitats that have been developed for use in space include the Astroculture system, the Advanced Astroculture system, the Biomass Production System, the Plant Generic Bioprocessing Apparatus, the Advanced Biological Research System, the Lada Greenhouse and the European Modular Cultivation System. However, these systems are limited in their growing area, limiting their potential to supplement space crew diets, as they were developed primarily for small-scale experiments (Morrow 2014). The habitats currently in use for food production and experiments on-board the ISS are the Veggie units and the Advanced Plant Habitat, developed by Orbitec, now Sierra Nevada Corporation.

Space agriculture research and its subsequent developments has both contributed to and benefitted from terrestrial agriculture, particularly through controlled agriculture systems (Wolff et al., 2014; Stankovic 2018). The resulting novel technologies developed initially for space agriculture include the use of LED lighting systems for crop production, hydroponic system development, significant increases in crop yields and innovating waste recycling approaches (Stankovic 2018).

Automated plant monitoring in space and on earth

Currently, real-time crop monitoring in space uses automated camera image capture with relatively low pixel and temporal resolution intended for remote communications, as captured images are used for visual review by experts on the ground who can communicate recommended next steps to the space crew. The newest advancements in machine vision systems for space agriculture come from the EDEN II research facility in Antarctica. This facility is a container-sized greenhouse test facility which was built to demonstrate and validate technologies for safe food production in space (Zabel *et al.,* 2016). Single image NDVI capable cameras were incorporated for monitoring of tomatoes in the EDEN ISS Future Exploration Greenhouse for a year. The NDVI cameras consisted of GoPro Hero4 cameras modified with dual-bandpass filters. NDVI calculated from these cameras were used to develop an aggregate NDVI for monitoring tomato health (Tucker *et al.,* 2020).

Current research on machine vision systems for terrestrial agriculture on Earth offer potential advancements in addition to NDVI for monitoring of plants in space. Machine vision incorporates colour, texture, shape and spatial image information using machine learning and traditional hand-crafted algorithms, and on Earth is commonly applied to precision agriculture tasks including plant detection, grading, counting and yield estimation (Mavridou *et al.,* 2019).

New approaches for plant monitoring with machine vision

NDVI-based approaches are currently reported as being developed and tested for use on the ISS (Zeidler *et al.,* 2019). The new USQ/ASA project is enabling development of novel automated plant stress algorithms for space, based on knowledge from precision agriculture and machine vision systems. Currently, early discrimination between water and nutrient stress of lettuce and cabbage with machine vision are being developed, with further experiments focusing on pathogens. Plant stress algorithms are being designed in parallel with the refinement of a ground-based laboratory and sensor test rig(s) (Figure 1) which are translatable to both microgravity and planetary surface facilities for potential further research and development of automation and commercial deep space technology.

Figure 1. Experimental setup in ground-based laboratory – a) experimental rig, b) top view image from visible colour camera, c) basic image processing to segment plant leaves from the background

Discussion and conclusions

The development of sustainable food production systems in space is critical to the success of future deep space missions. A project led by USQ is supporting food production for space missions by developing automated machine vision techniques for detecting plant stress for use in space, allowing real-time and precise monitoring of plant health. The development of launch-ready software for the identification of plant stressors in space will allow plant habitats to respond to detected stresses automatically, decreasing the reliance on experts on the ground and freeing space crew time for other tasks. Potential future priorities for the continued development of space agriculture systems are automated remediation for identified plant stressors, increased volume of current plant habitats, and increased water and nutrient resource recycling and recovery.

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Contact details

Jacob Humpal
University of Southern Queensland, Centre for Agricultural Engineering
P9 Handley St, Darling Heights QLD 4350, Australia
Ph: 0455 220 027
Email: jacob.humpal@usq.edu.au

Farming system nutrient legacies – impacts of N strategies on N inputs, cycling and recovery over multiple years

Lindsay Bell[1], Jon Baird[2], David Lawrence[3], David Lester[3], Jayne Gentry[3], Darren Aisthorpe[3], Andrew Erbacher[3], Kathi Hertel[2] and Brook Anderson[1]

[1] CSIRO
[2] NSW DPI
[3] DAF Qld

Key words

fertiliser, nutrition, efficiency, recovery, economics

GRDC codes

CSA00050, DAQ00192

Take home messages

- Soil mineral N and fertility status has a long-term influence on productivity of a farming system
- Robust N application strategies have legacies of building/maintaining higher soil N status beyond the immediate crop
- Fertilising crops to maximum compared to average yield potential (approx. double N budget) has only required an average of 100 kg of N/ha extra applied over 6 years
- A high proportion of surplus N is recycled or recovered in the soil mineral N pool and is available in subsequent crops
- Robust nutrient strategies have incurred additional costs ($134/ha over 6 years on average), but much of this is 'invested' in soil mineral N stores ($75/ha)
- Only in above median seasons, when crops are responsive to high N rates will economic benefits accrue, but these can be significant.

Introduction

Nitrogen (N) inputs is a major variable cost in most cropping systems and matching the supply to crop demand is critical to maximising water use efficiency and system profitability. Hence, developing a nutrient management strategy that provides sufficient N when crops need it whilst also mitigating the risk of losses to the environment is critical. This problem has been the focus of a plethora of research, with well tested and refined recommendations available to optimise fertiliser applications to individual crops (Angus and Grace 2017). However, nutrient budgeting and evaluation of nutrient use efficiencies has typically taken a crop-by-crop approach, which often overlooks some of the legacy impacts that can occur. For example, a crop provided with N surplus to its requirements often have low NUE and return on investment in that year because the extra N provided was not converted into grain yield; this often occurs in dry seasons. However, the unused N from that crop can contribute significantly to the N supply in subsequent years and may even be used more effectively by the next crop than fertiliser applied in that season (Dowling 2018). Hence, there is a need to take a longer-term more systematic view of N application approaches or strategies.

In the northern farming systems research project, we have been comparing 2 main fertiliser N management approaches over several years. We have tracked the dynamics of N over multiple seasons and how these fertiliser strategies have impacted nutrient input requirements, N utilisation and cycling, and overall system nutrient use efficiency.

System N management strategies deployed

Across the various farming systems experiments we have been deploying two different strategies to apply N fertiliser to crops – a *Baseline* (or standard approach) and a *High Nutrient* system. Both systems have employed the same sequence of crops and have varied only in their fertiliser inputs. A range of yield predictions were generated using APSIM for the specific location, crop sowing date and soil water content at sowing (see Figure 1).

In the *Baseline* system, crops were fertilised to a nutrient budget targeting a predicted yield in the 50th percentile of seasons. That is, adequate N is applied for the crop to reach its yield potential in half of seasons (or an average yield outcome), while in seasons with higher yield potentials it is possible that the crop may not have sufficient N supply to meet its water-limited yield potential.

In the *High Nutrient* systems, crops were fertilised to a nutrient budget targeting a predicted yield in the 90th percentile of seasons. That is, the crops are fertilised so that they should never be limited by nutrient availability in any season, but this means that the crops are 'over-fertilised' in all but the best seasons.

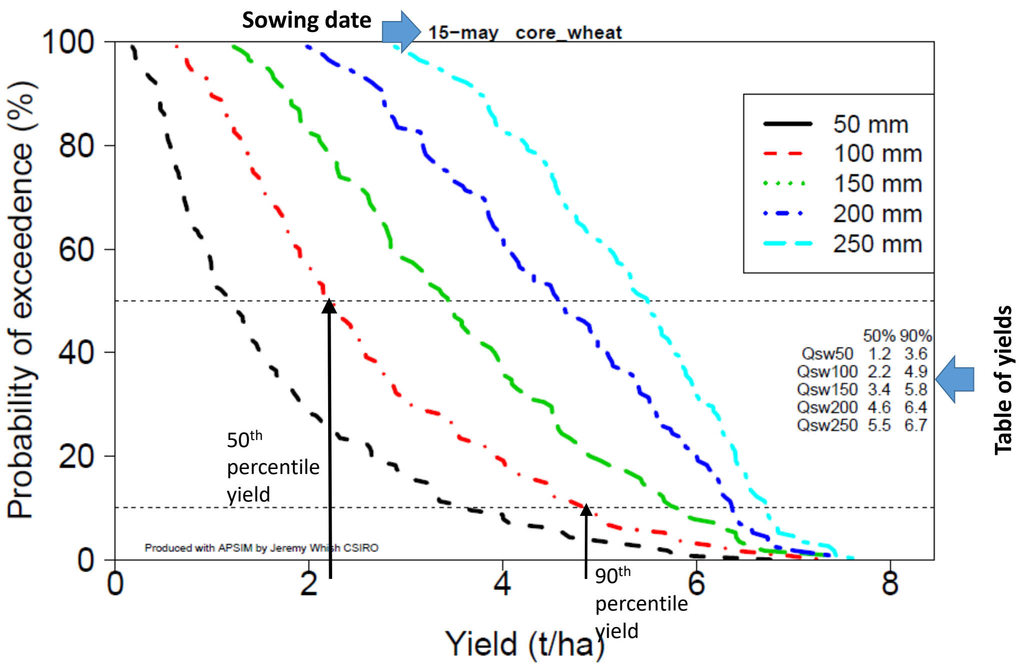

Figure 1. APSIM predictions of wheat yield probabilities with different starting soil water levels (50, 100, 150, 200 and 250 mm plant-available water). For 100 mm PAW at sowing (indicated by red line), the yield predictions for a 50th percentile season and a 90th percentile season are shown; these are used to calculate the N budgets for the crop.

The crop N budgets are determined prior to sowing of every non-legume crop from the predicted yield using well established N requirement calculations. An example for wheat is below (Equation 1).

So, for the example crop situation above in Figure 1, this would equate to a crop N fertiliser budget of 83 kg N/ha in the *Baseline* system and 185 kg N/ha in the *High Nutrient* system.

$$\textbf{\textit{Equation 1 - Wheat}}\ _{N\ budget} = \textit{Predicted yield (t/ha)} \times 12\ (\%\ \textit{protein}) \times 1.75 \times 1.8$$

Prior to each crop, the amount of fertiliser N to be applied was determined by deducting the amount of soil mineral N available in the top 90 cm of the soil profile from the total crop budget (Equation 2). Hence, if there was sufficient mineral N available in the soil to meet the crop demand, then no synthetic N fertiliser was applied (other than starter to provide other nutrients). This method also did not assume or account for additional in-crop N mineralisation or adjust this based on crop history (e.g., following legumes). In the experimental locations in Queensland, all the fertiliser N was applied at sowing, while in NSW locations a portion (up to 50%) was applied in-crop at the start of stem elongation.

$$\textbf{\textit{Equation 2 - N to be applied}} = \textit{Crop}\ _{Nbudget} - \textit{Soil mineral N (0-90cm)}$$

N inputs and export from systems

Over the various experimental locations there has been a large difference in the amount of applied N fertiliser across the 6 experimental years (Table 1). This is due to significant differences in the natural fertility and background starting N status at the sites. For example, the Billa Billa site was relatively new country and was only recently brought into crop production. This site had over 400 kg of mineral N in the soil profile at the outset of the experiments. No N fertiliser was applied to meet the annual crop budget for the first 5 years while this background N was exploited; only a small amount of N associated with starter fertilisers has been applied. Other sites have received significant N inputs of over 200 kg N/ha over the 6 years, but these application rates are still only 30-40 kg/ha/yr. over the life of the experiment (close to long-term averages nationally).

Despite the significantly different approach to crop N budgeting resulting in typically double the N budget in the *High Nutrient* system compared to the *Baseline*, when balanced over several years and the whole crop sequence this rarely translated into dramatically higher N inputs applied. The extra N applied over the whole 6 years was on average 100 kg/ha of extra N, or only 17 kg N/ha/yr., over the 6 years higher across all sites in the *High Nutrient* strategy. The difference ranged from only an extra 9 kg/ha at Emerald to 260 kg/ha at the Trangie – red soil site, with the larger differences accumulating at sites where the soil fertility or N cycling was lower.

Table 1. Total fertiliser N applied over 6 years of experiments across 11 farming system comparisons spanning the northern region between different N budgeting strategies: *Baseline* (Budget to 50th percentile yield prediction) and the *High Nutrient* (budget to a 90th percentile yield prediction).

Site comparison	Applied N (kg N/ha)			Exported N (kg N/ha)			System N balance		
	Base	High N	Extra	Base	High N	Extra	Base	High N	Diff
Emerald	51	60	9	399	411	12	-348	-351	-3
Billa Billa	17	77	60	344	378	34	-327	-301	26
Narrabri	205	442	237	270	268	-2	-65	174	239
Mungindi	70	154	84	178	193	15	-108	-39	69
Spring Ridge	234	304	70	377	393	16	-143	-89	54
Trangie – Red soil	137	396	259	297	384	87	-160	12	172
Trangie – Grey soil	63	139	76	289	284	-5	-226	-115	111
Pampas Mixed	50	152	102	435	453	18	-385	-301	84
Pampas - Summer	85	127	42	389	379	-10	-304	-252	52
Pampas - Winter	45	104	59	400	396	-4	-355	-292	63
Pampas - High inten.	138	274	136	420	422	2	-282	-148	134
AVERAGE			**103**			**15**			**91**

The *High Nutrient* strategy has not resulted in significantly higher exported N in any of the systems except Trangie on the red soil. This is largely because we have not seen any significant yield increases due to the higher N applications at any of the other sites (discussed further below). However, what can be seen is that across all sites the *Baseline* system is still exporting more N than is being applied. The *High Nutrient* strategy is maintaining a positive or neutral balance at several sites, but at sites with higher natural fertility (e.g., Billa Billa, Emerald or Pampas) the soil continues to meet most crop demand and provide most of the N inputs in the system even under a robust N fertilisation approach.

Crop responses to nutrient strategies

As mentioned above there have been few cases amongst these experiments where the higher nutrient application approach has resulted in a significant yield or protein increases. This is largely because of the below-average seasonal rainfall conditions across most of the seasons in these experiments, and hence the yields and crop demand for N has rarely exceeded the N available in the *Baseline* system. This occurred only at Trangie on a red soil in the wet and high yielding winter of 2016, where we saw a 1.2 t/ha yield increase and a grain protein difference (14.4% vs 11.8%) in the *High Nutrient* system. This highlights that the higher nutrient application approach is only likely to bring about significant yield gains in seasons with high yielding conditions, otherwise the *Baseline* provides sufficient nutrition.

In a couple of situations, we have seen a small reduction in grain yield associated with the *High Nutrient* strategy, where crops produced more vegetative biomass which is likely to have induced more severe water stress during dry grain filling periods. For example, at Mungindi in 2015 we saw a wheat yield reduction of 0.3 t/ha from the *High nutrient* application (50 vs 130 kg of N applied at sowing), but grain protein was higher in the *High nutrient* system (13.1% vs 8.8%).

Recycling and recovery of N

Because in most seasons we have provided N fertiliser in surplus to the requirement of the crop, it is critical to understand the proportion of fertiliser that is still available in the soil. On average across the various cereal crops, we have recovered 80% of the additional N applied at the post-harvest soil sampling after that crop. That is, most of the additional N available at sowing (from both fertiliser applied and starting mineral N) was still present in the soil mineral N pool when soil was sampled after crops were harvested. This value has varied from about 60-100% in most situations but has been lower particularly where crops grew more biomass with the higher nutrient applications but have not converted this to grain yield. In many seasons we have also observed additional N mineralisation in subsequent fallows in the higher nutrient systems.

In Figure 2 we show for 3 different sites the mineral soil N status and the accumulated N applications in the *Baseline* and *High Nutrient* systems. This demonstrates how N applications can have a long legacy in our farming systems. For example, at the Pampas site the legacy of the higher N application in October 2016 can be seen in the subsequent soil mineral N, meaning that the subsequent crop sown did not require additional N fertiliser inputs to satisfy the higher nutrient budget. The additional fertiliser applied in October 2018 sorghum crop is still available in the soil profile 2 years later in 2020. These legacies can take time to become clear, as is shown at Mungindi (Figure 2, bottom). Here, the only additional fertiliser application was made in Jun 2015, and this additional N was taken up by that crop. However, this was not recycled into the system until the fallow between December 2016 and March 2018, after which the difference in soil mineral N has been maintained.

Hence, over the long term a large proportion of the applied N is recovered again in the system, becoming available for use in subsequent crops. This recovery and recycling has been the main reason why the *High Nutrient* system has not required large additional inputs of fertilisers, because residual N from previous applications is contributing to the budget in subsequent years and hence offsetting the need for additional fertilisers.

At the last sampling across almost all sites, the *High Nutrient* system has between 25 and 100 kg of additional mineral N available in the soil profile compared to the *Baseline* system (Table 2). If you account for this current difference in soil mineral N and any additional export of N in grain from the *High Nutrient* systems compared to the *Baseline*, we have recovered on average 85% of the additional fertiliser N applied in the systems (Table 2). At some locations our calculations suggest this value is over 100, which is an indication of other inputs of N, such as from legume fixation, increased mineralisation of soil organic matter in those systems, and/or the variability in measuring soil N. Importantly, these recovery figures do not include the nitrogen in organic form and if there was any increased soil organic matter in those systems.

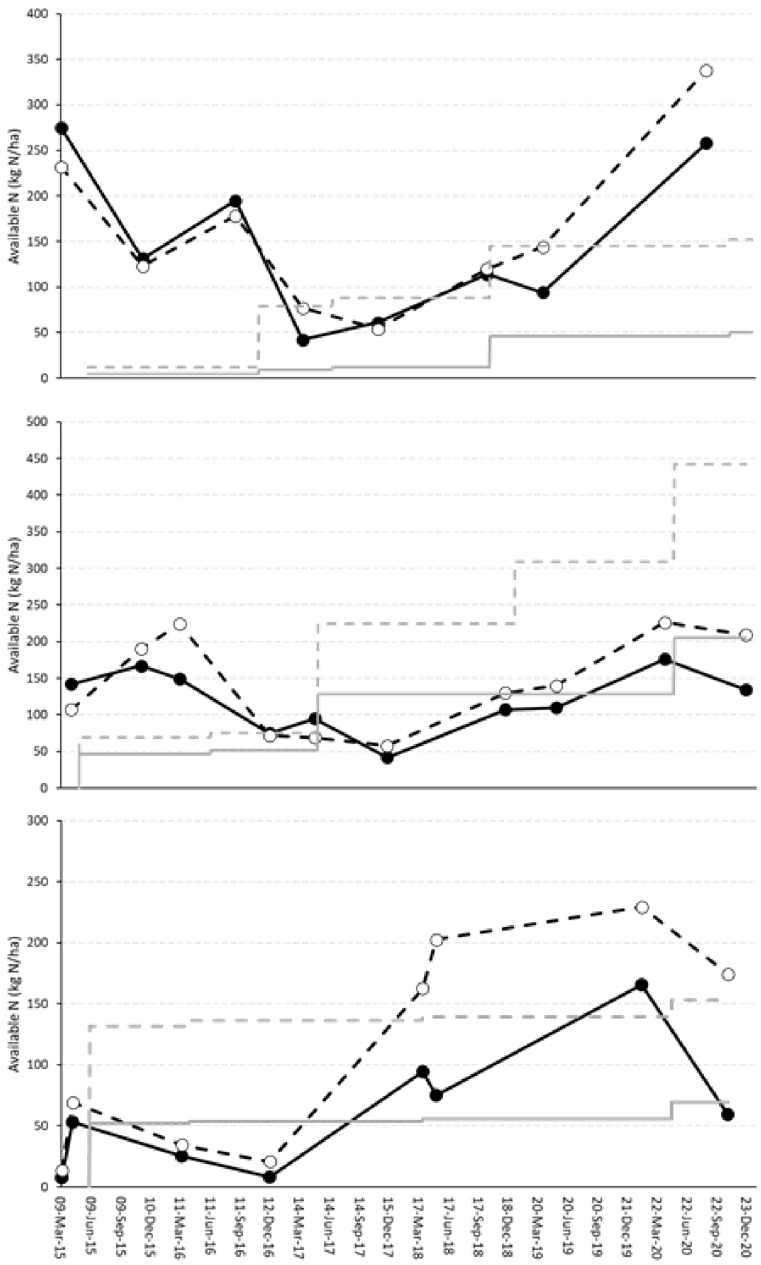

Figure 2. Changes in soil mineral N availability (Black lines - kg N/ha to 90 cm depth) and accumulated fertiliser N applied (grey lines) between *Baseline* (solid) and *High Nutrient* (dotted) systems at Pampas (top), Narrabri (middle) and Mungindi (bottom) over 6 years of experiments.

Table 2. Difference between *High Nutrient* compared to the *Baseline* fertiliser strategy in terms of soil mineral N status (at last sampling), recovery of additional fertiliser N applied (either present in the soil mineral pool or exported by crops), costs of additional fertilisers applied (over 6 years), the total relative economic position of the two systems after 6 years when either excluding or including the differences in most recent soil mineral N status.

Site comparison	Difference in change in soil mineral N at last sampling	Recovery of additional N applied	Cost of extra N fertilisers applied ($/ha)	Net benefit or cost excl. soil N ($/ha)	Net benefit or cost incl. soil N ($/ha)
Emerald	25	na	12	276	309
Billa Billa	47	135%	78	-214	-153
Narrabri	109	45%	308	-703	-561
Mungindi	99	136%	109	-201	-72
Spring Ridge	30	66%	91	-141	-102
Trangie – Red soil	31	46%	337	354	394
Trangie – Grey soil	36	41%	99	-662	-615
Pampas Mixed	123	138%	133	-85	75
Pampas Summer	89	188%	55	-76	40
Pampas Winter	4	0%	77	-442	-437
Pampas High intensity	38	29%	177	-321	-272
AVERAGE	**57**	**82%**	**134**	**-201**	**-127**

Return on investment from N strategies

Over the 6 years, the *High Nutrient* systems have incurred additional costs associated with the higher inputs of N fertilisers applied. While this value has varied between sites, depending on their inherent fertility, on average this has equated to $134/ha, or $22/ha/yr. difference in the costs incurred (noting we have assumed a fertiliser price of $1.30 per kg N). As mentioned earlier, rarely has there been a significant yield increase, and in some cases, some risks of yield penalties occurred. Only at Trangie on the red soil can we see an additional $354/ha has been generated. Across all sites on average the *High Nutrient* systems are around $200/ha behind the *Baseline* in terms of gross margin accumulated over the 6 years. However, if the additional fertiliser that has been invested into the soil mineral N pool is valued in these calculations this net cost is reduced to $127/ha or $21/ha/yr.

Conclusions

Over the experimental years we have been comparing the N strategies in the farming systems we have not had sufficiently favourable conditions to see significant grain yield increases. We have seen crop biomass increases from the additional N inputs, but this has not been converted into grain yield. Only time will tell how the expected higher returns in good seasons will change the long-term profitability and return on investment from this strategy. Regardless, this farming system strategy is likely to play out over the longer-term by maintaining the soils fertility, or lowering the net export of nutrients, and maintaining soil mineral N at a level that ensures crops have the nutrition available to utilise the better years. Ultimately our data shows that the *High Nutrient* strategy does not have a huge cost or risk to the farming system, with a high proportion of the extra N applied being recovered in subsequent years and potentially offsetting subsequent N applications. However, when conducting crop N budgets, it is critical to account for the current mineral N status which accounts for N recycling to avoid wasting unneeded fertiliser.

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Contact details

Lindsay Bell
CSIRO
203 Tor St, Toowoomba
Ph: 0409 881 988
Email: Lindsay.Bell@csiro.au

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

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

Key words

Nitrogen, efficiency, soil movement, timing

GRDC code

NGA00004

Take home messages

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

Background

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

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

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

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

Grain nitrogen recovery

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

1. Grain N recovery for each treatment was calculated as yield (kg/ha) x % protein/100 x 0.175

2. 'Net' grain N recovery was then calculated by deducting the grain N recovery in the Untreated (unfertilised treatment)
3. % grain N recovery was calculated by dividing the net recovery by the amount of N applied

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

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

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

Key points

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

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

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

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

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

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

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

Key points

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

Situations of concern

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

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

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

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

Movement of N

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

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

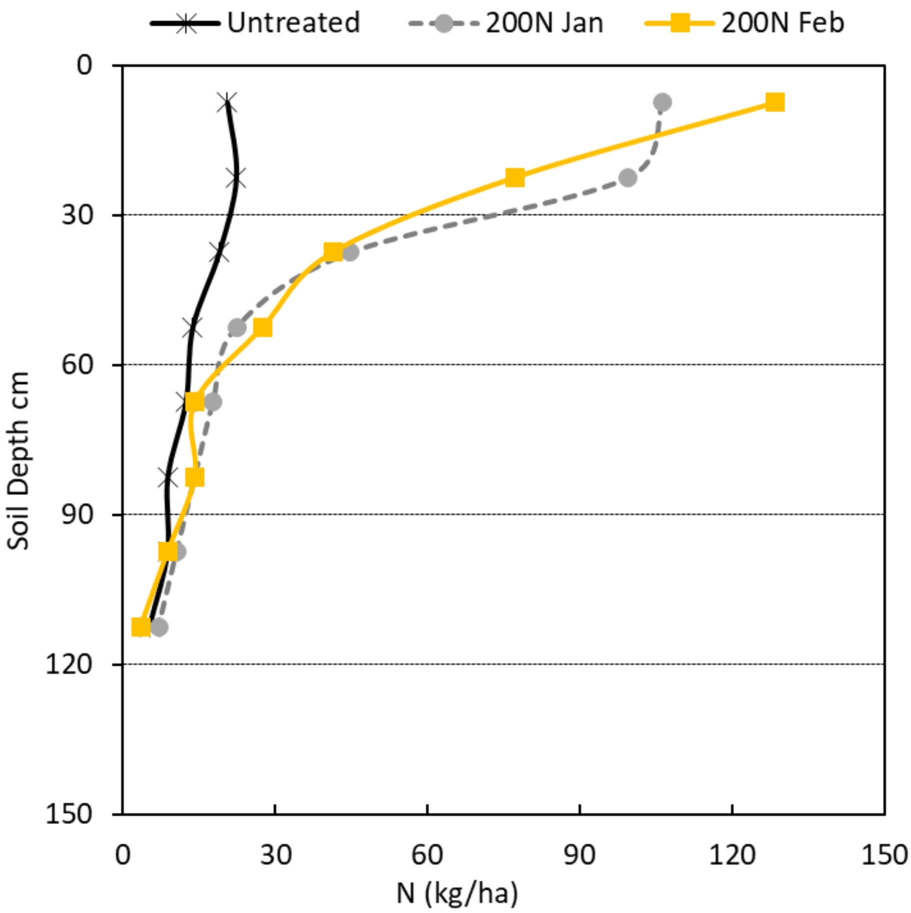


Figure 1. Soil distribution of N at Mullaley at planting (May 2017) following application of urea in January or February 2017. 175mm of rain were recorded between the January application and planting. 140mm of rain were recorded between the February application and planting.
(NB: Both N applications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

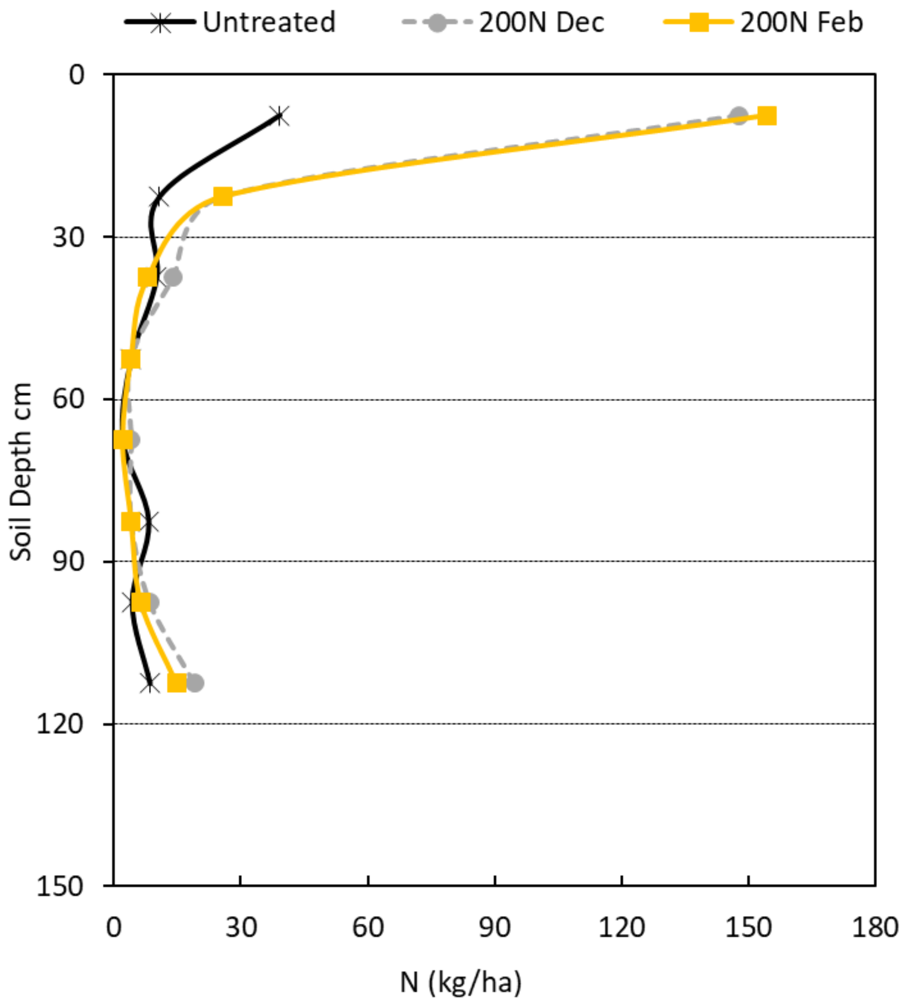


Figure 2. Soil distribution of N at Tulloona at planting (June 2016) following application of urea in December 2015 or February 2016. 225mm of rain were recorded between the December application (spread and incorporated) and planting. 65mm of rain were recorded between the February application (spread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

Key points

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

Implications of reduced N movement

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

Billa Billa 2017

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

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

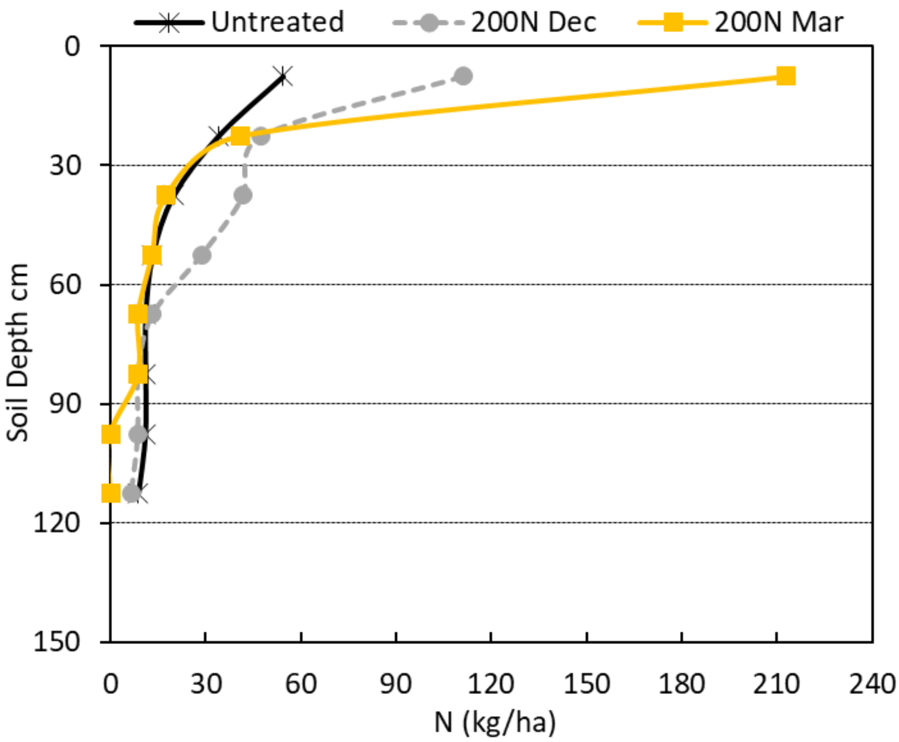


Figure 3. Soil distribution of N at Billa Billa at planting (May 2017) following application of urea in December 2016 or March 2017. 279mm of rain were recorded between the December application and planting. 154mm of rain were recorded between the March application and planting.
(NB: Both applications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

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

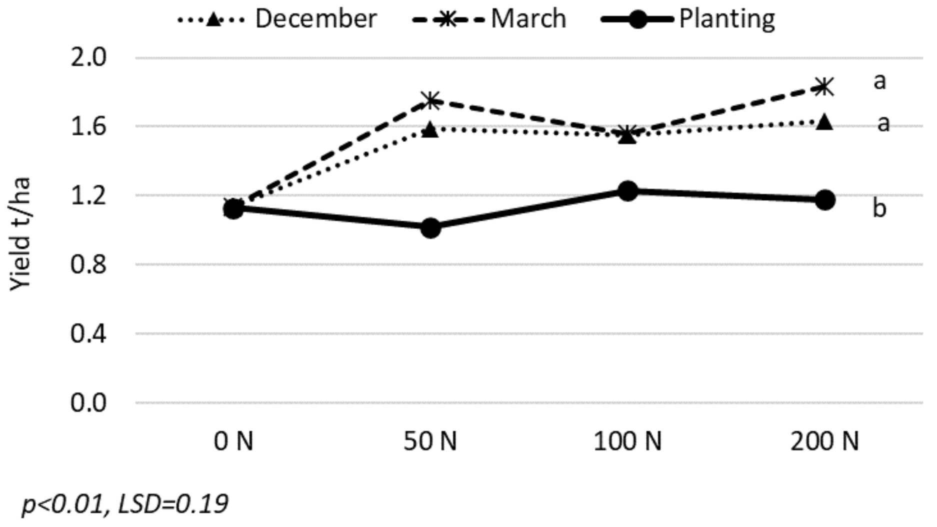


Figure 4. Effect of application timing and N rate on yield, Billa Billa 2017
(Treatments that share the same letter are not significantly different at P=0.05. All N rates were spread only)

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

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

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

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

Key points

1. Although the majority of N from December or March application was still in the 0-15cm zone at planting (Figure 3), the yield and protein results indicate it had moved deep enough to be available to the crop in a season with very low in-crop rainfall.
2. Increased benefit from fallow N application compared to application at planting are likely in situations with good levels of fallow rainfall but followed by low levels of in-crop rainfall
3. The majority of excess N applied in December was recovered in the top 45cm at harvest after a total of 465mm of rainfall.
4. The majority of N applied in March was recovered in the top 30cm at harvest after a total of 340mm of rainfall.

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

How much nitrogen was actually recovered at harvest?

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

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

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

Key points

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

Was nitrogen still available for the following crop?

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

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

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

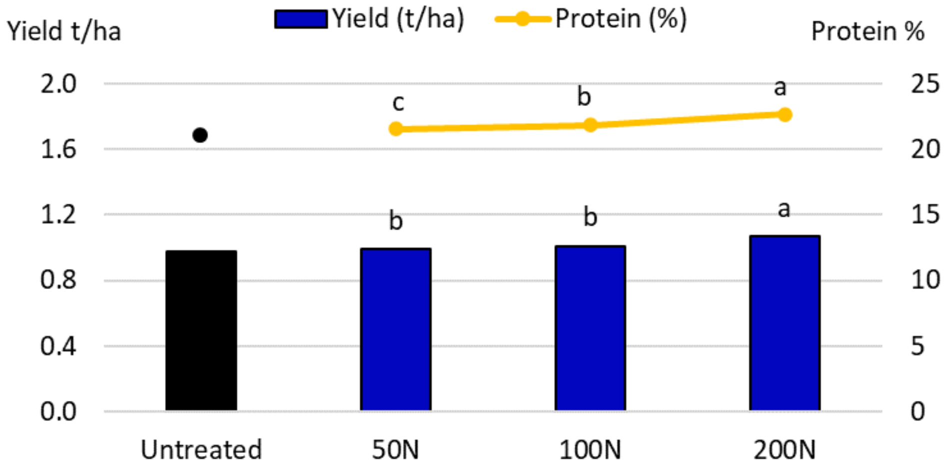
NB Sampling method - 4 individual 0-120cm depth cores taken per plot. Samples were separated into 0-30 and 30-90cm intervals with each depth bulked and a single sub sample taken for analysis. 4 replicates sampled in each treatment

Key points

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

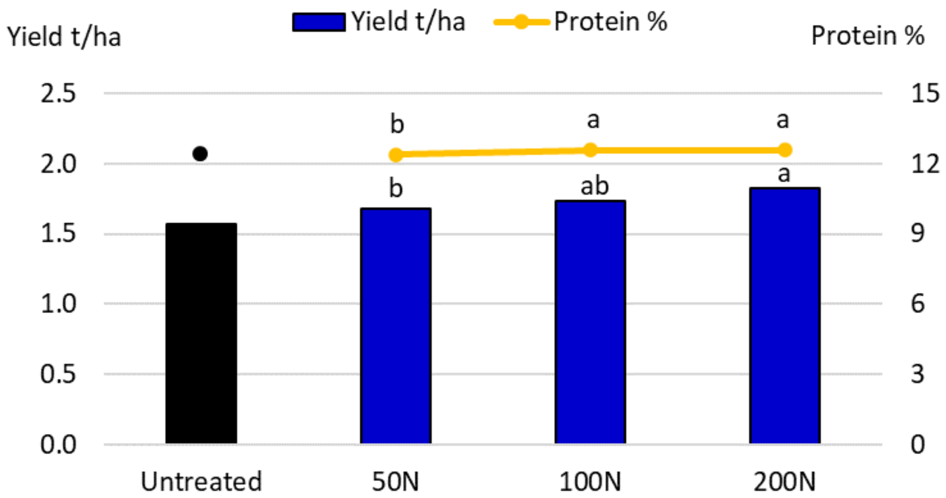
NB At the Tulloona site, ~60 % of the additional soil N was still found in the top 45cm with 45% found between 15 and 45cm. At the Macalister site, ~49 % of the additional soil N was still found in the top 45cm with 31% found between 15 and 45cm.

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



Yield: p=0.02, LSD=0.06 *Protein: p<0.01, LSD=0.29*

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



Yield: p=0.02, LSD=0.10 *Protein: p<0.01, LSD=0.1*

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

Key points

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

Economic Impact

Tulloona

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

Macalister

- Wheat 2016: there was no yield impact from applied N but increases in protein of ~2-3%. There was no net benefit with mean yields ~2.0-2.5t/ha.
- Wheat 2017: significant yield increases (0.1-0.25t/ha) were recorded from all 2016 rates compared to the Untreated in an ~1.6t/ha crop. Despite significantly increased protein from the 100 and 200 kg N/ha rates, all grain was H2 quality. Net benefits of $32-$73/ha were achieved in ‘crop 2’.
- The 50 kg N/ha rate was the only one to achieve a net benefit over the first 2 years of cropping (~$20/ha)
- Sorghum 2018/19: significant yield increases (~0.4-0.7t/ha) from the 100 and 200 kg N/ha rates compared to the Untreated in an ~5.7t/ha crop. Significantly increased protein from the 100 and 200 kg N/ha rates compared to the Untreated (~0.4-0.6%). Net benefits of $80-$120/ha were achieved in ‘crop 3’.
- Wheat 2020: no yield impact from the applied N in an ~1.4t/ha crop. Significantly increased protein from the 100 and 200 kg N/ha rates compared to the Untreated (~0.2-0.4%). No net benefit as all grain was classified as HPS1 in ‘crop 4’.
- Soil testing in October 2021 showed an extra 50-70 kg N/ha was still available to benefit the sorghum crop in 2021/22 (‘crop 5’) from the original 200 kg N/ha applications in 2016.

Conclusions

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

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

- At one of the two sites monitored in year 2, all of the net benefit from fertiliser occurred in year 2.
- The errors associated with soil testing (eg core number, uniformity of sample mixing and sub sampling) make ‘precise’ recommendations on fertiliser N levels difficult.

Key industry challenges

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

Where to next?

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

Acknowledgements

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Contact details

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

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Making nutrition decisions in high-cost environments

James Hagan[1] and Lindsay Bell[2]

[1] Department of Agriculture and Fisheries Queensland
[2] CSIRO Agriculture and Food

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Take home messages

- At average fertiliser costs, return on investment to nitrogen applications exceed 5:1, i.e. every dollar spent on nitrogen results in $5 of additional profit
- When N prices double, growers are still receiving $2.10 in profit for every dollar spent on nitrogen, and at triple the cost nitrogen is still expected to return $0.85 in additional profit for every dollar spent
- With higher N prices profitable N responses to winter cereals are only expected under favourable grain prices or seasonal conditions
- Soil testing and precision/variable nutrient application become more valuable as nutrition costs rise.

Background

Nitrogen (N) and phosphorus (P) are key nutrients in Australian cropping systems and in typical operating environments are among the largest variable input costs for grain producers. In 2021-22 rapid and large increases occurred in in fertiliser pricing. Urea prices are up over 200% and DAP/MAP up over 100% in the 12 months to November (Figure 1).

These current prices pose a challenge for grower decision making, many of whom may have paddocks with low N levels following high yielding winter crops in 2021.

Whether fertiliser is priced at $450/t or $1,350/t, understanding why it is being applied is essential. Specifically, what are you trying to achieve in terms of both yield and protein, how will the application of fertiliser help you meet that goal, and what is the impact of that on profit. High fertiliser prices increase the economic importance of decisions relating to nutrient applications. Finding the appropriate nutrition application rate will have a greater impact on profit than in years with more typical prices. This makes the benefits of soil testing and variable application to optimise yield and protein outcomes more significant.

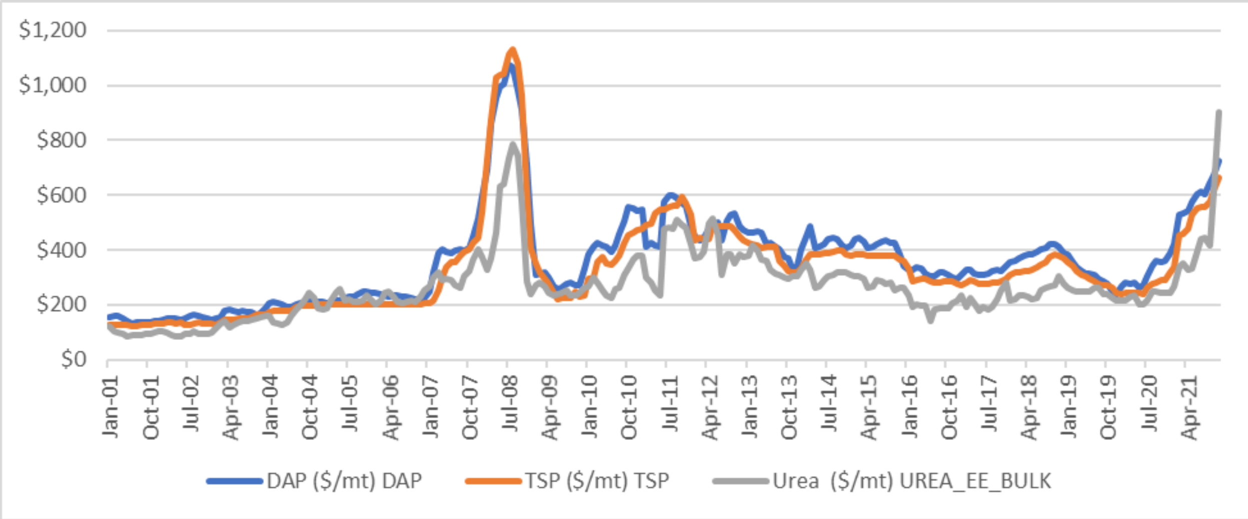

Figure 10. DAP, TSP and urea prices ($USD), 2001-2021 (World Bank)

Economics of N application – price and recovery effects

Economically optimal nutrition application is calculated as the point when marginal cost is equal to marginal return, i.e. when $1 of additional nutrient results in $1 in additional return (Point A, Figure 2). In nutrient response curves this point of optimisation is typically at a point lower than the fertiliser required to achieve maximum yield (Point B, Figure 2).

Whilst it might be expected that significant increases in prices for key nutrients would lead to a lower optimal application amount, this logic overlooks that we are typically in a moisture limited farming system, therefore our optimal N rates are typically matched to the point required to meet our water limited yield potential, or a percentage of this potential to allow for yield limiting factors such as disease, weeds, etc. Where available N is lower than this expected yield potential, as long as the cost of applying N does not exceed the value of the yield it generates then it is worth doing.

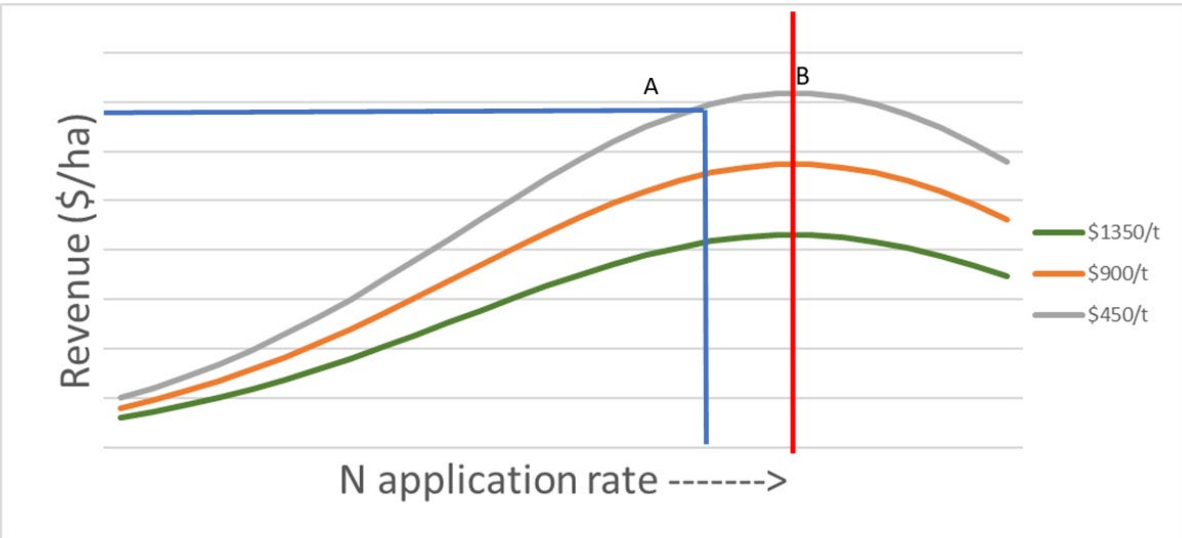

Figure 11. Revenue curves to nitrogen application at varying urea prices where A = point when marginal cost is equal to marginal return and B = fertiliser required to achieve maximum yield.

At long term average urea prices ~$450/t, and long-term average wheat price of $295/t, whilst using a rule of thumb that each tonne of yield potential needs 40kg of available N, the average return to N application exceeds 5:1 (Table 1). Whilst N responses are not linear, they can be treated as such until high rates where we reach diminishing returns. At lower rates, the response curve is close enough to linear that a general rule of thumb can be useful for N budgeting for crops.

It is thought that in good conditions approximately 80% of applied N fertiliser is available for plant uptake. However recent research in northern farming systems this figure is more commonly estimated at 15% in the year of application, whilst an average of 65% being left in the soil for subsequent crops and the remainder lost through different loss pathways. Based on past work by Dr Wayne Strong and Dr Mike Bell, total winter losses typically average 15-20%, whilst summer losses are higher at 20-40% (Angus and Grace, 2017).

There is some uncertainty about the proportion of N applied that is utilised by a crop due to soil, seasonal and other management decisions. Given this uncertainty, in Table 1 we explore how much the value, along with urea price influences the return on investment from N fertiliser applications.

Table 1. Return on Investment to N application at various pricing and applied N recovery rates.

	Applied N recovery			
Urea pricing ($/t)	**80%**	**60%**	**40%**	**20%**
450	6.29	5.87	5.04	2.54
540	5.03	4.62	3.78	1.28
675	3.78	3.36	2.53	0.03
900	2.52	2.10	1.27	-1.23
1125	1.77	1.35	0.52	-1.98
1350	1.26	0.85	0.01	-2.49
1800	0.63	0.22	-0.62	-3.12
2250	0.26	-0.16	-0.99	-3.49

Note: These ROI’s to N are calculated by increasing applied N rates to ensure that the crop available N is 40kg per tonne of grain yield.

If we only counted the 20% recovered in the year of application, then once N doubles in cost it would no longer be worthwhile continuing N applications. However, this ignores that up to 60% of that applied N is not lost to the grower and will provide yield benefits in the following season, thus it is best to look at total recovery for N decisions.

As an example of this, at a urea price of $900/t it is not economic to apply N at a total recovery of 20%, in the season of application, needing to put down 100kg of N for every 20kg required to be available by the plant, results in losing $1.23 for every kg of N accessible N applied. However, once the following crops access to this N is accounted for, we’re now making $2.10 per kg of N applied. So in this instance if we had not applied N due to low recovery in year of application we would be $2.10 worse off overall.

It is worth noting that despite significant potential differences in how much N applied may be available to crops this rarely shifts the relative economics of applying fertiliser N dramatically. At 60% availability for applied N urea is still generating a positive return on investment of 2.1 at double ($900/t) and 0.85 at triple ($1350/t) pricing respectively. As prices rise above this point it approaches the point where N applications on cereal crops are expected to be un-economic, even accounting for recovery in future crops, with the risk of lower-than-expected recovery further increasing the expected losses.

When considered in this context, it should come as little surprise that the optimal rate of nutrition doesn't change until the point at which return on investment approaches zero. However, while the optimal N rate remains the same across price points, the level of profit generated at this optimal point is reduced as fertiliser costs increase. (Figure 2 and Table 3).

What this means is that nutrition decisions should continue to be driven by underlying agronomic principals of source, timing, rate and placement. Whilst increased prices may impact each of these factors in different ways i.e., increasing urea costs may make feedlot manure a more attractive source to growers further away from feedlot, supply is going to be a major consideration.

Scenario analysis

Using CropARM (http://www.armonline.com.au/) it is possible to compare different cropping nutrition scenarios across a range of possible seasonal conditions. Past research has shown that soils in northern farming systems typically mineralise between 50 kg and 100 kg of nitrogen over the summer months (Cox and Strong, 2015).

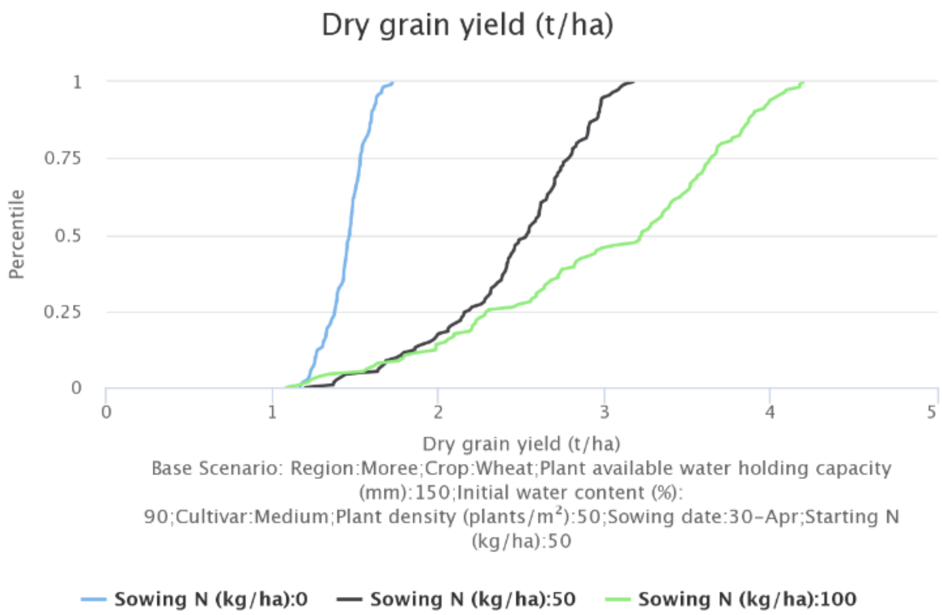

Figure 3. Nutrition scenario analysis, planting on a 90% profile - cumulative probability distribution

With good early summer rain across many regions, we can assume largely full profiles of moisture. CliMateApp (https://climateapp.net.au/A04_HowWetN) supports this assumption, suggesting 88% full profiles from rainfall over late spring and early summer throughout much of northern NSW.

Using this information, assuming 50kg of mineralisation, Figure 3 contrasts the expected yield results of applying 0, 50 and 100kg of Nitrogen to a soil with 150mm plant available water capacity (PAWC) at 90% capacity, on 30 April plant date, at Moree.

The cumulative distribution shows that the 50 kg of mineralised N has a 50% chance of achieving 1.5 t/ha or better, while having an additional 50 kg of N at sowing increases this to a 50% chance of 2.5 t/ha or better and having 100 kg of additional N gives a 50% chance of 3.2 t/ha or better. However, it also demonstrates that in the driest 25% of years (i.e. 1 in 4) there may not be a yield difference between applying 50 or 100kg of additional N.

Gross margin analysis

Given other inputs will largely remain the same we can then compare the scenarios at a gross margin level, to each other and to different price points for nutrition. Whilst prices of some chemicals (i.e. glyphosate), have increased at the same time as increases to nutrition, this analysis will use an average price to highlight the impact of nutrition changes Table 2.

Table 1. Average wheat variable production costs, excluding nutrition

Activity	Average cost
Fallow management ($/ha)	$43
Planting ($/ha)	$59
Crop protection ($/ha)	$77
Harvest ($/ha)	$86
Other (levy/insurance/etc) ($/ha)	$30
Total excluding nutrition ($/ha)	**$295**

The analysis used 10-year average wheat price ($295/t) for all scenarios and compared average urea ($450/t) and mono-ammonium phosphate MAP ($800/t) prices against those prices quoted in November 2021 for urea ($1,350/t) and (MAP, $1,800/t), when applied at the three different rates (0, 50 and 100 kg of applied N).

Using the predicted median yield of 3.2 t/ha from a full profile with 100 kg of N applied, and an applied N recovery rate of 60% in a year with average costs, we would expect a gross margin of over $450/ha using historical pricing.

In 2022 with the same inputs, yields and grain prices this gross margin would be more than halved to just $124/ha. Meanwhile, reducing the N applied to 50kg N, and 0 applied N would be expected to have gross margins of $162, and $170/ha respectively.

Table 3. Gross margin comparison of 3 scenarios at $1350/t urea vs average input costs at $295/t grain price assuming 60% recovery of applied N fertiliser

	Average pricing	**2022 pricing**		
N applied (kg/ha)	**100**	**100**	**50**	**0**
Median yield prediction (t/ha)	3.20	3.20	2.50	1.70
Income ($/ha)	$944	$944	$738	$501
Non-nutrition costs ($/ha)	$295	$295	$295	$295
MAP cost (20kg) ($/ha)	$16	$36	$36	$36
Urea cost ($/ha)	$166	$489	$244	$0
Gross margin ($/ha)	**$467**	**$124**	**$162**	**$170**

At grain prices of $350/t or a yield outcome for the best 25% of seasons, the expected gross margins at 2022 input prices are once again positive to N application with $300, $299 and $264/ha expected for 100N, 50N and 0N scenarios respectively.

Unfortunately predicting existence of a price, especially those relying on a protein premium at harvest is extremely challenging, as an example of this, the spread from APW to APH2, increased from ~$15/t in September, to ~$50 in November (Table 4), based on widespread downgrades due to harvest rain.

Table4. Grain prices by grade (AUD $/t) September vs November 2021 – (GrainCorp, Dalby)

Grain grade	Sep-21	Nov-21
APH2	304	371
H2	294	327
APW	290	317
AGP1	289	257

Alternative nutrition sources

One side effect of increases in urea and MAP/DAP prices is that other nutritional sources may be more attractive. For example, feedlot manure becomes a more economic option for producers located much further away from the source than usual. However, there is ~500,000t of feedlot manure generated in Queensland annually (Hagan 2018), which assuming an N requirement of 100 kg/ha would be enough to cover approximately 80,000 hectares.

Alternative crop options

With N prices high, growers may be considering adding additional pulses to their rotation, either to reduce their N requirements for the coming season, or supply N for following crops. Whilst pulse crops will reduce total program N requirements in the season they are grown, results from farming systems sites suggest that additional legume crops in the sequence have had variable impact on following soil mineral N availability (Erbacher *et al.,* 2020). In situations where pulses were planted on profiles with high available nitrogen, they are unlikely to fix substantial inputs of additional N, and under high yielding conditions export large amounts of N in their grain. The most important aspect of whether there will be any benefit of planting a pulse crop for its nitrogen contribution is knowing the starting soil mineral N it is being planted into.

Table 5. Comparison of N mineralisation during subsequent fallows following pulse crops vs wheat in northern region farming systems experiments

Site + Season	Crop	Subsequent fallow mineral N accumulation (kg/ha)
Emerald 2015		
	Wheat	94
	Chickpea	94
Emerald 2016		
	Wheat	102
	Chickpea	**118**
Pampas 2015 – long fallow		
	Wheat	62
	Faba bean	97
	Chickpea	100
	Field pea	**123**
	Canola	90
Pampas 2016 – short fallow		
	Wheat	44
	Chickpea	42

Summary

When returns to N are positive, optimal rates for maximum gross margin returns remain largely unchanged irrespective of price, however the total profit and return on investment at this optimal rate will decline as nutrition costs increase. When N prices result in negative returns to N, the economic optimal amount from a single year gross margin point of view will be 0.

Hence, having a good understanding of your existing N levels through soil testing is now worth at least 3 times as much in 2022 as previous seasons. High N prices also make practices that improve efficient use of N more important to consider, with savings via variable rate and budgeting or applying fertiliser to better match crop demand more critical.

Using conservative prices and yields it is easy to see scenarios where negative returns to nitrogen applications in this season to many winter cereal crops are possible, however with good yields or above average prices, positive economic responses to N are still possible in 2022.

Finally, it is worth keeping in mind that the analysis in this paper has focused on N responses in a single season, there are legacy system impacts to fertiliser application which may only be observed in future years. For example, wider adoption of pulses will result in lower ground cover and future fallow soil water accumulation, or lower fertiliser application rates may result in a faster decline in soil organic matter, which will have impacts on soil N mineralisation for years to come.

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Contact details

James Hagan
Department of Agriculture and Fisheries
13 Holberton St, Toowoomba, 4350
Ph: 0476 828 018
Email: james.hagan@daf.qld.gov.au

Deep P and K - a call to action! Critical soil indicators, costs and benefits of deep P & K and timing.

Mike Bell[1], Michael Ledingham[2] and David Lester[3]

[1] University of Qld, Gatton
[2] Merinda Farms, Moree
[3] Department of Agriculture and Fisheries, Toowoomba

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phosphorus, potassium, placement, timing, subsoil depletion

GRDC codes

UQ00063; UQ00082

Take home messages

- Ensuring continued phosphorus (P) availability to crops under variable seasonal conditions is increasingly difficult across the northern region. Similarly, while potassium (K) infertility is currently restricted to specific soil types and regions, K deficiencies are increasing – particularly in drier years without access to enriched surface soils
- Both P and K are effectively immobile in clay soils, and with crops relying heavily on subsoil nutrient reserves when topsoils are dry, it is not surprising that subsoil depletion of P and K has occurred. The question is what to do about it, and at what stage of the fertility decline should management interventions start? Soil testing in layers is an effective mechanism to monitor fertility status
- Deep banding of P and K has been shown to be an effective and profitable strategy in soils with low subsoil reserves across southern and central Qld, but unless soils are extremely depleted in one or both nutrients, crop responses will vary with seasonal conditions. This variability can impact the returns from deep applications in the short term, but excellent residual value of deep P bands over multiple seasons reduces financial risk
- Deep banding of K is more effective if P is placed with K to encourage root activity around bands. The residual benefits of deep K may not persist as long as deep P, because luxury crop K uptake can occur. Grain K removal is relatively low compared to crop uptake, so most crop K is returned to surface soils in residues
- Root access to deep bands is normally limited by the small volumes of soil treated and rapid drying in response to root proliferation in treated zones. Therefore, view deep banding of P and/or K as (profitable) supplements to uptake from the top 30-40cm, where root density is greatest
- The solution to P and K infertility is using soil samples to identify the zones of greatest depletion and using the residual value of both nutrients to progressively enrich as much of the accessible root zone as possible over time.

Introduction

The overwhelming majority of dryland cropping in northeast Australia occurs on clay soils that had variable, but generally moderate, reserves of nutrients in either organic form (predominantly nitrogen and sulfur) or inorganic forms (particularly phosphorus (P) and potassium (K)) prior to the commencement of cropping. This level of native fertility was able to support grain production with little fertiliser input for a number of years, but as soil organic matter declined and the cumulative amounts of grain removal increased with years of cropping and improved production systems, background fertility could not continue to meet crop demands and fertilisers started to be used. Nitrogen was generally the first input required, and this was consistent with the much higher rate of N removal in grain (i.e. ~20 kg N/t in cereals) than for either P (2.5-3 kg P/t) of K (3-3.5 kg K/t). In soils with lower P fertility, starter P also started to become popular as a means of ensuring plants could access enough P during the early stages of growth when root systems were small and inefficient, and crops were going through key physiological processes like floral initiation and establishment of potential grain numbers. This starter P was only ever a short term 'fix' or supplement to overall crop P uptake, which was still largely achieved through exploitation of P from crop residues, residual fertiliser in the topsoil and indigenous P reserves in the rest of the effective root zone. Soil K was still largely adequate to maintain crop productivity.

Further declines in soil organic matter and continued nutrient removal have resulted in a greater dependency on fertiliser N and the emergence of widespread P and soil/region-specific K limitations to growth. While all represent the net effects of crop nutrient removal on soil fertility banks, the P and K deficiencies have an added dimension of occurring most strongly in subsoils (e.g. from immediately below the tilled/top 10cm layer to about 30-40cm depth). This is due to combinations of shallow fertiliser inputs (if used), residues returned to the soil surface with little or no mixing through tillage and the lack of mobility of these key nutrients in soil water. The implications for productivity are substantial, and the challenges for fertiliser management significant. Our cropping systems rely on stored soil water in subsoil layers for extended periods in the growing season. For that soil water to be efficiently used to create biomass and grain yield, adequate amounts of available nutrients are required in soil layers accessible to active roots. As soil P and K become increasingly depleted in subsoils, fertiliser applications in topsoil layers can only provide benefits when those layers are wet for extended periods, or if the nutrients can move with water into those deeper layers. While N can move deeper, P and K can't. We therefore have to physically place a significant proportion of our P and K directly into those subsoil layers (e.g. Bell *et al.,* 2019, 2020). Deep banding strategies have been developed in response to this issue.

Deep banding – how, where and when

GRDC supported research into effective deep banding strategies has been conducted with variable success from sites south of Narrabri to north of Emerald. There is now a large pool of data from Qld sites especially (NSW sites were adversely affected by a string of very dry seasons in the second half of the research program) that has sought to answer these practical questions. Results can be summarised as follows –

- **Depth of placement** – the most significant depletion of profile P and K are in the soil layers immediately below the top soil (i.e. the 10-30cm layers – see Figure 1 for local examples from NW Slopes of NSW). These layers avoid the most severe and prolonged drying that occurs in the topsoil and are still close enough to the soil surface to have a high root density – essential for efficient uptake of less mobile nutrients like P and K. Deep placement strategies target the middle and bottom half of this layer. The local soil test information here shows that 8 of the 11 sites have subsoil Colwell P at concentrations where responses to deep P bands would be significant. Subsoil K is also depleted, but crop responses to deep bands would be marginal (at best) in only around 3 of the 11 sites shown

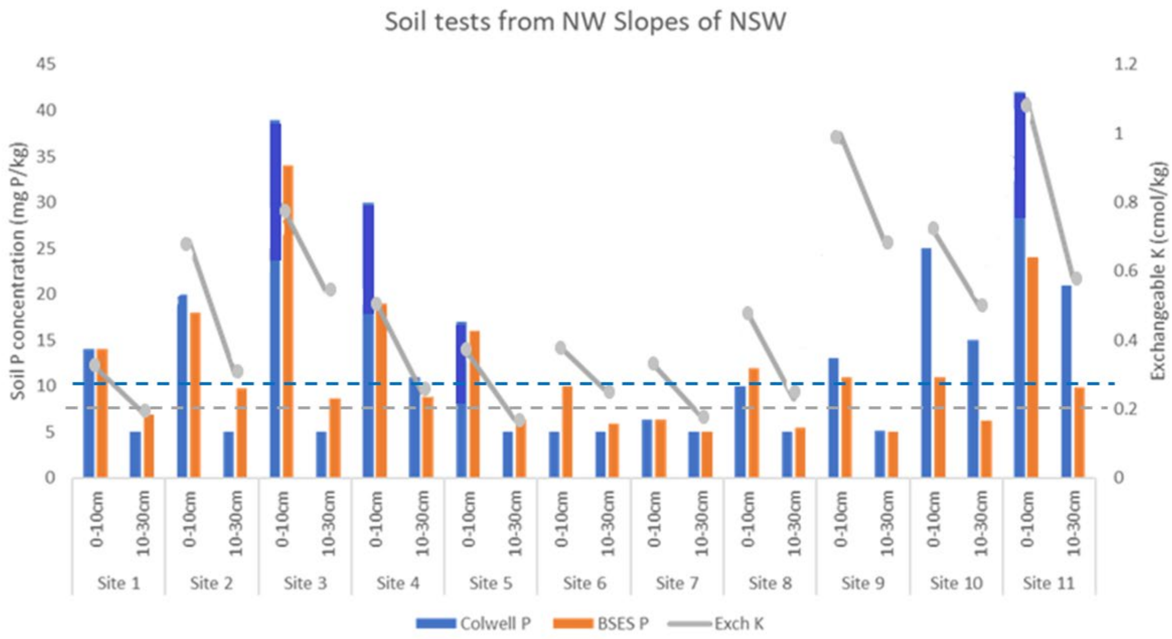

Figure 1. Soil test results from 11 locations in the Pallamallawa district. Data are shown for Colwell (blue bars) and BSES (orange bars) P, with units of mg P/kg, and exchangeable K (grey points joined by a line for each site), with units of cmol(+)/kg. The dashed blue line is the approximate critical Colwell P concentration below which a response to deep bands would be expected. The equivalent for exchangeable K is shown as a dashed grey line.

- **Band spacing** – this is a compromise between band frequency (to maximise the chance of roots intercepting deep bands), in band concentration (high in-band concentrations result in large concentration gradients between the band and the surrounding soil depleted by root activity. Strong gradients maximize the rates and distance of diffusion from the band to replenish P and K in the soil solution) and the plant response to P bands (i.e. how much root proliferates around the band). There is little difference between bands spaced 25-50cm apart, but efficiency of crop P access and yield responses decline at wider spacings. Optimal spacings are similar for P or K, noting that as crops do not proliferate roots around K bands, co-application of P and K are required to maximize crop K uptake
- **Product formulations** – Most research has focussed on the form of P fertiliser (ammonium phosphates v triple superphosphate - TSP), with ammonium phosphates having a clear advantage over TSP – especially when applied in bands. The difference between mono- and di-ammonium phosphates is negligible in most instances, with cost effectiveness a key consideration. There has been no evidence of any advantage of fluid forms of P fertiliser compared to conventional granular products.
- There have been no direct comparisons of muriate (MoP) v sulfate of potash (SoP) in K bands, with muriate preferred based on lower cost/kg K applied. Effective root exploitation of banded K required colocation of some P in the K bands, regardless of the K product.
- **Rates of application** – deep banded applications and associated soil disturbance are typically undertaken infrequently to minimise the disruption and cost of expensive tillage operations (see Table 1). To that effect, rates should be enough to maximise the crop response in each year to gain a return on the deep banding investment, as well as provide responses over 4-5 crop seasons. Our results suggest that while application of 20 kg P/ha and 50 kg K/ha are able to maximise yield responses in the initial cropping season or two, an increasing advantage is observed from higher P rates (e.g. typically 40 kg P/ha) in later seasons, and that K re-application

will be needed more frequently than P due to the greater crop uptake and redistribution into topsoil layers in residues.

Table 1. Treatment cost by P rate with basal N

Deep application ($/ha)	P rate (kg/ha)	MAP ($/ha)	K rate (kg/ha)	MoP ($/ha)	Deep P cost ($/ha)	Deep P + K cost ($/ha)
$30	0	$0	0	$0	$30	$30
$30	10	$40	25	$32.5	$70	$102.5
$30	20	$80	50	$65	$110	$175
$30	40	$160	75	$97.5	$190	$287.5
$30	60	$240	100	$130	$270	$400

Note: Using long term average MAP ($800/t) and KCl ($650/t) prices

- **When to re-apply?** – This is a complex question, due to (i) differences in soil properties that influence the availability of applied P in soil over time; (ii) current uncertainty with how much P and K are actually taken up from deep bands (all we have been able to use is differences in uptake or removal between fertilised and unfertilised treatments, which doesn't account for preferential uptake from either bands or bulk soil); and (iii) growing evidence that re-application of deep bands in different positions to the residual bands can provide another level of nutrient uptake and grain yield – possibly due to a larger volume of treated soil allowing more roots to encounter fertiliser.

As budgeting for removal and soil testing to detect residual deep bands are both ineffective, we currently suggest a combination of monitoring plant nutrient status (tissue tests) and use of re-application test strips as the most practical tools to determine the time to re-apply. The responses obtained to the initial applications and the cost of fertiliser will also factor heavily in these decisions.

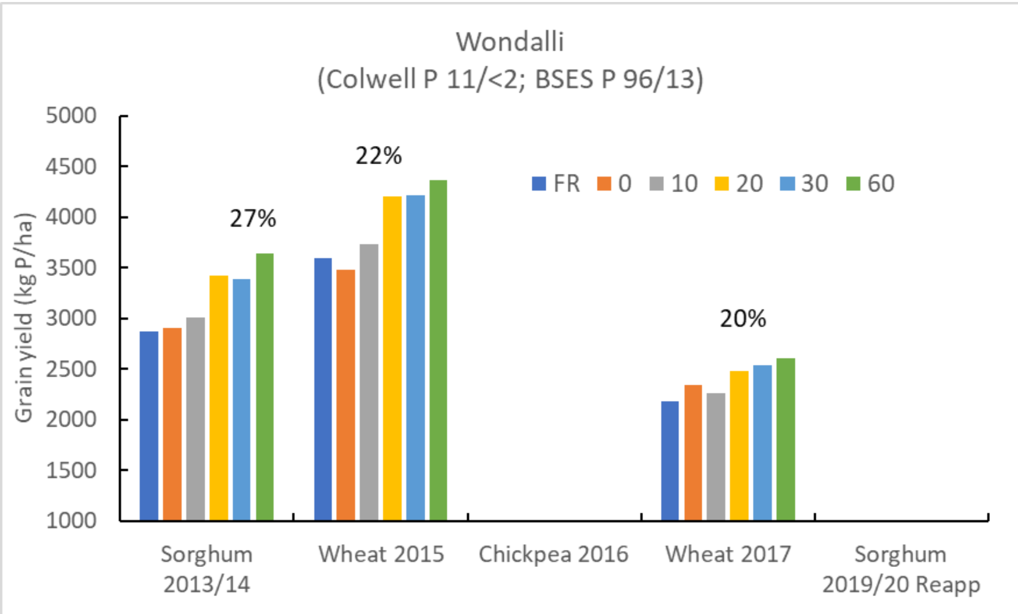

Figure 2. Contrasting P rate responses in wheat and chickpea crops in the 1st, 2nd and 5th crops in crop sequence at the deep P site at Wondalli. The chickpea crop in 2016 and the sorghum crop in 2019/20 were not harvested due to excessively wet conditions.

Plant responses to deep banded nutrients

At very low background P and K supply (mainly CQ sites)

We have had the opportunity to look at the minimum P and K requirements to grow sorghum and chickpea crops at sites in Central Qld (CQ), where both topsoil and subsoil P and K are very low and where fertiliser nutrients generate a very clear yield response. These results are shown in Figure 3 below for P (Figure 3a) and K (Figure 3b) and illustrate a number of important points. Firstly, chickpeas seem to be able to more efficiently convert additional P and K uptake from applied fertilisers into grain yield compared to sorghum. The reasons for this are currently not known but may be related to the timing of nutrient uptake relative to the yield determining processes. Chickpeas are slower to develop an extensive root system and proliferate roots in P bands, but when they do it is closer to the onset of flowering and pod addition. Conversely, sorghum quickly develops a root system that can rapidly exploit sources of P or K, but this early nutrient access occurs long before determination of grain yield and may not as directly contribute to yield development. For example, additional tillers that typically form in response to improved crop P status may not have sufficient moisture (or nutrition) to deliver higher grain yields later in the season.

The second point to notice is that ‘poor’ sorghum crops are able to acquire more P and K from soils with similar low nutrient status than chickpeas. This is consistent with more frequent in-season rainfall events that either enhance root access to stratified topsoil layers or having in-season rainfall events that allow deep bands to ‘re-wet,’ providing prolonged access to those deep bands. It is worth noting here that deep sowing of chickpeas, which commonly occurs in CQ, would further restrict access to stratified topsoil P or K during the season.

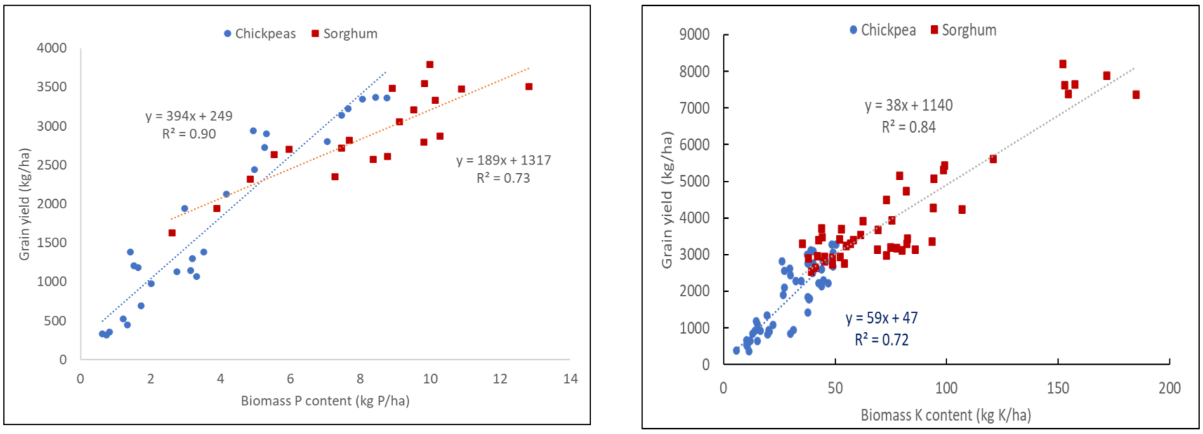

Figure 3. The relationship between biomass P (a (left)) of K (b (right)) uptake and grain yield for sites characterised by low P and K in the soil profile. Most sites in this analysis were from CQ, although the single low K Vertosol site in Southern Qld was included in the K dataset.

The third point is that in these studies we generally did not see any evidence of luxury uptake of P or K from deep banded fertilisers of either kind. This suggests that for every additional kg of P or K acquired in these soils, a relatively predictable grain yield increase will occur, and that the higher the seasonal yield potential the greater the crop nutrient requirement. While handy for discussions with the bank manager, this finding does highlight that a single application of deep bands of P and K will not be enough to overcome the yield constraints that have developed from prolonged nutrient run down. This is consistent with other glasshouse and lysimeter studies (van der Bom *et al.,* 2022) and supports the hypothesis that a multi-pronged approach to restoring soil fertility is required. Deep bands are not THE solution to declining soil P and K fertility. While they can produce significant and economic yield responses, they need to be combined with fertiliser strategies that also ensure adequate P and K is maintained in the topsoil layers, so crops can utilise multiple soil layers when seasonal conditions permit.

Including sites with higher topsoil P, introducing variable reliance on deep P bands

The inclusion of sites with a broader range of soil P fertility, primarily in the top 10cm, brought more site-years into the analyses shown in Figure 3, and provided enough wheat seasons to provide relationships to compare with chickpeas and sorghum. Unfortunately, there were not enough K sites on vertosols to undertake a similar analysis, although there is very low soil K found in other soil types like the ferrosols of the inland Burnett.

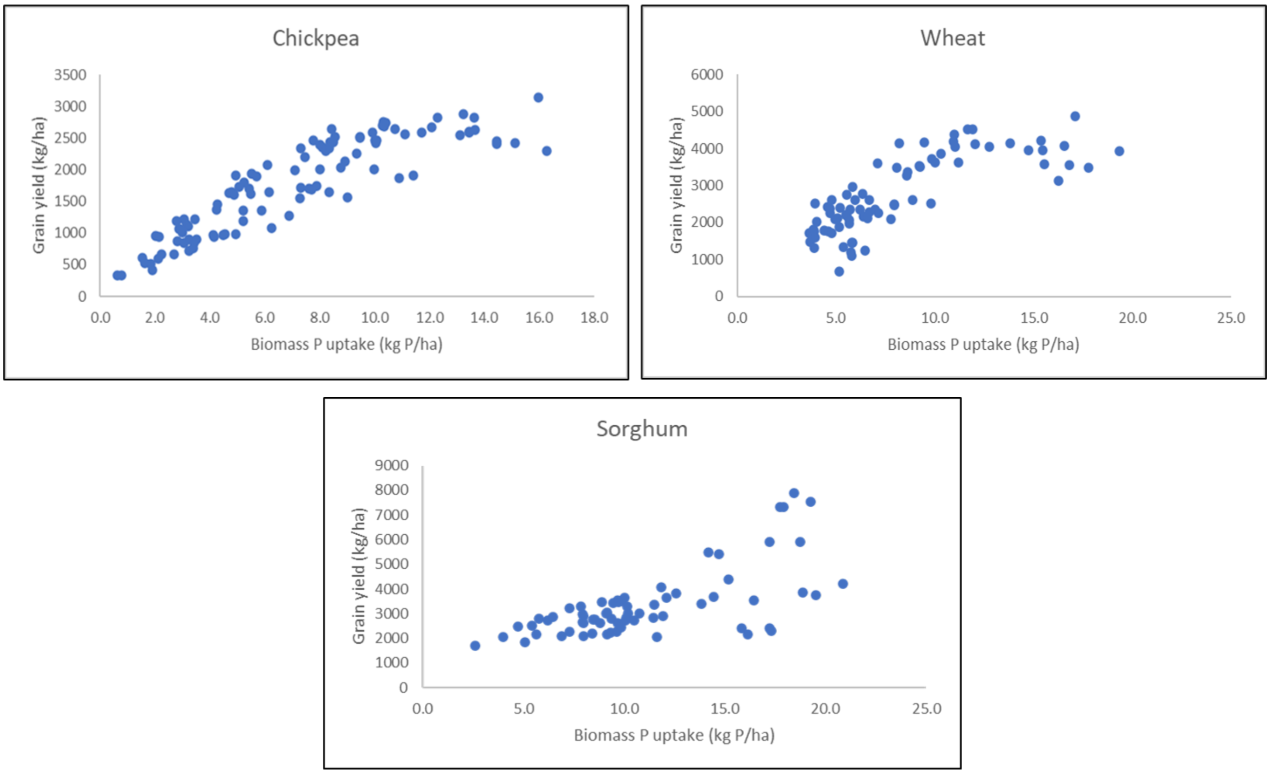

Figure 4. The relationship between biomass P uptake and grain yield for all sites regardless of topsoil P status, and in SQ as well as CQ. All sites had subsoil Colwell P ≤8 mg P/kg. Higher topsoil P concentrations and wet seasonal conditions resulted in higher crop P uptake and non-linearity in the relationship between P uptake and grain yield in both wheat and chickpeas.

This analysis showed that for both wheat and chickpea, up to 10 (chickpeas) to 12 (wheat) kg P/ha in crop biomass was required to meet demands of the highest yielding crops in these studies (i.e. 3t/ha for chickpeas and 4-5 t/ha in wheat). Each kg P/ha less than those thresholds would see potential yields drop by 330 kg/ha in wheat and by 230 kg/ha in chickpea. The data for sorghum is less clear, although there is also a suggestion that crop P uptake of 12-15 kg P/ha would meet demands of all except very high yielding sorghum crops (>6 t/ha). If the crops that achieved low yields despite high P uptake (often due to N deficiency) were excluded from this analysis, yield potentials would fall at a similar rate to wheat for each 1 kg P/ha reduction in crop uptake.

How much P can crops acquire from deep P and K bands

We have been unable to precisely quantify where the P or K accumulated in crop biomass has come from – either the background soil or the applied fertiliser in the deep bands, or varying proportions of each depending on seasonal conditions. We have instead primarily used differences in crop P/K accumulation between fertilised and unfertilised treatments, or deep ripped and tilled treatments versus the standard commercial practice (Farmer Reference) at each site. This is probably a reasonable approximation in sites with very low P in the topsoil and subsoil, as there is not much other P to find. However, these calculations become less certain when there is either high P/K in the top 10cm (with seasonal conditions determining different access to that layer from year to year), or still some background Colwell P or exchangeable K in the soil profile (e.g. when subsoil Colwell P is >5 mg P/kg or exchangeable K is >0.15-0.25 cmol(+)/kg). The use of tracers in deep bands will improve the precision of these estimates. This will be important to determine how efficiently these potentially expensive deep banded applications are being utilised. We have had some success using the natural abundance of Rubidium (Rb) to track uptake of fertiliser K, but have typically found that this approach is less successful after the first crop in the sequence following deep banding. Using isotopes of P (and K?) are approaches that are currently planned for investigation as options in future research.

Accepting the uncertainties in the estimates based on the preceding paragraph, our best estimates suggest that the most additional fertiliser P accumulated by winter crops (wheat or chickpea) is ~3-4 kg P/ha, while that of summer sorghum can be a little higher at 4-6 kg P/ha. Apparent uptake of fertiliser K is higher than P, ranging from 10-30 kg K/ha in winter crops and 10-40 kg K/ha in sorghum. We suspect the slightly greater recovery from deep bands in sorghum is due to seasonal conditions that typically see at least one in-season rainfall event where falls of 50mm or so can rewet the profile to the depth of the deep bands. Rainfall events in winter are typically smaller, and once the deep band vicinity is dried out by root activity, it remains dry and the nutrients unavailable until the profile refills again during the fallow. The timing of deep band access, when any rewetting occurs, the amount of nutrient acquired from the bands and the background nutrient supply from other soil layers (P and K in the top 10cm, and N from the whole soil profile) will determine the impact of that acquisition on crop response.

There are two observations that should be noted in relation to this. The first is that the figures above represent crop recoveries from a single application of deep banded P and/or K, with bands spaced 50cm apart. While we do not have many examples of situations where we have re-applied these bands after 5-6 years, we have seen a doubling of apparent P acquisition when fresh P bands were applied in different positions in some sites from CQ. We can’t say whether this is because the residual P in the old bands has been depleted/less available, or whether the crops are responding to a doubling of the P-enriched soil volume in the 10-30cm layer (i.e. now two bands rather than one). However, it does lend support to a potential rebuilding of subsoil P fertility by repeated deep P banding over time.

The second is that the much larger apparent recovery of K from deep bands than P and the implications this will have for the frequency of reapplication. Crop removal of K in harvested grain (15-30% of total crop uptake) is a much smaller fraction of total nutrient uptake than the equivalent for P (70-90% of total crop uptake, or greater in low P crops). When combined with the greater total uptake of K, we see an apparently rapid depletion of the deep banded K and a re-enrichment of the surface 10cm layer by the residues. This would suggest that once subsoil K is depleted, more frequent applications may be required for this nutrient than for P, although more work is needed in this instance.

Some local experiences with deep P at Merinda Farms (Michael Ledingham)

Exposure to deep P started some years ago when we hosted trial work organised by Dave Lester. Through soil testing and these trial observations we realised P concentrations were generally low at depth across the farm, although surface P levels were not too bad.

In 2013 we applied fertiliser to 50ha in different fields across the farm in test strips to assess the benefits at a larger scale. We applied 100 kg/ha Starter Z, at row spacing of 20cm to depths of 20-

25cm using an old AFM cultivator with 650 lb tyne breakout. It was slow and time consuming, as the AFM wasn't really up to the task.

Gavin McDouall inspected the crops grown for a year or two later. I think both Gavin and our team thought that there were visual differences during various crops and crop growth stages, although yield recording proved difficult. Problems with header monitors and operators inputting incorrect settings were just some of the issues. The onset of the drought curtailed crop activity and any attempts to monitor those strips ceased.

To the present day.

We feel that improved telematics on the headers, combined with weigh scales on chaser bins and trucks, may mean that many of the harvest issues are now behind us. More recently we have converted a 'cotton ripper' with tyne spacing at 75cm, and so we are able to place fertiliser 25-30 cm deep. Our aim is to apply at a sufficient rate to last for 5 years through our cropping rotation. We just need fertiliser prices to come down!

Conclusions

Our farming system relies on accessing soil water stored in the profile over fallow periods to overcome the large in-season variability experienced in the northern grains region. For this system to function, crops need to be able to access both water and nutrients from subsoil layers for extended periods in the growing season. Depletion of native fertility reserves from these deeper layers, and the inability to leach P and K into deeper layers mean that unlike N, fertiliser strategies are increasingly having to consider direct subsoil nutrient replacement.

Soil surveys and conversations with growers, agronomists and advisers across the NW slopes tend to indicate subsoil K could be marginal based on experiences from sites in southern and central Qld, but being a soil and region specific limitation, on-farm test strips are most likely best method of validating this.

Deep banding methods have been well researched, with aspects of the fertiliser products, placement depth and band spacing now well defined. Relationships between additional crop P/K uptake from deep bands and likely grain yield responses have been developed to help in economic considerations. However, the size of crop response to deep banded applications of both nutrients in any season will depend on factors such as soil fertility status in topsoil and subsoil layers, in-crop rainfall and the availability of the other nutrients needed to support higher crop yield potentials.

Deep banding has proven to be profitable in many situations, but responses have been less impressive in others for a variety of reasons. Gowers need to develop a clear picture of the nutrient status of the topsoils and subsoils of all their fields to identify likely nutrient constraints and where they occur. Then apply test strips in the fields most likely to be responsive, applying the likely limiting nutrient(s) at rates you would like to apply, and then at rates of double that (to make sure you can see potential responses). Don't forget to include other nutrients that may be needed to support higher yield potentials (e.g. extra N) and be prepared to measure the crop response over time. The residual value of these applications will be a large contributor to the profitability of deep banding strategies. Ensuring that residual effects on crop yield can be measured easily is a key step to deciding whether an expanded program will pay in your soils.

Fertiliser prices will obviously impact on the profitability of any additional fertiliser inputs in cropping systems. However, there are some very depleted soils across the NGR, especially with P and the potential yield response to improved P nutrition is large. Weighing the costs of deep placement against additional crop production will ultimately determine individual investment decisions, but allowing the decline in subsoil fertility reserves to continued will create even larger problems for profitability and sustainability in the future.

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Contact details

Prof Mike Bell
University of Queensland
Gatton Campus, Gatton 4343
Ph: 0429 600 730
Email: m.bell4@uq.edu.au

Panel discussion on N issues and strategies for 2022

Notes

KEY CONTACTS

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

NORTHERN REGION

TOOWOOMBA
214 Herries Street
TOOWOOMBA, QLD 4350

P: +61 7 4571 4800
northern@grdc.com.au

OPERATIONS

SENIOR REGIONAL MANAGER
Gillian Meppem
Gillian.Meppem@grdc.com.au
M: +61 4 0927 9328

BUSINESS SUPPORT TEAM LEADER
Adam van Genderen
Adam.vangenderen@grdc.com.au
M: +61 4 2798 4506

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

CONTRACT ADMINISTRATOR AND PANEL SUPPORT
Camilla Pettersson
Camilla.Pettersson@grdc.com.au
M: +61 4 4878 1277

CONTRACT ADMINISTRATOR
Mark Waterhouse
Mark.Waterhouse@grdc.com.au
P: +61 7 4571 4800

APPLIED RESEARCH DEVELOPMENT AND EXTENSION

GENERAL MANAGER APPLIED RD&E
Peter Carberry
Peter.Carberry@grdc.com.au
M: +61 4 1965 6955

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

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

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

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

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

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

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

GROWER RELATIONS MANAGER
Graeme Sandral
Graeme.Sandral@grdc.com.au
M: +61 4 0922 6235

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

GENETIC AND ENABLING TECHNOLOGIES

GENERAL MANAGER GENETIC AND ENABLING TECHNOLOGIES
Nicole Jensen
Nicole.Jensen@grdc.com.au
P: +61 7 4571 4800

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

COMMUNICATIONS

HEAD OF COMMUNICATIONS (NATIONAL)
Toni Somes
Toni.Somes@grdc.com.au
M: +61 4 3662 2645

COMMUNICATIONS OFFICER
Amelia Williams
Amelia.Williams@grdc.com.au
M: +61 4 6030 6003

STRATEGY AND BUSINESS DEVELOPMENT

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