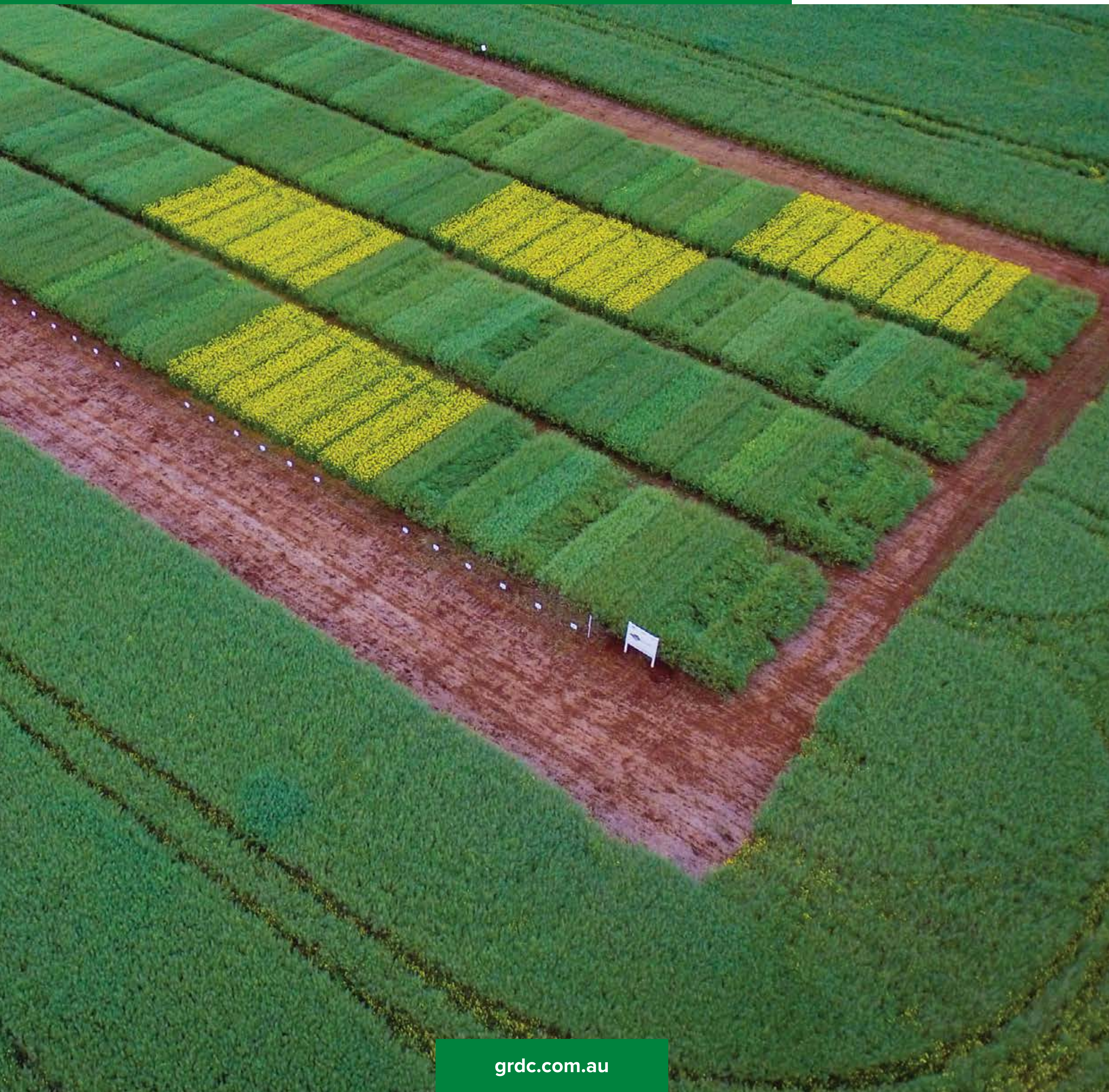
WEEK 1
NEW SOUTH WALES
TUESDAY 15,
WEDNESDAY 16,
THURSDAY 17
FEBRUARY 2022

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION



Agendas for Northern GRDC Grains Research Updates, online
Week 1 – 15, 16 and 17 February 2022

Tuesday 15 February 2022 - Carbon system footprints, sequestration and climate models

Time (AEDT)	Topic	Speaker
8:30 AM	GRDC	John Minogue and Peter Carberry (GRDC)
8:55 AM	How large is the greenhouse gas footprint of grains farming systems and options to reduce this?	Maartje Sevenster (CSIRO)
9:35 AM	Carbon sequestration options for grain producers in NSW & Qld - pros, cons and pitfalls.	Peter Grace (Queensland University of Technology)
10:10 AM	AgScore. A form guide for selecting the best climate model to use - how accurate are different models in different regions and situations?	Patrick Mitchell (CSIRO)
10:40 AM	Morning tea	

Tuesday 15 February 2022 - Farming systems - crop sequence and nutrition – SNSW

Time (AEDT)	Topic	Speaker
11:10 AM	Farming systems performance at a 'macro' scale – productivity, profit, risk, WUE and interactions between management strategies. Drill down topics: - Pulses, oilseeds and crop sequence - Dual-purpose crops - N management	John Kirkegaard, (CSIRO) & Mathew Dunn (NSW DPI)
11:50 AM	What is the N legacy following pulses for use by subsequent crops and what management options are important to optimise N fixation?	Mathew Dunn (NSW DPI) & Tony Swan (CSIRO)
12:25 PM	Consultant led panel discussion - key insights from farming systems research	Tim Condon (Delta Agribusiness), Greg Condon (Grassroots Agronomy), Mathew Dunn (NSW DPI), Tony Swan (CSIRO), John Kirkegaard (CSIRO)
12:55 PM	Lunch	

Tuesday 15 February 2022 - Nutritional strategies for 2022 – SNSW

Time (AEDT)	Topic	Speaker
1:55 PM	Balancing the risk and reward of high N and P input costs for 2022	Jim Laycock (Incitec pivot)
2:25 PM	Nutrition and rotation strategies after two big years and with high fertiliser prices – where can you cut, when is cutting false economy and is crop rotation an option?	John Kirkegaard (CSIRO), Mathew Dunn (NSW DPI), Jim Laycock (Incitec Pivot), Heidi Gooden (Delta Agribusiness), Tim Condon (Delta Agribusiness)
3:05 PM	Close	

Wednesday 16 February 2022 - Weed recognition technologies and disc seeders

Time (AEDT)	Topic	Speaker
8:30 AM	Weed recognition technologies - developments and opportunities for Australian grains systems	Derek Long (USQ Centre for Ag Engineering)
9:05 AM	Drilling down into disc seeders - issues to manage when transitioning to a disk seeder and optimising performance (residue, stripper fronts, soil moisture and crop establishment)	Neil Durning (Riverina Independent Agronomy)
9:35 AM	Practical considerations when transitioning to disc seeders	Roger Bolte (Grower, West Wyalong)
9:50 AM	Panel session: Farming system impact and changes when moving to disc seeders	Neil Durning (Riverina Independent Agronomy), Roger Bolte (Grower, West Wyalong)
10:10 AM	Morning tea	

Wednesday 16 February 2022 - Cereal disease and subsoil – SNSW

Time (AEDT)	Topic	Speaker
10:40 AM	Subsoil management to improve crop productivity in dryland cropping: Linking changes in PAW and root responses to sub soil amendments. Varietal differences and novel new ameliorants.	Ehsan Tavakkoli (NSW DPI)
11:05 AM	Stripe rust outbreaks in 2021 - what did we learn that's helpful to planning for 2022?	Robert Park (University of Sydney)
11:35 AM	Cereal disease issues for 2022. What did we learn in 2021 and how can we use this to improve management this season?	Brad Baxter (NSW DPI)
12:00 PM	Fusarium crown rot in southern farming systems - how big an issue is it? - Harvest height implications - Integrated management - Potential fit of Victrato® seed treatment	Steve Simpfendorfer (NSW DPI)
12:25 PM	Lunch	

Wednesday 16 February 2022 - Cereals and sensor technologies

Time (AEDT)	Topic	Speaker(s)
1:25 PM	How do wheat varieties compare for heat tolerance?	Richard Trethowan (University of Sydney)
1:55 PM	Cereal breeding frontiers - awnless wheats, heat and drought risk with grazing/hay wheats, 100 day wheats for late sowing - can we breed another H45? Advances with long coleoptile wheats for deep sowing.	Greg Rebetzke (CSIRO)
2:25 PM	Satellite imagery, smart phones and drones to classify crops, interpret and predict seasonal growth patterns for on farm decision making and support variety selection.	Scott Chapman (UQ) & Andries Potgieter (UQ)
3:05 PM	Close	

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Thursday 17 February 2022 - Hyper yielding crops

Time (AEDT)	Topic	Speaker(s)
8:30 AM	Fungicide resistance update - what's happening nationally and issues for the northern grains region	Nick Poole (FAR Australia)
9:00 AM	Hyper yielding cereal agronomy; outcomes benchmarks, decision points, key levers and interactions to capitalise on great seasons or irrigation. Varieties, N and fungicide lessons learnt	Kenton Porker & Nick Poole (FAR Australia)
9:35 AM	Grower experience growing hyper yielding crops without irrigation - risk and rewards	Craig Marshall (Grower, Mulwala NSW)
9:50 AM	Grower experience growing hyper yielding crops with irrigation - risk and rewards	Geoff McLeod (Grower, Finley NSW)
10:00 AM	Panel discussion	
10:15 AM	Close	

Contents

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Australian grains baseline and mitigation assessment

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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.

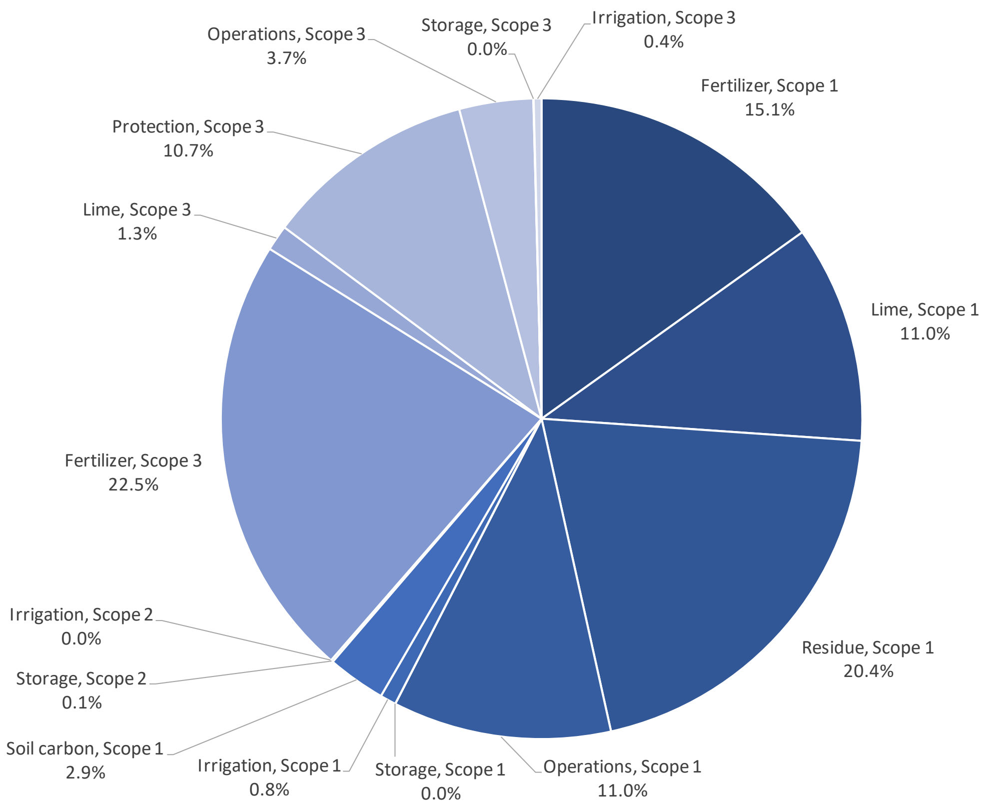

Figure 1. Contributions of emission source categories to the total GHG emissions baseline using 2005 data. Residue emissions are those from the burning and decomposition of crop residue.

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.

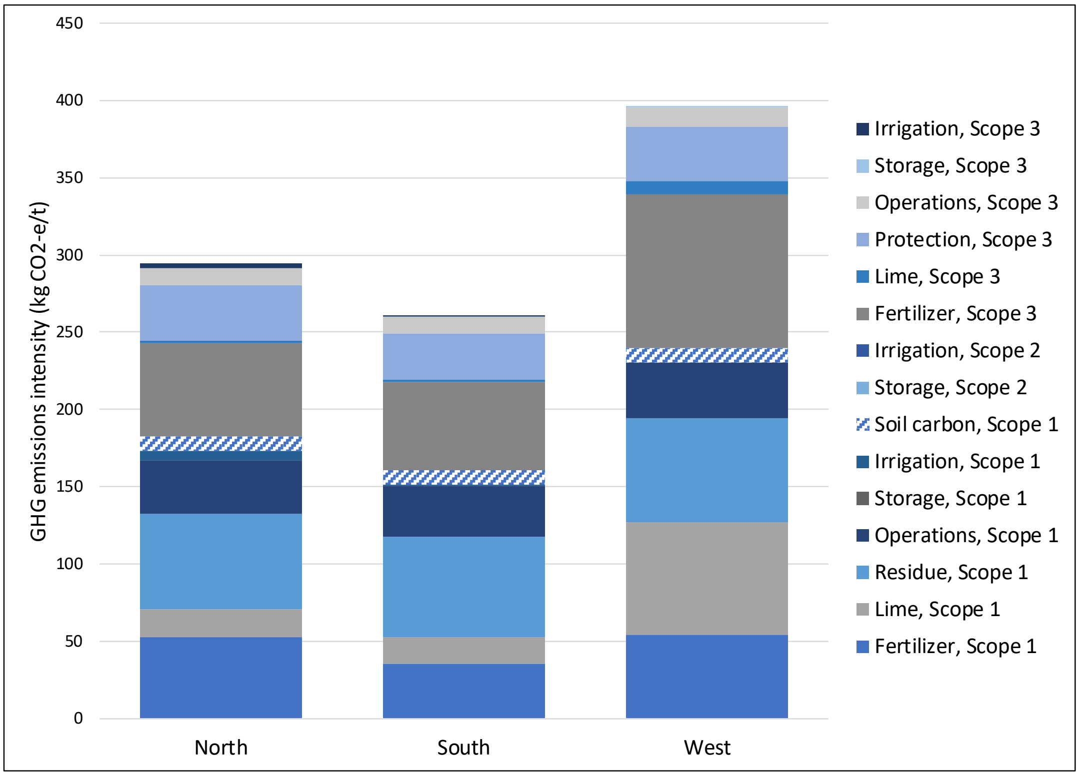

Figure 2. GHG emissions intensity and the contributing sources of emission in 2005 for each GRDC region.

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.

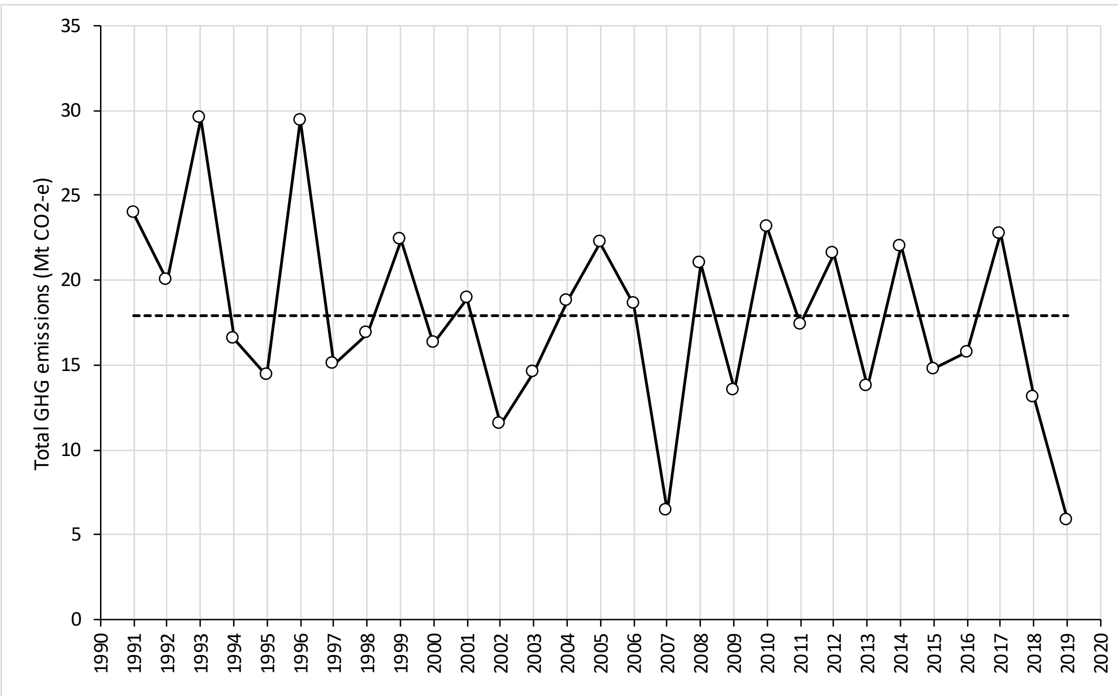

Figure 3. National year-by-year variability in simulated GHG emissions using APSIM (dotted line indicates the 29-year average).

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.

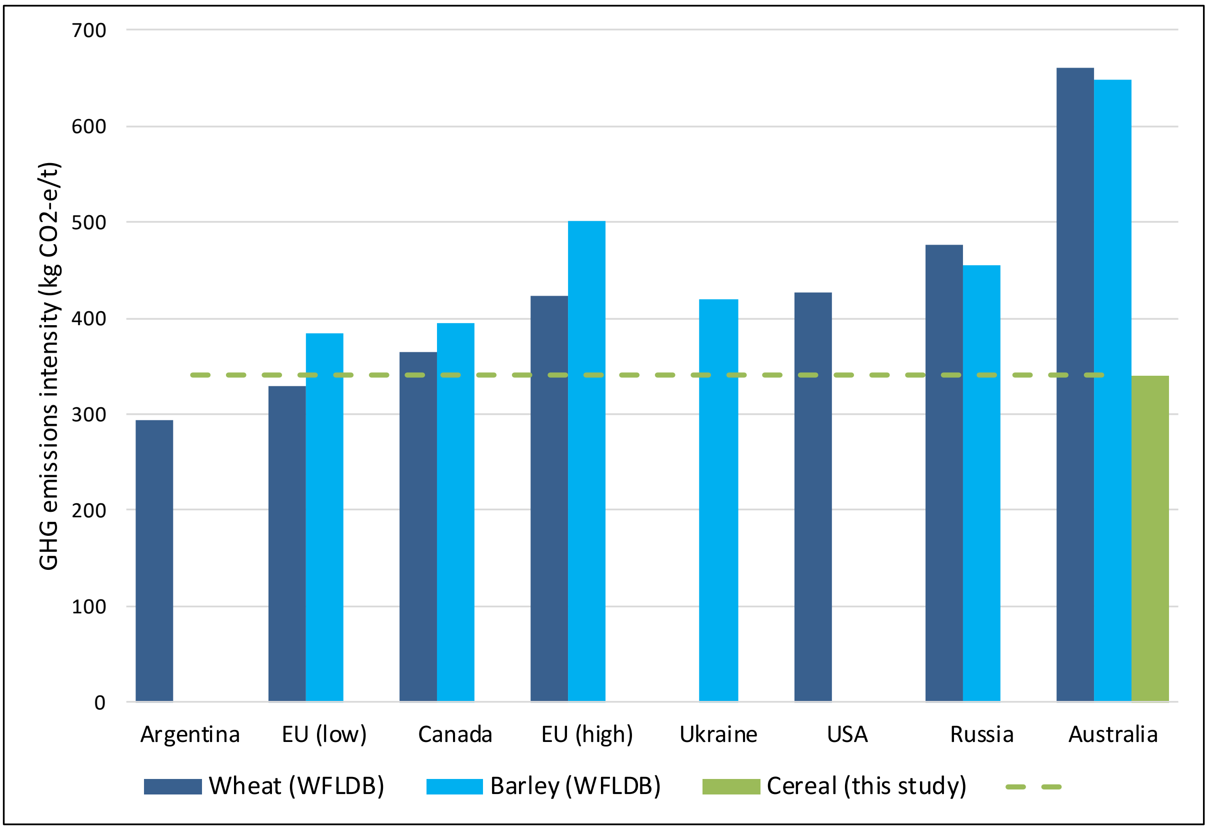

Figure 4. Comparison of GHG intensity results for wheat and barley, by country as available in the World Food Life Cycle Assessment Database (WFLDB), with the result from this baseline assessment for cereals. All data exclude emissions from soil carbon change and land use change.

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.

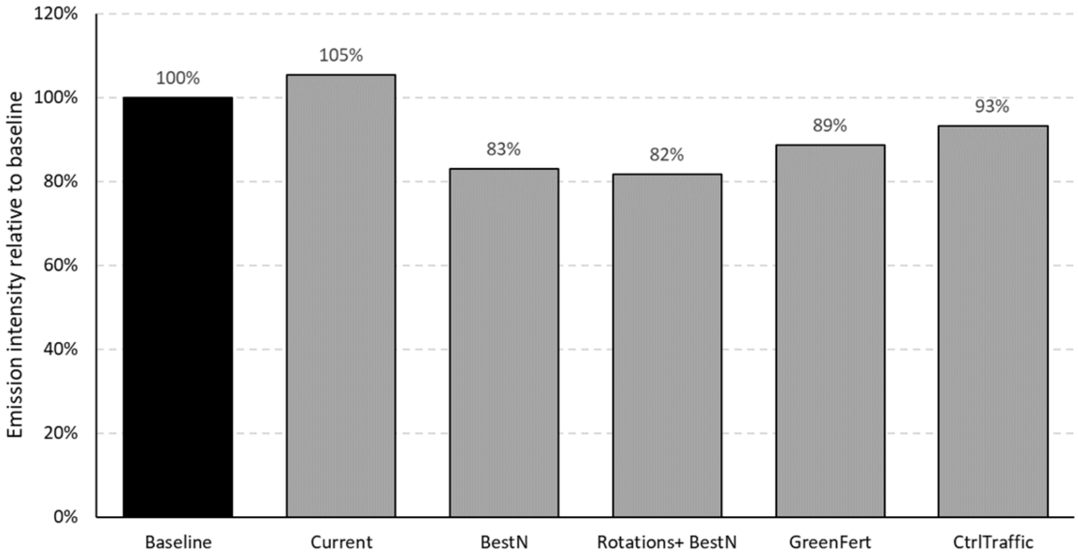

Figure 5. Relative total emission intensity in kg CO_2-equivalent per tonne grain nationally by mitigation scenario modelled compared to the static baseline (2005). The Current (2015) scenario reflects the effects that changes in rotation and nitrogen application rates since 2005 have had. Values for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

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Building soil carbon for your business

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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 - Biochemical energy - Increased resilience - Biodiversity	- Water retention - Structural stability - Thermal properties - Erosion	- Cation exchange - pH buffering - Complex cations

(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).

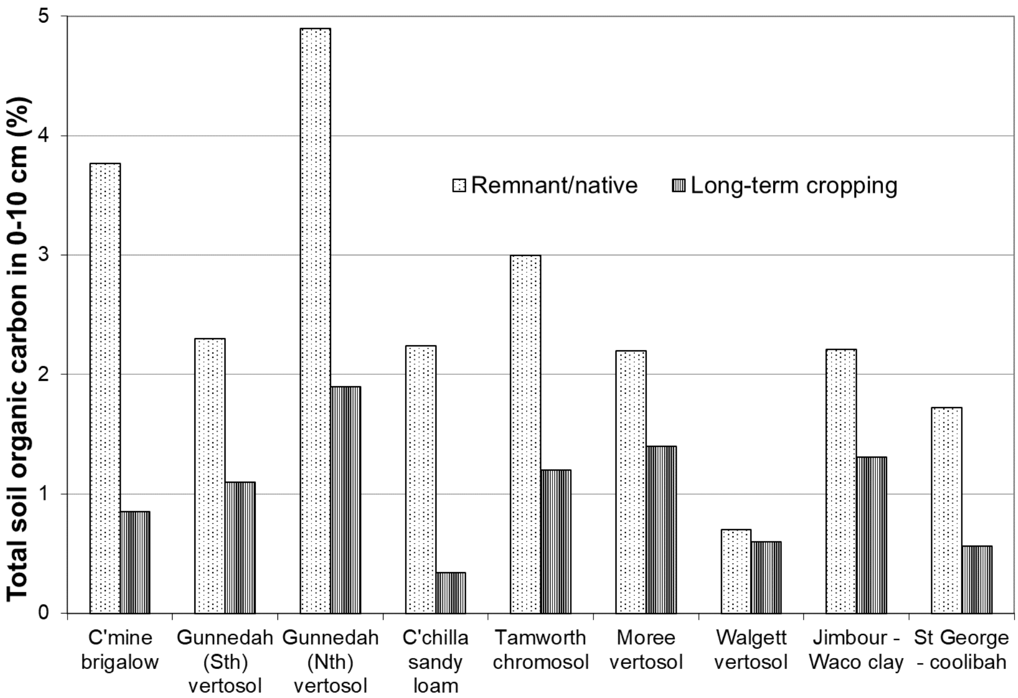

Figure 1. Impact of long-term cropping on soils of the northern grains zone (Lawrence *et al.,* 2017).

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

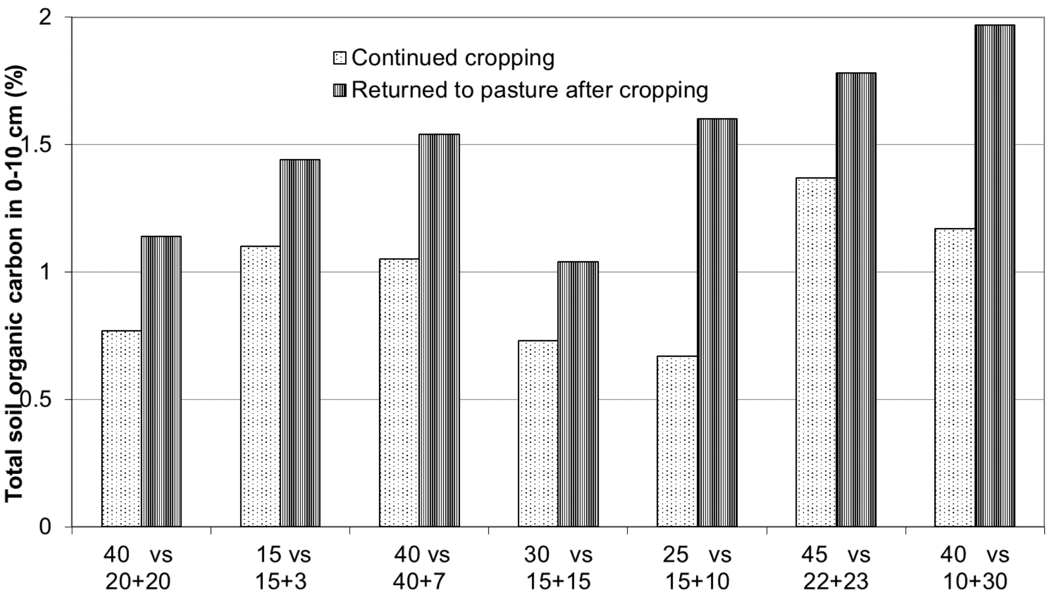

Figure 2. Changes in soil organic carbon levels after shifting from crop to pasture in the northern grains region (Lawrence *et al*., 2017). First value is the total duration of the cropping phase, second value is the duration of the cropping and pasture phases.

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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AgScore: A form guide for selecting the best climate model to use - how accurate are different climate models in different regions and situations?

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GRDC code

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Take home message

- The regional inter-model comparison of 12 seasonal forecast systems showed that no single forecast system stood out as superior in predicting rainfall for all regions and seasons. However, our analysis did identify groups of models having skill, particularly in winter and spring
- The Bureau's model (ACCESS-S1) was consistently one of the top performers across most of eastern and northern Australia based on our regional analysis
- A more in-depth evaluation of wheat yield forecasts generated from the top performing forecast systems indicated sufficient skill from mid-way through the season (July). This implies that at best, seasonal climate forecasts can provide guidance on yield estimates during the middle to latter stages of the winter growing season.

Introduction

The AgScore project represents a new approach to a pertinent question in agri-climatology: How good is my seasonal climate forecast? Seasonal climate forecasts (SCFs) can provide important information and can reduce agricultural decision-making risk, provided they are timely, relevant and accurate (Meinke *et al.,* 2006). Seen as a critical innovation for farming in the last three decades, the uptake of SCFs is increasing but still faces major challenges particularly around their quality and usefulness (Hayman *et al.,* 2007; Taylor, 2021).

The agricultural sector is one of the largest users of SCFs, particularly for farming systems that are dependent on seasonal patterns of rainfall e.g., grains and livestock industries (Centre for International Economics, 2014; Robertson *et al.,* 2016). A skilful SCF can mean many different things depending on the user and how the forecast information affects their decision-making process. Agriculturally relevant forecasts can include climate-based predictions for specific time windows or relevant thresholds (e.g., probability of receive in excess of 20 mm in the next month) and more sophisticated predictions of yield or farm productivity (Cowan *et al.,* 2020; Hansen *et al.*, 2004).

A central premise of the AgScore project is that the evaluation of seasonal climate models, and the forecasts derived from them, often lack information on how their performance might influence agricultural decision-making. Broad regional indicators of model skill (e.g., ability to simulate ENSO over the Top End) may help to inform climate researchers about the model's ability to simulate high-level climate drivers (Duan and Wei, 2013) but may provide little information on forecast value for agricultural users (Jagannathan *et al.,* 2020). Agricultural users of forecasts often require the translation of climate-based forecasts into particular climate-driven indicators to inform the seasonal trajectory of productivity and their overall profitability (Lacoste and Kragt, 2018; Meinke *et al.,* 2006). This has motivated the AgScore project to look at SCF performance and value from several perspectives and develop a common benchmarking approach to comparing different SCFs.

This paper reports on two components of the AgScore project, namely:

1. A side-by-side evaluation of different forecast systems from a suite of international forecasting agencies for the major agricultural regions across Australia.
2. Further examination of a subset of these forecast systems in terms of their ability to predict wheat yield.

How good are the forecasts for my growing region?

At the core of our approach was gauging the performance of various seasonal forecasting systems on an even playing field. We performed a regional inter-model comparison involving 12 different forecast systems including 10 dynamical global climate models and 2 statistical models (Table 1 and Table 2). The analysis presented here, is based on hindcast datasets, or forecasts generated in the past. This allows us to verify the performance of different model predictions with observations. The verification process measures the accuracy, reliability and skill of the different forecast systems over the entire hindcast period which was between 20 to 24 years (Table 1 and Table 2).

Data from the different hindcast datasets and observations were remapped to a common grid so that we could compare each forecast system at a similar spatial resolution (approximately 100km x 100km). Total rainfall and average temperature forecasts for three- and six-month forecasting windows were generated for the first month of each season (i.e., March, June, September and December). Data for key verification metrics are presented for individual grid points and averages across different Australian Agro-Ecological regions (AAEs, Williams *et al.,* 2002).

Table 1. Details of the hindcast datasets from ten Global Circulation Models included in the regional inter-model comparison.

Label	Forecasting Agency	Model	Ensemble size[#]	Data period available	Data period included in the assessment	Variables*
ACCESS-S	Bureau of Meteorology	ACCESS-S1	11	1990-2012	1993-2012	Rainfall, T_{min}, T_{max}
CANCM4I	Canadian Met Centre	CanSIPSv2 / CanCM4i	10	1980-2010 + 2011-2018	1993-2016	Rainfall, T_{mean}
CMCC	Euro-Mediterranean Center on Climate Change	CMCC-SPS3	40	1993-2016	1993-2016	Rainfall, T_{min}, T_{max}
DWD	Deutscher Wetterdienst (German Meteorological Service)	GCFS 2.0, system 2	30	1993-2017	1993-2016	Rainfall, T_{min}, T_{max}
ECMWF	European Centre for Medium Range Forecasting	SEAS5, system 5	25	1993-2016	1993-2016	Rainfall, T_{min}, T_{max}
GEMNEMO	Canadian Met Centre	CanSIPSv2 / GEM-NEMO	10	1980-2010 + 2011-2018	1993-2017	Rainfall, T_{mean}
METEO-FRANCE	Météo France	Météo-France System 7	25	1993-2016	1993-2016	Rainfall, T_{min}, T_{max}
NASA	NASA Global Modelling and Assimilation Office (GMAO)	GEOS S2S	4	1981-2016	1993-2016	Rainfall, T_{min}, T_{mean}, T_{max}
NCEP	National Centers for Environmental Prediction	CFSv2	24	1982-2011 + 2011-2019	1993-2017	Rainfall, T_{mean}
UKMO	UK Met Office	GloSea5-GC2-LI, system 14	28	1993-2016	1993-2016	Rainfall, T_{min}, T_{max}

*T_{min}, T_{max} and T_{mean} denote minimum air temperature, maximum air temperature and mean air temperature respectively.

#Ensemble size refers to the number of separate model runs available

Table 2. Details of the statistical forecast systems included in the regional inter-model comparison.

Model	Forecasting centre	Ensemble size[#]	Historical dataset	Data period included in the assessment	Variables*
SPOTA-1	Queensland Department of Environment and Science	25	1890-1992	1993-2016	Rainfall, T_{min}, T_{mean}, T_{max}
SOI-Phase	Queensland Department of Environment and Science / USQ	Variable	1890-1992	1993-2016	Rainfall, T_{min}, T_{mean}, T_{max}

*T_{min}, T_{max} and T_{mean} denote minimum air temperature, maximum air temperature and mean air temperature respectively.

#Ensemble size refers to the number of separate model runs available

We developed an interactive dashboard that presents the results of our verification analysis by allowing users to explore their regions and seasons of interest. It covers all Australian Agro Ecological regions (AAEs) excluding the arid zone, making it useful for many different agricultural sectors and provides the most comprehensive side-by-side comparison of seasonal forecasts for Australia to date. Skill is defined as a forecast that has accuracy and reliability that is better than climatology. At best a skilful forecast needs to provide more information than a forecast with an equal likelihood of a particular outcome (e.g., above median rainfall).

Across the entire set of AAEs there were similar levels of performance across the majority of the forecast systems in terms of: accuracy (weighted percent correct and Continuous Rank Probability Skill Score; CRPSS), reliability and correlation.

However, there were larger differences among SCFS for different AAEs. Some key results include:

- No clear standout forecast systems in terms of superior skill across each region and season. There was at least one model (NASA) that had consistently poor skill (worse than climatology)
- The skill (based on the CPRSS) for rainfall and temperature among SCFS tended to be lowest in autumn and higher in spring and summer months
- The Bureau of Meteorology's ACCESS-S1 model performed soundly, and skill values were consistently as good as or better than other forecast systems considered in this study (Figure 1). This was particularly true for autumn and spring forecasts for much of eastern Australia
- The Western Wheatbelt AAE (overlaps Western GRDC region) had limited skill for most of the year, with some skill in winter (Figure 2)
- The skill of forecasts for AAEs overlapping the Southern GRDC region were mixed, with those areas further west (South Australia) having lower skill than areas further east (Figure 3)
- The Northern GRDC region had higher skill in winter and spring than other wheatbelt AAEs (Figure 4)
- The SCFs based on statistical models (SPOTA-1 and SOI-Phase) did not have superior skill or accuracy to the forecasts based on dynamical models. This included AAEs where the statistical models were originally developed i.e. Queensland/Northern NSW.

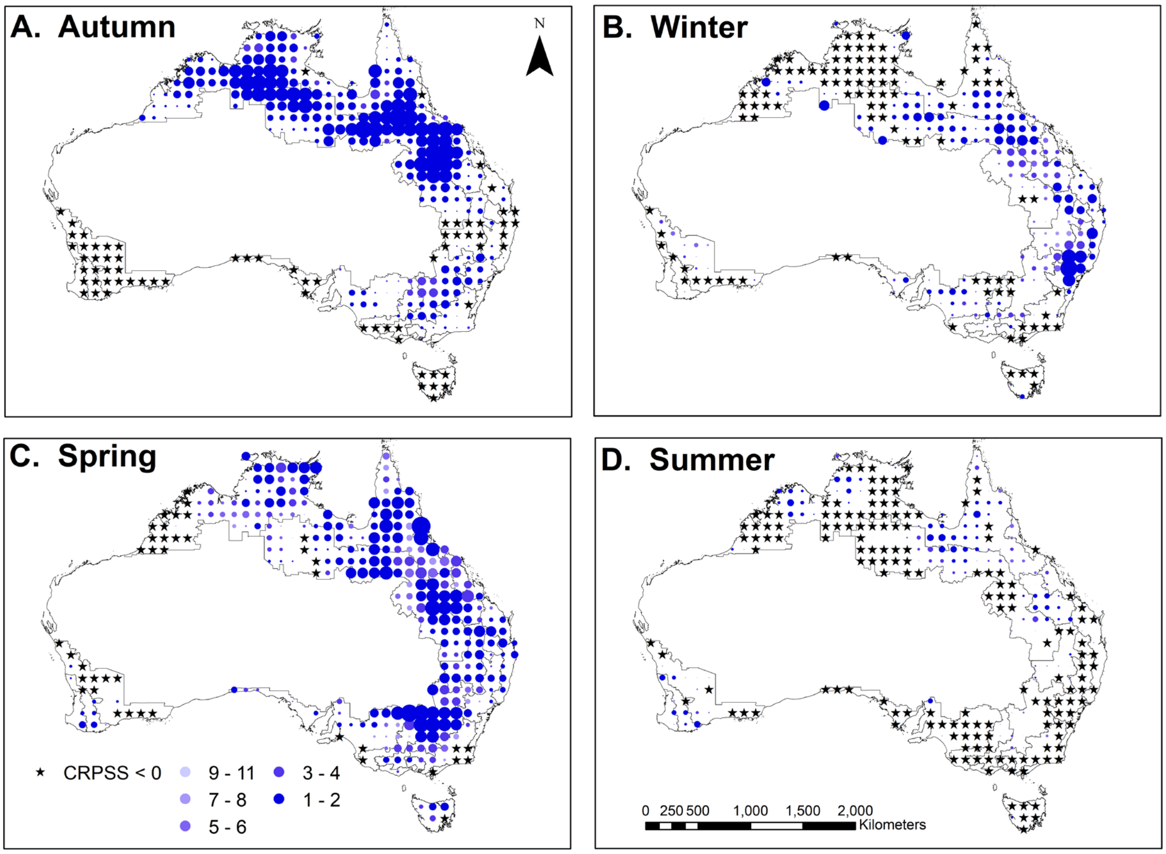


Figure 1. The ranking of the Bureau's model (ACCESS-S1) relative to the other 11 SCFs for a three-month rainfall forecast window i.e. one meaning ACCESS-S1 is the top-ranking model among the twelve models tested. The ranking was based on the Continuous Rank Probability Skill Score (CRPSS) at that grid point. The size of the symbol is scaled by the CRPSS and values less than zero are denoted by the star symbol (indicating no skill).

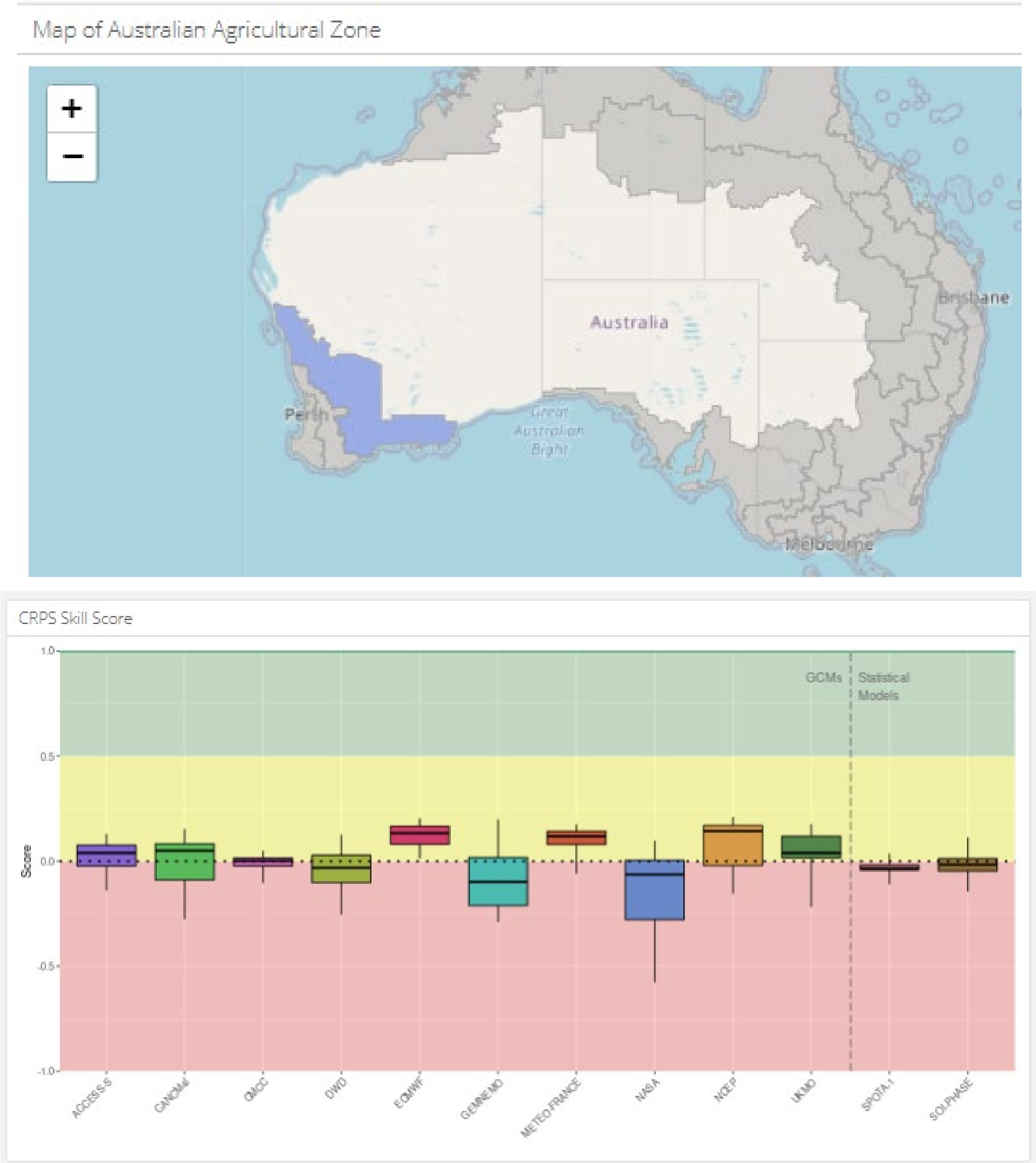


Figure 2. Top: Map of Australian Agro Ecological zones, with the Western Wheatbelt of WA in highlight. Bottom: Continuous Rank Probability Skill Scores (CRPSS) among the 12 SCFs for winter in the western wheatbelt AAE over a three-month forecast period. The background shading of each panel indicates level of skill: red (lower half of graph, CRPSS < 0) – poor or worse than climatology, yellow (middle, CRPSS between 0 and 0.5) – moderate or slightly better than climatology and green (top, CRPSS > 0.5) – good or substantially better than climatology.

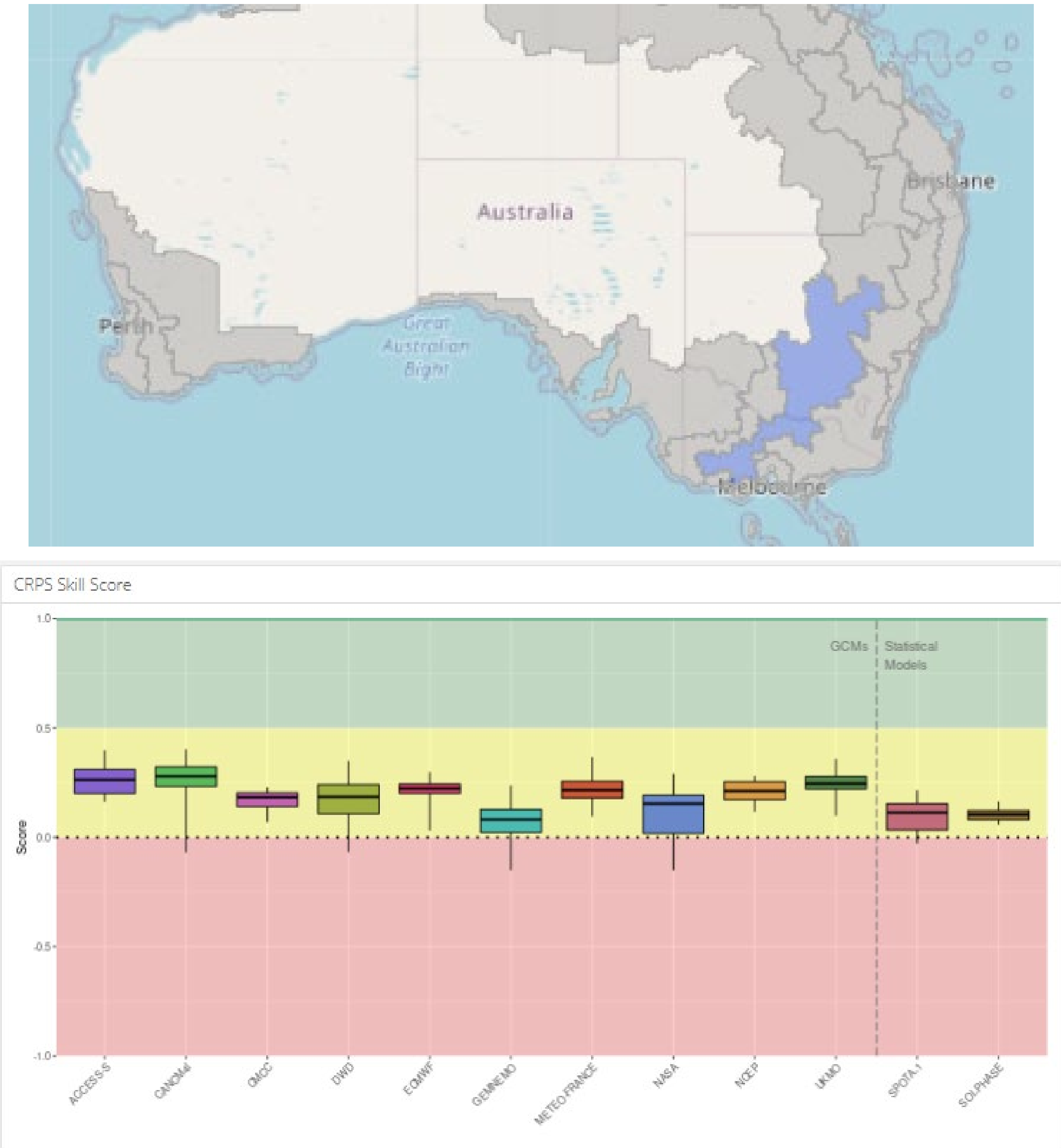


Figure 3. Top: Map of Australian Agro Ecological zones, with the Eastern Wheatbelt area in NSW and VIC in highlight. Bottom: Continuous Rank Probability Skill Scores (CRPSS) among the 12 SCFs for spring in the Eastern Wheatbelt AAE over a three-month forecast period. The background shading of each panel indicates level of skill: red (lower half of graph, CPRSS < 0) – poor or worse than climatology, yellow (middle, CPRSS between 0 and 0.5) – moderate or slightly better than climatology and green (top, CPRSS > 0.5) – good or substantially better than climatology.

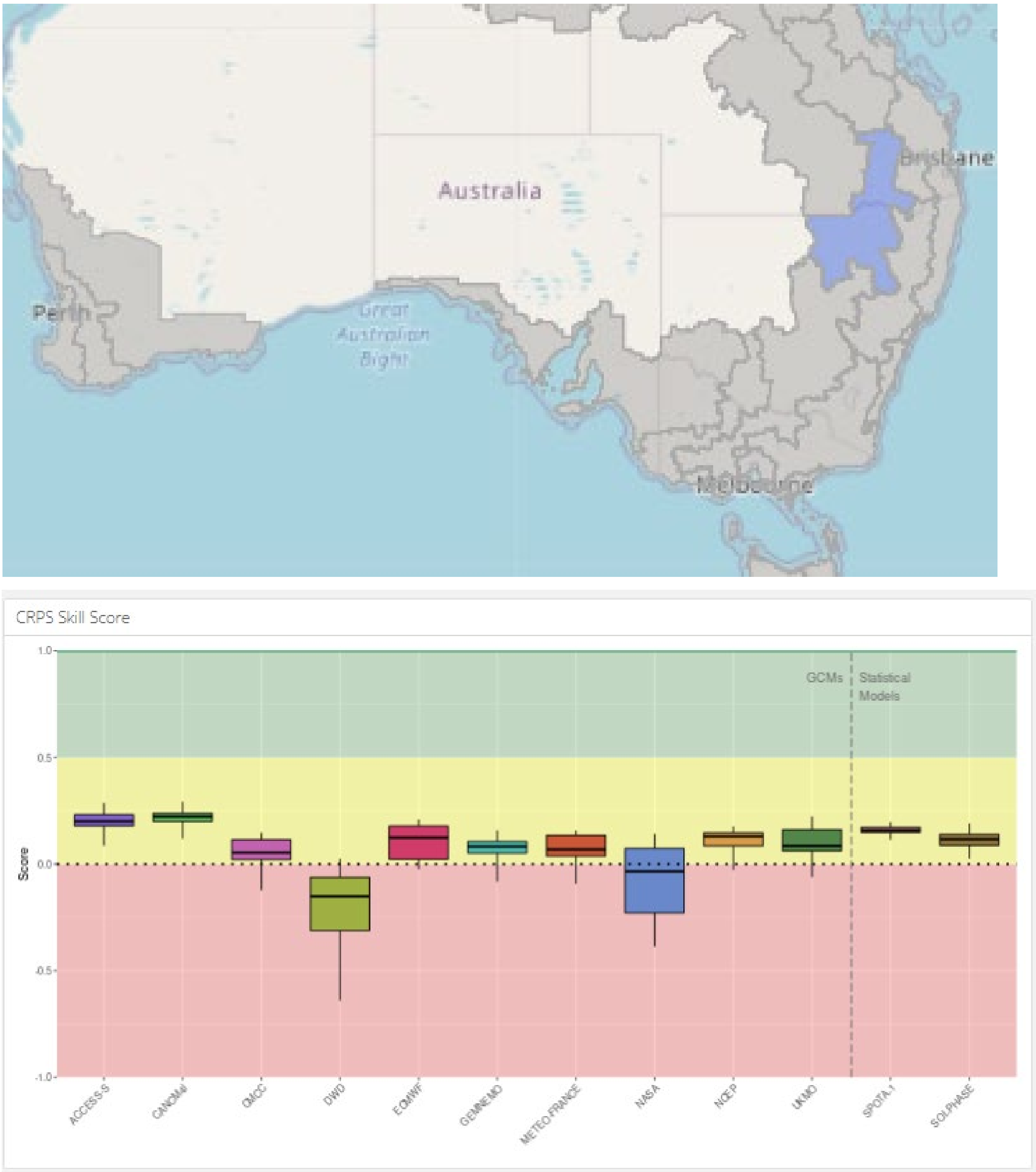


Figure 4. Top: Map of Australian Agro Ecological zones, with the Northern Wheatbelt area in NSW and QLD in highlight. Bottom: CRPSS scores among the 12 SCFs for spring in the Northern Wheatbelt AAE over a 3-month forecast period. The background shading of each panel indicates level of skill: red (lower half of graph, CPRSS < 0) – poor or worse than climatology, yellow (middle, CPRSS between 0 and 0.5) – moderate or slightly better than climatology and green (top, CPRSS > 0.5) – good or substantially better than climatology.

Limitations of the inter-model comparison

The results produced by this study need to be treated with caution. Like all climate inter-model comparisons, the verification process has several caveats that need to be considered when making conclusions from the data. Inconsistencies in hindcast data among forecast systems include differing spatial resolution, hindcast verification periods and ensemble size all contribute to further uncertainties in the analysis. Furthermore, verification of hindcast data does not capture performance of operational forecasts and it is these forecasts that can influence public perception of forecast quality and overall confidence in seasonal climate modelling overall.

Do yield forecasts offer improved performance?

The second part of the project looked at forecasting seasonal patterns in productivity in terms of wheat yield. We used a new software service, AgScore™, developed by CSIRO (Mitchell, 2021). The AgScore service was used to test five different forecast datasets including the Bureau's ACCESS-S1 and the newly released ACCESS-S2 models as well as the ECMWF-SEAS5 model (European forecasting agency). Three different calibration and downscaling methods were also tested, to compare different approaches applied to the same raw forecast data (ACCESS-S1). These downscaling methods include: a relatively simple quantile-quantile matching approach (QQ) and two more complex approaches - Empirical Copula Post-Processing (ECPP) and Bayesian Joint Probability (BJP).

The AgScore service ingests forecast datasets for a select group of locations and automatically creates and executes workflows that run simulations of wheat and performs verification analyses. The results for a particular forecast dataset are provided to the user as a report card, providing a summary of the performance of the data from an agricultural perspective. The wheat simulations were performed using APSIM and configured in a way to allow for a comparison of a model-based forecast and a climatology forecast. The wheat simulation for a particular location had a fixed sowing date (late April) and used a combination of weather observations and forecasts initiated at different start months (i.e., May, July and September) to grow the crop. This means that a simulation using a forecast data starting in May had a larger contribution of its weather input from the model-based data compared to a forecast starting in September. As in the first component of the study, forecast skill is measured as the level of improvement of the model-based forecast over climatology.

The AgScore service provides a report in the form of an interactive dashboard (Figure 5). The results use several different measures of forecast quality as well as diagnostics to identify underlying issues with the forecasts provided to the service. The target user of the service is researchers interested in climate modelling, development of calibration approaches and agricultural forecasters.

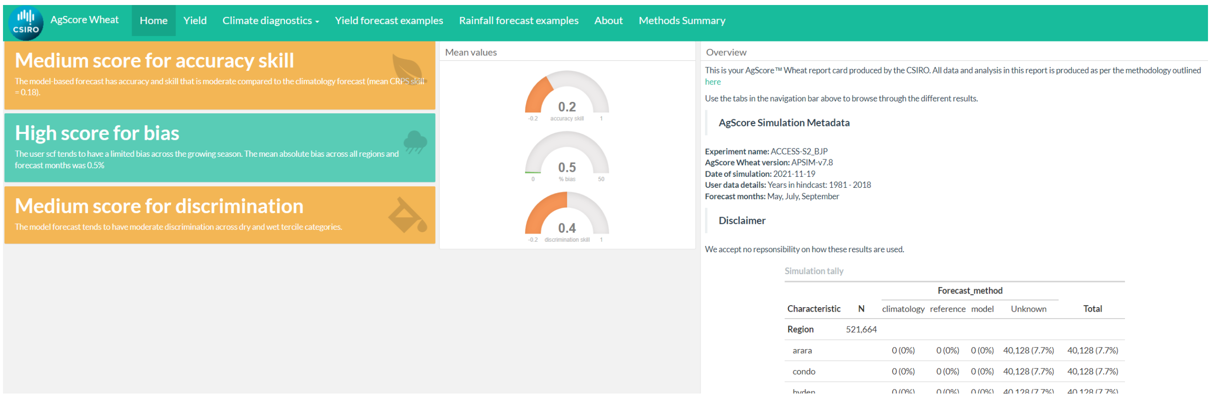
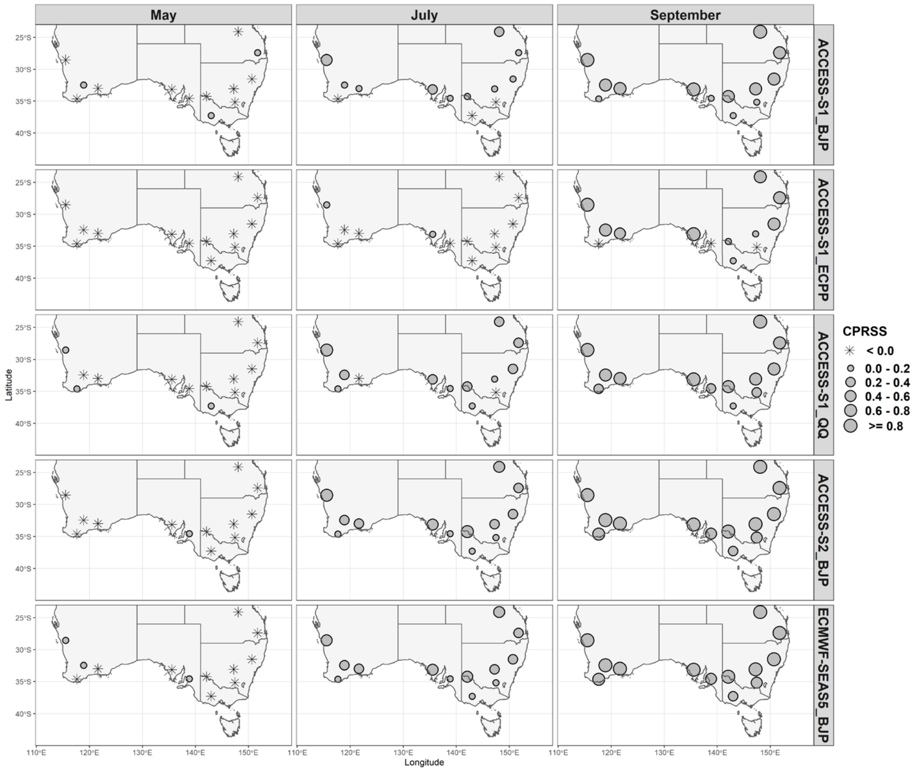


Figure 5. Example of an AgScore™ Wheat report card. Results are presented as an interactive dashboard.

A.



B.

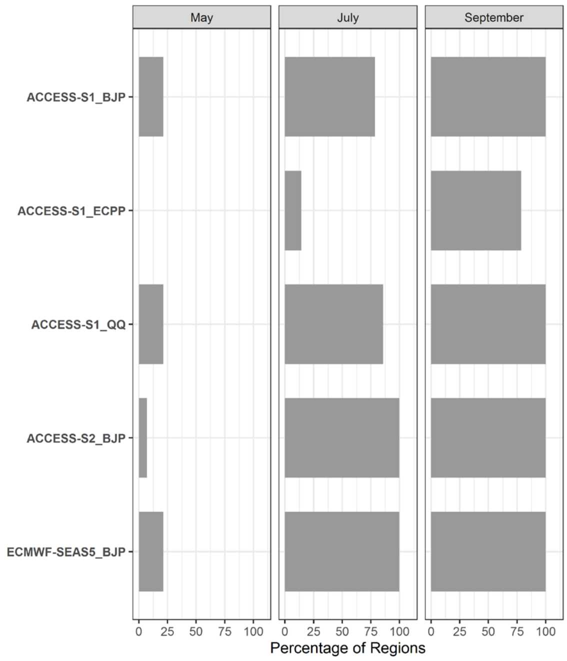


Figure 6A. Map of Continuous Rank Probability Skill Score (CRPSS) for yield among regions for different forecast months and **6B.** percentage of regions with a CRPSS greater than 0 (positive skill) for yield across all forecast months. The five different forecasts are denoted by the climate model name and downscaling method (see text for details)., The key results from this second component were:

- For most locations, yield forecasts based on the Bureau models (ACCESS-S1 and ACCESS-S2) and ECMWF-SEAS5 had skill from mid-way through the growing season (July; Figure 6).
- The new Bureau model (ACCESS-S2) showed small improvements in skill from the previous version (ACCESS-S1; Figure 6 A). This may in part be explained by the former having a longer hindcast dataset (1981-2018) over which to test the performance.
- The downscaling method applied to the climate model data had some influence on the skill of the yield forecasts, with one method (ECPP) having poorer skill compared to the other methods (Figure 6). Whereas no clear differences were found for the other two methods: Quantile Quantile matching (QQ) and Bayesian Joint Probability (BJP). This suggests that some improvements in skill can be realised using the appropriate downscaling method.

Conclusions

While there is a tendency to try and 'pick winners' when comparing forecasting performance among different global forecasting systems, this study exposes some of the complexities of taking such a position. We did not identify a single model with superior skill in all locations and seasons. For grains regions there are several models that provide skill for southern and eastern regions during winter and spring. While the Western region has limited skill across the winter growing season, noting we did not include DPIRD's Statistical Seasonal Forecast system (https://www.agric.wa.gov.au/newsletters/sco), the Bureau's model, the most widely used seasonal outlook in Australia, ranked highly among the top-performing models.

These results provide a comprehensive and standardised comparison of seasonal forecast systems whilst emphasising the need for improvement in the overall forecast performance. Furthermore, we recommend continued use of the Bureau's forecast products, but advocate for a consensus-based approach to presenting forecast information. This means presenting results of forecasts from high-performing models' side-by-side to instil confidence for growers when reading seasonal forecast information.

Forecasts translated into yield-based predictions have obvious benefit to users in that they incorporate multiple climate drivers i.e., rainfall and temperature and integrate seasonal trajectories of plant growth. Our results show that the best forecast systems and corresponding downscaling methods, can provide skill during mid to late stages of the winter wheat growing season (July onwards). This is likely to offer benefit to in-season management decisions around fertilising, marketing and logistics. Both models tested, the Bureau's new ACCESS-S2 and Europe's ECMWF-SEAS5 had similar performance and could be applied to existing wheat forecast systems such as CSIRO's National Graincast™ service (Hochman and Horan, 2019).

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Farming systems performance at a 'macro' scale: effects of management strategies on productivity, profit, risk, WUE

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Key words

risk, water use efficiency, early sowing, nitrogen, diversity, legumes

GRDC code

CFF00011, CSP2110-004RMX

Take home message

- Field experiments and simulation at 4 sites in southern NSW (2018 to 2020) investigated effects of crop diversity, early sowing (+/- grazing) and N fertiliser strategies on productivity, profit, risk and WUE of the system – using typical May-sown canola-wheat-wheat systems as a 'Baseline'
- At all sites we identified systems that were (1) more profitable by $200-300/ha, (2) less risky, (3) had stable/declining weed and disease burdens, (4) lower average input costs and (5) robust in the long term - compared to the baseline systems
- In mixed (grazing) systems, the most profitable systems involved early sown grazed crops (wheat-canola) with a higher (decile 7) N fertiliser strategy or in sequence with a legume (vetch)
- In crop-only systems, timely-sown, diverse sequences with high value legumes and a more conservative (decile 2) N strategy were most profitable
- A second phase of the experiments (2021-2023) has commenced, along with further analysis of phase 1 data and its implications at the whole-farm scale.

The Southern Farming Systems Project – a brief description

The southern NSW farming systems project (CFF00011) was established in July 2017 after a 12-month consultation period and extensive literature review demonstrated a significant gap in profitability and efficiency ($/ha/mm) of current cropping systems (i.e., actual *vs* potential) despite good agronomy of individual crops. The average annual gross margin of the best 3-4-yr sequences was often ~$400/ha higher than the worst, and $150 to $250/ha higher than the most common 'baseline' sequences. We established research sites in 2017 and associated simulation studies to investigate strategies to increase the conversion of rainfall to profit ($/ha/mm) across a crop sequence while managing weeds, diseases, soil fertility and risk.

Four sites established in 2017 covered soil and climate variability across southern NSW at Greenethorpe, Wagga Wagga and Condobolin (high, medium and low rainfall sites on red acidic loam soils), and a 4th site on a sodic clay vertosol at Urana. At each site, the 'baseline' system (sequence of canola-wheat-wheat or canola-wheat-barley; timely sown in late April-early May; and with a conservative decile 2 N strategy – i.e. N applied assuming rainfall under decile 2 (drier) conditions) was compared with a range of other systems that varied in (i) crop diversity (inclusion of legumes), (ii) sowing time (early and timely) and (iii) N strategy (conservative decile 2 and optimistic decile 7 (wetter)). Management protocols for all other input and management decisions (e.g., tillage and stubble management; variety choice; herbicide, fungicide and pesticide applications) were agreed by the project team using a consensus approach of best practice that was continually reviewed.

In the following sections we will focus on selected results that explore the consequences of these strategies in terms of productivity, efficiency and risk in different systems outlined in Table 1.

Table 1. Selected treatments common to most sites including crop sequence, time of sowing and N strategies. Early sown (March) treatments included winter grazed crops at Wagga and Greenethorpe. Diverse systems that include different legume options are shown in grey.

Treatment description	Sequence	Sowing time	N strategy (Decile 2 or 7)	Grazing
Baseline	Canola-wheat-barley	Timely	2, 7	No
Intense Baseline	Canola-wheat	Early, timely	2, 7	Yes
Diverse high value 1	Lentil-canola-wheat	Early, timely	2, 7	No
Diverse high value 2	chickpea-wheat	Timely	2	No
Diverse low value	(Faba/lupin)-canola-wheat	Timely	2	No
Diverse (mix)	HDL*-canola-wheat	Early, timely	2, 7	Yes
Continuous wheat	Wheat-wheat-wheat	Timely	2, 7	No
Fallow	Fallow-canola-wheat	Early, timely	7	No

Early sowing= from March 1; Timely sowing = late April to mid-May

N strategies: Decile 2 or Decile 7 apply top-dressed N each year in July assuming the season will finish as Decile 2 (lower yield and less N) or Decile 7 (higher yield so more N). N requirement is adjusted in each to account for soil N measured pre-sowing, so carry-over N from previous seasons means less N will be required and so legume or fertiliser legacy effects are captured.

Seasonal conditions at the sites 2018-2019-2020 seasons

The 2018 and 2019 seasons were dry (decile 1-2) across the sites, while 2020 was decile 7-9 across the sites (Table 2).

Table 2. Rainfall (+irrigation) (mm) at the experiment sites from 2018 to 2020 and the long-term median rainfall (LTM) and the decile for that season (brackets).

Site	2018	2019	2020	LTM
Greenethorpe	359 (2)	353 (2)	726 (10)	579
Wagga Wagga	403 (3)	320 (2)	557 (8)	526
Urana	276 (1)	222 (1)	488 (6)	449
Condobolin	218+120 (1)	162+118 (1)	685 (9)	434

As would be expected, the productivity and profitability of the individual crop options differed significantly between the Decile 1-2 conditions in 2018 and 2019, and the wetter conditions in 2020 (and 2021). A detailed consideration of the productivity and profitability of the different crops and systems under the dry conditions in 2018 and 2019 was provided in two previous papers and are provided in the reading list (Kirkegaard *et al* ,2020a, b).

In this paper we report productivity, profitability, WUE, risk for selected systems (Table 1) during Phase 1 (2018-2020).

Productivity

A summary of overall productivity (grain yield) at the sites is shown in Table 3 with the mean yield for each crop type at the sites in the dry years of 2018/2019 and the wet years of 2020/21 separated for comparison. Some general observations regarding the yield in different systems can be made.

Typically, the grain yield did not respond to the higher N strategy in the dry years although hay yield and grazing forage was increased, but in the wetter years of 2020 and 2021 there were significant and profitable responses to the increased N supply, either from the higher Decile 7 N strategy, or from a previous legume crop. Grain yield and protein, as well as the response to higher N tended to be greater in systems with higher crop diversity and less intense cereal systems (e.g., double break compared to continuous wheat. For example, in early sown, un-grazed systems, with high N supply (either fertiliser or legume) and high diversity (i.e., after double breaks) wheat yields of 8 to 9 t/ha with 12-14% protein, and canola yields of 4 to 5.5 t/ha with >45% oil were achieved.

Table 3. Average yield and yield range for crops at 4 farming systems sites during dry (2018-19) and wet (2020-21) seasons.

Crop	Sow	Greenethorpe		Wagga		Urana		Condobolin	
		2018-19	2020-21	2018-19	2020-21	2018-19	2020-21	2018-19	2020-21
Wheat	E Gr	2.0	6.1	2.1	6.0	-	-	-	-
	E	2.5	8.5	1.3	6.3	1.4	7.2	1.8	5.8
	T	2.5	7.6	2.1	6.6	2.6	7.3	2.2	4.4
Canola	E Gr	0.4	3.8	0	2.8	-	-	-	-
	E	1.5	4.3	0.5	3.6	1.2	3.5	1.8	3.1
	T	1.1	4.8	1.3	3.8	1.6	2.2	1.2	3.0
Lentil	T	1.3	3.0	1.1	4.1	1.7	3.6	1.1	2.2
Chickpea	T	2.0	3.5	0.9	3.1	-	4.2	1.5	2.3
Lupin	T	-	-	1.5	4.1	-	-	1.2	2.4
Faba	T	2.2	6.5	-	-	1.9	6.6	-	-

E=Early sowing (March); T=Timely sown (mid-April to mid-May); Gr=Grazed (i.e., dual-purpose)

Systems performance at the macro scale

In the following sections on profitability, WUE and risk we will consider the impacts of early sowing (+/- grazing), crop diversity, and N strategy at each of the sites by comparing the systems with the baseline system which involves sequence of canola-wheat-wheat or canola-wheat-barley sown in early May, and with a conservative Decile 2 N strategy. In all Figures, the baseline system is shown in solid black for easy identification and comparison.

Important note: Assumptions made to calculate profit (earnings before interest and taxes (EBIT)) for the systems, including estimating a potential value for the forage removed by grazing are provided in the Appendix. Crops were heavily grazed over short periods providing very effective forage utilisation, so the grazing income should be considered as **potential.** The actual profits realised will be enterprise dependent so modifications to the assumptions made (see Appendix) should be considered (i.e. trading, breeding, agistment etc).

Profitability (EBIT)

Early sown grazed systems

Early sown (March) grazed crops (wheat and canola) were highly profitable in all seasons at both sites compared to the early-sown un-grazed equivalent treatments (Table 4). This was due to the income from grazing which has more than compensated for any grain yield penalties. The early-grazed systems were also more profitable than the baseline systems (Table 4). More detailed grazing forage and yield information are provided in a separate paper on dual-purpose crops.

Grazing provided a much greater increase in profit at Greenethorpe than at Wagga Wagga due to the longer-season, higher rainfall, deeper soil to accommodate deep rooting and higher background fertility. Grazed crops were especially profitable in the dry years (2018-19) when many grain crops failed or were cut for hay. Grazed wheat and canola crops were also responsive to the higher N supply (from both fertiliser and/or the vetch legacy effects) due to increases in both forage and grain yield from higher N.

In the un-grazed systems, the early-sown system (lentil-canola-wheat) was less profitable than the timely-sown baseline system at both sites, mostly due to the fact that the true winter wheat and canola types performed poorly in the 2018 and 2019 droughts due to later flowering under hot, dry conditions. Early sowing (March) for un-grazed crops (as in Phase 1) is unwise, however careful varietal selection and more appropriate sowing dates for early-sown crops (early to mid-April) have been included in Phase 2 to better investigate the benefits of earlier sowing in un-grazed systems.

Table 4. Average annual 3-year EBIT for early-sown grazed systems compared with early-sown un-grazed systems (winter wheat and canola, vetch) at Wagga Wagga and Greenethorpe. The baseline system of timely-sown spring canola, wheat and barley is shown for comparison.

System	Sequence	N Strategy	Wagga Wagga	Greenethorpe
Early-sown (March) grazed				
Intense Baseline	W-C-W	Decile 2	$642	$1,191
		Decile 7	$754	$1,421
Diverse	Vetch-C-W	Decile 2	$671	$1,267
		Decile 7	$777	-
Early-sown (March) un-grazed				
Diverse High Value	Lentil-C-W	Decile 2	$477	$473
		Decile 7	$386	$450
Timely-sown (early May) un-grazed				
Baseline	C-W-W or C-W-B	Decile 2	$528	$720
		Decile 7	$542	$653

W=wheat, C=canola, B=barley

Timely-sown grain-only systems

For timely-sown systems, several diverse sequences that include legumes outperformed the Baseline canola-wheat sequences at all sites (Table 5). This was true during both dry and wet seasons (data not shown). However different legume options performed best at different sites (as shown in grey in Table 5) demonstrating the need to consider the best option for different situations. The profitability of the diverse systems resulted from both the profitability of the legumes, and in some cases the significant legacy of increased soil water (20-60 mm) and/or soil N (50-100 kg/ha) on subsequent crops (See paper - What is the N legacy following pulses for subsequent crops and what management options are important to optimise N fixation?).

The most consistently profitable diverse system was timely-sown, high-value legume systems (chickpea or lentil)-canola-wheat with Decile 2 N, but the low-value diverse system (faba-bean or lupin-canola-wheat) also outperformed the baseline at three of the sites.

Adopting a higher N strategy in the baseline treatment reduced profit at Greenethorpe and had little impact at Wagga, and at both sites did not exceed the profit in the diverse systems at the lower N2 strategy. In other words, using more N fertiliser was not as profitable as adopting a more diverse system involving a legume under the conditions experienced in Phase 1.

Table 5. Average annual 3-year EBIT for timely-sown grain-only systems at four sites in southern NSW (2018-2020). The Baseline system of timely-sown canola-wheat-wheat/barley with Decile 2 N strategy is shown in bold, while the most profitable system at each site is shown in grey. At all sites, there were diverse systems that included legumes that were more profitable than the baseline.

System	Sequence	N Strategy	Greenethorpe	Wagga	Urana	Condobolin
Baseline	C-W-W or C-W-Barley	**Decile 2**	***$720***	***$528***	***$488***	***$534***
		Decile 7	$653	$542	-	-
Diverse High Value 1	Lentil-C-W	Decile 2	-	$588	$775	$522
		Decile 7	-	$510	$609	-
Diverse High Value 2	Chickpea-W	Decile 2	$808	$505	-	$735
		Decile 7	-	-	-	-
Diverse Low value	Faba-C-W or Lupin-C-W	Decile 2	$739	$626	$655	$517
		Decile 7	-	-	-	-

W=wheat, C=canola

System water-use efficiency (WUE)

To compare how efficiently the different systems convert rainfall to profit for the entire 3-yr crop sequence, we estimated system WUE as (average annual profit)/ (average annual rainfall). By using annual rainfall and not growing season rainfall, we account for the use of out-of-season rainfall. Our initial literature review predicted we could lift the system WUE from ~$1/ha/mm up to $2/ha/mm. Due to the relatively similar patterns of rainfall across the years at all three sites (Table 2), the trends in system WUE tend to follow very similar trends to those shown in Tables 4 and 5 for profitability (Table 6).

In timely-sown systems (Table 6, upper section), the diverse sequences including legumes outperformed the baseline sequences at all sites. Highest efficiency (>$2/ha/mm) was achieved at Urana in high-value diverse systems with decile 2 N strategy, which decreased to $1.5/ha/mm with the higher N strategy. Thus, adopting a higher N strategy in baseline systems reduced profit at Greenethorpe and also at Wagga, presumably due to the dry 2018/19 year limiting N response.

The early-sown grazed systems (lower Table 6) generated the highest profit from the available rainfall. The high N intense baseline treatment at Greenethorpe generated close to $3/ha/mm, and low N or diverse systems with grazed vetch also exceeded $2/ha/mm. At Wagga levels were lower, but higher N or inclusion of a legume increased System WUE, but the combination was less effective. Early un-grazed systems were much less efficient than the grazed systems, and less than (Greenethorpe) or similar too (Wagga) that achieved in the baseline system.

Table 6. The system water use efficiency ($/ha/mm) for selected systems at 4 sites in southern NSW (2018-2020). System WUE = average annual EBIT/average annual rainfall.

System	Sequence	N Strategy	Greenthorpe	Wagga	Urana	Condobolin
Baseline	C-W-W or C-W-Barley	Decile 2	*1.4*	*1.0*	*1.2*	*1.5*
		Decile 7	1.2	0.9	-	-
Diverse High Value 1	Lentil-C-W	Decile 2	-	1.1	2.0	1.2
		Decile 7	-	0.9	1.5	-
Diverse High Value 2	Chickpea-W	Decile 2	1.5	0.9	-	1.6
		Decile 7	-	-	-	-
Diverse Low value	Faba-C-W or Lupin-C-W	Decile 2	1.4	1.2	1.7	1.2
		Decile 7	-	-	-	-
Early-sown (March) systems						
Intense Baseline	C-W (Grazed)	Decile 2	2.3	1.2		
		Decile 7	2.8	1.5		
Diverse Mix	Vetch-C-W (Grazed)	Decile 2	2.1	1.6		
		Decile 7	-	1.3		
Diverse High Value	Lentil-C-W Ungrazed	Decile 2	0.8	1.0		
		Decile 7	0.8	0.8		

W=wheat, C=canola

Risk

One risk measure is the return-on-investment (ROI) which is the $ profit generated (EBIT) per $ spent. For these estimates we divided the EBIT by the total input costs (see Appendix).

In general, the ROI follows a similar pattern to the profit and systems WUE in the timely-sown treatments with highest ROI at each site in the diverse systems with decile 2 N (Table 7, upper). However, there were some differences in ranking of the systems at Greenethorpe, where the baseline strategy matched the diverse high value systems and exceeded the diverse low value system. The relative input costs for the more diverse strategies outweighed the additional profit generated compared to the baseline strategy. At Wagga Wagga and Urana, the ROI decreased when higher N strategy was applied to the diverse high value system, as the additional N cost more for little benefit due to the higher N available after the legumes.

In the early-sown intense baseline grazed systems (lower Table 7), the ROI was not improved in the higher N strategy despite high profit (Table 7 lower), indicating more investment was required to generate the profit. The diverse grazed system with vetch had lower ROI than the intense baseline at Greenethorpe, but higher ROI at Wagga Wagga. The early-sown, un-grazed systems with lentils had low ROI due to the very low profit generated although at Wagga the ROI matched that of the baseline.

Table 7. Return on investment (ROI) ($ profit/$ input) for selected systems at 4 sites in southern NSW (2018-2020). Efficiency is estimated as average annual EBIT divided by average input cost and is a measure of financial risk.

System	Sequence	N Strategy	Greenthorpe	Wagga	Urana	Condobolin
Baseline	C-W-W or C-W-Barley	Decile 2	*1.2*	*0.7*	*0.7*	*1.3*
		Decile 7	1.0	0.6	-	-
Diverse High Value 1	Lentil-C-W	Decile 2	-	0.8	1.2	1.1
		Decile 7	-	0.6	0.8	-
Diverse High Value 2	Chickpea-W	Decile 2	1.2	0.6	-	1.4
		Decile 7	-	-	-	-
Diverse Low value	Faba-C-W or Lupin-C-W	Decile 2	1.0	0.9	1.0	1.0
		Decile 7	-	-	-	-

Early-sown (March) systems				
Intense Baseline	C-W (Grazed)	Decile 2	2.4	1.1
		Decile 7	2.4	1.1
Diverse Mix	Vetch-C-W (Grazed)	Decile 2	2.1	1.5
		Decile 7	-	1.1
Diverse High Value	Lentil-C-W Ungrazed	Decile 2	0.7	0.8
		Decile 7	0.6	0.6

W=wheat, C=canola

Simulated performance of systems in the longer term

Long-term simulation studies (which capture the water and N impact only) show a range in annual median EBIT of different systems consistent with the experimental outcomes ($400/ha to $1400/ha). Figure 1 shows a summary at the four sites of three different un-grazed sequences (intense baseline C-W; high value diverse Cp-C-W; baseline C-W-W) timely sown, and with different N strategies of decile 2, 5, 7 and 9. The long-term simulation results show consistency with the experimental results for example:

1. The sequence including a legume is more profitable than the baseline
2. The response to increasing N from decile 2 to 7 N strategy is profitable in the baseline and intense baseline sequences without legumes, but less profitable in sequences with a legume
3. Interactions exist between sites and systems.

For example, earlier sowing and more robust N strategies were more profitable at Greenethorpe (high rainfall) but resulted in profit penalties at Condobolin. The diverse crop sequence option with lower N rates generated some of the highest gross margins with less variability.

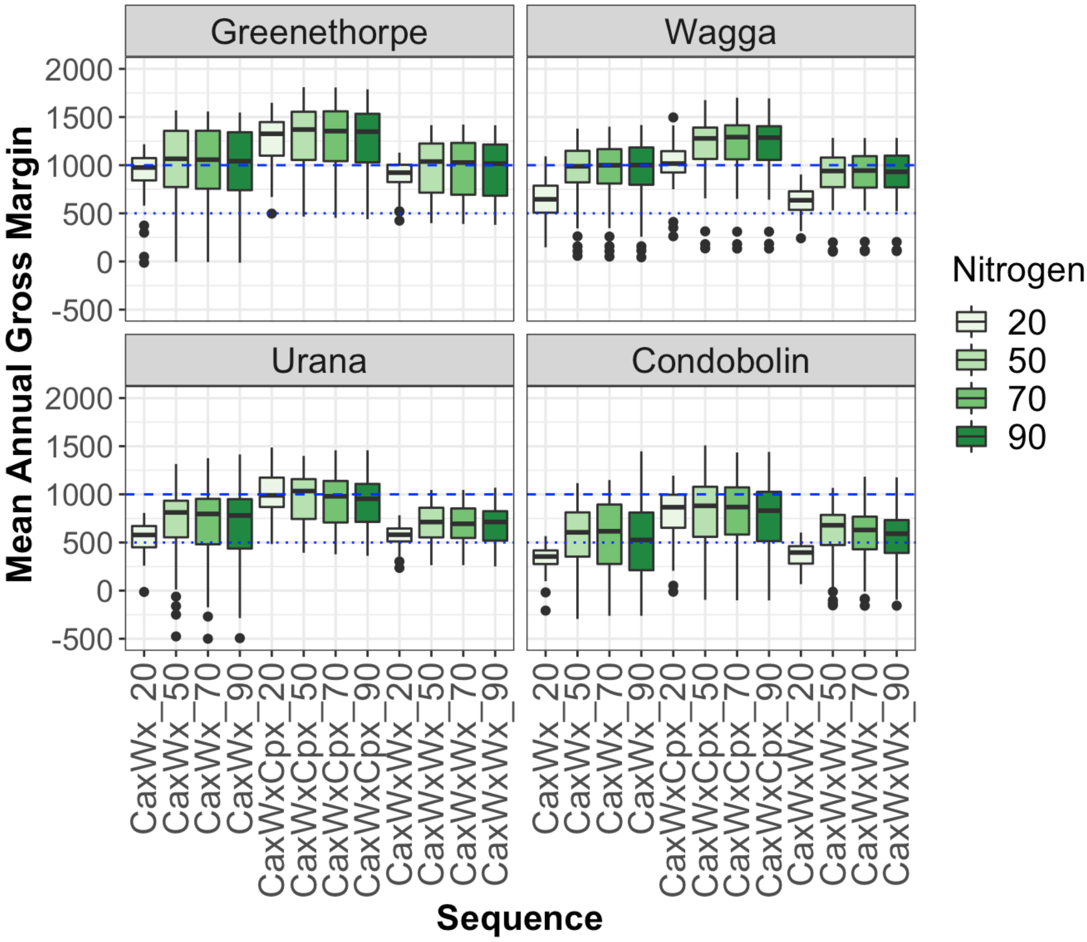

Figure 1. Average gross margins ($/ha/yr) calculated on a sequence basis across all sites for three selected sequences (intense baseline Ca-W; high value diverse Ca-W-Cp; baseline C-W-W) with four different N fertiliser topdressing strategies (decile 2, 5, 7, 9 are shown as 20, 50, 70, 90). (Ca=canola; W=wheat; Cp=chickpea).

These diverse options also combine higher average profit, with higher profit in the lowest 20% of years, demonstrating reduced risk and increased resilience (Figure 2) and more efficient water use in both average and poorer seasons (Figure 3).

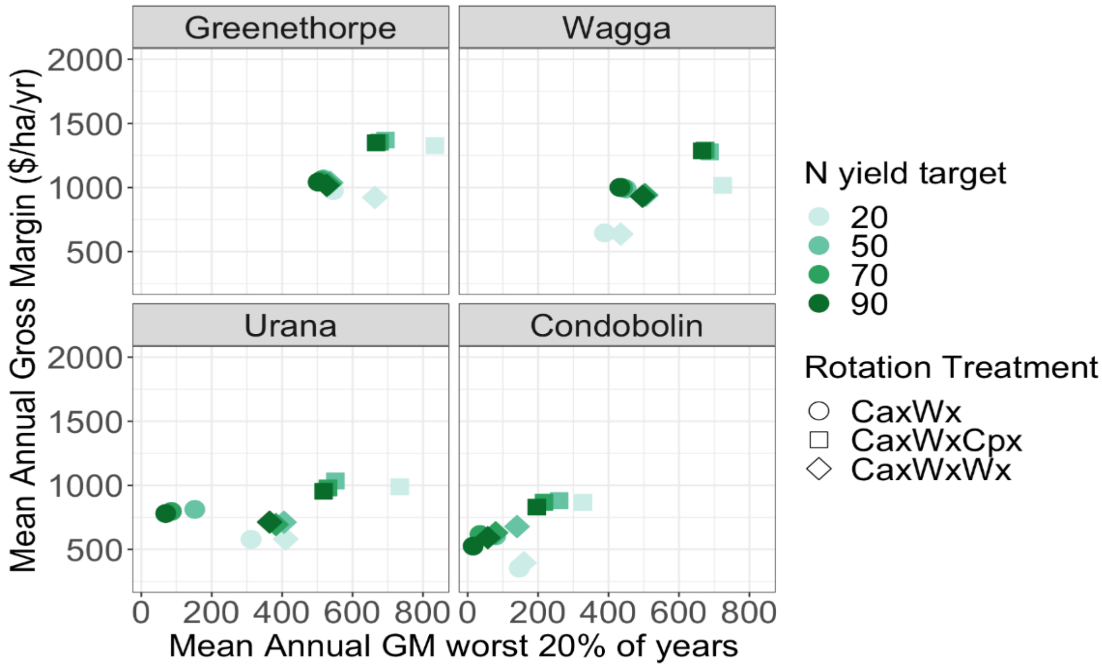

Figure 3. Average gross margins ($/ha/yr) plotted against average gross margin in the worst 20% of years as an indicator of risk. Sequences (intense baseline Ca-W; high value diverse Ca-W-Ch; baseline Ca-W-W) with four different N fertilizer topdressing strategies. (decile 2, 5, 7, 9 are shown as 20, 50, 70, 90). (Ca=canola; W=wheat; Cp=chickpea.)

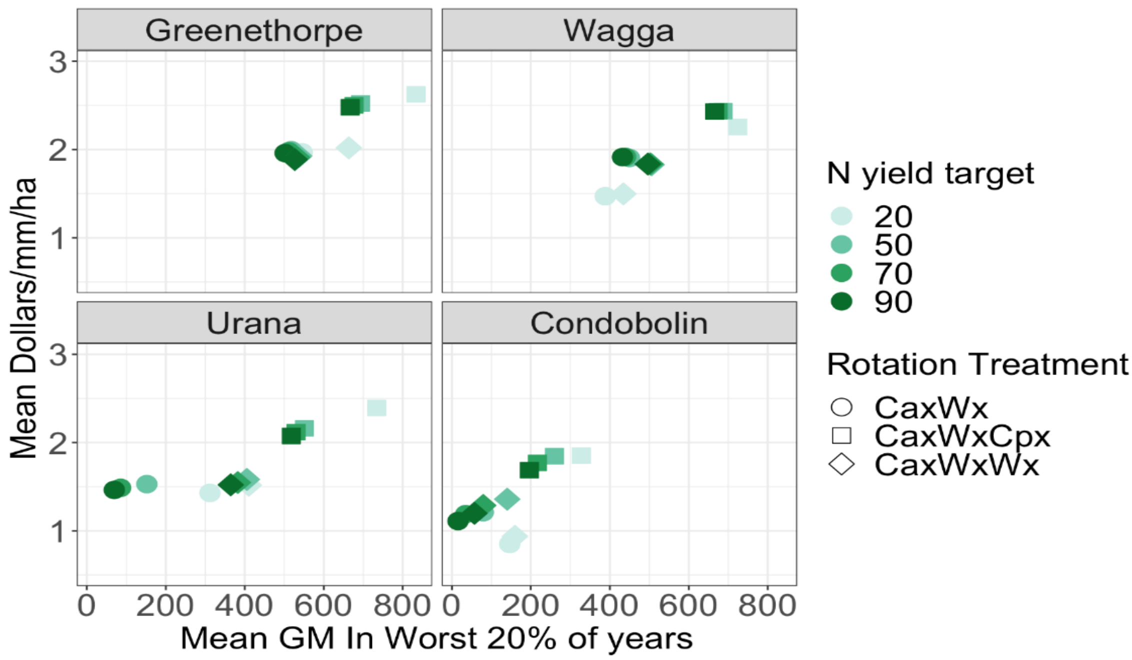

Figure 4. Average water use efficiency ($/ha/mm) plotted against average gross margin in the worst 20% of years as an indicator of risk. Sequences (intense baseline Ca-W; high value diverse Ca-W-Cp; baseline Ca-W-W) with four different N fertilizer topdressing strategies (decile 2, 5, 7, 9 are shown as 20, 50, 70, 90). (Ca=canola; W=wheat; Cp=chickpea).

Conclusion

At all experimental sites, we identified systems with higher 3-yr average annual profit (EBIT) (2018-2020), higher WUE and ROI than the baseline system. These more profitable systems included early-sown, grazed crops (wheat, canola) with either a legume (vetch) or higher N strategies. In crop only (un-grazed) systems, the timely sown, diverse sequences with high value legumes and more conservative N (decile 2) strategies were the most profitable. There was also evidence of decreasing disease risk and stable or declining weed populations and a much lower average herbicide cost in the diverse systems compared to the baseline systems at all sites. Longer-term simulation modelling also predicted that these diverse systems also carried lower risk as expressed by both variability in annual profit, and profit in the lowest 20% of years.

Our first 3-year experimental phase has identified systems at all sites with significantly higher profit and lower risk than the current baseline systems, with stable or declining weed and disease burdens and with economic benefits that appear robust in the longer-term. These improved strategies and systems (worth $100 - $300/ha) are immediately relevant to the ~3.5 Mill ha of winter cropping in southern NSW which produces around 7.5 Mt of grain valued at ~$2.5 Bill pa. Assuming adoption of strategies worth only half the demonstrated increase (i.e., $100/ha) could be achieved on only 10% of the area, would still represent a potential value from the investment of $35 Mill pa.

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Further reading

Kirkegaard et al., (2020a) https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/08/farming-systems-profit,-water,-nutritional-and-disease-implications-of-different-crop-sequences-and-system-intensities-in-snsw

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Swan et al., (2022) What is the N legacy following pulses for subsequent crops and what management options are important to optimise N fixation? https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/02/what-is-the-n-legacy-following-pulses-for-subsequent-crops-and-what-management-options-are-important-to-optimise-n-fixation

Appendix 1: Determining earnings before interest and tax (EBIT)

To calculate the annual EBIT for all treatments, we have initially used the following assumptions/prices.

A. Expenditure

1. All herbicides/fungicides/insecticides, seed dressings, fertilisers, GRDC levies and crop insurance costs were obtained from the annual NSW winter cropping guide or the annual SAGIT farm gross margin and enterprise planning guides with links at:
    i. https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/weed-control-winter-crops
    ii. https://grdc.com.au/resources-and-publications/all-publications/publications/2019/farm-gross-margin-and-enterprise-planning-guide
2. All seed was priced according to purchasing as pure treated seed from seed companies. i.e. In 2019, prices used were wheat seed at $1/kg, faba bean seed at $1.20/kg, chickpea seed at $1.80/kg and canola seed ranging between $23-30/kg.
3. All operations costs (sowing, spraying, spreading, haymaking, harvest) were based on the principal that a contractor performed the task. These costs were extracted from the yearly SAGIT Farm gross margin and enterprise planning guides. i.e. In 2019 prices used included sowing at $50/ha, ground spraying at $10/ha, cereal harvest at $70-85/ha, cut/rake/bale hay at $115/ha, with links at: https://grdc.com.au/resources-and-publications/all-publications/publications/2019/farm-gross-margin-and-enterprise-planning-guide
4. All variety levies for all crops and varieties were determined from the variety central website at: (e.g. for pulses) http://www.varietycentral.com.au/varieties-and-rates/201920-harvest/pulse/

B. Income

1. Wheat, barley and canola grain prices were obtained on the day of harvest from the AWB daily contract sheet for specific regions relating to trial location at: https://www.awb.com.au/daily-grain-prices
2. Pulse grain prices were obtained on the day of harvest from Del AGT Horsham and confirmed with local seed merchants.
3. Hay prices were obtained in the week of baling from a combination of sources including The Land newspaper and local sellers.

Appendix 2: Determining grazing value

To determine the estimated value of grazing the early sown crops, we have used the following formulae:

Winter Grazing Value ($/ha) = Plant dry matter (kg) removed x Liveweight dressed weight (c/kg) x Feed conversion efficiency (0.12) x Dressing % (lambs) x Feed utilisation efficiency (0.75)

Dressed weight and value:

- Lambs = 22.9kg (3-year average of light, heavy and trade lambs)
- Dressed weight = $6.25/kg (3-year average NSW)
- Dressing percentage = 50%

An example of 45kg lambs grazing winter Hyola 970 canola:

3800kg plant DM removed x $6.25 x 0.12 x 50% x 0.75 = $1069/ha

Note:

- These calculations assume a "trading margin" of zero – i.e. animals are bought and sold for the same price/kg
- We have not deducted a cost associated with the grazing livestock – this must be estimated and deducted for relevant enterprises (breeding, trading, etc)

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

What is the N legacy following pulses for subsequent crops and what management options are important to optimise N fixation?

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Keywords

pulse legumes, farming systems, sustainability, management strategies, crop diversity, nitrogen fixation, subsoil constraints, N cycling, subsequent crops

GRDC code

CFF00111.
Data also supplied by past GRDC projects: CSP00146, DAN00191.

Take home messages

- Pulse legumes can improve the profitability and sustainability of your farming system. We found average legume legacy benefits to subsequent canola crops worth **$237/ha** from both higher grain yields and savings in urea costs
- ’Grow what you can and grow it well‘ to maximise N input. Select the best legume crop, variety and sowing time for your soil and get the agronomy right - ensure effective nodulation, maximise pulse dry matter, remove subsoil constraints, and avoid high soil mineral N and damaging herbicides
- Crop end use (grain, silage/hay or brown manure) affects N legacies in subsequent crops – understand and account for these benefits
- Pulse crops with high grain yield or cut for hay production may not always provide a net input of mineral N, but other benefits include the role as a double break, emergence in heavy stubble and high N residues that assist conversion of cereal stubble to humus to improve soil fertility.

Legume crops - introduction

The benefits of crop rotation are widely recognised in modern farming systems. In Southern NSW, cereal-dominated sequences (wheat and barley) often include canola as a break crop, but rarely include a legume break crop. The uptake of more diverse cropping sequences can provide a range of benefits that may outweigh the challenges and risk associated with growing and marketing legume crops, especially if viewed from a whole-of-system perspective.

System benefits from growing legumes can include soil chemical, structural and biological changes as well as impacts on pests, disease and weed levels that can influence the performance of subsequent crops in the sequence. However, much of the legacy benefit derived from legume crops relates to N supply (Angus *et al.,* 2015; Peoples *et al*., 2017).

In a recent paper on sustainable intensification of cropping systems, Reeves (2020), highlighted several changes to farming systems to ensure our farms remain productive, profitable and sustainable. He concluded that a “new revolution of diversified farming based on the effective integration of crops, pastures, livestock, shrubs and trees together with diverse practices are required to make farms more resilient financially and to the increasing challenges of climate change and climate extremes.” To build this resilience, he notes that it is imperative to build soil C and N content and soil health generally (Reeves 2020). Unfortunately, our current intensive cropping systems are reducing both total soil C and N (Sanderman and Baldock 2010), soil organic N is declining over time (Figure 1; Lake 2012) and despite widespread use of lime, current acid soil management programs are not preventing acidification of layers within the 5-15 cm depth layers (Burns and Norton 2018).

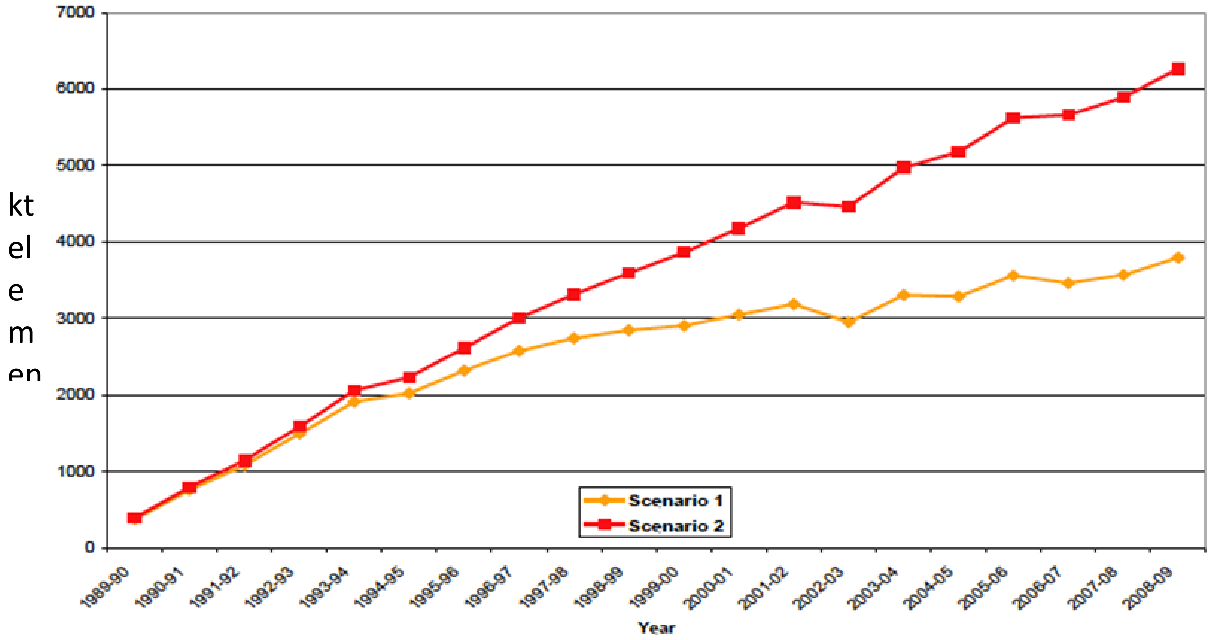

Figure 1. Accumulated deficits expressed as elemental N fertiliser equivalent in Australian temperate crop soils as estimated by two scenarios: Scenario 1 being the best possible case of N fertiliser usage on those crops and Scenario 2 being a more realistic assessment of likely N usage levels. (Lake 2012).

Angus and Peoples (2012) calculated that a fallow typically reduced total soil N by 4.4 % annually and crops by 2.5 % and determined that more frequent inclusion of legumes would be required to offset this decline in soil organic N, or otherwise increased rates of fertiliser N application would be required to maintain yields. If this was to occur it has been predicted that fertiliser N costs would rise as a percentage of gross margin from 9-10 % to around 14.8% by 2037 and 17.5 % by 2067 (Table 1).

Table 1. The increase in fertiliser N calculated to maintain a 4 t/ha and a 2 t/ha wheat crop on a red Mallee soil between 2017 and 2067 (Angus and Peoples 2012).

Year		Soil N (kg N/ha)	Fertiliser N required (kg N/ha)	N cost (% of GM)
2017	Red Soil GSR = 300mm 4t/ha @ 10.5% protein	108	80	9.1
2037		54	134	14.6
2067		27	161	17.7
2017	Mallee Soil GSR = 200mm 2t/ha @ 10.5% protein	45	53	10.5
2037		23	75	15.0
2067		10	88	17.5

In this paper we utilise the findings from recent systems experiments undertaken in southern and central NSW to quantify the contributions of N fixation to legume growth and soil N fertility and to examine the N legacy for following crops. Management options will also be described that can assist in optimizing both the performance of the legume and the flow-on N benefits for subsequent crops.

The GRDC Farming Systems experiments 2018-2021

Experiment outline

Four contrasting locations were selected in 2017 that represented a range of soil types and environmental factors and which encompassed a diverse range of grower and consultant groups. The main core experiment site is located at the Wagga Wagga Agricultural Institute with three regional node sites located at Condobolin Research and Advisory Station, Greenethorpe and Urana. There are six treatment sequences that are common to all sites, with the Wagga Wagga site encompassing all treatments. The crop sequence treatments applied are provided in Table 2. All sites were sown to wheat in 2017 with the treatment sequences starting in 2018. Data from the Wagga Wagga, Greenethorpe and Urana sites are presented in this paper.

Table 2. Farming systems sites with sowing timing, N management and winter grazing strategies applied to different crop sequences.

Crop sequences	Condobolin & Urana		Wagga Wagga		Greenethorpe	
	Sowing	**Nitrogen**	**Sowing + grazing**	**Nitrogen**	**Sowing + grazing**	**Nitrogen**
Canola-wheat	**E, T**	**Low, High**	**E+G, T**	**Low, High**	**E+G, T**	**Low, High**
Canola-wheat-barley	**T**	**Low**	**T**	**Low, High**		
Canola-wheat-wheat					**T, L**	**High**
Lentil-canola-wheat	**E**	**Low, High**	**E, T**	**Low, High**	**E**	**Low, High**
Lupin-canola-wheat			**T**	**Low**		
Faba bean-canola-wheat	**T**	**Low**			**T**	**Low**
Chickpea-wheat			**T**	**Low**	**T**	**Low**
*Legume-canola-wheat	**T**	**Low**	**E+G, T**	**Low, High**	**E+G, T**	**Low**
Faba bean/canola-wheat			**T**	**Low**	**T**	**Low**
Wheat-wheat-wheat			**T**	**Low, High**	**T**	**Low**
Fallow-canola-wheat	**E**	**High**	**E, T**	**High**		
Flexible one	**Flexible**	**Flexible**	**Flexible**	**Flexible**	**Flexible**	**Flexible**
Flexible two	**Flexible**	**Flexible**			**Flexible**	**Flexible**

E = Sown early from mid-March to mid-April period
T = Timely sown crops from 3rd week April to mid-May
G = Grazing (always winter grazed and sometimes a 2nd grazing or stubble graze)

Nitrogen = Low (top-dressed nitrogen in June-July for a decile 2-year (N2) grain yield, High (top-dressed nitrogen in June-July for a decile 7-year (N7) grain yield)

Prior to sowing the cereal crop at all sites in 2017, soil samples were taken and analysed for chemical characteristics. It was determined that at Condobolin, Greenethorpe and Wagga lime would need to be applied to ameliorate the soil and increase the soil pH ($CaCl_2$) to > 5.5 in the surface 0-10 cm and > 5.2 between 10-20 cm. A rate of 3 t/ha, 3.5 t/ha and 1 t/ha of lime was applied at the Condobolin, Greenethorpe and Wagga sites, respectively and incorporated to a depth of around 10 cm. The aim was to incorporate the lime deeper (> 15cm) at the Greenethorpe site, however due to the dry conditions, the offset discs were not able to penetrate deeper. To ensure that the early March sown treatments were able to be sown on time with sufficient surface soil moisture to ensure germination and plant emergence at the start of 2018, the Greenethorpe site was not ploughed following a rainfall event in January 2018. We envisaged that the alkalinity from the lime would move lower in the profile to 10-15 cm over the next few years with sufficient rainfall.

Section 1: Nitrogen fixation and legume impacts on soil N dynamics - Results from previous and current farming systems experiments

Many experiments have demonstrated a close relationship between soil mineral N and wheat yield across a range of environments in eastern Australia (Angus *et al.,* 2015). Both soil mineral N and wheat yields are generally lower following wheat crops and highest following legumes. The amount of N mineralised from legume residues that becomes available for a subsequent crop can be influenced by legume species and its end use (i.e., whether it is grown for grain, green or brown manured, grazed or cut for hay), and the amount of rainfall over the summer fallow between crops.

Legume inputs of fixed N

Cost-effective supply of legume N depends on productive and efficient N fixation. Matching species choice to the environment is an important factor that impacts on the total input of N fixed (kg N/ha). Specifically, the amounts of N fixed by legumes are regulated by two factors:

(i) The amount of legume N accumulated over the growing season (as determined by shoot dry matter (DM) production and %N content); and
(ii) The proportion of the legume N derived from atmospheric N_2 (often abbreviated as %Ndfa).

Equation 1: Amount of legume shoot N fixed = (legume shoot DM x %N/100) x (%Ndfa/100)

The greater the amount of biomass that a legume can produce, the higher the potential for more N fixation to occur (Peoples *et al.,* 2009). Where a species is well suited and doesn't have any obvious constraints to N fixation (see section on subsoil constraints), it is likely legumes will derive more than half of their N requirements for growth from atmospheric N_2 via N fixation. Under these conditions it is common for around 15-20 kg of shoot N to be fixed on average per hectare for every tonne of legume shoot DM accumulated during the growing season (Table 3). However, there can be a wide range in %Ndfa and the amounts of N fixed by different legumes across different environments. Analyses of on-farm samples of legumes collected from 61 commercial grower paddocks, indicated an average %Ndfa of 65%, but the range was 8 to 89%. Similarly, the average shoot N fixed per tonne of shoot biomass was 16 kg N/t DM, with a range of between 2 to 25 kg N/t DM (Table 3).

Table 3. Summary of on-farm estimates of N fixation by 61 commercial pulse crops sampled between 2001-2017 (Peoples *et al*. un-published data).

Legume	Number paddocks	%Ndfa	Shoot N fixed (kg N/ha)	Mean shoot N fixed & (range) (kg N/t DM)
Chickpea	8	67%	47	14 (7-25)
Fababean	23	68%	126	17 (10-25)
Fieldpea	8	56%	46	14 (2-20)
Lentil	5	65%	83	18 (4-25)
Lupin	14	63%	83	16 (9-21)
Vetch	3	69%	89	17 (13-22)
Mean		65%	90	16

The estimate of amounts of N fixed per t of DM accumulated can be used to compare N fixation efficiency: 20+ indicating excellent fixation; > 15 is considered OK; but < 10 kg/t DM generally indicates that there is some constraint to root nodulation, the N fixation process or crop growth which will need to be identified and addressed to maximise future inputs of fixed N (see section on constraints to N fixation). In the case of the 61 commercial pulse crops summarized in Table 3, 20 % of the crops sampled (i.e., 12 crops) were deemed to have had sub-optimal N fixation.

Net inputs of fixed N_2

The amount of shoot N fixed by legumes are informative, but what is more important is how much fixed N might be contributed to the soil at the end of the growing season. Since the root systems of legumes can contain between 25 % to 50 % of the total plant N, this below-ground contribution of fixed N can be a substantial component of the potential carry-over N benefit for following crops and should not be ignored (Peoples *et al.,* 2009). Since it is extremely difficult to fully recover root systems of legumes in the field, total N fixed is usually calculated by adjusting the shoot measures of N fixation to include an estimate of how much fixed N might also be associated with the nodulated roots using a 'root factor' (Unkovich *et al.,* 2008*;* Unkovich *et al.,* 2010*,* Peoples *et al.,* 2012). For many pulse legumes around one-third of the plant N is commonly below-ground in roots and nodules; in this case a 'root factor' of 1.5 would be used (Table 4).

Equation 2: Total N fixed = (shoot N fixed) x root factor.

Table 4. A ROUGH RULE OF THUMB for estimating the total amount of N fixed by different legume species to include shoot and root fixed N.

Species	Estimated shoot N fixed (kg N/t DM)	Estimated below ground N (% of total N)	Root factor	Estimated total plant N fixed (kg N/t DM)
Fieldpeas, lupins, fababeans, vetch	20	33%	1.5	30
Chickpeas	20	52%	2.06	41
Lucerne	20	50%	2.0	40
Subclover	20	42%	1.72	34

The net inputs of fixed N (Equation 3) are derived by comparing the total amounts of N fixed to the amounts of N removed in harvested grain, hay, and/or animal products, or lost from the system via ammonia volatilisation from urine patches where the legume-based pastures or legume stubbles are grazed (Peoples *et al.,* 2012).

Equation 3: Net input of fixed N = (total amount of N fixed) – (N removed + N lost)

The total amounts of N remaining in the crop vegetative residues and roots at the end of the 2011 growing season (Table 5) were calculated for pulse crops using Equation 4.

Equation 4: Total residue N = (total crop N) – (grain N removed)

Junee Reefs experiment 2011-2013

Data generated by experimentation at Junee Reefs indicated that brown manured legumes (BM: legume crops killed with knock-down herbicide before weed seed-set as a weed management tool) provided greater net returns of fixed N to soils than grain crops, as large amounts of N were removed in the high-protein legume grain (Table 5). However, it is clear from this dataset and others, that different legume species have very different potential for growth and N fixation, regardless of their eventual end-use (Table 5). In this experiment, legume DM ranged between 5.7 and 9.9 t/ha, with the lupin BM and lupin grain crops having the highest %Ndfa, lentils lower at 59 % and field peas and chickpeas lowest at 50 %. When we examined the net N balance after grain removal compared to brown manuring, there was a range in net N balance between -1kg N/ha in the lentils to an additional 241 kg N/ha following the lupins BM (Table 5).

Table 5. Shoot and grain dry matter (DM) production, N accumulation, grain yield, inputs of N fixed by legume grain or brown manure (BM) crops and estimates of the amount of residual N remaining at the end of the growing season that was derived by fixation and total residual N at Junee Reefs in 2011.

Crop 2011	Biomass (t DM/ha)	Grain yield (t/ha)	Total plant N[A] (kg N/ha)	Ndfa (%)	Inputs of fixed N[A] (kg N/ha)	Grain N (kgN/ha)	Net N balance of fixed N (kgN/ha)	Total residue N (kgN/ha)
Lupin BM	8.4	-	290	83	241	-	+241	290
Field Pea BM	6.3	-	215	52	112	-	+112	215
Lupin	9.9	3.5	398	85	338	210	+128	188
Chickpea	6.4	1.8	247	50	141	77	+64	170
Lentil	5.7	3.2	248	59	137	138	-1	110
Wheat +N[b]	11.1	4.8			49	87		64
Canola +N[b]	10.6	3.2			49	94		111
LSD P<0.05)	1.3	0.5	-	9	-	11	-	22

Source: Legume data from Peoples *et al.,* 2015 GRDC update and Peoples *et al.,* 2017.

[A] The amount of total plant N and shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as described by Unkovich *et al.,* (2008), Unkovich *et al.,* (2010).

[b] Urea fertiliser was applied to wheat at 49 kg N/ha and canola at 66 kg N/ha.

The GRDC farming systems experiments 2018-2020

A summary of the average N dynamics from the pulse legume crops for phase 1 (2018-2020) of the current GRDC farming systems experiments located at Greenethorpe, Wagga and Urana are outlined in Table 6. Generally, the high-density legume pastures (HDL) have produced on average, the highest quantities of shoot N fixation with estimates of shoot N fixed ranging between 16-20 kg N/t DM (Table 6). The faba bean at Urana, faba bean-canola inter-crop treatments at both Wagga and Greenethorpe in 2018 and 2019, lupins at Wagga and lentils (N2) at Urana also all had reasonable fixation rates that were > 17 kg N/t DM. Generally, the chickpeas and lentils at both the Wagga and Greenethorpe sites and the chickpeas at Urana had the lowest rates of N fixed with < 12 kg N/t DM (Table 6).

In the GRDC project experimental sites, no legume crop was managed as a brown manure (BM) crop. Rather the early sown HDL legume crops were grazed in June before cutting for hay in October, whilst the mid-April to early-May sown HDL crops were cut for hay in October of each year, with the aim to increase gross margin from the sale of the hay and the grazing if applicable. When we calculated the average net inputs of fixed N remaining in crop residues following grain or hay removal, we found that across the two decile 1 and one decile 9 year treatments at each site, the faba beans at Urana had the highest net return of fixed N of 116 kg N/ha, the HDL averaged across all sites was 75 kg N/ha, and generally all other crops produced less than 40 kg fixed N/ha in remaining residues (Table 6). In the cropping sequences where the wheat and canola preceding the pulse crop were fertilised at a higher nitrogen level (Decile 7 strategy), the fixation rate and the quantity of fixed N remaining after grain harvest was generally reduced (lentils at Urana - 9 *cf* 33, lentils at Wagga = 6 *cf* 40). However, at the Greenethorpe site, less than 25 kg N/ha remained following the harvest of the faba bean or lentil crops.

Table 6. Average N dynamics of the legume crops at each field site in the 'Southern Farming Systems' project. Values presented are averages across three seasons (2018, 2019 & 2020).

Field Site	Crops 2018, 2019, 2020	Legume biomass (t/ha)	Shoot N fixed (kg N/t DM)	Total fixed N from root & shoot[A] (kg N/ha)	N removed from grain or hay (kg N/ha)	Fixed N remaining in crop resides (kg N/ha)	Total Residue N in crop (kg N/ha)
Greenethorpe	HDL[C] un-grazed, T	4.7	20	166	78	89	167
	HDL grazed, E	4.5	19	136	63	73	153
	Chickpea	5.5	10	133	88	45	169
	Fababean/canola[B]	4.4	17	112	88	24	94
	Fababean[D]	5.9	14	128	144	24	91
	Lentil (N7) [E]	4.5	12	84	82	1	65
	Lentil (N2) [E]	4.2	10	66	81	-15	66
Wagga	HDL grazed, E (N2)	4.6	21	148	69	79	116
	HDL grazed, E (N7)	4.9	18	135	63	72	120
	HDL un-grazed, T (N7)	4.4	18	116	54	62	117
	HDL un-grazed, T (N2)	4.8	16	115	54	61	137
	Lupin	4.4	25	144	131	47	85
	Lentil (N2)	4.9	16	114	74	40	105
	Chickpea	4.1	11	101	63	38	126
	Lentil (N7)	5.0	11	83	77	6	111
Urana	Fababean	9.6	17	235	119	116	218
	HDL un-grazed, T	6.1	17	168	79	38	182
	Chickpea	4.7	12	118	79	38	107
	Lentil (N2)	4.6	18	130	97	33	109
	Lentil (N7)	3.7	16	91	82	9	86

[A] The amounts of shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as describe by Unkovich et al. (2010)
[B] Sown mixture of fababean and canola – Intercrop in 2018 and 2019 only
[C] HDL – Pasture mix consisting of vetch, Arrowleaf and Balansa clover
[D] Average results from fababean at Greenthorpe in 2018 and 2019 only
[E] The N7 and N2 relate to the nitrogen requirement in the crop sequence, not the legume crop.

To better examine the year-to-year interaction across the three sites, a complete dataset for each year is provided in Tables 7 to 9.

2018

In 2018, the %Ndfa of the chickpea crops at Greenethorpe and Wagga were very low (26-31%) and shoot N fixed were 5-7 kg N/t DM. The %Ndfa of the lentil crop at Greenethorpe was also low (30-40%), with shoot N fixed representing 6-7 kg N/t DM (Table 7). By comparison, the lentil and faba bean crops performed very well on the alkaline soils at Urana with high shoot N fixed values (17-23 kg N/t DM). The HDL crops across all sites performed the best with high %Ndfa (58-79%), and high shoot N fixed (16-27 kg N/t DM). However, more N was removed in grain and hay than was estimated to be fixed for the chickpeas and lentils at Urana and Greenethorpe (Table 7).

2019

In the extremely dry 2019 year, the total amount of total legume biomass produced was low and this ultimately reduced the quantity of fixed N remaining in the crop residues. Nonetheless, the faba bean/canola intercrop, faba bean, lupin and HDL treatments had good %Ndfa (67-81 %) and generally had the highest amounts of fixed N in the crop residues following harvest or hay cut (Table 8). The higher soil mineral N concentration at the start of 2019 at both Wagga and Urana probably resulted in the poorer N fixation and lower net inputs of fixed N (Table 8).

2020

In 2020, all sites received substantial rainfall and this impacted different pulse crops in different ways. The Greenethorpe site received 767 mm of rainfall and the combination of the high rainfall, the persistent subsoil acidity layer (7-15 cm) with a high aluminium concentration resulted in the death of the rhizobia in the faba bean crops. To ensure a successful faba bean harvest and to not damage the long-term treatment, 170 kg/ha of urea was applied to ensure a 4-5 t/ha faba bean grain yield. As such no analysis of N fixation could occur. The HDL and chickpea crops at Greenethorpe had a high legume biomass, high Ndfa% (70-92 %) and high rates of shoot N fixed (17-34 kg N/t DM), which resulted in significant net inputs of fixed N remaining in the residues after grain or hay was harvested (Table 9). By comparison, there was little or no fixed N remaining in the lentil residues.

At the Wagga site in 2020, all legume crops produced between 5 and 8t/ha of legume biomass and all crops except the lentil (N7) had > 50 % Ndfa. The HDL and chickpea crops generated the highest net inputs of fixed N following harvest (74-106 kgN/ha). The lupin crop had a high %Ndfa (75 %) and high rates of shoot N fixed (24 kg N/t DM), but after removing the 4.7 t/ha of grain, only 32 kg fixed N/ha was calculated to remain in that treatment’s residues (Table 9).

The Samira faba beans at the Urana site in 2020 produced a massive 18.2 t/ha of legume biomass with a high %Ndfa and good shoot N fixed (17 kg N/t DM). So, after subtracting the N removed from the 5.3 t/ha of grain yield, there was potentially a net input of 256 kg fixed N/ha in the crop residues (Table 9). All crops performed very well in the alkaline soils of Urana in 2020, with high grain yields; however, the lower legume biomass from the lentil (N7 treatment) and the chickpea resulted in considerably less fixed N remaining in crop residues following harvest (Table 9).

Apparent mineralisation (calculated soil mineral N benefit)

Even though elevated concentrations of soil mineral N are frequently observed after legume crops (Angus *et al*. ,2015), only a fraction of the N in legume residues remaining at the end of the growing season becomes available immediately for the benefit of subsequent cereal crops (Peoples *et al*. 2009). The microbial-mediated decomposition and mineralisation of the N in legumes organic residues into plant-available inorganic forms, is influenced by three main factors: (i) rainfall to stimulate microbial activity, (ii) the amount of legume residues present, and (iii) the N content and quality of the residues (Peoples *et al.,* 2015: Peoples *et al.,* 2017).

We calculated the apparent mineralisation at Junee Reefs (Tables 10 and 11) in the year following the pulse crops (2012) using three different equations (Equations 5 to 7).

Equation 5: Apparent mineralisation of legume residues (kgN/ha per tonne of grain yield)

= 100 x [(mineral N after legume) – (mineral N after wheat)] / (grain yield 2011).

Equation 6: Apparent mineralisation of legume residues (kgN/ha per tonne of shoot residue N)

= 100 x [(mineral N after legume) – (mineral N after wheat)] / (legume shoot residue N). Where shoot residue = (peak biomass DM) – grain yield.

Equation 7: Apparent mineralisation of legume N (as a % 2011 total residue N) = 100 x [(mineral N after legume) – (mineral N after wheat)] / (total legume residue N).

Results suggest that the net mineralisation over the wet 2011/12 summer fallow period represented the equivalent of 11- 46 kg N/ha per tonne of grain yield, 16 -18 kg N/ha per tonne of shoot residue DM, and 22-56 % of the pulse crop residues (Table 10). Interestingly, the apparent net

Table 7. Soil mineral N at sowing, legume biomass (DM), shoot N content (%N), reliance upon N fixation for growth (%Ndfa), shoot N accumulation and estimated quantity of shoot N and total plant N (shoot+root) fixed, grain and hay DM yields, N removed in grain or hay at harvest and the calculated net inputs of fixed N at Greenethorpe, Wagga and Urana in 2018 for a range of legume crops and treatments.

Field Site	Crops	Starting soil Mineral N* 0-2m (kgN/ha)	Total Biomass ( ) & Legume Biomass[#] (t/ha)	Legume (%N)	Ndfa (%)	ShootN (kgN/ha)	Shoot Nfixed (kgN/ha)	Shoot NFixed (kgN/tDM)	Total N fixed by shoot & roots[A] (kgN/tDM)	Total Hay () & Legume Hay Yield[B] (t/ha)	Grain Yield (t/ha)	Grain[EF] (%N)	Total Fixed N from root & shoot (kgN/ha)	N removed from grain or hay (kgN/ha)	Fixed N remaining in crop resides (kgN/ha)
Greene-Thorpe	HDL[C] Grazed, E	145	(4.2) 4.0	3.5	78	140	108	27	41	(3.0) 2.8			163	76	87
	HDL Un-Grazed, T	144	(5.0) 3.7	3.3	68	124	82	22	33	(3.5) 2.6			123	58	66
	Fababean	139	6.1	2.3	58	141	83	13	20		2.1	4.4	124	94	30
	Fababean/Canola[D]	133	4.4	2.2	78	96	75	17	26		2.1	4.4	113	91	21
	Chickpea	153	5.0	2.1	26	106	27	5	11		1.9	3.9	55	74	-19
	Lentil (N2)	141	5.4	2.0	30	108	31	6	9		1.7	4.2	47	72	-25
	Lentil (N7)	158	5.4	1.8	40	98	39	7	11		1.7	4.3	58	73	-15
Wagga	HDL Grazed, E	64	3.8	2.7	65	102	68	18	27	2.6			102	47	54
	HDL Un-Grazed, T	64	4.1	2.2	79	87	67	17	25	2.8			100	47	54
	Lentil (N2)	64	3.3	2.6	70	85	59	18	27		1.4	4.0	88	57	31
	Lentil (N7)	69	3.1	2.3	74	72	52	17	26		1.3	4.0	79	54	24
	Chickpea	64	2.5	2.4	31	59	18	7	15		1.3	3.7	38	47	-9
Urana	HDL Un-Grazed, T	73	3.0	2.8	58	82	47	16	24	2.1			71	33	38
	Fababean	73	3.0	2.9	78	88	68	23	35		1.8	3.9	103	72	31
	lentil (N2)	73	2.3	2.6	64	59	38	17	25		2.6	4.0	57	104	-47
	lentil (N7)	73	2.2	2.7	68	58	39	18	27		1.9	4.0	58	76	-18

* Soil mineral nitrogen determined from 0-2m at Greenethorpe and Urana.

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

[A] The amounts of shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as described by Unkovich et al. (2010)

[B] Hay calculated as 70% of the total plant dry matter

[C] HDL - Pasture mix consisting of Vetch, Arrowleaf and Balansa clover

[D] Sown mixture of fababean and canola - Intercrop

[E] Lentil grain %N at Urana and Wagga were derived from average grain nitrogen concentrations at Greenethorpe, Urana and Wagga (2018-2020).

[F] The chickpea grain %N for Wagga was derived from the Greenethorpe analysed chickpeas (2018-2021)

Note: Legume crops had <8kgN/ha of added fertiliser at sowing. N2 or N7 refer to the other crops in the sequence fertilised at a low (N2) or high (N7) rate. If no rate indicated, other crops fertilised at low rate.

Table 8. Soil mineral N at sowing, legume biomass (DM), shoot N content (%N), reliance upon N fixation for growth (%Ndfa), shoot N accumulation and estimated quantity of shoot N and total plant N (shoot+root) fixed, grain and hay DM yields, N removed in grain or hay at harvest and the calculated net inputs of fixed N at Greenethorpe, Wagga and Urana in 2019 for a range of legume crops and treatments.

Field Site	Crops	Starting soil Mineral N* 0-2m (kgN/ha)	Total Biomass ( ) & Legume Biomass[#] (t/ha)	Legume (%N)	Ndfa[E] (%)	ShootN (kgN/ha)	Shoot Nfixed (kgN/ha)	Shoot NFixed (kgN/tDM)	Total N fixed by shoot & roots[A] (kgN/tDM)	Total Hay () & Legume Hay Yield[B] (t/ha)	Grain Yield (t/ha)	Grain[FG] (%N)	Total Fixed N from root & shoot (kgN/ha)	N removed from grain or hay (kgN/ha)	Fixed N remaining in crop resides (kgN/ha)
Greene-thorpe	Fababean/Canola[D]	177	4.5	2.5	67	109	75	16	25		1.8	4.7	112	85	27
	Fababean	220	5.7	2.3	69	128	88	16	23		2.4	4.7	132	114	18
	HDL Grazed, E	193	(3.8) 3.7	3.3	13	119	15	4	6	(2.6) 3.7			22	10	12
	HDL Un-Grazed, T	229	(5.2) 3.4	3.5	12	117	14	4	6	(3.7) 2.4			21	10	11
	Lentil (N7)	236	2.7	2.5	49	68	33	12	19		0.8	4.6	50	39	11
	Chickpea	217	2.9	2.3	39	68	27	9	19		1.2	4.1	55	52	4
	Lentil (N2)	252	2.4	2.5	27	61	17	7	10		0.9	4.7	25	40	-15
Wagga	HDL Grazed, E (N2)	93	4.4	2.7	80	120	96	22	33	3.1			144	67	77
	HDL Grazed, E, (N7)	112	4.4	2.4	72	106	76	17	26	3.0			114	53	61
	HDL Un-Grazed, T (N7)	113	4.0	3.1	75	97	73	18	27	2.8			109	51	58
	Lupin	82	3.9	2.8	70	111	78	20	30		1.3	4.5	117	59	58
	Lentil (N2)	82	4.0	2.1	62	86	54	13	20		0.6	4.0	81	26	55
	Chickpea	82	3.2	1.9	50	61	31	10	20		0.5	3.7	63	20	44
	HDL Un-Grazed, T (N2)	82	3.7	2.9	46	108	50	14	20	2.6			75	35	40
	Lentil (N7)	113	4.2	2.2	22	90	17	4	7		0.7	4.0	26	30	-5
Urana	Fababean	73	7.7	2.4	51	183	92	12	18		2.0	3.9	138	78	60
	lentil (N2)	73	4.6	2.3	63	105	67	14	22		1.1	4.0	101	46	55
	HDL Un-Grazed, T	73	4.6	2.5	57	114	64	14	21	3.2			96	45	51
	lentil (N7)	159	4.2	2.5	43	103	45	11	16		1.3	4.0	68	51	16

* Soil mineral nitrogen determined from 0-2m at Greenethorpe and Urana.

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

[A] The amounts of shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as described by Unkovich et al. (2010)

[B] Hay calculated as 70% of the total plant dry matter

[C] HDL - Pasture mix consisting of Vetch, Arrowleaf and Balansa clover

[D] Sown mixture of fababean and canola - Intercrop

[E] The non-refernce plant delta's that were used to dermine the percentage of nitrogen fixed by the legume at Urana was from 2018 and 2020 non-legume weed species.

As such, all of the Nitrogen fixation values and estimates of nitrogen remaining after grain or hay removal are to be used as a guide only and not to be used for journal publisable data.

[F] Lentil grain %N for 2019 were derived from average grain nitrogen concentrations at Greenethorpe, Urana and Wagga (2018-2020).

[G] The chickpea grain %N for Wagga and Urana is derived from the Greenethorpe analysed chickpeas (2018-2021)

Note: Legume crops had <8kgN/ha of added fertiliser at sowing. N2 or N7 refer to the other crops in the sequence fertilised at a low (N2) or high (N7) rate. If no rate indicated, other crops fertilised at low rate.

Table 9. Soil mineral N at sowing, legume biomass (DM), shoot N content (%N), reliance upon N fixation for growth (%Ndfa), shoot N accumulation and estimated quantity of shoot N and total plant N (shoot+root) fixed, grain and hay DM yields, N removed in grain or hay at harvest and the calculated net inputs of fixed N at Greenethorpe, Wagga and Urana in 2020 for a range of legume crops and treatments.

Field Site	Crop 2020	Starting soil Mineral N* 0-2m (kgN/ha)	Total Biomass ( ) & Legume Biomass[#] (t/ha)	Legume (%N)	Ndfa (%)	ShootN (kgN/ha)	Shoot Nfixed (kgN/ha)	Shoot NFixed (kgN/tDM)	Total N fixed by shoot & roots[A] (kgN/tDM)	Total Hay () & Legume Hay Yield[B] (t/ha)	Grain Yield (t/ha)	Grain[E] (%N)	Total Fixed N from root & shoot (kgN/ha)	N removed from grain or hay (kgN/ha)	Fixed N remaining in crop resides (kgN/ha)
Greene-thorpe	HDL Un-Grazed, T	139	(7.0) 6.9	3.3	92	247	236	34	51	(4.9) 4.9			355	165	189
	Chickpea	184	8.4	2.4	70	200	140	17	35		4.1	3.4	289	139	149
	HDL Grazed, E	167	(6.2) 5.8	3.7	86	174	149	26	39	(4.3) 4.1			224	104	119
	Chickpea/Linseed[D]	225	5.0	2.2	85	109	93	19	39		2.3	3.1	192	73	119
	Lentil (N7)	230	5.4	2.4	74	129	96	18	27		3.1	4.4	143	135	8
	Lentil (N2)	174	4.8	2.6	68	125	84	17	26		3.0	4.3	127	131	-4
	Fababean[F]	235	7.9	2.6	NA	201	NA	NA	NA		5.2	4.3	NA	225	NA
Wagga	HDL Grazed, E (N2)	106	5.5	2.7	83	148	132	23	35	3.9			199	93	106
	HDL Grazed, E (N7)	81	6.7	2.4	79	158	127	19	29	4.7			191	89	102
	HDL Un-Grazed, T (N2)	107	6.7	2.9	59	186	113	17	25	4.7			169	79	90
	Chickpea	101	6.6	2.4	64	155	99	15	31		3.4	3.7	203	124	79
	HDL Un-Grazed, T (N7)	121	5.0	3.1	60	157	92	18	28	3.5			138	65	74
	Chickpea/Linseed[D]	81	5.6	2.3	53	130	68	12	26		2.7	3.7	140	100	40
	Lentil (N2)	79	7.4	2.5	62	186	116	16	23		4.0	3.5	174	138	35
	Lupin	87	6.7	3.3	75	219	163	24	37		4.7	4.5	245	213	32
	Lentil (N7)	148	7.8	2.7	45	214	96	12	19		4.2	3.5	144	147	-3
Urana	Fababean	102	18.2	2.2	77	403	309	17	25		5.3	4.0	464	208	256
	HDL Un-Grazed, T	101	10.6	3.1	70	326	226	21	32	7.4			339	158	181
	lentil (N2)	120	6.8	2.6	87	178	154	23	34		4.0	3.5	232	140	91
	lentil (N7)	137	4.7	2.6	79	124	98	21	31		3.3	3.6	146	117	29
	Chickpea	121	6.2	2.1	66	129	87	14	27		4.3	3.7	169	158	11

* Soil mineral nitrogen determined from 0-2m at Greenethorpe and Urana.

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

[A] The amounts of shoot N fixed were adjusted to include an estimate of N contributed by the nodulated roots as described by Unkovich et al. (2010)

[B] Hay calculated as 70% of the total plant dry matter

[C] HDL - Pasture mix consisting of Vetch, Arrowleaf and Balansa clover

[D] Sown mixture of chickpeas and linseed - Intercrop

[E] The chickpea grain %N for Wagga and Urana is derived from the Greenethorpe analysed chickpeas (2018-2021)

[F] Fababean: The interaction between subsoil acidity and a wet season resulted in the rhizobia being killed. An additional 170kg/ha of urea was applied to ensure sufficient N for fababean grain yield.

Note: Legume crops had <8kgN/ha of added fertiliserN at sowing. N2 or N7 refer to the crops in the sequence fertilised at a low (N2) or high (N7) rate. If no rate indicated, other crops fertilised at low rate.

Table 10. Concentrations of total residue N from legume crops in 2011, soil mineral N (0-1.2m) measured in autumn 2012 following either wheat, canola, lupins or field peas from brown manure (BM), and lupins, chickpeas or lentils for grain at Junee Reefs, NSW in 2011, and calculations of the apparent net mineralisation of N (soil mineral N net benefit) from legume residues.

	Total residue N from legume & non-legume crops by end 2011	Peak Biomass 2011 minus grain/hay yield	Additional soil mineral N from legumes	Calculated soil mineral N benefits (kg N/ha)		
				Per tonne of grain yield	Apparent mineralisation of 2011 legume N (kg N/t DM)	Apparent mineralisation of 2011 legume N (% residue N)
Crop 2011	(kg N/ha)	(t/ha)	(kg N/ha)			
Lupins BM	290	8.4	86	-	10	30%
Field Pea BM	215	6.3	43	-	7	20%
Lupin	188	6.4	40	11	6	21%
Chickpea	170	4.6	82	46	18	48%
Lentil	110	2.5	41	13	16	37%
Wheat	64		-			-
Canola	111		-			-
Average after BM crops			65	-	8.5	25%
Average after grain crops			54	23	13	35%

Source: Peoples *et al.,* 2015 GRDC update, Peoples *et al.,* 2017 and un-published results.

mineralisation of the crop residues from the legume BM and lupin grain crop in the 2011 year represented around 10 % of the soils mineral N prior to sowing the second cereal crop (Table 11). It is evident that in those crops (chickpea and lentil 2011) that mineralised more N from their residues prior to sowing the first cereal crop, they provided no detectable N benefit for the second cereal crop in 2013 (Table 11). Peoples *et al.,* (2017) also calculated that the soil mineral N benefit from the legume crops was 0.13 kg N/ha per millimetre of summer rainfall.

Table 11. Concentrations of total residue N from legume crops in 2011, soil mineral N (0-1.6m) measured in autumn 2013 following either wheat, canola, lupins or field peas from brown manure (BM), lupins, chickpeas or lentils for grain at Junee reefs, NSW in 2011, and calculations of the apparent net mineralisation of N from legume residues. (Chickpea and lentil were not included as they did not provide benefits through to the second cereal crop)

Crop 2011[a]	Total residue N from legume & non-legume crops by end 2011 (kg N/ha)	Soil mineral N autumn 2013 (kg N/ha)	Additional soil mineral N from legumes in autumn 2013 (kg N/ha)	Apparent mineralisation of legume N (% 2011 residues)
Lupins BM	290	167	34	12%
Field Pea BM	215	151	18	9%
Lupin	188	151	18	10%
Wheat	64	133	-	-
Canola	111	115	-	-
Average BM crops			26	11%
Average of grain crops			18	10%

Source: Peoples *et al.,* 2015 GRDC update, Peoples *et al.,* 2017 and un-published results.

[a] measures of soil mineral N in 2013 following the 2011 chickpea and lentil treatments were not significantly different from the soil mineral N detected after the 2011 wheat treatment so were not included in the analysis.

How to optimise N fixation

Where a legume species is well suited and doesn't have any obvious constraints to N fixation, it is likely to derive more than half of its N requirements for growth from N_2 fixation. To achieve the desired outcome of increased inputs of fixed N by legumes, the interaction between the best legume and rhizobial genotypes tailored to the local environment and grown with the best agronomic management is required. As outlined in equation 1, to maximise the amounts of N_2 fixed by legumes for the subsequent crop, the grower needs to produce the highest amount of legume N by growing the maximum quantity of legume DM with the highest %N content and ensure that there is a very high proportion of the legume N derived from atmospheric N_2 (%Ndfa).

Given the close relationships that have frequently been observed between legume productivity and the amounts of N_2 fixed by many different crop and forage legumes growing across a diverse range of locations in Australia (e.g., see Peoples *et al.,* 2009; Unkovich *et al*., 2010; Peoples *et al*., 2012), management options specifically aimed at supporting greater legume growth will generally have the desired effect of improving inputs of fixed N.

Constraints to N_2 fixation and pulse growth

A. Restricted legume growth:

- Drought
- Poor in-crop weed control
- Carry-over of herbicide residues or in-crop residues
- Nutritional constraints associated with acid soils and P or Mo deficiency.

B. Low % Ndfa resulting from:

- Failure of legume to nodulate due low rhizobia numbers in the soil or poor inoculation
- Acidic subsurface layers
- High soil mineral N (60kgN/ha in Chickpeas, >100 kg N/ha in faba beans and other pulses).

Sub-surface acidity

Many growers are trying to diversify their cropping programs to include higher value pulse legumes to increase the profitability and sustainability of their properties. Most growers have been implementing a liming program since the late 1980's, however in a recent survey of paddocks sown to pulse crops across SE Australia between 2015-17, 83 % of these sites had acid sub-surface layers between 5-15 cm or 5-20 cm (Burns and Norton 2018) (Figure 2). Of the 55 sites, only 9 (17 %) of those soils were in the low-risk category and had a soil type suitable for growing acid-sensitive pulse crops.

The authors point out that the mean soil pH_{Ca} in the moderate and high-risk category soils at depths between 5 and 15 cm were (4.8-5.2, and 4.6-4.8) respectively, indicating that root development, nodulation and therefore production could be compromised. The severity and depth of the acid layer in the extreme risk category soils make these unsuitable for acid-sensitive pulse crops. To obtain maximum growth and maximum nitrogen fixation, correct paddock selection for each species with optimal soil pH are critical factors.

The optimal soil pH_{ca} for a range of pulse legumes is outlined in Table 12. Burns indicates that any potential paddocks where pulse crops are to be sown should be identified and checked for acidic

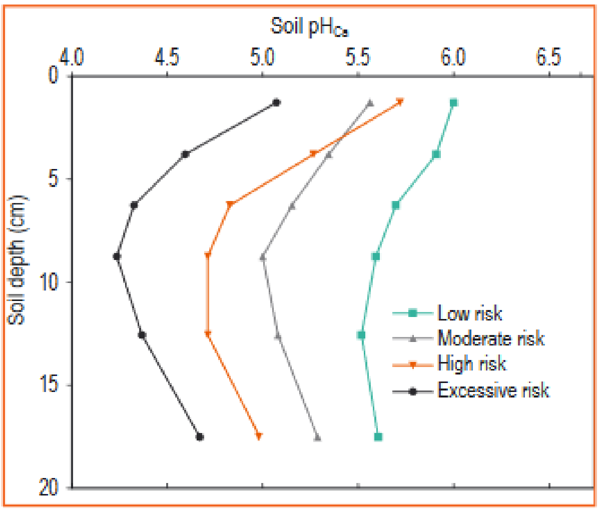

Figure 2. Mean soil pH_{Ca} in surface and subsurface layers of the 55 acidic sites surveyed, categorised (Low, Moderate, High or Excessive) for potential risk of poor nodulation and reduced seedling vigour of acid sensitive pulse species (Burns and Norton page 16).
pulses (Burns and Norton 2018).

sub-surface layers well in advance of sowing acid-sensitive pulses. A liming program to rectify the surface and sub-surface layers then needs be implemented which may require more specialised machines to ensure the lime is moved into the sub-surface layer and enough time allowed for the pH to sufficiently increase to sow acid-sensitive pulses. Depending on the environment, rainfall, soil type, mixing and quality of lime used, this may require up to 24 months in low rainfall zones.

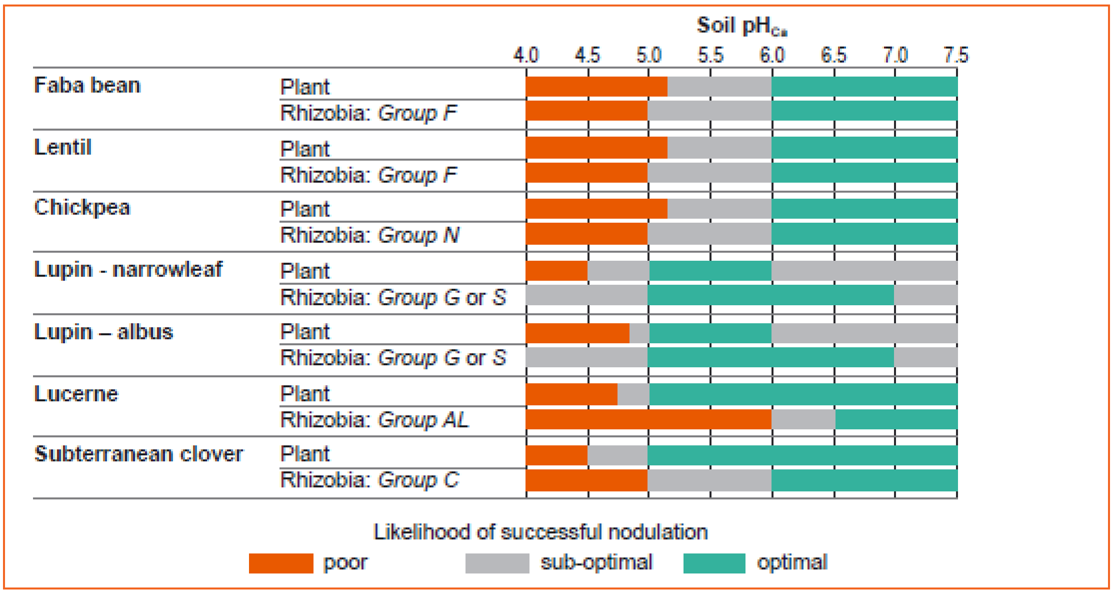

Figure 3. The tolerance of legume species and their associated rhizobia to a range of soil pH_{ca} and the likelihood of successful nodulation (poor, sub-optimal or optimal). (Extracted from Burns and Norton 2018).

The GRDC/NSW DPI publication 'Legumes in acidic soils' (Burns and Norton 2018) and GRDC Update paper (Burns and Norton 2020) offer some practical information to assist growers to better understand the agronomic management required to grow pulses and ensure maximum biomass potential and N fixation is achieved. There are a range of publications that can assist growers better understand the requirements for paddock selection, constraints, crop and variety selection, time of sowing, fertiliser/herbicide and fungicide applications. A few of these publications include:

- Pulses: putting life into the farming system (2015). Armstrong E and Holding Di;
- GRDC Inoculating legumes: A practical guide (2011) Drew et al.
- GRDC Legumes in acidic soils – maximising production potential. (2018) Burns and Norton;
- GRDC Grow Notes for Lentil, Chickpea, Fababean, Lupins (all available at https://grdc.com.au/resources-and-publications/grownotes/crop-agronomy/lentil-southern-region-grownotes).

Sodicity and salinity

Unfavourable and hostile soils that limit legume root exploration (e.g. soil compaction, sodicity, salinity), inhibit nodulation or restrict shoot growth (e.g. soil acidity, nutrient deficiencies) should also be ameliorated (Peoples *et al.* 2009; Santachiara *et al.,* 2019; Vanlauwe *et al.,* 2019). Lentils and chickpeas are also very sensitive to saline soils. Where the electrical conductivity (EC_{se}) of the saturated soil extract is 2 dS/m and 3 dS/m, a yield reduction of 20 % and 90 % has been found.

Soil mineral N

To achieve high %Ndfa, concentrations of available soil mineral N would also need to be low at sowing (<55-85 kg N ha^{-1}; Voisin *et al*. 2002; Salvagiotti *et al.* 2008), and > 60 kgN/a in the soil at depths of 0-1.2m prior to sowing chickpeas (Doughtan *et al.,* 1993; Drew *et al.,* 2012). Higher concentrations of soil N would inhibit nodule initiation and the N fixation process (Peoples *et al.,* 2009; Guinet *et al.,* 2018). High N and ensuing suppression of N fixation is less likely to occur under reduced tillage practices where the retention of stubble from a previous cereal crop is more likely to immobilize soil mineral N resulting in higher rates of N fixation (Torabian *et al.,* 2019).

Effective inoculation

Prospective agronomic practices to achieve this would include the use of high quality rhizobial inoculants at sowing, efficient inoculation practices, and the ameliorating of any soil conditions that are either hostile to rhizobia's survival and persistence or results in erratic nodulation (e.g. soil pH or nutrient deficiencies).

Crop species

In terms of genetic factors, the choice of legume species (and maturity group) most adapted for the local soil type, season or climate is likely to play a crucial role (Peoples *et al.,* 2009; Tagliapietra *et al.,* 2021), as will plant improvement for enhanced disease resistance (Peoples *et al.* 2019).

Greenethorpe farming system trial results in 2021

In January 2020, 3.3/ha of lime was applied and incorporated using a Horsch-Tiger to a depth of 26 cm at the Greenethorpe Farming system site. The 2021 year was extremely wet (952 mm) which resulted in some significant challenges such as higher disease levels in the pulse crops than experienced in 2020 (767 mm rainfall year). The ameliorated lime improved the %Ndfa and shoot N fixation (12-24 kg N/t DM) in all pulse crops at Greenethorpe compared to 2020 even in such a wet year with high disease pressure (Table 12). A new northern type of faba beans was grown in 2021 that produced excellent grain yields (7.7 t/ha), but potentially produced less biomass compared to the longer maturing Samira faba bean that was sown in 2020. The high grain yield and reduced faba bean biomass DM has resulted in lower net inputs of fixed N remaining in the crop residues compared to what may have been remaining if a southern later maturing variety such as Samira had been sown (Table 13).

Table 12. Soil mineral N at sowing, legume shoot biomass, %N content, and estimates of the proportion (%Ndfa), and amounts of shoot and total plant (shoot+root) N fixed at Greenethorpe in 2021 for a range of legume crops.

Crop 2021	Starting soil Mineral N 0-2m (kgN/ha)	Legume Biomass (t/ha)	Legume (%N)	Ndfa (%)	ShootN (kgN/ha)	ShootN fixed (kgN/ha)	ShootDM (kgN/tDM)	Total N fixed shoot & root (kgN/tDM)
Vetch Un-Grazed (T)	110	7.1	2.9	82	207	171	24	36
Faba bean	146	11.2	2.8	79	310	244	22	33
Chickpea (N2) (ChP-W)	106	9.4	1.9	63	176	111	12	24
Chickpea (N7) (C-W-ChP)	92	9.5	2.0	67	188	127	13	28
Chickpea (N2) (C-W-ChP)	91	8.9	2.5	57	226	128	14	29
Chickpea intercrop	150	6.2	2.1	78	127	99	16	33

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

The cool September/October resulted in delayed flowering of the chickpea variety Captain when compared to previous years. The site did not reach the average daily temperature of 15 degrees Celsius until late October, with the daily temperature between mid-August and the end of October generally staying below 15 degrees Celsius (Figure 4). The longer growing season assisted chickpea to produce more biomass and reasonable grain yields despite the continued impact of fungal diseases that included Ascochyta blight, sclerotinia and botrytis grey mould. This higher biomass resulted in high net inputs of fixed N (Table 13). The same chickpea population (35 plants/m^2) was sown and established in the chickpea/linseed intercrop treatment, but the chickpeas were sown in alternate rows, 50 cm wide. The linseed did not emerge in high numbers and this treatment became a predominately chickpea crop sown on 50 cm wide rows. Interestingly, there was considerably less biomass and grain yield compared to the chickpea monoculture sown on 25 cm row spacing.

Table 13. Grain and hay yields, grain %N, N removed in grain or hay and the estimated residual fixed N remaining after grain or hay removal from a range of legume crops at the Greenethorpe site in 2021.

Crop 2021	Total Hay () & Legume Hay Yield (t/ha)	Grain Yield (t/ha)	Grain (%N)	Total Fixed N from root & shoot (kgN/ha)	N removed from grain or hay (kgN/ha)	Fixed N remaining in crop resides (kgN/ha)
Vetch Un-Grazed (T)	(5.0) 5.0			257	120	137
Faba bean		7.7	4.3	366	331	36
Chickpea (N2) (ChP-W)		3.1	3.2	229	101	128
Chickpea (N7) (C-W-ChP)		2.6	3.2	262	84	177
Chickpea (N2) (C-W-ChP)		2.9	3.2	263	94	169
Chickpea intercrop		2.0	3.2	203	64	139

Total plant biomass is indicated in brackets if it is different than the total legume biomass.

* Hay calculated as 70% of the total plant dry matter

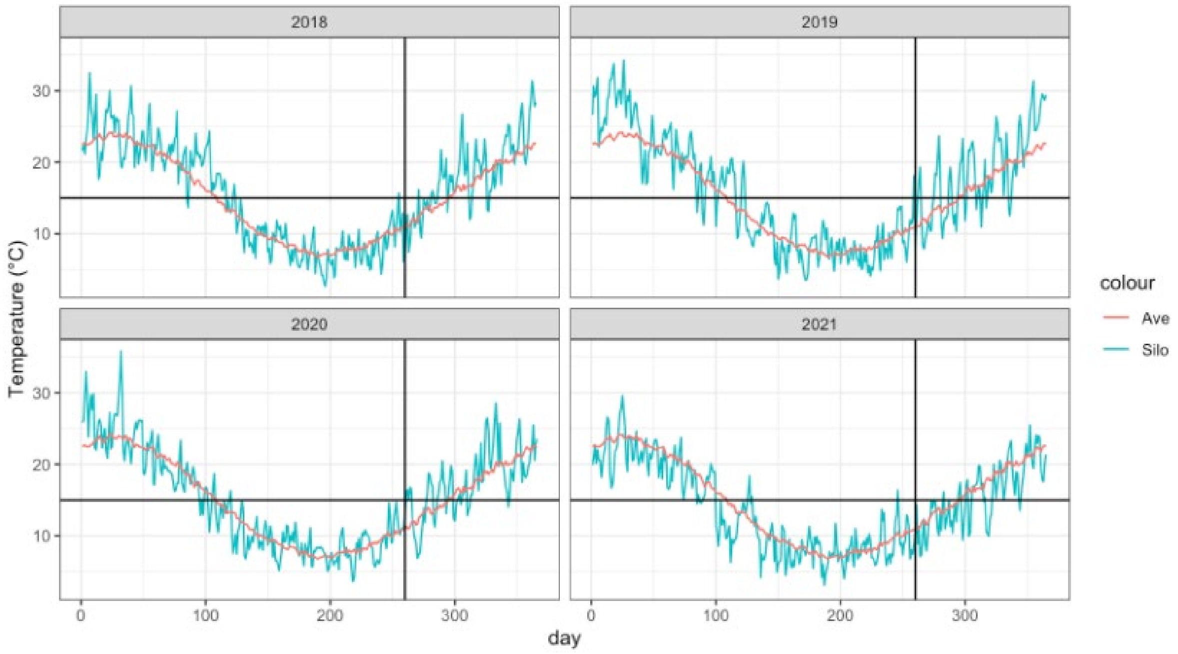

Figure 4. The daily and average daily temperature at the Greenethorpe trial site in 2018-2021 from interpreted data (Silo). Data courtesy of Dr Jeremy Whish.

Section 2: Legume crop legacy

Soil N

The main route for biologically fixed N to enter the soil N pool is through the decomposition of legume crop residues. The magnitude and timing of the release of legume N as plant-available forms represents a balance been the microbial-mediated mineralisation and immobilisation processes in the soil, which in turn are affected by the efficiency of use of the legume organic C by the decomposer population, and the microbial demand for C and N for growth (Kumar and Goh, 2000; Fillery, 2001). Inorganic N tends to be released from plant residues once excess C has been consumed by microbial growth. As compared to cereal crop residue, legume crop residue contains both a higher N content as well as a lower C to N ratio. These characteristics favour net N mineralisation and therefore lead to higher soil mineral N concentrations as legume crop residue breaks down. While legume crop residue breakdown is the primary source of soil N availability improvements after legume crops, this is not the only source. Other sources include: the carry-over of un-utilised mineral N after the legume crops and reduced N immobilisation by the soil biology compared to cereal stubbles.

Junee Reefs experiment 2011-2013

The large differences in soil mineral N observed following pulses grown for grain or BM in 2011 at the Junee Reefs experiment compared to wheat or canola top-dressed with fertiliser N at stem elongation, resulted in increases in wheat N uptake and higher wheat grain protein percentage in 2012 (Table 14). However, the impact of the additional N supply was not fully reflected in grain yields, with only a 0.6-0.7 t/ha increase in wheat grain yield. The drier growing season of 2012 reduced the maximum grain yield to 4.1 t/ha. The subsequent calculations indicate that the 2012 wheat crop recovered the equivalent of 29-39 % (mean 32 %) of pulse residue N (Table 14). This compared to 49-61 % (average 55 %) of the top-dressed fertiliser N. When Peoples *et al.* (2017) examined a range of crops between 1990 and 2016 across New South Wales and South Australia,

Table 14. Grain yield and crop N uptake by wheat in 2012 following either wheat, canola, and lupin or field pea grown for brown manure (BM) or lupin, chickpea or lentil grown for grain at Junee, NSW in 2011, and calculations of the apparent recoveries by wheat of either N from pulse crop residues, or top-dressed fertiliser N.

	Soil mineral N autumn 2012 (kg N/ha)	N fertiliser applied 2012 (kg N/ha)	Wheat grain yield (t/ha)	Wheat grain protein %)	Wheat total N uptake (kg N/ha)	Apparent recovery of legume or fertiliser N (%)
Lupins BM	152	49	4.0	13.6	198	29%
Field Pea BM	113	49	4.1	12.3	177	29%
Lupin	110	49	3.9	12.4	170	30%
Chickpea	152	49	4.0	12.4	181	39%
Lentil	111	49	4.0	11.2	152	35%
Wheat	70	49	3.4	9.9	114	-
Wheat	70	100	3.8	11.7	145	61%
Canola	72	49	3.4	9.8	118	-
Canola	72	100	3.8	11.8	143	49%
Mean legume						32%
Mean fertiliser						55%

Source: Peoples *et al.,* 2015 GRDC update, Peoples *et al.,* 2017 and un-published results.

they found that the average apparent recovery of legume N was 30% from grain legume crops and 29% from BM crops.

The CSIRO/NSW DPI farming system teams will examine the current farming systems and determine if the apparent recovery legume N by the following crop is within the range that Peoples *et al.* (2017) reported.

Southern Farming Systems project results (2018-2021)

The inclusion of fully phased crop sequences with and without legumes across a range of locations (Wagga Wagga, Greenethorpe, Urana & Condobolin) and seasons (2018, 2019, 2020 & 2021) in this project has allowed the investigation of a number of key questions:

(i) To what degree do legume crops boost the soil mineral N available to subsequent crops?
(ii) To what degree do legume crops boost the grain yield of subsequent crops, and
(iii) What is the approximate dollar value of these legume legacy benefits?

The legume crops at all four sites often resulted in more mineral N being available at sowing of the subsequent crops (Figure 5 and Table 15). Averaged across legume crop types, seasons and sites, an extra 50 kg/ha of extra mineral N was available at sowing in the subsequent season as compared to a cereal crop in the same season. Much of this N wasn't available directly after the legume harvest, but became available over the summer fallow period.

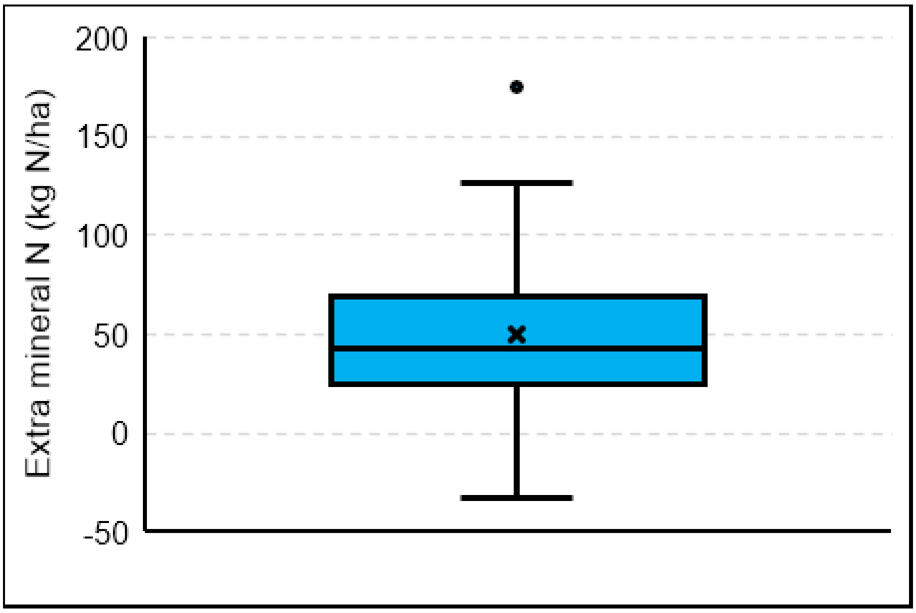

Figure 5. Extra soil mineral N (0-2 m) available at sowing following a legume crop compared to a cereal crop; averaged across four legume crops (lentil, lupin, faba bean & vetch), four sites (Wagga Wagga, Greenethorpe, Urana & Condobolin) and three seasons (2018, 2019 & 2020). Comparisons made between equivalent timely sown, decile 2 N strategy crop sequences. n=33, average=50 kg N/ha. The blue area represents the middle 50 % of data points, the two outside lines represents the maximum and minimum data point and the dot represents an outlying data point.

As evident in Figure 5, a significant amount of variability exists in the amount of extra soil mineral N that was available to the subsequent crops following a legume crop. Some trends exist between field site and season, however few clear trends are evident between preceding crop type (Table 15). This highlights that legume crop choice is better governed by performance and profitability potential for a given farm enterprise rather than potential soil mineral N benefits, which is a secondary consideration.

Table 15. Extra soil mineral N (0-2 m) available at sowing following a range of legume crops compared to a cereal crop at each site; averaged across three seasons (2018, 2019 & 2020). Comparisons made between equivalent timely sown, decile 2 N strategy sequences.

Preceding crop type	Field site			
	Wagga Wagga	Greenethorpe	Urana	Condobolin
	Extra mineral N (kg N/ha)			
Lentil	34	-	70	42
Lupin	15	-	-	60
Fababean	-	67	50	-
Vetch	37	63	77	37

With synthetic fertiliser prices at current all-time highs, more people are looking to legumes as a potential N source. One way to compare synthetic N sources to legume N sources is to value the short-term N benefit that legume crops can provide at the equivalent cost of urea. This comparison is presented in Table 16. At high urea prices as are currently being experienced ($1,200/t in early 2022), the value of legume N benefits can be significant at over $200/ha. It is important to note that this valuing of the soil N legacy left by legume crop only considers the extra mineral N accumulation over the summer period and does not consider any further in-crop mineralisation that can occur during the following growing season.

Table 16. Average extra soil mineral N (0-2 m) available at sowing following a legume crop compared to a cereal crop at each field site, with the value of this extra mineral N displayed at a range of urea prices. An assumption of 30 % N loss from applied urea has been applied.

	Field site			
	Wagga Wagga	Greenethorpe	Urana	Condobolin
	Average extra mineral N (kg N/ha)			
	29	64	66	47
Urea price ($/t)	Value of extra mineral N as Urea ($/ha)			
600	54	119	123	88
800	72	159	164	117
1,000	90	199	205	146
1,200	108	239	246	175
1,400	126	278	287	204

Using the crop sequences implemented in the southern farming systems project, not only are we able to examine the soil N legacy effects following legume crops, but we are also able to examine the urea savings and grain yield benefits provided to subsequent crops.

The N management strategies compared across some crop sequences in this project were based on either a conservative seasonal outlook (decile 2), or a more optimistic (decile 7) seasonal outlook. For each non-legume crop in each year of the sequences, soil mineral N was measured pre-sowing and a potential yield estimate was made based on starting soil water, N level and seasonal conditions up to that time. N was then applied as urea assuming either a decile 2 or a decile 7 finish to the season. Assuming an average season is decile 5, this means that often the decile 2 N strategy would be too low, and the decile 7 treatment too high to maximise yield potential in any year. Using this approach, the legacy benefits of carry-over N from either legumes or unused fertiliser N would be accounted for in the pre-sowing tests and less N applied accordingly. This approach (compared to set N rates) better mimics farmer practice.

For a given N management strategy, the extra soil mineral N often available following legume crops results in a reduction in the rate of top-dressed urea needing to be applied to the subsequent canola crops. This saving is urea cost combined with any grain yield benefit can be used to provide an indication of the legume legacy benefit in $/ha. Averaged across the three field sites, four legume crop types and three seasons, the average urea saving and grain yield benefit to the following canola crop was 78 kg/ha and 0.22 t/ha respectively (Table 17). When these benefits are valued at $1,200/t for urea and $650/t for canola, the total value of the legume value ranges from $171 to $330/ha depending on the field site, with an average of $237/ha (Table 17).

The above comparisons are made under a decile 2 N strategy. However, at the Wagga Wagga field site we can also make comparisons with decile 7 N strategy cereal sequences. This allows the comparison of legume legacy benefits to non-legume sequences where N is less limiting due to higher rates of urea applied.

Table 17. Urea saving, extra canola grain yield and the dollar value of these benefits following a legume crop compared to a cereal crop at each field site; averaged across a range of legume crops (lentil, lupin, faba bean & vetch) and three seasons (2018, 2019 & 2020). Comparisons made between equivalent timely sown, decile 2 N strategy crop sequences.

Field site	Wagga Wagga	Greenethorpe*	Urana	Condobolin	Average
Average urea saving (kg/ha)	29	120	69	94	78
Average extra canola yield (t/ha)	0.21	0.18	0.38	0.11	0.22
Value of urea saving: Urea=$1,200/t ($/ha)	35	144	83	113	94
Value of extra canola yield: Canola=$650/t ($/ha)	137	117	247	72	143
Total value of legume legacy ($/ha)	171	261	330	184	237

*Only legacy effects from the 2019 legume crops included for the Greenethorpe site.

The implementation of the higher decile 7 nitrogen strategy instead of the decile 2 strategy on the non-legume sequence resulted in an increased canola grain yield. However, this increase in grain yield was not high enough to offset the significant extra urea cost. As a result, the $/ha value of the legume legacy benefits are even higher when compared to the decile 7 non-legume sequence (Table 18).

Table 18. Urea saving, extra canola grain yield and the dollar value of these benefits following a legume crop compared to a cereal crop across two N management strategies (decile 2 & decile 7) at the Wagga Wagga field site; averaged across a range of legume crops (Lentil, lupin, faba bean & vetch) and three seasons (2018, 2019 & 2020). Comparisons made between equivalent timely sown, decile 2 & 7 N strategy crop sequences.

Nitrogen strategy of non-legume crop sequence	Decile 2	Decile 7
Average urea saving (kg/ha)	29	204
Average extra canola grain yield (t/ha)	0.21	0.02
Value of urea saving: Urea=$1,200/t ($/ha)	35	245
Value of extra canola yield: Canola=$650/t ($/ha)	137	13
Total value of legume legacy ($/ha)	171	258

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Consultant led panel discussion - key insights from farming systems research

Notes

Balancing risk and reward with high phosphorus and nitrogen input costs

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Key words

nitrogen, phosphorus, critical P values, P and N off-take, fertiliser, nutrition

Take home message

- Results from two long term P and N sites indicate that targeting P and N balance (long term off-take in grain + losses/fixation) was more profitable using a range of input price scenarios than targeting the highest yields which were achieved with significantly greater fertiliser inputs
- Where soil Colwell P values are above the critical range (e.g., 50 or above), P inputs estimated at long-term P off-take rates (P off-take in grain) provides yield and profit optimisation with a very slow decline in soil Colwell P
- Even in very high Colwell P soils, starter P is necessary to obtain potential yield in a wheat canola rotation where late April through to mid-May sowings are applied
- Early sowing times (early April) with good soil moisture reduce the grain yield response from starter P in a range of soil Colwell P settings
- A sound paddock history of Colwell P and soil pre-sowing mineral N values is essential to inform optimisation of P and N profits
- N replacement rates below grain off-take levels results in lower yields and lower profits even where soil Colwell P levels and starter P rates were high
- Two long term P and N site indicate that about half of the crop N requirements were provided by soil mineralisation.

Introduction

It's estimated that 3.54 billion people are supplied food that is only made possible with the addition of inorganic fertilisers (Erisman *et al*., 2008). It's also clear that where nitrogen (N) or phosphorus (P) is deficient in soils and/or phosphorus is not applied in adequate amounts at sowing (starter P), crop yields are often much lower than the water limited potential yield. (e.g., Bell *et al.,* 2013; Nkebiew *et al*., 2016; Sandral *et al.,* 2018; 2019). This context is important whenever lower fertiliser inputs are considered, as the downside profit risk of lower inputs is significant.

Phosphorus

Annual P inputs are essential in all broadacre crops to maximise profits with the exception of broadleaf lupins (*Lupinus albus*). However, lowering P inputs can be considered where the soil P status is in excess to that of plant requirements. This may occur because (i) historic applications have been in excess of P exports and soil fixation or (ii) the particular crop species being grown has low soil critical P requirement. Other factors that are important considerations include the phosphorus buffering index (PBI) of the soil, the pH of the soil and the crop time of sowing. Fundamental to the potential to lowering P inputs is the fact that most crop P requirements are extracted from soil reserves and not from P applied at sowing. Even so, because of its low mobility in the soil, there is often a positive effect of having some P placed close to the seed at sowing (Nkebiwe *et al.*, 2016; Figure 10).

The critical soil P value or critical P range is usually defined as the soil P that will provide 90 to 95% of crop water limited yield. The critical P range is mostly impacted by the crop type, sowing time, soil PBI, soil type and soil pH. Examples include, narrow leaf lupin (*Lupinus angustifolius*) which have a critical P range two thirds that of wheat (Anderson *et al.*, 2015), April sowing times with adequate soil moisture that have at least half the starter P requirement compared with later May sowings of wheat (Batten *et al*., 1999, Mason and McDonald 2021), high PBI soils that bind more P in the soil resulting in a higher soil critical P requirement for Colwell P, and soil pH that impacts on P binding by changing the availability of Fe, Al, and Ca.

Phosphorus cycling: P fertiliser that is added to the soil in cropping systems primarily goes into the 'soil reserve' (Figure 2) where the P bind to soil in a process referred to as P sorption or fixation. Fixation occurs when P reacts with other minerals to form insoluble compounds and becomes unavailable to crops. An important factor controlling P fixation is soil pH and where soils are acid and have high Fe and/or Al, liming will provide additional plant available P (Figure 1). Studies that have compared the return on investment in P verses lime on acid soils (<4.8 $CaCl_2$) have shown that returns are higher for lime when the time horizon is greater than 3 (Cho *et al.,* 2020) to 5 years (Katitbie *et al.*, 2002).

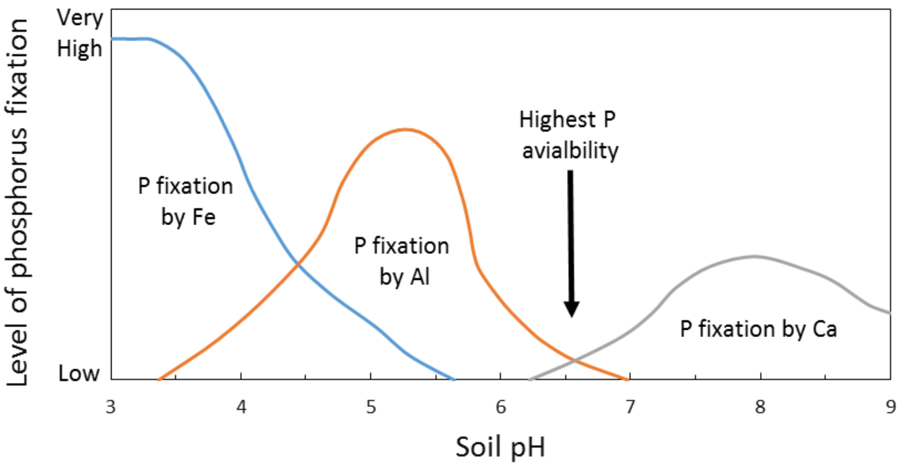

Figure 1. The effect of soil pH on phosphorus availability.

Plant available P in soil solution is predominantly present as H_2PO_4- (Dihydrogen phosphate) or as HPO_4^{-2} (hydrogen phosphate) in more neutral and alkaline soils. Various estimates indicate approximately 70–95% of P fertiliser added in the crop year becomes part of the soil reserve (Price 2006, McBeth *et al.,* 2012). The soil reserve is made up of:

1. Sorbed P (P held on the surface of fine clay particles),
2. Secondary P minerals (freshly bounded Fe, Al and Mn phosphates [acid soils] and Ca and Mg phosphates [alkaline soils]) and
3. Primary P minerals (age and crystallised Fe, Al, Mn, Ca and Mg phosphates).

The soil P reserve (Figure 2) in P adequate soils (Table 2) provides the largest percentage of crop requirements in any one year which is estimated at ~30–95% (Price 2006, McBeath *et al*., 2012). Phosphorus fertiliser applied at sowing can directly provide ~5–30% of crop requirements (McBeath *et al*., 2012) with the percentage of available P in stubble estimated at ~9–44% (Noack *et al*., 2012) and in roots ~21–26% (Foyjunnessa *et al*., 2016).

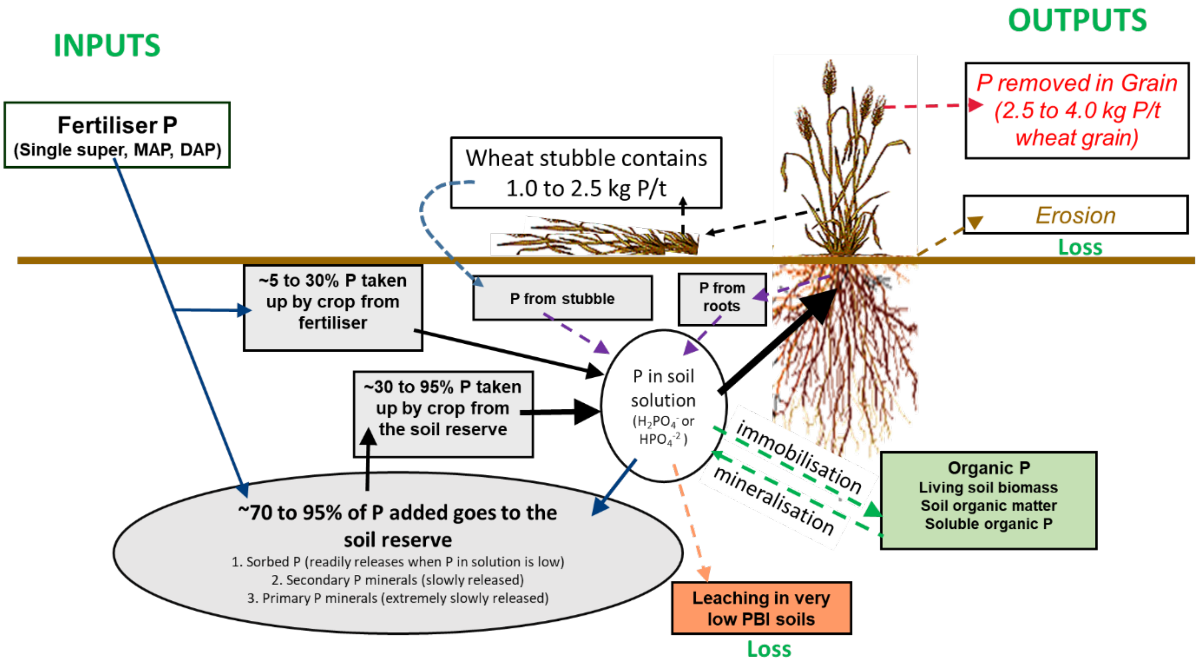

Figure 2. Soil phosphorus cycling in winter cropping systems.

PBI: The Phosphorus Buffering Index (PBI) test measures the P sorption of the soil. This is the process by which soluble P becomes adsorbed to clay minerals and/or precipitates out in soil and it determines the partitioning of P between the solid and solution phases of the soil. A high PBI will quickly bind P to soil exchange sites and make it less available for plant uptake. Consequently, P sorption capacity of soil influences the availability of P to plants and can be useful for determining Colwell P critical values. Figure 3 shows the relationship between PBI and Colwell P critical for wheat. Usually, large changes in PBI values are required to change crop critical values. Examples of this are provided in Table 1 calculated from Moody (2007) and Bell *et al.,* (2013).

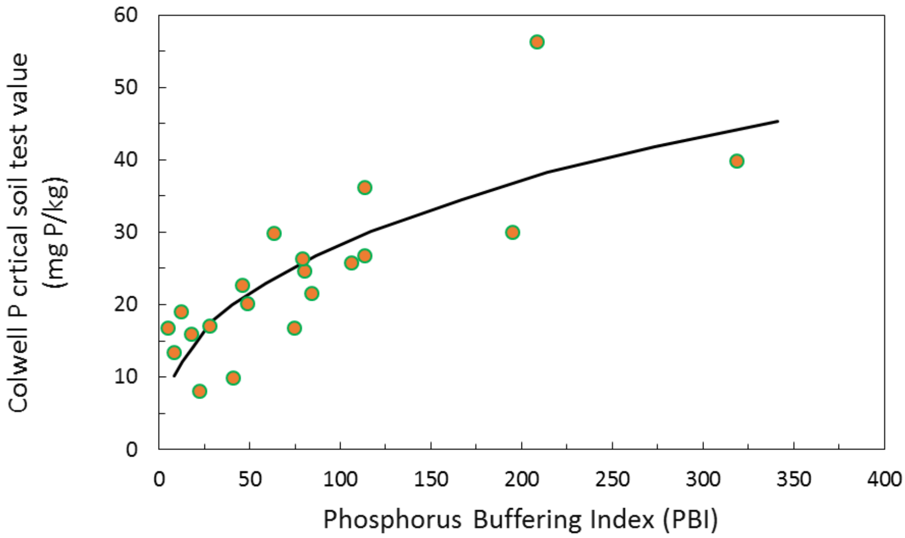

Figure 3. Effect of PBI on critical Colwell-P (0–0.10 m) required for 90% maximum grain yield of wheat. Critical Colwell P = 4.6 x PBI$^{0.393}$ (Moody 2007).

Table 1. Estimated 90% critical Colwell P soil values (mg P/kg soil) for wheat grown in soils with differing PBI (Moody 2007 and Bell *et al.,* 2013).

P Buffering	PBI	Estimated 90% critical P	P Buffering	PBI	Estimated 90% critical P
Extremely low	10	11.4	Low	80	25.7
Very very low	20	14.9	Moderate	180	35.4
Very low	40	19.6	High	350	46

Critical Colwell P soil test values: An analysis of data from the BFDC database using Mitscherlich equations indicates 90 and 95% critical values for canola across soil types are estimated at 23 and 26 mg P/kg soil using Colwell P at 0-10cm soil depth (Figure 4b). While the quadratic equation for canola predicts a Colwell P range from 20 to 25 kg P /kg soil (Table 2). The same comparisons for wheat on red chromosols indicate a Colwell P critical of 34 and 45 (Figure 4a) using the Mitscherlich equation, while the quadratic equations predict 30 to 38 mg P/kg soil (Table 2). This suggests for canola and wheat where Colwell P values are above 26 and 45 mg P/kg soil respectively, the opportunity exists to provide a more conservative P input program focused on P replacement rather than P accumulation.

Table 2. Colwell P (mg /kg soil) values for 90 and 95% of maximum grain yield for various crop and soil type combinations extracted from the BFDC database. Estimated Colwell P critical values for chickpea, faba bean, lentil and broadleaf lupins are not available from the BFDC database due to no or insufficient data. Similarly, not enough data exists for feed barley, field pea, canola and narrow leaf lupin to provide specific soil type estimates of Colwell P critical values. Where states are nominated under 'location' this refers to the state where most of the experiments (not necessarily all) were conducted (BFDC database 2022).

Species	Soil	90%	95%	Location
Feed barley	All soils	20	25	National
Field Pea	All soils	27	34	National
Narrow leaf lupin	All soils	22	26	National
Canola	All soils	20	25	National
Wheat	All soils	24	32	National
Wheat	Chromosol red	30	38	NSW, QLD, Vic
Wheat	Chromosol brown	17	19	WA, SA
Wheat	Chromosol grey	18	21	WA
Wheat	Calcarosol calcic	24	29	SA, Vic, Wa
Wheat	Dermosol	27	35	NSW
Wheat	Kandosol red	24	30	NSW
Wheat	Tenosol	16	20	WA, SA, Tas
Wheat	Sodosol brown	27	32	NSW, Vic, SA
Wheat	Vertosol black	25	33	NSW, QLD
Wheat	Vertosol brown	24	32	NSW, SA
Wheat	Vertosol grey	18	21	Vic, NSW, QLD

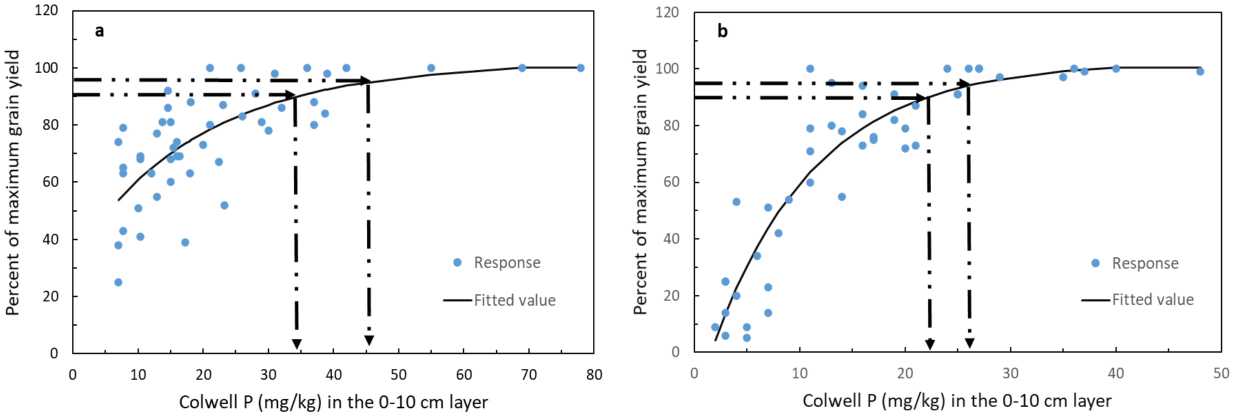

Figure 4. Grain yield response of (a) wheat on red chromosol soils of NSW and (b) canola on a range of soils using Mitscherlich equations. Raw data taken from the BFDC (2022).

Long term experimental results – Dahlen: At Dahlen near Horsham in Victoria a long-term P and nitrogen experiment was conducted over the period 1996 to 2014 on a vertosol soil with a phosphorus buffering index of 110. Since establishment, the site has been in a canola, wheat, barley, pulse rotation. The fertiliser treatments include five rates of nitrogen (0, 20, 40, 80, 160 kg/ha as urea) and four rates of phosphorus (0, 9, 18, 36 kg/ha as triple super) applied annually over 18 years. Nitrogen was not applied during the pulse phase of the rotation. Annual rainfall over the period varied between 270 and 630 mm with average annual rainfall of 420 mm. The experiment had two complete crop failures (2002, 2006) and these years were fertilized and yields (nil) included in the averages in Figures 5 and 6.

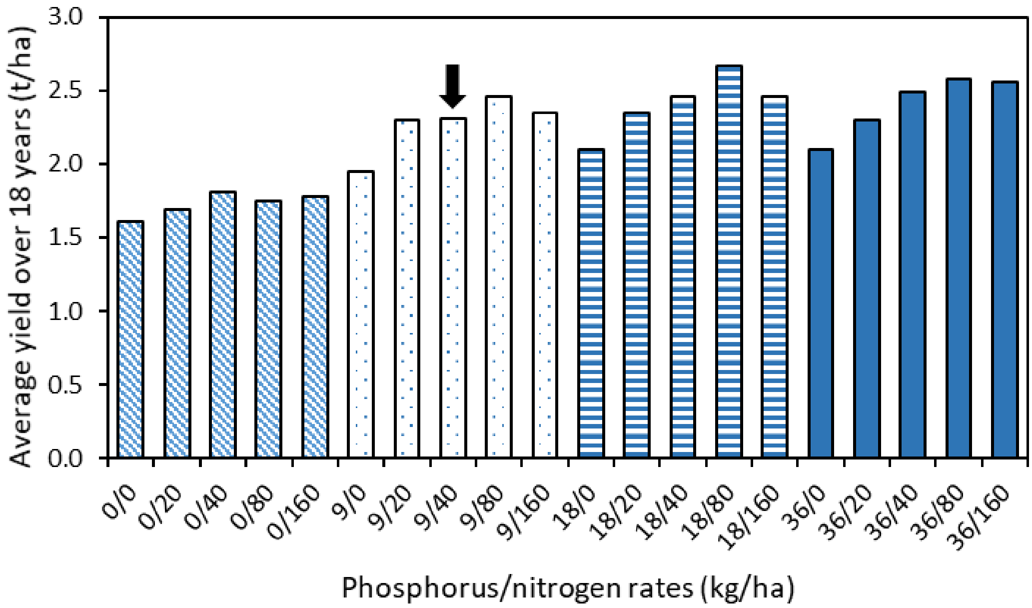

Figure 5. Average grain yield response at Dahlen for canola, wheat, barley, oaten hay and pulse over 18 years to different P and N rate combinations. Filled arrow indicates approximate P and N balance. The code on the x axis indicates the P rate followed by the N rate hence 9/40 means 9 kg P and 40 kg N were applied per hectare.

Approximate phosphorus and nitrogen balance (long-term fertiliser inputs equal long-term P and N off-take in grain) was achieved at applied treatment rates of 9 kg P/ha and 40 kg N/ha and provided an average yield of 2.31 t/ha. Calculated P and N offtake for the 9 P/ 40 N treatment was estimated at 8 and 46 kg/ha of P and N respectively. Consequently the 9 P/ 40 N treatment was slightly under supplied with N slightly over supplied with P which is supported by cumulative P balance presented in Figure 6. The highest average yield (2.67 t/ha) was achieved by inputs of 18 P/80 N which was an average increase of 0.36 t/ha. However, this treatment (18 P / 80 N) was less profitable than the 9 P/ 40 N using a number of fertiliser price scenarios.

The starting Colwell P for the Dahlen site in 1996 was 24 mg P/kg soil and it took 10 years (2004) for the 9 kg P/ha rate to raise the soil Colwell P to 30 mg P/kg soil. During this period the soil Colwell P value would have limited grain yield response. This should be considered when interpreting average yield results in Figure 5 reported above. The best estimates of P and N rates for the Dahlen site are 8 to 9 kg P/ha and 45 to 50 kg N/ha. These estimated P and N inputs are best perused after firstly rapidly raising the soil P Colwell P value from 24 (site starting Colwell P) to between 30 and 38 mg P/kg soil (critical P range for this wheat in this soil).

Annual P removal varied with crop type and yield at Dahlen. Seed P concentrations at delivered moisture concentrations were 2.7 kg P/t for barley, 2.8 kg P/t for wheat, 3.3 to 3.8 kg P/t for pulses, and 5.1 kg P/t for canola. Seed P concentrations were higher under higher P rates and these differences were included in the nutrient balances shown in Figure 6. The seed P concentrations for wheat and canola from Dahlen were similar to those reported by Norton (2012; 2013) from NVT trials and presented in Table 5.

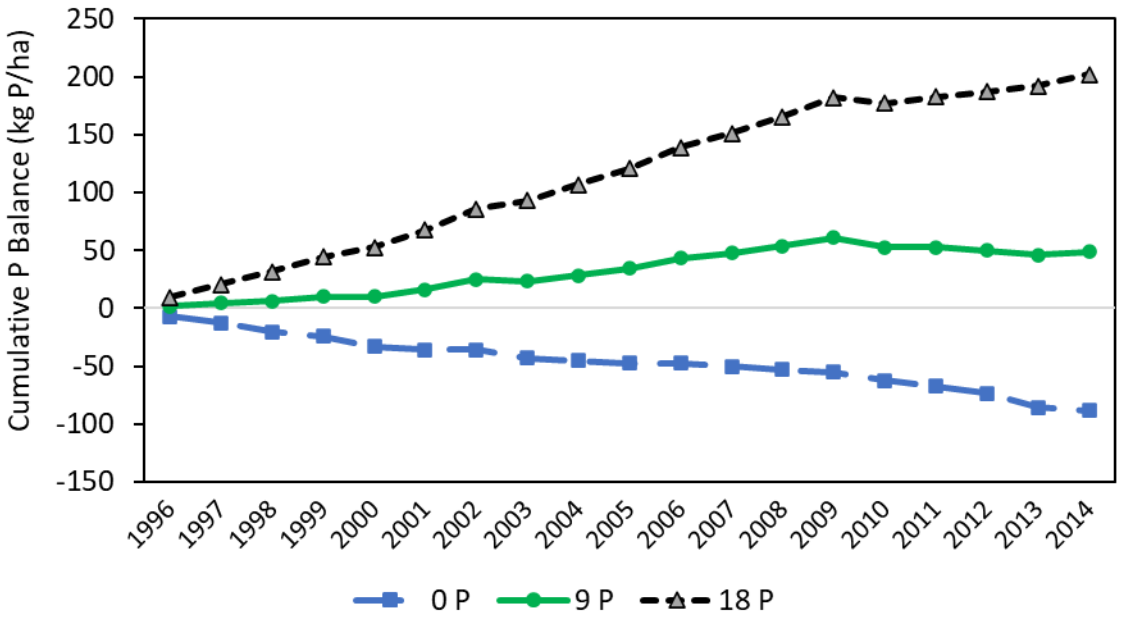

Figure 6. The cumulative P balance in the soil over 18 years of the 0P/40N, 9P/40N and 18P/40 N treatments at the Dahlen.

Over the duration of the experiment, Colwell P (0-10 cm) started at ~24 mg/kg in 1996, and by 2015 soil test values were 17, 40 and 72 mg/kg under the 0P/40N, 9P/40N and 18P/40N treatments (Figure 6). At the 9P/40N annual rates, 88% of the P applied was recovered in grain and the soil test increased by 16 units (Colwell P 24 in 1996 and Colwell P 40 in 2014). The last 11 years of the 9P/40N treatment provided optimal P for this system. Applying 18P/40N did not give a significant yield increase over 9P/40N, with the extra P largely going into increasing the soil test values through time and higher P concentrations in grain.

Long term experimental results - Glenelg: At Glenelg near Grenfell in central New South Wales a long-term P and N experiment on a red chromosol soil has been continually assessed since 2007. The soil phosphorus buffering index is 46, soil pH on the phosphorous only treatments was 4.8 ($CaCl_2$) in 2008 and 4.6 ($CaCl_2$) in 2021. The site has been in a canola, wheat and pulse rotation with five P and N fertiliser treatments (0, 10, 20, 30, 40 kg/ha as triple super and 0, 30, 60, 90, 120 kg/ha as urea). Nitrogen was not applied during the pulse phase of the rotation. Drought years were 2007, 2017, 2018 and 2019, canola was resown in 2014 and Albus lupins were grown in 2010. Stubble was burnt the week before planting in 2011, 2015, 2017 and stubble was retained in the other years. Annual rainfall over the period has varied between 285 and 1066 mm with average annual rainfall of 657 mm. Growing season rainfall (April-October) has varied between 127 mm and 616 mm for an average annual of 315 mm (Table 3).

Table 3. Annual and growing season rainfall (GRS) at Glenelg for years 2007 to 2021.

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Annual	517	559	611	1066	806	640	486	611	664	921	618	347	285	736	996
GSR	212	278	318	483	243	249	308	340	429	616	188	173	127	511	419

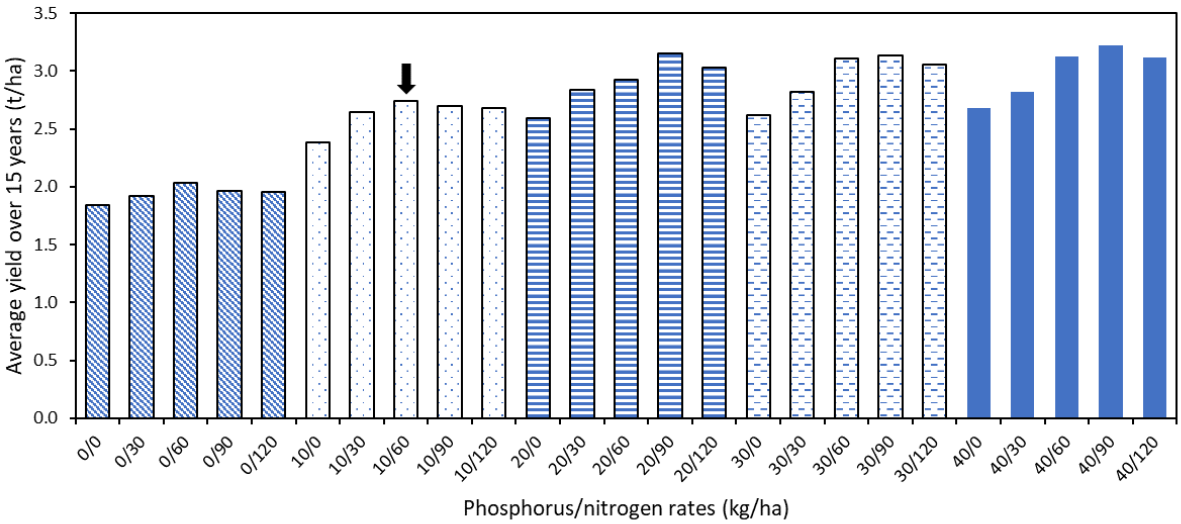

Figure 7. Average grain yield response at Glenelg for canola, wheat, and pulse over 15 years to different P and N rate combinations. Filled arrow indicates approximate P and N balance. The code on the x axis indicates the P rate followed by the N rate hence 10/60 means 10 kg P and 60 kg N were applied per hectare.

Phosphorus and N balance (long-term fertiliser inputs equal long-term P and N off-take in grain) was achieved at applied rates approximating 10 kg P/ha and 60 kg N/ha and achieved an average yield of 2.74 t/ha. Calculated P and N offtake for the 10 P/ 60 N treatment was estimated at 11 to 13 and 55 to 62 kg/ha of P and N respectively. At long term average P and N costs the highest profit was achieved at long term P and N off-take rates (appendix 1). The highest yielding treatment (20 P/90 N) was not more profitable and has accumulated soil phosphorus levels (Figure 8) above crop critical requirements and increased the soil N bank (data not shown). Phosphorus removal in grain approximated 4.2 kg P /t across the rotation.

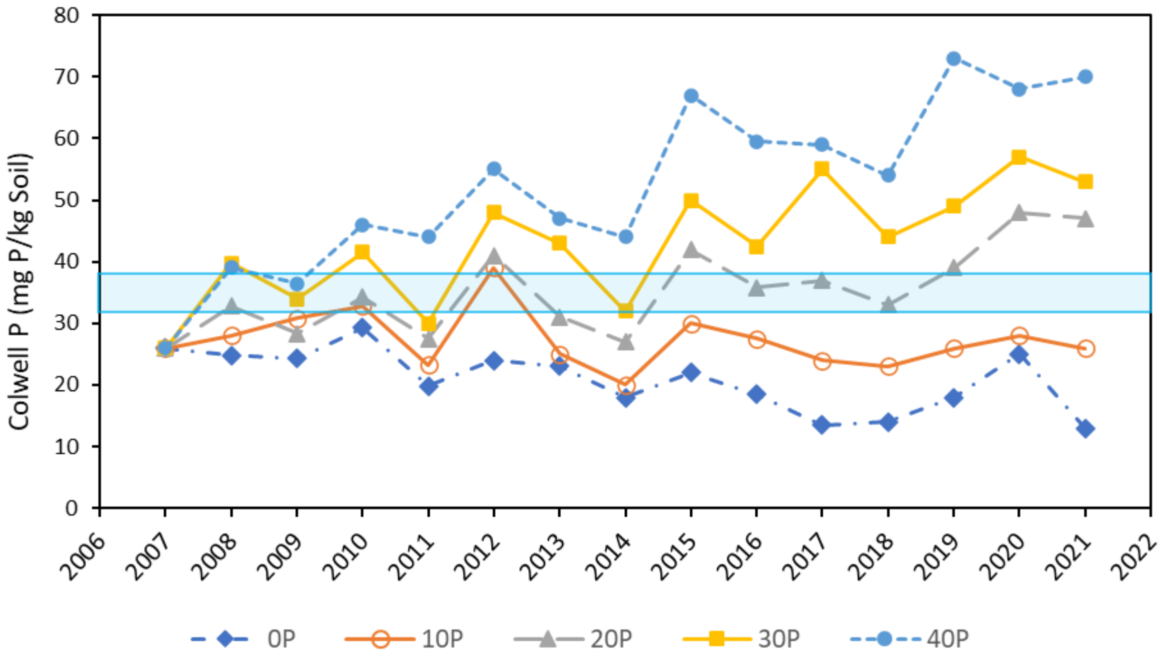

Figure 8. Annual Colwell P values for five P treatments (0, 10, 20, 30, 40) at the Glenelg site applied annually to all crops for the unlimited N treatment (120 kg N/ha). The light banded area represents the preferred Colwell P range for the Glenelg site.

The starting Colwell P for the Glenelg site in 2007 was 26 mg P/kg soil and the 10 kg P/ha rate maintained this same Colwell P through to 2021 (open circle, Figure 8) but did not increase Colwell P into the critical range (open circles compared with shaded area Figure 8). Consequently, this Colwell P would have limited grain yield in some years effecting average yield shown in Figure 7. It took ~7 years for the soil Colwell P value to be consistently higher in the 20 kg P/ha rate (solid triangle, Figure 8) compared to the 10 kg P/ha rate (open circle, Figure 8). When considering Figure 8 in a paddock context it is clear that the 20 kg P/ha rate (closed triangle) could have been reduced to 11 to 13 kg P/ha (long term P off-take levels) at sowing in 2021 to reduce P input costs without likely impacting yield (Figure 8 and Figure 7).

The important question that arises from Figure 8 is how much can P inputs be reduced if there is a starting Colwell P above the critical range. In Figure 8 we identified that a P input of 10 kg/ha (open circle) was able to maintain the same soil Colwell P value through time. In Figure 9 the P input of 10 kg P/ha (also open circle) started at a Colwell P value of 50 and after 7 years reduced to Colwell P 35 which is within the critical range for wheat on this soil type. This suggests the actual replacement rate for P at this site is at the upper end of the calculated off-take rate of 11 to 13 kg P/ha.

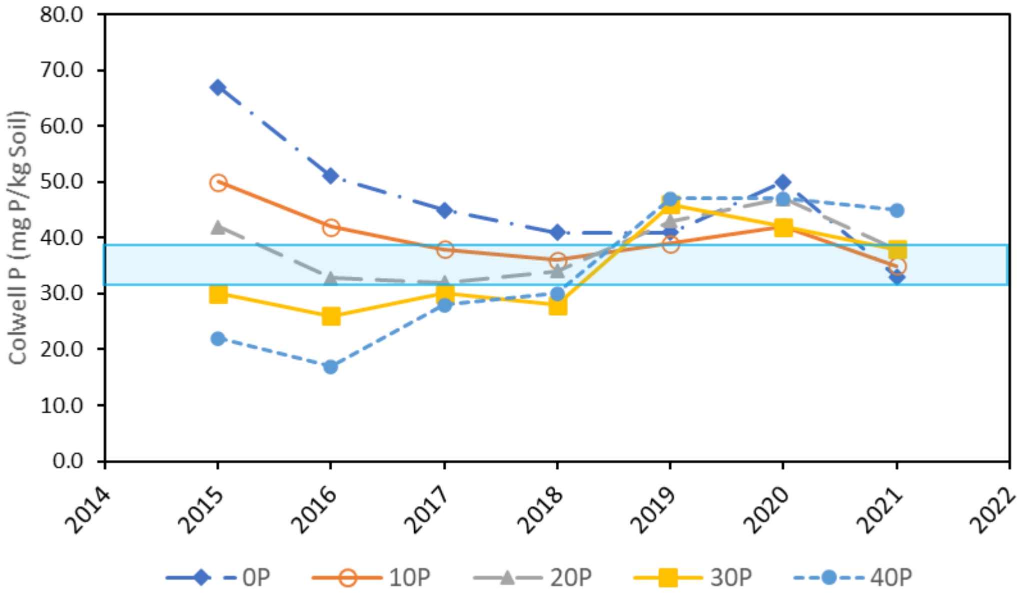

Figure 9. Annual soil Colwell P for different P inputs where the starting Colwell P ranged from 67 to 22 mg P/kg soil at Glenelg. Nitrogen was supplied at 120 N /ha. The shaded area represents the preferred Colwell P range.

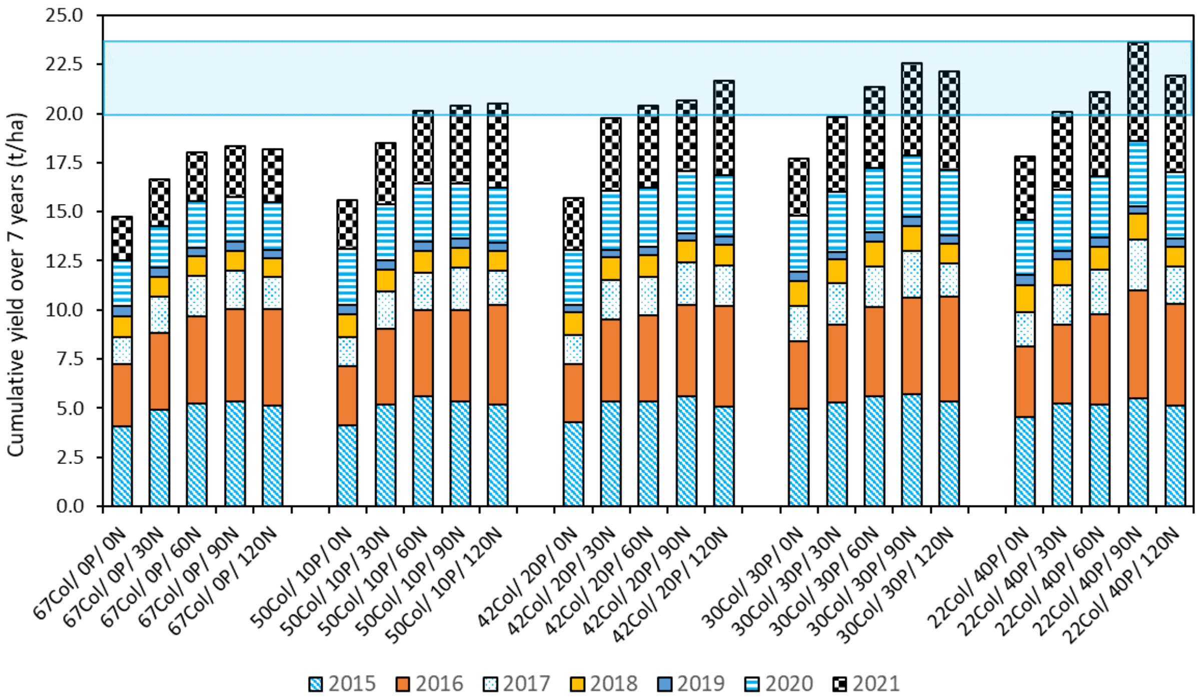

Figure 10. Cumulative grain yield response at Glenelg for canola and wheat, over 7 years to different P and N rate combinations as well as different starting Colwell P values. Shaded section represents the error term (LSD 5%) of 3.45 t/ha. The code on the x axis (e.g., 67Col/ 0P/ 0N) means this treatment started with a Colwell P value of 67 mg P/kg soil and received no additional P or N.

The results in Figure 10 indicate that even with a high starting Colwell P value of 67 mg P/kg soil, nil P application at sowing results in lower yields and that this is exacerbated by N rates below 60 kg

N/ha. This clearly shows that even with very high soil Colwell P values, starter P applied at sowing is necessary to obtain potential yield in a wheat canola rotation (Figure 10) where sowing times are late April and May. In a high Colwell P soil adding 10 and 60 kg/ha of P and N respectively increased cumulative yield by 5.4 t/ha over 7 years or 770 kg of grain per ha per year. The high grain yield from the use of starter P may be partly explained by; McBeath *et al*., (2012) who showed that starter P increased total plant P uptake which was in turn explained by higher subsoil P uptake (e.g., higher uptake of native P below 10 cm), and Singh *et al*., (2005) who showed P applied at sowing resulted in improved subsoil water extraction.

Where the starting soil Colwell P was 50 the most profitable treatment inputs were 10 kg P/ha and 60 kg N/ha. Increasing P (20, 30 and 40 kg P/ha) and N (90 and 120 kg N/ha) above these rates did not improve cumulative grain yield at Colwell P starting values of 50, 42, 30 and 22 (Figure 10).

Time of sowing impacts on P requirements: Research by Batten *et al*., (1999) in NSW showed that on two P responsive sites at Cowra and Condobolin there was a significant effect of sowing time on starter P requirements. At the Cowra site, starter P requirements with June sowing were greatest (>20 kg/ha), however this rate had no effect on grain yield when the crop was sown in early April with good stored soil water. Similar sowing time effects were recorded at Condobolin where optimal starter P rates increased from 5 kg P/ha to 10-15 kg P/ha to 25 kg P/ha for April, May, and June sowing times respectively (Figure 11a).

Recent work has assessed sowing time effects on P requirements in SA on P responsive soil types driven by high PBI (> 100) associated with soil calcium carbonate contents > 10%. In accordance with previous work, it found, if adequate soil moisture was present at April sowing times, starter P rates could be reduced without any impact on grain yield (Figures 12a and b). This benefit diminished if either low moisture was prevalent in April or sowing times were delayed to mid-May or later.

The changes in Phosphorus Use Efficiency (PUE) for starter P applied for an April sowing is improved by early rainfall (Figure 11b). Under high soil moisture and warm temperatures crop root systems are more extensive and therefore exploration of soil P reserves is higher placing less reliance on fertiliser P inputs. Soil diffusion rates of P in these conditions are also optimised. It's estimated from Figure 11a and b that reducing starter P rates is an option where April stored soil water is >40mm and an early sowing rainfall event is received.

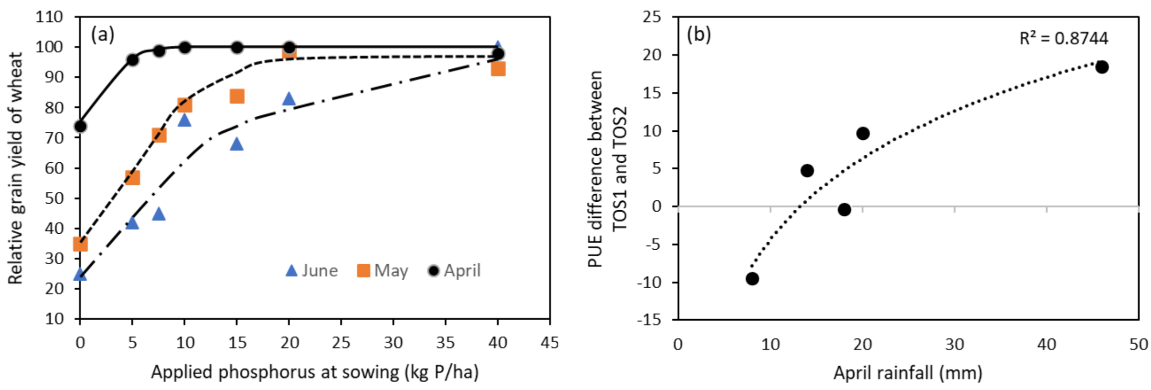

Figure 11. **(a)** Relative grain yield of wheat sown with applied P at Condobolin on a low P soil for April, May and June sowing times (Batten *et al*., 1999), and **(b)** relationship between the amount of April rainfall (mm) and PUE difference for TOS1 (Late April) and TOS2 (mid-late May). A higher PUE (phosphorous use efficiency) difference indicates a lower response to P fertiliser.

Diffusive gradients in thin-films (DGT) soil P test: The relative new method for measuring available P called Diffusive Gradients in Thin-films (DGT) was first invented in the UK in the late 1990's and on the back of promising glasshouse and field trial results, DGT was first made available in Australia in 2012 as a commercial soil test for P. DGT measures the diffusive supply of available P in the soil by employing a P sink (an iron oxide gel) and membrane which controls movement of P to the sink. DGT testing differs from the traditional Colwell P testing by mimicking the plant roots uptake of P rather than relying on a chemical extraction and displacement of P with another anion under fixed pH conditions.

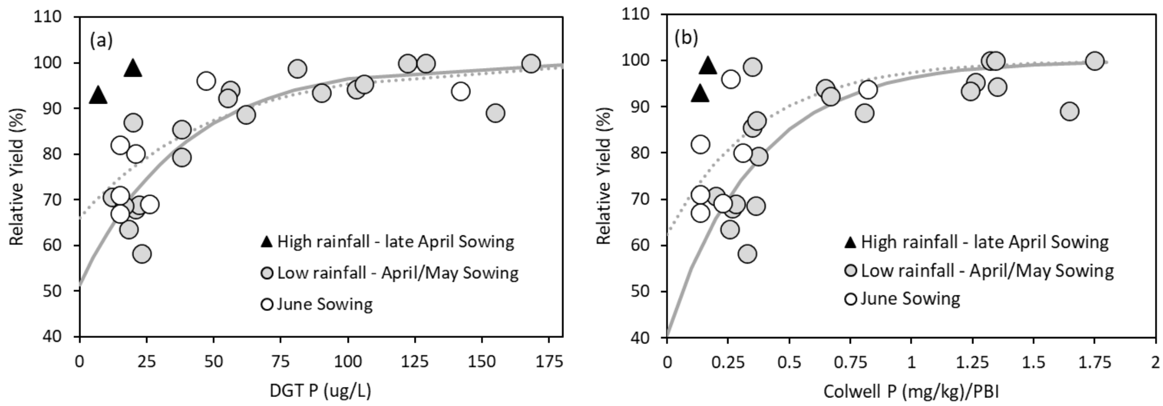

Figure 12. DGT-P **(a)** and Colwell P/PBI **(b)** relationship with relative yield for field trials performed in SA between 2017 and 2021 for different TOS and expected soil moisture conditions.

The power of DGT P over traditional methods of measuring P is the identification of P responsive soils where traditional tests such as Colwell P overestimate crop P supply. For example, soils containing calcium carbonate have been key targets for DGT P testing as P forms in these soils can be easily fixed which has led to replacement P programs undersupplying crop requirements where traditional P testing methods such as Colwell P were applied. With continued inclusion of trial work, DGT P has shown significant promise on soil types where P complexation and fixation attributed to soil Fe and Al commonly present in acids soils. Recent trials in NSW and WA have indicated an improved detection of P deficiency in soils where higher PBI values indicate additional P input requirements are necessary above P removal rates via grain. DGT P critical values continue to be stable for wheat as testing is expanded across sites and years (Mason *et al.,* 2010 vs Table 4). Critical values are also being developed for other crops (Table 4). Opportunities exist to use DGT P to provide greater confidence on plant available P and thereby better inform P replacement programs.

Table 4. DGT critical values and critical ranges produced from 95% confidence intervals around the critical value for various crop types. Field trials were predominantly conducted in WA, SA, VIC and NSW. NA means the critical ranges don't cross 90% relative yield due to a poor correlation caused by very low yielding sites.

Crop type	Number of trials	DGT critical Value (ug P/L)	Critical Range (ug P/L, 95% CI)	R^2 with relative yield
Wheat	134	63	56-73	0.66
Barley	45	65	51-84	0.63
Canola	27	33	24-46	0.55
Lentils	23	44	NA	0.25
Field Pea	10	51	26-84	0.63
Chickpeas	17	48	NA	<0.2

P Budgeting: Phosphorus is exported in grain and recycled in stubble and roots provided the stubble component is retained. Phosphorus in wheat grain ranges from 2.7–3.9 kg P/t, while in canola seed the range is 3.9–7.8 kg P/t (Table 5). Phosphorus in stubble for wheat and canola ranges from 1.0-3.0 kg P/t and 2.0–4.0 kg P/ha, respectively. Root P concentrations in wheat and canola ranges from 1.5–3.0 and 2.0–2.5 kg P/t respectively.

Table 5. Concentrations of phosphorus (kg/t) for wheat and canola grain samples selected from NVT sites. Values are expressed on a dry weight basis (Norton 2012; 2014).

State	NSW min	NSW max	NSW mean	SA min	SA max	SA mean	Vic min	Vic max	Vic mean
Wheat									
P in grain (mg/kg)	2.7	3.6	3.1	3.1	3.9	3.4	2.9	3.6	3.2
Canola									
P in grain (mg/kg)	3.9	6.6	5.2	5.1	7.8	6.2	5.2	6.5	5.7

Approximations used for P budgeting in wheat include grain P export (2.7–3.6kg P/t) plus stubble P not accessible to the following crop (0.4–0.8kg P/t) plus soil fixation (0.3–0.7kg P/t grain production) which provides an estimated 3.4–5.1kg P required per tonne of grain production. Note this is similar to the estimate provided by the Glenelg long term experiment of 4.2 kg P/t of grain production. Canola seed P export (4.0–6.5kg P/t) plus stubble P not accessible (0.4–0.8kg P/t) plus soil losses (0.2–0.6kg P/t grain production) which provides an estimated 4.6–7.9kg P required per tonne of grain. On a per hectare basis, the export of P for wheat and canola is approximately the same assuming canola has half the water use efficiency for grain production as wheat. These budgets are of course very approximate, and they must be assessed and adjusted by tracking soil P values over several years to determine if soil test values are increasing (over estimate of P budget), decreasing (under estimate of P budgeting), or remaining within the critical 90 and 95% range for your particular soils. After several years of soil testing and adjusting P inputs it is possible to ensure relatively stable soil P test values.

Nitrogen

Nitrogen requirements for wheat, barley and canola grain production are approximately 10 to 13 times greater than that of P requirements for these crops and typically soil mineralisation of N is often inadequate to meet crop demands (Angus and Grace, 2016; Hochman and Horan, 2018). For example, Armstrong *et al.,* (2021) found at a long-term site in western Victoria near Horsham, the 17 year mean minimum and mean maximum preseason mineral N for different crop rotations was 32 and 104 kg N/ha respectively, in an environment where the average wheat crop soil N requirement is approximately 150 kg N/ha. This suggests preseason N can supply as low as 21% of crop demand and as high as 70%. The long-term sites at Dahlen and Glenelg supplied approximately 50% of crop N requirements from soil mineralisation. The important consideration from these data is that crop rotation choice and previous N fertiliser history can make an enormous difference to preseason N supply and the only direct way to assess this is to undertake preseason soil N estimates using in-situ soil cores.

Typically, the industry rule of thumb for N is, wheat needs approximately 40 kg of soil mineral N per tonne of grain production while canola requires 80 kg of soil mineral N per tonne of grain production - assuming 50% crop recovery. Yield is then estimated on longer term average rainfall (stored plant available water at sowing (mm) + average growing season rainfall [mm] – soil evaporation [110 mm] x 20 = estimated yield in kg /ha). For wheat, the predicted grain yield in tonnes per ha is multiplied by 40 kg N/ha to indicated total soil N required for an average season. From this, pre-season soil N is subtracted to provide an estimate of the fertiliser N requirement to maximise grain yield in an average season. In this rule of thumb, 40 kg N/t of grain production assumes 50% crop recovery of soil N, however several studies suggest this is an over estimate. For example, Angus and Grace (2016) found after reviewing an extensive list of literature that wheat recovery of fertiliser N was on average 44%. In recent studies Armstrong *et al.,* (2021) found an average N recovery of 35% and Sandral *et al.,* (2018) found that to achieve 13% protein, 51 to 58 kg N/t of wheat production was required where crop recovery of soil N was between 35 to 40%. This suggests in the year of application an estimate of 50% crop recovery of fertiliser N is optimistic. Retrospective checking of N inputs can be undertaken by using a grain protein monitor to assess if grain protein was between 11.5 and 12.5%. Grain protein results below this range indicates insufficient N supply and that additional N would have produced a higher yield (Brill *et al.,* 2013; Sandral *et al.,* 2018; Unkovich *et al.,* 2020).

In recent times there has been a growing emphasis on N banking targets that provide a base level of fertility (Meier *et al*., 2021) for cropping system. N banking for example uses a decile 7 season as the rainfall basis for estimating crop yield and N demand. Once this approach is established in the crop rotation, the annual fertiliser N input is buffered by the soil N bank, where carryover N from the preceding season(s) increases pre-sowing N which is subtracted from the N banking target to provide the fertiliser N input. This approach works well in environments that are not subject to high N losses as it relies on surplus N carryover from season to season. An approach similar to that described here has been tested by Kirkegaard et al., (2021). Their results at the Wagga Wagga Farming Systems site showed over two below average rainfall years (2018 and 2019) and one above average rainfall year (2021), the N banking approach using decile 7 rainfall to estimate crop N demand was more profitable than using a decile 2 N estimate. Similarly, Hunt *et al.,* (2020; 2021) showed that N banking over three years maximised profit at neutral to slightly above positive N balance (long-term fertiliser inputs equal long-term P and N off-take in grain). This result agrees with the long-term experiments at Dahlen in Victoria and Glenelg in NSW.

The ongoing challenges for nitrogen management in cropping systems are associated with; (i) a general net negative N balance for many cropping paddocks while these same paddocks are often net P positive (Norton and Elaina vanderMark 2016), (ii) declining soil organic matter and soil N mineralisation (e.g., Heenan *et al*., 1995) and (iii) a half-life of total soil N between 18 to 34 years (Heenan *et al*., 2004; Helyar *et al*., 1997; Dalal *et al*., 2013). These circumstances highlight the current increasing requirements for fertiliser N and the lack of opportunity to reduce fertiliser N inputs unless these issues are addressed.

Conclusion

In the coming season N budgeting should proceed as the industry rule of thumb provided suggests. Growers and consultants should consider moving to an N banking approach which self-corrects based on pre-season soil N testing. Consideration should also be given to the lower fertiliser crop N recovery rates highlighted by a number of studies.

Care should be taken when reducing P inputs as long-term trials show yield improvements with the inclusion of starter P, even in high Colwell P soils. The yield increase from starter P is however diminished with early April sowing and good soil moisture conditions. Safe reductions in P inputs are therefore possible where soil test values are above crop critical requirements and early April sowing with good soil moisture is available. In these examples P can be reduced to estimated long term P removal rates in grain. However, this practise cannot be sustained if soil test values decline below the critical P range for the target crop. Long-term P budgeting along with soil testing will provide guidance on where phosphorus inputs can be altered to avoid over or under application.

Acknowledgements

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Appendix 1

To estimate profits from long term P studies at Dahlen in Victoria and Glenelg in NSW the following assumptions were made:

(i) The average wheat price was $280/t
(ii) The average cost of P was tested in the range of $3.60 to $5.60 per kg and
(iii) The average N cost was tested in the range of $1.40 to $3.00 per kg.

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Discussion session - Nutrition and rotation strategies after two big years and with high fertiliser prices – where can you cut, when is cutting false economy and is crop rotation an option?

Notes

Weed recognition technologies: development and opportunity for Australian grain production

Michael Walsh, Asher Bender and Guy Coleman, University of Sydney

Key words

Weed recognition, machine learning, ML, site-specific weed control, SSWC

GRDC Project codes

UOS2002-003, UOS1806-002AWX

Take home messages

- Visual spectrum weed images can be used to develop highly accurate weed recognition algorithms
- The ready availability of low-cost digital camera and processor technologies has created the opportunity for superior weed recognition capability
- Accuracy of recognition algorithms continues to improve, increasing the opportunity for precise weed detection and identification in Australian cropping systems
- Currently there is a lack of suitably collected and annotated weed image datasets that encompass the diversity of crop and weed species, as well as the complexity of the Australian grain production environment.

Background

Site-specific weed control (SSWC) involves the specific targeting of weeds with control treatments creating the potential to substantially reduce weed control inputs in low weed density situations. The availability of low-cost, durable processors and digital cameras, combined with increasingly accurate recognition technologies, has enabled highly accurate weed recognition capability for fallow and in-crop scenarios. Globally there is currently considerable research and development activities aimed at delivering SSWC across a range of production systems. Australian grain producers lead the world in the use of SSWC in fallow systems and their positive experiences have created the opportunity to fill a demand for the use of this approach for in-crop weed control.

Reflectance-based weed detection

In the 1980s and 1990s the development of technologies that allowed the detection of living plants led to the introduction of SSWC treatments for fallow weed control (Haggar *et al.* 1983; Felton 1990; Visser and Timmermans 1996). The weed detection systems used were based on a relatively simple process of using spectral filters and photodiode sensors to detect growing (green) plant tissue. As all living plants present in fallows are considered weeds, the reflection of near infrared light (NIR) by the chlorophyll in living plants enables the discrimination between these plants and the background soil or crop residues (Visser and Timmermans 1996). With the use of additional light sources, these weed detection systems can be used in a range of light conditions, including at night.

In Australia, reflectance-based weed sensing systems have been in use for over two decades in spot-spraying systems that are now widely adopted by Australian growers for fallow weed control

(McCarthy *et al.* 2010). The application of herbicide in spot-spraying treatments can effectively control fallow weeds with substantially reduced amounts of herbicide. The substantial savings in weed control costs through the use of SSWC treatments has created opportunity to use more expensive herbicide treatments and non-chemical methods for the management of herbicide resistant weed problems (Walsh *et al.* 2020).

Camera-based weed detection

The expanded use of digital cameras and machine learning (ML) algorithms for image-based weed recognition in combination with smaller more powerful processors has enabled the development of field-scale and real-time SSWC for in-crop scenarios. The Raspberry Pi is an example of a low-cost single board computer that was developed as a teaching resource to promote computer science in schools. When coupled with a digital camera, the Raspberry Pi has many uses in simple computer vision related tasks, including fallow weed detection scenarios. SSWC systems for real-time use have been developed previously using Raspberry Pi computers for plant feature-based weed detection (Sujaritha *et al.* 2017; Tufail *et al.* 2021). Recent work has focussed on promoting to the Australian weed control community, the accessibility and availability of these technologies for construction of fallow weed detection. At present, although these camera-based weed detection systems are less-expensive, provide greater development opportunity and potentially more effective than current reflectance-based sensors, their use has been limited.

Development of machine learning (ML) based in-crop weed recognition for Australian grain production

Accurate recognition of commonly occurring weeds in Australian grain crops requires a highly sophisticated approach that can manage the complexities of crop-weed scenarios. The substantial benefits to using SSWC for fallow weed control has created a demand for the introduction of this approach for in-crop weed control across the cropping regions. The development of accurate weed recognition systems in horticultural crops is more easily achievable, with highly structured and predictable planting arrangements with slow travel speeds and consistent backgrounds. By contrast, the differences between crop and weed appearances are less pronounced in large-scale grain production systems, increasing the difficulty of developing reliable SSWC. Dense crop coverage in grain production systems exacerbates this challenge as large amounts of visual clutter makes it difficult to distinguish individual plants. Reflectance and simple image-based weed detection methods (e.g. colour thresholds and leaf edge detection) developed for fallow SSWC are not capable of dealing with this complexity. The substantial advance that a ML approach offers is the ability to reliably differentiate between weed and crop plants potentially to the point of identifying plant species. This opens a whole new application domain for in-crop SSWC. The use of digitally collected imagery has been identified as an approach that collects the type and quantity of data that allows for accurate discrimination between crop and weed plants (Thompson *et al.* 1991; M. Woebbecke *et al.* 1995). Imaging sensors, such as the standard digital camera, provide richer data streams with three channels (red, green and blue [RGB] images) of spatial and spectral intensity information. The richer data collected by these systems can be used for machine learning (ML) approaches that develop accurate weed recognition algorithms (Wang *et al.* 2019). With the promise of highly accurate (99%) in-crop weed recognition, there is now considerable research towards developing SSWC opportunities in cropping systems. These efforts are now resulting in commercial availability of detection systems for in-crop SSWC.

Recent examples of weed recognition algorithm development for Australian grain cropping

As part of a recently completed project 'Machine Learning for weed recognition', with GRDC investment weed recognition algorithms were developed for annual ryegrass (*Lolium rigidum*) and turnip weed (*Rapistrum rugosum*) plants present in wheat and chickpea crops. The weed recognition context evaluated was the early post-emergence stage where crop canopies are open, and weeds are readily visible in images collected from above. Using digital cameras mounted at a set height above the crop canopy, images of wheat and chickpea crops were collected in Narrabri and Cobbitty (NSW) during the winter growing seasons of 2019 and 2020. This image dataset was collected over two growing seasons and covers variable background and lighting conditions as well as different crop and weed growth stages. To prepare the image dataset so that it can be used to develop and train ML recognition algorithms, annual ryegrass and turnip weed plants in images were manually annotated with bounding boxes using 'Labelbox' image annotation software (Figure 1).

Figure 1. Sample bounding box annotations. Top row (red boxes): annual ryegrass (*Lolium rigidum*). Bottom row (green boxes): turnip weed (*Rapistrum rugosum*).

A range of convolutional neural network (CNN) architectures are freely available to use in developing object recognition tasks. These architectures are being continually challenged and improved by the machine learning community. To evaluate weed recognition capability, two recently developed ML architectures, YOLOv5 (June 2020) and EfficientDet (June 2020) as well as the more 'classical' architecture, Faster R-CNN (2015) were trained on the annual ryegrass and turnip weed dataset to develop recognition algorithms. To determine whether the background (crop type) of the images had an impact on weed recognition, the 2000 image dataset was split into three scenarios. In scenario one, only images of weeds in wheat were used for training (~1300) and testing (~300). In scenario two, only images of weeds in chickpea were used for training (~200) and testing (~50). In scenario three, the datasets were combined - images of weeds in both wheat and chickpea were used for training (~1500) and testing (~350).

The precision for all classes (wheat, chickpeas, annual ryegrass, turnip weed and background) reaches up to 0.3 for the YOLOv5-S algorithm (Table 1). This is much lower than the standard of 0.5 achieved by this algorithm on urban image datasets, clearly indicating the difficulty of weed recognition in cropping systems. There was consistently higher accuracy in the recognition of turnip weed (~0.6) than annual ryegrass (~0.08) for all ML architectures across all three crop scenarios. Superior accuracy in recognition of the broadleaf weed (turnip weed) in comparison to the grass weed (annual ryegrass) is an indication of the respective challenges for these weed types. Broadleaf weeds have a very different and distinct phenotype when compared to a cereal grain crop. This makes identifying them a simpler task for both human experts and ML algorithms. Conversely, grass weeds can be nearly indistinguishable from the crop and even pose a difficult challenge for human experts when annotating the data. Recognition of turnip weed was substantially more accurate in wheat (0.6) than in chickpea (0.1) crops, potentially reflecting the influence on accuracy of differences in plant morphologies between the crop and weed species, but also that there was a smaller chickpea data set.

Table 1. Summary of precision results for YOLO v5 XL, YOLOv5 S, EfficientDet-D4 and Faster R-CNN ResNet-50 deep learning architectures. Each model was trained on three scenarios, weeds in wheat, weeds in chickpea and weeds in both wheat and chickpea. Cells coloured dark grey indicate best performance with progressively lighter grey shading highlighting reducing precision. White cells coloured red indicate poorest performance.

Context	Algorithm	Approx. parameters (M)	Rank	All	Annual ryegrass	Turnip weed
Ryegrass and *turnip weed* in **wheat**	YOLOv5 XL	87.7	2	0.28	0.079	0.640
	Faster R-CNN ResNet-50	41.5	4	0.178	0.048	0.471
	EfficientDet-D4	19.5	5	0.184	0.024	0.506
	YOLOv5 S	7.3	1	0.300	0.080	0.600
Ryegrass and *turnip weed* in **chickpea**	YOLOv5 XL	87.7	1	0.136	0.036	0.116
	Faster R-CNN ResNet-50	41.5	4	0.058	0.010	0.034
	EfficientDet-D4	19.5	5	0.055	0.011	0.015
	YOLOv5 S	7.3	2	0.130	0.050	0.084
Ryegrass and *turnip weed* in **wheat** and **chickpea**	YOLOv5 XL	87.7	2	0.288	0.069	0.577
	Faster R-CNN ResNet-50	41.5	5	0.139	0.023	0.330
	EfficientDet-D4	19.5	4	0.169	0.020	0.437
	YOLOv5 S	7.3	1	0.310	0.076	0.590

In a recently completed 'Intelligent Robotic Non-Chemical Weeding project which was part of a GRDC Innovation Program, ML based weed recognition algorithms were developed for turnip weed and annual ryegrass plants present in wheat and chickpea crops during the late-post emergence stage. Weed images were collected by a camera contained within a shroud with a constant light source (Figure 2). The shroud allowed images to be collected of weeds present beneath the crop canopy in a consistent light environment.

The collected images were subsequently labelled using a labour-intensive, pixel-wise annotation process for a more precise algorithm that returns detections at the pixel-level rather than the previous bounding box level. The algorithms from this approach resulted in high levels of weed recognition precision for turnip weed 0.75 and annual ryegrass 0.65 in wheat (Figure 3). These substantially, higher levels of precision compared to the early post-emergence results are likely due to a combination of factors. These include the use of a more precise pixel-wise annotation technique compared to the bounding box approach, consistent lighting used in the collection of all weed images with these images taken in the same field. Essentially the more accurate weed recognition algorithm developed for the late post-emergence scenario was based on a more specific and precise weed image dataset.

Figure 2. Autonomous platform with suspended shroud containing a digital image collection system and a constant light source.

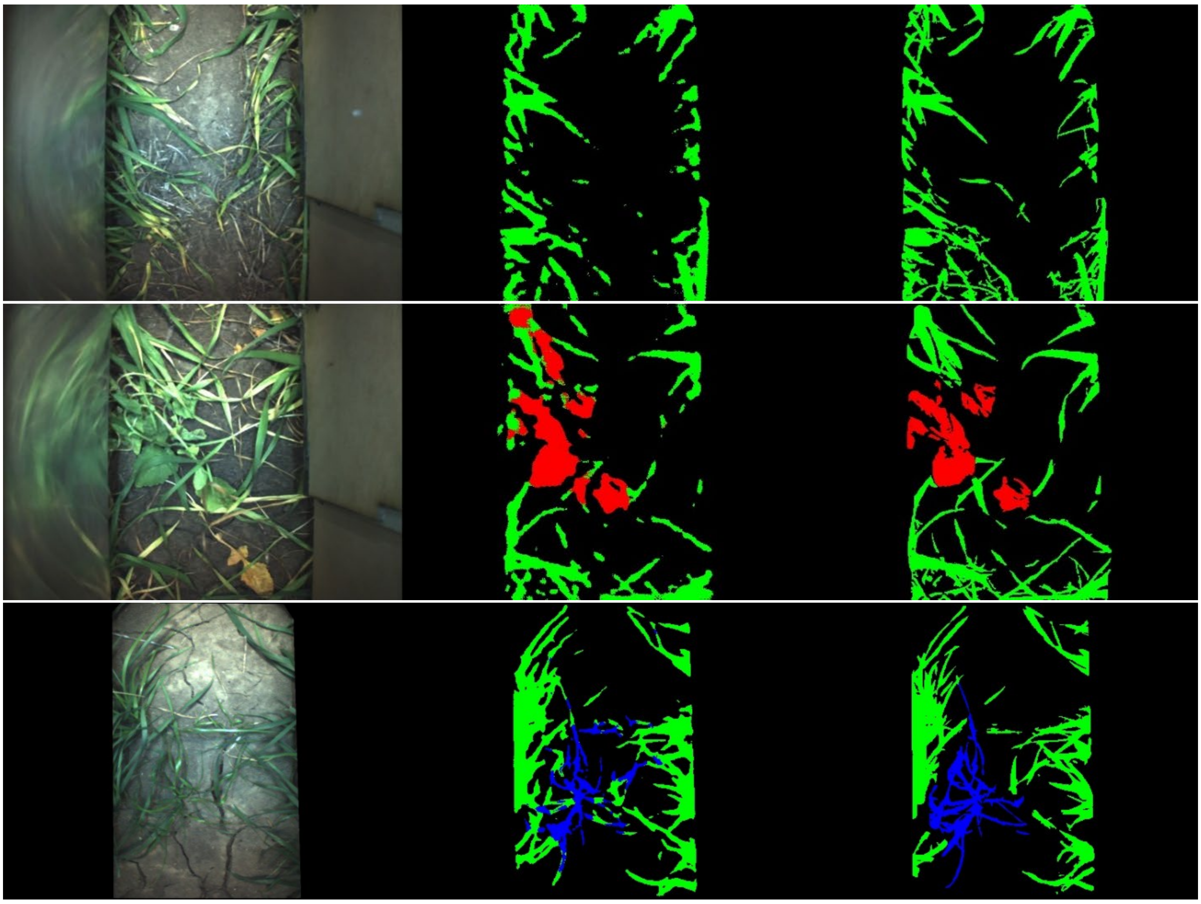

Figure 3. Sample images of image segmentation. Each row is a different example. Images from the left to right columns are: the input RGB image, segmentation results from the ML algorithm, and pixelwise manually segmented 'ground-truth' training data. In the segmented images, green pixels are wheat, red pixels are broadleaf weed, and blue pixels are ryegrass weed.

Summary

The development of weed recognition technologies for SSWC is now focused on the use of ML approaches that will enable accurate detection and identification of weeds in fallows and crops. As well as high potential accuracy, the focus on this approach is being driven by recent ML developments and the low-cost and ready availability of suitable digital cameras and processors. Camera based systems that use algorithms for fallow weed detection have proven high levels of accuracy that are similar if not better than the current reflectance based sensing systems. Increasing interest in the development of in-crop SSWC has resulted in a focus on more sophisticated weed recognition systems for use in both crop and fallow situations. Future SSWC in Australian grain production will be driven by highly accurate ML developed weed recognition algorithms. At present though there is a need to define the weed image dataset requirements, image annotation processes and appropriate ML architectures that are required to enable this opportunity.

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Notes

Amelioration of hostile subsoils via incorporation of organic and inorganic amendments and subsequent changes in soil properties, crop water use and improved yield, in a medium rainfall zone of south-eastern Australia

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Key words

dispersive alkaline subsoils**,** amendments, soil pH, exchangeable sodium percentage, root growth, grain yield

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Take home messages

- Deep placement of organic and inorganic amendments increased grain yield in the order of 20 to 50% for five successive years on an alkaline dispersive subsoil at Rand
- Deep placement of organic and inorganic amendments increased root growth and crop water use from the deeper clay layers during the critical reproductive stages of crop development
- Improvements in grain yield with deep placement of organic and inorganic amendments were associated with a reduction in subsoil pH and improvement in soil aggregation.

Background

Sodicity, salinity and acidity are significant surface and subsoil constraints that reduce crop productivity throughout the cropping regions of Australia (Sale *et al.,* 2021). The majority of cropping soils contain at minimum one, but more multiple constraints (McDonald *et al.*, 2013). The economic impact to Australian agriculture, expressed by the 'yield gap' between actual and potential yield, attributable to subsoil constraints was estimated to be more than A$1.3 billion annually by Rengasamy (2002), and as much A$2.8 billion by Hajkowicz and Young (2005). Of the 'three', sodicity is thought to be the most detrimental to productivity, resulting in the greatest yield gap. In Australian wheat-cropping regions alone, this 'gap' was estimated to be worth A$1.3 billion per annum in lost income (Orton *et al.,* 2018), while close to 20% of Australia's land area is thought to be sodic.

Sodic soils, which are characterised by an excess of sodium (Na^+) ions and classified as those with an exchangeable sodium percentage (ESP) greater than 6% (Northcote and Skene, 1972), are often poorly structured, have a high clay content, high bulk density, and are dispersive. These factors result in poor subsoil structure that can impede drainage, promote waterlogging (low water infiltration), and increase de-nitrification (nutrient imbalance), and soil strength (Orton *et al.*, 2018).

These properties also impede the infiltration of water into and within the soil, reduce water and nutrient storage capacity, and ultimately the plant available water (PAW) content of the soil. Subsequently, root growth and rooting depth are impeded, as is crop ability to access and extract deeper stored water and nutrients (Passioura and Angus, 2010). This is particularly problematic in environments characterised by a dry spring, where the reproductive phase often coincides with periods of water stress, and when the conversion of water to grain has the greatest effect both on yield (Kirkegaard *et al.,* 2007), and the likelihood and magnitude of a yield gap (Adcock *et al.,* 2007).

In southern NSW, winter crops commonly have sufficient water supply during their early growth stages either from stored soil water or rainfall. However, the reproductive phase is often affected by water stress or terminal drought and this is thought to be the major cause of variable grain yield (Farooq *et al.*, 2014). The effect of water stress in the reproductive phase is further impacted by shallow root depth induced by subsoil sodicity. Under such conditions, a key to improving crop productivity is to improve root growth in and through sodic subsoils to enable use of deep subsoil water later in the growing season. Water use at this late stage has a 2 to 3 fold greater conversion efficiency into grain yield (Kirkegaard *et al.,* 2007) than seasonal average based conversions efficiencies (e.g. 20 – 25 kg/mm verses 50 – 60 kg/mm).

While there are large advantages to be gained by improving the soil environment of sodic subsoils, the various amelioration approaches (deep ripping, subsoil manuring, applying gypsum, improved nutrition and use of 'primer-crops') have produced variable results (Adcock *et al.,* 2007; Gill *et al.,* 2008). Furthermore, the use of subsoil organic material is also impacted by limited local availability, the high cost of suitable organic ameliorants delivered in-paddock, the sometimes large quantities required, the lack of suitable commercial-scale machinery and the poor predictability of when and where the amelioration will benefit crop productivity (Gill *et al.,* 2008; Sale *et al.*, 2019).

Gypsum application has been the most widespread traditional approach used to correct subsoil sodicity. However, problems have included; surface application when the problem is evident in the subsoil, the large quantities of gypsum required to displace significant amounts of sodium and the somewhat low solubility of gypsum.

This paper reports on the performance of a barley-wheat-canola-wheat rotation on a Sodosol (Isbell, 2002) soil two sites in Rand and Grogan in southern New South Wales in the five (Rand) and four (Grogan) years immediately following incorporation of a range of amendments, and the residual effects of 'subsoil manuring' on crop performance, soil physical properties, and access to PAW stored in the soil profile over subsequent seasons. A range of treatments comprising deep-ripping and subsoil incorporation of organic and inorganic amendments at a depth of 20–40cm were compared to, and contrasted with, surface applications, ripping-only and untreated controls. Amendments that could be easily procured or produced as part of a farming system were used in the trial. It is hypothesised that subsoil incorporation of organic or inorganic amendments will provide significant improvements in grain yield, which are associated with changes in the physical properties of the subsoil that result in improved root growth, and access to, and use of, deep soil water.

Method

Rand amendment site

The trial sites were located at Rand and Grogan in southern New South Wales in paddocks that had been under a continuous cropping (cereal-canola) for more than 50 years. The soil at both sites was a Sodosol with a texture-contrast profile increasing in clay content at depth, and with physical and chemical properties (Table 1.) unfavourable for root growth, including a high bulk density and low hydraulic conductivity.

Table 1. Chemical and physical properties of the soils at different depths at the Rand trial site

Depth (cm)	pH (H_2O)	EC (1:5) (μS/cm)	Nitrate N (mg/kg)	Exchangeable cations (cmol/kg)	Exchangeable sodium percentage (%)	Bulk density (g/cm³)	Volumetric water content (θv)
0–10	6.6	132.1	20.6	16.1	3.8	1.40	0.120
10–20	7.8	104.0	5.8	22.6	7.3	1.52	0.163
20–40	9.0	201.5	4.1	26.7	12.5	1.50	0.196
40–50	9.4	300.5	3.0	27.5	18.1	1.48	0.232
50–60	9.5	401.3	3.0	28.8	21.8	1.53	0.237
60–100	9.4	645.0	2.9	29.7	26.4	1.55	0.218

The trials were established in February 2017 (Rand) and March 2018 (Grogan) as a randomised complete block with a range of treatments (Table 2) and four replicates. Experimental plots were arranged in two blocks (ranges) of 26 plots, separated by a 36m cropped buffer. Individual plots within each block were 2.5m wide (south-north) × 20m long (east-west), separated on their long sides by 2m buffers of uncultivated ground. Plots were ripped to a depth of 40cm, and amendments incorporated into the soil via a custom built 3-D ripping machine (NSW DPI), comprising a 'Jack' GM77-04 5-tyne ripper (Grizzly Engineering Pty Ltd, Swan Hill, VIC, Australia), configured to 500mm tyne spacings, and topped with a custom designed frame supporting two purpose built discharge hoppers (bins) and a 300L liquid cartage tank. The larger, ~1.6 cubic meter-capacity hopper was designed to deliver organic materials and can accommodate approximately 1000 kg of material, roughly equivalent to a standard 'spout top, spout bottom' bulk bag. The organic amendments were obtained in pellet form for ease of application and consisted of dried pea straw pellets (1.13% N, 0.05% P, 1.34% K; extrusion diam. 7–10mm, length 6–35mm), wheat stubble pellets (0.34% N, 0.15% P, 1.59% K; diam. 7–10mm, length 6–35mm), and dried poultry manure pellets marketed as Dynamic Lifter® (3% N, 2% P, 1.7% K; diam. 7–10mm, length 6–35mm). The amendments were applied three months prior to sowing the first season.

In 2017, experimental plots were sown to Barley (cv. LaTrobe⦸) on the 11th of May at a seeding rate of 70 kg/ha (target plant density 100 plants/m²). Monoammonium phosphate (MAP) was applied at 80 kg/ha as a starter fertiliser at sowing. The crop was sown after spraying with Boxer Gold® (800 g/L prosulfocarb + 120 g/L S-metolachlor), Spray.Seed® (135 g/L paraquat dichloride + 115 g/L diquat dibromide) and Treflan™ (480 g/L trifluralin). The crop was harvested on the 21st of November.

In 2018, wheat (cv. Lancer⦸) was sown on the 15th of May at a seeding rate of 80 kg/ha (target plant density 150 plants/m²). MAP was applied at 80 kg/ha as a starter fertiliser at the time of sowing. The crop was sown after spraying with Spray.Seed, Sakura® (850 g/kg pyroxasulfone), Logran® (750 g/kg triasulfuron) and Treflan. Urea (46% N) at 110 kg/ha (50.6 kg/ha N) was applied at 106 DAS. The crop was harvested on the 6th of December.

In 2019, Canola (Pioneer® 45Y92CL) was sown on the 10th of April at a seeding rate of 4.4kg/ha (target plant density 40 plants/m²). MAP was applied at 90 kg/ha (9 kg/ha N, 19.8 kg/ha P) as a starter fertiliser at the time of sowing. The crop was sown after spraying with Roundup® (360 g/L glyphosate, present as the isopropylamine salt in a tank mix with Kamba® 750 (750 g/L dicamba). Urea at 220 kg/ha (101.2 kg/ha N) was applied as a top-dressing at 119 DAS, and Prosaro® (210 g/L prothioconazole + 210 g/L tebuconazole) at 50% bloom as a preventative for Sclerotinia stem rot (132 DAS). The crop was harvested on the 30th of October.

In 2020, wheat (cv. Scepter) was sown on the 16th of May at a seeding rate of 63 kg/ha (target plant density of 120 plants/m^2). Diammonium phosphate (DAP) was applied at 78 kg/ha as a starter fertiliser at the time of sowing. The crop was sown after spraying with Spray.Seed, Roundup, Sakura and Treflan. Urea at 150 kg/ha (69 kg/ha N) was applied as a top-dressing 7 DAS prior to rain. The crop was harvested on the 7th of December.

The long-term average annual rainfall at the site is 553mm with a reasonably uniform average monthly rainfall. In 2017, in-season rainfall (April-November) totalled 329mm, while 244mm and 242mm, respectively, were recorded for the same period in 2018 and 2019. Rainfall in both 2018 and 2019 was approximately 25% less than that recorded for 2017, and approximately 65% of the long-term average seasonal rainfall. The long-term average monthly rainfall, and average monthly maximum and minimum temperatures, daily (bars) rainfall events and monthly rainfall at the Rand experimental site for the period 2017–2021 (Figure 1).

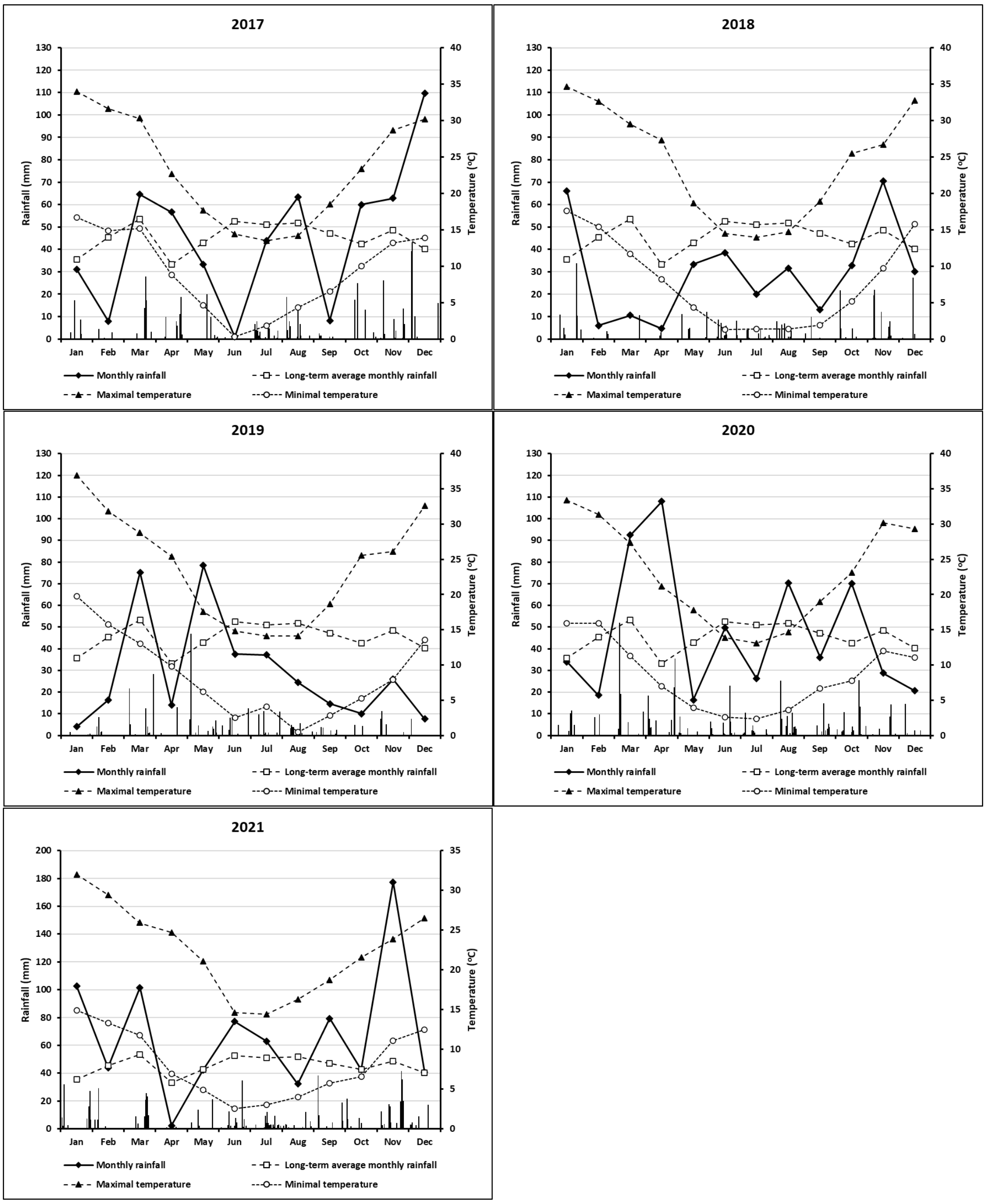


Figure 1. Long-term average monthly rainfall, and average monthly maximum and minimum temperatures, daily (bars) rainfall events and monthly rainfall at the Rand experimental site located at Urangeline East, NSW.

Table 2. Description of the treatments and organic and inorganic amendments used in the trial.

Treatment	Description	Amount of amendment added
1	Control	Direct sowing
2	Deep gypsum	5 t/ha, incorporated to depth of 20-40 cm
3	Deep liquid NPK	Incorporated to depth of 20-40 cm, the amount of NPK added was matched to NPK content of chicken manure
4	Deep chicken manure	8 t/ha, incorporated to depth of 20-40 cm
5	Deep pea straw	15 t/ha, incorporated to depth of 20-40 cm
6	Deep pea straw +gypsum+NPK	12 t/ha, 2.5 t/ha, incorporated to depth of 20-40 cm,
7	Deep pea straw+NPK	15 t/ha, incorporated to depth of 20-40 cm
8	Deep wheat stubble	15 t/ha, incorporated to depth of 20-40 cm
9	Deep wheat stubble +NPK	15 t/ha, incorporated to depth of 20-40 cm
10	Ripping only	To depth of 40cm
11	Surface gypsum	5 t/ha, applied at soil surface
12	Surface chicken manure	8 t/ha, applied at soil surface
13	Surface pea straw	15 t/ha, applied at soil surface

At late flowering soil coring was completed using a tractor-mounted hydraulic soil-coring rig and 45 mm diameter soil cores. The break core method was used to estimate rooting depth and exposed roots were recorded at the following depths 0 - 10, 10 - 20, 20 - 40, 40 - 60, and 60 – 100 cm. Quadrat samples of $2m^2$ were taken at physiological maturity to measure plant biomass and grain yield.

Grogan subsoil amelioration experiment

In 2018 an experiment was conducted near the township of Grogan in southern NSW, which included 27 amendments in a row column design with four replicates. The soil profile was slightly acidic in the top 10cm ($pH_{1:5\ water}$ 5.9) and pH dramatically increases with depth (Table 3). The changes in soil sodicity (exchangeable sodium percentage, ESP) followed a similar trend of soil pH with exchangeable sodium percentage (ESP) at 10.5% in the topsoil and increasing up to 40% in the subsoil (Table 3).

Table 3. Site characterisation for the Grogan experimental site. Values are means (n=5).

Soil depths (cm)	EC (µs/cm)	pH (1:5 water)	Colwell-P (µg/g)	CEC (cmol(+)/kg)	Exchangeable sodium percentage
0-10	309.40	5.87	58.80	16.66	10.53
10-20	133.00	7.65	7.40	22.06	11.97
20-30	136.90	8.76	2.62	24.53	15.94
30-40	207.66	9.12	2.50	25.55	20.12
40-60	338.94	9.60	1.34	27.17	26.27
60-80	530.40	9.53	1.00	31.63	36.68
80-100	897.20	9.43	1.48	34.07	40.25
100-120	1148.20	9.38	1.50	35.28	40.35

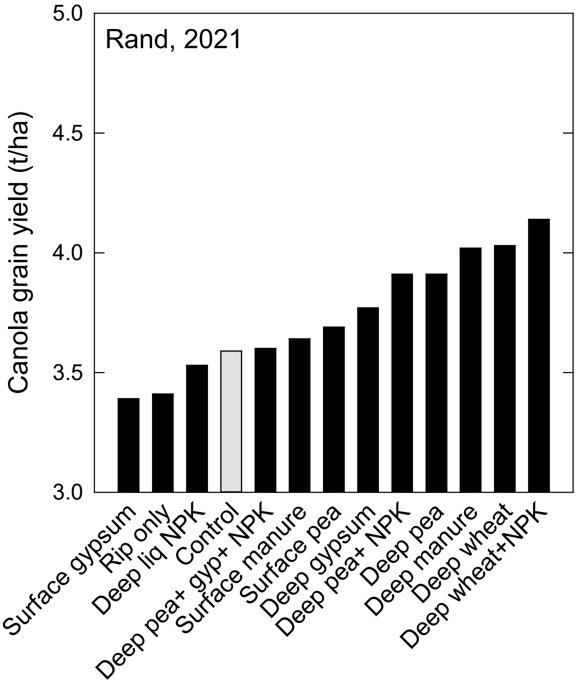
The agronomic management of the trial was similar to Rand site as outlined above. However, the effect of several additional treatments including elemental sulphur, and lucerne hay was investigated.

Results

Rand and Grogan amendment trial

The one-off application of various amendments (Table 2) significantly affected the crop grain yield over 5 consecutive years at the Rand site. For example, in 2021, canola grain yield (relative to control) increased following the deep placement of wheat stubble, wheat stubble + nutrient and manure by 15-12% ($P < 0.001$) (Figure 2). At the Grogan site, canola grain yield (relative to control) increased following the deep placement of manure, lucerne hay and gypsum + pea hay+ nutrient by 45, 42 and 39% respectively ($P < 0.001$) (Figure 2). The variations in yield in response to surface application of amendments or ripping only was not significantly different from the control at both sites.

At the Rand site, a multi-year cumulative analysis of grain yield response (2017-2021) indicated that deep placement of plant-based stubble, gypsum and their combination resulted in significant and consistent improvements in crop yield (Table 4). A preliminary cumulative gross return is also presented in Table 4.



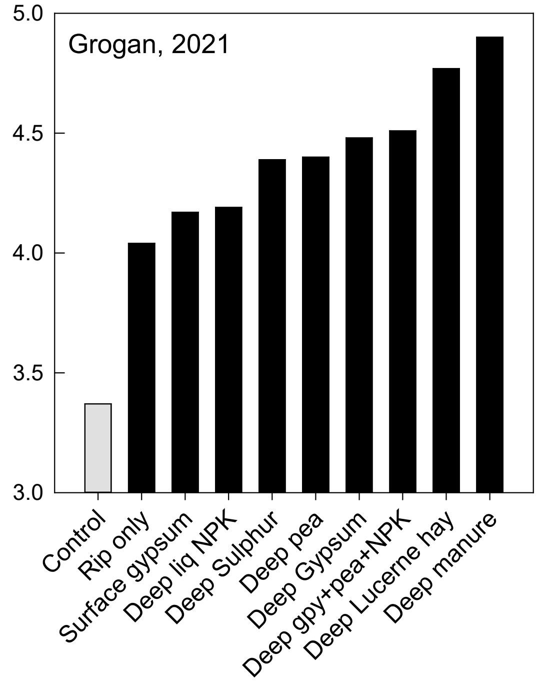


Figure 2. The mean effect of surface or deep-placed amendments on grain yield of canola (cv. Dimond⟠) grown in an alkaline dispersive subsoil at Rand (left) and Grogan (right), SNSW in 2021. Values are mean (n=4). $LSD_{0.05}$ = 0.28 (left) and 0.78 (right).

Table 4. Cumulative grain yield (2017-2020) and cumulative gross return ($) for barley (2017; $220/t), wheat (2018; $250/t), canola (2019; $600/t) and wheat (2020; $250/t), canola (2021; $800/t) at Rand.

Treatment	Yield (t/ha)		$	
Rip only	19.3	a	7465	a
Control	19.3	a	7497	a
Surface gypsum	19.1	ab	7550	ab
Deep liq NPK	20.6	ab	7671	ab
Surface pea	19.7	bc	7769	ab
Surface manure	20.6	bc	7981	bc
Deep pea+gyp+NPK	23.0	cd	8577	cd
Deep wheat	22.3	cd	8614	cd
Deep pea	22.7	cd	8635	d
Deep manure	22.3	d	8645	cd
Deep pea+NPK	22.3	d	8682	d
Deep wheat+NPK	22.6	d	8698	d
Deep gypsum	22.7	d	8700	d

*Results with the same letter after them are not significantly different P < 0.05

Over the course of this study several key measurements of soil and crop parameters were made to investigate the impact of various amendments on soil: plant interactions. Selected data from the Rand trial is reported below.

The number of visible roots in the amended subsoil layer (20 – 40cm depth) were significantly ($P < 0.05$) affected by different amendments (Figure 3). Deep placement of both manure and pea hay increased the number of visible roots by more than 3-fold. Neutron probe readings taken in September also indicate that the highest root counts were associated with the driest soil water profile (Figure 4). Variation in soil pH measured at the amended layer is shown in Table 5. Compared to the control, deep placement of gypsum reduced the soil pH by 0.86 units (8.99 to 8.13) at 20 – 40cm depth. However, pH was not affected by other treatments.

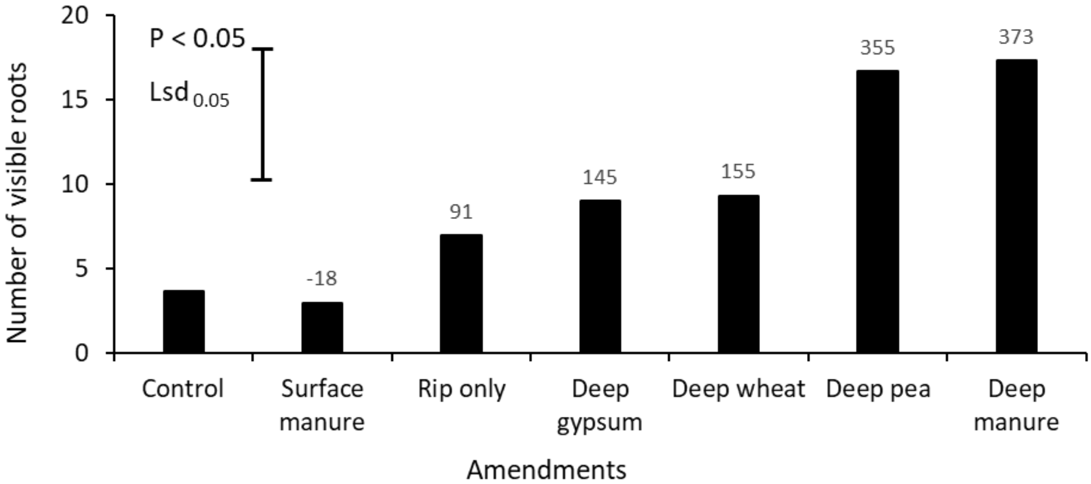


Figure 3. The mean effect of surface or deep-placed amendments on the number of visible roots at 30cm at late flowering of canola (cv. Pioneer 45Y91CL) grown in alkaline dispersive subsoil at Rand, SNSW in 2019. Values on the top of each bar represents the percent change of visible roots compared to control.

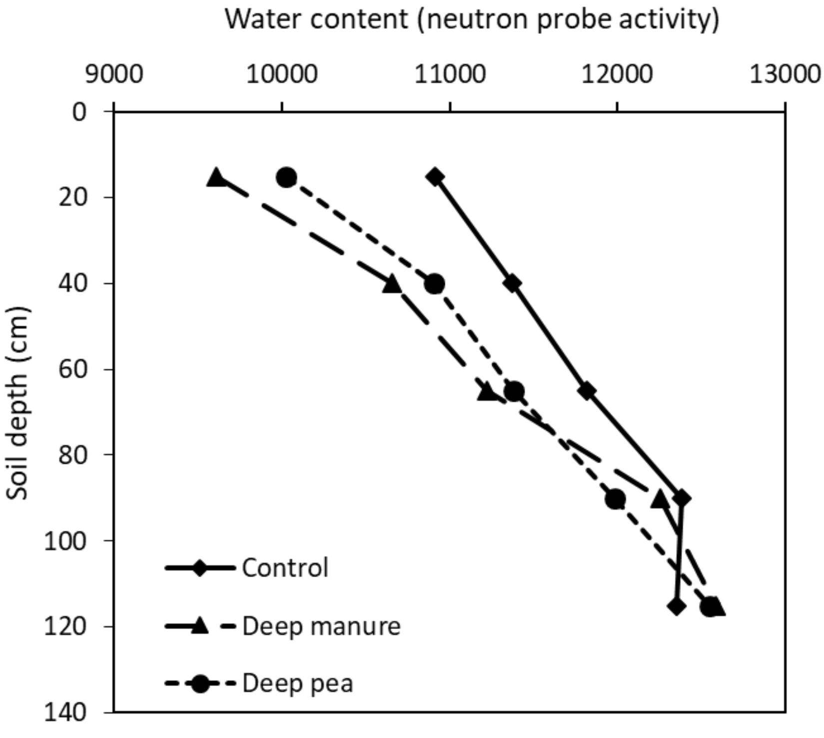


Figure 4. Neutron probe readings taken in September at the Rand amendment site for contrasting treatment comparisons. Results are based on the neutron activity (raw data) where higher values represent higher water content in the soil profile. Values are averages ($n = 4$).

Table 5. Mean soil pH (20-40 cm) in selected treatments at the Rand site. Samples were collected in May 2020. $LSD_{0.05}$ = 0.27.

Amendment	Predicted mean	Significant difference group
Control	8.99	a
Deep liq NPK	8.96	a
Rip only	8.94	a
Deep wheat+NPK	8.93	ab
Surface gypsum	8.92	ab
Deep pea	8.87	ab
Deep wheat	8.83	ab
Deep manure	8.60	bc
Deep pea+gyp+NPK	8.52	c
Deep gypsum	8.13	d

Discussion

In Alkaline dispersive soils, several properties of subsoils including, high pH, high levels of soluble carbonate species, poorly structured dense clay, and dispersion together with overall poor chemical fertility, represent a hostile environment for crop roots. Here we demonstrate the impact of various amendments on these properties and the potential to re-engineer these hostile subsoils for improved crop performance.

Barley, wheat, canola, wheat and canola were grown in 2017–2021, respectively. Growing season rainfall (April to November total) was average in 2017 (decile 5), and declined in 2018 (decile 1.5), with still drier conditions in 2019 (decile 1.0), when only 45 mm of rain (decile 0) fell during the spring months from September to November. This improved in 2020 and 2021 where the Rand trial received > 401 mm during growing the season. The amendments that consistently resulted in significant yield increases above the control, were the deep-placed combination of pea straw pellets, gypsum and liquid fertilizer nutrients, and the deep-placed gypsum and deep placed pea straw (Table 4). Improvements in subsoil structure were measured in the winter of 2019. The deep crop residue amendments significantly increased macro aggregation, as measured on the rip-line at a depth of 20-40 cm. Similarly, deep gypsum and the deep gypsum/pea straw/nutrient combination markedly increased water infiltration into the soil profile, with higher saturated hydraulic conductivities measured on the rip-line. Our results to date indicate that independent modes of action of various amendments (e.g., crop residue vs gypsum) are required in the amendment mix, in order to ameliorate these subsoils. For example, adding gypsum reduced pH in the amended subsoil to below 8.5 (Table 5). This indicates that significant changes in soil pH can occur with realistic application rates of gypsum in subsoil. Given high alkalinity also increases negative charges on the surfaces of clay particles (Rengasamy *et al.,* 2016), which increases clay dispersion, a reduction in pH following gypsum application also resulted in significant improvement (reduction) in soil dispersion (Tavakkoli *et al.*, 2015). In alkaline sodic soils, high ESP and high pH are always linked together and it is difficult to apportion their effects on the resulting poor soil physicochemical conditions and consequently on crop growth.

The addition of pea straw and nutrients provides substrate for enhanced biological activity resulting in increased macro aggregation and improved subsoil structure. When combined together, organic and inorganic amendments may result in additive effects to improve soil physical and chemical properties (Fang *et al.,* 2020a; Fang *et al.,* 2020b).

In a year of intensive drought like 2019, the grain yield improvements at Rand may be attributed to the additional root growth in the amended subsoil layer (Figure 3), which facilitated the use of extra subsoil water (Tavakkoli *et al.,* 2019 and Figure 4). Under dryland conditions, water captured by roots in the subsoil layer is extremely valuable as its availability coincides with the grain filling period and has a very high conversion efficiency into grain yield (Kirkegaard *et al.,* 2007; Wasson *et al.,* 2012). A major focus of this current research is to understand the amelioration processes of the subsoil application of organic and inorganic amendments. A tentative, but promising, finding from our field and controlled environment trials, is that farm grown products like wheat and pea stubbles when mixed with nutrients improve soil aggregation, root growth, water extraction and grain yield and these treatments are comparable to animal manures and gypsum. If confirmed, this means that grain growers have a potentially large supply of relatively inexpensive organic ameliorants already available in their paddocks, which will increase the application options and viability of correcting subsoil sodicity.

Conclusions

The findings from the current field studies demonstrate promising results of ameliorating alkaline dispersive subsoils in medium rainfall zones of southern NSW. Deep placement of organic and inorganic amendments resulted in significant yield improvement in successive years at Rand and Grogan. This yield improvement was facilitated by a reduction in soil pH and ESP% and increased microbial activity that can lead to improved soil aggregation. Furthermore, deep placement of organic and inorganic amendments increased root growth, which in turn increased soil water use from the deeper clay layers during the critical reproductive stages of crop development, thereby increasing grain yield.

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

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

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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 Astuteᶲ (triticale), Boreeᶲ, Catapultᶲ, Coolahᶲ, Cootaᶲ, Devilᶲ, Fusion (Triticale), KM10 (Triticale), LRPB Oryxᶲ, Rockstarᶲ, Sheriff CL Plusᶲ, Stingᶲ, Valiant CL Plusᶲ, Vixenᶲ and Yitpiᶲ.

Minor reductions (one resistance level only) to the ratings of varieties including Ascotᶲ, Caparoi ᶲ, Chief CL Plusᶲ, Corackᶲ, Cutlassᶲ, Denisonᶲ, DS Tullᶲ, Emu Rockᶲ, Illaboᶲ, Kinseiᶲ , LRPB Flankerᶲ LRPB Havocᶲ, LRBP Impalaᶲ, LRPB Kittyhawkᶲ, LRPB Mustangᶲ, LRPB Nighthawkᶲ, LRPB Nyalaᶲ, Mitchᶲ, RGT Ivoryᶲ, SEA Condamineᶲ, Sunblade CL Plusᶲ, Suncentralᶲ and Sunmasterᶲ.

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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Fusarium crown rot seed fungicides: independent field evaluation 2018-2021

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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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Is there a disease downside to stripper fronts?
Harvest height implications for Fusarium crown rot management

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Key words

cereal stubble, stubble management, integrated disease management, Kelly-chain, post-harvest, chickpea, wheat, barley

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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).

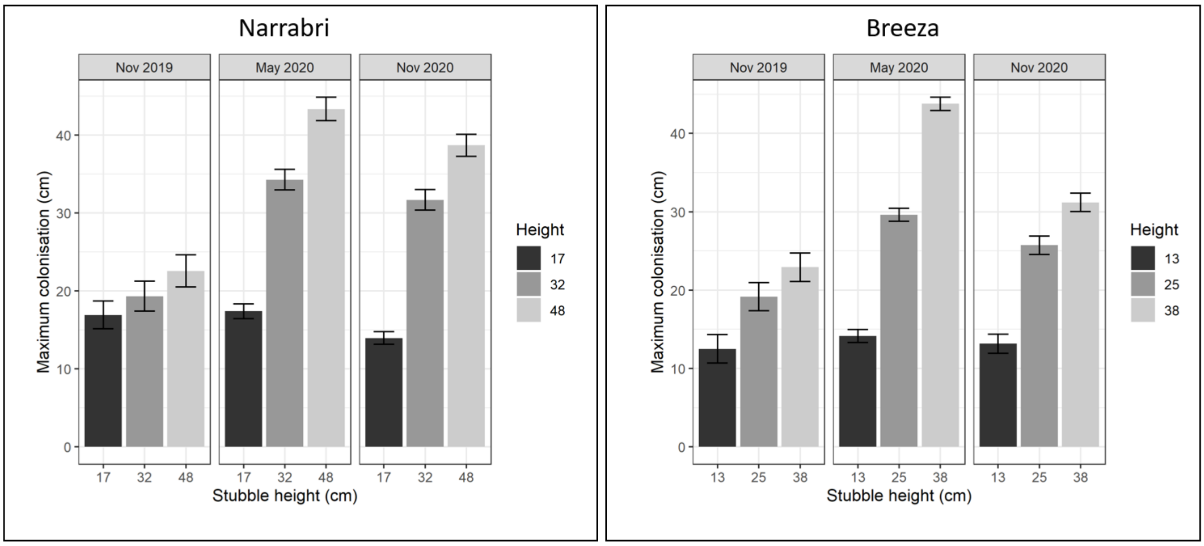

Figure 1. Maximum vertical colonisation by *Fusarium pseudograminearum* in cereal stubble of different heights (mean observed height, in cm) from harvest of the infected crop (Nov 2019), a summer fallow (May 2020) and a chickpea break crop (Nov 2020) at Breeza and Narrabri in NSW. Note harvest-heights 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.

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New insights into nitrogen and water interactions with Fusarium crown rot

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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⚘ and one durum, DBA Lillaroi⚘ 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.

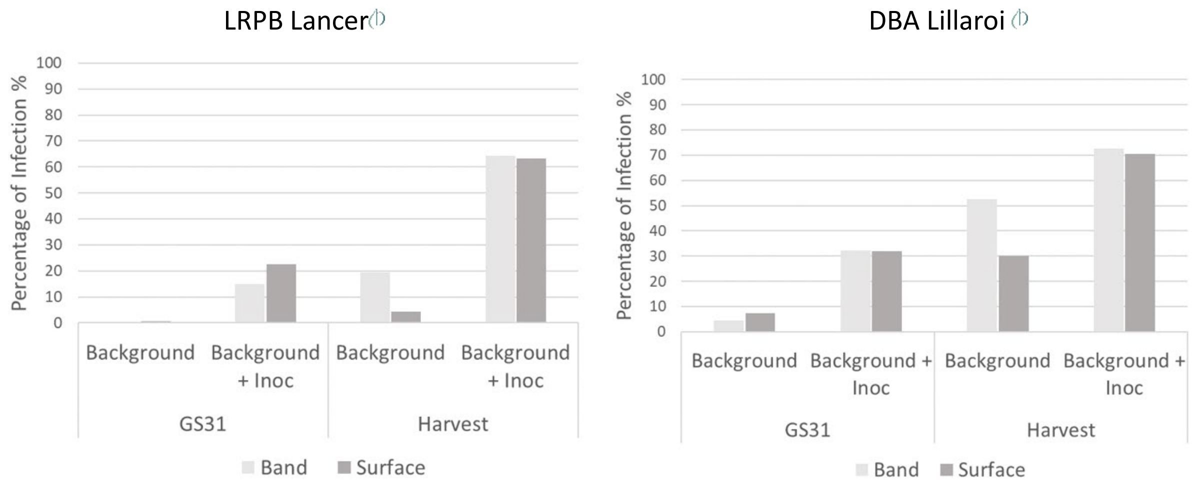

Figure 1. Effect of banded (35 cm) and surface (5 cm) nitrogen application on FCR severity (FCR index 0-100) conducted at GS31 and harvest of LRPB Lancer⦶ (left) and DBA Lillaroi⦶ (right) in the presence of background or background plus inoculation infection by *Fp*. Data averaged across water treatments.

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).

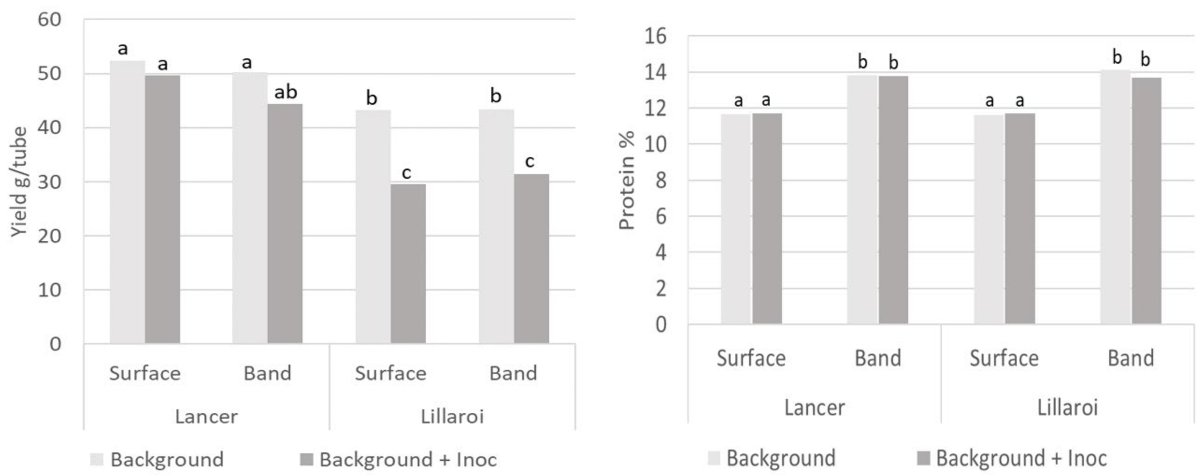

Figure 2. Average yield (left) and protein responses (right) of LPRB Lancer⦶ and DBA Lillaroi⦶ under banded and surface applications of urea with background and background plus inoculation FCR treatments. Significance letters indicate 95% confidence (p>0.05).

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⟮D⟯ 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⟮D⟯ 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⟮D⟯ (Figure 3) but was not significantly different with DBA Lillaroi⟮D⟯ (Figure 4). This is likely due to the increased susceptibility of DBA Lillaroi⟮D⟯ 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).

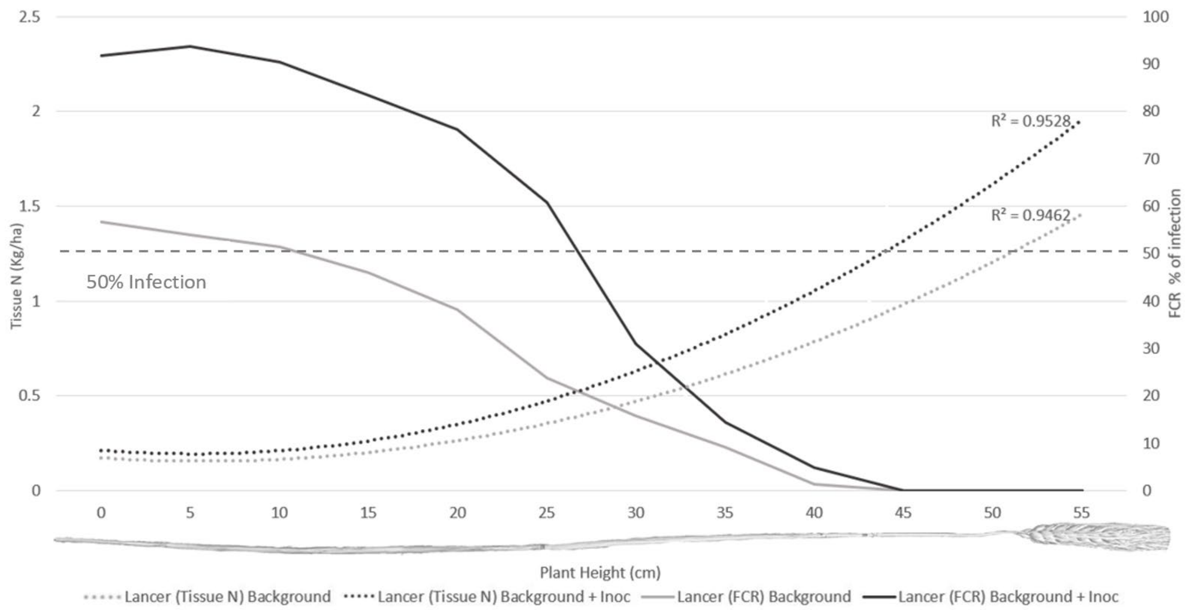

Figure 3. Tissue N (Kg/ha) and percentage of FCR infection as sampled vertically up the main stem of LRPB Lancer⟮D⟯. Data averaged across nitrogen and water treatments.

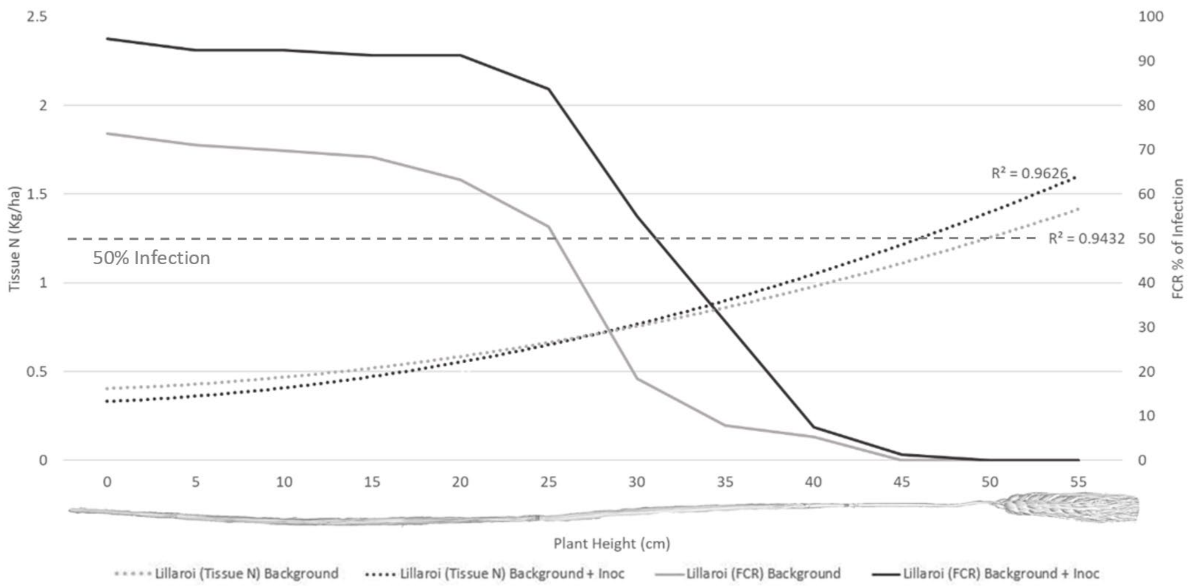

Figure 4. Tissue N (Kg/ha) and percentage of FCR infection as sampled vertically up the main stem of DBA Lillaroi⦶. Data averaged across nitrogen and water treatments.

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.

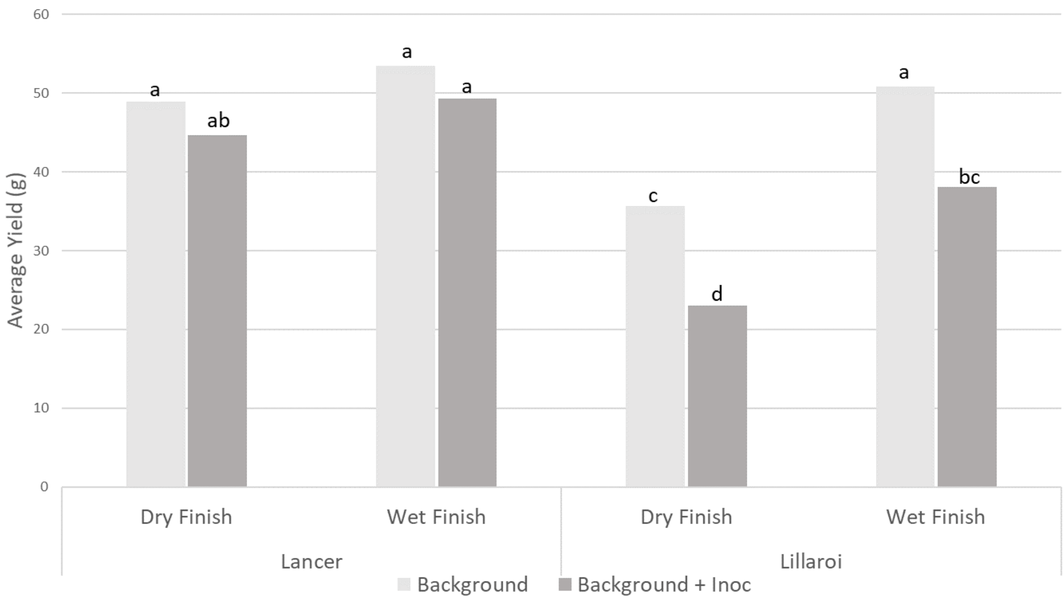

Figure 5. Average yield response of LPRB Lancer⦶ and DBA Lillaroi⦶ under dry and wet finishes to the growing period post flowering with varying levels of FCR infection. Significance letters indicate 95% confidence (p>0.05)

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

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

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Keywords

fungicide resistance, reduced sensitivity, disease, varietal resistance, management

GRDC code

DAN00213: Grains Agronomy & Pathology Partnership (GAPP) - A strategic partnership between GRDC and NSW DPI (Project BLG208) and CUR1905-001SAX

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⁽ᵇ⁾ and Vixen⁽ᵇ⁾ (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	Scepter⦶	100%	90%
Katamatite	2020	NE Vic	Scepter⦶	100%	90%
Cobram	2020	NE Vic	Scepter⦶	100%	46%
Cobram	2020	NE Vic	Scepter⦶	100%	28%
Balldale	2020	SE NSW	Scepter⦶	100%	98%
Walbundrie	2020	SE NSW	Scepter⦶	100%	5%
Rennie	2020	SE NSW	Suntop⦶	85%	27%
Rennie	2020	SE NSW	Scepter⦶	85%	20%
Deniliquin	2020	SW NSW	Scepter⦶	99%	35%
Deniliquin	2020	SW NSW	Scepter⦶	99%	20%
Deniliquin	2020	SW NSW	Scepter⦶	83%	20%
Jerilderie	2020	SE NSW	Scepter⦶	100%	37%
Hillston	2020	SW NSW	Vittaroi⦶	96%	21%
Hillston	2020	SW NSW	Vixen⦶	94%	3%
Hillston	2020	SW NSW	Vixen⦶	85%	6%
Yenda	2020	SW NSW	Cobra⦶	100%	44%
Yenda	2020	SW NSW	Vixen⦶	100%	12%
Edgeroi	2020	NE NSW	Lillaroi⦶	82%	29%
Wee Waa	2020	NW NSW	Bindaroi⦶	62%	51%
Corowa	2021	SE NSW	Scepter⦶	100%	94%
Wee Waa	2021	NW NSW	Aurora⦶	100%	20%
Finley	2021	SW NSW	Scepter⦶	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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How heat tolerant are our wheats?

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

GRDC code
US00081

Take home message
Many Australian wheat cultivars are heat tolerant. However, new materials developed from extensive diversity using field-based phenotyping and genomic selection show that the heat tolerance of Australian wheat can be significantly improved.

Aim

The work was conducted to improve the heat tolerance of Australian wheat. The research aimed to develop heat tolerant wheat germplasm, protocols for high-throughput field-based screening and molecular tools to assist commercial wheat breeders.

Introduction

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

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

What did we do?

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

These materials were phenotyped for various traits including yield using a three-tiered strategy. Firstly, thousands of lines were evaluated in the field in replicated yield plots at Narrabri in northwestern NSW at different time of sowing. Later sown materials were exposed to greater heat stress. Subsets of materials, based on performance in the previous year and estimated genetic values, were sown at sites in Western Australia (Merredin and Cadoux) and Victoria (Horsham) at 2-3 times of sowing to assess the transferability of traits. Each year, high performing lines were retained from the previous year, intolerant materials removed, and new materials added. Materials identified as heat tolerant in times of sowing experiments were subsequently evaluated in the field using heat chambers set at 4˚C above the ambient temperature to induce heat shock during reproductive development and grain filling to confirm heat tolerance. Finally, those lines that maintained heat tolerance in the heat chambers were screened in temperature-controlled greenhouses to assess pollen viability under heat stress. Materials surviving all three stages of testing were considered highly heat tolerant.

All materials (>6,000 lines) phenotyped in time of sowing experiments were genotyped using a 90K SNP platform and these formed the reference population for genomic selection from which all DNA marker effects were estimated. A prediction equation was developed and used to calculate genomic estimated breeding values (GEBVs) on selection candidates which were genotyped but not phenotyped. A genomic selection model that incorporated environmental covariates (e.g. temperature, radiation, rainfall) directly was developed and improved. This allowed the prediction of line performance under high temperature conditions. Environmental covariates were defined for each plot and growth development phase (vegetative, flowering, and grain fill). An in-field validation of GEBV selected lines was then conducted by correlating GEBVs with field trial phenotypes. Various cycles of crosses were made among diverse lines with high GEBVs and progeny subsequently selected for high GEBV. These formed the basis of our new elite heat tolerant materials.

What did we find?

Extensive field-based phenotyping over a 6-year period identified lines with superior adaptation to terminal heat stress. Many of the superior materials had high yield under heat stress, low percentage screenings and high kernel weights. However, stay-green was not an advantage and only an intermediate level of glaucousness was linked to higher yield under stress (Tables 1 and 2). (Glaucous leaves are covered with a grey/blue or whiteish waxy coating that is easily rubbed off). Materials with a wide range of GEBVs were identified and recombined in crosses to produce new heat tolerant lines with higher heat tolerance than current cultivars (Figure 1). The prediction accuracy of genomic selection using models trained at Narrabri was assessed in other environments around Australia (Table 3). The predictions were moderate indicating that phenotyping in Narrabri was relevant nationally.

Table 1. Influence of stay-green on yield in early and late sowing (576 genotypes) at Narrabri

Time of sowing	Non-stay green	Stay-green	Probability
Main season	5.585 a	5.501 b	P<0.01
Late	4.808 a	4.657 b	P<0.001
Numbers of lines	429	149	

Means in rows followed by different letters are significantly different at the probability indicated

Table 2. Impact of Glaucousness on yield at early and late sowing (576 genotypes) at Narrabri

	Glaucousness		
Time of sowing	Low	Medium	High
Main season	5.683 a	5.556 b	5.560 b
Late	4.756 b	4.804 a	4.694 b
Numbers of lines	71	431	74

Means in rows followed by different letters are significantly different at P<0.05

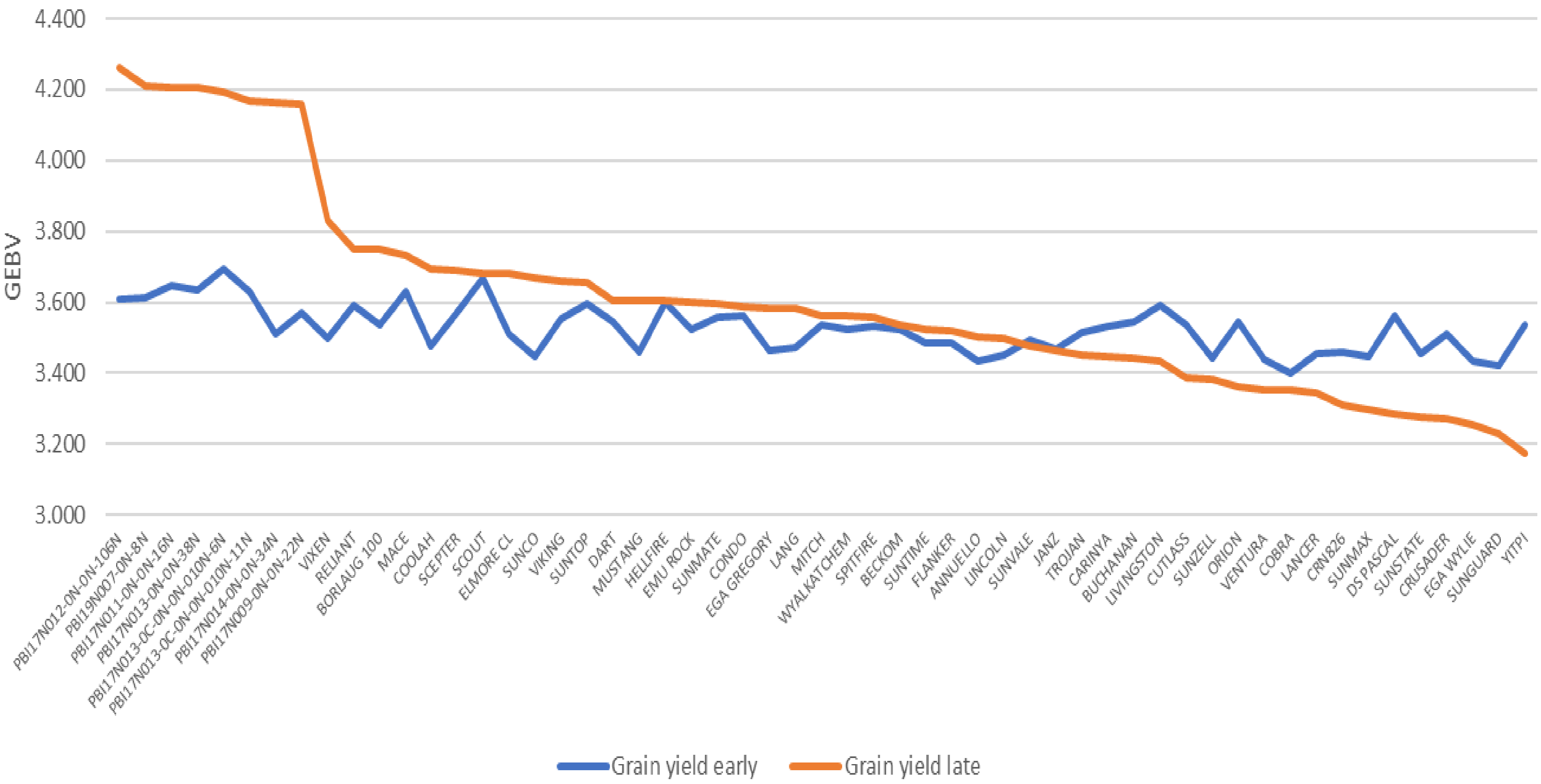

Figure 1. Genomic estimated breeding values (GEBVs) for yield of a subset of the most heat tolerant breeding lines and Australian cultivars (approx. 7,000 genotypes). Main season and late sowing (For PBR status of varieties in graph please refer to Table 5)

The heat tolerance of lines selected from time of sowing experiments in the field was subsequently confirmed using field-based heat chambers. Both night and daytime temperatures were observed to reduce yield, increase screenings and reduce kernel weights (Table 4).

Table 3. Prediction accuracy of materials trained in Narrabri (2017 – 2020) and validated at Cadoux (WA), Horsham (VIC) and Merredin (WA) for grain yield

Environment	**Early sowing**	**Late sowing**
Cadoux 2017	0.31	0.17
Horsham 2017	0.47	0.59
Horsham 2018	0.40	0.38
Horsham 2019	0.22	0.14
Merredin 2018	0.50	0.26
Merredin 2019	0.36	0.13
Merredin 2020	0.38	0.20

Note: accuracy determined as the correlation between GEBV and yield (environmental covariates not included)

Table 4. Impact of day/night temperature (heat chambers; 20 genotypes)

	Yield (kg/ha)	**% Screenings**	**1000 grain weight (g)**
Heat chamber (day, anthesis)	2925 a	3.423 b	38.74 a
No chamber (day, anthesis)	3363 b	2.369 c	41.75 b
Heat chamber (night, grain fill)	2894 a	4.134 a	39.21 a
No chamber (night, grain fill)	3275 b	3.034 b	41.28 b

Means in columns followed by different letters are significantly different

Lines that performed well in field-based heat chambers were then tested in the greenhouse and those lines with poorer pollen viability under high-temperature (35˚C/22˚C, day/night) and elevated CO_2 (800 ppm) tended to have reduced seed set and lower yield (Figure 2). Control conditions were maintained at 22˚C/15˚C and 400 ppm CO_2.

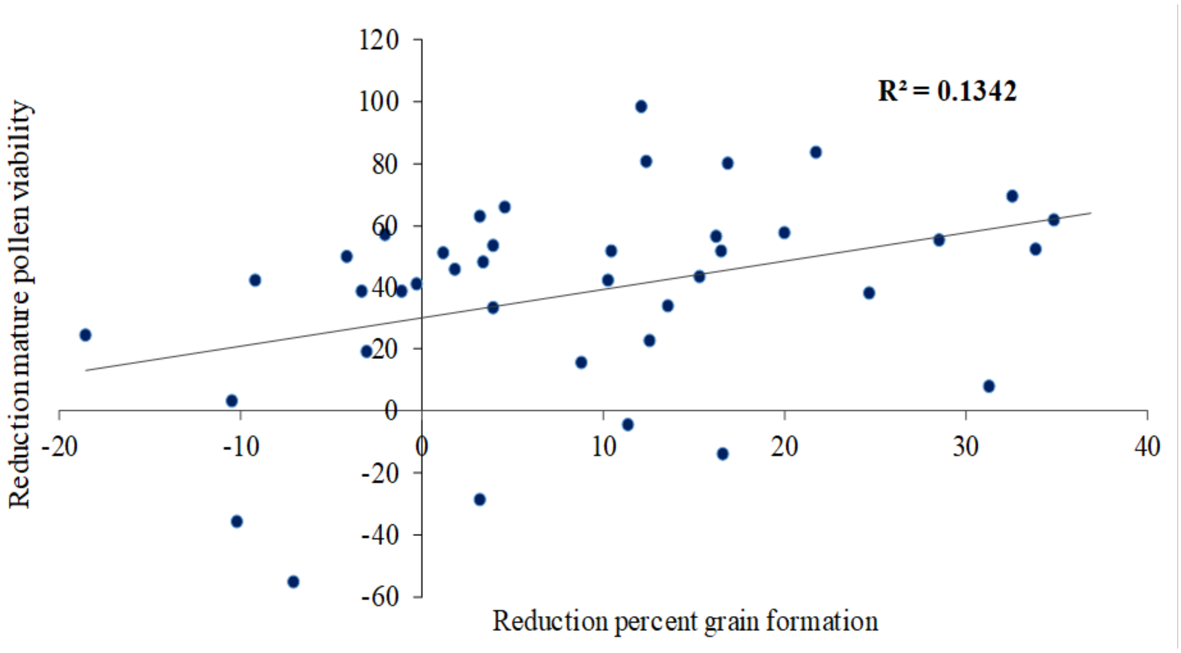

Figure 2. Relationship between pollen viability and grain yield at high CO_2

Based on extensive testing in time of sowing experiments, using field-based heat chambers and under controlled glasshouse conditions, the Australian cultivars evaluated between 2016-2020 were rated for heat tolerance (Table 5). Different varieties arrive at heat tolerance in different ways, with some yielding well in the field but more susceptible to high temperature during pollen formation. The rating in Table 4 is indicative only and based on a number of different observations.

The varieties for which we have detailed knowledge of both their genetics (genotype) and behaviour in a range of environments (phenotype) have enabled us to link the field impact and plant behaviour with parts of the genome that code for specific traits. The process used to do this is called genome wide association analysis. This process has been used to identify a number of meta quantitative trait loci (meta-QTL's) or locations on the genome that express as traits with varying levels of expression in different environments. This knowledge will assist wheat breeders to recombine this new diversity into new cultivars for all regions of Australia.

Table 5. Heat tolerance rating of Australian cultivars

Name	Field yield	Chamber yield	Thousand grain weight	Screenings	Pollen viability	Heat tolerance rating
MACEⓓ	HIGH	HIGH	HIGH	MODERATE	MODERATE	T
MUSTANGⓓ	HIGH	HIGH	MODERATE	LOW	MODERATE	T
DARTⓓ	HIGH	MODERATE	MODERATE	LOW	MODERATE	T
SCOUTⓓ	HIGH	MODERATE	HIGH	MODERATE	HIGH	T
SUNCHASERⓓ	HIGH	HIGH	LOW	LOW	MODERATE	T
BORLAUG 100ⓓ	HIGH		HIGH	MODERATE		MT
SCEPTERⓓ	HIGH	LOW	HIGH	MODERATE	MODERATE	MT
VIXENⓓ	HIGH	LOW	HIGH	HIGH	HIGH	MT
CONDOⓓ	MODERATE	MODERATE	HIGH	LOW	HIGH	MT
FLANKERⓓ	MODERATE	MODERATE	MODERATE	MODERATE	HIGH	MT
LANCERⓓ	LOW	MODERATE	MODERATE	LOW	MODERATE	MT*
HELLFIREⓓ	HIGH		HIGH	HIGH		M
RELIANTⓓ	HIGH		HIGH	MODERATE		M
EMU ROCK ⓓ	HIGH	LOW	HIGH	MODERATE	LOW	M
SUNTOPⓓ	HIGH	LOW	MODERATE	MODERATE	MODERATE	M
COOLAHⓓ	HIGH	MODERATE	LOW	MODERATE	LOW	M
SUNTIMEⓓ	MODERATE	MODERATE	HIGH	MODERATE	MODERATE	M
CUTLASSⓓ	MODERATE	LOW	MODERATE	LOW	HIGH	M
EGA GREGORYⓓ	MODERATE		HIGH	MODERATE		M
LIVINGSTONⓓ	MODERATE		MODERATE	LOW		M
MITCHⓓ	MODERATE		HIGH	MODERATE		M
SPITFIREⓓ	MODERATE		MODERATE	MODERATE		M
SUNMATEⓓ	MODERATE		MODERATE	LOW		M
SUNVALE	MODERATE		LOW	LOW		M
BECKOMⓓ	MODERATE		LOW	LOW		M
WYALKATCHEMⓓ	MODERATE		MODERATE	MODERATE		M
PHANTOMⓓ	MODERATE	HIGH	LOW	HIGH	MODERATE	M
VIKINGⓓ	HIGH	LOW	LOW	LOW	MODERATE	MS
SUNPRIMEⓓ	MODERATE	LOW	MODERATE	MODERATE	LOW	MS
SUNMAXⓓ	LOW	LOW	MODERATE	MODERATE	HIGH	MS*
BUCHANANⓓ	MODERATE		LOW	HIGH		S
LINCOLNⓓ	MODERATE		HIGH	HIGH		S
SUNZELL	MODERATE		LOW	HIGH		S
TROJANⓓ	MODERATE	MODERATE	MODERATE	HIGH	LOW	S
COBRAⓓ	LOW	HIGH	HIGH	HIGH	LOW	S
ZANZIBARⓓ	LOW	HIGHI	LOW	HIGH	HIGH	S
DEVILⓓ	LOW	HIGH	LOW	HIGH	MODERATE	S
CRUSADERⓓ	LOW		MODERATE	LOW	LOW	S
ORIONⓓ	LOW		LOW	HIGH		S
SUNGUARDⓓ	LOW		LOW	LOW		S
VENTURAⓓ	LOW		MODERATE	MODERATE		S
YITPIⓓ	LOW		MODERATE	HIGH		S

*Late maturity confounded field-testing

Hear tolerance rating scale: T=Tolerant; M=Moderate; S=Susceptible

Conclusion

Some recent Australian cultivars combine both high yield and heat tolerance. However, new pre-breeding materials developed using genomic selection offer commercial wheat breeders' new sources of diversity for both yield and heat tolerance that can be used to mitigate the effects of a warming environment. GEBVs and QTL linked to key traits will allow wheat breeders to integrate this new diversity into their existing genomic selection pipelines.

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Early learnings from multi-site, multi-system assessment of new long-coleoptile genetics for deep sowing of wheat

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Take home messages

- Long coleoptile wheats provide successful establishment from deep sowing into subsoil moisture thus increasing the window when growers can sow into moisture. A longer window for sowing into moisture, reduces the need to sow dry with associated risk and uncertainty in some areas and seasons
- Yield was largely unaffected by deep sowing to 12 cm in long coleoptile Mace18 whereas yield penalties of up to 34% were observed with deep sowing of shorter coleoptile Mace⦶
- Soil type influenced establishment of short coleoptile wheat when sown deep. On dry, sandier soils, leaf growth continued slowly upward to permit some seedling emergence. However, on heavier-textured, compacted and/or crusted soils, leaf growth was restricted and slow, commonly prevent seedling emergence.

Background

Timely and successful plant establishment is critical to crop productivity in rainfed farming systems. Early emergence combined with optimal phenology increases yield potential due to a longer duration for root, tiller and crop growth while ensuring conditions are suitable for growth and flowering, and during grain-filling. Well-established crops also provide ground cover to protect soils, reduce water loss through soil evaporation, and increase crop competition with weeds.

Changing weather patterns are associated with proportionally greater summer rainfall and increasingly later sowing breaks (Flohr et al. 2021; Scanlon and Doncon 2020). There is increasing interest in deep sowing at depths exceeding 10 cm to better utilise sowing opportunities after summer and early autumn rainfall and ensure earlier germination and establishment (Rich et al.

2021; Flohr et al. 2022). However, the shorter coleoptiles (65-95mm) associated with the green revolution *Rht1* and *Rht2* dwarfing genes in current wheat varieties limits sowing depths to less than 10 cm and commonly 3 to 5 cm. Coleoptile length is a key consideration with sowing depth as the coleoptile elongates from the seed through the soil protecting the elongating sub-crown internode and crown.

Alternative dwarfing genes have been identified with potential to reduce plant height and increase yields while increasing coleoptile length by 50-80% (e.g. Rebetzke et al. 2022). Some of these dwarfing genes (e.g. *Rht8* and *Rht18*) have been used commercially overseas but have not been assessed for use in Australia. Improved establishment and grain yield in a grower-led trial in 2020 highlighted the potential for long coleoptile *Rht18* wheats for earlier, deep sowing to make use of deep sowing opportunities arising from late summer and early autumn rainfall (Rebetzke et al. 2021). This paper reports on a series of subsequent experiments conducted across Australia examining deep sowing of long coleoptile wheats. A separate pot study investigated the influence of sowing depth on shoot and root growth in contrasting soil types.

Methods

Multi-location experiments were designed to investigate the potential for emergence with deep sowing of long coleoptile, *Rht18* breeding lines bred at CSIRO from an Italian durum wheat variety, 'Icaro', into the semidwarf variety 'Maceᶲ'. Both Maceᶲ and the *Rht18*-containing Maceᶲ. 'Mace18', were grown together with the older, tall variety 'Halberd' (released in 1969) and two current semi-dwarf varieties, 'Scepterᶲ' and 'Calibreᶲ', at two depths (4 and 12 cm) at four sites in WA (Latham, Holt Rock, Hines Hill, Beacon). Maceᶲ and Mace18 are closely related differing in the presence of the coleoptile-reducing *Rht2* and coleoptile-increasing *Rht18* dwarfing genes. Separate experiments containing many of the same entries were sown at Cootra (SA), Tabitta and Griffith (NSW). Plant number was recorded at 200°Cd (degree-days) and crops harvested at maturity for grain yield. Separate experiments were also conducted in southern and central Queensland but issues with seed quality reduced the performance of long coleoptile wheats.

A separate pot experiment was conducted in a temperature-controlled glasshouse to investigate the influence of soil type on emergence and plant growth with deep sowing. Both Maceᶲ and Mace18 were sown at 4 and 12 cm depth in replicated deep pots (n = 8 reps) containing either a coarse-textured, sandy soil from Cootra (SA) or a heavy-textured, red-brown earth from Griffith (NSW). Plant growth measurements were undertaken at two times: an early sampling at 300°Cd post-sowing (1.5 leaves) and a later sampling at 600°Cd post-sowing (3.5 leaves). Seed used in all experiments were produced in the same environment and graded to the same size to minimise confounding maternal effects on seedling vigour.

Results and discussion

Sowing depth field experiments

Conditions were generally favourable at sowing and throughout the season across the different field sites in 2021. Establishment was excellent for shallow sowings with high emergence rates and final plant numbers at all sites (Fig. 1). Overall, plant number was reduced by an average 26% with deep sowing compared with shallow sowing. The largest reduction in plant number with deep sowing was at Beacon (WA) and Griffith (-32%), and the smallest reduction at Holt Rock (WA) (-17%) and Cootra (-20%). Across WA sites, percentage reduction in plant number with deep sowing was 54 and 3% for Maceᶲ and Mace18, respectively, and 38 and 21% for Scepterᶲ and Calibreᶲ, respectively (Fig. 1). Plant number for Mace18 was not statistically different from Halberd while the ranking for plant number for the different wheat varieties was consistent across all four WA sites. Plant heights of

Maceᶲ and Mace18 were not different (data not shown) yet the coleoptile length of Mace18 (131mm) is significantly longer than Maceᶲ (76mm) while Halberd and Mace18 have similar coleoptile lengths (Rebetzke et al. 2021). The moderately-longer coleoptile length of Calibreᶲ was associated with greater plant number with deep sowing compared with other shorter coleoptile *Rht2* varieties Maceᶲ and Scepterᶲ (Fig. 1).

Site mean grain yield ranged from 0.68 t/ha at Hines Hill (WA) (where crops were frosted) to 4.56 and 4.62 t/ha at Tabitta and Griffith in SNSW, respectively, where the latter sites received up to 550mm of rain in 2021. Shallow-sown Maceᶲ ranged in yield from 0.40 t/ha at Hines Hill to 5.78 t/ha at Griffith. In shallow sowings, Maceᶲ produced significantly (P<0.05) greater average yield than Mace18 (cf. 4.08 vs 3.81 t/ha). However, when sown deep, grain yields decreased to 3.11 t/ha (-20%) for Maceᶲ but was unchanged at 3.80 t/ha (-0.5%) for Mace18. The largest yield reduction with deep-sown Maceᶲ was at Griffith (-34%) with the smallest reduction at Cootra (-2%). These yield reductions appeared to reflect plant number with deep sowing at each of the sites assessed.

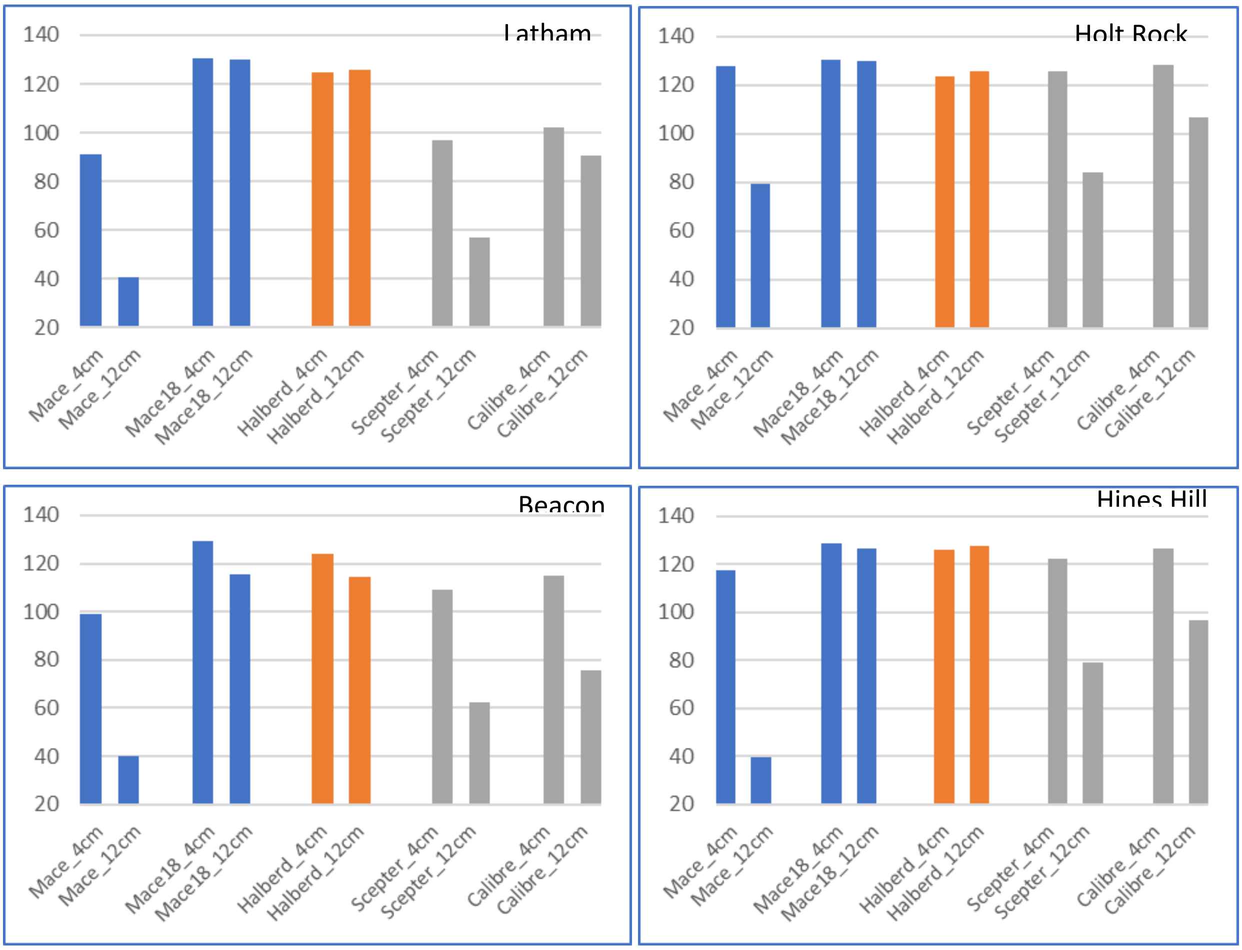

Figure 1. Mean numbers of plants per m² (at 200°Cd) at four WA sites for shallow-sown (4 cm) and deep-sown (12 cm) Maceᶲ *Rht2* and *Rht18* NILs, tall, long coleoptile variety Halberd ■, and commercial *Rht2* dwarfing gene varieties Scepterᶲ and Calibreᶲ ■. LSDs were 8, 16, 6 and 6 plants per m² for Latham, Holt Rock, Beacon and Hines Hill, respectively.

Sowing depth pot experiments

As reported, the Cootra and Griffith sites contrasted significantly (P<0.05) in plant establishment with deep sowing which was thought to be related to soil type. Pot experiments were designed to carefully examine seedling emergence and early seedling growth under controlled conditions in contrasting soils. In the early seedling assessment (at 300°Cd), coleoptile lengths were significantly (P<0.05) greater at 12 cm sowing depth, and were longer for Mace18 than Mace (Table 1). At 4 cm sowing depth, number of leaves per plant, and shoot and root length were similar for Mace and Mace18, and for both soil types. With deeper sowing to 12 cm depth, the sandy Cootra soil was associated with significantly (P<0.05) greater numbers of longer leaves, larger roots and fewer below-ground shoots than in the stronger Griffith soil (Table 1). Elongation of the first leaf to the soil surface is typically slow and restricted by soil type and factors including crusting and soil compaction. A soft, dry soil such as the Cootra soil allows for leaf elongation and emergence even with shorter coleoptile wheats sown deep (provided moisture at depth is adequate for germination). This contrasts with Mace in the Griffith soil where significant (P<0.05) shoot growth (as shoot length) was recorded below the soil surface (Table 1). There was a significant (P<0.05) variety × soil depth × soil type interaction with Mace18 producing a larger number of longer leaves, and greater root biomass than Mace particularly in the stronger Griffith soil. The reduced below-ground shoot growth for Mace18 reflected the long sub-crown internode and positioning of the Mace18 crown immediately below the soil surface (data not shown).

Table 1. Seedling growth characteristics at 300°Cd for the Mace and Mace18 near-isogenic lines (NIL) sown at 4 and 12 cm depths in a sandy Cootra and red-brown Griffith soil. All means are expressed on a single-plant or pot basis.

Seed depth	NIL	Coleoptile length (mm)		Number of leaves (no)		Above-ground shoot length (mm)		Average root biomass (mg)		Below-ground shoot length (mm)	
		Cootra	Griffith	Cootra	Griffith	Cootra	Griffith	Cootra	Griffith	Cootra	Griffith
4 cm	Mace	43	43	2.2	0.8	52	23	28	08	0	25
	Mace18	53	50	1.8	1.3	49	30	30	15	4	19
12cm	Mace	79	77	1.8	0.6	32	09	30	10	11	83
	Mace18	115*	121*	1.3	1.8*	38	43*	30	30*	34*	11*

*Mace and Mace18 means are statistically different at P = 0.05

Table 2. Seedling growth characteristics at 600°Cd for the Mace and Mace18 near-isogenic lines (NIL) sown at 4 and 12 cm depths in a sandy Cootra and red-brown Griffith soil. All means are expressed on a single-plant or pot basis.

Seed depth	NIL	Number of leaves (n)		Shoot biomass (mg)		Root biomass (mg)		Number crown roots (no)		Number seminal roots (no)	
		Cootra	Griffith	Cootra	Griffith	Cootra	Griffith	Cootra	Griffith	Cootra	Griffith
4 cm	Mace	3.8	2.6	389	206	301	95	2.6	1.1	6	5.7
	Mace18	4.1	3.8*	397	359*	202*	214	2.6	1.8	6	5.8
12cm	Mace	3.1	2.3	160	111	147	70	1.3	1.0	5.1	2.4
	Mace18	3.3	3.8*	185	216*	220*	163*	1.6	2.2*	5.9*	4.3*

*Mace and Mace18 means are statistically different at P = 0.05

Plants were predictably much larger with sampling at the later (600°Cd) seedling growth stage (Table 2). For example, average numbers of leaves more than doubled from 1.3 to 3.8 leaves from the earlier (300°Cd) seedling harvest (cf. Tables 1 and 2). Numbers of leaves, and both shoot and root biomass were reduced with deeper sowing with this reduction being greater for deep sowing in the Griffith soil. Numbers of crown and seminal roots were reduced at all depths in the Griffith soil (Table 2). Deep sowing was associated with fewer crown and seminal roots and particularly in the Griffith soil. Improved emergence and greater early seedling growth translated to increased shoot growth in Mace18 compared to Mace⌽ in the Griffith but not in the Cootra soil. In the Griffith soil, Mace18 produced significantly more leaves than Mace⌽ to increase shoot biomass. Root biomass was also significantly greater than for Mace⌽ reflecting larger numbers of crown and seminal roots (Table 2). Despite the similar shoot growth for Mace18 and Mace⌽ when sown deep in the Cootra soil, Mace18 produced greater root biomass and this largely reflected greater numbers of seminal roots when compared with Mace⌽ (Table 2).

The improved performance of Mace⌽ with deep sowing at Cootra appeared to reflect the observed ability of some short coleoptile wheats to continue growth of leaf 1 (and sometimes leaf 2) in soft, dry soils. Leaves continue to elongate upward until reaching the soil surface whereupon a crown is formed, and tillering commences. However, the reduction in seminal and crown root number, and reduced root biomass for the deep sown Mace (Table 2) does suggest that leaf growth through a soil might exhaust seed reserves to compromise early root development.

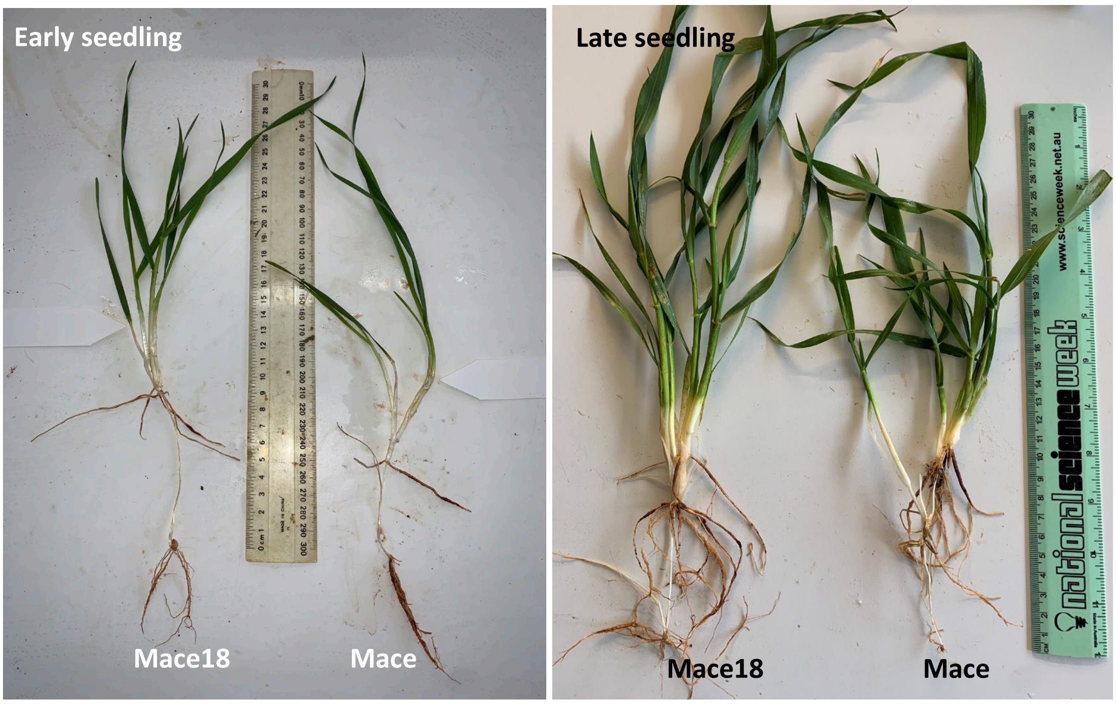

Figure 2. Long coleoptile Mace18 (L) and short coleoptile Mace⌽ (R) early and late seedling at 12cm seeding depth at Griffith

Field observations in the heavier, Griffith and Tabitta red-brown soils confirm the reduced above-ground shoot biomass and fewer crown and seminal roots in short compared with long coleoptile Mace⌽ near-isolines (Fig. 2). The slow movement of true leaves beyond the coleoptile can be supported with the promotion of new leaves and shoots initiated from nodal buds that would normally give rise to mainstem tillers. In some instances, as many as three nodes can initiate to support emergence with deep-sowing. However, early growth (leaf area and biomass) develops slowly with these commonly rare emerging seedlings.

Conclusions

Improved plant establishment with deep sowing at 12 cm confirmed the benefit of the long coleoptile trait first reported in separate on-farm experiments in 2018 and 2020. The 2021 studies highlighted the potential for increased grain yield with deep sowing for maximising water productivity. Improved performance in heavier soils suggests there may be potential for the long-coleoptile trait to aid in plant emergence and establishment in situations where furrow-fill occurs after sowing from wind or heavy rain, or with transient waterlogging at emergence (M. Lamond *pers. comm.*). The potential for coleoptile elongation should aid in ensuring emergence with variable depth control on large planters (B. Haskins *pers. comm.*), and with high soil temperatures when sowing early into warmer soils (Rebetzke et al. 2016).

Germplasm containing the *Rht18* dwarfing gene have been delivered along with selectable molecular markers for use in commercial breeding programs. Populations have been developed and are currently under assessment toward delivery of higher-yielding, long coleoptile wheat varieties for Australian growers.

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

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Key words

digital technologies, national variety trials, phenotyping, remote sensing

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.

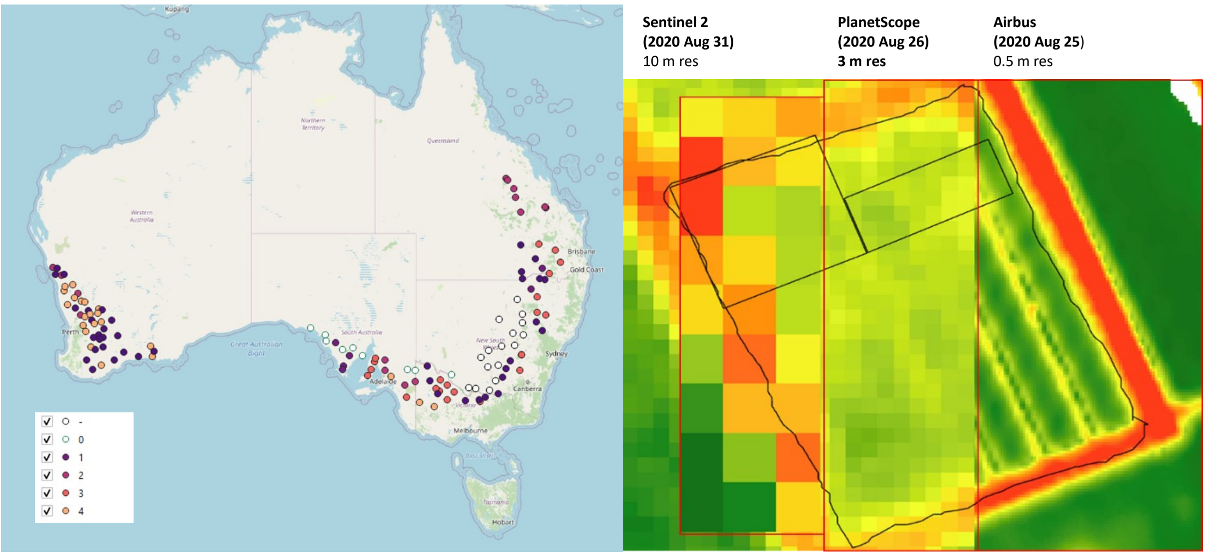

Figure 1. Overview of main wheat trials and (in colour) the level of measurements being collected for INVITA in 2021 winter season. Example of different satellite resolutions in 2020 WMaA20BEVE6

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.

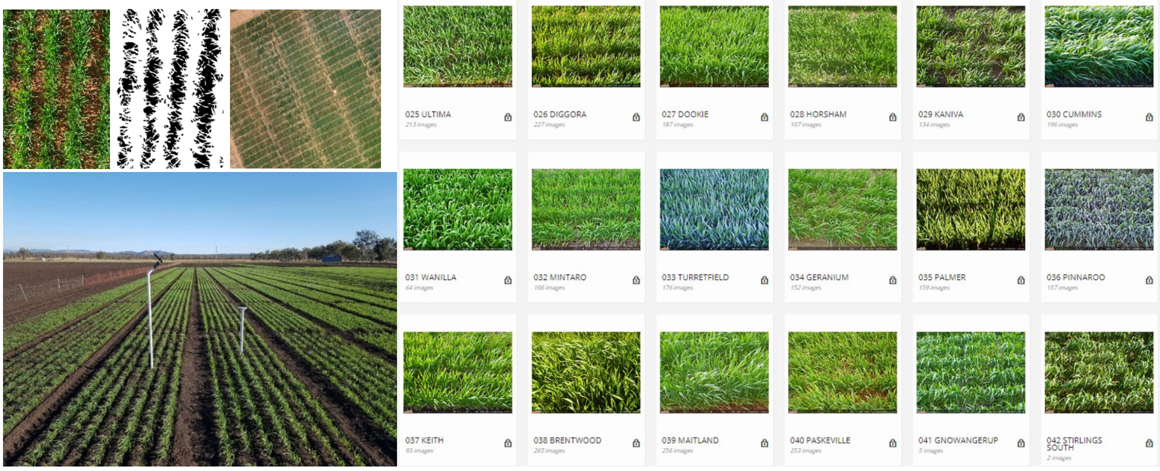

Figure 2. Early season 4G camera images from 2020 NVT with camera and spectral sensor shown on left and an example of camera photo masked to provide an estimate of ground cover from phone, field camera or UAV

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.

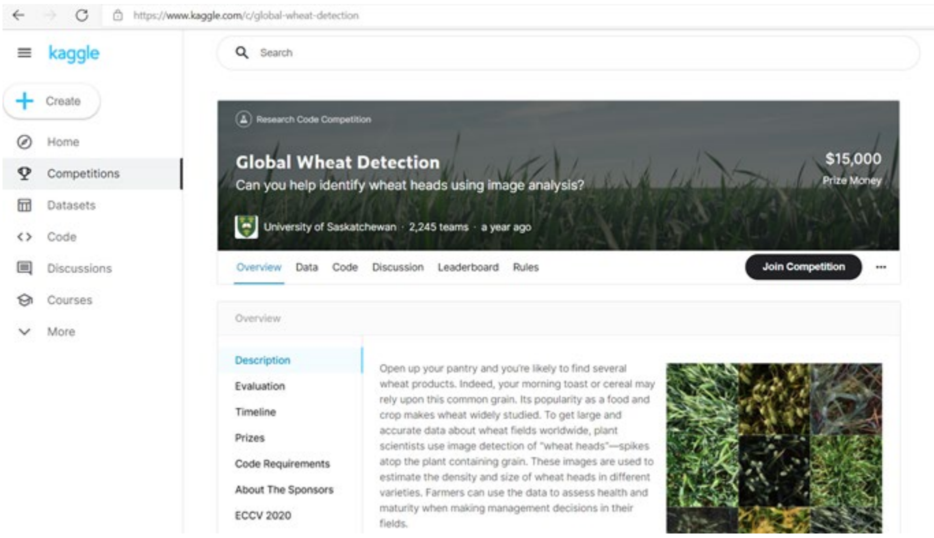

Figure 4. The 1st GWHD competition on Kaggle https://www.kaggle.com/c/global-wheat-detection which attracted 2245 teams

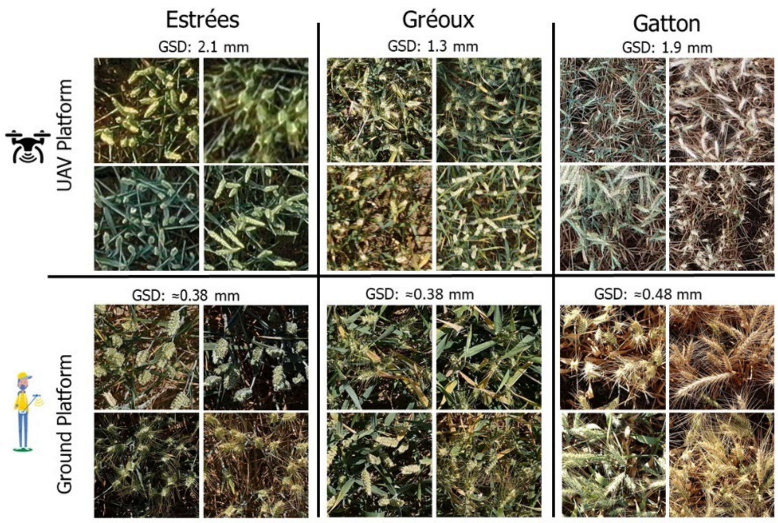

Figure 5. UAV and ground platform photos for testing of wheat head counting. Data from France and from Australia (INVITA trial at Gatton)

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.

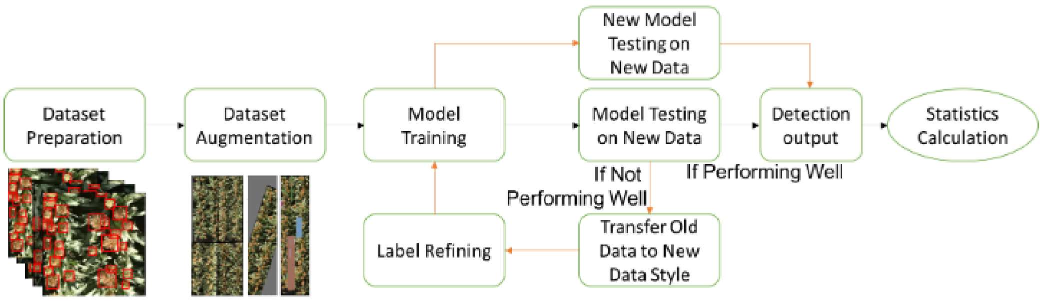

Figure 6. Analysis pipeline for counting sorghum heads from UAV images

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.

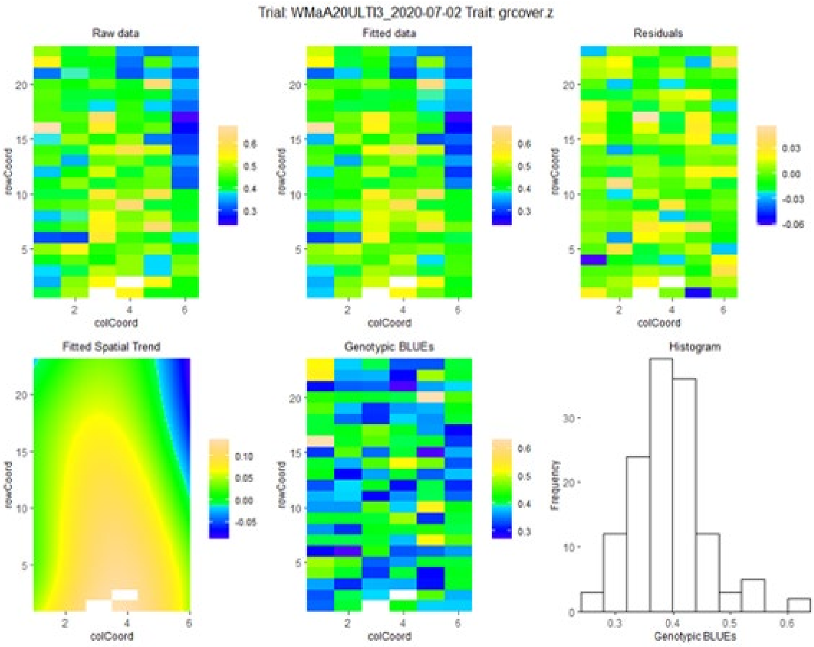

Figure 7. Spatial analysis of ground cover estimate for wheat main season trial, 2 July 2020. The lower left image shows the spatial trend which has been found in the data and has been adjusted in the estimates of the genotype means (the 'BLUEs')

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.

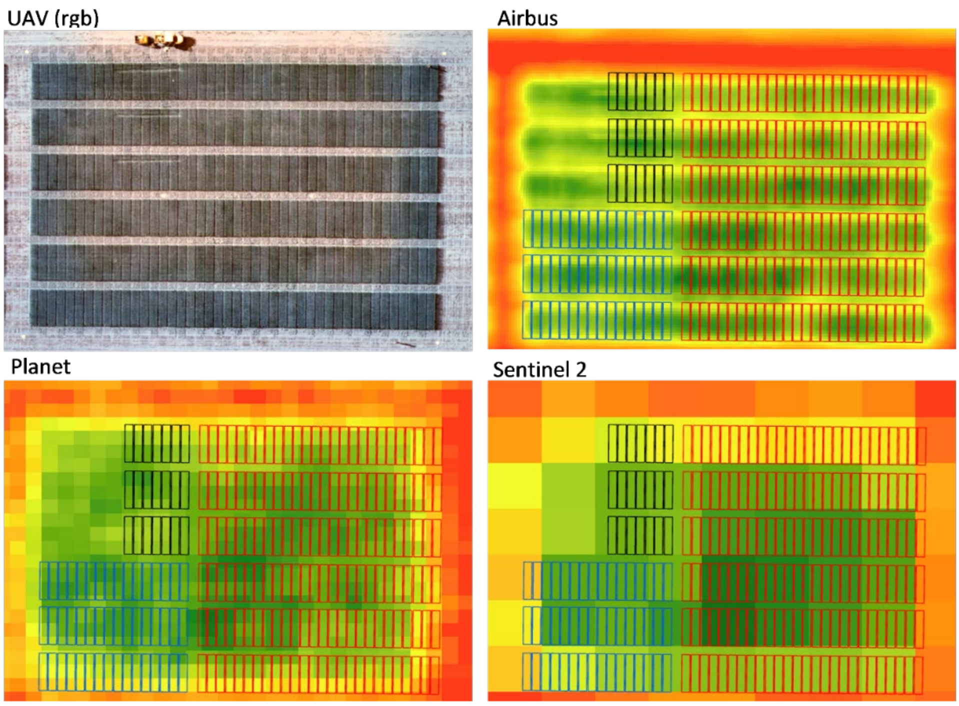

Figure 9. Comparison of UAV (RGB <1cm resolution), Airbus (0.3m), Planet (3m) and Sentinel-2 (10m) images of trial WMaA20BENC6 during the mid-vegetation stage. The plot boundaries overlaid on these images show the limitation of Sentinel-2, in terms of spatial resolution.

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.

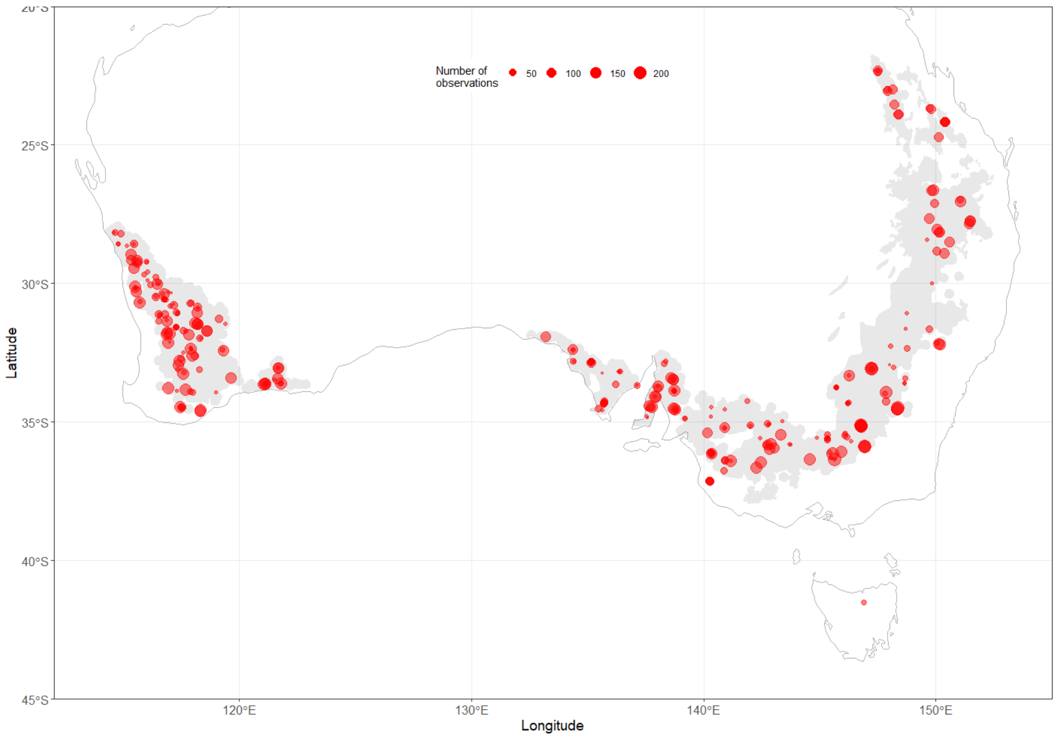

Figure 10. Analysis of 21 000 flowering observations across 2015 to 2020 in 310 trials at 129 locations. Dots show how many observations were used from each historical NVT location

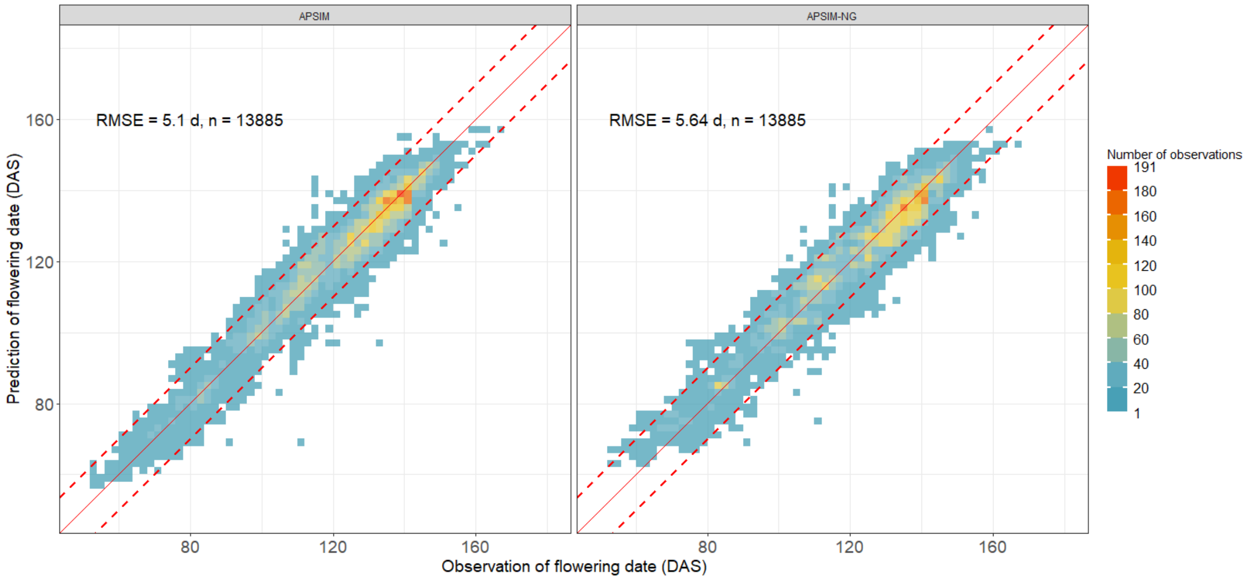

Figure 11. Comparison of prediction of wheat flowering time using parameterisations of two types of APSIM phenology models. This shows we can predict flowering time of most trials and genotypes quite well from weather data alone.

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.

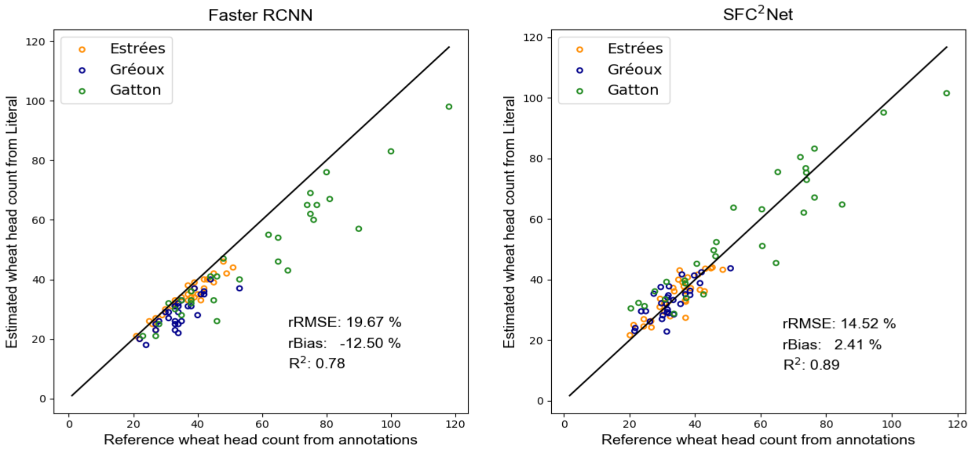

Figure 12. Performance results from independent testing of two head counting algorithms (RCNN and SFC²Net) on quadrat counts of wheat heads in France and Australia (Gatton)

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.

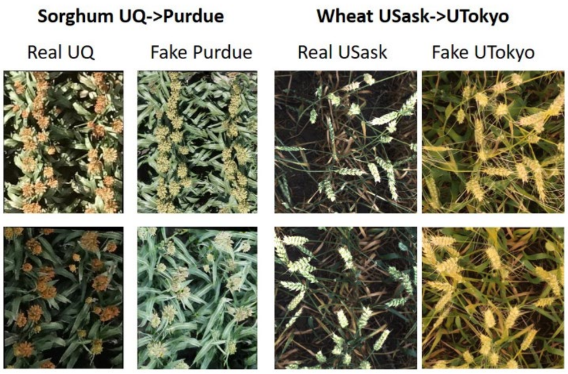

Figure 13. CutGAN 'fake' images generated using UQ image + Purdue 'style' (sorghum) and USaskatchewan + UTokyo 'style' (wheat). Note how the heads are in the same position in the 'fake' images as in the 'real' images. So now the 'fake' images can retrain the model in a new style.

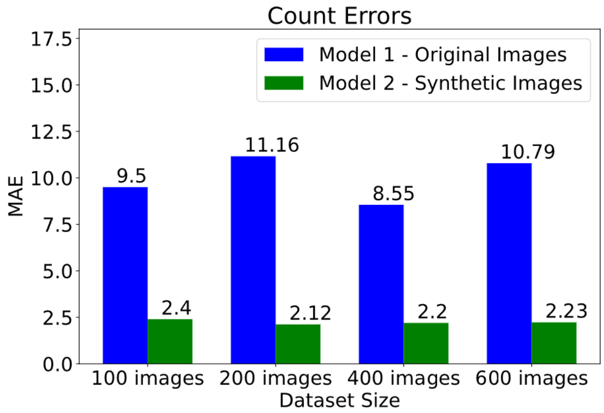

Figure 14. Performance of sorghum head counting model trained on Original or Original+Synthetic images for different size datasets. Use of fake images makes model training work better

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.

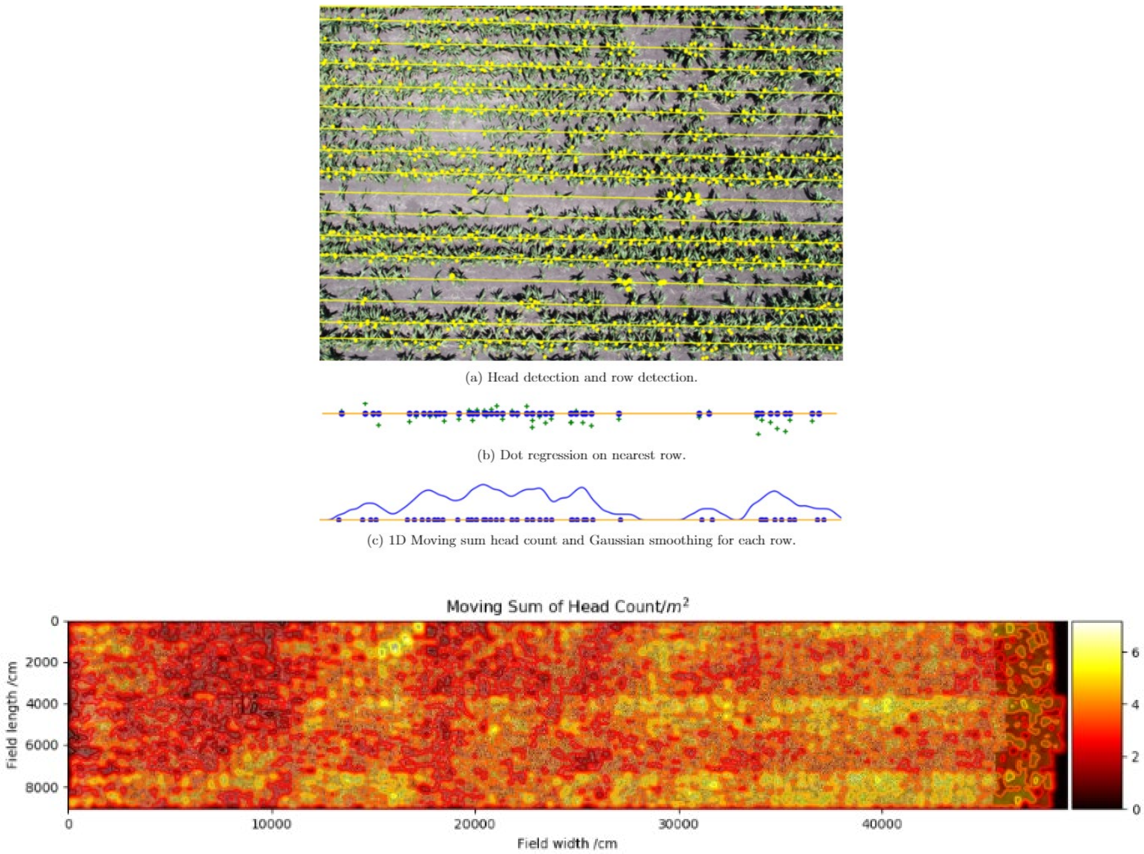

Figure 15. Head and row detection in UAV images (top) and fitted map of head density for entire 90 x 500m field (below). These analyses can be generated from UAV images without full mosaic processing and are viable for computation in the field.

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).

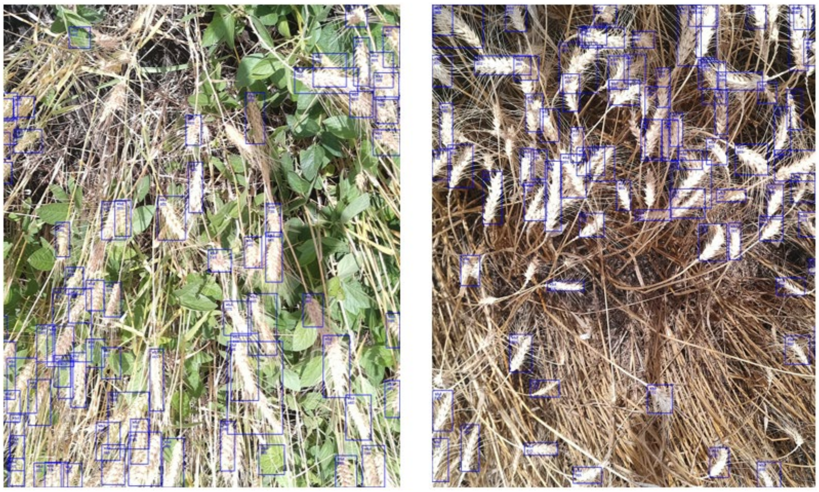

Figure 16. Real time 4K still image processing to count wheat heads using a machine-learning camera

Acknowledgements

INVITA is a large research project that runs at NVT sites and includes researchers from CSIRO (BZ) and WU (FvE, MB, DB-K, JR, JH). We greatly appreciate the work of the NVT trial service providers who have been contracted to undertake additional measurements on NVT and adjacent trials and install and maintain sensors to enable this project. AGFEML has been a collaboration with numerous researchers in France (Arvalis: BdS, SM, ED; INRAe: FB) and U Tokyo (WG).

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Beyond the paddock: Remote mapping of grain crop type and phenology

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Key words

digital technologies, mapping of crop growth stage, reducing risk and increasing profitability

GRDC code

UOQ2002-010RTX

Take home messages

- Harnessing high resolution digital technologies will create more accurate and location specific information such as crop type and crop phenology stage
- Mapping of likely specific crop type and phenological stages across environments are critical for reducing in season risk and thus optimising crop management practices at field scales
- Scaling out of such tools will allow fast and robust applications across multiple fields, farms, and regions
- The CropPhen digital tool will be delivered to industry via a national commercial partner.

Aims

The adoption of digital technologies can be constrained by demands such as, which data provider platform and the financial cost placed on users. Furthermore, there are a plethora of digital platforms currently available to industry, but key gaps in the underpinning science and a need to develop analytics that have been rigorously calibrated and tested on independent data sets for different genotypes, environments, and management practices within the Australian broadacre cropping landscape. The CropPhen project aims to map crop phenology per crop type across multiple fields and farms. Specifically, we aim to

- Determine crop phenology and cropping dynamics from high resolution earth observation (EO) data at the field scale
- Determine the ability of hyperspectral data from ground sensors, unmanned aerial vehicles (UAV) and satellites to augment the estimation of phenological stages at field scales by variety and environment, and
- Through project partners Data Farming, develop and deliver a web-based information system that provides data on crop type classification and phenological stages within fields and field scales across large regions.

Outputs generated from this project will assist industry to determine crop type, and individual growers to spatially map the current stage of development and predicted dates of development stages more accurately at fine spatial and temporal scales throughout the growing season. That phenological data could further provide a basis for the real-time estimation of potential damage, crop risks and losses at the field and sub-field scales from diseases, frost and heat events, and other production constraints.

Background

In the Australian grain cropping environment, accurate spatial and temporal information about crop type and phenological stage is essential for managing operations such as disease, weed control and the sequential decisions of application of N-fertiliser in cereals. For example, different chemical controls are often certified only for use at specific crop growth stages. This project will develop the analytics to provide reliable, accurate and spatially specific crop type classification and phenological estimates for wheat, barley, chickpea, and lentils (winter) and summer crops (sorghum) across the Australian Grain Belt. This will be achieved by integrating climate, crop modelling and high-resolution EO technologies. Knowing the likely area of crop emergence and main phenological stages, at a farm and regional scale, will help enable operators to optimise management decisions relating to improved timeliness and variable application of in-season nutrition rates. Furthermore, this will inform grower’s existing knowledge on optimal disease, weed control and crop management practices to optimise return on investment.

Methods

Crop type classification

Nation-wide surveyed ground truth data covering cropping fields for the 2018-2021 seasons (summer and winter) provided by industry partners are used to calibrate and validate a carefully designed deep learning (DL) model to accurately and timely discriminate between crop types across Australia. A pipeline for evaluating the field data and filtering noise (due to human errors) based on crop season start and flowering (peak vegetation index) information from MODIS NDVI has been applied. The refined field records will be overlaid with the high spatiotemporal resolution Sentinel 2 imagery to derive selected spectral features for training the DL models. Figure 1 illustrated the overall distributions of the valid field polygons across the GRDC growth region and north-eastern Australia (NEAUS). The model for each region will be trained individually using filed polygons available in the region to reflect its unique crop characteristics.

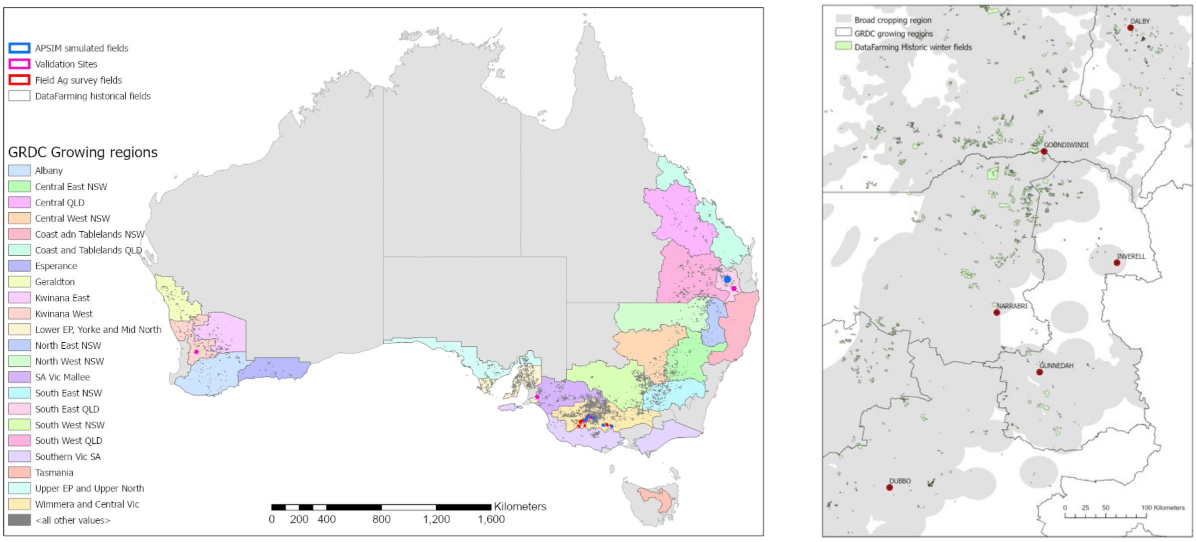

Figure 1. (Left) Distribution of Data Farming historic field polygons covering seasons from 2018 to 2021; Location of crop validation sites, APSIM simulations and survey fields in Victoria. (Right) Zoomed in view of field data for north-eastern Australia (NEAUS).

Crop phenology validation sites

To understand the phenological cycles for the targeted crops in this project, field trials have been designed and planted for seasons since 2020. In 2020, a sorghum trial consisting of 6 plots (30 m x 30 m) covering 3 genotypes was set up in Jondaryan, Queensland (-27.46, 151.54). In 2021, winter crop trials were set up in Allora (-28.061, 151.963), Callington (-35.141, 139.073) and Dale (-32.197, 116.754). Trial layouts, along with planted crop types and crop genotypes are depicted in Figure 2.

For each site, a weekly ground survey of phenological stage was collected using a simple survey form (Kobo Toolbox, USA). Additional data points included the recording of fresh and dry biomass at stem elongation (i.e., Zadok's stage 31 for wheat) as well as at maturity along with final harvested yield data were collected.

Capturing crop attributes from UAVs

At each validation site multispectral data was captured using a high resolution MicaSense Altum camera (MicaSense, Inc., Seattle, USA) with 6 bands: blue (400-500 nm), green (500-600 nm), red (600-680 nm), red edge (680-750 nm), near infrared (750-1050 nm), and long wave thermal infrared (LWIR) (8000-14000 nm). The camera was mounted on a UAV at 60 m height to capture images at weekly intervals during the crop season. These flights were also designed to align with on ground phenology and crop morphological and physiological measurements.

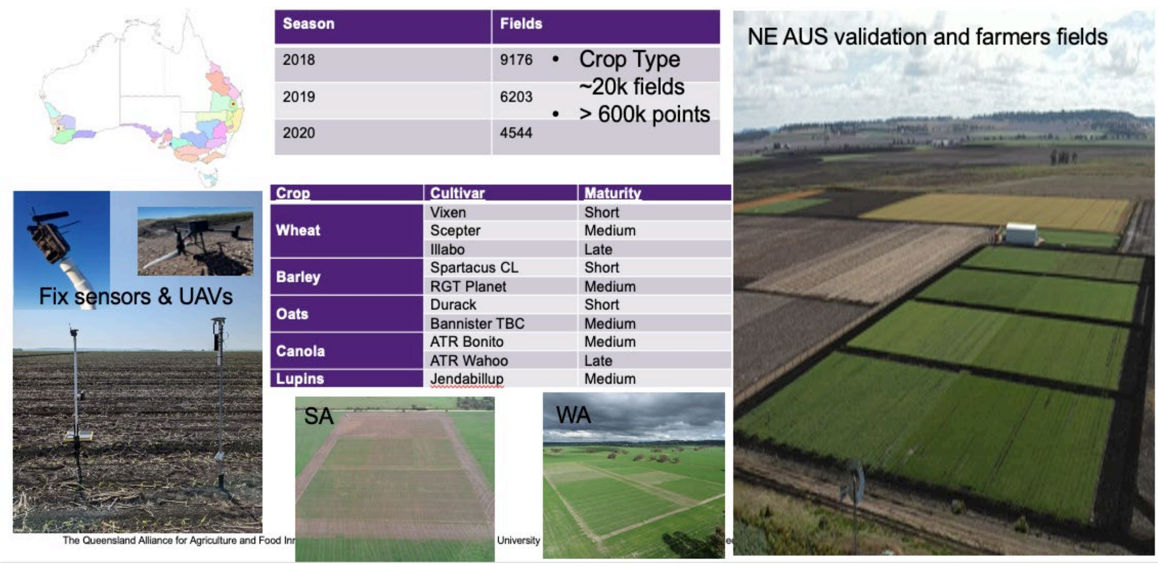

Figure 2. The three winter (one summer) validation sites. The GRDC ecological regions are coloured in the Australian map (top left). Fix sensors installed at each validation site also depicted.

Results

Examples of some of the preliminary results are given below.

Measuring crop growth from multispectral UAV platforms

Sensing of crop growth over time using high-resolution multispectral data enables the investigation of morphological and physiological crop traits for different genetics (G) x environment (E) x management (M) (Potgieter *et al.*, 2021). Extracted vegetation metrics from the multispectral camera on the UAV show a strong relationship between canopy architecture and canopy temperature (Figure 3). Creating a sequential profile of crop development for wheat, barley, and canola at the three sites highlights differences of in-season phenological development of crops measured using vegetation indices across environments during the 2021 winter season (Figure 4). This will be further analysed to determine the impact of canopy temperature on final crop yield at field scales (Zhao *et al.*, 2020) across the selected main winter crops, genotypes and environments (Das *et al.,* 2022 submitted).

Crop phenology

We applied the process of 'mathematical curve fitting' and 'feature point detection' to get sequential, (every 5-days) vegetation indices (VIs) from Sentinel-2. Observed phenology stages both recorded from on ground field surveys and in field cameras were used to calibrate and validate phenology models. Figure 5 depicts data recorded from remote sensing and some of the feature point metrics (OSAVI: the Optimized Soil Adjusted Vegetation Index, and the PSRI: Plant Senescence Reflectance Index.)

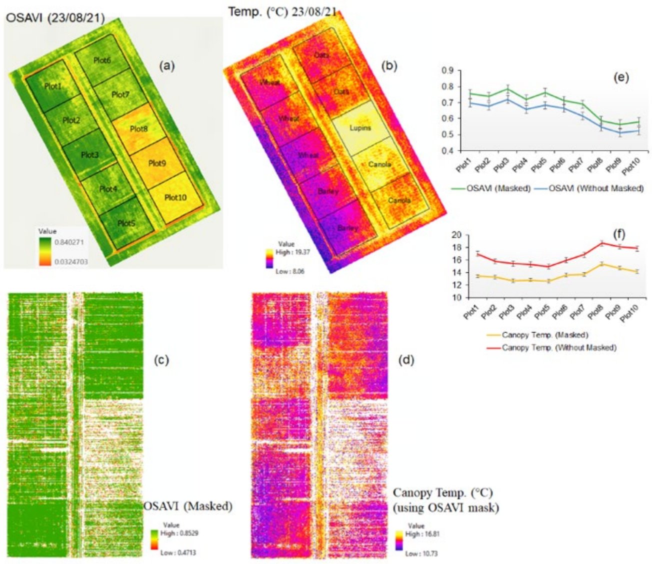

Figure 3. Example of one of the representative trials at Dale (Western Australia) indicating plot layout and crop species. (a) An optimized soil adjusted vegetation index (OSAVI) (b) and surface temperature (imagery date: 23/08/2021). Values of OSAVI and temperature aggregated for entire whole plot ('without mask') average reflectance values from both soil and canopy pixels; (c) & (d) OSAVI and canopy temperature (on top of green plants only, i.e. 'masked') using a 0.5 threshold on for canopy delineation (e) & (f) plot-wise variation of OSAVI and canopy temperature and differences between 'masked' and 'without mask' OSAVI and canopy temperature statistics on the same date of imagery.

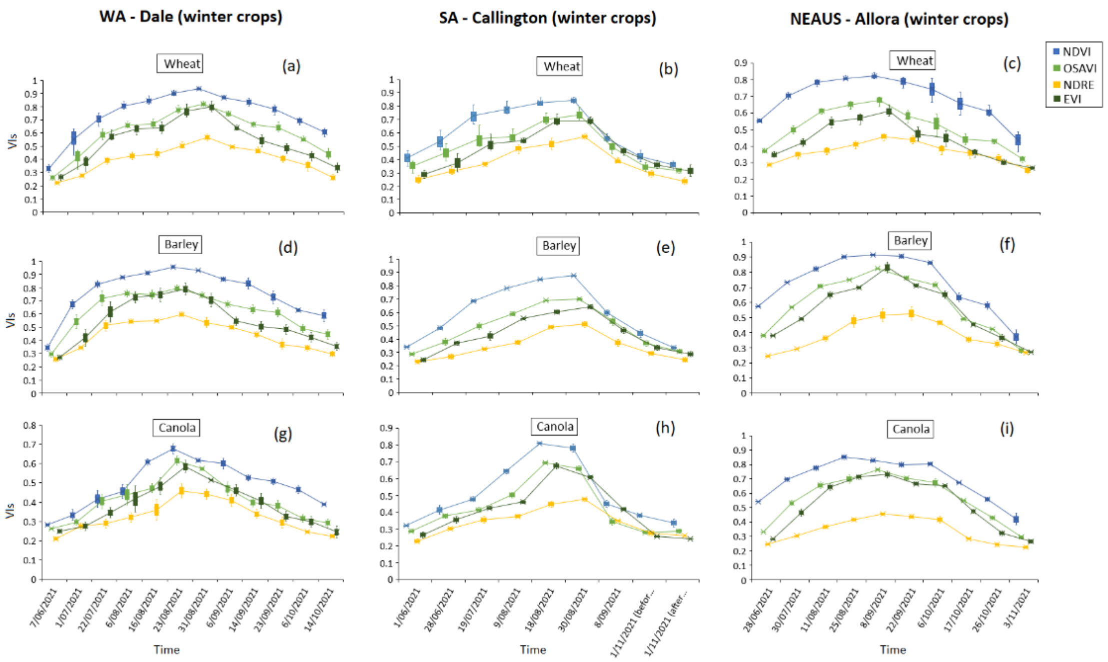

Figure 4. In-season phenological development of crops using vegetation indices (Vis) in different environments of Australia.

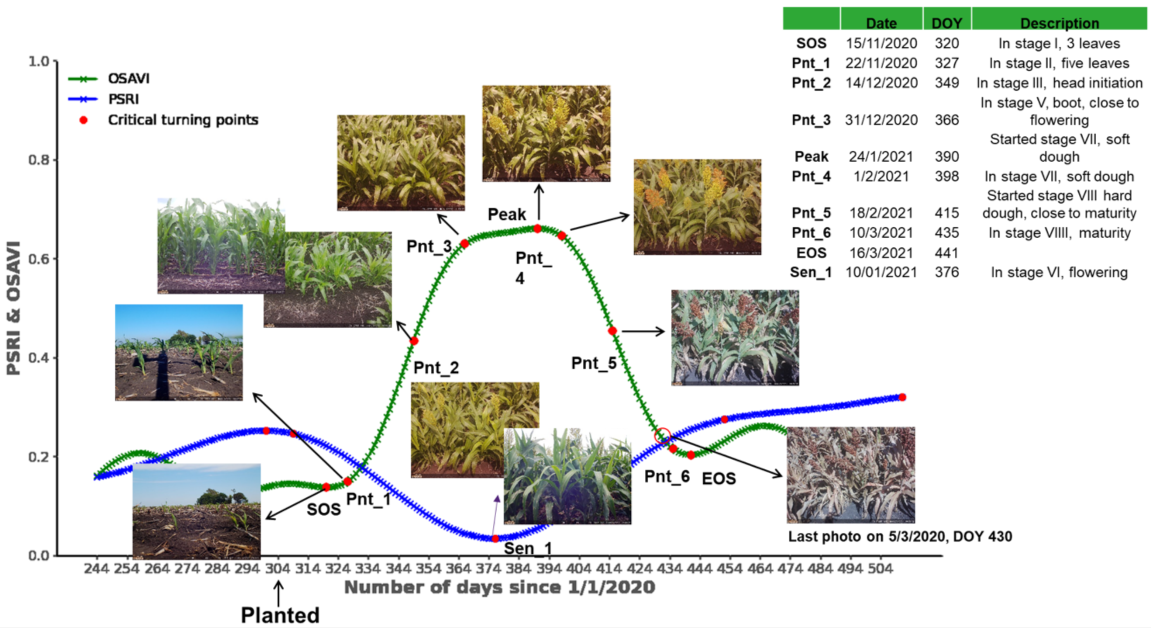

Figure 5. Crop growth curve for derived mathematical attributes - the Optimized Soil Adjusted Vegetation Index (OSAVI) and Plant Senescence Reflectance Index (PSRI) - and measured crop phenology for Sorghum 2020/2021 season in Jondaryan.

Crop type model validation and development

Figure 6 shows the recurrent neural network (RNN) deep learning model derived and the classification of winter crops and non-crops for the 2020 cropping season for Moree. Five main crop types in the region were considered. The model was able to determine what crop type was being grown with an accuracy of wheat (99%), barley (98.8%), canola (99.9%), chickpea (99.7%), and faba bean (97.8%). The current outputs were calibrated and validated with a model using Sentinel-2 spectral features. Finally, analysis is currently underway that harnessing synchronous dynamic features from multi-spectral data, including physiological and morphological crop growth attributes (Nguyen *et. al.,* 2022 submitted, data not shown).

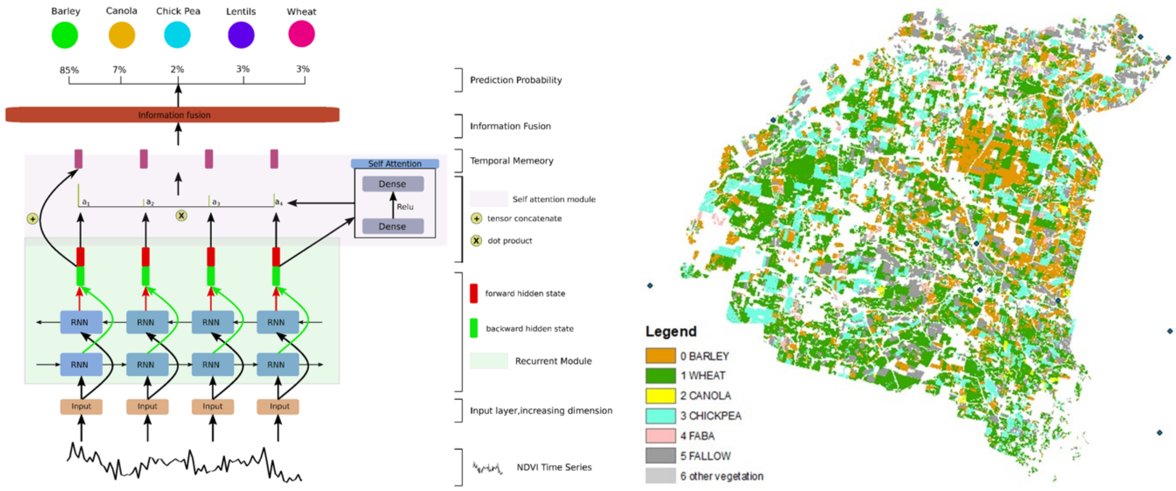

Figure 6. The model structure and the model output for classifying crop types for Moree in 2020.

How will this information be delivered to farmers and industry?

The methods to remotely map crop types at scale at different points in the season will be delivered to industry through project partners Data Farming (https://www.datafarming.com.au/), with an intent to make initial data available in the 2022 winter cropping season. The methods to remotely map crop phenology spatially are in an earlier stage of development, but will similarly be delivered to growers, agronomists, and other end-users through commercial partners.

How can famers make use of this information?

This project will deliver spatial information on crop phenology at scale, and in easily use-able formats that could be linked to other agronomic models and information systems. to near-real time spatial data on developmental stage would provide key data to supplement grower and agronomist decision making. For example:

- More localised and accurate phenology data will help deliver better estimates of crop yield potential across a grower's cropping operation, and thus enable more informed management strategies
- A better understanding of the likely spatial variability in crop development in-season and across paddocks in different points in the landscape – that data could be used to forward plan harvest logistics, but also guide future variety x sowing date decisions for different paddocks
- It will assist crop scouting through guiding agronomists on where to scout for damage from biotic and abiotic stresses based on which part of the crop in which paddocks is at a susceptible developmental stage

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Other commercial partners:
UAV operators: Airborn Insight Pty Ltd.(https://airborninsight.com.au/)
Industry commercial delivery partner: Data Farming Pty. Ltd. (https://www.datafarming.com.au/)

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Fungicide resistance update - national situation and issues for the northern grains region.

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Keywords

wheat powdery mildew (WPM), net blotch, Septoria tritici blotch (STB), Integrated Disease Management (IDM), fungicide resistance, DeMethylation Inhibitors (DMI)

Take home messages

- Monitoring and analysis of pathogen populations by CCDM in 2021 revealed new resistance mutations affecting fungicide performance for the first time in Australia and in other cases existing mutations being more widespread and affecting more states
- In a field trial in NE Victoria which combined field efficacy with laboratory analysis, testing has revealed significant differences in DMI (Group 3, triazole) performance for control of wheat powdery mildew (WPM)
- The results illustrated that the weaker compounds (triadimefon, epoxiconazole, tebuconazole, cyproconazole and propiconazole) provided less than 50% control of WPM
- Fungicide resistance and reduced sensitivity can be slowed down by using integrated disease management (IDM) approaches that reduce the number of fungicide applications required
- To 'slow the train that's heading to fungicide resistance', growers and advisers need to adopt fungicide resistance management strategies that avoid repeated applications of the same modes of action and active ingredients
- IDM strategies can include crop rotation, stubble management, green bridge control, sowing more disease resistant (avoid susceptible) cultivars, nutrition and canopy management (e.g. grazing) to minimise disease pressure.

Background

Fungicide resistance is a major concern for Australian growers as it potentially reduces the efficacy of fungicides and their ability to protect grain yield and profit potential. To minimise the yield gap on cropping farms, it is essential to maintain impact of these agrichemicals through fungicide resistance management strategies.

The first step in recognising the significance of this problem is to understand which pathogens are developing issues and to which fungicide actives.

The research reported in this paper includes fungicides that may not be registered in Australia either alone or in combination with other actives for the diseases mentioned. Their use was necessary for the express purpose of determining the resistance profile for specific mode of action groups and actives. Only products that are registered for use in Australia should be used and in accordance with directions for use on their respective labels.

What is the current status of fungicide resistance and reduced sensitivity in Australia?

Over the last decade the Fungicide Resistance Group (FRG) at the Centre for Crop and Disease Management, (CCDM at Curtin University) has been working with industry and other researchers to establish a fast and cost-effective monitoring system for fungicide resistance of common fungal pathogens of broad acre grain crops. Current cases of fungicide resistance and reduced sensitivity in Australian broadacre grain crops are outlined in Table 1.

Table 1. Fungicide resistance and reduced sensitivity cases identified in Australian broadacre grains crops.

Disease	Pathogen	Fungicide Group	Compounds affected	Region (status*)	Industry implications
Barley powdery mildew	*Blumeria graminis* f.sp. *hordei*	3 (DMI)	Tebuconazole Propiconazole Flutriafol	WA (R), Qld, NSW, Vic, Tas, (L)	Field resistance and reduced sensitivity to some actives
Wheat powdery mildew	*Blumeria graminis* f.sp. *tritici*	3 (DMI)	Propiconazole Tebuconazole	NSW, Vic (R), Tas, SA (L)	Field resistance to some actives in NSW and Vic. The gateway mutation is the first step towards resistance. This mutation does not seem to reduce efficacy in the field but combined with other mutations can affect DMI efficacy
		11 (QoI)	Azoxystrobin Pyraclostrobin	Vic, Tas, SA & NSW (R)	Field resistance to all Group 11 fungicides
Barley net-form of net blotch	*Pyrenophora teres* f.sp. *teres*	3 (DMI)	Tebuconazole Epoxiconazole Propiconazole Prothioconazole	WA (R), VIC, SA (RS)	Field resistance and reduced sensitivity to some actives
		7 (SDHI)	Fluxapyroxad Bixafen Benzovindiflupyr	SA (R & RS), VIC (L)	Reduced sensitivity or resistance depending on the frequency of resistant population
Barley spot-form of net	*Pyrenophora teres* f.sp. *maculata*	3 (DMI)	Tebuconazole Epoxiconazole Propiconazole	WA (R, RS) VIC (L)	Field resistance to some actives

blotch			Prothioconazole		
		7 (SDHI)	Fluxapyroxad Bixafen Benzovindiflupyr	WA (R, RS)	Field resistance and reduced sensitivity
Wheat septoria tritici blotch	*Zymoseptoria tritici*	3 (DMI)	Tebuconazole Flutriafol Propiconazole Cyproconazole Triadimenol Epoxiconazole	NSW, Vic, SA, Tas (RS)	Reduced sensitivity
		11 (QoI)	Azoxystrobin Pyraclostrobin	SA, (Millicent region) (R)	Frequency of A143 mutation in Millicent region unknown. 32 STB samples collected from 29 locations across Victoria, South Australia and NSW in 2021 did not detect the mutation associated with resistance to QoI fungicides
Canola Blackleg disease	*Leptosphaeria maculans*	3 (DMI)	Tebuconazole Flutriafol Prothioconazole Fluquinconazole	VIC, NSW, SA, WA (RS)	Reduced sensitivity

***Table 1 definitions:**

Reduced sensitivity (RS): Fungi are considered as having reduced sensitivity to a fungicide when a fungicide application does not work optimally but does not completely fail. In most cases, this would be related to small reductions in product performance which may not be noticeable at the field level. In some cases, growers may find that they need to use increased rates of the fungicide to obtain the previous level of control. Reduced sensitivity needs to be confirmed through specialised laboratory testing. Note that mutations that cause field failure (full resistance) present at lower frequencies in a pathogen population would give similar field symptoms to mutations that cause small reductions in field performance but which do not cause field failure.

Resistant (R): Resistance occurs when the fungicide fails to provide an acceptable level of control of the target pathogen in the field at full label rates. Resistance needs to be confirmed with laboratory testing and be clearly linked with an unacceptable loss of disease control when using the fungicide in the field at full label rates.

Laboratory detection (L): Measurable differences in sensitivity of the pathogen to the fungicide when tested in the laboratory. Detection of resistance in the lab can often be made before the fungicide's performance is impacted in the field.

Fungicide reduced sensitivity and resistance in NSW/SA/Victoria in 2021

The following section carries results from three states. Although resistance results from Vic and SA may seem less relevant to the northern GRDC region, they give us an early warning of potential issues in southern NSW where farming systems are more similar to SA and Victoria.

Wheat powdery mildew in the northern grains region

Wheat powdery mildew (WPM) was particularly problematic in NSW in 2020 but was less damaging in 2021.

Steven Simpfendorfer (NSW DPI) co-ordinated 22 samples of WPM for testing with CCDM over the last two seasons and the results revealed widespread fungicide reduced sensitivity in the DMIs and resistance in the QoIs (Table 2). The F136 mutation in WPM is a gateway mutation that doesn't confer field resistance but in combinations with other mutations (which are still being characterised) in the same gene does confer reduced sensitivity in the field.

Table 2. Location of 22 wheat powdery mildew samples; 19 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	Scepterⓑ	100%	90%
Katamatite	2020	NE Vic	Scepterⓑ	100%	90%
Cobram	2020	NE Vic	Scepterⓑ	100%	46%
Cobram	2020	NE Vic	Scepterⓑ	100%	28%
Balldale	2020	SE NSW	Scepterⓑ	100%	98%
Walbundrie	2020	SE NSW	Scepterⓑ	100%	5%
Rennie	2020	SE NSW	Suntopⓑ	85%	27%
Rennie	2020	SE NSW	Scepterⓑ	85%	20%
Jerilderie	2020	SE NSW	Scepterⓑ	100%	37%
Corowa	2021	SE NSW	Scepterⓑ	100%	94%
Deniliquin	2020	SW NSW	Scepterⓑ	99%	35%
Deniliquin	2020	SW NSW	Scepterⓑ	99%	20%
Deniliquin	2020	SW NSW	Scepterⓑ	83%	20%
Hillston	2020	SW NSW	Vittaroiⓑ	96%	21%
Hillston	2020	SW NSW	Vixenⓑ	94%	3%
Hillston	2020	SW NSW	Vixenⓑ	85%	6%
Yenda	2020	SW NSW	Cobraⓑ	100%	44%
Yenda	2020	SW NSW	Vixenⓑ	100%	12%
Finley	2021	SW NSW	Scepterⓑ	100%	38%
Edgeroi	2020	NE NSW	Lillaroiⓑ	82%	29%
Wee Waa	2020	NW NSW	Bindaroiⓑ	62%	51%
Wee Waa	2021	NW NSW	Auroraⓑ	100%	20%

FAR working in collaboration with CCDM and NSW DPI ran an irrigated trial at Katamatite in NE Victoria in 2021 to determine the field performance of different modes of action and DMI active ingredients for control of WPM. The results illustrated some interesting differences in field performance which, whilst not all statistically significant, illustrated that the weaker compounds of triadimefon, epoxiconazole (Opus), tebuconazole, cyproconazole plus propiconazole (Bumper) were giving less than 50% control (Figure 1). Isolates from this trial were taken in October (post application) and the samples sent to CCDM for fungicide resistance testing. Analysis for the presence of the A143 mutation that affects WPM control globally when using group 11 QoIs (strobilurins) was present in all treatments (Figure 2) but as might be expected was highest in the experimental treatment that received straight strobilurin alone (azoxystobin - Mirador®). Therefore, although the WPM control within this experimental treatment was not the poorest (still less than 50% control) it indicates that the population that remains post application will be less effectively controlled. Clearly, we don't apply this fungicide alone in Australia but in mixtures with DMIs, however it demonstrates the selection pressure that can occur in a season when we use fungicide actives that are at higher risk of resistance development in the pathogen. Significant differences to the untreated in the level of the QoI mutation in plots treated with DMIs and the Group 5 fungicide Prosper® (spiroxamine) will be investigated further.

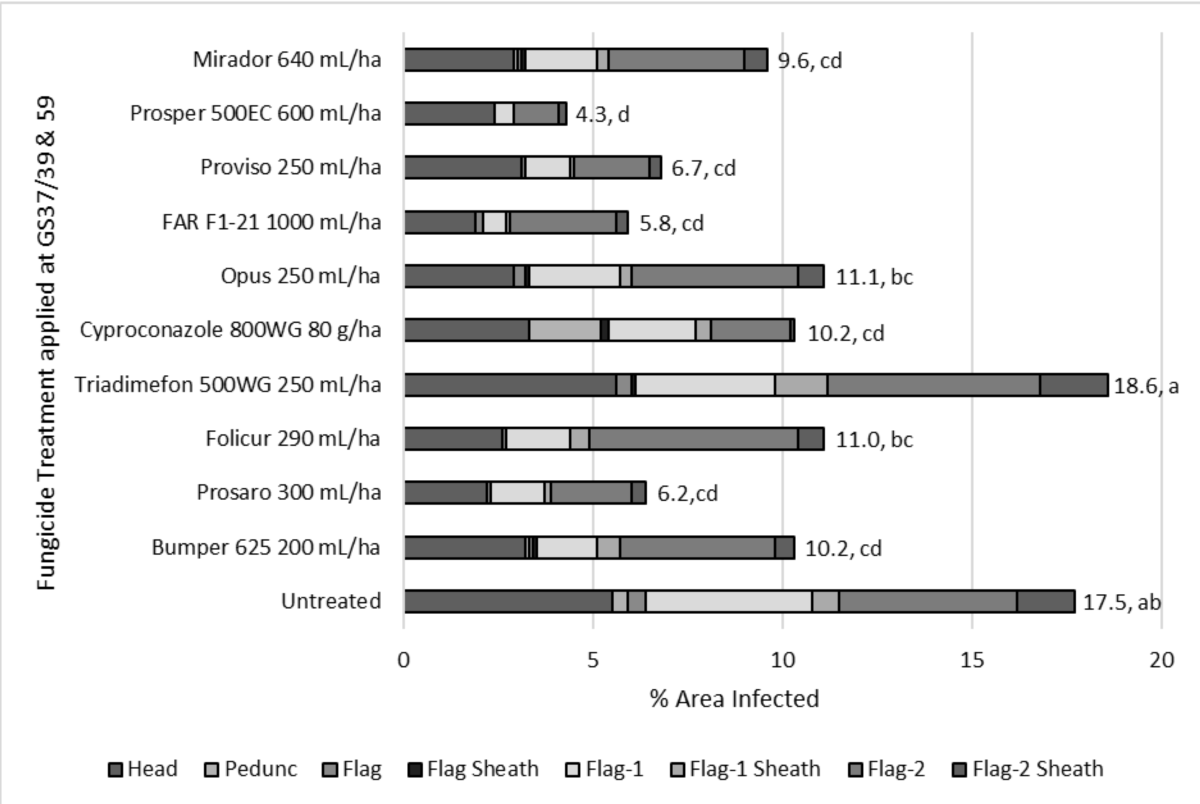

Figure 1. Influence of two spray fungicide application (GS37/39 and GS59) on wheat powdery mildew (WPM) infection on different components of upper canopy – cv Scepter⦶, Katamatite, Vic 2021.

Notes: Data labels and statistical significance based on total WPM infection of all plant components listed

Notes: Please be aware that cyproconazole, FAR F1-21, Prosper and Mirador have been included in this experimentation as experimental treatments that currently cannot be used commercially in this form. These treatments were included to test the full range of available individual fungicide actives some of which are only approved in mixtures

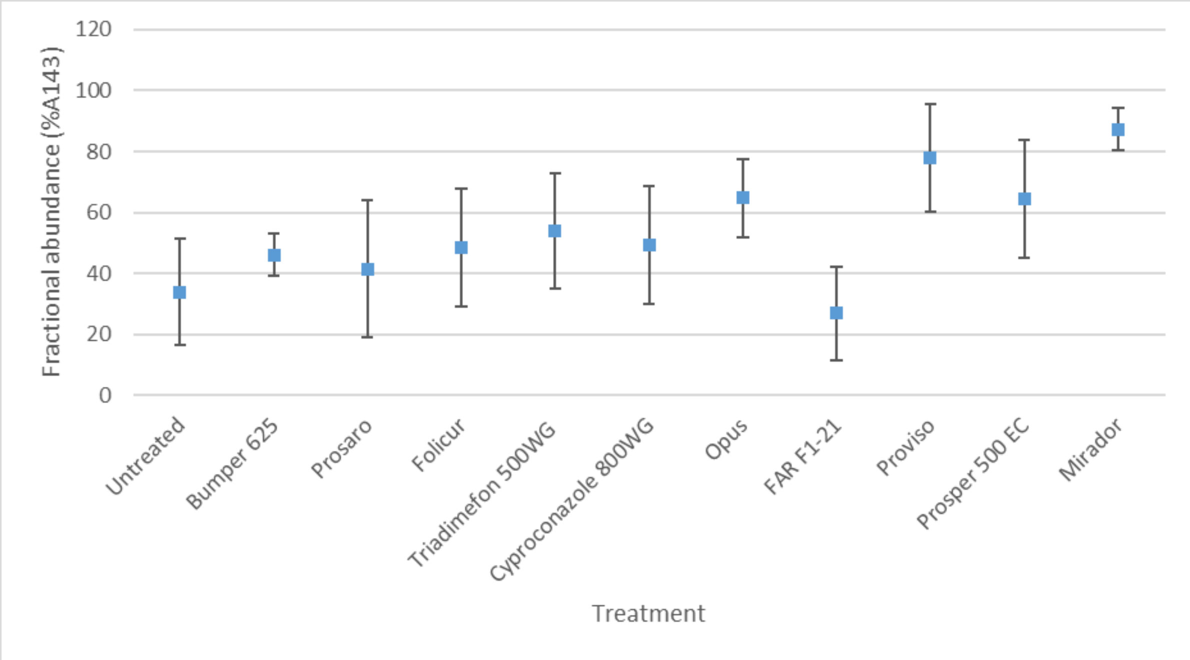

Figure 2. Fractional abundance of the A143 mutation in the different fungicide treatments applied for WPM control – cv Scepter⦶, Katamatite, Vic 2021. (CCDM analysis)

Note: When the mutation at G143A occurs the G amino acid in the wild type is replaced with an A amino acid

SDHI resistance and reduced sensitivity in net form of net blotch (NFNB) in barley

The *SdhC*-H134R mutation in the SDHI (Group 7) target site, was detected in six samples from Victoria and one sample from South Australia in 2021. This mutation was first observed in Australia in NFNB from the Yorke Peninsula of South Australia in 2019 and is associated with the highest resistance factors affecting the key SDHI compounds such as fluxapyroxad, bixafen and benzovindiflupyr.

Four other samples from Victoria and one sample from South Australia in 2021 were associated with low resistance factors for SDHI compounds and classed as the mutations conferring reduced sensitivity. These mutations have been detected previously. In the case of the SdhD-D145G mutation it was first observed in Australia in NFNB from the Yorke Peninsula of South Australia in 2019 and in the case of SdhC-N75S in spot form of net blotch (SFNB) in the Cunderdin region in WA in 2020.

DMI reduced sensitivity in net form net blotch (NFNB) in barley

The F489L-2 mutation in the DMI (Group 3) target, *Cyp51A*, was detected in six samples from Victoria and one sample from South Australia in 2021. This mutation was previously observed in Australia in NFNB from the Yorke Peninsula of South Australia in 2019 and is associated with reduced sensitivity to DMI compounds.

Genetic changes in the region that controls the DMI target were detected in one sample from South Australia in 2021. This different type of mutation has been previously observed in Australia in spot form net blotch (SFNB) from Western Australia since 2016 and is associated with reduced sensitivity to DMI compounds.

QoI resistance in septoria tritici blotch (STB)

Fungal cultures isolated from two STB samples collected in South Australia in 2020, were found to carry the fungicide resistance mutation A143, which is associated with full resistance to QoI (Group 11) fungicides. *In vitro* analysis of two STB resistant isolates obtained from these samples showed a 200-fold increase in azoxystrobin resistance compared to sensitive reference isolates. Subsequent molecular analysis of 32 STB samples collected from 29 locations across Victoria, South Australia and NSW in 2021 did not detect the mutation associated with resistance to QoI fungicides.

So what does this mean for growers and advisers

Fungicide resistance management strategies which should be used within broader IDM include:

- With wheat and barley crops where two to three fungicide applications occur within a season, avoid repeat applications of the same product/active ingredient and where possible also avoid the same mode of action in the same crop. This is particularly important when using Group 11 QoI (strobilurins) and Group 7 SDHIs, which preferably would only be used once in a growing season
- Avoid using the seed treatment fluxapyroxad (Systiva®) year after year in barley without rotating with foliar fungicides of a different mode of action during the season
- Avoid applying the same DMI (triazole) Group 3 fungicide twice in a row, irrespective of whether the DMI is applied alone or as a mixture with another mode of action
- Avoid the use of tebuconazole alone and flutriafol for Septoria tritici blotch (STB) pathogen control in regions where reduced sensitivity is problematic, as these Group 3 DMIs are more affected by reduced sensitivity strains than other DMIs
- Group 3 DMIs such as epoxiconazole (Opus®) or triazole mixtures \such as prothioconazole and tebuconazole (Prosaro®) when used alone are best reserved for less important spray timings, or in situations where disease pressure is low in higher yielding scenarios.
- With SDHI seed treatments such as fluxapyroxad (Systiva®) or QoI fungicides used in-furrow such azoxystrobin (Uniform®), consider using a subsequent foliar fungicide with a different mode of action, and therefore avoiding, if possible, a second application of SDHI or QoI fungicide active.

Clearly, the best way to avoid fungicide resistance is not to use fungicides! However, in high disease pressure regions, this would be an unprofitable decision. When a cultivar's genetic resistance breaks down or is incomplete, it is imperative that growers and advisers have access to a diverse range of effective fungicides (in terms of mode of action) for controlling leaf disease. Hence, we need to protect their longevity. In order to protect them, one of the most effective measures is to minimise the number of fungicide applications applied during the season. Therefore, consider all aspects of an Integrated Disease Management (IDM) strategy when putting your cropping plans together at the start of the season, since this will help reduce our overall fungicide dependency.

Principle components of IDM

Rotations – where possible avoid high risk rotations for disease, for example, barley on barley or wheat on wheat.

Seed hygiene – minimise the use of seed from paddocks where there were high levels of disease that could be seedborne (e.g. Ramularia, net form net blotch).

Use less disease susceptible cultivars, particularly when sowing early. Where this is not possible delay the sowing of the most susceptible cultivars to reduce disease pressure where the phenology of the cultivar is adapted to the later development window.

Cultural control such as stubble management, where disease risks are high and the penalties for stubble removal are not as high.

Grazing early sown cereal crops up to GS30 to reduce disease pressure.

AFREN (Australian Fungicide Resistance Extension Network)

The Australian Fungicide Resistance Extension Network (AFREN) was established to develop and deliver fungicide resistance resources for grains growers and advisers across the country. It brings together regional plant pathologists, fungicide resistance experts and communications and extension specialists.

AFREN wants to equip growers with the knowledge and understanding that they need to reduce the emergence and manage the impacts of fungicide resistance in Australian grains crops.

As members of AFREN, the authors of this paper are keen to hear if you believe you are encountering reduced sensitivity or resistance in your broad acre crops.

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Hyper yielding and irrigated crop agronomy - cereal outcomes benchmark indicators, decision points, key levers and their interactions to capitalise on great seasons or irrigation. Varieties, N and fungicide lessons learnt.

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Key words

yield potential, feed winter genetics, canopy management, nitrogen, waterlogging, plant growth regulators (PGR), genetic disease resistance and disease management strategies, integrated disease management (IDM),

GRDC codes

FAR2004-002SAX, FAR1906-003RTX

Take home messages

- Increased yield potential of feed winter wheats and barley is expressed in better seasons from earlier sowing. RGT Accroc, RGT Cesario⏀ and Annapurna⏀ achieved yields of ~ 11 t/ha, 3t/ha higher yielding than the best milling wheat in NSW. Winter barley exceeded 10 t/ha (10.4) dryland in SA for the first time while Planet⏀ achieved 8.0 t/ha
- To maximise returns in milling wheats in better seasons, sound disease management is essential. Beckom⏀ and Scepter⏀ with either two or four units of fungicide produced the highest economic returns due to higher price per tonne compared to feed wheats ($356/t AH grade v $236/t for SFW1).
- The winter feed wheats are more disease resistant than milling wheats and gave their most profitable returns with a single flag leaf fungicide. Genetic resistance was insufficient alone to maximise returns without fungicide application
- Fertile soils in the high rainfall zone (HRZ) limit the ability to manage yield and early biomass production with applied nitrogen in wetter environments. Mineralised N timing, and other canopy management factors such as plant growth regulators (PGR) and fungicide are equally or more important
- Principles of canopy management also apply to irrigated scenarios, however the nitrogen rates required to achieve irrigated canola yields of greater than 4 t/ha are not as high as dryland budgets would suggest. Minimum durum protein requirements of 13% to achieve DR1 can be met with attention to nitrogen management in irrigated scenarios
- Canopy management benefits of PGR and fungicides extend beyond the growing season and limit pre harvest yield losses (lodging, brackling, head-loss) and improve harvest logistics
- Waterlogging tolerance of barley compared to wheat is poor in wetter seasons, however earlier sowing and slow developing cultivars increases the chances of improved yield recovery.

Hyper yielding crops research

Led by Field Applied Research (FAR) Australia, the Hyper Yielding Crops (HYC) project is a Grains Research and Development Corporation (GRDC) national initiative which aims to push the economically attainable yield boundaries of wheat, barley and canola in those regions with higher yield potential. The project team at the time of writing is just completing harvest of the second year of project trial results at five HYC research centres across the higher yielding regions of southern Australia (NSW, WA, SA, VIC and TAS) which have been established to engage with growers and advisers. With the 25 focus farms and the HYC community awards, the aim is to scale up the research results and create a community network aimed at lifting productivity.

Canopy management is key to building and protecting high yielding crops in wet environments (seasons) and irrigated crops

Canopy management is a broad term but fundamentally relies upon adopting techniques that allow crops to intercept more radiation (sunlight) and transpire more water into biomass at the right time in the season to contribute to yield. This is first achieved by ensuring flowering is matched to environment and secondly that a high proportion of the upper crop canopy leaves remain intercepting light (retain green leaf area, disease control) during the 'critical period' for grain number formation (month prior to flowering in cereals). Unlike low rainfall environments, excessive growth prior to stem elongation is unproductive and leads to lodging, shading and poorer light interception in the critical period. Equally nitrogen (N) limitation, and or poor disease control during this period will lower grain number potential and yield either by limiting biomass production or its conversion into yield (harvest index). Harvest indices of greater than 50% should be possible with good management. Therefore to achieve 10t/ha cereal grain yields, the final biomass needs to be greater than 20 t/ha.

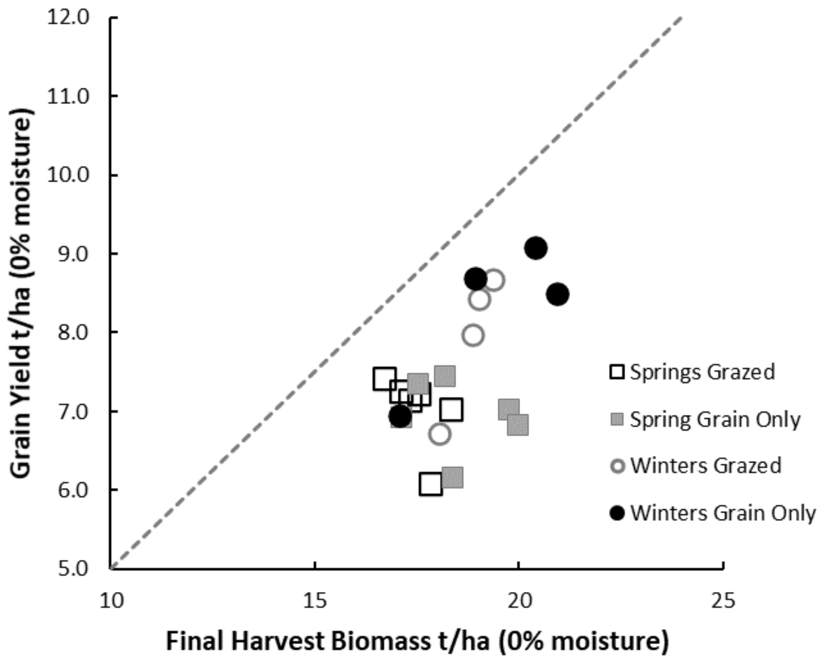

Figure 7. Relationship between dry matter and grain yield (t/ha) at 0% moisture across cultivars grouped as spring and winter types and when grazed or left for grain only in 2020 at Wallendbeen NSW. The dotted line represents aspirational yields that are possible with a harvest index of 50%.

While canopy management techniques can improve harvest index, they should not come at the expense of reduced final biomass. For example, grazing (mowing) spring and winter wheats at Wallendbeen 2020 increased harvest index (HI) but yields were not increased due to lower biomass (Figure 1). Spring wheats that achieved similar final dry matters as winter wheats yielded lower (lower HI) due to reduced light interception in the critical period from developing under sub-optimal conditions (early) and reduced green leaf area in upper canopy (increased disease infection).

Optimising irrigated grains research

The principles of canopy management also apply to irrigated scenarios and during 2020 and 2021, over 50 irrigated research trials (in six crops) were established at FAR Australia's Finley Irrigated Research Centre (Southern Growers Irrigation Complex) in southern NSW. This has been part of a major regional GRDC investment referred to as the 'Optimising Irrigated Grains' project with agronomy and soil amelioration research led by FAR Australia in collaboration with the Irrigated Cropping Council (ICC). Work in canola has been targeted at growing 5 t/ha crop of canola and 10 t/ha crop of durum wheat under irrigation. In particular, looking at the canopy management and nutritional requirements for high yielding crops. These canopy management factors include, cultivar crop development, genetic disease resistance, fungicide chemistry and timing, other intervention techniques such as the addition of a PGR, defoliation and additional nitrogen.

Two years of irrigated canola and durum research

Research in canola has indicated that extremely large doses of applied nitrogen fertiliser are not the route to the most economic returns and that crop establishment, absence of water logging and healthy soils with good available soil N reserves are the best combination of factors to maximise yield in irrigated canola. In 2020 following wheat, the hybrid 45Y28 RR gave a significant response to applied nitrogen that illustrated an optimum N rate for yield of approximately 160 kg N/ha with a yield of 4.55 t/ha (Table 1). In 2021 the optimum response was higher at 240 kg N/ha with a yield of 3.9 t/ha. Although yields in 2021 peaked at a nitrogen rate of 320 kg N/ha, the yield was not statistically greater than at 240 kg N/ha. Measured levels of available starting N were little different to 2020 (at 129 v 110 kg N/ha (0 – 90cm)) but unfertilised crops produced considerably lower yields in 2021 with significant evidence of water logging in the winter 2021 that may have both restricted the rooting of the crops and or generated losses of N from the soil under the anaerobic conditions. In 2020, differences in oil content were small but significant with a 1.2% oil content decline covering N rates between 80 – 320 N applied. There were no significant differences in oil content in 2021.

Table 1 Influence of applied nitrogen rate at stem elongation on grain yield (t/ha) and oil content (%) of canola across 2 years

				2020		2021	
Soil profile N prior to sowing (0-90cm)				**129 kg/ha**		**110 kg/ha**	
	Nitrogen timing and rate			**Grain yield and quality**			
	6 Leaf	**Green bud**	**Total**	**Yield**	**Oil**	**Yield**	**Oil**
	Kg N/ha	**Kg N/ha**	**Kg N/ha**	**t/ha**	**%**		
1	0	0	0	3.91 d	43.0 ab	2.21 f	48.3 -
2	40	40	80	4.30 c	43.3 a	3.38 e	46.9 -
3	60	60	120	4.41 bc	42.0 d	3.46 de	45.9 -
4	80	80	160	4.55 ab	42.4 bcd	3.56 cde	46.9 -
5	100	100	200	4.59 ab	42.4 bcd	3.76 bcd	47.4 -
6	120	120	240	4.62 a	42.8 a-d	3.90 abc	46.3 -
7	140	140	280	4.71 a	42.9 abc	4.05 ab	48.0 -
8	160	160	320	4.71 a	42.1 cd	4.22 a	46.3 -
	Mean			4.475	42.6	3.57	47.0
	LSD			0.19	0.84	0.35	n.s
	P Val			<0.001	0.032	<0.001	0.065

Durum research at Finley over the last two years (Table 2 and 3) illustrated much lower available soil N reserves in the 2021 season compared to 2020. 232 kg N/ha in the soil profile (0 - 90cm) following fallow in 2019 compared to 146 kg/ha over the same depth in 2021 following canola. Consequently, DBA Vittaroi⦶ gave no significant yield response to applied N fertiliser (urea 46% N) at levels between 10 – 350 kg N/ha in 2020, with yields ranging from 6.93 – 7.43 t/ha. By comparison, yields in 2021 were between 4.87 – 6.74 t/ha , with no significant yield response to N application above 100 kg N/ha. However, it required another 100 kg N/ha of applied fertiliser (200 kg N/ha total) to increase protein above 13%, the minimum required to achieve DR1 quality when applied N was split between GS30 and GS32 (pseudo stem erect & second node). However, in a separate experiment it was illustrated that when N timing was delayed until GS32 and GS37 (flag leaf visible) a protein of 13.4% was achieved with no more 100 kg N/ha of applied nitrogen (Table 3) and no loss of yield. (data not shown).

Table 2. Influence of applied nitrogen rate at stem elongation on grain yield (t/ha) and protein content (%) in durum across 2 years

					2020		2021	
Soil profile N prior to sowing (0-90cm)					**232 kg/ha**		**146 kg/ha**	
Nitrogen timing and rate					**Grain yield and quality**			
	GS30	**GS32**	**GS39**	**Total**	**Yield**	**Protein**	**Yield**	**Protein**
	Kg N/ha	**Kg N/ha**	**Kg N/ha**	**kg N/ha**	**t/ha**	**%**	**t/ha**	**%**
1	0	0		0	7.10 -	13.0 c	4.87 b	10.3 e
2	50	50		100	7.17 -	13.9 b	6.40 a	11.9 d
3	75	75		150	6.93 -	14.5 ab	6.43 a	12.5 d
4	100	100		200	6.97 -	14.4 ab	6.63 a	14.6 c
5	125	125		250	6.96 -	14.8 a	6.73 a	15.0 bc
6	150	150		300	7.05 -	14.9 a	6.74 a	15.5 b
7	100	100	100	300	7.43 -	14.5 ab	6.52 a	15.7 ab
8	125	125	100	350	7.11 -	15.0 a	6.51 a	16.3 a
	Mean				7.09	14.4	6.35	14.0
	LSD				0.33	0.7	0.57	0.8
	P Val				n.s.	<0.001	<0.001	<0.001

Table 3. Influence of N rate and timing strategies on grain protein (%) in durum grown at Finley in 2021, based on split application of N at total rates of 0, 100, 200 and 300kg N/ha.

	Nitrogen application rate				
	0kg/ha N	**100kg/ha N**	**200kg/ha N**	**300kg/ha N**	**Mean**
Nitrogen timing	**Protein %**	**Protein %**	**Protein %**	**Protein%**	**Protein%**
PSPE & GS30	10.9 -	12.4 -	13.8 -	15.0 -	13.0 b
GS30 & GS32	10.6 -	12.5 -	13.7 -	15.0 -	13.0 b
GS32 & GS37	10.9 -	13.4 -	15.3 -	16.4 -	14.0 a
Mean	10.8 d	12.8 c	14.3 b	15.5 a	
N timing		LSD 0.4		**P val**	<0.001
N rate		LSD 0.5		**P val**	<0.001
N timing x N		LSD ns		**P val**	**0.235**

Hyper yielding research: achieving high yields from the better seasons

Consider the genetic potential of the cultivar and delivery price splits between feed and higher quality grades to maximise economic returns

The wet 2021 season and HYC research has highlighted that the increased yield potential of feed wheats and winter barley is expressed in the better seasons and exceeds current commercially available milling wheats and malt barley cultivars. While it is possible to grow higher yield of feed wheats and barley, they need to be profitable. The durum example above shows it possible to achieve high yields and higher proteins with N management and highlights possibilities to make the most of quality price spreads with management. The HYC results below demonstrate the milling wheats at Wallendbeen are capable of yielding 8 t/ha and milling grade with adequate disease control, whereas feed winter wheats achieved greater yields of ~ 11 t/ha. Under this scenario milling wheats were more profitable at current feed price spreads despite yielding 3 t/ha less than feed winter wheats at Wallendbeen in 2021 (Table 8). Figure 2 below can be used to determine how much higher feed wheats need to yield across different quality grade yield potential environments to equal or exceed milling wheat gross margins. At Wallendbeen for example; at current feed splits of $100 between APW and feed wheat, a feed wheat would have to yield 12 t/ha (or an extra 4 t/ha) to equal the gross margin of APW yielding 8 t/ha (at $300/tonne delivery price). If the spread reduces to $50/t, the yield required by a feed wheat is 9.6 t/ha. This assumes higher quality grades are achieved in the milling wheat. The same applies to Durum in reverse, if Durum attracts a $50 price premium over milling wheat, then it would only need to yield 6.2 t/ha to match the gross margin of a milling wheat at 8 t/ha. These yields have been achieved under irrigation in 2020, and 2021. This may be a more profitable system than chasing the extra yields of feed wheat under irrigation.

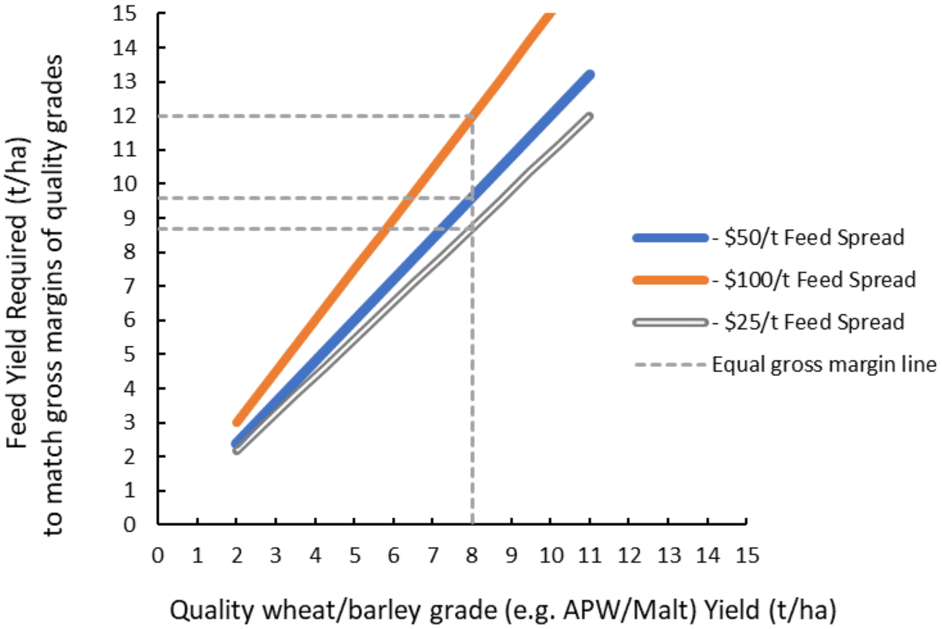

Figure 8. Relationship between the grain yield of feed cereals and quality grades required to achieve similar gross margin returns at different feed delivery price spreads (assuming quality delivery price is $300/t)

Barley is a different story, as high yields and malt can be achieved in spring barley. However, introduction of higher potential winter feed barley cultivars could raise yield expectations. The price spread is lower between feed and malt barley ($20 – $25) than feed and milling wheat. If 8 t/ha of malt barley was achieved with a price spread of $25 over feed, then an additional 0.7 t/ha (or 8.7 t/ha) of feed barley is required to provide and equal gross margin. This is an important comparison, because for the first time winter barley has now exceeded 10 t/ha under dryland conditions (Table 4). Yields of 10.4 t/ha were achieved in 6 row winter Pixel and 9.7t/ha in 2 row winters in the Southern HRZ, while Planet⦶ achieved 8.0t/ha from the same sowing date and 8.15t/ha from a later more optimal sowing date (yields not shown). Planet⦶ barley remains the benchmark cultivar for achieving high yields across all higher production environments. The key limitation to Planet⦶ is poor disease resistance.

Table 4. Grain yield (t/ha) and variety type evaluated under high yielding management conditions at Millicent in SA from early sowing 2021[1]

Variety		Type	Grain yield (t/ha)	
1.	Planet⟑	2 Row Malt Spring (Control)	8.0	d
2.	Rosalind⟑	2 Row Feed Spring (Control)	8.0	d
Experimental Lines[2]				
3.	AGTB0244	2 Row Spring	7.9	d
4.	Laureate	2 Row Spring	8.0	d
5.	Cassiopee	2 Row Winter	7.9	de
6.	Madness	2 Row Winter	8.7	c
7.	Newton	2 Row Winter	9.7	b
8.	Memento	2 Row Winter	8.9	c
9.	Pixel	6 Row Winter	10.4	a
10.	Visual	6 Row Winter	7.5	de
		P Val <0.001, LSD 5% 0.64, Mean	8.10	

[1] High yielding management conditions include a robust fungicide strategy, plant growth regulators and extra N described in the flow diagram below. [2] Lines are experimental and yet to be commercialised in Australia or receive a quality classification.

Feed winter barley is yet to achieve the same adoption as feed winter wheats. European introductions have demonstrated superior disease resistance to all spring cultivars, however, they grow too tall, and are more prone to yield losses from lodging, head loss, and grain shattering. These production constraints can be managed with principles of canopy management in both contrasting cultivar types highlighting the importance of disease resistance and fungicide lessons presented in the HYC wheat data below.

The summary of two wet seasons (three experiments) at Millicent SA, and Gnarwarre Vic of earlier sowing is below (Figure 3.). A key finding was that the addition of an SDHI fungicide in the susceptible cultivar Planet⟑ increased yield by 1.2 t/ha (6.1 – 7.3 t/ha) irrespective of any other management factor. Whereas in the winter barley, yields were 6.6 and 6.7 t/ha under standard and increased disease management respectively. The addition of plant growth regulators or defoliation by grazing, or an extra 80 kg of applied N did not increase yield and demonstrates in the barley variety Planet⟑, that **disease management is the number one factor to achieve high yields.**

In winter barley the use of plant growth regulators (PGRs) to reduce height, lodging and head loss increased yield and was more important than extra fungicide application alone, however in combination they both increased yield. Under standard management, grain yield increased by 0.4 t/ha (6.6 – 7.0 t/ha) with the application of a PGR, whereas the more robust fungicide strategy did not increase yield unless it was combined with the PGR, and then increased yield by 0.7 t/ha (6.6 – 7.3 t/ha). Grazing or extra N didn't further increase yield.

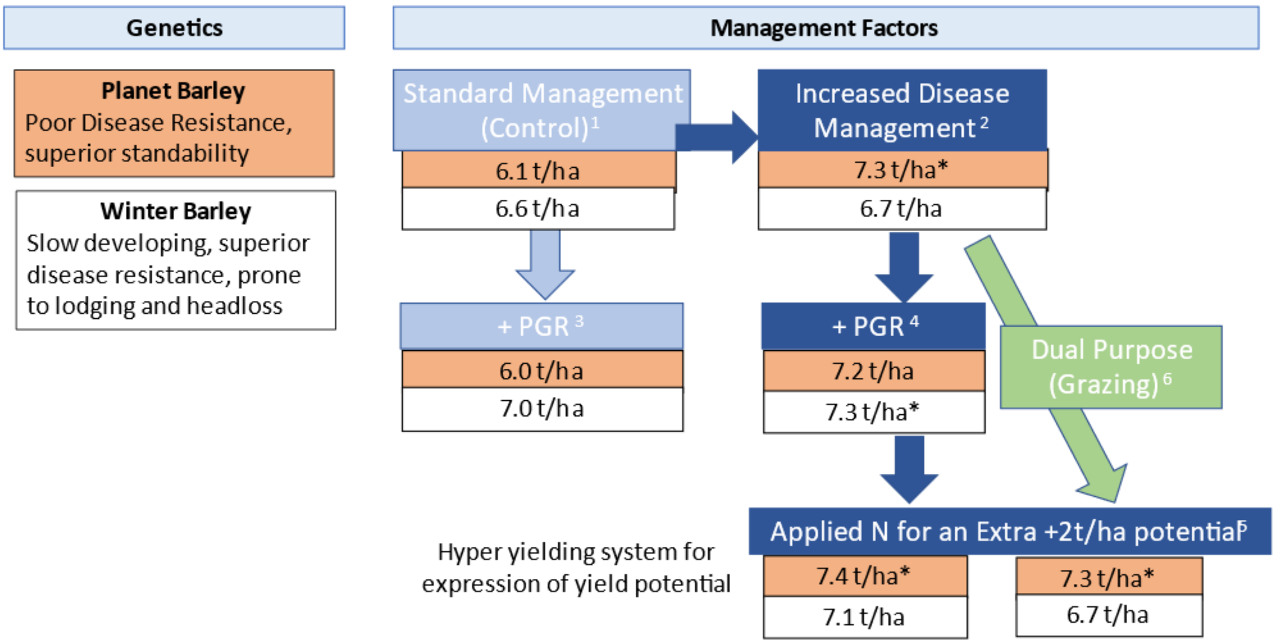

Figure 9. Mean yields and response to canopy management factors, fungicide, plant growth regulators (PGR), nitrogen, and grazing in two contrasting barley cultivars across 3 earlier sown experiments (~20 April) in the HRZ of SA, Vic (2020/2021).

Definitions of management factors

[1] Standard Management Control – 2 x cheaper foliar fungicide propiconazole (Tilt® 250 EC at 500mL/ha) @GS31 and tebuconazole(tebuconazole 430 SC 290 mL/ha) @GS39-49. Nitrogen managed for 8 t/ha yield potential

[2] Increased disease management – Systiva® seed treatment, 2 x foliar fungicides including QoI (strobilurin) & SDHI combinations with DMIs) with third fungicide if required.

[3,4] Plant growth regulation (PGR) (Moddus® Evo 200 mL/ha @GS30 & Moddus Evo 200mL/ha @GS33-37).

[5] Extra applied nitrogen (N) = Additional 80 units (kg of N) applied at GS31

[6] Defoliation = simulated grazing @GS16 and GS30 or before Aug 15 in winters.

All other inputs of insecticides and herbicides were standard across the trial. Timings of PGRs and fungicides were adjusted to take account of the differences in spring and winter barley phenology (development).

Essential role of disease management in better seasons with higher yield potential and in wheat and barley cultivars of poorer disease resistance.

Irrespective of whether its medium or high rainfall zone (M-HRZ), it's essential growers and advisers consider disease management as one of the most important components of growing high yielding cereal crops in seasons with higher yield potential. In HYC trials in 2020 and 2021 we have been looking at how to utilise and combine genetic resistance and disease management strategies to generate the most profitable crops. The primary research objective (first year reported at the 2020 GRDC Wagga Update) has been centred on examining whether newer wheat cultivars suitable for high yielding regions (correct phenology and standability) might have sufficient genetic resistance to delay fungicide intervention and as a result use fewer fungicide applications. If a cultivar has sufficient genetic resistance to prevent disease development, it may be possible to delay fungicide application until flag leaf emergence or at least later into stem elongation (GS33-37). This has two primary benefits; firstly, it allows a much better appraisal of whether the seasonal conditions have the potential to support fungicide expenditure and secondly it means that a fungicide can be applied to more of or all of the upper canopy leaves at the same time. In those seasons where the spring progressively cuts out, it means the flag leaf spray expenditure could be cut back or removed altogether. However, the industry needs good genetic resistance in our high yielding cultivars to make this a reality. ***So, of the cultivars tested so far do we have enough genetic resistance to make this reduced fungicide input an economic reality?***

Seven cultivars in 2021 were treated with four levels of fungicide management with timings adjusted to take account of the differences in phenology between winter and spring wheat (Table 5).

Table 5. Treatment and disease management applied to 2021 trials.

	Timing	**Untreated**	**1 fungicide unit**	**2 fungicide units**	**4 fungicide units**
Seed treatment		Vibrance®/ Gaucho®	Vibrance/ Gaucho	Vibrance/ Gaucho	As others + Flutriafol
Fungicide	GS31 (F-3 emerging)	---	---		Prosaro® 300 mL/ha
	GS33 (F-1 emerging)			FAR F1 -19 750 mL/ha	
	GS39 (Flag leaf emerged)	---	FAR F1 -19 750 mL/ha		FAR F1 -19 750 mL/ha
	GS59 (head emergence)	---	---	Opus® 125 500 mL/ha	Radial® 840 mL/ha
Total Cost ($/ha)		---	40	67	120

Notes: *Fungicide units include both application & fungicide cost. The pre commercial compound FAR F1-19 (not registered) has been used in this trial and has been given a nominal costing in terms of the economics table (Table 7&8).*

Septoria tritici blotch (STB) was the principal disease in untreated crops of Scepter⦶ and Beckom⦶, whilst stripe rust was the main disease to affect Trojan⦶ (strain 198 E16 A+ J+ T+ 17+), Catapult⦶ (239 E237 A- 17+ 33+) and Rockstar⦶ (239 E237 A- 17+ 33+) (Figure 4). Other cultivars were subject to low levels of both stripe rust, leaf rust and STB disease pressure. The yield results from the trial were exceptional and exceeded 2020 yields with the winter feed wheats. The data indicated for the second year running a large yield advantage to winter feed wheats over the spring milling wheats (Table 6). There was a significant interaction between cultivar and fungicide management that indicated large yield increases due to increasing fungicide application with cultivars such as Catapult and Trojan and no statistical difference between one and four fungicides with the more disease resistance cultivars such as Beckom and the winter feed wheats. Anapurna gave its highest yield with a single flag leaf fungicide but there were no statistical differences between any of the disease management treatments for this variety - including the untreated. The results at this higher altitude HYC research site in 2020 were similar with Anapurna and RGT Accroc producing almost 11t/ha with no advantage to applying more than a single flag leaf fungicide in order to achieve those yields. The grades achieved by the different treatment combinations improved significantly with the susceptible milling wheat cultivars, but all the winter feed wheats achieved a standard SFW1 grade.

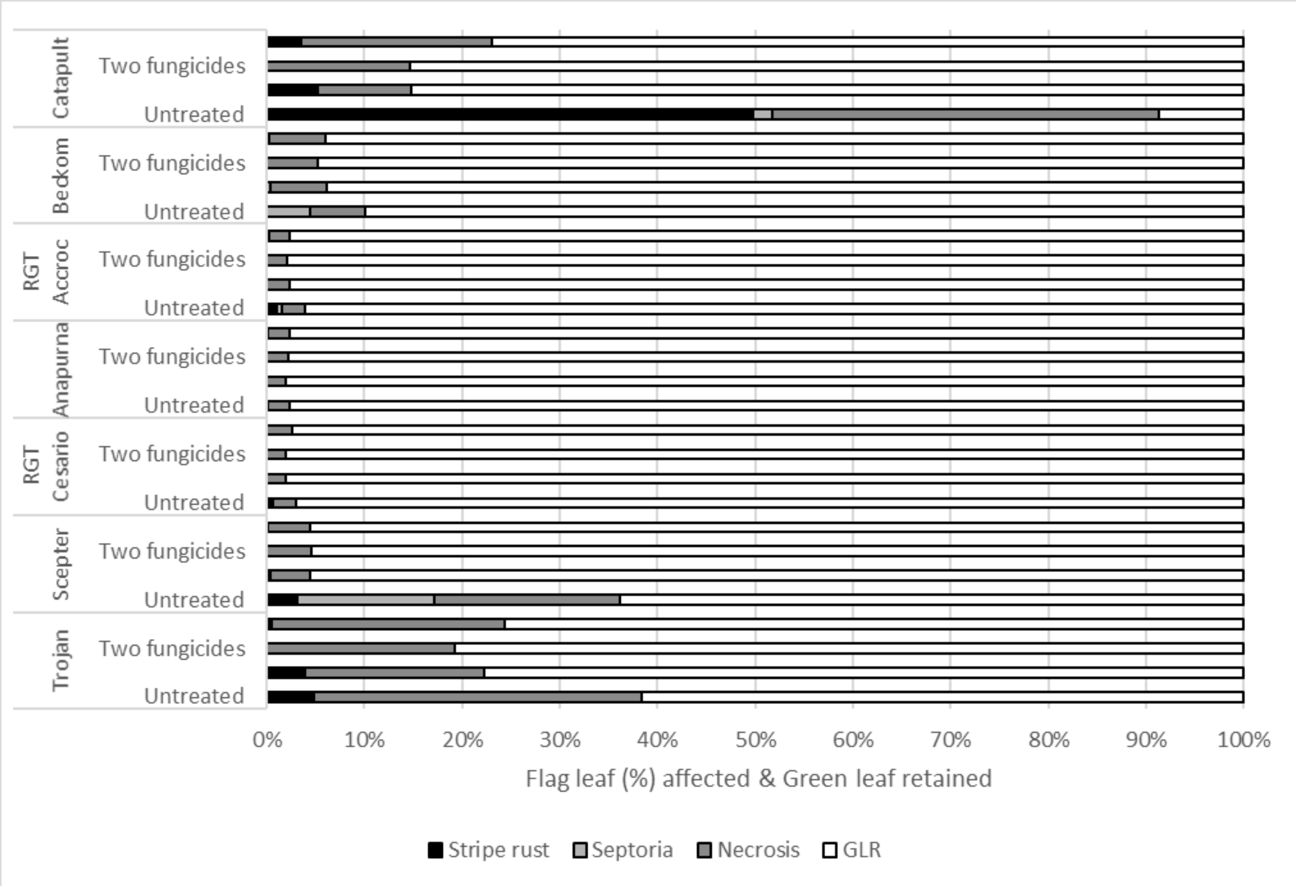

Figure 4. Influence of different fungicide input strategies on seven different cultivars in 2021 - HYC Wallendbeen, NSW.

Table 6 Influence of fungicide strategy and cultivar on wheat grain yield (t/ha) in 2021 – Wallendbeen, NSW.

	Management level (yield t/ha)								
Cultivar	**Untreated**		**1 Fungicide**		**2 Fungicide**		**4 Fungicide**		**Mean**
Trojan⍊ (S)	3.51	l	4.60	k	5.24	j	6.56	i	**4.98**
Scepter⍊ (S)	7.14	gh	7.67	efg	7.92	e	8.05	e	**7.70**
RGT Cesario⍊ (W)	10.50	bcd	11.14	a	10.89	abc	10.87	abc	**10.85**
Annapurn**a** (W)	10.46	cd	10.84	abc	10.83	abc	10.79	abc	**10.73**
RGT Accroc (W)	9.99	d	11.05	a	11.01	ab	10.94	abc	**10.75**
Beckom⍊ (S)	6.94	hi	7.71	ef	7.84	e	8.10	e	**7.65**
Catapult⍊ (S)	3.18	l	6.76	hi	7.28	fgh	7.59	efg	**6.20**
Mean	**7.39**		**8.54**		**8.71**		**8.99**		
Cultivar		**LSD**		0.36 t/ha		P val			<0.001
Management		**LSD**		0.20 t/ha		P val			<0.001
Cultivar x Management		**LSD**		0.54 t/ha		P val			<0.001

** All timings for spring and winter wheat were adjusted to take account of cultivar phenology, W = winter wheat, S = spring wheat. Yield figures followed by the same letter are not considered to be statistically different (p=0.05).*

The most profitable approach to growing each cultivar is specified in Table 7 & 8. This illustrated that the European longer season winter wheats gave their best returns relative to the untreated crop with only a single flag leaf fungicide applied. With the four more disease susceptible spring wheats, margins were optimised with either a two or four fungicide approach with little difference in margin between the two approaches.

Table 7. Increase or decrease in margin ($/ha) as result of fungicide expenditure relative to the untreated crop (extra income from fungicide minus fungicide and application cost).

	Management level (increase/decrease in margin $/ha)			
Cultivar	**1 Fungicide**	**2 Fungicide**	**4 Fungicide**	**Mean**
Trojan⦶ (spring)	365	493	**757**	**538**
Scepter⦶ (Spring)	149	**210**	**204**	**188**
RGT Cesario⦶ (Winter)	**111**	25	-33	**34**
Anapurna (Winter)	**50**	20	-42	**9**
RGT Accroc (Winter)	**210**	173	104	**162**
Beckom⦶ (Spring)	907	**926**	**966**	**933**
Catapult⦶ (Spring)	1232	**2046**	**2103**	**1794**
Mean	**432**	**556**	**580**	

Prices as of 11/1/21 trading at Cootamundra GrainCorp. (grade prices used SFW1- $236/t, AGP1- $241/t, AUH2-$286/t, AH2-$356t)

Table 8. Influence of disease management strategy and variety on margin ($/ha) (Gross income-fungicide cost)

	Management level (margin after fungicide cost $/ha)				
Cultivar	**Untreated**	**1 Fungicide**	**2 Fungicide**	**4 Fungicide**	**Mean**
Trojan⦶ (spring)	702	1067	1195	**1459**	**1106**
Scepter⦶ (Spring)	2540	2689	**2751**	**2744**	**2681**
RGT Cesario ⦶ (Winter)	2475	**2586**	2500	2442	**2501**
Anapurna (Winter)	2466	**2516**	2486	2424	**2473**
RGT Accroc (Winter)	2355	**2565**	2529	2459	**2477**
Beckom⦶ (Spring)	1796	2703	2722	**2761**	**2496**
Catapult⦶ (Spring)	477	1709	2523	**2580**	**1822**
Mean	**1830**	**2262**	**2386**	**2410**	

Prices as of 11/1/21 trading at Cootamundra GrainCorp. (grade prices used SFW1- $236/t, AGP1- $241/t, AUH2-$286/t, AH2-$356t)
**Price unavailable as poor quality in untreated crops of Catapult⦶ and Trojan⦶, nominal value used*

The other important lessons for the wetter seasons from these and adjacent experiments on the Hyper Yielding Crop centres will not be discussed here in great detail but have demonstrated in wheat and barley that:

- Fertile soils in the HRZ limit the ability to manage yield and early biomass production with applied nitrogen in wetter environments - other techniques such as PGRs, cultivar, and fungicide are more important for active management in the critical period
- Canopy management benefits extend beyond the growing season – disease control and the combined application of PGRs and timely harvest ensures pre harvest yield losses are reduced, particularly in barley (e.g., head loss and brackling)

- Waterlogging tolerance of barley compared to wheat is poor in wetter seasons, however earlier sowing of slow developing cultivars increases the chances of improved yield recovery post water logging.

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Collaborating partners acknowledgement

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Hyper yielding crops lifts canola yield above 6 t/ha

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Take home messages

- Grain yield reached well over 6 t/ha at Millicent and Wallendbeen in 2021, 1 t/ha above the highest yields observed in 2020
- Yield plateaued from nitrogen application either below or up to 150 kg/ha applied N
- The application of animal manure lifted yield by a further 11-18% above the maximum yield from applied N
- Variety choice has a major impact on achieving hyper yields, with 45Y95 CL being the standout variety in 2021.
- Further research will determine the mechanisms behind the strong yield response from animal manure and how nutrition can drive hyper yields of canola.

Background information

The canola component of the GRDC and FAR Australia Hyperyielding Crops project commenced in 2020 with sites at Gnarwarre, Victoria; Millicent, South Australia; and Wallendbeen NSW. The focus has been on determining the management factors including variety choice, nutrition, fungicide and canopy management required to achieve a canola yield of 5 t/ha. Variety choice and nutrition were the two most important factors driving canola yield in these high yielding environments in 2020, with fungicide and seeding rate less important. Highest yields were at Wallendbeen with 5.6 t/ha of 45Y28 RR with 225 kg/ha N applied. At Gnarwarre, highest yield was 4.8 t/ha of 45Y28 RR with 106 kg/ha N applied with 5 t/ha pig manure. At Millicent highest yield was 4.6 t/ha of 45Y93 CL. All results from 2020 are available at: https://faraustralia.com.au/wp-content/uploads/2021/04/210325-HYC-Project-2020-Results-Canola-Final.pdf.

2021 hyper yielding canola trials

Trials with a similar focus were conducted in 2021 in the same environments as 2020. Yields were higher in 2021 at all sites, with two of the three sites achieving a grain yield of 6 t/ha, well above the target yield of 5 t/ha (Figure 1). This paper outlines the key management strategies to achieve these very high yields at each site.

Figure 1. Grain yield of the highest yielding canola treatments at three sites in 2020 and 2021.

Methodology

This paper reports on two key trial series (Table 1), the first a genotype x environment x management (GEM) trial which were split into separate winter and spring trials with three management strategies (low, medium and high input) applied to each variety (blocked by herbicide tolerance) at three locations; Gnarwarre, Millicent and Wallendbeen (Site descriptions in Table 2). The second trial series was a nutrition trial again split into separate spring and winter trials with six nutrition treatments, focusing on nitrogen management and the addition of animal manure.

There were separate fungicide, seeding rate and variety screen trials conducted at each site. Results from these will be presented at GRDC Updates and available on the FAR Australia website on completion of reports.

Table 1. Variety entries and treatments in a canola G x E x M trial and canola nutrition trial, conducted at three sites in 2021.

GEM trial series			Nutrition trial		
Spring varieties	*Winter varieties*	*Treatments*	*Spring variety*	*Winter variety*	*Treatments*
ATR Wahoo	Hyola 970CL	Low input: Seed = Maxim® XL 20% Bloom = Aviator® Xpro® 0.8 L/ha N = 150 kg/ha	45Y28 RR	Hyola Feast CL	0 kg/ha N
HyTTec® Trifecta					75 kg/ha N
45Y93 CL		Medium input: Seed = Maxim XL 20% Bloom = Aviator Xpro 0.8 L/ha N = 225 kg/ha			150 kg/ha N
45Y95 CL	Hyola Feast CL				225 kg/ha N
45Y28 RR		High input: Seed = Saltro® Duo 6-Leaf = Prosaro® 0.45 L/ha 20% Bloom = Aviator Xpro 0.8 L/ha 50% Bloom = Prosaro 0.45 L/ha N = 225 kg/ha			300 kg/ha N
Condor TF					225 kg/ha N + Animal Manure*

*Manure applied – 6.7 t/ha pig manure at Gnarwarre and Millicent (2.7% N, 1.3%P) and 3 t/ha chicken manure at Wallendbeen (3.3% N and 0.7% P).

Table 2. Site description for three hyper yielding canola sites in 2021.

Location	Region	Average rainfall	Elevation	Soil type	Available N at sowing	Organic Carbon	Colwell P	Applied P	Applied S
Gnarwarre	Southern Victoria	600 mm	190 m	Sodic Vertosol	70 kg/ha (0-100 cm)	1.4%	34 mg/kg	22 kg/ha	30 kg/ha
Millicent	South-East SA	710 mm	20 m	Organosol	173 kg/ha (0-10 cm)	9.7%	56 mg/kg	22 kg/ha	30 kg/ha
Wallendbeen	South-West Slopes NSW	680 mm	540 m	Red Ferrosol	340 kg/ha (0-90 cm)	2.0%	63 mg/kg	30 kg/ha	30 kg/ha

Results and discussion

Nutrition trials

In the spring nutrition trials, yield from the application of N alone (as urea) plateaued at 150 kg/ha at Gnarwarre and 75 kg/ha at Millicent (Table 3), with no yield increase from applied N at Wallendbeen which had a starting nitrogen of 340 kg/ha in the top 90 cm. In the winter nutrition trials, there was no yield response from applied N (urea) at either Gnarwarre or Wallendbeen (winter results not yet available for Millicent) (Table 4).

Despite high starting fertility levels and saturated N responses, there were still strong responses to applied animal manure over and above high rates of applied N. This response was observed in all spring trials and one winter trial, Gnarwarre. The yield response from manure in the spring trials ranged from 11% at Wallendbeen to 18% at Gnarwarre and in the winter trials from not significant to 17.5%.

It is exciting to see such strong yield responses from nutrition above the response from applied N (urea) alone, especially to yield levels above 6 t/ha. The challenge for the project team is to better understand the reason for the strong yield response from animal manure and how that can be cost-effectively implemented across the wider grains industry.

Table 3. Effect of nutrition (applied N and animal manure) on 45Y28 RR canola at three hyper yielding canola sites in 2021. Shaded cells denote highest yield in trial.

Treatment (kg/ha N)	Gnarwarre, Vic	Millicent, SA	Wallendbeen, NSW
0	4.0	4.9	4.5
75	4.5	5.6	4.4
150	4.9	5.8	4.6
225	5.1	6.1	4.5
300	5.0	5.8	4.5
225 + Manure	5.9	6.5	5.0
l.s.d. ($p<0.05$)	0.36	0.56	0.32

Table 4. Effect of nutrition (applied N and animal manure) on Hyola Feast CL canola at two hyper yielding canola sites in 2021. Shaded cells denote highest yields in the trial.

Treatment (kg/ha N)	Gnarwarre, Vic	Wallendbeen, NSW
0	3.8	3.8
75	3.9	3.7
150	4.1	3.6
225	4.1	3.8
300	4.0	3.7
225 + Manure	4.7	3.5
l.s.d. ($p<0.05$)	0.51	n.s.

GEM trials

There were large differences between varieties in the spring GEM trial, with a small response from management at Gnarwarre and Wallendbeen and no management response at Millicent. At Wallendbeen there was an average yield response of 0.3 t/ha in the high input versus medium and low input management. At Gnarwarre there was 0.3 t/ha higher yield in the high input compared to low input management.

At Millicent and Wallendbeen, 45Y95 CL was the standout variety with yield of 6.4 t/ha (averaged across management levels) (Table 5). This yield is 28% higher than the target yield of 5 t/ha and highlights what can be achieved with canola when seasons, variety choice and management all align. The addition of manure to improve crop nutrition may raise the bar even higher for canola and this will be tested in the GEM trial in future years. Further sample processing and data analysis will help understand the reasons behind the standout yield of 45Y95 CL at these two sites.

45Y28 RR was the highest yielding variety in the GEM trials at Gnarwarre where Clearfield varieties were not included. However, 45Y95 CL was the highest yielding variety in the adjacent spring screen trial.

In the winter GEM trials, Hyola Feast CL yielded higher than Hyola 970CL at Wallendbeen, but there was no yield difference between the two at Gnarwarre (Table 6). There was no yield difference between the management levels in the winter GEM trial at either site.

Table 5. Effect of variety choice on grain yield (averaged across three input levels) in Spring G x E x M trial at Gnarwarre, Millicent and Wallendbeen in 2021. Shaded cells denote highest yields in the trial.

	Gnarwarre Vic	Millicent SA	Wallendbeen NSW
ATR Wahoo⦇	3.5	3.3	3.6
HyTTec Trifecta	3.9	4.4	5.2
45Y95 CL	*	6.4	6.4
45Y93 CL	*	5.7	5.6
45Y28 RR	4.5	5.1	4.9
Condor XT	3.9	5.1	5.2
l.s.d. (p<0.05)	0.21	0.34	0.36

Table 6. Effect of variety choice on grain yield (averaged across three input levels) in Winter G x E x M trial at Gnarwarre, Millicent and Wallendbeen in 2021. Shaded cells denote highest yields in the trial.

	Gnarwarre Vic	Wallendbeen NSW
Hyola Feast CL	4.3	3.8
Hyola 970 CL	4.0	3.4
l.s.d. (p<0.05)	n.s.	0.34

Discussion and conclusion

There were three major stories to emerge from 2021 hyper yielding canola trials:

1. Yield levels were above even the most optimistic forecasts for canola. 6 t/ha should be a commercial target for industry and 7 t/ha will be the next frontier for research in these environments.
2. Nutrition is not just about applied urea. Strong responses from animal manure showed the importance of nutrition to push yields to new levels. This needs to be further investigated by the project team to determine if the yield response from manure is due to its slow-release nature or from nutrients such as phosphorus and potassium that are applied along with nitrogen in animal manure.

3. Like 2020, variety choice had a large impact on grain yield outcomes. 45Y95 CL was the standout variety across the three sites in 2021.

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Grower experience growing hyper yielding crops without irrigation - risk and rewards

Craig Marshall

Notes

Grower experience growing hyper yielding crops with irrigation - risk and rewards

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Notes

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