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AUGUST 2023

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

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GRDC 2023 Grains Research Update Welcome

Welcome to the July/August northern GRDC Grains Research Updates for 2023.

We are ecstatic to be able to offer growers and advisers from across the region the opportunity to attend a series of events that have been tailored with the latest grains research, development and extension (RD&E) to help boost their businesses and profitability.

One benefit of the COVID-19 pandemic is that it forced us to be more flexible with how we deliver this information to our key stakeholders, so while we're pleased to be able to facilitate plenty of face-to-face networking opportunities across this Updates Series, we have also committed to livestreaming and recording some of the events for anyone who is unable to attend in person.

The past 12 months have been a whirlwind for northern growers, with wet seasonal conditions continuing to impact productions during pivotal times on farm, including sowing and harvest.

We have heard some devastating stories from across the region of total crop loss and severe downgrades from untimely weather events, but we've also heard a lot of optimism from growers who have stepped into this year with high hopes for a productive season.

With that positive mindset comes a need to provide the latest information and advice from grains research and development. There's also been a significant push from the industry to make more informed management decisions to ensure productivity isn't impacted by the increasing costs of inputs.

We would like to take this opportunity to thank our many research partners who have gone above and beyond normal expectation this season to extend the significant outcomes their work has achieved to growers and advisers.

For more than a quarter of a century the GRDC has been driving grains research capability and capacity with the understanding that high quality, effective RD&E is vital to the continued viability of the industry.

Sharing the results from this research is a key role of the annual GRDC Updates, which bring together some of Australia's leading grains research scientists and expert consultants. We trust they will help guide your on-farm decisions this season and into the future.

To ensure this research answers the most pressing profitability and productivity questions from the paddock, it is critical the GRDC is engaged with and listening to growers, agronomists and advisers. To this end, GRDC has established the National Grower Network Forums and I encourage you to look out for these forum opportunities in your local area.

We feel more connected to the industry than ever when we are out in the regions and encourage you all to take any opportunity to engage with us to help inform our important RD&E portfolio.

If you have concerns, questions or feedback please contact our team directly (details on the back of these proceedings) or email northern@grdc.com.au.

Regards,
Gillian Meppem
Senior Regional Manager – North

NORTH STAR
GRDC Grains Research Update
Thursday 3 August 2023

North Star Sporting Club, North Star Rd, North Star, NSW 2408
Registration: 8:30am for a 9am start, finish 3:05pm

AGENDA

Time	Topic	Speaker(s)
9:00 AM	**GRDC welcome**	*GRDC*
9:10 AM	**Through the looking glass: Relative performance of farming systems over the short and long-term**	*Lindsay Bell (CSIRO)*
9:45 AM	**Legume contribution to the farming system - is it as much as we thought?**	*Jon Baird (NSW DPI)*
10:10 AM	**Optimising the nitrogen investment. Understanding and minimising N losses while feeding the crop what it needs. Address loss pathways and do we need to be feeding the system rather than individual crops**	*Mike Bell (UQ)*
10:50 AM	**MORNING TEA**	
11:20 AM	**Rust management in 2023 and beyond**	*Robert Park (Sydney Uni)*
11:50 AM	**How much did crown rot reduce yield in different varieties in 2021 and 22, and can observed differences in canopy temperature during grain fill help us to identify more crown rot resistant varieties?**	*Phil Davies (AGT Breeding)*
12:05 PM	**Strategies to reduce losses from fusarium crown rot**	*Steven Simpfendorfer (NSW DPI)*
12:20 PM	**Crown rot discussion** ○ How much of a problem did we plant this year? ○ New Syngenta product - expectations and stewardship ○ Management & varieties	*Steven Simpfendorfer (NSW DPI), Phil Davies (AGT Breeding) & Katie Slade (Syngenta)*
12:40 PM	**LUNCH**	
1:30 PM	**Farming system sustainability - grower and market expectations, risks and opportunities**	*Richard Heath (Australian Farm Institute)*
2:05 PM	**Finding profit in the face of increasing input and overhead costs, interest and land value**	*Kim Bowman (Agripath)*
2:40 PM	**SwarmFarm Robotics & sensors for spraying - a grower's experience.**	*Simon Doolin*
3:05 PM	**CLOSE**	

Contents

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Short and long-term profitability of different farming system strategies in the Border Rivers

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Key words

crop rotation, soil water, economics, costs, legumes, break crops

GRDC code

DAQ2007-004RMX

Take home message

- Farming system decisions – crop choice and soil water required for sowing can have a large influence on system profitability over the short- and long-term; differences of >$100/ha/yr occur regularly
- While the last 6 years have presented a diverse range of seasons, this period does not necessarily reflect the potential of alternative farming strategies to enhance long-term profitability
- Adjusting soil water triggers to sow crops can also provide advantages over conventional approaches, particularly during more favourable periods
- Systems involving alternative crop types can not only help manage biotic threats (e.g., diseases and weeds) but also be profitable compared with conventional systems
- Greater diversity of crops offered wider range of sowing windows allowing potential to make use of variable rainfall conditions
- Simulated predictions of relative profitability of the systems generally correspond well with those calculated from experimental data over the same period.

Introduction

The northern farming systems project has been examining how different farming system strategies impact on various aspects of the farming system since 2015. Across a diverse range of production environments, we have tested the impacts of changing:

A. the mix of crops grown by increasing the frequency of legumes or diversifying crop choices to provide disease breaks, or
B. the intensity of the cropping system, by either increasing it by reducing the soil water threshold to sow more crops, or by reducing it and only growing higher profit crops once the soil profile is full; and
C. the supply of nutrients provided to crops.

Despite now collecting data for over 6 years on each of these farming strategies, the full range of climatic conditions that are experienced across the region have not been captured. In particular, most sites have experienced extremely dry periods over the past 6 years, which is likely to bias or favour some particular farming systems. Simulation modelling can be useful to help explore how the different farming strategies might perform over the long term and under a range of climatic conditions. In this paper we compare APSIM predictions of system profitability over the long term with those for the period 2016–2021. This paper reports specifically on results from the two sites in the Border Rivers region, Billa Billa and Narrabri.

System simulations and estimates of profitability

The different farming systems were simulated from 1957 to 2021 using APSIM. Soil type used in simulations was that characterised at each location, and long-term climate data were sourced from the closest meteorological station. For each farming system at each location, the simulation was provided a list of crops (prioritised), their sowing window, and minimum soil water required to allow them to be sown. An example of the rules dictating crop choices at each of the locations here are outlined in Table 1.

Revenue, costs and gross margin for each crop were calculated using predicted grain yields and estimates of crop protection, non-N fertilisers and operational costs for each crop (see Table 2). Fertiliser inputs were simulated dynamically based on a crop budget targeting a median yield (N fertiliser was costed at $1.30/kg N), and fallow herbicide applications ($15/ha/spray) were also predicted using the model based on the number of germination events that occurred.

Table 1. Rules associated with crop choice, crops available and their plant-available water threshold required to be sown in the *Baseline* and modified farming system strategies at Billa Billa and Narrabri sites.

System	**Crop choice rules**	**Crops**	**Soil water threshold (mm PAW)**	
			Billa Billa (PAWC = 180 mm)	**Narrabri** (PAWC = 210 mm)
Baseline	No more than 3 winter cereals or sorghum in a row ≥2 yrs between chickpea	Wheat	90	110
		Barley	90	*
		Chickpea	90	100
		Sorghum	120	120
High legume frequency	*As above +* Legume every second crop	*As above +*		
		Faba bean	120	120
		Mungbean	80	110
		Soybean		120
Higher crop diversity	*As in Baseline +* ≥1 yr break after any crop ≥50% crops nematode resistant	*As above +*		
		Canola	150	120
		Durum	*	110
		Field pea	90	110
		Cotton	150	120
		Sunflower	90	*
		Millet	100	*
Higher crop intensity	*As in baseline*	Wheat	50	70
		Chickpea	50	50
		Barley	50	70
		Sorghum	100	90
		Mungbean	70	50
		Faba bean	90	100
		Canola	*	100
Lower crop intensity	*As in baseline*	Wheat	150	180
		Barley	150	180
		Chickpea	*	180
		Sorghum	150	180
		Durum	*	180
		Cotton	*	180

* Indicates that this crop was not available as an option in this system at this site.

Table 2. Assumed prices (10-year average, farm gate after grading/bagging/drying) and variable costs for inputs and operations (e.g., seed, pesticides, starter fertilisers, sowing, spraying) and harvest costs (for viable yields only) for each crop simulated.

Crop	Price ($/t product)	Variable crop Costs ($/ha)	Harvest costs ($/ha)
Wheat	269	175	40
Durum	335	175	40
Barley	218	175	40
Chickpea	504	284	45
Sorghum	221	221	55
Mungbean	667	276	55
Fababean	382	341	40
Field pea	382	341	40
Canola	503	351	70
Soybean	607	305	55
Maize	250	218	55
Cotton	1800[A]	774	280

A – Calculated on total harvest assuming 45% cotton lint turnout and 55% seed.

Because of the dynamic nature and range of different crops across these simulations, we generated only a single crop sequence over the simulated period. To allow analysis of the climate-induced variability, we aggregated the system gross margins over sequential 6-year periods; for example, from 1957–1962, 1958–1963 and so on. Hence, we were able to compare which simulations predicted would occur during the experimental period of 2016–2021 compared to 54 other 6-year periods, thus allowing us to examine how this period compared with longer-term conditions. We were also able to compare the relative performance of the different simulated systems over this period compared to their performance from our experimental data. Differences in how costs were calculated, with simulations assuming a set crop input cost, meant there was always a difference in the actual gross margins estimated from the model compared to the actual costs attributed in the experiments.

Crop sequences & frequencies in simulated systems

The simulation rules imposed (Table 1) resulted in some clear differences in the frequency and types of crops grown in each farming system. Despite quite different compliments of crops between the two locations, similar trends were seen at both.

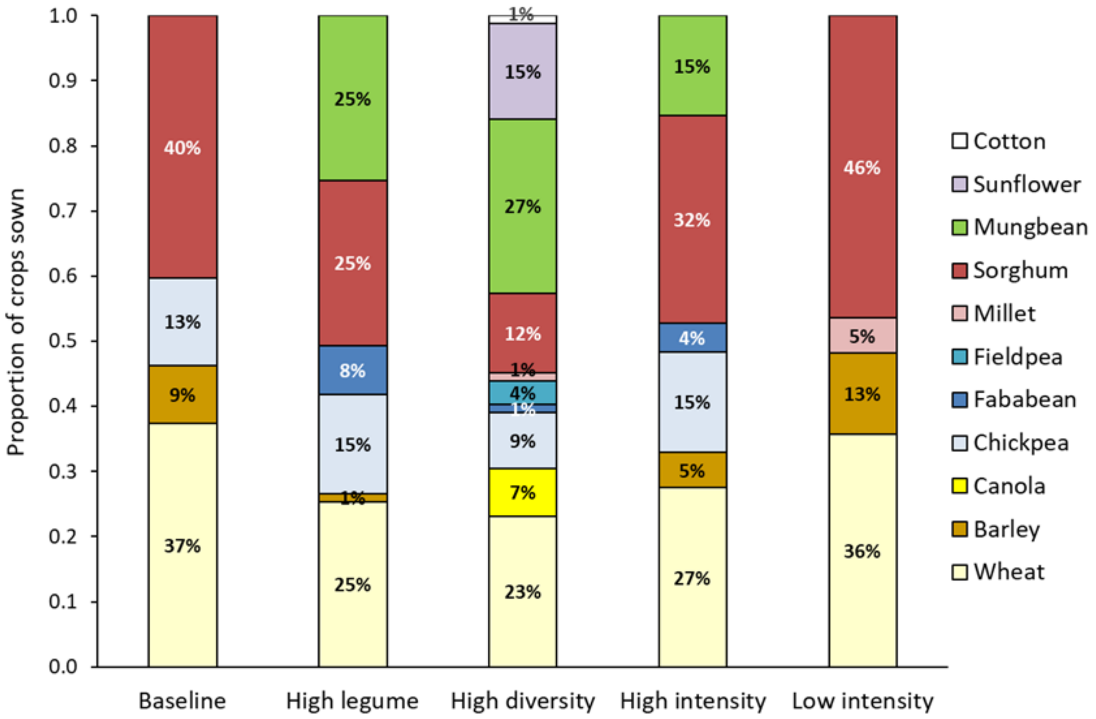
Billa Billa

At the Billa Billa site, the long-term simulation of the *Baseline* system resulted in an average crop frequency where a winter cereal was grown 1 in 2 years, a sorghum crop 2 in 5 years, and a chickpea crop 1 in 6 years (Figure 1). The *Higher legume* system with the addition of mungbean crops as an option, saw them now constitute ¼ of crops grown, replacing sorghum but also allowing an increase in crop intensity compared with *Baseline* (Figure 1). Faba bean crops replaced barley in the crop sequence (Figure 1).

In the *Higher crop diversity* system less winter crops were grown, with an increase in summer opportunity crops (mainly mungbean). The frequency of sorghum also dropped, replaced by mungbean, sunflower and occasional crops of millet or cotton. Canola was also incorporated, often instead of barley, and field pea replaced chickpea occasionally.

The *Higher intensity* strategy (*i.e.,* lower soil water thresholds to sow crops) saw an increase in crop frequency by about 0.3 crops/yr (1.04 to 1.35 crops per year), mainly due to the incorporation of mungbean double crop as an option.

The *Lower intensity* system (*i.e.,* a higher soil water threshold to sow crops) saw the crop frequency drop by 0.2 crops/yr and this included just cereal crops with chickpea not amongst the crop choices in this scenario.



Crops/yr	**1.04**	**1.20**	**1.23**	**1.35**	**0.82**
% Winter	56	48	44	46	51
% Cereal	87	52	37	65	100
% Legume	13	48	40	35	0
% Oilseeds	0	0	23	0	0

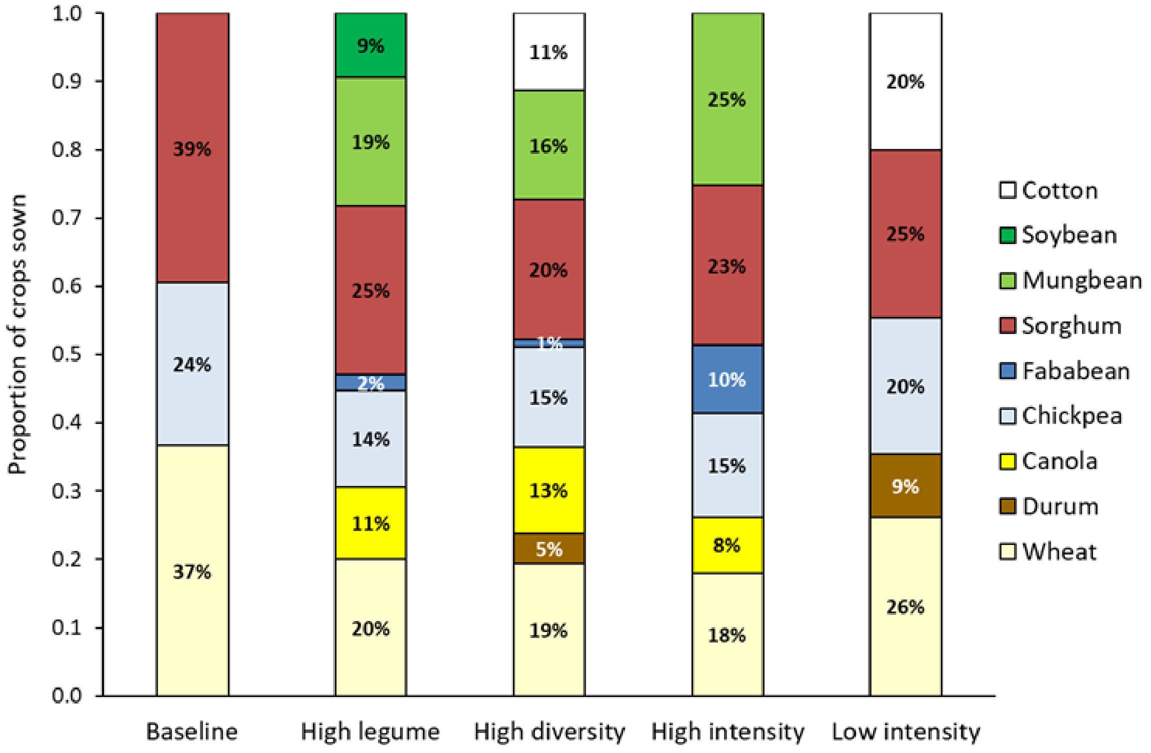
Figure 1. Cropping intensity (crops/yr) and the proportion of different crops simulated under different farming system strategies at Billa Billa over the long-term.

Narrabri

At Narrabri, the long-term simulation of the *Baseline* system resulted in an average crop frequency where a winter cereal was grown 2 in 5 years, sorghum 2 in 5 years and chickpea 1 in 4 years on average. The *Higher legume* systems resulted in additional mungbean and soybean crops and occasionally faba bean replaced chickpea in the crop sequence (Figure 2). The additional summer legumes also saw the crop intensity increase (by 0.2 crops/yr).

In the *Higher crop diversity* system sorghum was replaced by cotton at times and canola or durum wheat replaced some wheat crops. Again, in this system, the addition of mungbean saw the crop intensity increase compared to the *Baseline*.

The *Higher intensity* strategy saw a further increase in crop frequency by about 0.5 crops/yr, with additional mungbean or faba bean/chickpea crops sown as double crops, frequently in the system. The *Lower intensity* system saw the crop frequency drop by only 0.15 crops/yr – less than might be expected; cotton replaced some sorghum crops and durum replaced some wheat crops in the system. While the proportion of winter crop dropped from the *Baseline* system, the winter crop proportion remained around 50% under all the alternative cropping sequences.



Crops/yr	**1.10**	**1.30**	**1.32**	**1.64**	**0.95**
% Winter	61	47	52	51	55
% Cereal	76	45	44	41	60
% Legume	24	45	32	50	20
% Oilseeds	0	11	24	8	20

Figure 2. Cropping intensity (crops/yr) and the proportion of different crops simulated under different farming system strategies at Narrabri over the long-term.

Long-term predictions of system profitability

Figure 3 shows the range in average annual gross margin predicted over all the 6-year periods between 1957 and 2021 for the five farming system strategies. These are arranged from the lowest to the highest to show the probability distribution of these predictions as a result of climate variability (note prices are held constant at 10-year average values).

At both sites, the *Higher intensity* system (grey circles) frequently exceeds the profit generated in the *Baseline*, particularly under more favourable conditions. The *Low intensity* system (white circles) also performs relatively well compared to *Baseline*.

The analysis also shows that the systems that alter the mix of crop (*Higher legume* frequency or *Higher crop diversity*) achieve similar potential profits to the other systems in the lower profitability periods, but potentially offer significant upside under more favourable conditions. In particular, the *Higher crop diversity* system was able to offer a broader range of crop options to make use of seasonal rainfall and hence was better able to make use of additional crop opportunities when they occurred.

At Narrabri, the predicted profit achieved in the experimental period (2016–2021) reflects potential profitability in the lowest 15% of occurrences in all systems, and particularly low in the *Baseline*, *High* and *Low intensity* systems (lowest 5% of periods in the historical record). Based on these predictions this indicates that we would expect relatively small differences between the systems over this period, and that over other periods much larger differences in profit may have been generated.

In contrast, the period of 2016-2021 at Billa Billa, was predicted to represent a median outcome (i.e., 50th percentile) from the longer-term conditions in both the *Baseline* and *High intensity* systems. The *Low intensity* system ranked about the lowest third of periods, while the *High Legume* and *Higher diversity* systems over this period ranked about the 25th percentile and 15th percentile, respectively.

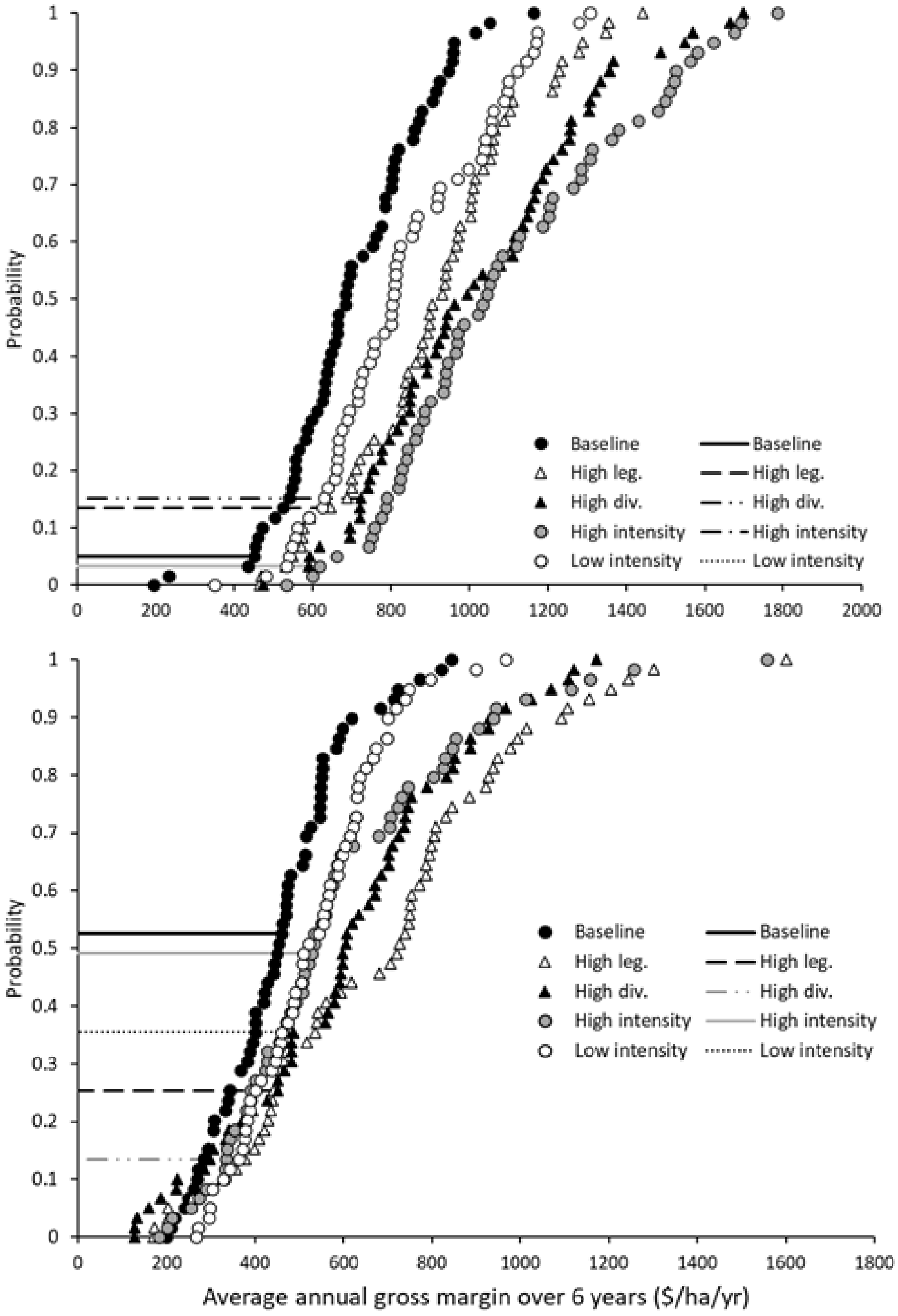


Figure 3. Distribution of simulated gross margins (average of 6-years) over 60 year period (1957–2021) of different farming systems strategies at Narrabri (top) and Billa Billa (bottom). Each data point indicates the outcome of a 6-year period and the lines indicate the predicted GM for the 2016–2021 period.

Short-term (experimental period) relative to the long-term

When the relative returns achieved from the various systems over the same 6-year period are compared to the *Baseline* system, this shows that the modified farming system strategies frequently produce higher average returns (Figure 3). At both sites, the *Higher diversity* and *Higher legume* systems were predicted to produce higher returns most of the time. At both sites, the *Lower intensity* systems had significantly lower profit in some periods, around one third of the time, but had advantage over the *Baseline* otherwise. The largest difference between the sites, was the large advantage predicted by *Higher crop intensity* strategy at Narrabri, while this was less common at Billa Billa, apart from about 15% of periods.

The modelled differences between the *Baseline* and the other systems for the experimental period (indicated by the larger symbols) is compared to the experimental data over the same timeframe (indicated by lines) in Figure 4.

At Narrabri over this period, both modelled and experimental data suggested the *Higher intensity* and *Lower intensity* systems would be ahead of the *Baseline*. The advantage predicted by the model was more ($200 and $450/ha/yr) than found in the experiments ($70 and $350/ha/yr), but the difference between them was consistent. On the other hand, the *Higher legume* and *Higher crop diversity* systems have performed less well experimentally compared to the *Baseline*, indicating that perhaps the long-term simulations may overestimate the frequency of their advantage. At Narrabri, a key contributing factor to this large discrepancy was a poor return from a frosted canola crop in 2016.

At Billa Billa, the *Lower intensity* and *Higher intensity* systems in the experiments generated significantly lower returns compared to the *Baseline*, much lower than was predicted by the model simulations. Experiments have had several failed (negative gross margin crops) that were not predicted to have hit critical sowing thresholds in the modelled scenarios, which goes some way to explaining this discrepancy. This has also induced a legacy impact on differences in subsequent crop productivity. On the other hand, the predictions of the relative profit for the *Higher legume* and *Higher diversity* systems compared to the *Baseline* align reasonably well with the observed experimental outcomes over the experimental period – showing that much better performance might be expected under a different experimental period.

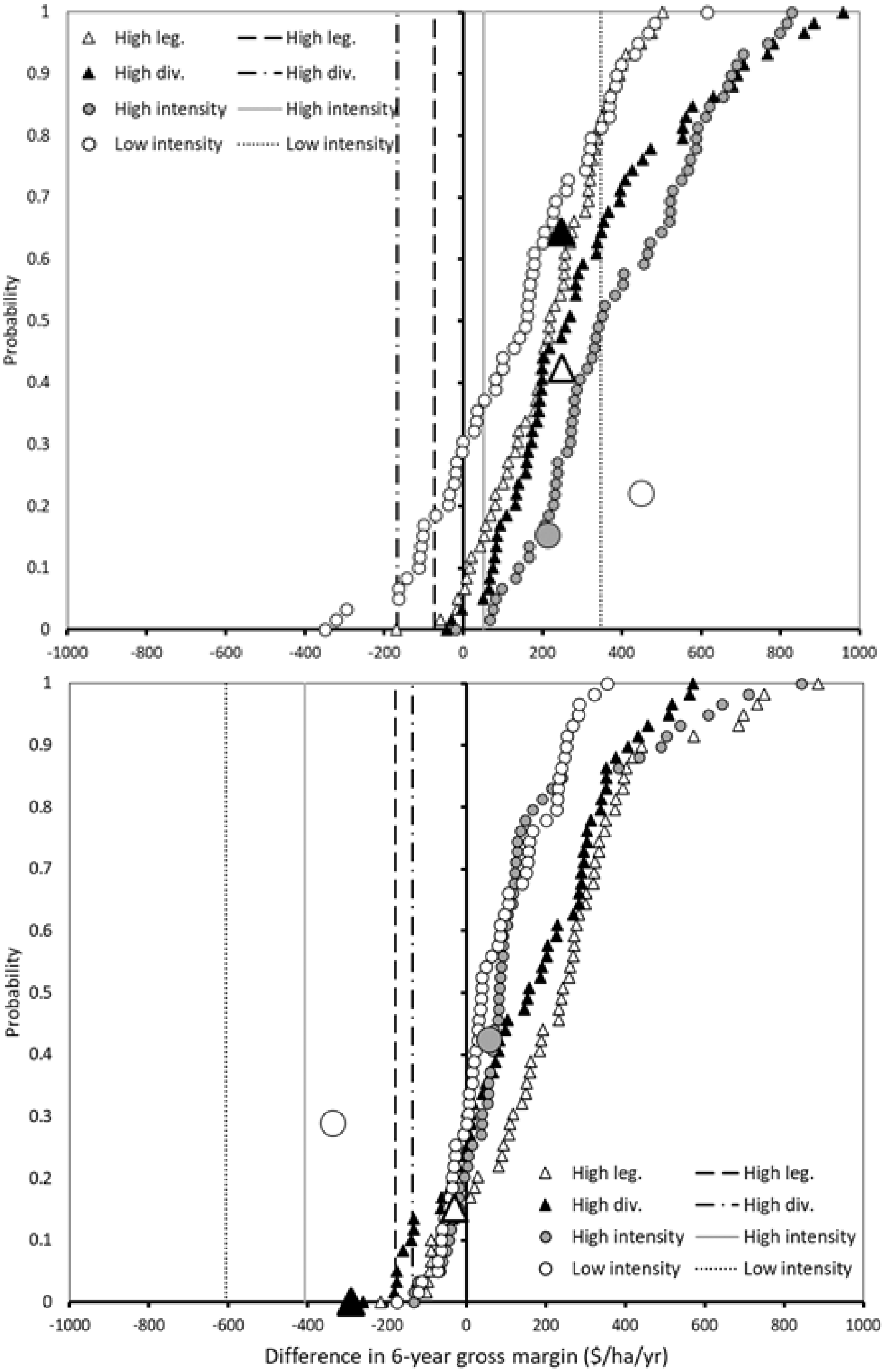


Figure 4. Difference in simulated 6-year gross margin between the *Baseline* and modified farming systems strategies at Narrabri (top) and Billa Billa (bottom) between 1957 and 2021. Small symbols show the difference in annual returns over the distribution of the 54 different 6-year periods, the large symbols indicate the difference for a simulation of the period of 2016–2021. The vertical lines indicate the differences measured in our experiments over this same period. Negative values indicate the alternative system has produced a lower GM than the *Baseline*, and vice versa.

Conclusions

Farming strategies or systems need to consider resilience and relative performance across the full range of likely climate variability. While our experimental work has captured a range of seasons, the modelling here adds further insight into how the various farming system strategies might perform over the long term. While some of the alternative systems have not proved to be advantageous and in some cases worse over this experimental period, the long-term analysis suggests there is potential to make use of a greater diversity of crops and alter our cropping intensity that could add significant upside under more favourable growing seasons. Further examination of the influence of price and input cost volatility and risk on these findings is required to understand how robust different strategies are, and the key factors that might influence this.

Acknowledgements

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

We acknowledge the various collaborators involved with collecting the experimental data and farmer collaborators for hosting the farming systems experiments across the region.

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Northern farming systems – long-term strategies and their legacy impact on nitrogen and phosphorus

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Key words

Legumes, cropping intensity, mineral N, nitrogen use efficiency

GRDC codes

CSA00050, DAQ00192

Take home message

- Incorporating more frequent legume crops boosted system gross margins at some sites, although grain nitrogen and potassium uptake and export is increased.
- Farming system yield improvements due to growing higher frequency of grain legumes are variable across the research sites.
- A higher nutrient strategy boosted mineral N levels post harvest compared to the Baseline system and also saw increased cycling of N in subsequent fallows meaning most of (i.e. > 50%) the additional N was recovered.
- High cropping intensity restricts the accumulation of mineral N, forcing a decline to critical levels, especially when multiple crops are grown back-to-back.
- Higher cropping intensity systems need more robust nutrient application strategies to maintain fertility and crop nutrient supply.
- Long fallow lengths, even during low rainfall periods, allow the build-up of mineral N, boosting yield potential and offsetting the need for fertiliser N inputs.

Introduction

Farming systems need to evolve to manage the challenges of climate variability, increasing soil-borne pathogens, herbicide resistance and problem weeds, declining soil fertility and increasing reliance on costly fertiliser inputs. A major challenge for our farming systems is to match crop nutrient supply and demand under variable growing conditions and maintain our soil's underlying fertility in the long-term. The northern farming systems project investigated long-term implications of several farming strategies that are likely to influence these processes. Particularly how different fertiliser application strategies and using more legumes in the farming system affect requirements for N inputs.

The project investigated the performance of various system modifications compared to the local 'best management practice' (*Baseline*) at seven research sites spanning the northern grain growing region. The modifications included the application of more nitrogen and phosphorus fertiliser, incorporating greater frequency of grain legumes (growing legumes every second crop) and varying degrees of cropping intensity (planting crops with more or less stored water; *Lower intensity* and *Higher intensity)*. These modifications followed base rules, where crop selection was triggered on planting soil water, previous crop type and sequence, and current disease levels (determined by soil predicta B and plant diagnosis).

Experiments commenced in 2015 at seven locations: a core experimental site comparing 38 farming systems at Pampas near Toowoomba, and a further six regional sites that included six to nine locally relevant farming systems at Emerald, Billa Billa and Mungindi in Queensland and Narrabri, Spring Ridge and Trangie covering red and grey soils in NSW.

This paper will focus on three farming systems research sites – Billa Billa, Narrabri and Spring Ridge- and compare the following farming systems treatments and their impact on nutrient balance and system fertility.

1. *Baseline* – derived to represent local best management practice where the selection of crops and their management were designed in partnership with local grower panels and analysed as the control treatment. Crops were planted at or above soil moisture of 50% plant available water (PAW) and fertiliser N and phosphorus (P) rates were applied to meet the demand of a 50th percentile crop yield.
2. *Higher nutrient system* — contains identical crop sequence to *Baseline* but with higher N and P fertiliser rates applied to meet the demands of a 90th percentile crop yield.
3. *Higher legume* system where at least 50% of planted crops are legumes, crops were planted at or above 50% PAW. Legume crops did not have N fertiliser applied and P fertiliser rates were calculated to meet export rates, and fertiliser N and P rates were applied to meet the demand of a 50th percentile crop yield for non-leguminous crop.
4. *Higher cropping intensity* – planting frequency determined by soil water. This system is activated when soil water is 30% or higher.
5. *Lower cropping intensity* – planting trigger is determined by greater soil water levels (80%). High value crops are selected to ensure greater economic returns are achieved from optimum planting water triggers.

Over the six years of the project (2015 to 2021), seasonal conditions at regional experiment sites have varied, including extremes of drought and local flooding, as well as 'average' and 'favourable' seasons. The research sites selected had varied starting characteristics, as Billa Billa began with around 300 kg N/ha, while Narrabri's available mineral N was 145 kg N/ha (**Error! Reference source not found.**). Billa Billa also had the highest organic carbon (OC) content with 1.25% (0-10 cm depth) compared to Spring Ridge (1.09%) and Narrabri (0.83%).

Table 1. Starting soil characteristics at the three focus sites

Site	Mineral N (kg/ha)	% Clay		Organic Carbon (%)		pH ($CaCl_2$)	
	0 – 90 cm	*0–10 cm*	*10–30 cm*	*0–10 cm*	*10–30 cm*	*0–10 cm*	*10–30 cm*
Billa Billa	366	34	44	1.25	0.70	6.4	7.6
Spring Ridge	199	58	60	1.09	0.66	6.2	7.4
Narrabri	145	50	53	0.83	0.55	7.5	8.1

Long-term system trends

1. Incorporating 'more' legumes into our systems

Grain legumes have become an important crop option for northern grain farming systems. The benefit of improved agronomy and breeding resulted in exceptional yields, reducing the reliance on fertiliser use and the periodic high commodity prices have contributed to incorporating legumes in current cropping sequences. The Farming System project investigated this further by growing a legume crop every second crop or 50% of total planted crops in the *Higher legume* system. The

Higher legume system achieved similar system yields to the *Baseline* system at the majority of farming systems sites.

Generally, there was an economic benefit with the *Higher legume* system over the *Baseline* system, especially at Narrabri and Spring Ridge. This is attributed to the good legume grain yields and higher grain values of pulse crops, often surpassing the gross returns from cereals in the same season. One note is that input costs were slightly increased due to additional seed costs and greater requirements for crop protection (e.g. fungicide applications). However, the economic risk of growing legumes (such as chickpea and fababean) in modern cropping systems is low and potential economic returns are high compared to systems based solely on cereals.

The *Higher legume* system had higher plant N compared to the *Baseline* system, reflecting their higher N content. However, we have struggled to find a significant improvement in available soil mineral N prior to subsequent crops and thus fertiliser budgets for most cereal crops post a legume crop were equivalent to the *Baseline* system. Compared to *Baseline*, N export in grain was higher for the *Higher legume* system, and N left in plant residues (i.e. above ground Plant N - Grain N exported) was lower in *High Legume* systems. This was a function of the high harvest indexes achieved with good agronomy and modern cultivars for most legume crops. The approach for N budgeting here involves using mineral soil N (nitrate-N and ammonium-N) as the basis for crop fertiliser budgets, however, a more complex budgeting tool that includes crop uptake and export may improve fertiliser recovery and better account for the legume organic material (Dowling, 2023). Of the three sites reported in this paper, Billa Billa, did have sampling dates where the Higher legume system trended with higher amounts of soil mineral N compared to the *Baseline* system. These spikes in mineral N were attributed to a higher accumulation of mineral N during the fallow periods, resulting in differences of up to 150 kg N/ha.

Higher legume systems elevated nitrogen use efficiency (NUE) at the system scale, calculated as the accumulated exported N against the change in soil mineral N and fertiliser inputs. The *Higher legume* system resulted in a mean NUE of 1.81 kg grain per kg of N across the three sites, compared to the *Baseline* system (1.43 kg grain/kg N). The improvement in the system NUE was attributed to the N fixation of the legumes, and the high conversion of plant N to grain N (N harvest index). Highlighting that although the project did not reduce fertiliser N application rates, there is still improved N use efficiency within the *Higher legume* system.

Table 2. Farming system productivity, nutrient balance and efficiencies at Narrabri, Spring and Bill Billa between 2015 and 2022

	Narrabri					**Spring Ridge**					**Billa Billa**				
System	**Baseline**	**Higher Nutrient**	**High Legume**	**High Intensity**	**Low Intensity**	**Baseline**	**Higher Nutrient**	**High Legume**	**High Intensity**	**Low Intensity**	**Baseline**	**Higher Nutrient**	**High Legume**	**High Intensity**	**Low Intensity**
Productivity															
Grain yield (t/ha)	19.8 ±0.6	20.3 ±0.5	21 ±0.7	22.8 ±0.4	11.1 ±0.7	27.3 ±0.8	27.1 ±0.8	23.8 ±0.4	26.1 ±0.6	13.4 ±0.7	24.8 ±0.6	24.7 ±0.6	17.6 ±0.5	20.9 ±0.4	13.3 ±0.8
Dry matter (t/ha)	55.6 ±1.2	52.9 ±1.4	59.0±1.5	77.5±0.9	31.0 ±1.9	77.3 ± 0.9	76.4 ±0.9	75.2 ±1.9	76.6 ±1.1	35.5 ±0.9	67.1 ± 1.4	69.9 ±1.4	51.5 ±1.2	67.9 ±1.1	47.9 ±1.6
Gross margin (S/ha) 2015-21	3775	3097	3269	4049	5801	4994	4812	5454	5903	6318	5246	4972	4201	2831	1714
Nitrogen use															
N fertiliser (kg N/ha)	234	533	234	437	138	301	440	321	330	181	29	84	30	29	21
Exported N (kg N/ha)	451 ±13	453 ±14	578 ±21	486 ±5	319 ±25	586 ±15	606 ±15	708± 24	603 ±17	377 ±12	522 ±29	552± 24	406±18	326 ±17	285±17
Plant N uptake (kg N/ha) 2019-22	601 ±17	639 ±24	701 ±55	698 ±11	417 ±44	530 ±11	476 ±27	890 ±71	711 ±18	376 ±21	444 ±24	475 ±28	356 ±30	551 ±25	367 ±51
System N balance (kg N/ha)	-217	80	-344	-49	-181	-285	-166	-387	-273	-196	-493	-468	-376	-297	-264
Nitrogen use efficiency															
System N use efficiency (kg grain N/kg N)	1.36	0.77	1.86	0.92	3.30	1.31	1.04	1.68	1.38	1.28	1.61	1.74	1.89	1.02	1.32
System N use efficiency ($/kg N)	16	6	14	9	42	17	11	17	18	35	181	59	140	98	82
Phosphorus use															
Applied P (kg P/ha)	42	66	48	59	39	50	52	44	61	39	47	82	51	44	34
Exported P (kg P/ha)	61 ±1.4	65 ±1.7	79 ±2.4	81 ±1.2	52 ±3.7	74 ±2.5	76 ±2.6	75 ±2.7	72 ±2.4	41 ±3.1	92 ±6.3	92 ±6.6	64±5.6	55 ±4.1	46 ±4.4

Note: exported N (or P) = grain dry weight x grain N (or P) %, system N balance = applied N - exported N, system NUE = exported N/applied N + change of mineral N, system GM NUE = gross margin/ applied N + change of mineral N.

2. Applying higher amounts of fertiliser to maximise yield

The *Higher nutrient* system aimed to test the long-term implications of fertilising each crop to maximise its yield potential and how this translates into fertiliser use and soil fertility. The *Higher nutrient* system is identical to the crop choice and sowing date of the *Baseline* system, with the only difference being that crops are fertilised to meet a 90-percentile yield expectation rather than the 50th percentile for the *Baseline* system. The distinct fertiliser strategies in crop budgeting led to differing application rates between the two systems. On average across the three sites, the *Higher nutrient* system applied double the amount of fertiliser N compared to the *Baseline* system, with the cumulative system rates ranging between 299 (Narrabri) and 55 kg N/ha (Billa Billa).

In the *Higher nutrient* systems, the fertiliser inputs balanced or exceeded crop requirements in most seasons for both Narrabri and Spring Ridge. This resulted in a positive or neutral system N balance (where system inputs matched systems outputs) and maintained higher soil mineral N status over this time. We found the application of extra nitrogen fertiliser could take up to two cropping seasons to develop a significant difference in soil mineral N from the *Baseline* system, but once that difference was established, it was maintained until it was used by a high-yielding crop. It is unclear if additional N was lost from the system by denitrification due to extreme weather events, but there was one notable event at Spring Ridge (September 2019) where mineral N levels decreased significantly during a fallow which received heavy rainfall.

We found no additional grain yield between the Baseline and Higher nutrient systems over the first 6 experimental years at the three sites. This was across various seasonal conditions, including seasons with above average rainfall where yield potential was high and drier seasons where crop demand was low. Other factors may contribute to the lack of crop response to the additional fertiliser, including inherited soil fertility and even underlying soil constraints, such as subsoil sodicity (present at the Narrabri and Billa Billa sites).

3. Higher cropping intensity impact on soil fertility

Increasing levels of cropping intensity, also impacted soil fertility, soil N dynamics and fertiliser use. *Higher intensity* systems involved planting crops with a lower soil water as the trigger for sowing (e.g. 30% of a full profile), compared to the *Baseline* which required a moderate threshold (e.g. 60% of a full profile).

The main influence of these cropping intensity effects were: 1; the higher cropping intensity reduced the fallow period, therefore less time to accumulate mineralised N between crops, hence there was a greater reliance on fertiliser N to balance the crop nutrient budget, and 2; the higher cropping intensity, because of growing more crops and biomass had greater drawdown (use) of soil mineral N due to higher overall crop nutrient uptake, and greater export of N.

Because the cropping decisions are driven by soil water accumulation, the ultimate cropping intensity will naturally vary due to environments and seasonal weather conditions. During the project life, we have witnessed severe drought conditions through to growing seasons with rainfall exceeding 90th percentile levels. Generally, mineral N has continuously accumulated during dry conditions with the longer fallow periods, building soil fertility for crop use when the seasons allow. In contrast, when conditions improved and the *Higher intensity* system implemented several back-to-back crops, mineral N was utilised by crops preventing significant soil mineral N accumulation within the system.

Additionally, when the *Higher intensity* system increased to 1.5 to 2 crops per year during high rainfall periods, the export rates of nutrients outweighed the system's potential to maintain mineral N levels. Even with greater application of fertiliser N and phosphorus (P) the export rates of nutrients were higher, and the mineral N declined drastically during these periods. Further pressure on this system was the stratification of mineral N and P, as the subsoil became ‘mined’ and deficient in plant available nutrients. The implication is that to counter this problem, subsoil application of fertiliser is required, but the *Higher intensity* system has minimal fallow time in which to perform the operation without impacting the next crop.

An early observation of the Higher intensity system is the greater production of plant biomass and lower harvest index. At Narrabri, there was a 22 t/ha extra dry matter production in the *Higher intensity* compared to the *Baseline* system, and 46 t/ha extra in the *Higher intensity* than the *Lower intensity* system over the same period. This extra biomass may benefit building soil organic carbon, and at Narrabri we have seen OC content increase from 0.76% to 0.91% since 2015 in this system. The higher turnover of organic material may aid the system’s soil health long term and will increase the rate of N mineralisation and, therefore N available to future crops.

4. Greater mineral N accumulation within the Lower cropping intensity system

The *Lower intensity* system employed higher water planting triggers (> 80% of a full profile) that forced longer fallow periods and less time in crop. The advantage of the longer fallow was the system’s ability to cycle, retain and accumulate higher levels of mineral N. This led to less need for fertiliser to meet crop nutrient budgets, reducing the system’s reliance on nitrogen fertiliser application. The potential downside of this is that the extra nutrients available to crops comes at the expense of soil organic carbon breakdown to provide this mineral N. This was observed at Billa Billa, where the OC decreased from 1.25% in 2015 to 1.1% in 2019, while the *Baseline* and *High intensity* systems maintained OC at 1.25%

When production is optimised, similar to what happened at Narrabri, nitrogen use efficiency (NUE) is improved in the *Lower intensity* system compared to the *Baseline* (Table 2). When high value crops are grown to take advantage of the ideal growing conditions into the cropping sequence, such as at Narrabri and Spring Ridge, the *Lower intensity* doubled the economic NUE ($/kg N) over the Baseline system.

This general improvement of NUE provides greater scope for reducing input costs and reducing the potential losses of environmentally harmful gaseous emissions due to high fertiliser application. For western farming systems that inherently contain numerous ‘dry’ periods where planting varies and soil moisture accumulation may take longer than expected, these findings show that low intensity systems can adapt to variable seasonal conditions. While there might be long fallow periods (while producers wait for soil moisture to accumulate), when planting triggers are reached, soil fertility is high and the system is primed to produce high yields without the reliance of large applications of fertiliser.

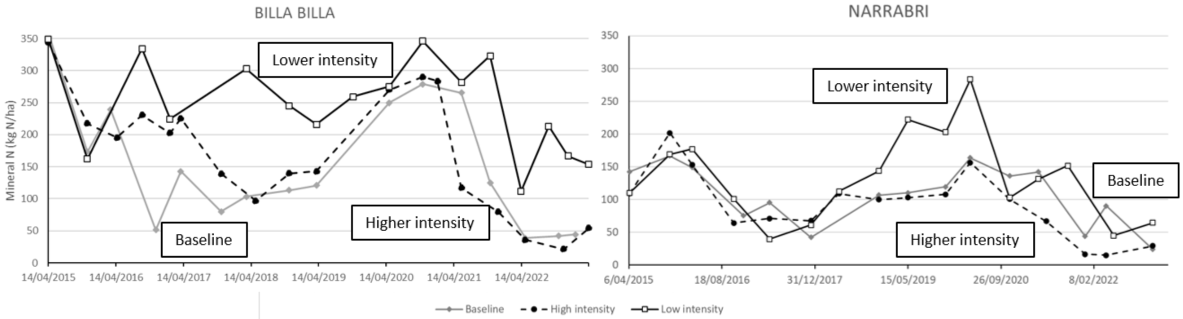

Figure 1. Time course dynamic levels of mineral N (nitrate-N and ammonium-N) at Billa Billa and Narrabri for the Baseline (grey line), Higher intensity (broken black line) and Lower intensity systems (black line).

Conclusion

Ensuring adequate soil fertility and health is paramount to maintaining sustainability and long-term farming system productivity. The project identified trends and legacies of implementing a number of nutrient management strategies and cropping scenarios across sites in the northern grains' region. Implementing these strategies resulted in various legacies from increased legume frequency with greater system N use, but a declining trend for soil mineral N. While higher cropping intensity led to higher grain productivity but at the expense of high fertiliser use and again, reduced soil mineral N.

The variability in weather conditions and seasonal outlook means Australia's grain producers need to implement a dynamic farming system that includes flexibility and resilience to a changing environment. The project implemented modified farming systems to improve industry understanding of the legacies and impacts of our systems to improve productivity and sustainability.

References

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Optimising the nitrogen investment. Understanding and minimising N losses while feeding the crop what it needs

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Key words

fertiliser N, N use efficiency, residual value, N losses, N redistribution

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Take home message

- Achieving co-location of water and available N within the soil profile are keys to maximizing efficient use of water and fertiliser N in rainfed grains cropping systems
- Seasonal rainfall (both amount and distribution) is the dominant factor driving fertiliser N use efficiency and environmental losses on clay soils employing these cropping systems
- This makes it difficult to successfully employ fertiliser N management strategies that attempt to manipulate N availability to match individual crop demands in individual seasons
- Increasing the mineralizable soil N pool through enhanced soil organic matter and greater legume frequencies in crop rotations, combined with manipulation of fertiliser rate, timing and mode of application, offer the best opportunities to improve system N use efficiency
- Soil sampling remains an important tool to determine when and how fertiliser N management strategy should change in response to particular events and wetter or drier seasonal conditions.

Background

The processes that determine the availability, loss and cycling of nitrogen (N) in soils are complex, representing the interactions between management practices, the soil microbial community and seasonal conditions – especially temperature and moisture availability. These processes and interactions are illustrated in the diagram developed by Barton et al. (2022) and shown in Figure 1.

The N fertility of a soil is determined by the initial size of the soil N pool (a product of soil type and native vegetation), modified by the net effects of land management that have impacted on that starting condition. In the case of land opened to cropping, those management effects will be cumulative soil N inputs (fertilisers, fixed N in legumes, plant and animal residues, atmospheric deposition) minus the cumulative removal of N in harvested produce (forage, grain) and losses of N to the environment. The soil N pool is dominated by N stored in organic matter, which is itself not available for crop N uptake until microbial activity has broken down (‘mineralised’) that organic matter to release ammonium (NH_4) and nitrate (NO_3) N that are taken up by plants. These forms of N (collectively called mineral N) represent a small but critical fraction of the total soil N pool that can increase or decrease quite rapidly in response to prevailing conditions. These mineral N forms are typically found dissolved in soil water or held electrostatically to positively or negatively charged sites on clays and organic matter.

In Figure 1, two of the key parts of the soil N cycle have been highlighted and will be the focus of this paper:

1. the soil-plant N pool itself (within the solid yellow hexagon), where N is cycling between the organic and inorganic fractions under the influence of microbial processes, fertiliser N inputs and plant N uptake; and
2. the important processes by which N is lost from the soil N pool to the environment (in the dashed boxes). It is important to note that except for soil erosion, environmental losses are

almost exclusively from the mineral N pool (especially NO_3-N), and so the size of the mineral N pool at times when conditions favour different loss pathways will be critical. We will discuss these pools and processes and the key rate controlling factors, and then move onto discussing how the net effects of these processes, interacting with crop management, can influence crop N uptake and the efficiency of fertiliser N use in cropping systems.

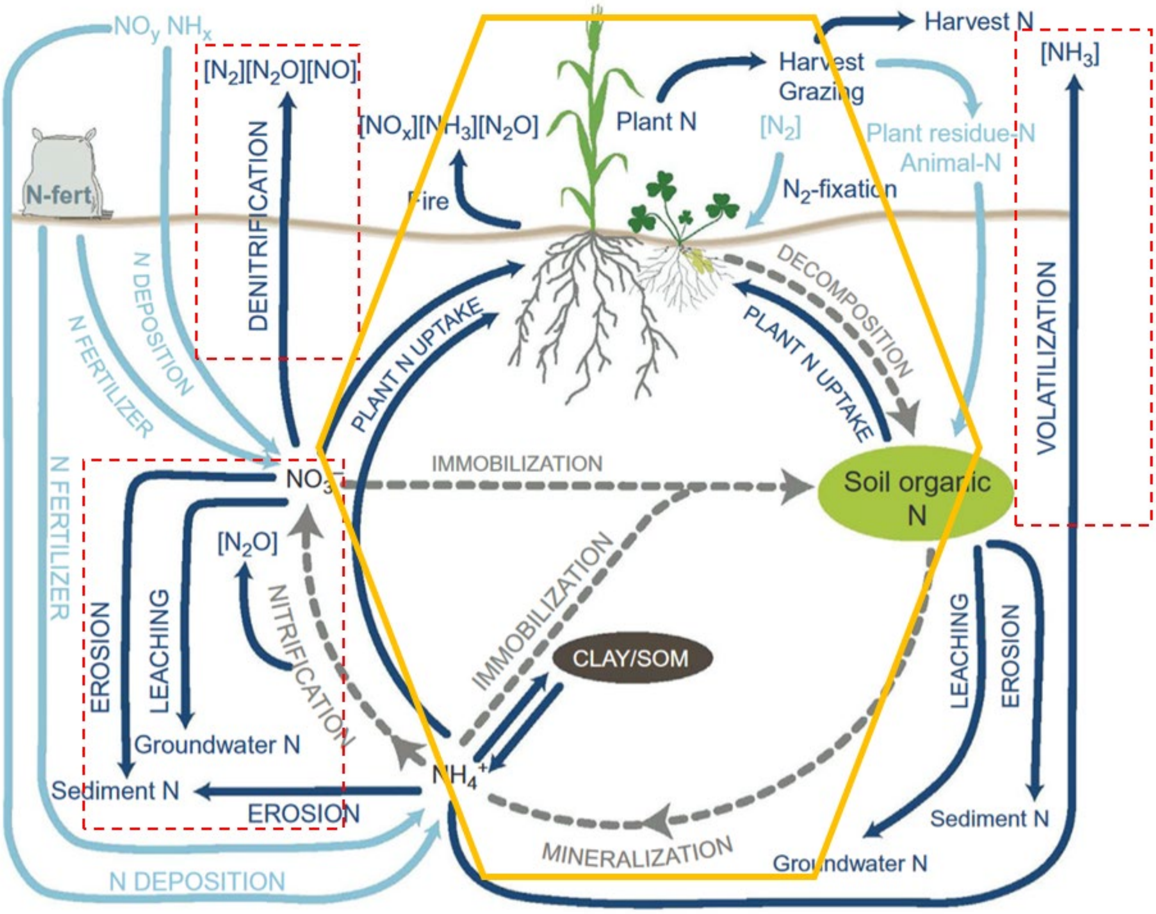

Figure 1. Terrestrial nitrogen (N) cycle showing pathways responsible for the supply and loss of N in soil and plants. Dashed lines indicate soil N transformations. Gases appear in square brackets.
(Reproduced from Barton et al. 2022)

Cycling of N in the soil and availability to plants

The net gain or loss of soil organic matter is a function of the relative rates of addition of organic inputs (crop residues, manure) and the breakdown/mineralisation of these fresh materials and the resident soil organic matter by microbes that exploit these as sources of nutrients and energy. Soil organic matter acts as a reservoir of organically-bound N that must be mineralized to plant available forms [e.g. NH_4^+ and NO_3^-] before agricultural crops can access this stored N. The size of the mineralizable organic N pool and the rate of mineralisation relative to crop demand will determine the ability of this pool to meet crop needs. When the Vertosol soils of northern NSW and Qld were ‘new’ to cropping, the pool of soil organic matter was high and mineralisation of soil organic matter was able to generate enough surplus mineral N to meet, or exceed, crop N demand. Crops rarely responded to fertiliser N inputs. However, as soil organic matter contents have declined under cropping the pool of mineralizable organic N has declined, microbial mineralisation is increasingly unable to produce enough surplus mineral N to meet crop demand, and fertiliser N is increasingly needed to meet the N supply deficit. Application of N fertiliser can rapidly increase the pool of plant-available N, but there are a number of soil and environmental factors that determine whether that increase will result in more plant N uptake in the short term.

Soils in which there is a reduced pool of labile organic matter and mineral N availability can result in conditions where the microbial community can be a net consumer of mineral N (e.g., from fertiliser applications) rather than the source of a mineral N surplus. This microbial competition for mineral N may be sporadic (e.g., after the return of cereal crop residues with low N content), resulting in short term immobilisation of mineral N in organic matter and microbial biomass that is typically reversed over longer time frames. However, these shorter-term dynamics can be particularly important in terms of meeting the mineral N requirements of a crop at critical crop growth stages. The timing of fertiliser N application relative to the demand for N by the plant, combined with the relative rates of N immobilisation and mineralisation and the environmental conditions that influence the rates of microbial processes and environmental losses (e.g., soil moisture), will collectively determine whether that applied N will be actually taken up by plants, and when.

Losses of N to the environment

Essentially, nitrogen can be lost from cropping soils via downwards, sidewards or upwards movement. Nitrate N primarily moves down into the soil profile with soil water infiltration, with the rate and depth of movement a function of the rate of movement of the wetting front and the concentration of NO_3 in the soil solution. This process is called leaching. In lighter textured soils, especially those with low water holding capacities, wetting fronts and associated leaching of NO_3-N can be rapid and extend below the depth of the crop root zone. In this case, leaching can result in loss of plant available N, and depending on the connectivity of that deep water infiltration with drainage lines or water tables, can result in negative effects on environmental water quality. In other situations (e.g., in soils like the black and grey vertosols on which much of the northern cropping industry is based), this leaching of N is unlikely to penetrate beyond the depth of crop root access and is a critical success factor for cropping systems that rely on stored soil water rather than in-season rainfall. Crops extracting stored soil water during dry periods need access to N (and other nutrients) to continue to produce dry matter and grain.

Sideways movement can occur rapidly through erosion of topsoil rich in organic matter during intense rainfall events, or more slowly through lateral subsoil movement of nitrate-N in soil water. The widespread adoption of minimum or no tillage and the associated maintenance of surface cover in grains cropping, combined with the relatively dry seasonal conditions, means lateral N losses are typically minor.

Gaseous N losses to the atmosphere are of much greater significance and can occur through two main pathways viz. volatilisation of ammonia or denitrification of nitrate as dinitrogen (N_2) or nitrous oxide (N_2O).

- Ammonia volatilisation is a process that primarily occurs when urea or ammoniacal N fertiliser (DAP, MAP or UAN) is broadcast onto the soil surface without incorporation, or if shallow fertiliser bands are not covered with soil and left exposed to the air. Losses typically occur soon after fertiliser is applied to soil, with a range of factors influencing the actual amount of N lost. Simple models such as the one published by Fillery and Khimashia (2015) use a maximum potential loss figure (65% of applied N when urea is applied to moist soil) that is discounted according to factors such as clay content, soil pH, fertiliser rate, rainfall in the week after application, presence of a crop canopy and the placement of the fertiliser. This model was reasonably effective at predicting volatilisation losses from top-dressed urea fertiliser applied on vertosol soils in northern NSW (Schwenke 2014). In those studies, losses averaged 11% (5–19%) of applied N when urea was broadcast onto the surface of fallow paddocks, 5% (3–8%) when applied in a growing wheat crop (mostly when soils were dry), and as much as 27% when applied to pasture. In the latter situation, there had been little rain after spreading to wash the urea into the soil. This resulted in a significant proportion of the urea being suspended on the pasture thatch rather than in direct contact with soil particles, greatly increasing the risk of volatilisation loss. Wind-speed after fertiliser application was a critical factor determining the amount of N lost over time in all studies.

Schwenke (2021) recently concluded that ammonia (NH_3) volatilisation loss will be low when urea is broadcast onto dry, clay soil under non-humid, non-windy conditions followed within a few days of application by sufficient rainfall to move the urea/ammonium into the soil. In contrast, NH_3 loss will be higher when urea is applied to wet soil followed by dry, windy conditions with little or no follow-up rainfall. However, while recent laboratory studies suggest that risks of volatilisation loss may be greater on lighter textured soils with lower clay contents, there is real uncertainly extrapolating the losses from the NSW field studies to other soil types and climatic conditions.

- Nitrate denitrification losses can be large but require the simultaneous occurrence of low soil oxygen availability (e.g., when soil is waterlogged for an extended period, or in wet soils with a high level of microbial activity), high soil NO_3-N concentration (soon after soils have been fertilized) and readily available (labile) carbon to support an active microbial community. Clearly these set of circumstances do not coincide every year, but when they do (e.g., 2011, and more recently in 2022), denitrification losses can be high. Rates of loss are typically higher when soils are warmer in spring and summer rather than late autumn and winter.

  Unlike ammonia volatilisation, it is more difficult to quantify total N losses due to denitrification. This is because variable proportions of those losses can occur as N_2 or as N_2O. While direct measurement of N_2O losses under field conditions is possible, losses as N_2 are far harder to quantify due to the high background atmospheric N_2 concentrations (~78% of the atmosphere). There are reports in the literature of the ratio of losses as N_2:N_2O being anything from 1:1 to 70:1, depending on soil and environmental conditions. To put this uncertainty into perspective, measurements of annual N_2O losses at fertilizer N rates delivering maximum yield of 1–2 kg N_2O-N/ha could be indicative of total denitrification losses ranging from negligible to >100 kg N ha^{-1}.

  The use of N fertilizers labelled with the stable ^{15}N isotope allows the fate of applied N to be studied in detail (e.g., Figure 2), with the difference between fertilizer N applied and that recovered in the plant (tops and roots) or remaining in the soil after harvest representing fertilizer N lost to the environment. In soils where fertilizer N has been banded below the soil surface and leaching losses are minimal (such as in the alkaline vertosols), most of the unaccounted-for fertilizer N (20–40% of N applied – Rowlings *et al.* 2022) is presumed to have been lost via denitrification. When cumulative N_2O emissions data are available (such as in 12 of the 18 NANORP sites in Qld and NSW where ^{15}N was used), the ratio of total N lost (from ^{15}N results) to that lost as N_2O can be used to estimate the ratio of N_2 to N_2O for these summer cropping systems. Direct measurement of these N_2 and N_2O losses is being undertaken in the project "Predicting nitrogen cycling and losses in Australian cropping systems - augmenting measurements to enhance modelling" UOQ2204-010RTX.

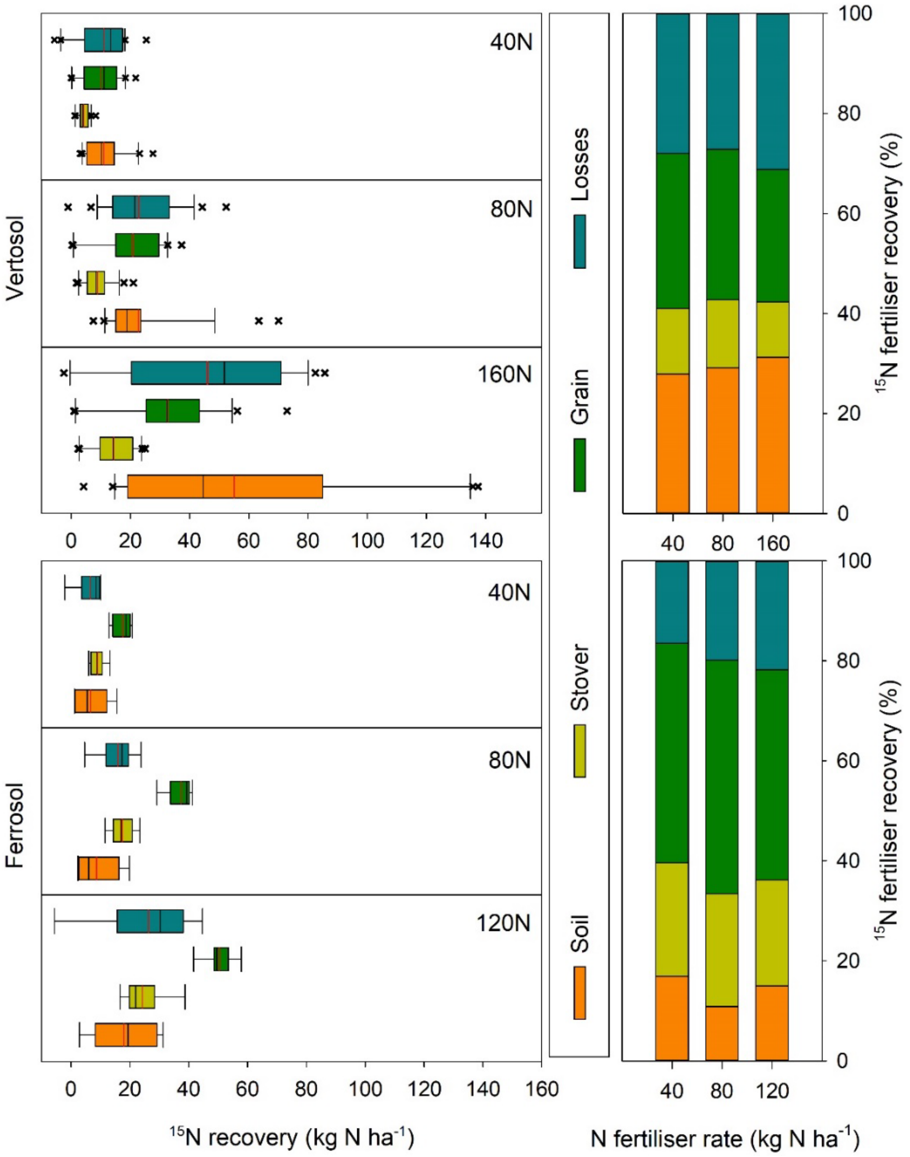

Figure 2. Fate of applied ^{15}N fertiliser, expressed as both kg ^{15}N ha^{-1} recovered and as a percentage of total ^{15}N applied for different N fertiliser rates applied in 4 farmer field sites and in 5 experiments conducted on research stations at Kingaroy (red ferrosol) and Kingsthorpe (black vertosol) from 2012–2014.
(Reproduced from Rowlings *et al* 2022)

Implications for N management and efficient use of fertiliser N

In theory, achieving efficient use of N in our rainfed cropping systems should require the timing and amount of N supply via soil mineralization and N fertilizer addition to be tightly coupled to crop demand, consistent with the ‘4R’ nutrient stewardship concept (Bruulsema et al., 2009). This should ensure minimal loss of surplus reactive N into the environment. Whilst fine in theory, achieving this synchrony presents challenges in our warmer climate and with systems that accumulate water during fallows. The combination of moist soil, warm temperatures and stubble/soil organic matter will result in N mineralisation (or immobilisation, depending on N availability) that primarily occur during the fallow, and indeed, production of mineral N (particularly NO_3-N) during the fallow will be essential if we are to achieve the necessary co-location of water and mineral N deeper in the soil profile.

In combination with this, we have the decisions about when and how to apply fertiliser N to top up the available N pool to achieve the water limited yield potential for that growing season. Our current practices are focussed on trying to finesse the 'right' N rate for this purpose, and on delaying our fertiliser application until a cropping decision is certain and seasonal yield indicators (stored soil water and seasonal climate forecasts) are locked in. In many ways, this strategy will effectively ensure the fertiliser recovery in the season of application is limited, unless in season rainfall distributions are favourable, as it limits the likely distribution of fertiliser N to topsoils that are often dry for significant parts of the growing season – especially in winter. Examples of the seasonal variability in the fate of applied N are shown in Figure 3 for summer sorghum.

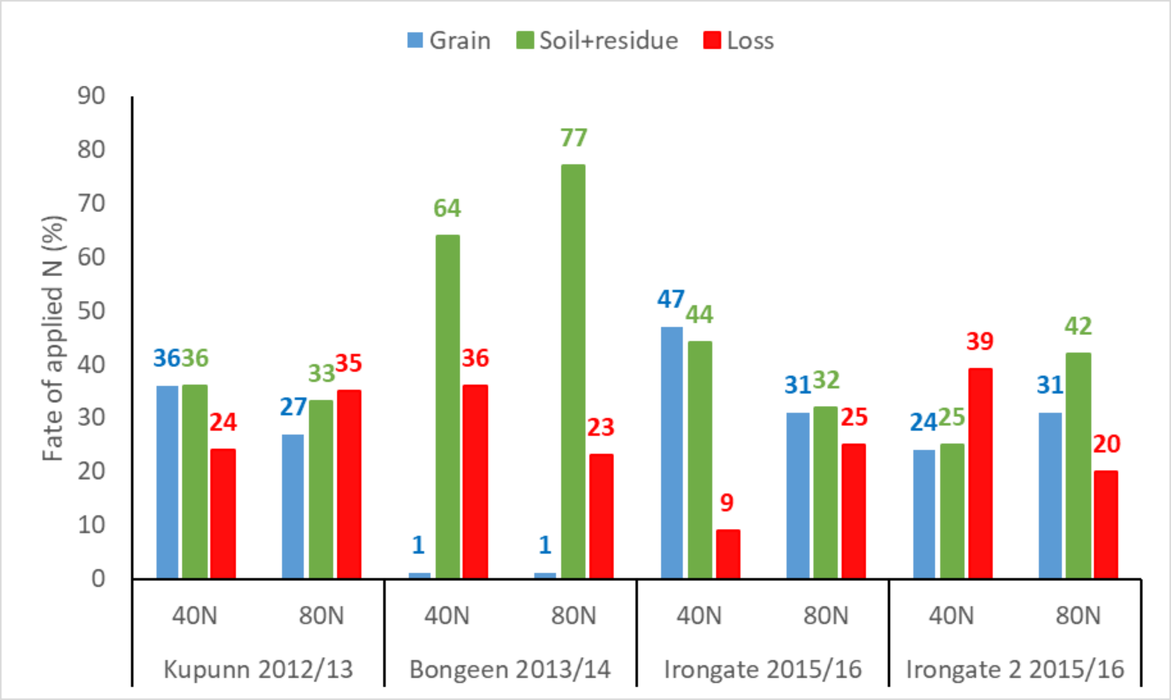

Figure 3. Percentages of fertiliser N either removed in sorghum grain, lost to the environment (presumably via denitrification) or carried forward to the following cropping seasons in soil and crop residue. Data were from sorghum crops grown on vertosols in commercial fields on the Darling Downs from 2012–2015. (Bell *et al* 2015)

Considerations for improving management of soil and fertiliser N

Some important principles to improve fertiliser nitrogen use efficiency (NUE) in northern cropping systems are:

- Fertilise the soil and not just the crop – this recognises that building a bank of labile N in the soil profile, both in organic and inorganic forms, is important to achieve water limited yield potentials. The current decline in soil organic matter and mineralizable N has resulted in less fallow N mineralisation and a greater reliance on fertiliser N to meet crop demand. Systems are now characterised by longer periods of immobilisation of N while crop residues with low N concentrations are broken down, and this is resulting in slower recharge of subsoil mineral N. Maximising the return of residues, improving the N content of residues through increasing legume frequency, and improving overall soil nutrient availability will help to maximise the building of soil organic matter and help fallow N recharge.

- Be more flexible with timing of fertiliser N application – this is particularly relevant in situations where profiles have been depleted of mineral N, much as they have been over the last 18 months. Combinations of wetter seasonal conditions, high crop yields and widespread denitrification losses have further increased the reliance on fertiliser N to meet current crop demands, so ensuring at least some of that N is distributed with water in deeper profile layers will be very important. This can be achieved by applying a proportion of the fertiliser N when soils are dry early in the fallow period, to ensure the wetting front moves nitrate N into deeper soil layers as the profile refills. While more research is needed to quantify the net benefits of early application, important considerations are likely to be: the extent to which immobilisation of N may delay nitrate leaching early in the fallow (e.g., with high cereal stubble loads); and the relative denitrification risk of early application with differing amounts and distributions of moisture in the soil profile.

- Consider the implications of different N formulations and application methods. There has been considerable recent focus on the relative merits of in-soil banding v top dressing in terms of crop N responses, with the results generally inconclusive and apparent crop recoveries from both application methods similarly poor (Daniel et al. 2019). We should not forget there are also considerations in choosing the right product (e.g., granules v liquids; enhanced efficiency fertilisers v conventional products). When N fertiliser is banded, there is little evidence of either coated or stabilised N fertilisers producing improved fertiliser N recovery by crops in rainfed systems. This is thought to be because these technologies either slow the formation, or release, of NO_3 into the soil solution, and so delay the movement of N into deeper soil layers that are accessible during drier periods (Dang et al. 2021). In the case of top-dressed N, there may be advantages in the use of urease inhibitors to coat urea granules (e.g., NBPT in products like Green Urea NV®) to reduce the risk of volatilisation losses – especially when stubble loads prevent direct soil-granule contact. However, the protection window for these products is short (e.g., <7–10 days) in field environments (Janke et al. 2020).

  With conventional fertilisers, comparisons between fluid and granular formulations are confounded by the different products that are typically used (e.g., urea-ammonium-nitrate (UAN) liquids *cf*. urea granules), and use is typically governed by convenience rather than performance. When fertiliser is sub-surface banded, use of products like UAN may limit the chemical changes in the band area and allow N to move deeper into the profile from early season rainfall events. Conversely, the more rapid conversion of UAN to NO_3-N may increase denitrification risks when wet conditions occur. Clearly the seasonal conditions will affect the impact of these formulation choices, and so developing principles for such variable conditions will be challenging.

  Similarly, the relative effectiveness of topdressing v subsurface banding will also vary. The delays in formation of NO_3-N that occur in concentrated N bands can be a benefit in situations where in-crop rainfall is an important yield determinant (mid-row banding in southern systems with winter rainfall) but can cause delays in movement of N into deeper soil layers and contribute to stranding of N in dry topsoils unless banding is done early in the fallow. Topdressing, particularly during a fallow, can overcome some of these issues and provide a greater volume of soil enrichment, but this application method also maximises the interaction with the microbial community, and can result in similar delays in N movement due to immobilisation. The relative benefits of each strategy will therefore change with the amount and type of crop residue, the timing of N application and subsequent rainfall.
- Soil sampling as a guide to fertiliser N management strategies – the to's and fro's of soil sampling to determine fertiliser N requirement have been discussed extensively over recent updates, but mainly in the context of trying to determine the 'right' rate in situations with unreliable seasonal rainfall forecasts. Hopefully this discussion has shown that while fertiliser responsiveness will vary in response to crop sequences, seasonal conditions etc, so will the fertiliser application strategy required to give the best chance of meeting crop demand. Soil sampling to periodically

check the performance of your fertiliser N strategy, or to determine the impact of an unusual set of seasonal conditions (like the recent wet seasons from 2020–2023), will be essential to determine when and how future N management should change. For example, the current extremely low soil mineral N, especially in the subsoil, will indicate problems meeting crop N demand from fertilisers unless seasonal conditions are exceptional. Fertiliser strategies will need to focus more heavily on timing and placement of fertiliser N, and perhaps cause a rotational shift to a higher legume intensity in coming seasons. Once profile mineral N returns to more normal amounts and distribution, a more conventional approach can be adopted.

Current research to develop better guidelines for N decision support

The focus of current fertiliser N research nationally is to improve our understanding of the fate of applied N fertiliser in grains cropping systems with investment by GRDC in project : Predicting nitrogen cycling and losses in Australian cropping systems - augmenting measurements to enhance modelling" – UOQ2204-010RTX. This involves studying N transformations and how these vary in different soils, climatic conditions and cropping sequences, and what this means for crop N demand, fertiliser use efficiency and environmental losses. There are a total of 15 experimental sites established across the country, with ^{15}N labelled urea fertiliser used to track the fate of applied fertiliser across up to 3 consecutive growing seasons. Soils and crop residues from these sites are being provided to undertake more fundamental studies under controlled conditions, to better quantify the key processes involved in soil and crop N dynamics. Detailed monitoring of denitrification and volatilisation losses are being undertaken in the field and controlled conditions. Collectively, the data generated in this intensive research program will be used to validate and improve our ability to accurately simulate N dynamics in grains cropping systems nationally, with this improved capability to be used to improve decision support systems for fertiliser N management.

An additional DAWE-funded project in Qld (Project 4-H4T03F0: Understanding impacts of contrasting cropping systems on soil organic matter and the dynamics of soil water and nitrogen in rainfed cropping systems on vertosols in northeast Australia) runs in parallel with this work. It is using ^{15}N-labelled fertilisers applied at different times during the fallow to track the leaching, crop recovery and environmental losses of fertiliser N in vertosol soils. It is collaborating with the GRDC farming systems sites at Pampas and Mungindi to explore these dynamics under contrasting crop sequences, with information also to be utilised to test the ability of crop models to predict these dynamics, and ultimately to evaluate contrasting fertiliser N strategies.

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Rust in 2023 and beyond – pathotypes and varieties and strategies for durable deployment of new genes for resistance

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Key words

barley, fungicide insensitivity/resistance, rust, wheat

GRDC code

UOS2207-0002RTX (9178966)

Take home messages

- Stripe rust in particular is likely to be important again in 2023; monitor for the presence of the green bridge, and if present, make sure it is destroyed at least 4 weeks before crops are sown, either by heavy grazing or herbicides
- The structure of stripe rust populations in eastern Australia has become more complex in recent years. This has changed the stripe rust response of many varieties of common wheat, durum wheat and triticale, stressing the need for close monitoring of varieties rated S or above and being prepared to apply fungicides if needed.
- Five incursions of stripe rust have been documented since it was first detected in Australia in 1979 (Ding et al. 2021). Three originated from Europe (1979, 2017 and 2018) and one North America (2002). Each has cost the industry hundreds of millions of dollars; for example, it was estimated that between $40-$90 million was spent on fungicides annually in 2003, 2004 and 2005 following the second 2002 incursion (Wellings, 2007). The critical importance of thoroughly laundering clothing and personal effects after interstate or overseas travel cannot be overstated.
- Insensitivity to DMI fungicides has been detected experimentally in the leaf rust pathogens of barley (nationally) and wheat (eastern Australia). Please monitor barley and wheat crops that have been sprayed for leaf rust and notify us of the success or otherwise of the treatment.
- The variability of rusts and their rapid spread across the Australian continent reinforces the importance of regular and nationally coordinated monitoring of these pathogens. All stakeholders are encouraged to monitor crops, barley grass and wild oat for rust throughout 2023, and to forward freshly collected samples in paper only to the Australian Cereal Rust Survey, at University of Sydney, Australian Rust Survey, Reply Paid 88076, Narellan NSW 2567.

Wheat stripe rust pathotype update

Cereal rust pathotypes (aka races, strains) are isolates of rust that differ in ability to overcome the resistance genes in cereal varieties. They are identified by using a field-collected sample of rust to infect a set of cereal varieties ('differentials'), each carrying a known resistance gene, and determining which resistance genes are overcome and which are not. This process takes about 3 weeks. Given favourable conditions for rust development, the pathotype/s present is a major determinant of how varieties perform and whether or not yield loss will occur.

Knowing what pathotypes are present, their distribution and impact on cultivars is the foundation of all rust control. This information is used to:

- monitor the effectiveness of resistance genes in cereal varieties
- interpret and determine varietal rust response
- provide new or relevant rust pathotypes for breeding and research
- understand how new pathotypes develop
- understand pathogenic and genetic variability, and the evolutionary potential of rust pathogen populations.

Epidemics of wheat stripe rust in eastern Australia in 2020, 2021 and 2022 were caused almost entirely by two pathotypes that found their way into Australia, from probably Europe/South America, in 2017 and 2018. These two pathotypes belong to two genetic groups, defined by internationally accepted Multi Locus Genotypes ('MLGs') based on DNA fingerprinting markers: PstS10 (pathotype 239 E237 A- 17+ 33+; '239'; 2017); PstS13 (pathotype 198 E16 A+ J+ T+ 17+; '198'; 2018). In 2022, these two pathotypes, along with a third pathotype of unknown MLG (pathotype 238 E191 A+ 17+ 33+; '238') that was first detected in 2021, were responsible for the extensive and damaging stripe rust epidemic experienced.

Figure 1 depicts the relative frequencies of all wheat stripe rust pathotypes detected annually since 2016, including the two previously detected MLG pathotype groups PstS0 (first detected in 1979, originating from Europe) and PstS1 (first detected in 2002, originating from North America; aka the 'WA' pathotype group). Of note in 2022 was the rapid increase in frequency of pathotype '238' (PstS?) after its initial detection in 2021, and reductions in the frequencies of pathotypes belonging to the other four MLGs. Our greenhouse tests are yet to detect any virulence advantage of pathotype 238 over the other groups, meaning that its increase in frequency in 2022 is likely due to increased 'aggressiveness' – for example, faster growing, producing more spores.

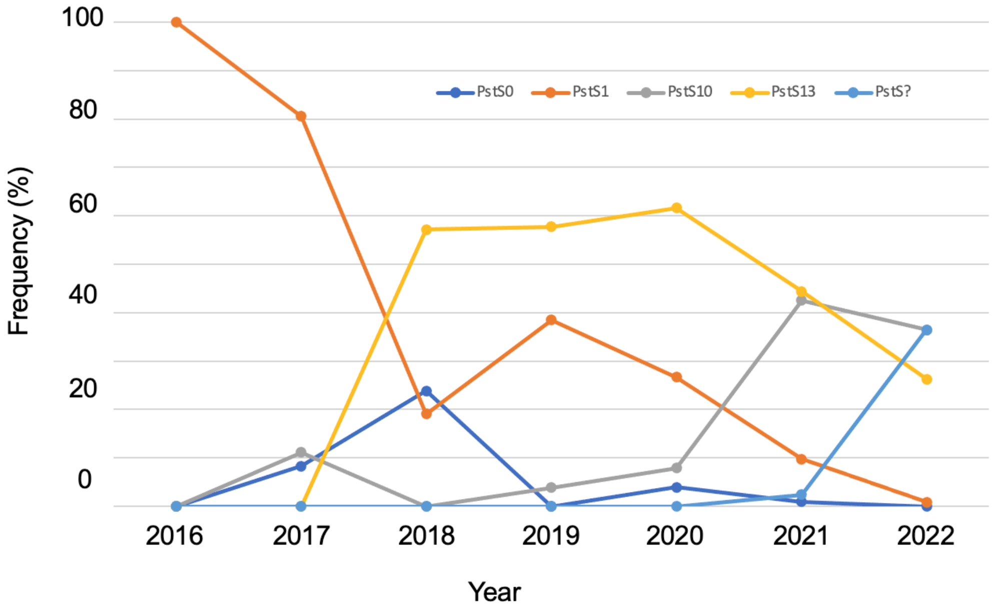

Figure 1. Frequency (%) of four internationally accepted DNA fingerprint MLG groups (PstS0, PstS1, PstS10, PstS13) of wheat stripe rust pathotypes, and a fifth as yet undefined group (PstS?) in eastern Australia, 2016 through 2022.

The expression of adult plant resistance (APR)

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.

Much remains to be known about the expression of APR. 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 GS 30–GS 32 (early stem elongation), MR-MS by GS 37–GS 39 (flag leaf emergence), MS by GS 49–GS 60 (awn peep-start of flowering) and MSS by GS 61–GS 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 of the pathogen, depending on its resistance genes and the corresponding virulence of different stripe rust pathotypes.

Mild temperatures during 2021 and 2022 that extended well into spring slowed crop development, which consequently delayed the expression of APR genes whilst also favouring multiple cycles of stripe rust infections. This extended the time between growth stages and affected management strategies, which in more susceptible varieties is based around early protection with fungicides until APR within a variety is reliably expressed.

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 MR/MS variety an S. Under high levels of N nutrition, growers need to manage a variety as one category lower in resistance (that is, manage a MR/MS as an MS).

Fungicide insensitivity/resistance in rust

The use of fungicides in Australian broadacre farming since the early 1980s has resulted in the emergence of fungal pathogen isolates with insensitivity to them, especially DMI fungicides. This has been well documented in, for example, septoria tritici blotch, wheat powdery mildew, barley powdery mildew, and net form of net blotch, and in blackleg in canola.

Cases of fungicide insensitivity in rust pathogens are fortunately much less common. Apart from reports from Brazil of a decline in the field performance of DMIs against the Asian soybean rust pathogen, few if any agronomically important cases of fungicide insensitivity in a rust pathogen are known.

We tested more than 800 rust isolates of wheat (stem rust, leaf rust, stripe rust), barley (leaf rust) and oat (crown rust, stem rust) for sensitivity to the DMI fungicide tebuconazole under controlled conditions. Importantly, these tests revealed insensitivity in isolates of the leaf rust pathogens of barley (*Puccinia hordei*) and wheat (*Puccinia triticina*) collected in 2021 to not only tebuconazole, but also epiconazole, prothioconazole, propiconazole and triadimenol. While tebuconazole is not registered for the control of leaf rust in barley, it is registered for scald and mildew control in barley (maximum rate 290 mL/ha) and for rust diseases in wheat and oat (maximum rate 290 mL/ha).

More extensive testing using standard historical isolates of both rust pathogens from our rust collection revealed that in *P. hordei*, insensitivity occurs in a clonal lineage of pathotypes that trace back to an exotic incursion into WA that was first detected in 2001. All isolates within this lineage that we tested, including the original 2001 isolate, were insensitive to tebuconazole at rates of more than six times the maximum rate of 290mL/ha recommended for rust control in wheat and oat. Insensitive isolates are common in all Australian barley growing regions.

Within the wheat leaf rust pathogen *P. triticina*, insensitivity to the four DMI fungicides was identified in a single pathotype, namely 93-3,4,7,10,12 +Lr37, which could grow and sporulate on leaves treated with rates of tebuconazole up to 25 times the recommended high field application of 290 mL/ha. This pathotype was first detected in southern NSW in October 2020 and is considered to be of exotic origin. It was isolated again in 2021 and 2022, and although it increased in frequency and has spread to Victoria and Queensland, it remains at low levels in the overall *P. triticina* population.

Our work appears to be the first documented case of insensitivity to a fungicide in a cereal attacking rust pathogen. Further in-field testing of these findings needs to be undertaken and at this stage there have been no reports of in-field failures of fungicides associated with cereal rust insensitivity. However, it reminds us of the remarkable abilities of these pathogens to change and adapt to circumvent the strategies used to control them, be they genetic resistance or agrochemicals.

Broader threats posed by cereal rust pathogens

Ongoing frequent changes in cereal rust pathogens, well documented by our rust surveillance over the past 10 years, have presented new challenges to resistance breeding and in crop rust control. They include:

- loss of important resistance genes in wheat, barley, oat and triticale, due to local mutations (for example, *Rph3* and *Rph7* in barley, *Yr27* in wheat, *Pc91* in oat)
- more frequent east-to-west spread of new rust pathotypes within Australia, resulting in new virulences in the west that have rendered varieties susceptible (for example, *Lr13*, *Lr27+31*)
- introductions of exotic wheat leaf rust pathotypes in 2014 (from North America) and 2020 (source currently unknown)
- introductions of two exotic wheat stripe rust pathotypes in 2017 (Europe) and 2018 (Europe or South America)
- local emergence of two genetically divergent stripe rust isolates in 2021, one that infects wheat and one with increased virulence on barley
- emergence and spread of fungicide insensitivity in the leaf rust pathogens of barley (national) and wheat (eastern Australia).

These new rusts have reduced profitability for growers of wheat (bread and durum), barley, oat and triticale. The loss of genetic resistance has also impacted breeding programs, slowing genetic gain with an anticipated knock-on effect to grower profitability in the years ahead. Combined, they highlight the need for ongoing RD&E to ensure effective and timely industry-wide rust protection.

Strategies for durable deployment of new genes for resistance

The term durable resistance is sometimes mistakenly equated with enduring rust control in agriculture. Clearly, growing only varieties that carry high levels of durable resistance at a large scale would be expected to provide enduring rust control across agro-ecological zones, continents and possibly beyond. However, it is important to appreciate that resistance that has proven durable may not remain effective forever, stressing the importance of genetic diversity in the resistances deployed.

The durability of resistance genes when deployed over large areas is complex, being determined not just by the ability of the pathogen to acquire matching virulence, but also other traits in the pathogen and host that can impact on overall disease epidemiology. For example, on the pathogen side, our long-term surveys of pathogenicity of cereal rust pathogens in Australia have provided many examples where certain pathogen genotypes seem to have greater fitness, which is independent of virulence for resistance genes (such as the recent example of wheat stripe rust pathotype ‘238’). On the host side, a change to growing early maturing wheat varieties developed by William Farrer in Australia had a huge impact in reducing losses to stem rust through ‘disease escape’. Both of these factors can influence the overall size of the pathogen population, and in so doing, affect the timing of epidemic onset, disease pressure on varieties carrying incomplete levels of resistance, and how frequently virulent mutant pathotypes emerge.

In view of this complexity, diversity of genetic resistance must be seen as a key ingredient in large scale enduring control of plant diseases. It has been argued that even where specific or major resistance genes are used, diversity in the resistance genes deployed insures against lack of durability and hence reduces genetic vulnerability. Above all, responsible use of resistance genes, which relies on knowing what resistance genes are present in varieties and breeding populations, and monitoring pathogen populations with respect to deployed resistances, are crucial in ensuring that the genetic bases of resistances are not narrowed.

Conclusion

The confirmation of two further incursions of the wheat stripe rust pathogen brings to four the number documented since this disease was first detected in Australia in 1979. The evidence available implicates Europe as the source of three of these incursions (1979, 2017 and 2018) and North America as the source of the other one (2002). Along with the two exotic incursions of the wheat leaf rust pathogen detected in 2014 and 2020, this continues the trend that has emerged from our long-term pathogenicity surveys of cereal rusts of an increasing frequency of exotic incursions with time, presumably associated with increased international movement of people and inadvertent transport of rust spores on contaminated clothing. Exotic wheat rust incursions have cost the industry hundreds of millions of dollars. The importance of thoroughly laundering clothing and personal effects after interstate or overseas travel cannot be emphasised enough.

Stripe rust was very common and damaging in wheat crops in eastern Australia during the 2022 season, and there were many situations in which fungicides were used to control the disease. This was in part due to the occurrence of pathotype 198 E16 A+ J+ T+ 17+. The amount of stripe rust that developed was, however, nowhere near that caused by this pathotype in Argentina in 2016/17 and 2017/18. The much lower impact of pathotype 198 in Australia compared to its impact in Argentina and Europe is a clear endorsement of the value of genetic resistance in controlling rust diseases in cereals, and of the efforts of all stakeholders in using genetics as the foundation of rust control here in Australia.

The latest responses of Australian wheat and triticale cultivars to the pathotypes reported here, based on detailed greenhouse and field testing, are provided in our Cereal Rust Report (Volume 19 Issue 1, released August 2022), which can be downloaded from our website.

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Useful resources

Cereal disease guide (https://agriculture.vic.gov.au/biosecurity/plant-diseases/grain-pulses-and-cereal-diseases/cereal-disease-guide)

Cereal seed treatments 2021 (https://www.pir.sa.gov.au/__data/assets/pdf_file/0005/237920/Cereal_Seed_Treatments_2021.pdf)

Australian cereal rust survey (https://www.sydney.edu.au/science/our-research/research-areas/life-and-environmental-sciences/cereal-rust-research/rust-reports.html)

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Breeding for crown rot tolerance – can technology help?

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Key words

crown rot, breeding, variety selection

GRDC code

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Take home message

Research into improving phenotyping strategies for crown rot resistance and tolerance to crown rot have identified a relationship between yield loss and canopy temperature. This relationship is being used to attempt to develop higher throughput and more reliable phenotyping strategies for this disease. The aim is to enable breeders to more efficiently select for improved crown rot resistant and tolerant germplasm.

Yield loss trials conducted during the last two seasons have identified surprising amounts of yield loss, despite the favourable conditions. Losses of around 10% in elite tolerant varieties have represented production losses exceeding 0.5 t/ha, with higher losses in intolerant varieties.

Introduction

Despite significant research efforts, crown rot remains an intractable disease for plant breeders and growers alike. A number of factors contribute to this, including a lack of significantly useful genetic resources, difficulties in phenotyping (assessing germplasm for resistance and tolerance) and a lack of understanding of the mechanisms driving resistance and tolerance traits. Consequently, breeding efforts, both at a research and varietal development level, have often relied on indirect methods of selection, using proxies such as the extent of stem browning, incidences of whiteheads or yield under disease to identify germplasm with enhanced levels of resistance and/or tolerance. In an effort to improve the delivery of improved genetics to growers, recent GRDC investments have sought to improve phenotyping strategies by investigating both existing and novel phenotyping strategies. While this research is still underway, some initial findings suggest canopy temperature may be correlated with tolerance to this disease.

Proximal and remote sensing technologies have rapidly progressed in recent years and been proven in a range of agricultural fields including weed science, yield prediction and crop monitoring. They provide researchers significant opportunities for additional phenotyping strategies, although are yet to be widely deployed in routine commercial breeding applications. Canopy temperature in particular presents breeders with an opportunity for phenotyping a genotype's response to stressed conditions (Jackson *et al*. 1981), with the value of canopy thermography already demonstrated for drought and heat stress (Amani *et al.* 2008). As the crown rot pathogen infects cereals, it disrupts the vascular system restricting the ability of the plant to transpire. Given that transpiration provides a canopy cooling effect, it is hypothesised that plants with differing resistance and tolerance to crown rot will display differential canopy temperature reactions.

Measuring canopy temperature

To assess the relationship between canopy temperature and crown rot resistance and tolerance, a series of bread wheat, durum wheat and barley trials were planted across the northern region in both 2021 and 2022. A total of 60 bread wheat, 12 durum and 24 barley varieties were included representing the phenotypic range of resistant to susceptible and intolerant to tolerant. Canopy temperature data was collected using a FLIR One Pro® thermal camera attached to a vehicle mounted rig at 3m above the canopy (Figure 1). Each paired plot was captured in a single image to reduce the impact of temporal variation. Thermal images were taken at multiple opportunities through the growing season, as dictated by weather and ground access conditions.

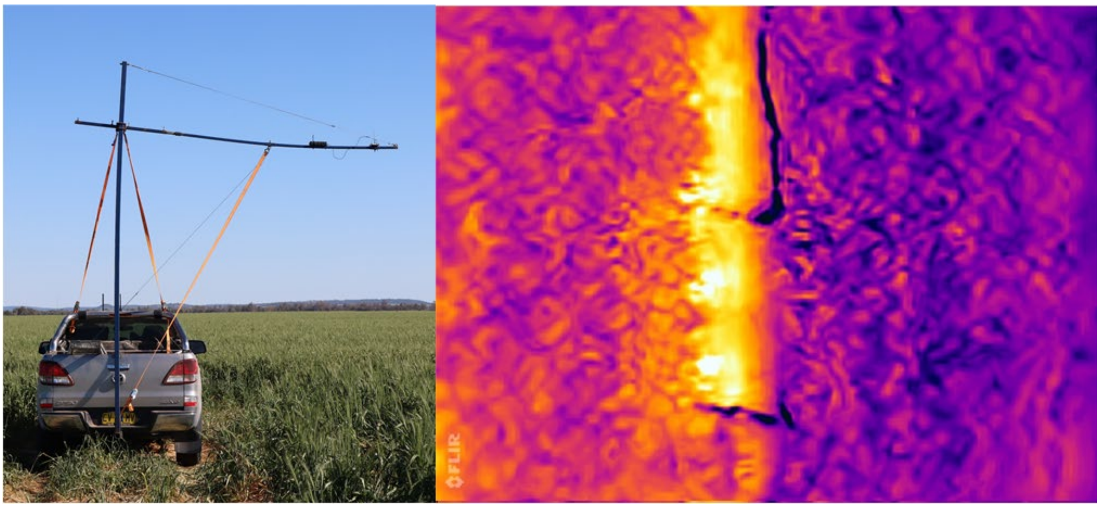

Figure 1. The canopy temperature phenotyping platform (left) used for high-throughput phenotyping of thermal imagery in a wheat breeding program and (right) an example of a thermal image of a paired plot of a single genotype, with (left of image) and without (right of image) crown rot inoculum.

Yield loss to crown rot in favourable seasons

Growing conditions in both 2021 and 2022 were very favourable, and not conducive to obvious crown rot symptom development. Indeed, across the 12 trials completed in these two seasons, only a handful of whiteheads were observed in a single trial. Conventional wisdom indicates that in such seasons, yield loss to crown rot is largely absent, and it is the build-up of large amounts of *Fusarium* inoculum through accumulation of large amounts of biomass that is of most concern to growers with respect to crown rot.

While data from these experiments confirms that yield loss was limited when compared to observations made in seasons more conducive to disease expression, the extent of yield loss was still of concern. An example of this was Walgett in 2022, where trials were planted on a near full profile and received ~260mm in-crop rainfall. Despite the mild conditions during grain-fill, average yield losses were around 11%, 13% and 14% for bread wheat, durum and barley, respectively, with intolerant varieties such as EGA Gregory⦇ losing around 21% of yield to crown rot. This represents lost production of around 0.9 t/ha for this variety in a season when stripe rust, flooding and grain storage challenges were the main issues faced by growers. Even in more tolerant varieties such as Sunchaser⦇ and LRPB Lancer⦇, yield losses were approximately 10%, representing lost production of 0.53 t/ha and 0.40 t/ha, respectively. While such losses are more palatable when offset by the high yields observed in 2022, they nevertheless represent a significant and likely hidden loss in production. Similar observations were made at North Star in 2022, where average yield losses of around 9% in bread wheat genotypes (rising to 17% in EGA Gregory⦇) were recorded.

Clearly, these results suggest that avoiding highly susceptible and intolerant varieties can significantly improve productivity, even in seasons conventionally not seen as favourable to crown rot expression. Indeed, improvements in varietal performance under crown rot in the last decade or so have made it easier to avoid highly intolerant or susceptible varieties.

Relationship between yield loss and canopy temperature

There has been a significant relationship between crown rot and canopy temperature in all the trials conducted over two years as part of this project, with plant canopies of inoculated plots consistently warmer than their uninoculated pairs. This observation is likely attributable to the disruption of the vascular system by the crown rot pathogen and the resulting restriction of transpiration. Differences were observed in the magnitude of the effect of inoculation on canopy temperature between both crop types and the stage of crop development, with a general trend towards greater differences between treatments increasing through crop development.

Significant differences between genotypes in the degree of increase in canopy temperature following crown rot inoculation were observed consistently, even in sites where limited disease expression was observed. Differences were more pronounced later in the crop's development and are consistent with our understanding of the putative mechanisms driving the canopy temperature response. During grainfill, the crops moisture requirement increases, subsequently increasing the demands put on the plant's vascular system. In plants where the vascular system has been disrupted through fungal proliferation by the crown rot pathogen, rates of transpiration are likely to be suppressed, leading to greater differences in canopy temperature between inoculated and uninoculated plots.

Importantly, these differences were associated with yield loss. Correlations between the increase in canopy temperature following inoculation and yield loss ranged between $R^2 = 0.42$ and $R^2 = 0.75$ (average R^2=0.6) for bread wheat and between $R^2 = 0.42$ and $R^2 = 0.75$ (average R^2=0.59) for durum. Unfortunately, correlations for barley were less reliable, averaging $R^2 = 0.38$. A number of factors have contributed to the less favourable finding for barley; the most notable of which is the impact of lodging on reliable canopy temperature data collection.

Despite the mild conditions experienced, thermography, and particularly measuring the temperature difference between inoculated and uninoculated plots, has still been able to discriminate between genotypes based on their crown rot tolerance levels. This is an important finding as it indicates that genetic progress can be achieved even in seasons where abiotic stress pressures are intermittent or indeed completely absent. This is critical for breeding programs where cohorts of germplasm may only be screened at certain intervals, particularly with segregating populations and early generation yield testing, and thus being able to make informed selections independent of seasonal variations is necessary.

What's next?

There remains significant further research in understanding the role of canopy temperature in phenotyping crown rot tolerance. The timing of data collection requires experimental work. This includes the impact on diurnal variations in transpiration, and the role that crown rot infection may play in effecting these patterns. Further to this, the value of night canopy temperature assessments should be investigated. Indeed, such observations have proven useful when phenotyping both heat and drought stresses and warrant investigation with respect to crown rot. These studies must also be conducted under higher levels of crown rot expression, where heat and moisture stresses stimulate high levels of disease pressure to determine whether the observed relationships hold under a greater range of conditions.

In addition to investigating canopy temperature, research is also seeking to identify further strategies to improve the efficiency and efficacy of crown rot phenotyping. Once approach is to use machine learning to identify whiteheads amongst healthy heads. Assessing whiteheads is a routine phenotyping methodology, widely used within commercial breeding programs due to its ability to readily identify intolerant lines. By incorporating machine learning approaches to whitehead detection, both the speed and accuracy of this phenotyping method would be improved.

Further, a more fundamental understanding of the relationship between resistance to crown rot and its impact on yield loss is being sought. Historically, much of the breeding and research efforts have focussed on resistance to crown rot, measured largely by the extent of stem browning. Relationships between this trait and tolerance, however, have not been fully examined. Data collected from these trials is being used to identify the relative impact of resistance on yield loss, so that breeders and researchers alike can more efficiently deploy their resources for maximum production gains.

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Fungicide resistance in wheat powdery mildew in Qld and NSW in 2022

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Take home messages

- The wheat powdery mildew (WPM) pathogen has a high risk of developing fungicide resistance
- The 2022 season, with frequent rainfall and prolonged mild temperatures in spring, was conducive to WPM development in susceptible wheat varieties across southern Qld and NSW
- Widespread resistance or reduced sensitivity to Group 3 DMIs is considered a high risk and a DMI 'gateway' mutation was detected at a high frequency (range 53 to 100%) in all samples collected across southern Qld and NSW in 2022
- Resistance to Group 11 (QoI) fungicides has been detected across most of the southern growing region and was detected at a lower frequency than DMI resistance in 9 of 10 southern Qld samples (range 7 to 56%) and 8 of 9 NSW samples (range 10 to 58%)
- Careful use and rotation of available fungicide actives will help control the spread of resistance in WPM
- 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

Wheat powdery mildew (WPM), caused by *Blumeria graminis* f. sp. *tritici* (*Bgt*), 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.

In 2020, there were concerns across wheat-growing regions of New South Wales and northern Victoria on the performance of fungicides from the DMI group. Despite crops receiving 2–4 fungicide applications during the season, wheat powdery mildew remained a problem for growers in some areas.

DMI fungicide resistance was detected at very high frequencies in samples collected from paddocks around Edgeroi, Wee Waa, Albury, Rennie, Balldale, Deniliquin, Jerilderie, Hillston and Yenda in NSW, and Cobram and Katamatite in Victoria. Genetic and phenotypic analyses of the isolates obtained from these locations revealed a combination of mutations in the DMI fungicide target gene that were associated with the observed resistance to some DMIs. Additionally, all samples tested had some level of strobilurin fungicide resistance (Simpfendorfer *et al.* 2021). Further research by the Centre for Crop Disease Management (CCDM) has associated the DMI mutations to reduced sensitivity to some triazole fungicides such as propiconazole under glasshouse conditions (Lopez-Ruiz *et al.*2023). The 2022 season was conducive to the development of WPM due to frequent rainfall and prolonged mild temperatures during spring. This favoured the development of WPM across parts of NSW and into Qld, so the opportunity was taken to conduct a further survey of fungicide resistance in collaboration with CCDM. This was particularly important for Qld production areas where the status of fungicide resistance within the WPM population has not been previously characterised (Poole *et al.* 2022).

What we did

WPM samples were collected by collaborating agronomists, sent to Tamworth for processing to help ensure viability in transit, then sent to CCDM for molecular analysis of frequency of mutations for DMI (F136 'gateway' mutation, triazoles) and QoI (A143 mutation, strobilurins) resistance within the WPM population in each sample. In 2022, nineteen viable WPM samples were analysed by CCDM from across Qld and NSW, with sample distribution being Qld (10), SW NSW (3), SE NSW (2), CE NSW (2), NE NSW (1) and NW NSW (1) (Table 1).

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.

Table 1: Location of 19 wheat powdery mildew samples collected across Qld and NSW in 2022 along with frequency of DMI (triazole) 'gateway' and QoI (strobilurin) mutations

Location	**Year**	**Region**	**Variety**	**Frequency of mutation**	
				DMI F136	**QoI A143**
Bell	2022	Qld	Sunflexᶲ	53%	10%
Bell	2022	Qld	Sunchaserᶲ	99%	17%
Chinchilla	2022	Qld	Sunmaxᶲ	100%	22%
Chinchilla	2022	Qld	Sunchaserᶲ	100%	7%
Gatton	2022	Qld	LongReach Hellfireᶲ	100%	51%
Jandowae	2022	Qld	Sunchaserᶲ	90%	38%
Jandowae	2022	Qld	Sunchaserᶲ	83%	16%
Macalister	2022	Qld	LongReach Hellfireᶲ	100%	56%
Macalister	2022	Qld	Sunchaserᶲ	99%	29%
Surat	2022	Qld	Sunmaxᶲ	72%	0%
Ashley	2022	NW NSW	Westcourtᶲ durum	66%	18%
Narrabri	2022	NE NSW	Breeding line	100%	10%
Grenfell	2022	CE NSW	Sunflexᶲ	100%	20%
Grenfell	2022	CE NSW	Breeding line	100%	0%
Balldale	2022	SE NSW	Scepterᶲ	100%	28%
Tocumwal	2022	SE NSW	Livingstonᶲ	100%	47%
Deniliquin	2022	SW NSW	Scepterᶲ	100%	11%
Finley	2022	SW NSW	Scepterᶲ	100%	58%
Widgelli	2022	SW NSW	Breeding line	100%	47%

All Qld and NSW WPM samples collected in 2022 had a DMI F136 mutation frequency of between 53 and 100% (Table 1). A lower frequency of the Qol A143 mutation was detected in 17 of the 19 WPM samples in 2022 which ranged from 7 to 58% (Table 1). This is the first report of DMI and QoI resistance within WPM in Qld but has been previously reported in NSW from testing conducted in 2020 and 2021. 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 concerning; as 2 of the 10 WPM samples tested from Qld (Gatton and Macalister) and 1 of 9 from NSW (Finley) had 100% resistance mutations to DMI (Group 3) in combination with >50% QoI (Group 11) modes of action (MoA), which could potentially result in dual resistance to both fungicide 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 Qld and NSW 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) whether applied as a foliar spray or seed treatment.

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 or heading towards increased selection of dual resistance within WPM populations in some paddocks in southern Qld and NSW, 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 susceptible–very susceptible (S–VS) 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 southern Qld 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 southern Qld 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 to a lesser but developing extent QoI (strobilurin) fungicides. 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). Further information on fungicide resistance and its management in Australian grain crops is available at the AFREN website at grdc.com.au/afren.

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Cereal disease management in 2023: what does a return to a ‘normal’ spring mean?

Steven Simpfendorfer, NSW DPI Tamworth

Keywords

leaf diseases, perspective, Fusarium head blight, Fusarium crown rot, climatic conditions

GRDC codes

DPI2207-002RTX: Disease surveillance and related diagnostics for the Australian grains industry
DPI2207-004RTX: Integrated management of Fusarium crown rot in Northern and Southern Regions

Take home message

- The 2022 season was very conducive to a range of cereal leaf diseases and Fusarium head blight (FHB) during flowering and grain fill
- However, this exceptional season for cereal diseases needs to be kept in perspective
- Leaf disease pressure, especially stripe rust, will likely be high again in 2023 requiring management early in the season, but plans need to be responsive to spring conditions
- Widespread FHB in 2022 was the Fusarium crown rot (FCR) fungus letting you know that it has not gone away with wetter and milder spring conditions the last few seasons
- It was important to test seed retained from any crop where FHB or white grains were evident in 2022 as Fusarium infection negatively impacts on germination and vigour but can also introduce FCR into paddocks
- However, retained cereal stubble is still likely to be the main source of FCR inoculum
- Help is available with testing, and stay abreast of cereal disease management communications throughout the season, as 2023 is likely to be another dynamic year

Introduction

Cereal disease management has been more complicated over the past three consecutive wet seasons with multiple stripe rust pathotypes blowing around and an increase in diseases not frequently seen in central and northern areas (e.g., Septoria tritici blotch, wheat powdery mildew and Fusarium head blight). This has all occurred in combination with the added stress of increased input costs, with many growers stating that ‘2022 was the most expensive wheat crop they have ever grown’. This certainly created an elevated level of anxiety for growers and their agronomists.

So, if 2022 taught us nothing else, it is that we cannot control the weather. However, nothing has changed and in 2023 growers need to have extra focus on ‘controlling the controllable’. The 2022 season needs to be kept in perspective, as it was the year for leaf diseases and by default multiple fungicide applications in susceptible varieties. However, what are the chances of a wet and prolonged mild spring again in 2023? Current long-term Bureau of Meteorology (BoM) forecasts are indicating a warmer and drier spring for much of the northern grain region in 2023 which needs to be considered in cereal disease management and other decisions this year.

2022 – an exceptional season

The 2022 season was wet! Records were broken and flooding was widespread in some areas. Frequent rainfall is very conducive to the development of leaf diseases such as stripe rust, as causal pathogens require periods of leaf wetness or high humidity for spore germination and initial infection. However, just as significant a contributing factor to the prevalence of cereal leaf diseases was the spring (Sep–Nov) temperatures in 2022, even compared with 2020, which remained mild (Figure 1).

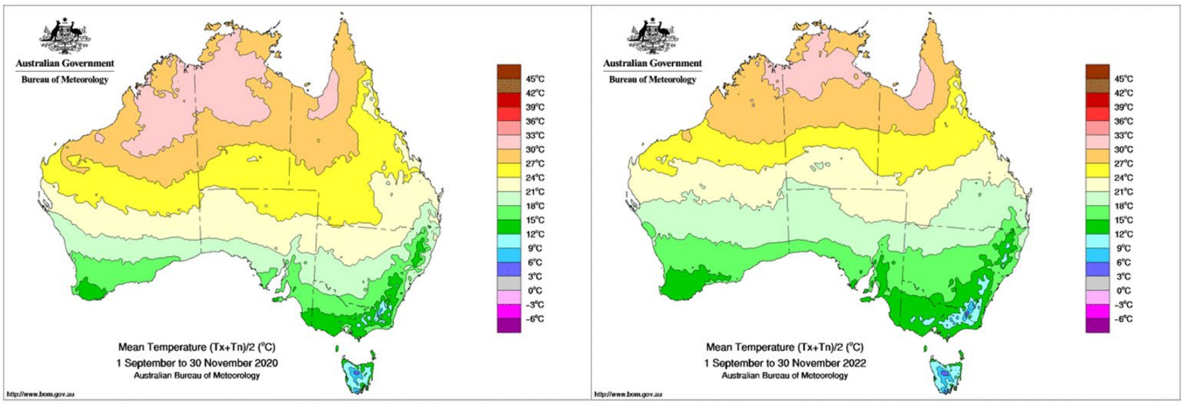

Figure 1. Mean daily temperature for spring (Sep–Nov) in 2020 (left) compared with 2022 (right).

Temperature interacts with cereal diseases in two ways. Each pathogen has an optimal temperature range for infection and disease development (Table 1). Time spent within these temperatures dictates the latent period (time from spore germination to appearance of visible symptoms) of each disease, which is also often referred to as the cycle time. Disease can still develop outside the optimum temperature range of a pathogen, but this extends the latent period. Hence, prolonged mild temperatures in 2022 were favourable to extended more rapid cycling of leaf diseases such as stripe rust, Septoria tritici blotch and wheat powdery mildew (Table 1).

Table 1. Optimum temperature range and latent period of common leaf and head diseases of wheat.

Disease	Optimum temperature range (°C)	Latent period (opt. temp)
Stripe rust	12–20	10–14 days
Septoria tritici blotch	15–20	21–28 days
Wheat powdery mildew	15–22	7 days
Leaf rust	15–25	7–10 days
Yellow leaf spot	15–28	4–7 days
Fusarium head blight	20–30	4–10 days

The second effect that temperature can have on disease is more indirect, on the plants themselves. The expression of adult plant resistance (APR) genes to stripe rust can be delayed under lower temperatures. However, cooler temperatures also delay development (phenology) of wheat plants, extending the gap between critical growth stages for fungicide application in susceptible wheat varieties. The slower development under cooler spring temperatures therefore increases the time of exposure to leaf diseases in between fungicide applications, which is the case for stripe rust which is also on a rapid cycle time under these temperatures. Hence, underlying infections can be in their latent period and also beyond the curative activity (~1/2 of cycle time with stripe rust) when foliar fungicides are applied. This can result in pustules appearing on leaves 5 or more days after fungicide application. The fungicide has not failed, rather the infection was already present but hidden within leaves and was too advanced at the time of application to be taken out by the limited curative activity of fungicides. At optimum temperatures, stripe rust has a 10-day cycle time in an S rated variety, whereas it is a 14-day cycle in a MRMS variety. Disease cycles quicker in more susceptible varieties!

Reliance on fungicides for management made susceptible (S) wheat varieties critically reliant on correct timing of fungicide application. Frequent rainfall in 2022 caused plenty of logistical issues with timely foliar fungicide applications related to paddock accessibility by ground rig and/or delay in aerial applications. The associated yield penalty was significantly higher in more stripe rust susceptible varieties due to the shorter disease cycle time. There were plenty of reports of 10-day delays in fungicide applications around flag leaf emergence (GS39) due to uncontrollable logistics that saw considerable development of stripe rust, particularly in S varieties. Yield loss at harvest has been estimated at around 30–50% due to this 10-day delay. This simply does not happen in more resistant varieties, where there is more flexibility in in-crop management, because the disease is not on speed dial when climatic conditions are optimal. The 2022 season has certainly challenged the risk vs reward of growing susceptible varieties – the management of which does not fit logistically within all growers' systems.

The prolonged cool conditions in spring 2022 also extended the flowering period in wheat and durum varieties, which in combination with extended high humidity, was very conducive to Fusarium head blight (FHB). The prevalence of FHB and white grain disorder (*Eutiarosporella* spp.) across large areas of eastern Australia in 2022 is unprecedented. However, what is the likelihood of these specific conditions occurring at a time-critical growth stage (early flowering) again in 2023?

Can we really grow susceptible varieties in the long term?

Always a solid topic for debate. From a plant pathologist viewpoint, the following are simply fact.

- Pathogens with longer distance wind dispersal (e.g., stripe rust and powdery mildew) are 'social diseases'. What you do impacts your neighbours and the rest of industry. Yes, 'it blows'
- Stripe rust has a shorter cycle time in more susceptible varieties which increases disease pressure
- More susceptible varieties can place increased disease pressure on surrounding MS, MRMS and MR varieties
- The more susceptible the variety, the greater 'green bridge' risk volunteer plants are to survival of biotrophic pathogens such as stripe rust and wheat powdery mildew during fallow periods
- Mutations within the pathogen population which lead to 'break down' of resistance genes or development of fungicide resistance is all a numbers game. More susceptible varieties produce more fungal spores, which increase the risk of mutations
- Susceptible varieties have less flexibility with in-crop fungicide timings. The yield penalty is much larger if application is delayed (i.e., increased production risk)
- Susceptible varieties are reliant on fungicides, often multiple within conducive seasons, to control leaf diseases. This increases selection for fungicide resistance or reduced sensitivity within the pathogen population either directly (e.g., with rust) or indirectly on other fungal pathogens also present at the time of application (e.g., powdery mildew)
- Rust pathogens CAN develop fungicide resistance!! (Park *et al.* 2023)

Keep the 2022 season in perspective

The 2022 season was the year for fungicides, especially in more susceptible varieties and with the mix of diseases that occurred. The prolonged mild conditions also extended the length of grain filling so there was a benefit of retaining green leaf area through this period in 2022. Remember, fungicides do NOT increase yield, they simply protect yield potential (i.e., stop disease from killing green leaf area). As highlighted above, disease is very dependent on individual seasonal conditions, so the same returns are not guaranteed from fungicide use in 2023. What's your disease management plan if spring returns to closer to normal temperatures and rainfall? There is no talk of La Niña again in 2023 and seasonal outlook must be part of disease management planning. Early leaf disease pressure is likely to be high again in 2023, given elevated inoculum levels from 2022 and decent levels of stored soil moisture. However, dry conditions during April-May and into June in some areas, especially more western regions, has been less conducive to green bridge survival of rusts and leaf disease development in cereal seedlings. Manage early leaf disease pressure in 2023 if present, then adapt management to spring conditions. The most effective fungicide can often be 2 to 3 weeks of warmer and dry weather in spring.

Where has Fusarium crown rot gone?

Fusarium crown rot (FCR) has NOT disappeared with the last few seasons of wetter and milder spring conditions. FCR risk was particularly elevated in more northern areas leading into planting in 2022. Increased frequency of cereal crops within rotations following drought conditions from 2017–2019, along with reduced sowing of chickpea crops being underlying causes. However, FCR requires moisture for infection, so inoculum levels have progressively been building up within paddocks (Figure 2). The wetter and milder spring conditions have limited the expression of FCR infection as whiteheads.

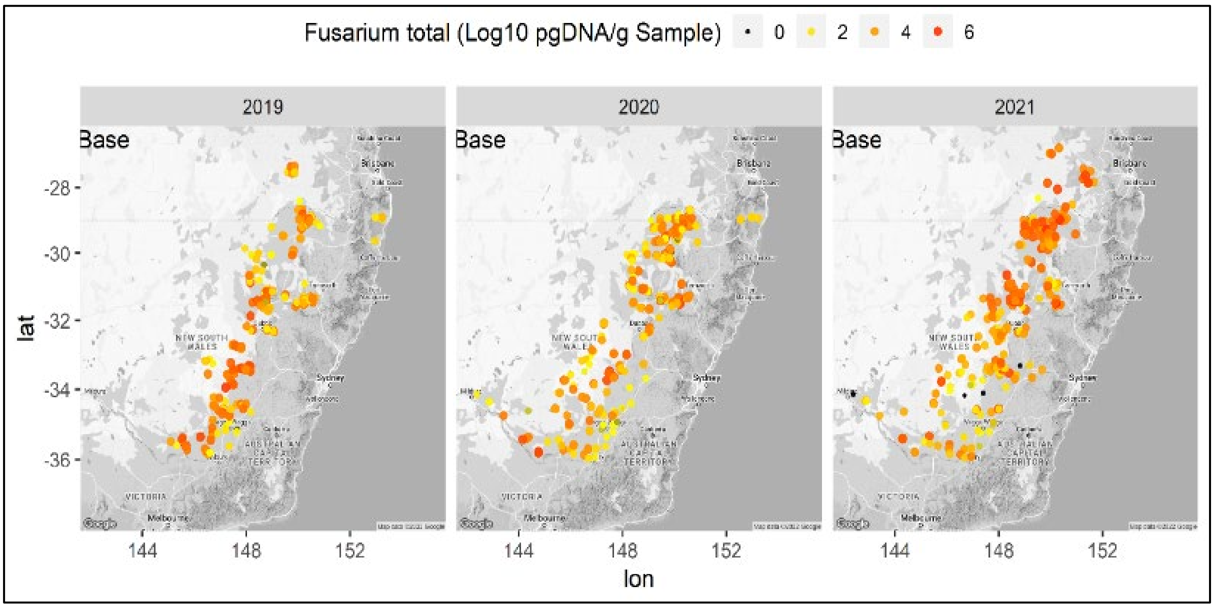

Figure 2. Levels of Fusarium crown rot within the base of randomly surveyed winter cereal crops (2019 to 2021) as assessed using quantitative PCR of pathogen DNA levels. Map from collaborative surveys conducted with Dr Andrew Milgate and Brad Baxter, NSW DPI Wagga Wagga.

Fusarium head blight (FHB) which caused premature partial bleaching of heads and white or pink grains was widespread at varying levels across eastern Australia in 2022 along with white grain disorder (WGD) caused by *Eutiarosporella* spp. in some regions, especially southern Qld. More detailed information around the specific causes, management and implications of this epidemic in 2022 are available (Simpfendorfer and Baxter 2023). Testing of 1880 grower retained grain samples from the 2022 harvest showed that the dominant cause of FHB across eastern Australia in 2022 was related to tiller bases infected with FCR. That is, Fusarium infection of bread wheat, durum and barley crops in 2022 expressed as FHB due to the wetter/milder conditions during flowering and grain fill. This basal Fusarium infection would have expressed as whiteheads if crops had been temperature and/or moisture stressed during this period in 2022. This was a massive warning sign of the levels of FCR risk that have developed and largely gone unnoticed within some cropping systems over the past three wetter seasons.

Why was seed testing so important prior to sowing in 2023?

FHB was widespread in 2022 with implications for seed retained from infected crops. Fusarium grain infection reduces germination and vigour of seed retained for sowing along with causing seedling blight (death) in plants arising from infected grain. The fungus replaces the contents of infected seed with its own mycelium, so while seed treatments can help reduce the level of seedling blight, they cannot restore the quality of heavily infected seed sources. Sowing Fusarium infected seed also introduces FCR into paddocks. The level of pink or white grains in a grain sample is likely an underrepresentation of the true level of Fusarium grain infection, as later infections (i.e., high humidity) during grain fill, can allow some fungal spread into formed grains which appear normal. Sourcing quality seed for sowing in 2023 created issues in some regions.

General advice if retaining seed for sowing is:

- <1% Fusarium grain infection = no issues;
- 1% to 5% Fusarium grain infection = consider using seed treatment (full rate Vibrance® or EverGol® Energy) to limit seedling blight and slightly increase sowing rate;
- >5% Fusarium grain infection = source cleaner seed if possible.
- Same values apply for Eutiarosporella and are additive for mixed infections where the combined Eutiarosporella + Fusarium infection level should not be greater than 5% in a seed source.

A ‘free’ seed testing service was offered to growers to support them in determining Fusarium grain infection levels. In total 1,880 grower retained seed lots from 2022 and 64 from the 2021 harvest were tested through the NSW DPI laboratory at Tamworth under a collaborative project with GRDC. Fusarium grain infection levels were considerably lower in seed retained from 2021 (average 0.75%; range 0 to 9%) compared with 2022 harvested grain (average 6.5%; range 0 to 70.5%). This highlights that FHB was also present in 2021 but went largely unnoticed. If available, seed retained from 2021 was likely a good source of planting seed with low Fusarium infection levels. However, appropriate storage of seed over this extended period appears to have impacted on germination of some 2021 retained seed. With 2021 retained seed 63% of grower seed lots had greater than 90% germination, 17% had 70 to 90% germination, 14% had 50 to 70% germination and 6% had less than 50% germination.

In total, 1,880 seed lots from the 2022 harvest were tested, consisting of 1,566 bread wheat, 183 durum and 131 barley samples (Table 2). The biggest issue with Fusarium grain infection levels was in durum wheat, which is very susceptible to FCR and FHB, with 81% of 2022 seed lots having greater than the recommended 5% level of Fusarium infection (average 20.3% infection, range 0 to 70.5%). Fusarium grain infection levels were still a widespread issue in bread wheat and barley seed retained from 2022 with 33% of bread wheat (average 5.0% infection, range 0 to 43%) and 29% of barley (average 4.2% infection, range 0 to 49%) seed lots having greater than the recommended 5% level of infection (Table 2).

Table 2. *Fusarium* spp. grain infection levels in bread wheat, durum wheat and barley seed lots harvested across eastern Australia in 2022.

Region	Bread wheat			Durum wheat			Barley		
	<5%	>5%	Max	<5%	>5%	Max	<5%	>5%	Max
SE NSW	163	27	16%				3	1	6%
SW NSW	144	56	43%	12	45	71%	12	4	9%
CE NSW	141	74	37%	0	2	30%	17	4	49%
CW NSW	259	169	43%	0	2	45%	20	14	45%
NE NSW	81	94	42%	16	83	69%	13	11	34%
NW NSW	61	39	28%	1	15	68%	13	4	13%
Sth Qld	117	24	26%	0	1	23%	9	0	4%
Vic	71	36	33%	1	1	35%	6	0	5%
SA	10	0	2%	5	0	2%			

Values are the number of grower seed lots with less than or greater than 5% Fusarium grain infection.
Max = maximum level of Fusarium grain infection (%) measured in each cereal crop type and region.

Levels of FHB infection and resulting Fusarium grain infection were prevalent across eastern Australia in 2022 but varied between regions. For example, in bread wheat the incidence of grain infection levels greater than 5% was most common in north-east NSW (54% of samples) followed by north-west and central-west NSW (both 39% of samples), then central-east NSW and Victoria (both 34% of samples) and south-west NSW (28% of samples). Fusarium grain infection levels in bread wheat greater than 5% were less prevalent in Qld (17% of samples) and south-east NSW (14% of samples) with the lowest level in South Australia (0% of samples; maximum 2% infection) from limited testing (10 samples) conducted from that state (Table 2).

WGD and resulting grain infection by *Eutiarosporella* spp., although detected in all regions except South Australia, was predominantly an issue within southern Qld bread wheat crops in 2022. In southern Qld, 19% of bread wheat samples had greater than 5% Eutiarosporella grain infection (Table 3). Eutiarosporella grain infection levels were only greater than 5% in one south-east NSW bread wheat, three south-west NSW durum and four north-east NSW durum grain samples (all maximum 8% infection)(Table 3).

Table 3. *Eutiarosporella* spp. (white grain disorder) grain infection levels in bread wheat, durum wheat and barley seed lots harvested across eastern Australia in 2022.

Region	Bread wheat			Durum wheat			Barley		
	<5%	>5%	Max	<5%	>5%	Max	<5%	>5%	Max
SE NSW	189	1	8%				4	0	0%
SW NSW	200	0	1%	54	3	8%	16	0	0%
CE NSW	215	0	4%	2	0	1%	21	0	0%
CW NSW	428	0	2%	0	2	0%	34	0	1%
NE NSW	175	0	5%	95	4	8%	24	0	2%
NW NSW	100	0	2%	16	0	2%	17	0	1%
Sth Qld	114	27	48%	1	0	0%	9	0	0%
Vic	107	0	2%	2	0	0%	9	0	0%
SA	10	0	0%	5	0	0%			

Values are the number of grower seed lots with less than or greater than 5% Eutiarosporella grain infection.
Max = maximum level of Eutiarosporella grain infection (%) measured in each cereal crop type and region.

Identifying FCR risk prior to sowing in 2023

It was recommended to test any paddock planned for a cereal-on-cereal crop for FCR risk prior to sowing in 2023, using either PreDicta® B (SARDI) or 'free' cereal stubble plating by NSW DPI with GRDC co-investment. This was particularly imperative in any paddock where FHB was noticed in 2022, as there is a high probability that the infection came from FCR in the base of plants. A random survey of 198 cereal crops conducted across central/northern NSW in 2022 found that 5% had nil (0%), 39% had low (1 to 10%), 26% moderate (11-25%), 16% high (26-50%) and 14% very high (>50%) FCR infection at the time of sampling during grain filling.

In total, growers and their agronomists collected and submitted for 'free' testing of FCR infection levels, 152 cereal stubble samples after harvest in 2022 (Table 4).

High (>26%) FCR infection levels were most prevalent in cereal crops in north-east NSW (100% of crops), then south-west NSW (89%), central-west NSW (75%), north-west NSW (63%), southern Qld (50%) and central-east NSW (42%) in 2022. The prevalence of high FCR infection levels was lowest in south-east NSW (31%), Victoria (29%) and South Australian (14%) cereal crops in 2022 (Table 4). This was important information for the collaborating grower and their agronomist who used this individual paddock data to consider appropriate management options. The picture provided by these two surveys of FCR infection levels in 2022 has further implications across regions given that the 2022 season did not favour FCR expression as whiteheads. FCR infection often goes unrecognised in wetter seasons when significant levels of whitehead expression does not occur. However, significant infection levels and inoculum build-up within retained cereal stubble still occurs. FCR inoculum load and, hence, disease risk in 2023 is a function of the percentage of plants infected in 2022 (Table 4) and the stubble load produced in that season. This is particularly concerning as much higher cereal stubble loads were produced in 2022 and the prediction of drier or even El Niño conditions in spring 2023 is likely to favour expression and yield loss from FCR infection. These levels of underlying FCR infection across the survey regions also appeared to have some link to the prevalence of Fusarium head blight within these same areas in 2022 (Table 2).

Table 4. Percentage of paddocks with varying levels of Fusarium crown rot infection across eastern Australia from 152 cereal stubble samples submitted post-harvest in 2022.

Region (no. crops)	Nil	Low	Medium	High	Very High
	0%	1-10%	11-25%	26-50%	>50%
SE NSW (26)	27	8	35	23	8
SW NSW (9)	0	11	0	33	56
CE NSW (12)	0	17	42	42	0
CW NSW (16)	0	6	19	56	19
NE NSW (17)	0	0	0	35	65
NW NSW (24)	0	17	21	29	33
Sth Qld (20)	0	35	15	25	25
Vic (14)	0	21	50	29	0
SA (14)	0	43	43	7	7
Total (152)	5	17	25	30	23
Data based on plating of 50 surface sterilised primary tillers/crop from cereal stubble collected after harvest in 2022.					

FCR integrated disease management, all options are prior to sowing so knowing the risk level within paddocks is important.

If medium to high FCR risk, then:
1. Sow a non-host break crop (e.g., faba bean, chickpea, canola).

If still considering sowing a winter cereal:
1. Consider stubble management options
2. Sow more tolerant bread wheat or barley variety (not durum)
3. Sow at start of recommended window for each variety in your area
4. If previous cereal rows are intact – consider inter-row sowing (cultivation is bad as it spreads inoculum)
5. Be conservative on N application at sowing (urea exacerbates FCR and ‘hyper yielding’ is potentially ‘hyper risk’ when FCR is present)
6. Apply zinc at sowing – ensure that crops are not deficient
7. Current fungicide seed treatment is suppression only – useful but limited control
8. Determine infection levels around GS39 to guide other in-crop management decisions.

Summary

Cereal disease management is heavily dependent on climatic conditions between and within seasons. Therefore, the situation can be quite dynamic, including the unpredictable distribution of different stripe rust pathotypes across regions. Arm yourself with the best information available including the latest varietal disease resistance ratings.

FCR risk is at record highs across much of the northern grain region. Widespread FHB in 2022 was predominantly the FCR fungus letting you know that it has not gone away with wetter and milder spring conditions the last few seasons. Do not ignore the signs. Did you know your FCR risk in paddocks planned for cereals in 2023, especially if sowing durum? We cannot keep banking on wet and mild spring conditions as our main FCR management strategy. Sowing seed with as low a level of Fusarium grain infection as possible was an important first step to maximising crop establishment but also restricting the level of FCR introduced into paddocks. However, seed is only one source of inoculum with retained cereal stubble still likely to be the dominant source of FCR infection in 2023. It is not too late to submit cereal stubble for ‘free’ testing to NSW DPI. This is particularly important for any cereal-on-cereal rotations and could be useful data to assist understanding of where FCR infection arose from if we have a season conducive to disease expression. Contact details below if you want further information around ‘free’ stubble sampling.

Keep abreast of in-season GRDC and NSW DPI communications which address the dynamics of cereal disease management throughout the 2023 season. Do not just focus on leaf diseases in 2023. Pull up a few plants randomly across paddocks when doing crop inspections and look for browning of the outer leaf sheathes and lower stems which is characteristic of FCR infection. Unfortunately, this is already being observed in cereal crops during the seedling stage in 2023.

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Further resources

PreDicta®B sampling procedure - https://www.pir.sa.gov.au/__data/assets/pdf_file/0007/291247/Sampling_protocol_PreDicta_B_Northern_regions.pdf

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Crown rot discussion

Notes

Farming system sustainability - grower and market expectations, risks and opportunities

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Notes

Finding profit in the face of increasing input and overhead costs, interest and land value

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Notes

SwarmFarm Robotics and sensors for spraying - a grower's experience.

Simon Doolin

Notes