GOONDIWINDI
QLD

TUESDAY
28 FEBRUARY &
WEDNESDAY
1 MARCH 2023

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

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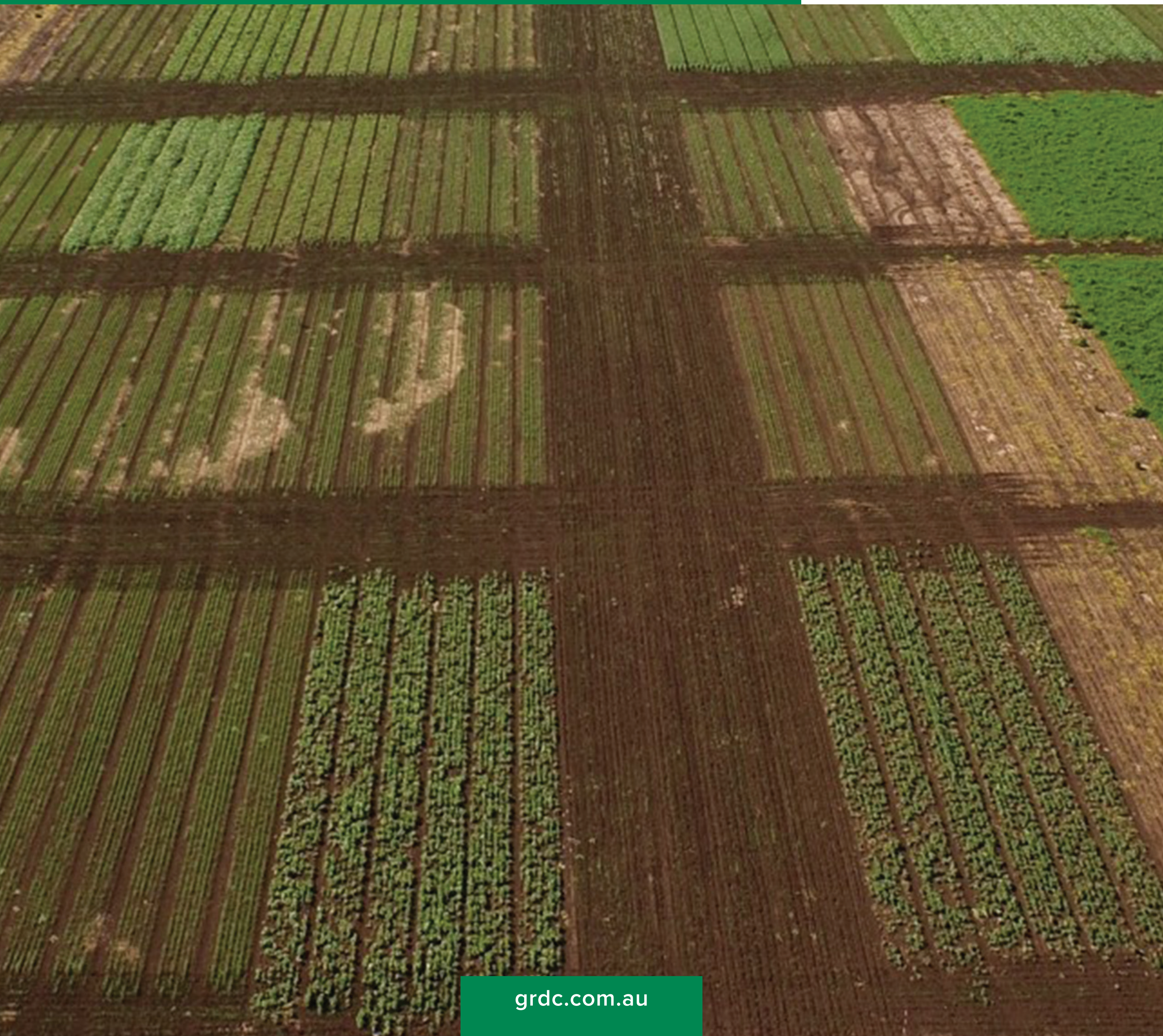
GRAINS RESEARCH & DEVELOPMENT CORPORATION



GRDC 2023 Grains Research Update Welcome

Welcome to the first of our 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

Day 1 Program: Tuesday 28 February 2023

9am registration for a 10am start, finish by 5:20pm

Time	Topic	Speaker(s)
9:00 am	Registration, morning tea & trade displays	
10:00 am	Welcome	*GRDC*
10:30 am	Farming system sustainability - grower and market expectations, ambitions, risks and opportunities	***Michael Anderson*** *(Graincorp)*
11:05 am	Key drivers of short & long-term profitability in different farming systems	***Lindsay Bell*** *(CSIRO)*
11:40 am	Maintaining long term soil fertility • The role of manure, legumes & N fertiliser strategy - lessons from farming systems research	***Jon Baird*** *(NSW DPI) &* ***Andrew Erbacher*** *(DAF Qld)*
12:20 pm	Lunch	
1:20 pm	Concurrent session 1 – *See concurrent sessions for details*	
3:05 pm	Afternoon tea	
3:35 pm	Concurrent session 2 – *See concurrent sessions for details*	
5:20 pm	Close	
7:00 pm	Networking dinner: O'Shea's Royal Hotel, 48 Marshall St (Supported by Adama & AGT)	

Day 2 Program: Wednesday 1 March 2023

7:30–8:20am early risers session. Day sessions 8:30am start, finish by 3:10pm

Time	Topic	Speaker(s)
7:30 am	EARLY RISERS DISCUSSION SESSION. In paddock decision-making on fungicide intervention • Interpreting the situation & decision-making for intervention under high inoculum loads • Varietal planning for 2023, disease resistance ratings and mitigating risk	***Steve Simpfendorfer*** *(NSW DPI)* ***Robert Park*** *(Uni of Syd, PBI)*, ***Lislé Snyman*** *(DAF Qld)*, ***Tim Poole*** *(Poole Ag Consulting) &* ***Hugh Reardon-Smith*** *(Nutrien Ag Solutions)*
8:30 am	Concurrent session 3 – *See concurrent sessions for details*	
10:15 am	Morning tea	
10:45 am	Concurrent session 4 – *See concurrent sessions for details*	
12:30 pm	Lunch	
1:30 pm	Future Farm & the potential value in data-driven N decisions	***Brett Whelan*** *(Uni of Sydney)*
1:55 pm	Nitrogen - strategies for building the pool and reducing losses • Organic vs different fertiliser N sources • Spread urea or drill it in? • How much N do legumes add? • A systems approach to N	***Chris Dowling*** *(Back Paddock Co.)*
2:35 pm	Panel session, including results from Colonsay long term nutrition site • How big have N losses been in recent years? • Managing NUE in and after wet to drowning years	***Mike Bell*** *(UQ)*, ***Chris Dowling*** *(Back Paddock Co.)*, ***Bede O'Mara*** *(Incitec Pivot Fertilisers) &* ***Brett Whelan*** *(Uni of Sydney)*
3:10 pm	Close	

Location & Timing of Concurrent Sessions

	Main auditorium (live streamed)	River room	Training centre
Day 1 – Session 1	Disease	Mental health & finding system profit	Cropping outside the box
Day 1 – Session 2	Cropping outside the box	Pick 'n' Mix	Disease
Day 2 – Session 3	Crop protection	Weeds	Pulses & sustainability
Day 2 – Session 4	Weeds	Crop protection	Pulses & sustainability

(Agenda subject to change)

Concurrent Sessions DAY 1

Disease (Sessions 1 & 2)

Session time 1 Live stream	Session time 2	Topic and Speaker(s)
1:20 pm	3:35 pm	Rust in 2023 & beyond *Robert Park (Uni of Syd, PBI)*
1:50 pm	4:05 pm	Cereal diseases - what could be done better in 2023? *Steve Simpfendorfer (NSW DPI) & Lislé Snyman (DAF Qld)*
2:50 pm	5:05 pm	Discussion

Cropping outside the box (Sessions 1 & 2)

Session time 1	Session time 2 Live stream	Topic and Speaker(s)
1:20 pm	3:35 pm	Companion cropping with wheat & chickpeas *Andrew Erbacher (DAF Qld)*
1:50 pm	4:05 pm	Experiences with summer sown chickpeas *Drew Penberthy (Outlook Ag)*
2:15 pm	4:30 pm	Advances in the biological control of flax leaf fleabane with a novel rust fungus *Ben Gooden (CSIRO)*
2:40 pm	4.55 pm	Silicon in cropping - should we care? *Chris Guppy (UNE)*

Mental health & finding farm profit (Session 1 only)

Time	Topic and Speaker(s)
1:20 pm	Looking after yourself to look after your clients in challenging times *Mary O'Brien (Are you bogged mate?)*
2:15 pm	Finding profit in the face of increasing input costs, interest and land value *Simon Fritsch (Agripath)*

Pick 'n' Mix (Session 2 only)

Time	Topic and speaker(s)
3:35 pm	Canola in northern farming systems • Varieties, time of sowing, flowering windows, phenology & legacy impacts *Lindsay Bell & Jeremy Whish (CSIRO)*
4:20 pm	PhD presentation: Root architecture • Impacts on late season crop development to improve yield & yield stability under water stress *Jack Christopher for Kanwal Shazadi (UQ)*
4:40 pm	Long coleoptile wheat • Can they deliver a longer sowing window & deeper seeding option? *Cameron Silburn (DAF Qld)*
5:05 pm	PhD presentation: • Spatial soil constraint diagnosis using remote sensing & soil data *Fathiyya Ulfa (UQ)*

Concurrent Sessions DAY 2

Crop protection (Sessions 3 & 4)

Session time 3 Live stream	Session time 4	Topic and Speaker(s)
8:30 am	10:45 am	Fall armyworm impacts by crop, management strategy & resistance *Melina Miles (DAF Qld)*
9:00 am	11:15 am	Effects of summer crop choice on root lesion nematodes, charcoal rot, AMF & winter crop pathogen levels - farming systems results *Steve Simpfendorfer (NSW DPI) & Andrew Erbacher (DAF Qld)*
9:40 am	11:55 am	Mice management strategies in the lead up to baiting and optimising bait effectiveness with different levels of background food *Steve Henry (CSIRO)*

Weeds (Sessions 3 & 4)

Session time 3	Session time 4 Live stream	Topic and Speaker(s)
8:30 am	10:45 am	The role & fit of new pre-emergent herbicides *Greg Condon (Grassroots Agronomy)*
9:05 am	11:20 am	Imazapic & diuron availability & toxicity in different soils *Michael Widderick (DAF Qld)*
9:30 am	11:45 am	Regulatory needs for green-on-green optical spot sprayers; & herbicide tolerance trait stacking *Rohan Rainbow (Crop Protection Australia)*
9:55 am	12:10 am	Crop competition effects on weeds & crops • Key trends from six years of research *Michael Widderick (DAF Qld)*

Pulses & sustainability (Sessions 3 & 4)

Session time 3	Session time 4	Topic and Speaker(s)
8:30 am	10:45 am	Grain farm sustainability • Can technology help monetise Australian grain farms sustainability? • Are there productivity rewards? *Alan Thomson (Hitachi Aust.)*
9:10 am	11:25 am	Mungbeans - are they a contributor or user of soil N? • Implications for nutrition in crop sequences *Doug Sands (DAF Qld)*
9:35 am	11:50 am	Swathing vs direct heading mungbeans - pros and cons *Jayne Gentry (DAF Qld)*
9:55 am	12:10 pm	PhD presentation: Pigeon pea • Temperature, photoperiod & radiation impact on flowering, biomass & yield in different pigeon pea varieties *Mahendraraj Sabampillai (UQ)*

Contents

Day 1 - Tuesday 28 February 2023

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General plenary day 1

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

Michael Anderson, Graincorp

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Notes

Short and long-term profitability of different farming systems - southern Qld

Lindsay Bell, Jeremy Whish & Heidi Horan, CSIRO

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.
- 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.
- While the last 6 years have presented a diverse range of seasons, this period in general has not favoured alternative farming systems compared to the Baseline.
- 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 over 6 years of data on each of these different 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 longer-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 2015-2020. This paper reports specifically on results from the two sites in southern Qld at Billa Billa (Western Downs, near Goondiwindi) and Pampas (Eastern Darling Downs near Brookstead).

System simulations and estimates of profitability

The different farming systems were simulated from 1957 to 2021 using APSIM. Soils used in simulations were those characterised at each location, and long-term climate data was 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 both sites are outlined in Table 1; each site varies in the crop choices, their sowing dates and soil water thresholds but the general rules dictating crop choice were constant.

Table 1. Rules associated with crop choice, crops available and their plant-available water threshold required to be sown in the Baseline and 3 modified farming systems at Trangie red and grey soil sites. * indicates that crop not included at that site in that system

System	Crop choice rules	Crops	Soil water threshold (mm PAW)	
			Pampas (PAWC = 250 mm)	**Billa Billa** (PAWC = 180 mm)
Baseline	No more than 3 winter cereals or sorghum in a row ≥2 yrs between chickpea	Wheat Chickpea Barley Sorghum Mungbean	150 150 150 150 100	90 90 90 120 *
High legume frequency	*As above +* Legume every second crop	*As above +* Fababean Fieldpea Soybean Mungbean	 150 150 200 	 120 * * 80
Higher crop diversity	*As in Baseline +* ≥1 yr break after any crop ≥50% crops nematode resistant	*As above +* Canola Sunflower Millet Maize Cotton Fieldpea	 200 150 120 200 200 	 150 90 100 * 150 90
Higher crop intensity	*As in baseline*	Wheat Chickpea Barley Sorghum Mungbean Fababean	100 100 100 100 70 *	50 50 50 100 70 90
Lower crop intensity	*As in baseline*	Wheat Chickpea Barley Sorghum Mungbean Cotton Millet Cover crop	200 200 200 200 150 200 	150 * 150 150 * * 50

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 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
Faba bean	382	341	40
Field pea	382	341	40
Canola	503	351	70
Soybean	607	305	55
Sunflower	1052	365	55
Maize	250	218	55
Millet	564	350	70
Cotton	1800[A]	774	280

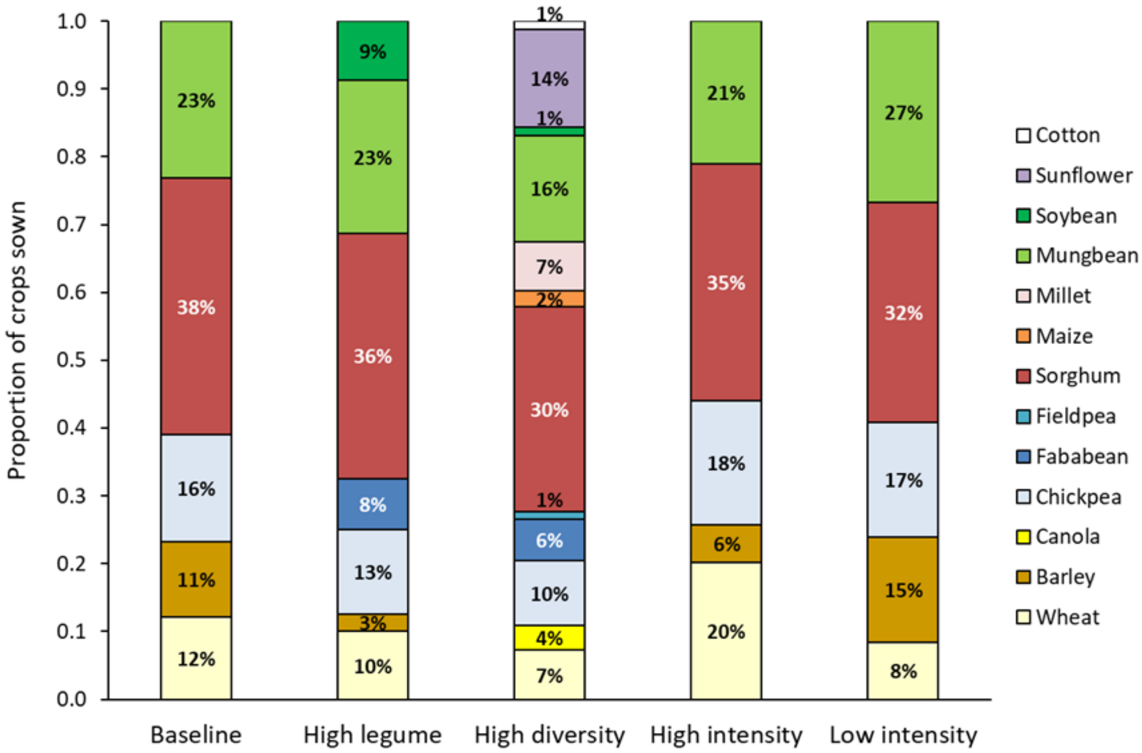
A – Calculated on total harvest assuming 45% cotton lint turnout and 55% seed.

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; for example, from 1957-1962, 1958-1963 and so on. Hence, we were able to compare what the simulations predicted would occur during the experimental period of 2015-2020 at Pampas and 2016-2021 at Billa Billa compared to more than 50 other 6-year periods. This allows 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 relative 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 amongst simulated systems

The simulation rules imposed (Table 1) resulted in some clear changes in the frequency and types of crops grown in the farming systems (Figures 1 and 2).

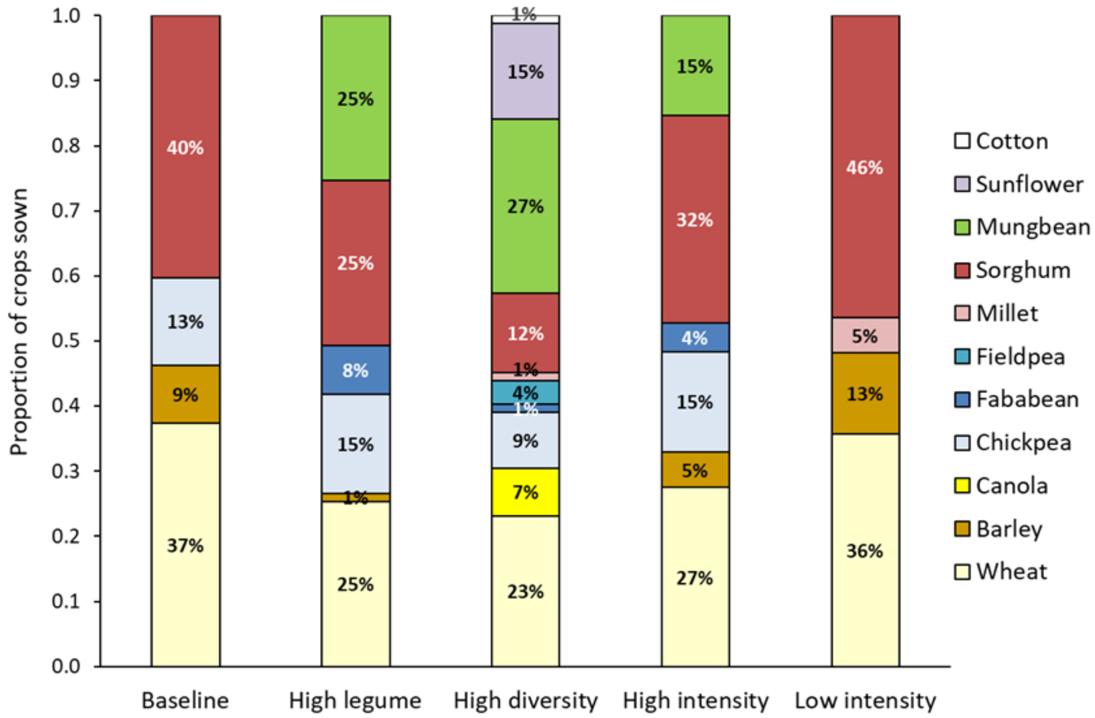
At the Pampas site, the *Higher legume* system resulted in some additional soybean crops and fababean replacing barley in the crop sequence (Figure 1). The *Higher crop diversity* system saw a drop in both legume and cereal frequency and less winter crops grown. Oilseeds increased to 20% of the crops grown - canola replacing barley and sunflowers replacing sorghum. Millet also often substituted for mungbean as a summer double-crop and maize occasionally replaced sorghum. The *Higher intensity* strategy (*i.e.,* lower soil water thresholds to sow crops) saw an increase in crop frequency by about 0.4 crops/yr (i.e., an additional 24 crops over the 60 year simulation), but the mix of crops was fairly similar to the *Baseline*. The *Lower intensity* system (*i.e.,* a higher soil water threshold to sow crops) saw the crop frequency drop by 0.2 crops/yr – less than might be expected; the proportion of different crops also remained fairly stable except early-sown barley often replaced wheat.



	Baseline	High legume	High diversity	High intensity	Low intensity
Crops/yr	**1.27**	**1.24**	**1.29**	**1.69**	**1.10**
% Winter	39	33	28	44	41
% Cereal	61	49	47	61	56
% Legume	39	51	34	39	44
% Oilseeds	0	0	19	0	0

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

At the Billa Billa site, the *Higher legume* system with the addition of mungbean crops as an option, saw them now constitute ¼ of crops sown, replacing sorghum but also allowing an increase in crop intensity (Figure 2). Fababean crops also replaced barley in the crop sequence (Figure 2). The *Higher crop diversity* system less winter crops 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 (i.e., from 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 2. Cropping intensity (crops/yr) and the proportion of different crops simulated under different farming system strategies at Billa Billa over the long-term.

Long-term predictions of system profitability

Figure 3 shows the range in average annual gross margin predicted over all the 5-year periods between 1957 and 2020 amongst the 4 different farming systems at both sites. These are arranged from the lowest to the highest to show the 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 either the *Baseline* or *Low intensity* systems, particularly under more favourable conditions. However, the *Higher intensity* system produces the lowest returns in the lower profit periods, particularly at Pampas. On the other hand, the *Low intensity* system (white circles) performs relatively well compared to *Baseline* and *Higher intensity* systems under the lower production and profit periods, exceeding them around 40% of the time.

The systems that alter the mix of crop (either *Higher legume* frequency or *higher crop diversity*) are predicted to generate higher profits reliably at both sites. In general, they achieve similar potential profits to the other systems in the lower profitability periods but potentially offer significant upside under more favourable conditions. In particular, these systems were able to offer a broader range of crop options to make use of seasonal rainfall and hence was more able to make use of additional crop opportunities when they occurred.

At the Pampas site the predicted returns over the experimental period (2015-2020) were in the lowest 10% of occurrences in all systems. Based on these predictions this indicates that we would expect relatively small differences in profit amongst the systems over this period and the lower intensity system may be more favoured relative to the other systems as a result.

In contrast the period of 2016-2021 at Billa Billa, was predicted to represent a median outcome (i.e., 50th percentile) amongst 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.

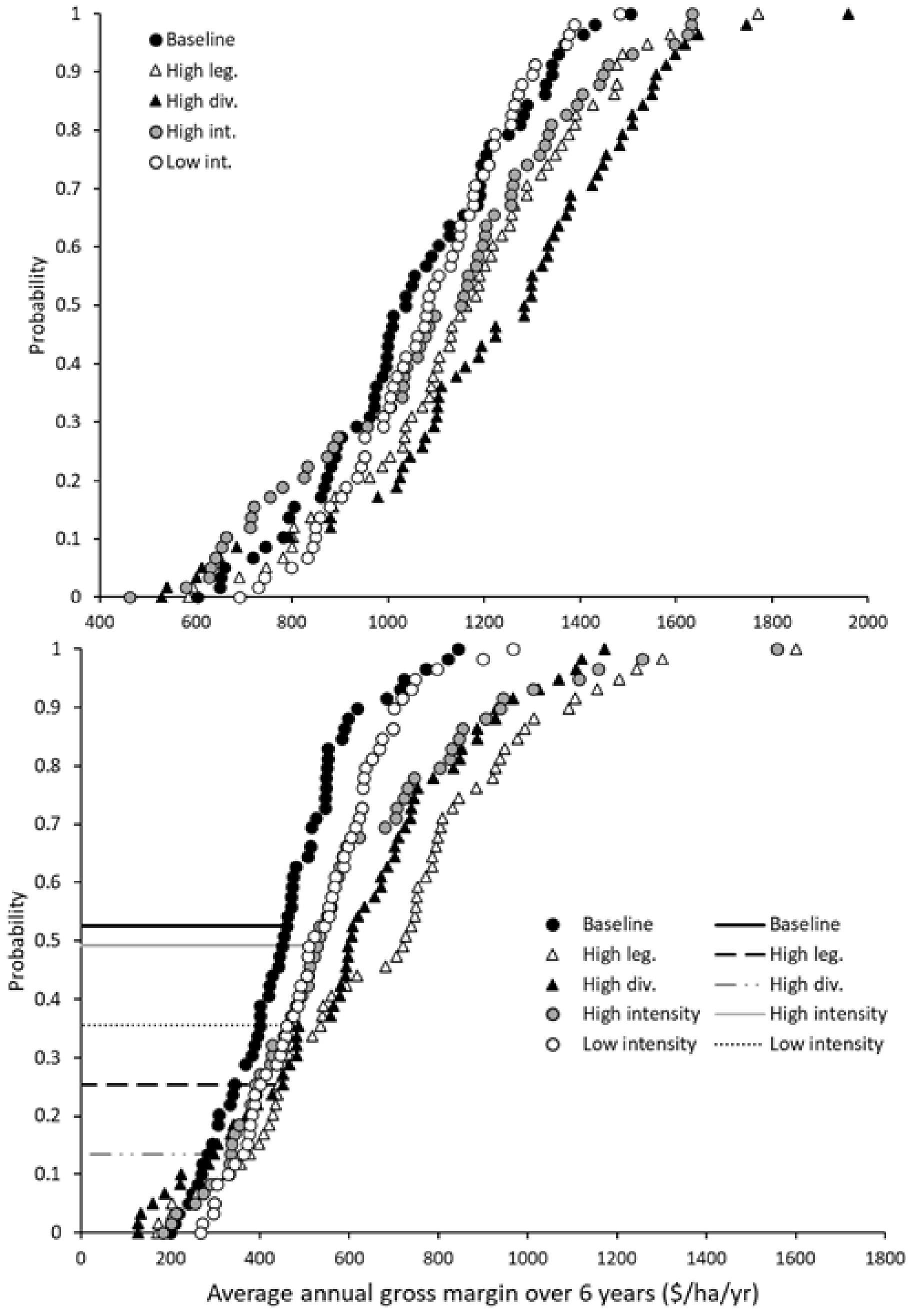


Figure 3. Distribution of simulated gross margins (average of 6-years) over 60 years period (1957-2020) of different farming systems strategies at Pampas (top) and Billa Billa (bottom). Each dot indicates the outcome of a 5-year period and the lines indicate the predicted GM for the 2015-2021 period.

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 systems frequently produce higher average returns (Figure 4). At both sites, the *Higher diversity* systems produced higher returns 85% of the time, *Higher legume* systems 70% of the time, *Higher and lower intensity* systems about 60-70% of the time. However, particularly at the Pampas site, the different intensity systems also had significantly lower profit in some periods.

When just comparing the modelled differences between the *Baseline* and the various other systems over the experimental period (indicated by the larger symbols in Fig 3), the predictions at Pampas were that the *higher intensity* system was predicted to be about $150/ha/yr behind, the *higher legume* system was predicted to be $70/ha/yr ahead of the *Baseline,* while the other two systems achieved similar gross-margins over that period (within $40/ha/yr). These predictions align very closely with the observed differences in calculated gross margins calculated over the same period using the experimental data (indicated with the vertical lines). The only exception is that experimentally the *Low intensity* has performed worse compared to the *Baseline* than was predicted by the model.

At Billa Billa, the *Low intensity* and *Higher intensity* systems in the experiments have 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 sown in the model simulations and hence subsequent crops then also performed better. 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.

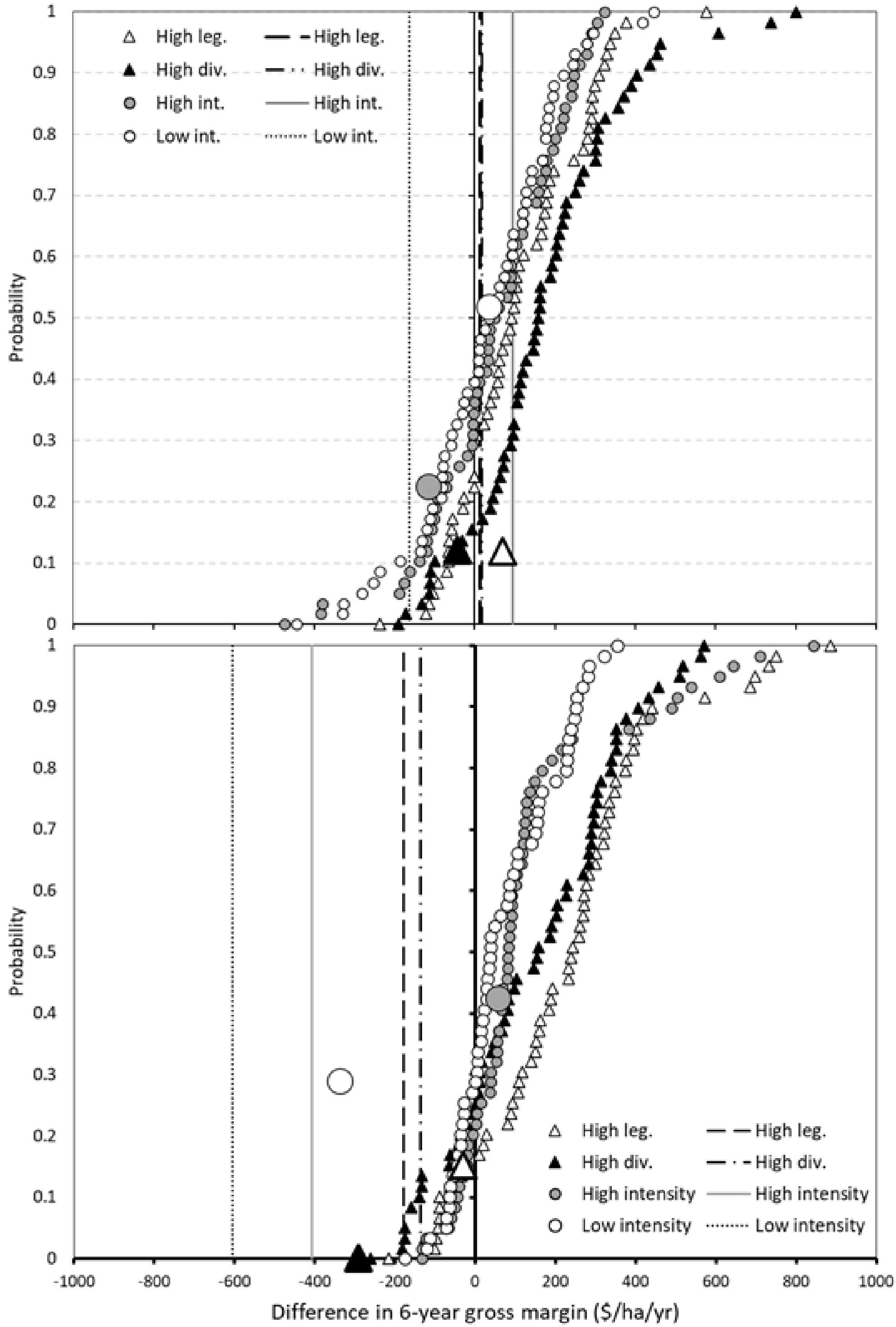


Figure 4. Difference in simulated 6-year gross margin between the *Baseline* and 3 modified farming systems at Pampas (top) and Billa Billa (bottom) between 1957 and 2020. Small symbols show the difference in annual returns over the distribution of the 54 different 6-year periods, the large symbols indicate the difference for a simulation of just the period of 2015-2020, and 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. The modelling predictions of the relative differences over the past 6 years correspond well with our experimental data over the same period. 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 which could add significant upside under more favourable growing seasons. Further examination of the influence of price variability 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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March 2023

Modifying farming systems in northern grains region – legacies, profit and risk of pulse and nitrogen strategies

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

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Key words

farming systems, nitrogen, pulses, economics, fertiliser

GRDC code

DAQ00192; CSA00050; DAQ2007-004RMX

Take home message

- Applying N fertiliser rates targeting high yields boosted long-term system productivity at three of the research sites compared to fertilising for a median crop yield
- 'Banking' soil N via a robust fertiliser N strategy can maintain higher soil N levels and reduce reliance on tactical fertiliser applications
- Over the long term, the profitability of systems growing 50% legumes can be equal or higher than current district *Baseline* systems
- Farming systems containing a high frequency of legume crops do not necessarily reduce fertiliser N use
- While legumes can provide inputs of N via fixation from the atmosphere, they can extract soil mineral N if it is available, similar to non-legume crops
- High yielding legumes will export N at a far higher rate than similar yielding cereals, often negating any N they have fixed
- Long term, soil mineral N reserves and system N balances are declining regardless of different farming system strategies, except where high N replacement has been applied
- Crops are more efficient at sourcing N from soil sources than applied fertiliser, so soil monitoring is essential to determine fertility levels to match crop requirements, and adjust for possible losses and trends over time.

Introduction

Long-term sustainability and profitability of farming systems need to evolve to manage the challenges of climate variability, increasing soil-borne pathogens, herbicide resistance and problem weeds, and 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 is looking at the long-term implications of different fertiliser application strategies and using more legumes in the farming system.

Nationally, legume (pulse) crops represent just 10% of the total cropping area (Pulse Australia 2023), with winter species dominating the pulse crop area in the northern cropping region. Legume crops both fix nitrogen (N) (via rhizobia symbiosis) and remove N from the system (via plant residues and grain). This creates a different dynamic to the overall farming system compared to that of non-legume crops. Given that N is a major variable cost in most farming systems with heavy reliance on off-farm sources (primarily urea), the effect of legumes on subsequent crops' N requirements, performance, and soil N balance can be significant. Understanding these impacts together with the legume crop profitability and risk are key to improving the future sustainability and profitability of farming systems.

The northern farming systems research project commenced in 2015 with long-term experiments at seven locations: a core experimental site comparing 38 farming systems at Pampas near Toowoomba, and a further six regional sites that included 6−9 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 core farming systems treatments implemented across the experimental sites: the local regional '*Baseline*' or current best management system, and systems with modified strategies which increase N fertiliser rates and legume crop frequency across the crop system.

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.

Over the seven 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.

Results

Grain productivity

High nutrient strategy

Applying the higher fertiliser rates strategy across seasons maintained higher residual N levels in the soil. The legacy of this higher soil fertility within the system provided a strong foundation for future crops to optimise production especially in average or above average rainfall seasons. At three of the seven regional sites, applying additional fertiliser in the *Higher nutrient* system increased grain productivity compared to the *Baseline* system. At these sites grain production was increased on average by half a tonne per hectare over the seven seasons (Figure 1). At other sites there was no positive response to the additional N applied, because the drier than average seasonal conditions meant that crop demand did not exceed supply provided in the *Baseline*, and hence the additional N was not required.

At one site (Trangie grey soil), grain yield was lower in the *Higher nutrient* system compared to the *Baseline*. In this example a lower yield was obtained in one crop year and in other crop years seasonal conditions were not favourable to take advantage of the extra soil N.

High legume frequency

Recently there has been increased plantings of grain legumes in cropping systems, driven in part by the profitable prices for pulses but also goals to reduce N fertiliser use and potentially improve soil health/fertility. The addition of legumes to the farming system had little to no influence on productivity over the seven years at most sites. However, we identified variability and a higher risk with the adoption of legumes as two sites – Pampas and Billa Billa which had lower system grain yield than the *Baseline* system. Grain legumes often produce lower yields than cereals but many have higher prices per tonne and hence, the economic outcome may look quite different to non-leguminous crops (Figure 2).

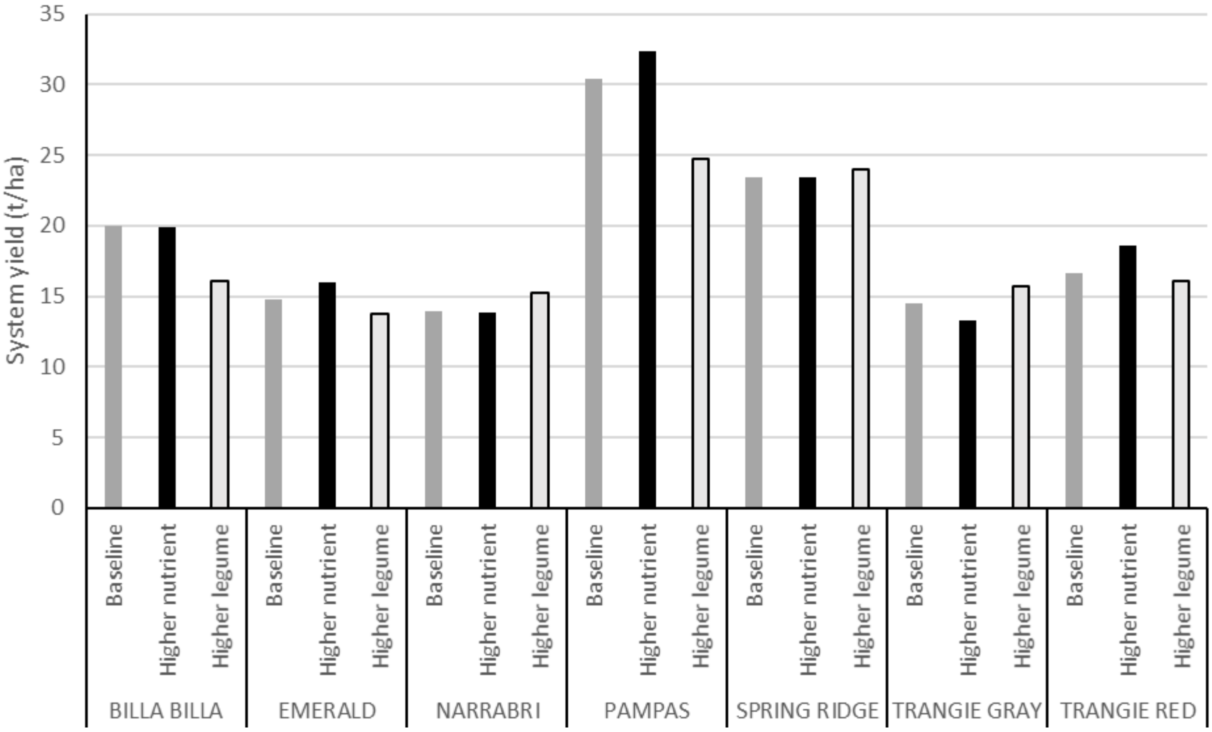

Figure 1. Grain production (t/ha) in the *Baseline*, *Higher nutrient*, and *Higher legume* systems over 7 years (2015−2021) at long-term farming systems experiments.

System Economics - profit/loss

Economic analysis of the farming systems was conducted using 10-year average grain prices (2011-2020) and general input/machinery/processing costs. System gross margins from the last six seasons show that while current growers' practices are performing well in their regions, several sites have improved returns by incorporating more legumes or applying more fertiliser for higher yield production (Figure 2).

High legume frequency

Over the 7 years, the *Higher legume* systems produced higher or equal returns at 5 of the 7 sites compared to the *Baseline*, while there was a small penalty ($500/ha) at 2 sites. For example, at the Spring Ridge and the Trangie red soil site, systems gross margins were >$1000/ha in the *Higher legume* system compared to the *Baseline* system (Figure 2). The higher gross margins are related to the higher grain value of legumes over this period. However, recently experience shows these high values can be variable; therefore, this advantage can disappear, reducing the profitability of growing legume crops. Growers should be aware of current grain prices and understand the often-higher input costs associated with high-yielding legumes.

High nutrient strategy

At only 3 of the 7 sites was there a benefit of growing higher grain yield with additional fertiliser application. Higher fertiliser input generated a greater cost to the *Higher nutrient* system, reducing long-term system profitability at the other sites where there was no grain yield response to the additional N applied. This analysis does not consider the value of N 'banked' in the soil. However, even with the added value, there were deficits to the gross margin compared to the *Baseline* system (Bell et al. 2022). Nonetheless, the cost of this high nutrient strategy is relatively small, equating to around $20/ha/yr. compared to the upside that can be achieved when seasonal conditions are positive.

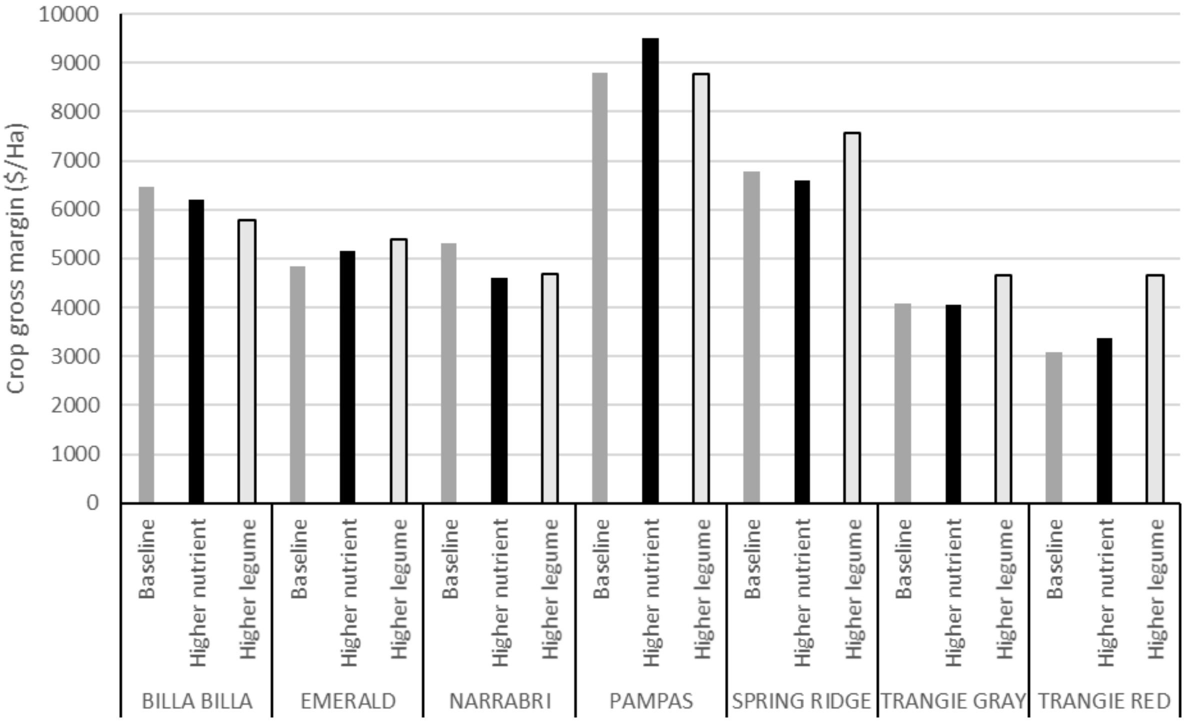

Figure 2. Cumulative crop gross margins over 7 years (excl. fallow costs) of the modified farming systems with additional fertiliser input and legume crops (2015−2021).

Legacy effects of legumes on crop yields and nitrogen use of following cereals

A closer investigation into the legacy of legumes in a farming system was conducted by examining particular crops and short-term sequences within the various systems across our experiments. Table 1 shows the grain yield and crop N use of subsequent crops grown after either a winter legume or non-legume crop. In addition, it highlights comparisons where the same crops were grown after a legume or cereal with similar moisture and fertiliser application rules.

Of the 7 comparisons, only 2 occasions saw an observable yield benefit following legumes compared to a non-legume crop. On all but one occasion the crop following the legumes also received a similar N application to meet the N budget predicted for that crop in that season. Typically crops grown after a legume crop had higher N use (i.e., the change in mineral N between sowing and harvesting plus applied fertiliser N). This was due to sourcing more N from the soil mineral pool and N derived from the legume's N fixation activity rather than applying higher fertiliser N rates.

Table 1. Legume crop influence on the following crop yield, N applied and used (applied fertiliser plus the change in soil mineral N) across various comparisons in farming systems experiments.

Site	Season	Crop	Previous crop	Grain yield (t/ha)	Applied N fertiliser (kg/ha)	Crop N use (kg N/ha)
Narrabri	2017	Wheat	Chickpea	2.4	76	129
			Fababean	2.2	76	112
			Canola	2.0	76	79
Spring Ridge	2017	Wheat	Chickpea	3.2	52	152
			Fababean	3.2	52	123
	2020	Wheat	Chickpea	4.8	27	139
			Canola	4.9	96	107
Trangie – grey soil	2018	Barley	Wheat	0.4	9	9
			Chickpea	0.1	9	9
	2020	Wheat	Canola	2.0	9	157
			Fababean	4.3	11	269
Emerald	2017	Wheat	Chickpea	1.8	26	93
			Wheat	1.6	26	43
	2020	Wheat	Chickpea	1.8	-	45
			Wheat	2.2	-	9

Farming system influence on fertiliser N input requirements

Current fertiliser prices are at record levels, so improving fertiliser recovery and efficiency is crucial to maximising growers' return on investment. Here we examine the degree that different farming systems have altered the N inputs required and the balance of N applied and exported over the 7 experimental years.

One aspect of the *Higher legume* system was to investigate whether additional legumes will maintain or improve soil fertility while at the same time reducing fertiliser input over the long term. At most sites, there was little if any change in the total fertiliser N required in the *Higher legume* system compared to the *Baseline* (Table 2). On average across all sites the *Higher legume* systems required 45 kg N/ha less over the 6 years than the *Baseline* (i.e. only 8kg N/ha/yr. less). This was because the legumes exported much more N from the system (Table 2), and this meant that there was little additional N cycled to offset subsequent N applications in non-legume crops. Spring Ridge is one site where the application of fertiliser input (N fertiliser) was significantly reduced under the *Higher legume* system compared to the *Baseline* system. This showed a potential saving in fertiliser use by growing more legumes in this region. However, soil N has also been extensively used during the same period (Figure 3), and therefore, growers need to monitor their soil nutrients to ensure native soil nitrogen use is not detrimental to long-term soil fertility.

A common theme across most farming system sites is that applying the higher fertiliser strategy clearly required additional N inputs (ranging from an additional 6 to 260 kg N/ha over the 6 years). However, the surplus N unused was retained in the soil and so maintained higher mineral N levels in the soil than the *Baseline* system – much of the additional N that was applied was retained and was available to offset N applications in subsequent crops (Figure 3). Maintaining a higher system N status via N banking is a potential management practice in northern farming systems to ensure greater yields can be achieved in high decile seasons. Lester et al (2021) found that fertiliser recovery can be improved when nitrogen is applied early in the fallow, and there is improved logistics for growers when they fertilise during lower labour demand period rather than at sowing or during the growing season. One implication growers need to be aware of when they apply fertiliser early in a fallow period, is the potential losses that may occur during the fallow, before the crop can utilise the N. For example, a severe weather event at Spring Ridge caused high mineral N loss in late 2019 when *Baseline* and *Higher nutrient* systems were in a fallow period and losses ranged between 203 and 152 kg N/ha (Figure 3).

Table 2. Fertiliser N applied and grain N exported from *Baseline*, *High nutrient* and *High legume* systems across 6 farming systems sites over 7 experimental years (2015-2021)

Location	Fertiliser N applied (kg N/ha)			Exported N (kg N/ha)		
	Baseline	Higher nutrient	Higher legume	Baseline	Higher nutrient	Higher legume
Billa Billa	18	77	23	417	451	430
Emerald	49	55	11	330	347	335
Narrabri	206	447	208	345	350	468
Pampas	155	337	80	498	538	556
Spring Ridge	307	446	146	482	496	450
Trangie Grey	63	169	89	235	287	322
Trangie Red	137	395	105	263	344	300

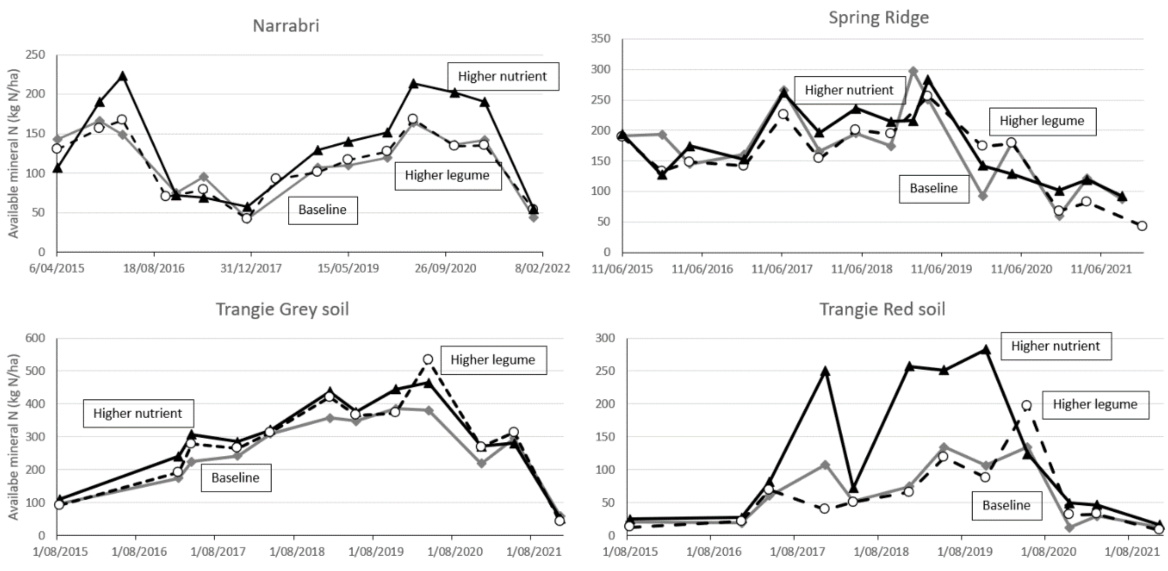

Figure 3. Mineral nitrogen long-term dynamics at Farming system sites in Northern NSW. The grey line and diamond marker are *Baseline* system, Black line and triangle is the *Higher nutrient* system, and the dashed line with open circle is the *Higher legume* system. Note y axis scale varies at each site.

Source of crop N use

For the three modified cropping systems across the seven experimental sites – *Baseline* (triangle), *Higher nutrient* (square) and *Higher legume* (circle), Figure 4 illustrates the source of N in terms of the percentage of the crop N used. The source of N is calculated over the experimental period (2015-

2021) for the proportion that was derived from either the starting soil mineral pool (i.e., the change in soil mineral N between the start and end of our sequence), applied fertiliser or was mineralised from the soil (i.e., N accumulated during a fallow or the balance of crop uptake not from fertiliser or soil mineral pools).

The study highlights the importance of cropping systems' efficiency in utilising N from stored organic sources. Most systems and experimental sites sourced at least 40% N from mineralised organic or stored N (spared N) rather than drawing down from starting N levels. This data supports findings from Daniel et al. (2019) where the efficiency of N grain recovery from soil N sources was ≈4 times greater than that of applied fertiliser N.

As stated before, incorporating more legumes resulted in crops utilising more N from mineralised N, attributable to the faster breakdown of legume residues that can be used in subsequent crops. This meant there is generally a lower reliance on using background N (starting N) and synthetic fertilisers.

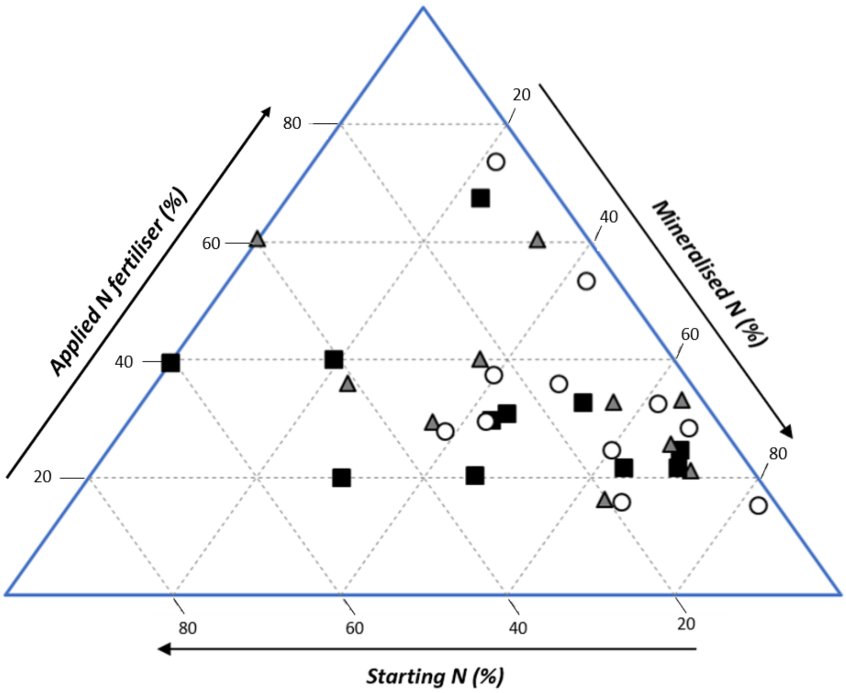

Figure 4. The source of N used by modified systems as a percentage of crop use. *Baseline* is grey triangles; *Higher nutrient* is black squares and *Higher legumes* is white circles. The dotted lines represent 20% levels of percentage for each N source.

Effect of crop choice on nitrogen export from a farming system

Previous reports from the Northern Farming Systems project have shown there is minor to no reduction in fertiliser application when legume crop frequencies were increased (Baird et al. 2019). This paper has shown that legumes increase cropping systems' N balance compared to cereals, with the majority of N sourced from increased cycling of N.

Crop N export rates help us understand the gap between system N balance and fertiliser input between legumes and cereals. High yielding legumes with a high harvest index will export N at a far higher rate than similar yielding cereals (Figure 5). The N export rate is significantly different for yields above 2.5 t/ha. For example, a legume crop yielding 5 t/ha will on average export 174 kg N/ha while wheat will export 110 kg N/ha.

Therefore, farming systems implementing more legumes should be mindful of the high use (and cycling) of N. It's recommended that growers monitor their soil N levels to ensure their systems won't be yield limited due to low soil N which may happen if a high loss event occurs. Knowing the current soil N status is always useful, rather than assuming that legumes will have left or contribute additional N to subsequent crops. The high N removal and potential to extract mineral N may in fact mean that legumes have little or no direct benefit or on occasion lower mineral N than following non-legume crops. The N balance outcome is largely dependent upon the grain yield (amount of N exported kg/ha) and peak biomass of the legume crop (directly related to the amount of N fixed kg/ha).

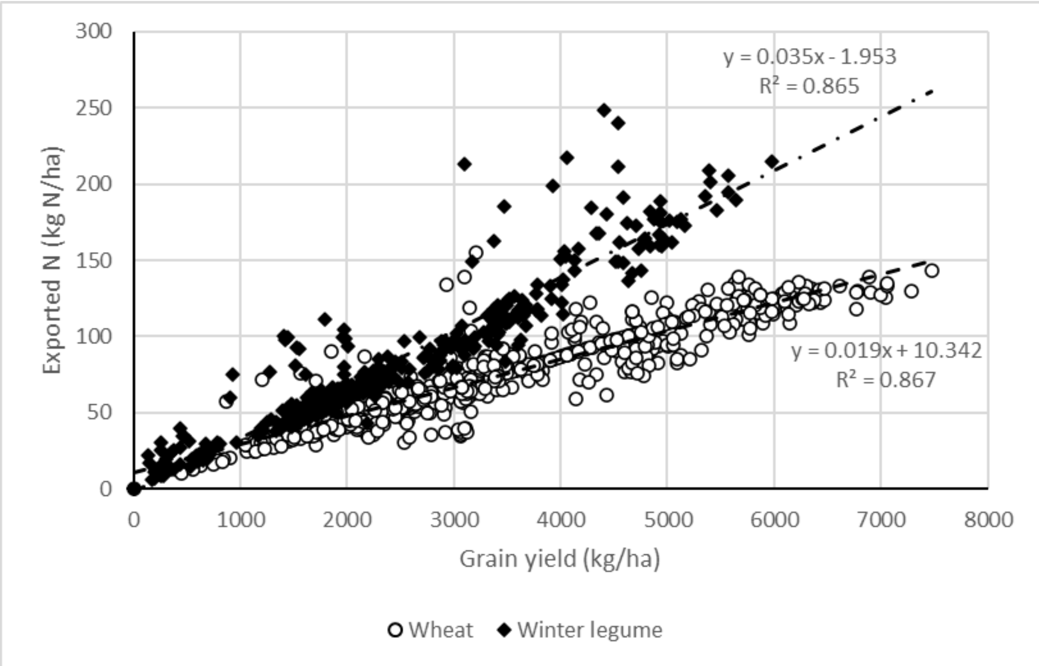

Figure 5. Crop export rates of wheat and winter legumes (including chickpea, fababean and field pea) from the farming system project (2015−2021).

Conclusion

Modifying farming systems can provide growers with potential improvements in yield and gross margins, but legacies need to be monitored as every system will have pros and cons. For example, adopting a system with a higher frequency of legumes will increase N cycling, but the system has higher export rates of N which ultimately result in no net benefit for N balance or a large offset of fertiliser N requirements.

Systems that include high application rates of N fertiliser maintain higher levels of background N, but this practice may not be economically viable at today's fertiliser prices and a positive return on investment is contingent on receiving favourable climatic conditions when the crop can convert the additional N supply into higher grain yields.

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Concurrent session – diseases

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

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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; for example, of many varieties of common wheat, durum wheat and triticale, stressing the need for careful varietal selection and preparedness given the heightened threat of rust in 2023.
- There have now been five documented incursions of stripe rust since it was first detected in Australia in 1979 (Ding et al. 2021). Three of these appear to have originated from Europe (1979, 2017 and 2018) and one North America (2002). These incursions have 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 incursion in 2002 (Wellings, 2007). The critical importance of thoroughly laundering clothing and personal effects after interstate or overseas travel cannot be emphasised enough.
- 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 and 2021 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 have not detected 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.

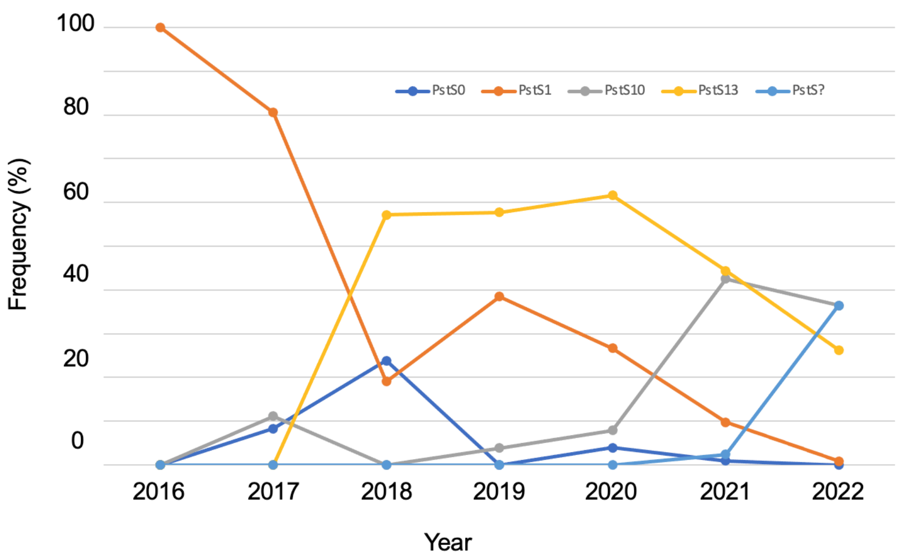

Figure 1. Frequency (%) of four internationally accepted DNA fingerprint MLG groups (PstS0, PstS1, PstS10, PstS13) of wheat stripe rust pathotypes, and a fifth as yet undefined group (PstS?) in eastern Australia, 2016 through 2022.

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 (aka strains) 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 prothioconazole, propiconazole and triadimenol. While tebuconazole is not registered for the control of leaf rust in barley, it is registered for scaled 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 known 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. These have included:

- 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 to 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 the complexity of host:pathogen interactions, genetic diversity of resistance must be seen as a key ingredient in large scale sustained control of plant diseases. It has been argued that even where specific or major resistance genes are used, genetic diversity can be used as insurance against lack of durability and hence, as a means of reducing genetic vulnerability. Above all, responsible use of resistance genes, which depends upon an understanding of the resistance genes 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). In addition to 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.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the author would like to thank them for their continued support. The national rust pathotype surveillance program, conducted by staff at the University of Sydney, involves active participation by many people including state-based regional cereal pathologists, scientists in universities and in the private sector, grain growers, and their critical contributions are gratefully acknowledged.

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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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2023: A TESTING year for cereal disease management!

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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
- Seed retained from any crop where FHB or white grains were evident in 2022 must be tested for Fusarium infection levels as it negatively impacts on germination and vigour
- Widespread FHB in 2022 is 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
- Do you know your FCR risk in paddocks planned for cereals in 2023, especially if sowing durum?
- 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 become 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. Deep breathe……

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 returns from multiple fungicide applications in susceptible varieties. However, what are the chances of still lighting the inside wood fire in November 2023?

2022 – What a season!

2022 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 a significant 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).

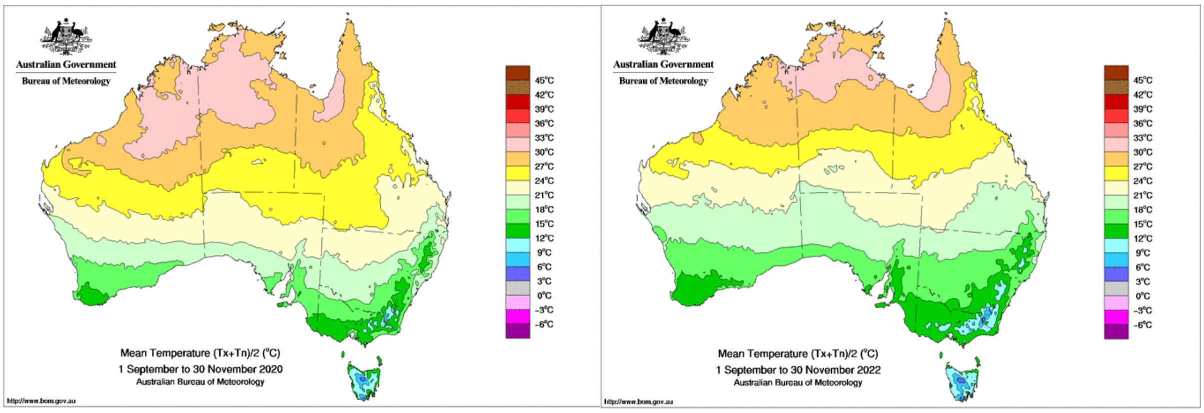

Figure 1. Mean daily temperature for spring (Sep-Nov) in 2020 (left) compared with 2022 (right).

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 milder 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	Latent period (opt. temp)
Stripe rust	12-20°C	10-14 days
Septoria tritici blotch	15-20°C	21-28 days
Wheat powdery mildew	15-22°C	7 days
Leaf rust	15-25°C	7-10 days
Yellow leaf spot	15-28°C	4-7 days
Fusarium head blight	20-30°C	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 phenology 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 was 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 longer 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 on your neighbours and the rest of industry. Yes, 'it blows'
- Stripe rust has a shorter cycle time in more susceptible varieties which equals increased 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 present 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 = increased 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!! (see Rob Park paper).

Keep the 2022 season in perspective

The 2022 season was the year for fungicides, especially in more susceptible varieties and with the mix of various 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., stops 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. Manage early leaf disease pressure in 2023 then adapt management to spring conditions. The most effective fungicide can often be 2-3 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.

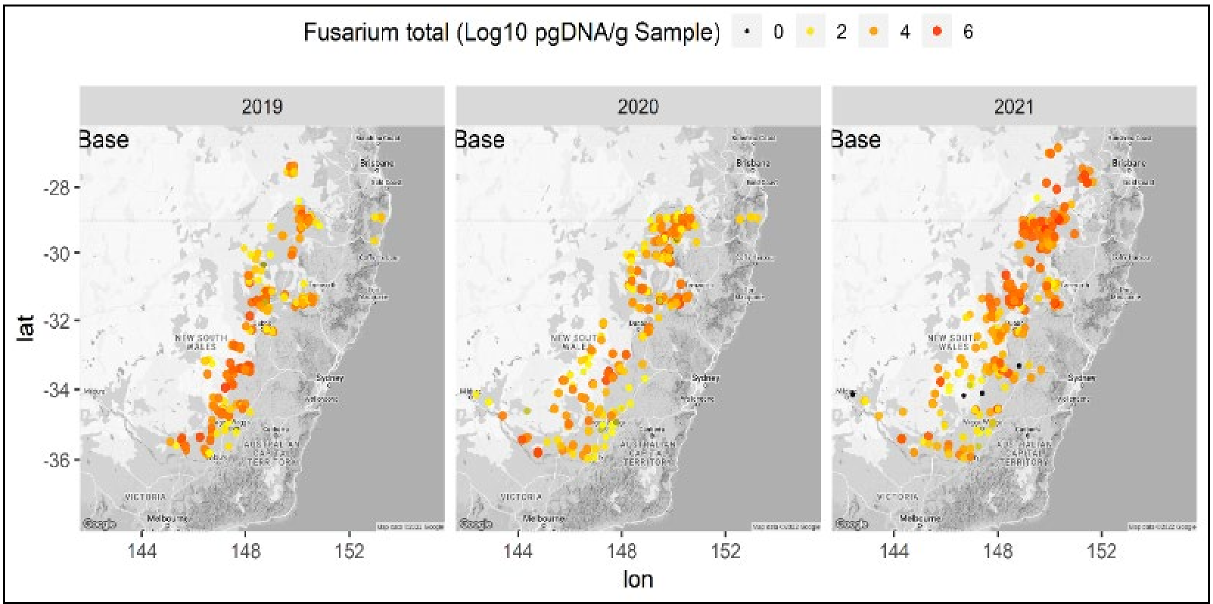

Figure 2. Levels of Fusarium crown rot within base of randomly surveyed winter cereal crops (2019 to 2021) as assessed using quantitative PCR of pathogen DNA levels – BLG208 and BLG207. Map from collaborative surveys conducted with Dr Andrew Milgate and Brad Baxter, NSW DPI Wagga Wagga.

Fusarium head blight (FHB) which caused premature partial bleaching of heads and white or pink grains was very widespread at varying levels across eastern Australia in 2022 along with white grain disorder in some regions (see separate FHB/white grain paper). Current testing of 218 head or grain samples indicates that ~79% of the FHB which occurred across NSW and southern Qld in 2022 was related to tiller bases infected with FCR. That is, Fusarium infection of wheat and durum 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. Do not ignore it. TEST, TEST, TEST!

Why is testing so important in 2023?

FHB was widespread in 2022 with implications for seed retained from infected crops. Fusarium grain infection reduces germination and causes 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 grain 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 is potentially a big issue. Do not assume, even if you have never tested seed before or thought things were fine with seed after 2021 which was also wet. The difference was the widespread levels of FHB in 2022. If you had any level of FHB in crops retained for sowing seed or noticed white or pink grain at harvest, then get a commercial germination and vigour test or send a sample to NSW DPI for ‘free’ Fusarium testing (see FHB paper) well in advance of sowing. Do not let 2023 be ‘the year of the re-sow’.

Testing of any paddock planned for a cereal-on-cereal rotation needs to be assessed for FCR risk using either PreDicta® B Sampling_protocol_PreDicta_B_Northern_regions.pdf (pir.sa.gov.au) or NSW DPI/LLS stubble plating (sampling bags available from LLS offices across NSW or contact author) prior to sowing in 2023. This is imperative in any paddock where FHB was noticed in 2022, as there is a high (79%) probability that the infection came from FCR in the base of plants. Yes, testing is painful and no doubt that some will just play the numbers from current testing of 2022 cereal crop infection levels across central/northern NSW. Of the 158 cereal stubbles assessed from the 2022 harvest so far, 34% had low (<10%), 27% moderate (11-25%), 20% high (26-50%) and 19% very high (>50%) FCR infection. However, FCR risk is very much dependent on the individual paddock, so is more like sending your neighbour for a prostate test to see if you will be okay! Trust me, testing cereal stubble and seed is less painful.

FCR integrated disease management options are all prior to sowing so knowing 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 a winter cereal;

1. Consider stubble management options
2. Sow more tolerant bread wheat or barley variety (durum is out)
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. Zinc application 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. Ensure you are sowing the best seed available based on testing. Do your own if you do not want to send samples away, simply count three lots of 100 random seeds and sow in separate spaced rows in the garden and see what comes up. Seed quality cannot be assured after the exceptional conditions in 2022, potentially seed retained from 2021 may be of better quality for planting in 2023. You don’t know if you don’t test. Do not do a whole paddock experiment to find out.

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. Do 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.

Keep abreast of in-season GRDC and NSW DPI communications which address the dynamics of cereal disease management throughout the 2023 season.

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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Fusarium head blight and white grain issues in 2022 wheat and durum crops

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Keywords

Fusarium head blight, Fusarium crown rot, white grain disorder, grain quality

GRDC code

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 messages

- Detection of Fusarium head blight (FHB) was widespread across eastern Australia in 2022
- White grain disorder (WGD, Eutiarosporella formerly Botryosphaeria) was also confirmed in some areas (mainly southern Qld)
- FHB and WGD can be confused with melanism (false black chaff) and stripe rust head infections. Use NSW DPI pathologists for correct identification
- FHB infection is a function of prolonged high humidity (>80%) during flowering and early grain fill
- FHB causes yield loss (up to 100%) but also potentially downgrading of grain due to production of mycotoxins in affected white or pink grains (deoxynivalenol, DON mainly) which can affect end use depending on the level of infection
- Retaining grain from FHB or WGD affected crops negatively impacts suitability for sowing so grain infection levels should be tested.

Where did it come from?

If caused by *Fusarium pseudograminearum,* then the Fusarium head blight likely came from basal infection of tillers from Fusarium crown rot. Rain splash transports spores on lower nodes into heads. If caused by *Fusarium graminearum*, then it likely came from air borne spores produced on maize or sorghum stubble or some grass weeds known to be hosts. It can also host on wheat and barley. However, climatic conditions during flowering through to soft dough are a key factor in disease development. Frequent rainfall, high humidity, and/or heavy dews or fogs that coincide with flowering and early grain fill periods favour infection and development of FHB and WGD. The most favourable conditions for FHB infection are prolonged periods (36-72 hours) of moisture (>80% humidity) and warm temperatures (20-30°C). However, infection does occur at cooler temperatures when high moisture persists for longer than 72 hours.

The abundance of inoculum and weather conditions during flowering determines the severity of FHB. The longer the wheat head stays wet during flowering and early grain development, the greater the chance of infection and increased severity. Early infections may produce spores that are responsible for secondary infections under optimum conditions for disease development, especially if the crop has uneven flowering due to late tillers or a prolonged flowering period due to cooler temperatures or phenology.

There is no information on the relative resistance of Australian wheat varieties to FHB with the exception that all durum varieties are very susceptible. The level of FHB infection is heavily related to climatic conditions during flowering with minor differences in flowering time potentially giving dramatic differences in the level of infection.

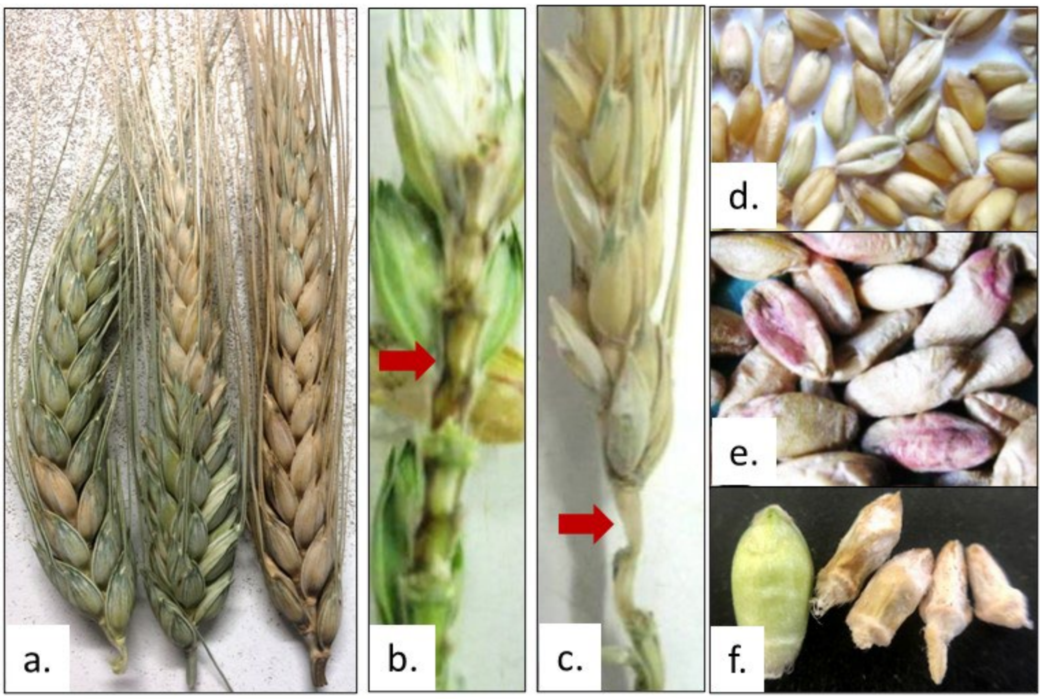

Figure 1. Correct diagnosis of Fusarium head blight and white grain disorder.

- **a.** FHB and WGD both cause partial bleaching or total bleaching of heads.
- **b.** If FHB is present, then the stem in the head (rachis) will be brown at the point where bleached spikelets attached.
- **c.** If WGD the rachis will be white where bleached spikelets attach.
- **d.** Both FHB and WGD cause production of white grains.
- **e.** If there is any pink coloration of grain, then this is diagnostic of FHB.
- **f.** Depending on infection timing, infected grains are often pinched and lighter and hence the majority blow out the back of the header at harvest. Try increasing header fan speed in infected paddocks or paddocks to be retained for seed. However, this only works if infection was early in the flowering/grain fill period and resulted in pinched grains.

Why is species identification important?

Knowing the Fusarium species of FHB or whether it is WGD is important to determining likely inoculum source and management going forward. FHB caused by *Fusarium graminearum* (*Fg*) likely produces larger quantities of more toxic forms of mycotoxins (15ADON and nivalenol) based on Australian studies in 2010 and 2016. FHB caused by *Fusarium pseudograminearum* (*Fp*) likely produces lower quantities of a less toxic form of DON (3ADON). WGD caused by *Eutiarosporella* spp. (*Eut*) produces no known mycotoxins (Simpfendorfer et al. 2017).

Species identification using quantitative PCR of 218 head or grain samples from 2022 submitted from across NSW and southern Qld shows FHB caused by *Fp* as the dominant issue (60% *Fp* only) followed by FHB caused by *Fg* (5% *Fg* only) and WGD caused by *Eut* (5% *Eut* only). Mixed infections occurred within some cereal crops with *Fp* + *Eut* (19%) most common followed by *Fp* + *Fg* (11%), *Fg* + *Eut* (1%) and *Fp* + *Fg* + *Eut* (1%).

Caution feeding infected grain to livestock

Take care when feeding *Fusarium* infected grain to stock. There are no specific Australian stock feed guidelines for mycotoxins. The US Food and Drug Administration (FDA) have guidelines that state: for the main DON toxin, advisory levels for food products consumed by humans is 1 part per million (ppm); 10 ppm for ruminating beef and feedlot cattle older than 4 months (cannot exceed 50% of diet); 10 ppm for poultry (cannot exceed 50% of diet); 5 ppm for swine (cannot exceed 20% of diet); and 5 ppm for all other animals (cannot exceed 40% of diet)(US Food and Drug Administration 2010).

Are there issues if retaining grain for sowing?

Absolutely because Fusarium and Eutiarosporella infection both reduce germination and can cause early seedling death (blight). Fusarium infected grain can also introduce Fusarium crown rot into clean paddocks through seed infection. The level of infection can be higher than the visual level of white or pink grains, as later infections may not discolour the seed. Up to 70% Fusarium grain infection has been measured in one durum wheat crop sent in from near Hillston from the 2022 harvest. So far, grain infection levels are generally much higher in seed retained from durum crops compared with bread wheat, highlighting their increased susceptibility to FHB. However, 20-30% Fusarium grain infection has been measured in a number of bread wheat seed sources retained from the 2022 harvest.

There are registered fungicide seed treatments to reduce the extent of seedling blight when sowing Fusarium infected grain. However, once infection levels get over 5% its best to try and find a cleaner seed source, if possible, as higher infection levels are also often linked to poor seedling vigour. Grading out lighter seed prior to sowing can also help as this will remove obvious severely infected grains.

Fungicide seed treatments will not eliminate Fusarium crown rot infections associated with sowing into infected cereal stubble or grass weed residues in a paddock and have no effect on FHB later in the season.

Could I have sprayed to stop it?

The only registered fungicide product to control FHB is Prosaro® 420 SC, which needs to be applied to protect the flowers at heading, follow label instructions. Research has shown that spraying at flowering (GS61) was more effective and had more yield benefit than spraying seven days before flowering. The anthers (flowers) are the primary infection site for *FHB*, so spraying before flowering provides reduced protection of these plant structures.

Overseas research has demonstrated the importance of spray coverage in FHB control, with twin nozzles (forward and backward facing) angled to cover both sides of a wheat head and high volumes of water (≥100 L/ha) being critical to efficacy. However, at best this still provides ~80% control. Aerial application gives poor coverage of heads and at best provides ~40 to 50% control. Some agronomists who used this application method in 2022 are questioning if the efficacy is even this high following their experience.

Prosaro® 420 SC is only usually applied to durum wheat (very susceptible to FHB) in parts of northern NSW which have dealt with FHB since 1999. Application to bread wheats has never previously been deemed economical but infection levels in many bread wheat crops in 2022 have challenged this thinking. Note, in north America strobilurin fungicides are not recommended from booting (GS45) onwards in paddocks with FHB risk as this can increase mycotoxin accumulation in infected grain (Chilvers et al. 2016).

Harvest considerations

Harvest order or separation – Infection levels vary from paddock to paddock. Ideally, each paddock's grain should be binned separately to optimise market opportunities. Based on assessments of FHB just after flowering, the harvesting of heavily infected paddocks or sections of paddocks may be abandoned or sold directly for feed. Alternatively, more heavily infected sections of a paddock may be harvested separately from the rest of the crop. Levels of FHB may also alter the priority in which individual paddocks are harvested. FHB damaged grain must also be stored properly to prevent further disease development. Grain infected with FHB with a moisture content greater than 13% should be dried to stop further mould and mycotoxin development.

Header set-up – Adjust header openings and wind so that shrivelled, light weight, infected grain is removed along with the stubble. This technique will also reduce the level of mycotoxins, if present, in the harvested grain and is one reason why high concentrations of toxins usually do not end up in harvested grain and eventually the milled product. However, this will not remove all infected seed, since some FHB infection occurs late in development of the grain, and these infected seeds may still be plump. This technique is also only an option when the rest of the grain is of good quality. In paddocks severely affected by leaf diseases (e.g., yellow spot), which are also favoured by warm moist conditions, separating shrivelled grain caused by leaf disease and FHB is not possible during the harvesting process.

Mixing with uninfected sections or paddocks – Sections of a paddock with low levels of FHB infection could be harvested separately and blended with uninfected grain from the rest of the crop to reduce infected seed below receival limits. Equally, grain from an uninfected paddock can be mixed with seed from an infected paddock if the combined grain remains below quality limits set at the receival point. This practice may be too risky if trying to mix grain harvested from a paddock heavily infected with FHB. A combination of gravity grading followed by blending with uninfected grain may be required under moderate disease levels.

Gravity grading – This technique can be used to remove a large proportion of the light weight, pinched, chalky white and/or pink FHB infected grain before delivery to the silo to hopefully limit downgrading or allow delivery. This technique may also reduce the level of Fusarium grain infection if retaining seed for sowing. This technique is probably not viable under severe infection from FHB when most of the grain is diseased.

Human safety precautions – FHB damaged crops can be harvested and handled safely, provided normal precautions are taken to avoid exposure to grain dust. Grain dust is a hazardous substance, regardless of whether the Fusarium fungus is present. Various fungi and moulds in the dust can cause allergic reactions and lung irritation, and prolonged exposure can lead to serious breathing problems. Growers should take all the same precautions they would if handling mouldy grain. These precautions include using masks, goggles and protective clothing.

Summary

The 2022 season with prolonged high humidity (>80%) during flowering and grain fill was extremely conducive to FHB and WGD infection and development. Extended cool conditions which prolonged the flowering period were also likely a big factor in the increased prevalence of FHB and WGD this season.

If FHB is the result of basal infection of Fusarium crown rot, then the underlying issue needs to be rectified through an integrated disease management plan including crop rotation. Determining the cause of FHB or WGD is important when providing appropriate future management advice. In the majority of situations tested so far it was the FCR fungus (*Fp*) reminding us that it does not go away in wet years. If grain fill conditions had been hot and dry what would the level of whitehead expression and yield loss from FCR been in your crop?

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Further information

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Testing of grain infection levels

Send 200-250 g seed in plastic double zip lock bags with variety and location to Steven Simpfendorfer at Tamworth laboratories (above). No charge as funded by GRDC project.

Pre-sowing paddock FCR/FHB risk

PREDICTA®B soil/stubble testing available through SARDI.
Sampling_protocol_PreDicta_B_Northern_regions.pdf (pir.sa.gov.au)

Or alternatively contact Steven Simpfendorfer or your Local Land Services office about stubble testing.

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Barley diseases – an autopsy of 2022 and what could be done better in 2023?

Lislé Snyman, Dept. Agriculture and Fisheries Queensland

Key words

barley, leaf rust, powdery mildew, smut, fungicide resistance, disease management

GRDC codes

National Variety Disease Screening (NVT)

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

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

Take home message

- High levels of leaf rust and powdery mildew were present in 2022 barley crops
- Wet conditions over summer favoured survival of pathogens on the green bridge
- Managing the green bridge will limit disease load of rust diseases early in the season
- Management strategies for foliar diseases includes resistant varieties, crop rotation, seed treatment, regular crop monitoring and timely fungicide application
- Resistance to fungicides have previously been reported in powdery mildew, net form net blotch (NFNB) and spot form net blotch (SFNB) in Australia and more recently in the leaf rust pathogen of both barley and wheat
- Fungicide resistance development should be managed by using an Integrated Disease Management (IDM) strategy.

Background

Above average rainfall from November 2021 onwards resulted in a green bridge over summer favouring the survival of biotroph pathogens such as leaf rust. As a result, high loads of inoculum were present early in the 2022 cropping season. Environmental conditions remained favourable for disease establishment and spread throughout autumn and winter. Many barley crops were severely impacted by foliar diseases. Leaf rust and powdery mildew were the most widespread diseases present, with net form of net blotch (NFNB) observed mostly in the variety RGT Planet⟮D. As in previous years, smut was present in some crops.

Leaf rust

Leaf rust of barley is widely distributed and occurs in all Australian barley-growing regions. It is considered one of the five major barley diseases in Australia and can significantly reduce yield and quality. Yield losses in excess of 50% have been reported under experimental conditions.

A new pathotype of leaf rust (5457P+), virulent on *Rph3* was identified in eastern Australia in 2009. (Cereal Rust Report 2009, Vol 7, Issue 5). This virulence is present in all major production areas. The emergence of this pathotype had a major impact on not only production, but also on barley breeding as it rendered a large portion of elite breeding material susceptible. Many current commercial varieties are still reliant on *Rph3* (Cereal Rust Report 2020, Vol 17, Issue 1).

Barley leaf rust was widespread in Queensland in 2016, but due to the prolonged drought conditions, was only present at very low levels until 2021. In the presence of a green bridge, the pathogen can survive over summer and be present at high levels early in the growing season.

Environmental conditions favourable for disease establishment and spread have led to an increase in leaf rust inoculum. Leaf rust is favoured by temperatures ranging between 15°C and 22°C and prolonged periods of leaf-wetness. Conditions remained favourable until late spring, resulting in heavy disease levels in commercial crops.

The disease is caused by the obligate parasite, *Puccinia hordei.* It spreads by means of airborne spores that have the ability to travel long distances. The pathogen spreads rapidly when conditions are favourable and large areas are planted to susceptible varieties, resulting in the development of epidemics. High inoculum levels put pressure on major resistance genes and can lead to the development of new, more virulent pathotypes.

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

Powdery mildew

Powdery mildew (*Blumeria graminis* f. sp. *hordei*) is a disease synonymous with barley cultivation in the northern region. Under mild and humid conditions, it will infect leaves and leaf sheaths of plants eventually covering them with white, fluffy mycelium and conidia. Generally, it does not persist once conditions turn to warm and dry, consequently, in our environment yield loss is usually less than 15%.

Powdery mildew survives between seasons on barley stubble and on volunteer plants. Once conditions become less favourable, the pathogen forms fruiting bodies (cleistothecia) in existing colonies. These are visible as small brown and black spheres which persist until the new growing season. When cleistothecia mature and conditions are favourable, they release ascospores to infect the new crop. These soon produce conidia (asexual spores) that spread the disease within and between crops.

Unless a variety is very susceptible to powdery mildew it is unlikely that the disease will progress to upper leaves of adult plants. In susceptible varieties where yield potential is high, fungicidal control can be justified. In 2022, environmental conditions remained favourable until late in the season, resulting in very high infection levels in susceptible varieties.

Powdery mildew resistance in Australia has a history of breakdown. Varieties such as Commander⊕, Compass⊕, La Trobe⊕ and Shepherd⊕ were all resistant when released; but changes in the powdery mildew population have rendered these susceptible. Continuous monitoring of the powdery mildew population provides knowledge on the virulences in the Australian powdery mildew population. This information guides the breeders when choosing resistance sources and facilitates screening of breeding material with relevant virulences.

Smut

Smut in barley crops has been increasing in recent years, with both forms detected in crops annually. Varieties of the Hindmarsh⊕ lineage e.g., Hindmarsh⊕, La Trobe⊕ and Rosalind⊕, are particularly prone to loose smut infection.

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

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

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

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

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

Fungicides - resistance risk and timing

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

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

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

Higher disease pressure indicates larger pathogen populations and increased probability of developing resistance to fungicides.

In Australia, fungicide resistance in barley pathogens has been identified to date in powdery mildew, spot form net blotch and net form net blotch. Most recently fungicide insensitivity has been reported in leaf rust of both barley and wheat in Australia (Cereal Rust Report 2022, Vol 19, Issue 3). This will have a major impact on the management of leaf rust epidemics in cereal crops in future.

Fungicide resistance can be managed through the use of an integrated disease management (IDM) strategy to reduce disease pressure and reliance on fungicides. Relying on:

- Resistant varieties
- Crop rotation
- Clean seed
- Green bridge management
- Stubble management

- Use fungicides only when necessary and apply strategically
- Rotate and mix fungicide MoA groups
- Monitor regularly for disease - fungicides are more effective at lower disease levels.

Conclusion

Barley foliar pathogens cause devastating yield and quality loss worldwide. Research has proven that the more susceptible a variety, the bigger the yield and quality loss resulting from disease. Thus, growing a susceptible variety increases risk and requires dedicated effort towards persistent monitoring and decision making. The presence of a green bridge will present an opportunity for many pathogens to survive over summer (e.g., rusts which require a green host for survival) and be present at high levels early in the growing season. Thus, the green bridge will need to be carefully monitored and appropriate measures taken to reduce inoculum load at the start of the season.

Planting barley on barley will increase the risk and disease pressure of stubble-borne pathogens and may aid the survival of fungicide resistant individuals. Growing resistant varieties is the most cost-effective and eco-friendly method of preventing yield loss. The most up-to-date disease ratings are available on the NVT website (https://nvt.grdc.com.au/nvt-disease-ratings).

The epidemiology of the pathogen, the biology of the host and environmental conditions all impact disease management. Foliar fungicides are very effective but need to be applied early in the epidemic as disease can increase rapidly. The use of an IDM approach will not only limit the development of fungicide resistance but will also reduce economic input and support sustainable farming.

Further reading

Australian Fungicide Resistance Extension Network (AFREN): https://afren.com.au/resources.

Cereal Rust Reports: https://www.sydney.edu.au/science/our-research/research-areas/life-and-environmental-sciences/cereal-rust-research/rust-reports.html

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⑪ Varieties displaying this symbol beside them are protected under the Plant Breeders Rights Act 1994.

Companion cropping wheat with chickpea to improve fallow efficiency

Andrew Erbacher & Doug Sands, DAF Qld

Key words

companion crop, intercrop, cover crop, wheat, chickpea

GRDC code

DAQ2104-006RTX

Take home message

- Wheat and chickpea can be grown as companion crops without a yield penalty in Queensland farming systems reliant on stored soil water for grain yield
- Planting rates and row spacings need to be adjusted to manage crop competition by the more competitive partner (wheat).

Background

It is widely accepted that chickpeas are well suited to Queensland growing conditions and as a result generate significant gross margins for our grain growers. Their popularity is stymied by the fact that the residual stubble of this crop is sparse and leaves the soil quite bare. This bare soil then reduces our fallow efficiency (amount of fallow rainfall captured and stored for use by the next crop), which is a big problem in an area that relies on stored soil water for yield.

The DAF research agronomy team recently completed a study growing cover crops in the fallow to improve ground cover and soil water available for the next crop. That study highlighted the value of ground cover in the system. As an extension of this work, the companion cropping concept extends the opportunity to grow a cover crop alongside our chickpeas.

The idea of companion crops or intercropping is not new or novel. Companion crops are found in every home vegetable garden; from marigolds to keep the pests out of tomatoes, or flowers to attract pollinators into the pumpkin patch. What is novel is applying this concept on a broadacre scale and with mechanically harvested crops.

A recent review of Australian intercropping research (Roberts et al 2022) showed potential to increase crop productivity. They found cereal-legume intercrops increase productivity by an average of 14%, and pea-canola increased productivity by an average of 31%.

Similarly, Fletcher et al (2016) showed potential to increase crop productivity with intercrops; particularly with 'peaola' (canola and field pea), which increase productivity by 50% in 24 of 34 studies reviewed. They also found cereal-legume intercrops to increase productivity in 64% of studies.

The studies in these reviews were from temperate cropping areas of southern Australia and internationally, so the question remains whether these systems will perform in a sub-tropical environment and a farming system reliant on stored soil water for yield stability.

We focused our efforts on wheat and chickpea given our reliance on stored soil water for maintaining grain yield and the fallow efficiency cost of low stubble cover following chickpea.

The research question was two-fold:

1. Can we increase stubble cover after chickpea?
2. What is the yield impact of growing wheat and chickpea together as companion crops?

What was done

Our objective of increasing ground cover after chickpeas was discussed with growers and agronomists at both Goondiwindi and Emerald and treatments (Table 1) were developed for each site. The challenge of growing these two crops so that the more competitive (wheat) crop doesn't dominate, was discussed at length.

The Emerald group also identified a four-week difference in the ideal planting windows for wheat and chickpea. Two plantings were used where an 'early' planting favoured the wheat and a 'late' planting favoured the chickpeas. Companion crops were then duplicated to match both of these planting dates as well as a relay planting treatment where the chickpea was planted between established wheat rows.

Cover crop treatments were also planted at these sites as another approach to improving ground cover after chickpea. Cover crop treatments were either traditional cereal cover crops in the fallow, or companion planted wheat and chickpea with one crop being sprayed-out prior to flowering.

Both sites had wheat planted across the whole site in the following winter season (2022) to measure yield impacts of the different cropping systems.

Treatments were reviewed and a second companion crop trial was planted in the 2022 winter growing season (Table 2).

Table 1. 2021 companion cropping treatments at Emerald and Goondiwindi

	Emerald	**Goondiwindi**
1	Wheat (control) (early)	Wheat (control)
2	Chickpea (control) (late)	Chickpea (control)
3	Chickpea followed by a cover crop	Chickpea followed by a cover crop
4	Early chickpea/wheat mixed, spray out chickpea	Chickpea/wheat mixed, spray out chickpea
5	Late chickpea/wheat mixed, spray out wheat	Chickpea/wheat mixed, spray out wheat
6	Early wheat/chickpea alternate row 25 cm	Chickpea/wheat, alternate rows
7	Early wheat/chickpea alternate row 50 cm	Chickpea/wheat, mixed within rows, 50:50
8	Early wheat/chickpea mixed within rows 25 cm	Chickpea/wheat, mixed within rows, 67:33
9	Wheat/chickpea relay cropped	
10	Late wheat/chickpea alternate row 25 cm	
11	Late wheat/chickpea alternate row 50 cm	
12	Late wheat/chickpea mixed within rows 25 cm	

Table 2. 2022 companion cropping treatments at Emerald and Goondiwindi

	Emerald	**Goondiwindi**
1	Wheat (control) 50 cm	Wheat (control)
2	Wheat, narrow rows (25 cm)	Chickpea (control)
3	Chickpea (control) 50 cm	Chickpea followed by a cover crop
4	Chickpea, wide rows (100 cm)	Chickpea/wheat, narrow alternate row, spray out chickpea
5	Chickpea followed by a cover crop	Chickpea/wheat, narrow alternate row, spray out wheat
6	Chickpea/wheat, narrow alternate rows, spray out wheat	Chickpea/wheat, narrow alternate row, spray out wheat earlier.
7	Chickpea/wheat, narrow row; 3 wheat: 1 chickpea, spray out wheat	Chickpea/wheat, alternate rows
8	Chickpea/wheat, relay cover: wide chickpea, with narrow wheat on next rain, spray out wheat	Chickpea/wheat, narrow alternate rows
9	Chickpea/wheat, alternate rows	Chickpea/wheat, mixed within rows, 50:50
10	Chickpea/wheat, narrow alternate rows	Chickpea/wheat, mixed within rows, 67:33
11	Chickpea/wheat, mixed within narrow rows, 50:50	Chickpea/wheat, mixed within rows, 80:20
12	Chickpea/wheat, mixed within narrow rows, 67:33	Chickpea/wheat, mixed within rows, 90:10

Standard row spacing was 50 cm at Emerald and 30 cm in Goondiwindi. For 'narrow rows' the inter-row fertiliser unit was used at both sites (25 cm Emerald and 15 cm in Goondiwindi). This gives us a commercial comparison to wheat and chickpea in separate boxes of the air-seeder plumbed to deliver seed to alternate rows (alternate row treatments); planting one crop, then nudging GPS and planting the second crop between the rows as a second pass (narrow alternate rows); and mixing the seeds in the same seed-box (mixed within rows).

Each species tested in the companion configuration was grown as a monoculture at the same time as a baseline yield comparison. These monoculture treatments were planted at standard commercial rates (1 million plants per hectare for wheat and 250,000 plants per hectare for chickpea). The 'cover crop' treatments were planted at a full rate of each crop, so the harvested population was the same as the monoculture treatments.

The companion treatments where both crops were harvested together had planting rates reduced to reflect a normal plant density. For alternate row treatments the in-row population was the same as the monoculture controls. The 'mixed' treatments were mixed in proportion to recommended planting rates. For example, 'mixed 50:50' had 500,000 wheat plus 125,000 chickpea plants per hectare spread evenly across all rows.

In the 'cover crop' treatments, one species was terminated (sprayed-out) before flowering occurred with herbicides registered for in-crop weed control in wheat or chickpea.

The monoculture crops will have different yield potentials, so it would be expected that combined yields of companion crops will be between the two monoculture crops being compared. In that situation it would be difficult to assess whether a benefit/penalty was achieved. Therefore, the crop yields were converted to a percentage of the monoculture crop, then they can be added together. This combined percentage is called a land equivalent ratio (LER). An LER of 100% (i.e., 60% wheat + 40% chickpea) suggests the same grain yield would have been achieved by splitting the area planted into separate paddocks of monocultures. An LER of 80% would mean there was antagonism between the crops resulting in a 20% reduction in yield, whereas our hope is to achieve an LER greater than

100%. For example, 70% wheat plus 50% chickpea equals 120% LER, which would require 20% more land planted with monocultures to harvest the same amount of grain.

Trials in Emerald were grown on the Emerald Research Facility in both 2021 and 2022. Goondiwindi trials were near Billa Billa (40km north) in 2021 and near Kioma (60km north west) in 2022.

Results

Goondiwindi 2021

Wheat monoculture yielded 2.2 t/ha, which was 0.7 t/ha more than the chickpea monoculture in the same season (1.5 t/ha, Figure 1)

All the companion crops, where both crops were harvested together, produced a similar LER (100%). This can be partially attributed to the low contribution to yield of the chickpea. When the chickpea was terminated prior to flowering the remaining wheat yield was statistically similar to the wheat monoculture. In the reverse scenario, the chickpea was unable to recover from the suppression by the wheat prior to the wheat termination. The harvested grain yield of the two 'terminated' treatments was the same as when the two crops were harvested together (mixed 50:50).

Separating the wheat and chickpea into separate rows or reducing the planting rate of the wheat reduced the competitiveness of the wheat, and therefore increased chickpea grain yield, but did not affect the overall LER.

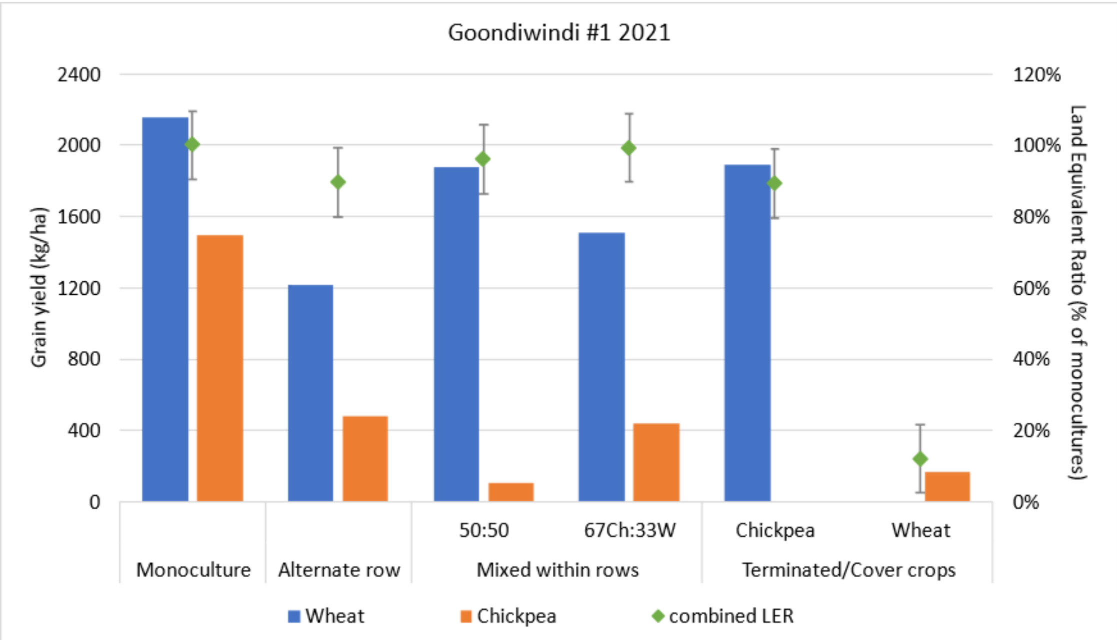

Figure 1. Grain yield of companion crops at Goondiwindi 2021 and land equivalent ratio (LER) showing yields relative to monocultures on standard row spacing. Error bars show LSD at p = 0.05; LERs with overlapping error bars are not significantly different.

Emerald 2021

Grain yields at Emerald were higher than Goondiwindi in 2021, with 4.3 t/ha in wheat monoculture and 2.1 t/ha in chickpea monoculture (Figure 2). Companion crops at Emerald yielded up to 115% LER when planted early, or 80% when planted late. In all of the companion crop configurations the chickpea had similar grain yield for both planting dates, whereas the wheat produced significantly higher grain yield when planted early.

Widening row spacing of alternate row companion crops reduced the competitiveness of the wheat and therefore increased the grain yield of the chickpea. Relay planting the wheat first provided a competitive advantage to the wheat, which was too much for the later planted chickpeas to overcome and the chickpea yields were almost non-existent. The wheat yields were also reduced given that the crop was effectively grown on one metre rows.

Similar to Goondiwindi, when wheat and chickpea were planted together and one crop terminated, the harvested grain yield in the two treatments was similar to when they were harvested together.

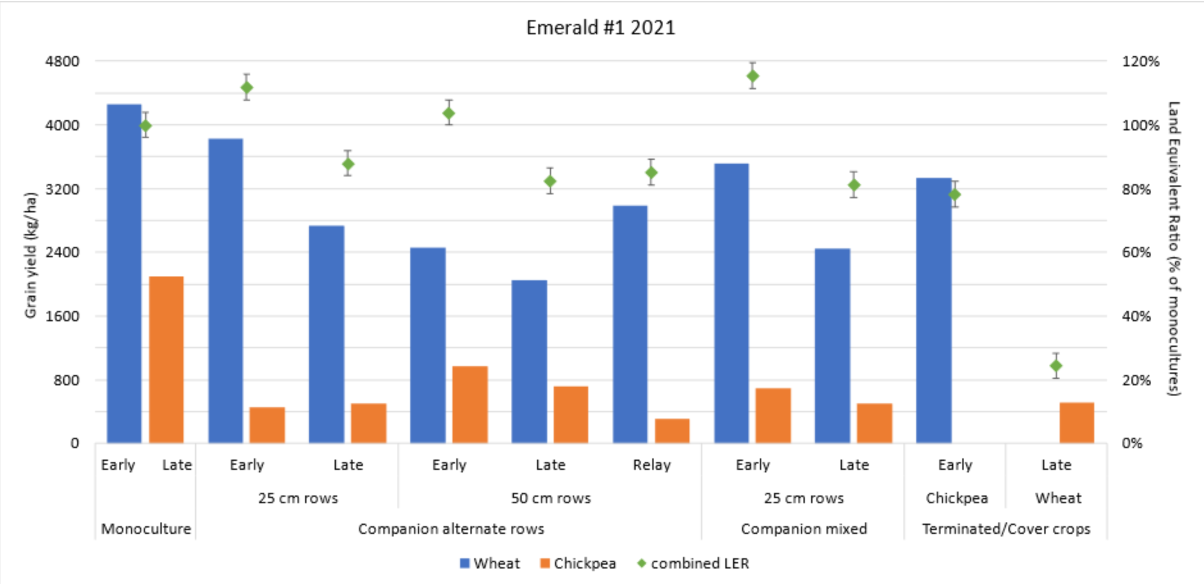

Figure 2. Grain yield of companion crops at Emerald 2021 and land equivalent ratios (LER) showing yields relative to monocultures on standard row spacing. Error bars show LSD at $p = 0.05$; LERs with overlapping error bars are not significantly different.

Goondiwindi 2022

Monoculture wheat and chickpea grain yield was similar at Kioma (3.1 & 3.3 t/ha). Companion crops in separate rows produced LER of 100%; wider rows increased yield of chickpea at the expense of wheat but produced the same LER.

Wheat and chickpea planted mixed together increased LER above 100%. Increasing the proportion of chickpea in the mixture increased chickpea grain yield and LER, with 90:10 producing the highest LER and 50:50 producing the lowest LER.

Terminating wheat or chickpea at flowering had similar effect as previous trials. Spraying-out the wheat earlier improved chickpea yield but was still 40% less than the chickpea monoculture and the stubble left by the wheat is unlikely to provide protection over the subsequent fallow.

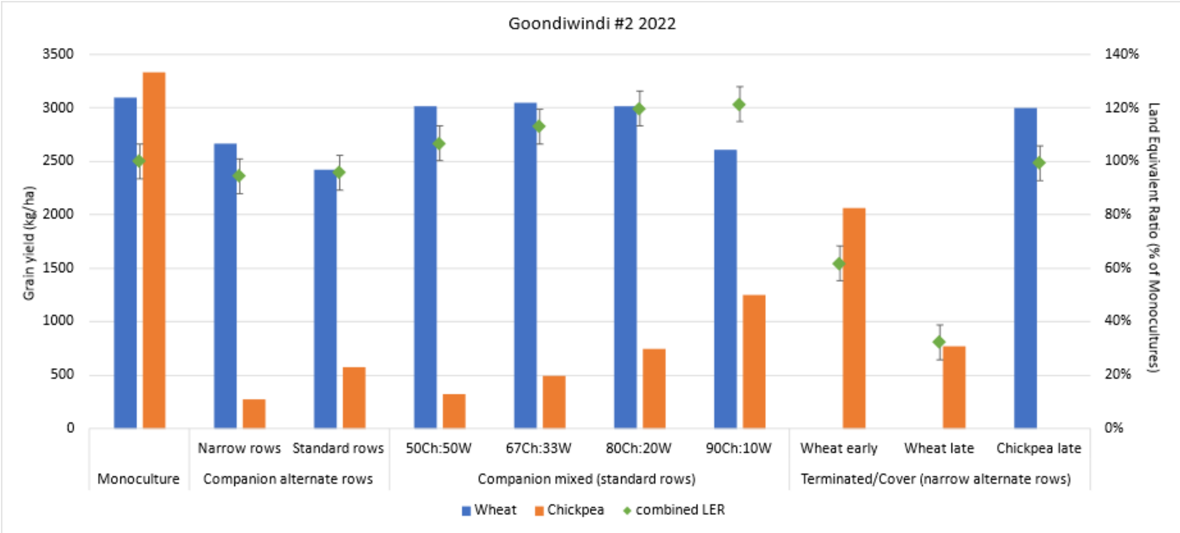

Figure 3. Grain yield of companion crops at Goondiwindi 2022 and land equivalent ratios (LER) showing yield relative to monocultures on standard row spacing. Error bars show LSD at p = 0.05; LERs with overlapping error bars are not significantly different.

Emerald 2022

Monoculture grain yields at Emerald were 5.8 t/ha in wheat and 3.66 t/ha in chickpea on 50 cm rows. Narrow rows (25 cm) produced similar wheat yields, while chickpea yield was reduced when planted on the wider rows (1 m, Figure 4).

Companion crops had similar reduced LERs. Reducing competition from the wheat by widening row spacing in alternate rows or increasing proportion of chickpea in mixtures improved chickpea yield, but at the expense of wheat yield, leading to the same LER.

Terminated wheat reduced chickpea yield again, but not to the same extent as the previous trial. The relay planted 'wheat cover crop' was difficult to establish and was supressed by the established chickpea. The chickpea yielded the same as the wide row chickpea monoculture in this scenario and the wheat did provide some extra cover.

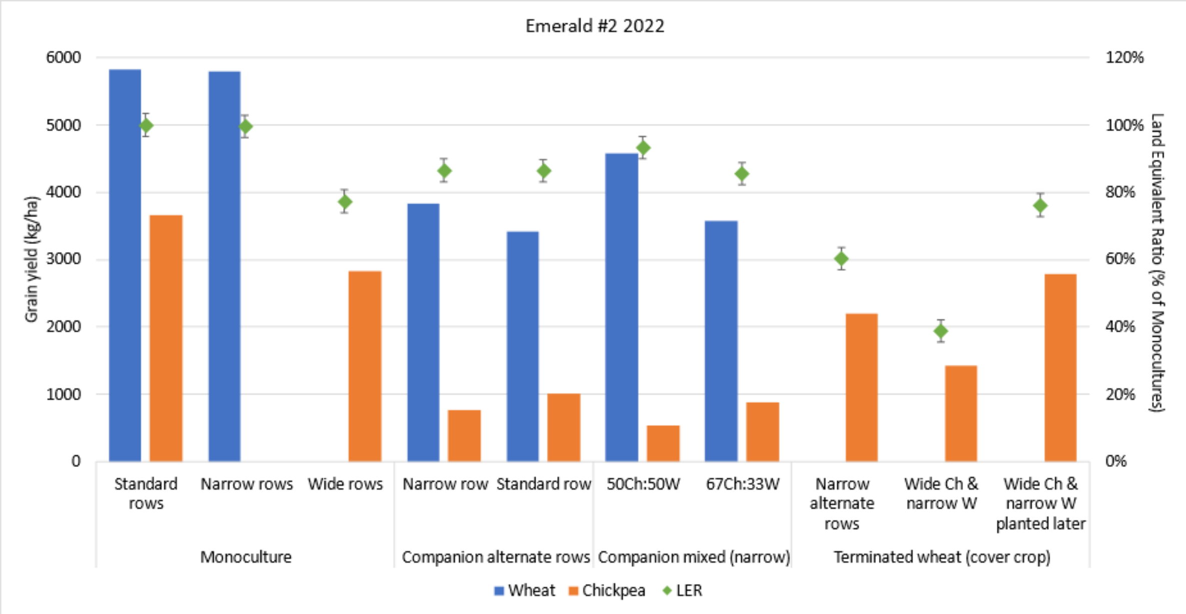

Figure 4. Grain yield of companion crops at Emerald 2022 and land equivalent ratios (LER) showing yields relative to monocultures on standard row spacing. Error bars show LSD at p = 0.05; LERs with overlapping error bars are not significantly different.

Carry-over benefits of companion crops

After the Goondiwindi and Emerald 2021 trials, summer fallows were monitored and wheat planted over the previous companion cropping treatments. Over the fallow period a sorghum cover crop was also planted after monoculture chickpea as an alternative strategy for improving ground cover after chickpea.

Goondiwindi had 500 mm of rain over the fallow, so all plots had a full profile at planting in 2022. Soil nitrogen measured at the site prior to the 2022 crop was sufficient for the 2022 crop to be N unlimited. There were significant differences in grain yield of the 2022 wheat crop, probably due to disease from back-to-back wheat (crown rot).

Wheat following wheat monoculture yielded 1.5 t/ha, and 2.1 t/ha after chickpea monoculture (Figure 5). A cover crop after chickpea, terminated wheat (harvest chickpea) and mixed companion crops all achieved similar yields to the chickpea monoculture; whereas the alternate row companion crop and terminated chickpea (harvest wheat) had similar disease issues as the wheat monoculture treatment and similar reduced yields as the wheat monoculture.

Emerald had similar trends, with wheat following chickpea monoculture yielding highest (5.5 t/ha) and following wheat yielding the least (5.0 t/ha, Figure 6). The Emerald site had 500 mm of rain over the fallow period between crops so the differences in soil water were small at 2022 wheat planting. The cover crop following chickpea monoculture had the least soil water at planting and yielded 0.5 t/ha less than after the chickpea monoculture without a cover crop, similar to the wheat following wheat monoculture treatment.

There were also yield differences from the companion crops, albeit less clearcut than at Goondiwindi. While eight companion crop treatments were statistically similar to each other, four were similar to the wheat monoculture's yield and four were similar to the chickpea monoculture's wheat yield. The companion crops similar to the wheat monoculture 2022 were those where the wheat was the most dominant 2021 crop.

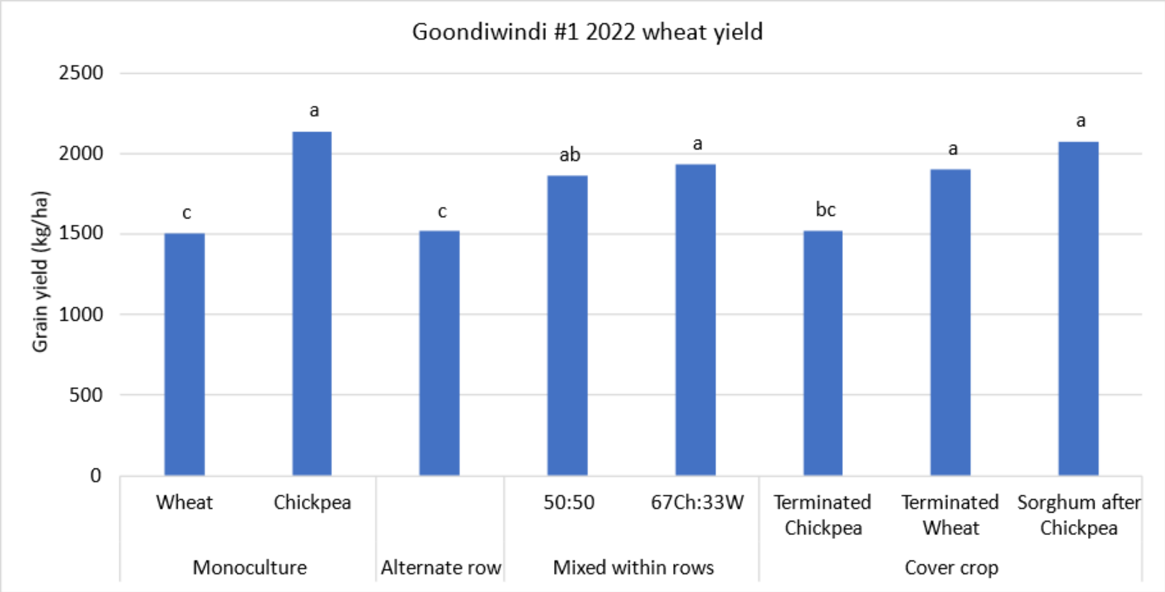

Figure 5. Wheat yield in 2022 at Goondiwindi after having grown monocultures, companion crops or cover crops in 2021. Letters show significant differences at p = 0.05. Treatments that share a letter are not significantly different.

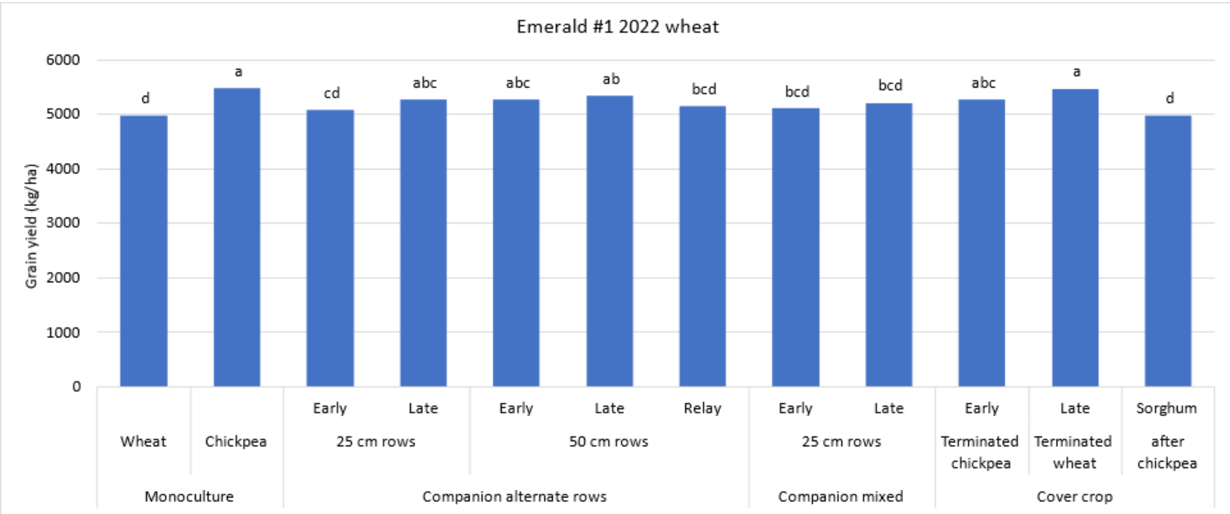

Figure 6. Wheat yield in 2022 at Emerald after having grown monocultures, companion crops or cover crops in 2021. Letters show significant differences at p = 0.05. Treatments that share a letter are not significantly different.

Implications for growers

With only two seasons' data we should be careful not to make strong conclusions. However, this does show that it is possible to grow companion crops in Queensland on stored soil water without a yield penalty.

More research is needed manipulating crop configuration to get the best mix of crop type in the harvested sample and looking at different crop combinations, however these results suggest reducing planting rates of the more competitive crop (wheat) in mixed companion crops, or wider row spacings in alternate row companion crops will increase the grain yield of the chickpea and improve the likelihood of achieving an LER above 100%.

There are several other agronomic challenges and opportunities that should be considered for companion cropping. Companion cropping provides an opportunity to reduce insect and disease pressure, with non-susceptible partners 'hiding' the susceptible crop, however success in this respect will change for mechanism of spread of pathogen, configuration of companion crop and seasonal conditions/disease pressure. For example, our 2022 wheat crop following companion crops (in 2021) also showed evidence of reduced crown rot in treatments where chickpea provided breaks in the wheat stubble and there is strong anecdotal evidence in southern Australia that fungicide applications can be reduced by one to two for aschocyta blight in chickpea.

Weed control also needs to be considered. Paddock selection for low weed pressure and/or species with herbicide options compatible for both crops is critical. Mixtures of crops can limit in crop herbicide options, residual herbicides can provide other options and the growing range of Clearfield® crops is providing further opportunities.

Critical to all pesticides (herbicides, insecticides, fungicides) used in companion crops is that the products need to be registered (or covered by a current permit) for ALL crops being sprayed, to ensure chemical residues comply with MRLs of the intended market.

Economics have not been discussed in this paper but need to consider grading and contamination costs. Separating the grain after harvest may add additional cost requiring a positive LER to maintain overall gross margin of companion cropping versus monoculture. The other risk is contamination of one species with the damaged seeds of the other after screening, which may affect the value of each crop. For example, wheat contaminated with chickpea splits may only be able to be sold into a feed market.

The objective of growing the cereal with chickpea was to increase fallow efficiency after chickpea, increasing the yield potential of the next crop. With a wet fallow over 2021-22 there was no differences in planting PAW from companion crops versus the low cover chickpea stubble or high cover wheat stubble. An average (drier) fallow may produce bigger differences in the fallow efficiency, but this was not the case in these experiments.

The 2022 trial sites have also been maintained over the (drier) summer fallow to measure any residual benefits (more water or nitrogen) achieved by having companion cropped last year.

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Experiences with summer sown chickpeas

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Notes

Advances in the biological control of flaxleaf fleabane with a novel rust fungus

Dr Ben Gooden, CSIRO

Key words

Conyza bonariensis, crop weed, plant pathogen, *Puccinia cnici-oleracei* (ex. *Conyza*), weed biological control

GRDC code

RDC1607-003OPX

Take home message

The long-term aspiration of the biocontrol program is to reduce the growth and reproductive output of flaxleaf fleabane plants in marginal habitats, reduce invasion pressure on crop fields and in turn reduce the reliance on chemical herbicide application to control the weed, especially during fallow.

CSIRO's research has shown the rust fungus to be a safe addition to the flaxleaf fleabane control 'toolbox', yet research into the efficacy of the biocontrol agent in a field setting has only just commenced. Future research is needed to optimise release methods and monitor the effects of fungal infection on weed populations over multiple growing seasons.

Introduction to the biological control of flaxleaf fleabane in Australia

Flaxleaf fleabane (*Conyza bonariensis*) is an annual herb, native to South America, that has become a significant agricultural weed of the grain growing regions of south-eastern Australia, where it greatly disrupts crop production (Wu 2007). This weed is a prolific seed producer that can spread long distances by both wind and water, thus necessitating an area wide approach to its management (Wu 2007). Example images of plant morphology and habitats prone to infestation are provided in Figure 1.

Flaxleaf fleabane affects crop production by greatly reducing stored water supplies in fallow, which affects subsequent crop emergence and growth. In recent years, the density and geographic extent of flaxleaf fleabane populations have expanded across south-eastern Australia, in part as a result of the adoption of minimum tillage practices that enhance seed survival and provide suitable conditions for germination and establishment. Populations of flaxleaf fleabane have also evolved resistance to some herbicides, making herbicide-resistant populations increasingly difficult to manage in many agricultural environments. Consequently, flaxleaf fleabane has become one of the most damaging summer fallow weeds in the northern grain region, with an estimated revenue loss in excess of $43 million per year for Australian grain producers (Llewellyn et al. 2016).

Flaxleaf fleabane infestations are considered by many grain growers to be particularly problematic in fallow, along roadsides, fencelines and irrigation embankments adjacent to crop fields. Flaxleaf fleabane populations are often able to proliferate in marginal habitats due to limited resources available for their control and challenges in coordinating control actions across various stakeholder groups that manage different land tenures in cropping regions. Uncontrolled flaxleaf fleabane populations in these marginal habitats in turn produce copious seeds that easily disperse to nearby crop fields, replenish the soil seed bank, and emerge in subsequent seasons. A key aim of management, therefore, is to reduce the reproductive viability of marginal flaxleaf fleabane populations and invasion pressure in adjacent crops.

Classical biological control (hereafter biocontrol) involves the introduction of a plant's natural enemy (usually an herbivorous insect or fungal pathogen) sourced from its native range, with the aim of reducing the weed's performance (usually a reduction in growth, competitive ability and/or reproductive output). Biocontrol represents a potentially valuable complementary control method for the management of flaxleaf fleabane given the success of previous biocontrol programs against other weeds in the Asteraceae family, such as parthenium (*Parthenium hysterophorus*) and skeleton weed (*Chondrilla juncea*). Indeed, the biocontrol of skeleton weed is deemed one of the most successful broadscale weed biocontrol programs in Australia (Ward 2014). By the 1950s, skeleton weed was considered one of the most destructive weeds in Australian productive systems. In the 1960s, CSIRO established the CSIRO Biological Control Unit in France (now the CSIRO European Laboratory), with the aim of identifying natural enemies of the weed that could potentially act as biocontrol agents in Australia. Subsequently, a rust fungus (*Puccinia chondrillina*) was identified and found to be highly host-specific to skeleton weed after rigorous risk assessment. The fungus was released into Australia in the 1970s (the first plant pathogen approved for deliberate introduction to Australia to help control a target weed) where it became widely established and dramatically reduced the population of the weed (by >80% in some areas) – benefits that have been sustained over the following five decades (Cullen 2012 and data provided to Ward 2014 by J Cullen).

The aims of the current CSIRO-led research into the biocontrol of flaxleaf fleabane were to:

(a) identify candidate biocontrol agents that attack flaxleaf fleabane in its native range
(b) undertake comprehensive host-specificity testing to demonstrate that they do not pose a threat to non-target plant species, and
(c) if approved by the authorities, release the biocontrol agents into Australia to help control the weed.

In this paper, CSIRO presents a summary of research that was undertaken to:

- select the microcyclic rust fungus *Puccinia cnici-oleracei* from Colombia (South America) as a candidate biocontrol for flaxleaf fleabane in Australia
- undertake host-specificity experiments to demonstrate the candidate agent's safety for native and other important plant species in Australia, and
- undertake a small trial release of the rust fungus into the Australian environment in partnership with grain growers and other related stakeholders.

It should be noted that CSIRO has also identified and is currently undertaking host-specificity trials for several potential insect biocontrol agents on flaxleaf fleabane, including the stem-boring weevil *Lixus caudiger* identified in Brazil.

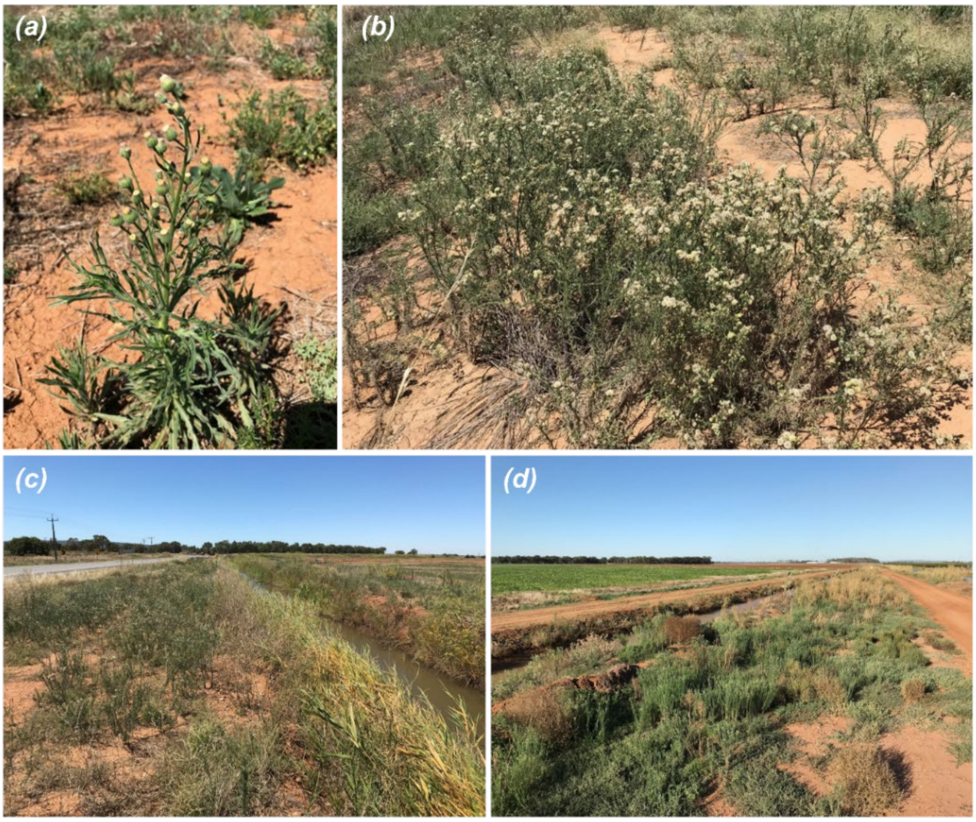

Figure 1. Example of (a) flaxleaf fleabane plant and (b) dense infestation in fallow; (c-d) examples of marginal habitats (e.g., roadsides, irrigation embankments, field margins, drainage lines) where residual flaxleaf fleabane populations are often not managed during the growing season and provide a seed source for re-invasion into adjacent crop fields.

Identification and risk assessment of the candidate biocontrol agent

In 2017, flaxleaf fleabane was endorsed by the Australian Government's then Invasive Plants and Animals Committee (currently Environment and Invasives Committee) as a target for biological control. Subsequently, between November 2017 and May 2019, exploratory surveys for pathogens on *Conyza* species were performed in different regions of Colombia (South America), where pathogenic fungi had been previously recorded on *Conyza*. A microcyclic rust fungus, *Puccinia cnici-oleracei*, was identified during these native range surveys and prioritised as a candidate biocontrol agent for further host-specificity testing as described below (Morin et al. 2020).

The rust fungus infects young and old leaves, stems, and green flower parts of flaxleaf fleabane (Figure 2). The fungus obtains all its nutrients from flaxleaf fleabane by establishing intimate contact with the plant's cells. Through continuous diversion of nutrients from the plant, the fungus reduces rates of photosynthesis, plant growth and reproduction but does not kill the plant altogether. Once a fungal spore germinates and penetrates the host plant leaf tissue, visible symptoms (yellowish speckling, followed by emergence of dark pustules where spores are produced) become evident after 2-4 weeks, after which time the infected leaves begin to die off (Figure 2). It is predicted that, if the fungus establishes widely and causes severe disease, it will decrease the reproductive output of flaxleaf fleabane populations and reduce the weed's invasion potential in cropping areas.

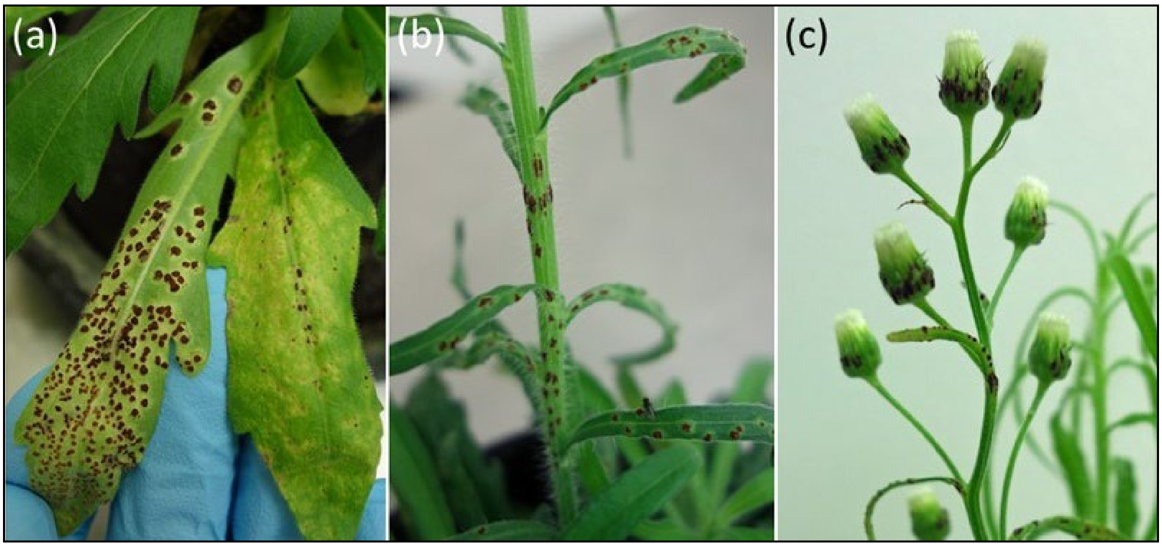

Figure 2. Characteristic disease symptoms caused by the flaxleaf fleabane biocontrol agent; a rust fungus named Puccinia cnici-oleracei. The fungus can infect leaves (a), stems (b) and flower heads (c). The dark brown pustules represent the reproductive stage of the fungal lifecycle, where spores are produced then released to infect nearby plants and gradually spread through the local flaxleaf fleabane population.

Candidate biocontrol agents are approved for release from quarantine into the Australian environment to help control a target weed only once rigorous host-specificity testing has been completed and the agent is shown to pose no risk of significant damage to non-target plant species. Such tests typically involve exposing a set of priority non-target plant species (including native Australian plants, ornamental and other important species) to the candidate agent under optimal conditions for growth and development, then assessing the level of damage to the plant and ability for the candidate agent to develop and complete its lifecycle.

In 2019, CSIRO commenced rigorous evaluation of the potential risks that the rust fungus could pose to non-target plant species in Australia (Morin et al. 2020). Research focused on species within the family Asteraceae that are most closely related to flaxleaf fleabane. This extensive host-specificity testing was performed in a quarantine facility and involved exposing flaxleaf fleabane and non-target plant species to the rust fungus under optimal conditions for infection. It was found that the fungus is highly host-specific to flaxleaf fleabane, is unable to complete its lifecycle on other plant species and poses no threat to the Australian environment (comprehensive results provided in Morin et al. 2020). Based on these research results and following a comprehensive risk assessment process and public consultation, the federal government regulators (then Department of Agriculture, Water and the Environment, DAWE) approved the release of the biocontrol agent into the Australian environment in June 2021.

An overview of current research on host-specificity trials for the stem-boring weevil *Lixus caudiger* can be found at https://research.csiro.au/flaxleaf-fleabane/progress-rrnd4p-rnd-4/.

Experimentally assessing the impacts of the biocontrol agent on flaxleaf fleabane

In December 2021, the fungus was experimentally released under field conditions on greenhouse-propagated flaxleaf fleabane seedlings. The aim of this experiment was to determine if flaxleaf fleabane plants could be successfully infected by the dried specimens of the lab-cultured rust fungus under variable light, humidity and temperature conditions in the Australian environment. The experiment was hosted outdoors at the CSIRO Black Mountain laboratories, as ongoing COVID-19 travel restrictions prevented us from undertaking the experiment in a crop setting.

The experiment consisted of planting multiple lab-germinated fleabane seedlings into a potting mix-sand propagation substrate within plastic tubs, exposed to the following treatments:

1. Seedlings inoculated with the rust fungus, surrounded by a plastic bag to create a humid microclimate to stimulate sporulation;
2. Seedlings inoculated with the fungus but without a plastic enclosure;
3. Seedlings not inoculated with the fungus (control; note the control plants were not covered by the plastic bags).

Twelve replicate seedlings per treatment were used. The fungal spores were applied using a passive process by first hydrating dried infected leaves obtained from the lab culture for 1-2 hours in a water bath, mounting them onto bamboo stakes with the pustules facing downwards, then covering the bamboo stake and healthy plants with a plastic bag to maintain a warm and humid microclimate for at least 12 hours until the fungal spores had been released (Figure 3). The seedlings were then placed on a nursery bench outdoors under prevailing light, humidity and temperature conditions, to allow for development of infection symptoms within an environmental context. Seedlings were watered *ad libitum* to prevent dehydration in between rainfall events.

Post-inoculation monitoring consisted of randomly selecting 15 leaves per seedling and estimating the % cover per leaf showing symptoms of fungal infection. Approximately 2 weeks after the recipient plants were inoculated with the rust fungus, we detected characteristic signs of infection – i.e., light yellow-green speckles across the leaf surface (Figure 4). Strikingly, all 12 plants within the infected-covered treatment showed signs of infection. On average, 53 % of leaves were infected (presence/absence) and 18 % of the surface area of those leaves showed symptoms. However, only a single leaf on a single seedling in the infected-uncovered treatment had symptoms of infection, and none in the non-infected control seedlings. This provided evidence that maintaining a still, humid microclimate at the time of inoculation is critical for successful infection transfer of the fungus to flaxleaf fleabane seedlings under field conditions. Approximately 6 weeks post-infection, the inoculated seedlings that showed the early signs of infection (yellowish speckles) had developed dark brown lesions consistent with severe fungal infection and completion of the fungal lifecycle (Figure 4).

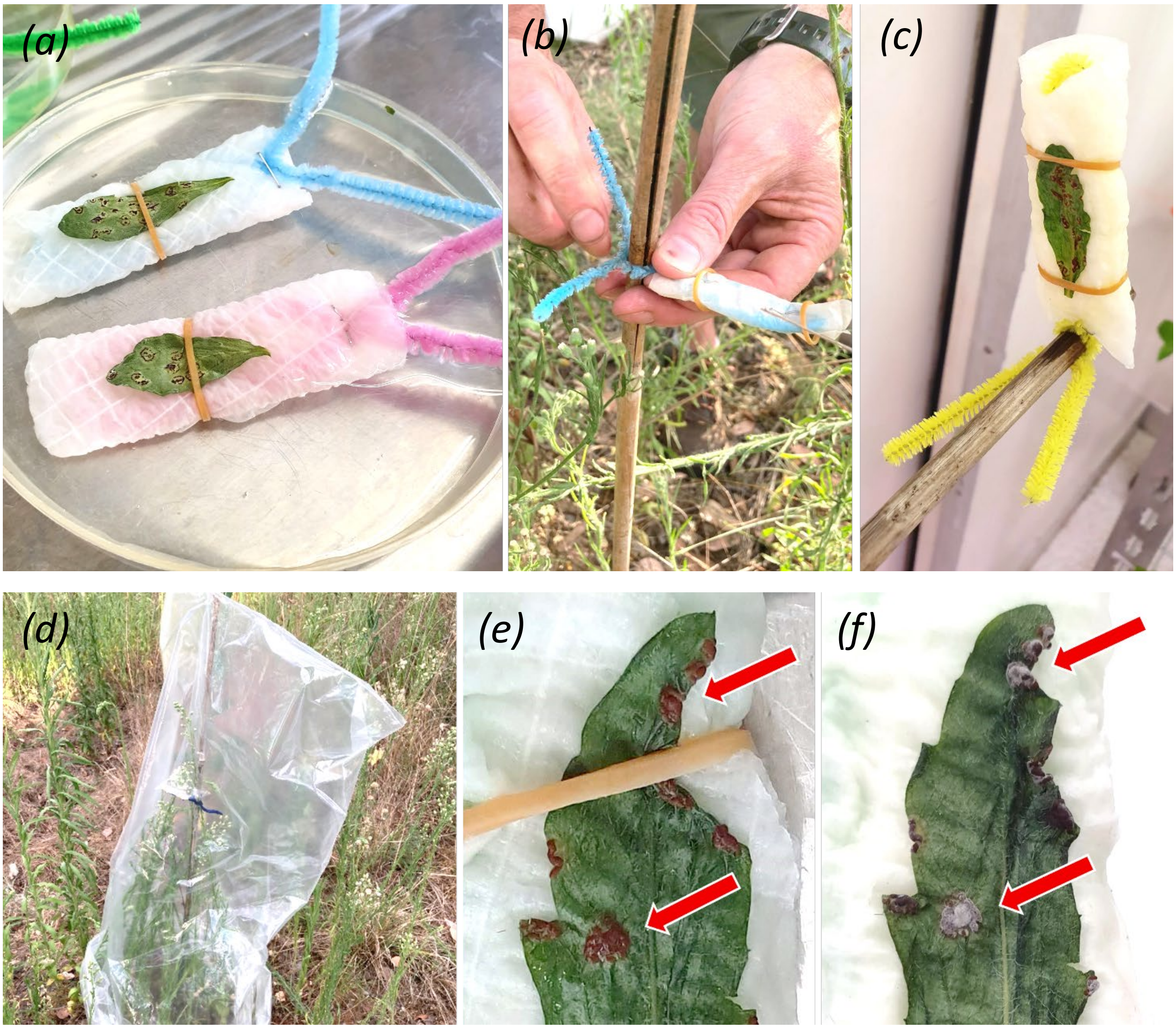

Figure 3. The process of setting up the biocontrol agent release. Dehydrated, infected leaves are (a) rehydrated in a water bath then (b-c) mounted and tied to a stake with rehydrated pustules facing downwards which is placed over a set of healthy flaxleaf fleabane plants and (d) covered with a plastic bag for at least 12 hours to maintain a humid and warm microclimate. Successful release of viable spores is indicated if the pustules turn from brown (e) to a fluffy grey colour (f).

Figure 4. Infection symptoms on flaxleaf fleabane plants experimentally inoculated with the rust fungus under field conditions.

Levels of infection, plant growth and reproductive output were monitored monthly to May 2022. Multiple infection events occurred between January and May 2022, whereby the first set of lesions that developed in January produced spores that spread to nearby healthy leaves that subsequently became infected, and so on. In this way, infection progressed over the entire body of each plant as they developed through to adulthood, with lesions eventually being detected on stems, inflorescences and flower heads. These observations confirmed that the fungus was able to readily infect flaxleaf fleabane plants growing outdoors over multiple months, under variable prevailing climate conditions.

At the conclusion of the experiment, plants were harvested, dried, and measured for height, biomass, number of inflorescences (flowering stems), capitulae (flower heads) and infection levels. There was no difference in the biomass of flaxleaf fleabane plants between the different inoculation treatments (data not presented). This may have arisen because the non-infected control seedlings eventually became infected with the fungus from spores spreading from the nearby infected plants. Future experiments would need to retain non-infected control plants for the duration of the experiment using fungal exclusion treatments to truly test the effects of infection on plant growth in the field.

A linear regression analysis revealed that reproductive output (measured as the number of flower heads per inflorescence, y-axis on Figure 5c) declined significantly with increasing percentage of leaves infected by the fungus (R^2 = 0.15, F = 8.6328, P = 0.0050); note the contrasting condition of the inflorescence with severe infection by the fungus and distorted, stunted flower heads (Figure 5a) versus the healthy inflorescence not infected by the fungus (Figure 5b). On average, severely infected inflorescences produced 50-60% fewer flower and seed heads than non-infected inflorescences (Figure 5c). These results indicate that, under optimal conditions supporting high infection severity, the fungus can reduce the overall reproductive output of host plants. Reduced reproduction is likely a direct consequence of the fungus lowering the photosynthetic efficiency of infected leaves, in turn reducing the plant's ability to assimilate available carbohydrates into inflorescence development and flower and seed production.

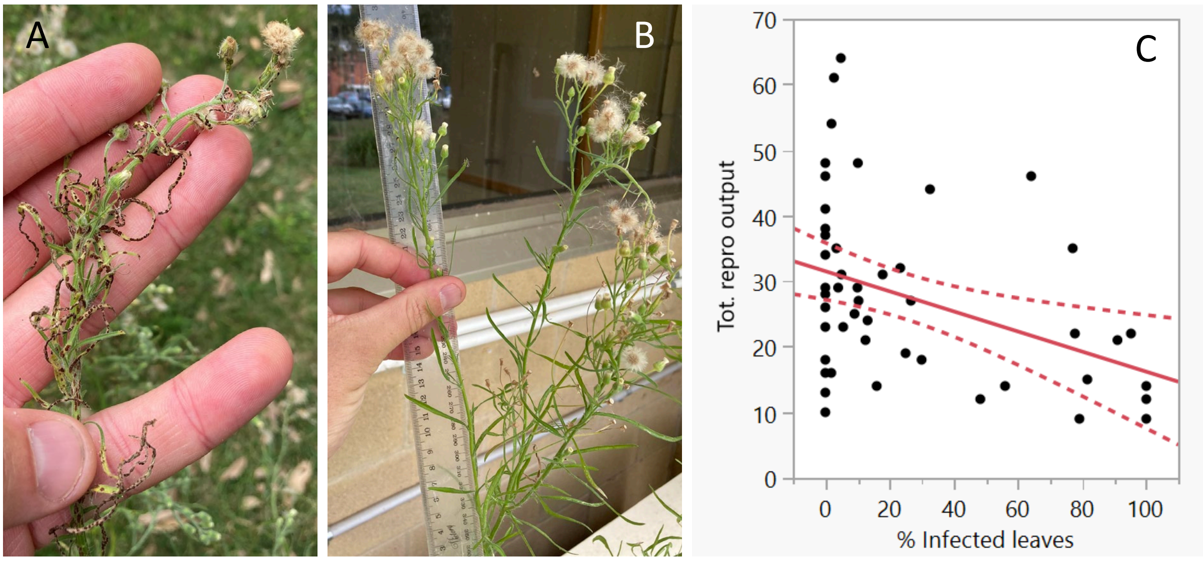

Figure 5. Results of fungal inoculation experiment on the reproductive output of host flaxleaf fleabane plants: (a) heavily infected and (b) non-infected inflorescences, and (c) linear relationship between reproductive output (number of flower heads per inflorescence) and % of infected leaves per inflorescence.

Pilot releases of the rust fungus throughout Australia with community stakeholders

Commencing in September 2022, CSIRO launched a small pilot program in partnership with select landholders and other weed management stakeholders from the grain sector that aimed to trial release of the rust fungus on flaxleaf fleabane across south-eastern Australia using the bamboo stake-bag method described above. Interest from potential participants in the program was elicited through a joint GRDC-AgriFutures-CSIRO media campaign. 54 stakeholders were selected for participation in the program, comprising 39 private landholders/growers, 7 professional agronomists, 3 research institutes (University of Sydney, CSIRO, Northern Territory Arid Zone Research Institute), 2 biosecurity officers from local councils, 2 plantation industry groups and 1 Landcare network. Altogether, participants were sent 336 biocontrol agent release kits for dissemination in the field using the agreed release method. Releases were made nationwide, focussing on the south-eastern parts of Australia where flaxleaf fleabane infestations cause the greatest impacts on crop yield (25 releases in NSW, 16 QLD, 5 SA, 5 VIC, 2 TAS, 1 NT, Figure 6).

Releases of the rust fungus were made by registered participants between late September and mid-December 2022 during fair weather days, usually shortly after periods of rainfall under high humidity conditions, in marginal areas adjacent to crop fields (e.g., fencelines, roadsides, drainage ditches, field in fallow) with a dense foliage coverage of flaxleaf fleabane. Participants were sent release kits containing dried flaxleaf fleabane leaves infected with the rust fungus and comprehensive instructions on how best to release the fungus to maximise likelihood of infection of recipient flaxleaf fleabane host plants. In March 2023, CSIRO will work with stakeholders to monitor for signs of fungal infection at the release sites and quantify overall rates of infection and identify regions and habitat conditions under which infection is most likely to occur. The results of this small pilot release program will improve the efficiency by which the biocontrol agent is released in future as part of a potential larger scale, nationwide mass-release program across Australia.

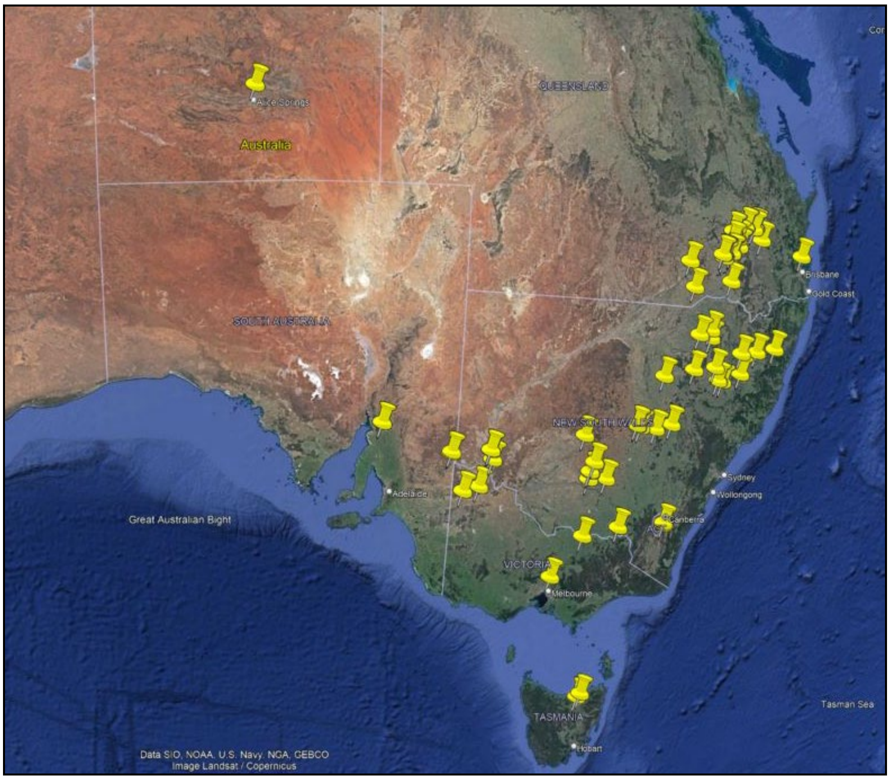

Figure 6. Distribution of biocontrol agent release sites across south-eastern Australia.

Management implications and future research aspirations

The long-term aspiration of the biocontrol program is to reduce the reproductive viability of flaxleaf fleabane plants in marginal habitats, invasion pressure on crop fields and in turn reduce the reliance on chemical herbicide application to control the weed, especially during fallow. CSIRO's research conducted over the past several years has shown the rust fungus to be a safe addition to the flaxleaf fleabane control 'toolbox', yet research into the efficacy of the biocontrol agent in a field setting has only just commenced, with future research needed to optimise release methods and monitor the effects of fungal infection on host plants over multiple growing seasons.

It is predicted that, even where the rust fungus establishes successfully in the field, infection is unlikely to result in significant reductions in the population size of flaxleaf fleabane for several years. As such, biocontrol represents a longer term and self-sustaining means of gradually reducing weed invasion pressure across productive landscapes. It is expected that the fungus will spread from one plant to the next very slowly at first, but the rate of spread will likely accelerate once the overall abundance of the rust fungus builds up in the local flaxleaf fleabane population. Based on our knowledge of other successful biocontrol agents that have been released previously in Australia (e.g., skeleton weed, Ward 2014), broadscale spread of the fungus would be expected to take several years. Furthermore, the combination of several biocontrol agents may enable more robust control of target weeds. In this way, further research into the biocontrol of flaxleaf fleabane with insects may provide enhanced biocontrol solutions.

When considered in isolation, classical weed biological control is not a silver bullet and will not eliminate flaxleaf fleabane from an area altogether or replace the need for deployment of chemical and mechanical control methods. However, by reducing flaxleaf fleabane's growth and seed set, biocontrol agents could slow the rate of weed spread both within and outside of cropping areas and hence reduce the frequency of re-infestation in fallow. Widespread establishment and spread of the rust fungus may gradually reduce the quantity of chemical herbicide required to suppress flaxleaf fleabane populations and may thus be especially valuable in areas where the weed has developed herbicide resistance. Future research would be required to develop methods of integrating the effects of the fungus (likely most active in marginal habitats comprising unmanaged flaxleaf fleabane populations) with intensive chemical and mechanical control methods deployed on flaxleaf fleabane infestation in fallow.

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Further information

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Exploratory surveys of the rust fungus in Colombia, South America, were coordinated by Dr Louise Morin (CSIRO), with assistance from collaborators based at the Universidad Nacional de Colombia Sede Medellín. Host-specificity testing of the rust fungus on native and other important plant species under quarantine conditions in Australia was delivered by CSIRO researchers Dr Gavin Hunter, Dr Kylie Ireland, Caroline Delaisse, and Isabel Zeil-Rolfe.

Development of fungus release methods and implementation of the small pilot community-led release program were undertaken by CSIRO researchers Dr Lauren Kaye, Caroline Delaisse and John Lester under direction of Dr Ben Gooden. We thank the many growers and weed management stakeholders throughout Australia for their generous support in testing the fungus during spring 2022.

Research into the biological control of flaxleaf fleabane with insects is being delivered by Dr Vincent Lesieur, Thierry Thomann, Mireille Jourdan, Dr Michelle Rafter and Dr Kumaran Nagalingam with assistance from collaborators based at the Universidade Regional de Blumenau (Brazil).

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Silicon in cropping - should we care?

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Notes

Concurrent session – pick 'n' mix

Canola in northern farming systems

Lindsay Bell[1], Jeremy Whish[1], Steven Simpfendorfer[2], Jon Baird[2], Kathi Hertel[2] & Andrew Erbacher[3]

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[2] NSW DPI
[3] DAF Qld

Key words

canola, soil water, nitrogen, rotation, risk, disease, root lesion nematodes

GRDC codes

DAQ2007-002RTX, CSP00187, CSA00050, DAQ00192

Take home message

- Canola offers a range of rotational benefits for disease management, weed management, and the potential to widen sowing windows
- Understand when canola would most likely fit into your system to maximise its benefits and mitigate its risks – that is, when you should put it in your mix of crop choices
- Farming system data shows significant opportunities for canola, but risks are still significant
- Canola won't suit all situations – several aspects need to line up to mitigate risk and maximise benefits. Critical aspects to consider include:
    - Soil water at sowing – threshold >150mm in most locations to mitigate risk of low crop yields
    - Sowing window – understand your optimal sowing window to manage the risk of frost and heat stress during critical periods
    - Disease or weed issues – use canola where you are going to reap the benefits in subsequent years (e.g., winter grass problems, high *Pratylenchus thornei* nematode populations)
    - Ensure sufficient N is available – avoid situations with low starting soil N, as this will be difficult to address in northern systems with applied fertilisers at sowing or in season.
    - Preceding crops – be cautious of crops that host sclerotinia which increases disease risk (e.g., chickpea)
    - Following crops – use canola leading into disease-sensitive crops/varieties, N availability is likely to be a little higher than after cereals, consider following with another break crop, i.e., a 'double-break' to 'reset' the system.

Introduction

Northern farming systems are challenged by a lack of reliable break crops that offer effective weed management options and help with reducing soil-borne diseases such as nematodes, Fusarium crown rot, and charcoal rot. Canola is one winter crop option that provides these benefits. Canola is a highly profitable staple crop in southern farming systems and a range of historical work has explored the wider potential of expanding its use further north (Holland et al. 2001, Robertson and

Holland 2004). However, canola has traditionally been perceived as a risky crop in northern farming systems due to the greater frequency of high/low temperatures during grain filling, which often result in significant yield, quality and oil content losses.

Despite this history, there is now a wide range of varieties that fit a diverse range of niches in the farming system, ranging in phenology (or growing season length) to fit different sowing windows, and herbicide tolerance packages. Alongside improved planting equipment with better depth control, these advances address some of the limitations to using canola more widely in northern grain systems.

Sowing opportunities & timing – how often do they line up?

As canola has relatively small seed that must be planted shallow (<40mm depth), the duration of the sowing window to plant into surface moisture is limited. The reliability and frequency of suitable sowing events in the right window for canola can be a critical constraint to incorporating it more reliably into northern farming systems. Below (Figure 1) we compare the frequency that a sowing event is likely to occur in different fortnightly windows through autumn at a selection of locations. A sowing event is defined as a rainfall event exceeding potential evaporation over a 7-day period. This shows that in more temperate, winter dominant rainfall locations where canola is widely used (e.g., Young), a sowing opportunity occurs during mid-April to mid-May in over 70% of years. In contrast, in northern NSW and southern Qld with less and more variable autumn rainfall, the frequency of this sowing event is significantly lower at around 40-50% of years. Whilst this is likely to limit the frequency that canola could be effectively established in the north, it does show that in around half the years we are likely to still receive conditions that should allow canola to be sown in a viable window. This also shows that at many of our locations there are often sowing opportunities in early April (about 1-in-4 to 1-in-5 years), which may allow longer season canola cultivars to be used.

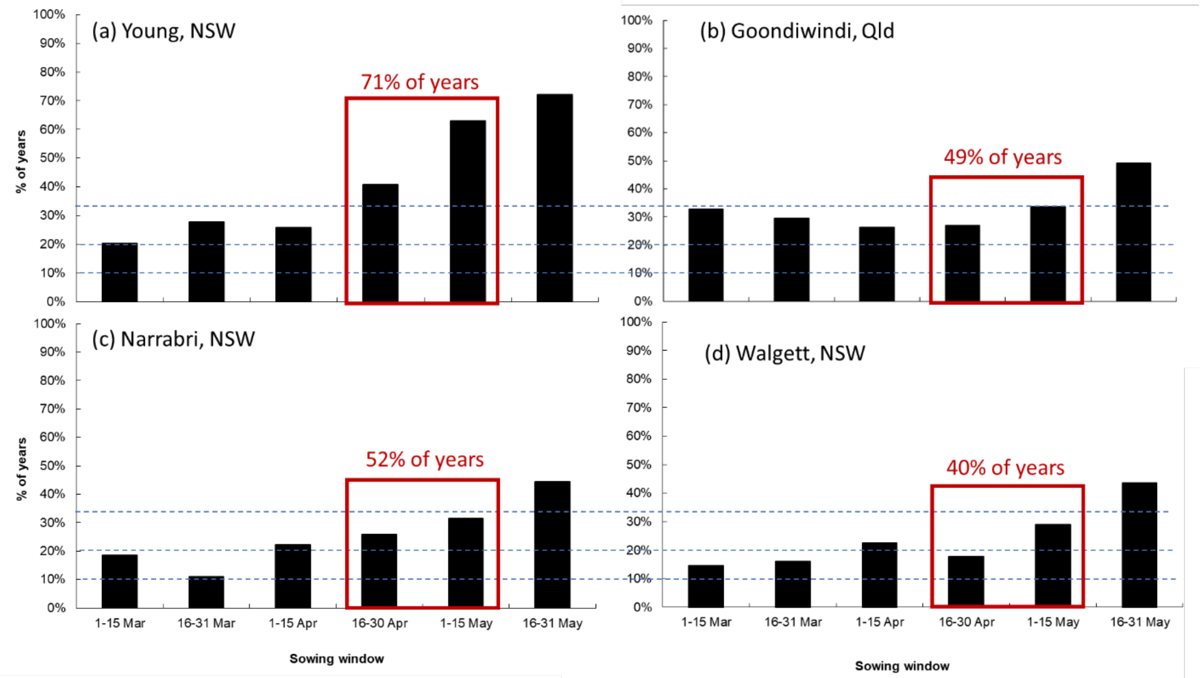

Figure 1. Historical (1956-2015) analysis of frequency of a sowing event (i.e. rainfall exceeding evaporation over a 7-day period) across fortnightly sowing windows comparing a southern NSW site (Young) with 3 northern locations. The red box depicts the optimal canola sowing window in late April and early May and the total frequency that such an event occurs in this period; blue dashed lines represent 1 in 10 years (10%), 1 in 5 years (20%) and 1 in 3 years (33%).

Matching variety and sowing time to mitigate heat/frost stress

Mitigating the risks of frost and heat stress at flowering is critical for maximising canola yield. In particular, the period 200–400-degree days after flowering (i.e., at peak flowering) is a key stress point when the crop is particularly susceptible to temperature or water stress (Whish et al. 2023). Table 1 shows the predicted optimal flowering windows for canola across various locations in southern Qld and northern NSW compared to a 'typical' canola growing region in southern NSW (Young – shown in bold). Firstly, the optimal window is typically shorter in northern environments due to a shorter period when frost and heat stresses are minimised. This results in narrow sowing windows for canola to flower in the narrow optimum window. Secondly, the optimal flowering window varies significantly across environments – from the earliest situations at Mungindi in the west, to later at Warwick in the east. This means it's particularly important to look at this for your environment and select canola varieties with the appropriate phenology to match this optimal flowering window for a particular sowing date. These issues can be explored for your location and specific situation using the Canola Flowering Calculator at: https://www.canolaflowering.com.au/

Table 1. Predicted optimal window to start flowering and sowing date for an example variety with early/fast phenology across various environments spanning the northern grains region compared to a traditional canola region at Young, NSW. Predicted using the canola flowering calculator.

Location	Optimal window to start flowering	# Days in window	Optimal sow date for an early cultivar (e.g., Stingray)
Young	**13 Aug – 15 Sept**	**33**	**1 May – 17 May**
Narrabri	18 July – 15 Aug	28	1 May – 15 May
Moree	10 July – 8 Aug	29	26 Apr – 10 May
Goondiwindi	6 July – 2 Aug	27	20 Apr – 3 May
Walgett	12 July – 6 Aug	25	26 Apr – 8 May
Mungindi	26 Jun – 23 July	27	19 Apr – 26 April
Warwick	2 Aug – 25 Aug	23	12 May – 20 May
Condamine	17 July – 12 Aug	26	3 May – 15 May

Soil water thresholds to mitigate risk

Seasonal rainfall variability and the availability of soil water at sowing are key drivers of yield expectations for canola in the northern region. In particular, soil water at sowing is far more important than in southern environments which receive more reliable winter rainfall. Figure 2 highlights the extent to which different starting soil water conditions impact yield potential for canola in some example northern locations. This shows that the median yield increases by about 0.5 t/ha for every 50 mm of extra PAW in the soil profile at sowing. To achieve a canola grain yield potential of >1.5t/ha (a benchmark break-even yield under typical price-input scenarios) in >60% of years, soil water at sowing would need to exceed 150 mm at Mungindi or Goondiwindi and exceed about 100 mm at Narrabri. When PAW at sowing is <100mm, the likelihood of achieving grain yields >2.0 t/ha is low (i.e., less than 1 in 5 years at most locations).

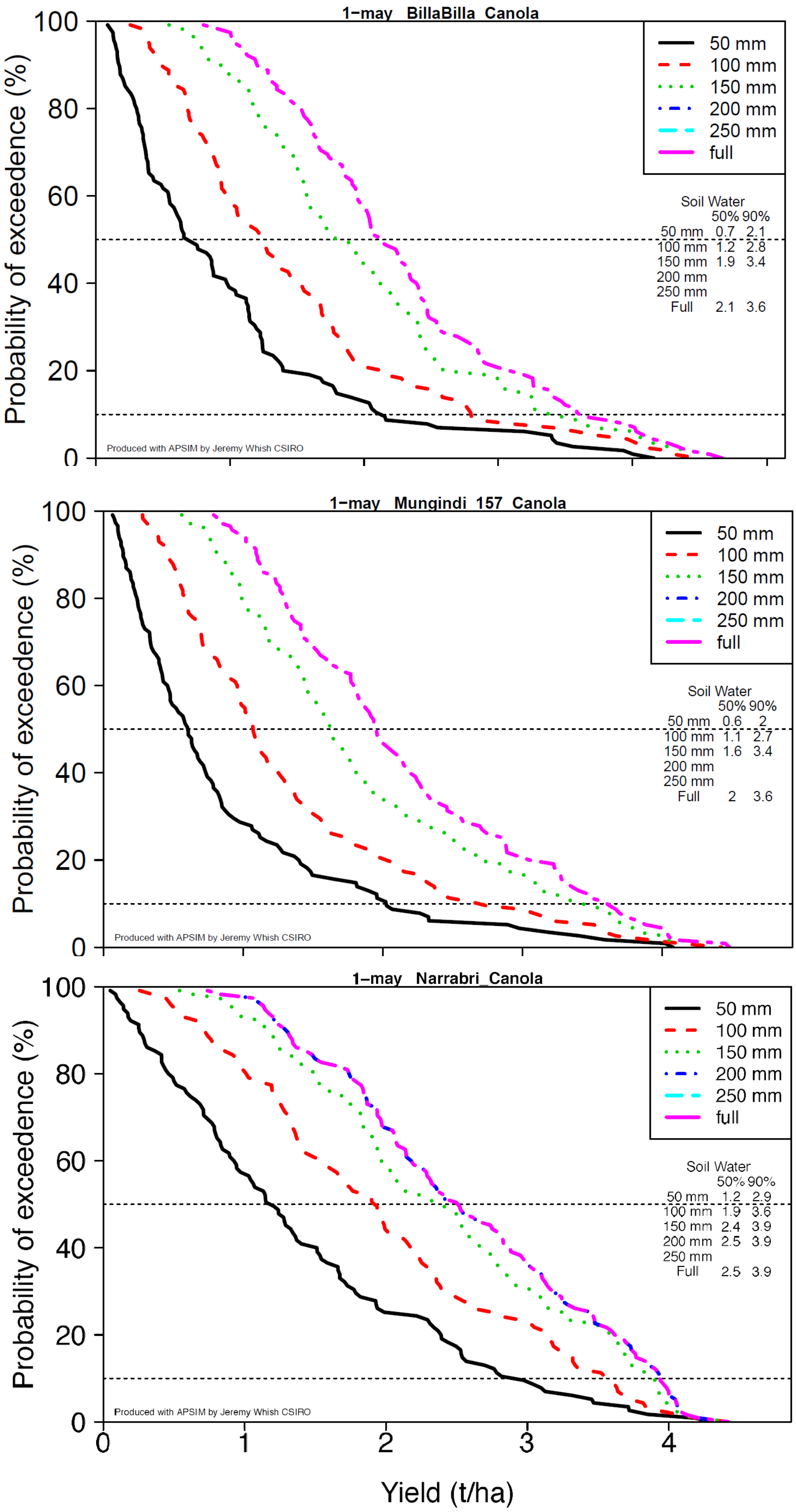

Figure 2. Simulated water-limited yield potential for canola across environments in northern NSW & southern Qld with different plant-available soil water conditions at sowing (indicated by different colours) (Top = Billa Billa, middle = Mungindi, bottom = Narrabri).

Canola yields, water use efficiencies and legacies in farming systems experiments

As part of the northern farming systems research sites over the past 6 years, canola has been grown on 9 unique occasions across southern Qld, central NSW, and northern NSW under a diversity of seasonal conditions (Table 2). This provides a useful snapshot of what might be expected for canola performance in the northern region. From these sites, 3 of the 10 site-seasons achieved low yields (<0.5 t/ha), which were attributable to a frost event during early pod-fill (Narrabri 2017) and very dry conditions after sowing in 2019, when less than 200 mm of water (as rain or stored water) was available to the crop throughout the season. Five of the 9 site-seasons achieved grain yields of 2.5-3.5 t/ha, which occurred under conditions where the crop had access to over 350mm of water during the season. Most of these crops started with soil profiles >60% full prior to reaching the sowing window, which contributed around 30% of the water used by the crop. This was augmented by additional in-crop rain similar to the long-term average winter season rainfall across these locations (i.e., 200-300mm) except for Trangie in 2020 on a red soil with a low plant available water content (PAWC). These high yielding crops all started with >150 mm of PAW prior to sowing. The harvest index (0.23-0.27) and grain water use efficiency (WUE) (≤8.0) measured in these studies were less than those that are typically expected in more traditional canola-growing regions.

Table 2. Canola crop productivity (grain yield and biomass produced) & water used across farming systems experiments conducted 2015-2021.

Site-Year	Year	Yield (t/ha)	Biomass (t/ha)	Harvest Index	Water used (mm)	Pre-sow PAW (mm)	Biomass WUE (kg DM/mm)	Grain WUE (kg grain/mm)
NARRABRI	**2017**	0[A]	8.0	0	320	146	25	0
NOWLEY	**2019**	0.21	1.9	0.10	183	53	10	1.1
TRANGIE RED	**2019**	0.44	1.8	0.25	139	22	13	3.2
BILLA BILLA	**2018**	1.46	6.0	0.24	255	114	24	5.7
TRANGIE GRAY	**2020**	2.70	13.6	0.20	403	148	34	6.7
TRANGIE RED	**2020**	2.94	10.8	0.27	371	63	29	7.9
NARRABRI	**2016**	3.06	10.5	0.29	642	225	16	4.8
PAMPAS	**2021**	3.18[B]	16.5	0.19	392	205	42	8.1
PAMPAS	**2015**	3.55	15.2	0.23	517	152	29	6.9

[A] – Frost damage during early podding; [B] – Mouse damage removed 10-20% of pods.

At various farming system sites, canola has been grown under comparable conditions to other winter crops, providing insights into its relative performance in terms of grain yield and legacies such as extraction and replenishment of soil water and N availability in subsequent crops.

Firstly, despite the variability in canola productivity shown in Table 2, canola has produced grain yields between 34 and 70% (average of 55%) of those achieved in wheat under the same seasonal conditions. Canola yields have typically equalled those achieved in chickpeas under comparable seasons. Of course, the relative prices and input costs required for these crops will influence a direct comparison of profitability.

Canola left similar amounts of soil water at harvest compared to winter growing cereal crops or grain legumes in the same season. Some small differences (<20 mm) occurred in some seasons where canola left 15-30mm more water than the winter cereals, often due to earlier termination of canola while the cereal was still finishing. Despite there often being a slightly lower fallow efficiency achieved after canola than following a winter cereal, in the seasons with comparisons of PAW at the end of the subsequent fallow, there was little if any significant difference compared to either the cereals or legumes.

One clear and consistent observation was that the nitrogen that accumulated during the subsequent fallow after canola was often 20-35kg N/ha higher than following a cereal. Similar results have been consistently reported in southern regions. This occurs because canola leaf residue has a lower C:N ratio, and hence breaks down more quickly and releases more N than cereal residues.

Table 3. Differences between canola relative to a winter cereal (wheat, barley) or a winter legume (chickpea, fababean) grown in the same season in terms of grain yield, residual soil water (SW) at harvest, soil water and N mineralised over the following fallow.

Site-Year comparison	**Canola yield (%) relative to:**		**Canola harvest SW (mm) relative to:**		**Canola SW at sow next crop (mm) relative to:**		**Canola fallow N mineralisation (kg/ha) relative to:**	
	Wheat	Chickpea	Cereal	Legume	Cereal	Legume	Cereal	Legume
Trangie-Red 2019	34		+20		+17		+18	
Trangie-Red 2020	42		-8		-4		+30	
Narrabri 2017[A]	0		+20		+17		+35	
Pampas 2015	68	95	-4	-9	+4	+2	+28	-10
Billa Billa 2018	60	108	+14	+3				
Trangie Gray 2020	57	300	+28	-20				
Pampas 2021	70	123						
Narrabri 2016	-	108	-	0	-	-18	-	-10
Spring Ridge 2019	-	-		0		-14		+34

[A] – Frost damage during early podding

Crop rotation considerations

Clearly an important rationale for using canola in a crop sequence is to achieve some rotational benefits such as reducing populations of cereal or legume pathogens (e.g., root lesion nematodes, Fusarium crown rot), providing an alternative weed control option, and/or opportunities for using alternative herbicide chemistry.

Consistent with previous understanding, our farming system data has shown that canola does not host the root lesion nematode, *Pratylenchus thornei* (*Pt*), the main problem species in the northern region. Hence, the population of this pathogen continues to slowly reduce under a canola crop whilst it will increase significantly under host crops like wheat or chickpea. The benefit for supressing *Pt* populations is further enhanced if the period of growing non-host crops can be extended for >24 months (Figure 3). Hence, growing canola in combination with non-host crops like durum wheat, cotton, or sorghum provides an effective mechanism for reducing the population of *Pt* to low levels in problem fields. However, it should be noted that canola is a host of a different root lesion nematode species *Pratylenchus neglectus* (*Pn*) which is more dominant on lower clay content soils in central and southern NSW. Hence, canola is not a good option for lowering *Pn* populations in these regions. Canola has also been shown to be a valuable alternative crop in northern cropping systems to reduce levels of Fusarium crown rot following winter cereal crops (Kirkegaard et al. 2004).

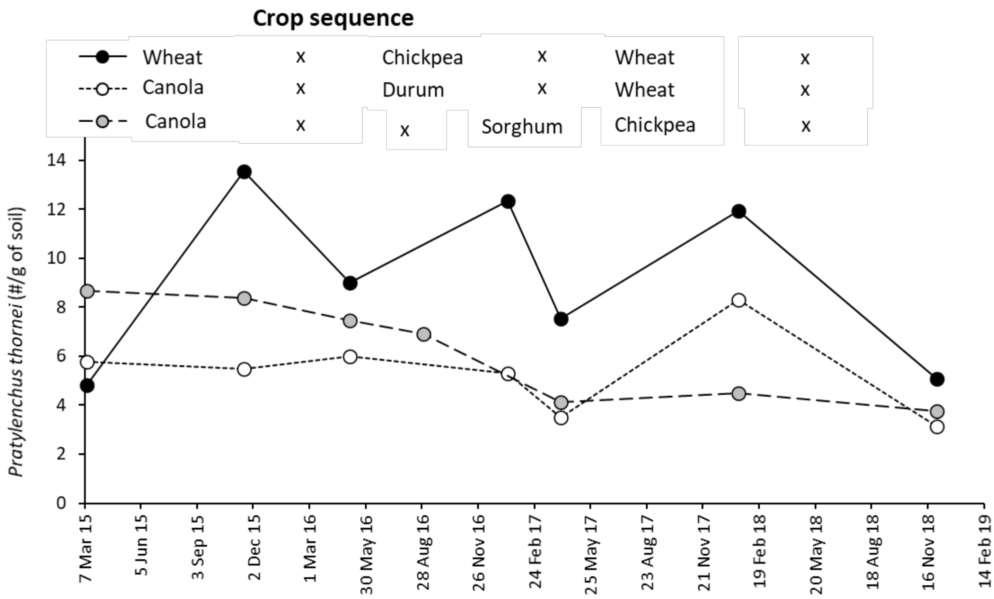

Figure 3. Root lesion nematode (*P. thornei*) populations in the soil over different crop sequences – shows the slow decline in numbers during non-host crops like canola coupled with durum or sorghum to provide a double break, compared to a rotation of host crops like wheat and chickpea.

While canola can offer several positive legacy benefits in a farming system, there are some potential risks to consider in subsequent crop management and selection. Firstly, canola doesn't host beneficial arbuscular mycorrhizal fungi (AMF), so there's a risk that these populations will be reduced during a phase of canola, especially if it is preceded or followed by a long fallow, creating a long period without a host plant. Hence, on sites with low or marginal soil P, it is probably best to avoid following canola with a more AMF dependent summer crop (cotton, sunflower, mungbean and maize) or winter crop (linseed, chickpea and fababean). Secondly, several herbicides used in canola can have significant plant-back restrictions for some crop choices. This is important to consider in situations with double-crop opportunities into summer crops (e.g., mungbeans, sorghum). Finally, volunteer canola plants, particularly herbicide tolerant canola varieties, can be difficult to control in some subsequent crops and fallows. This can sometimes require more expensive herbicides be used to clean up canola volunteer plants in fallows or control these in the following crop.

Conclusions

Canola offers many potential benefits of crop diversification in a farming system; widening sowing windows, disease and weed management. Both experimental data and modelling suggest there are opportunities to use canola in northern farming systems when we have the confluence of sufficient accumulated soil water and a sowing opportunity in the right window. Whilst these conditions are unlikely to occur every year, they are not infrequent across many environments in the northern grain region.

While considering many of the agronomic considerations outlined above, it is important to also consider the sowing and harvesting equipment available to you. Accurate seed depth control will achieve better and more consistent establishment in canola, and hence sowing machinery that provides this is advantageous. Similarly, accessing a windrower for canola is often challenging and whilst direct heading is possible, it does impose greater risk of harvest losses and requires more attention to timing of harvest to mitigate risk.

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Matching canola variety with environment and management - time of sowing, flowering windows and drivers of phenology

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Key words

critical period of yield formation, phenology, optimal flowering, canola, vernalisation, photoperiod, thermal time, daylength

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Take home message

- Avoiding stress during the critical period of yield formation improves productivity
- Identifying optimal time of flowering for an environment helps avoid stress during the critical period
- Knowing the phenology of a cultivar helps target flowering to the optimal time.
- Tools like the flowering predictor use probability to show the risk of different genetics in different environments.

Background

Canola's diverse genetics allows it to be grown as a short-season spring crop or a long-season winter crop. In Australian cropping regions, avoiding damaging frosts or high temperatures during flowering and early podding and minimising stress during the critical period for yield formation is the key to maximising yield and oil quality (Kirkegaard et al., 2018). Having confidence that a cultivar will flower when expected, ensures timely management and that crops will flower at the optimal time (Lilley et al., 2019). Recent climatic changes and the logistics of planting large areas have resulted in canola being sown outside the traditional window. This has seen some cultivars behave unpredictably with flowering occurring earlier or later than expected. Phenology is the term used to describe the development or lifecycle of a plant. Understanding the phenological mechanisms within each canola cultivar allows us to predict when it will flower in different environments (Whish et al., 2020) or different sowing dates, allowing growers to choose better adapted cultivars and management strategies for different environments.

What do we mean by critical period?

The critical period of yield determination is defined as the physiological stage in which abiotic stresses have the largest impact on yield determination. The critical periods for many crops have been determined over the years (Fischer, 1985; Lake and Sadras, 2014; Kirkegaard et al., 2018; Lake et al., 2019) and the value of reducing stress during these yield formation periods has been demonstrated (Dreccer et al., 2018). For canola, Kirkegaard et al. (2018) demonstrated that the critical period for canola is centred around 300-degree days (°Cd) following the start of flowering (Figure 1), growth stage 60 BBCH (Meier, 2001). At this point the indeterminant nature of the canola plant means it is producing new flowers, while developing pods and filling seed. Any stress at this time affects the supply of resources to the yield components of the plant. Critical periods are usually depicted as a u shape (Figure 1) because the plastic nature of many plants mean that if the stress occurs before the critical period the plant can compensate. To determine the critical period researchers apply stress for short periods then remove the stress and compare the results to an unstressed control.

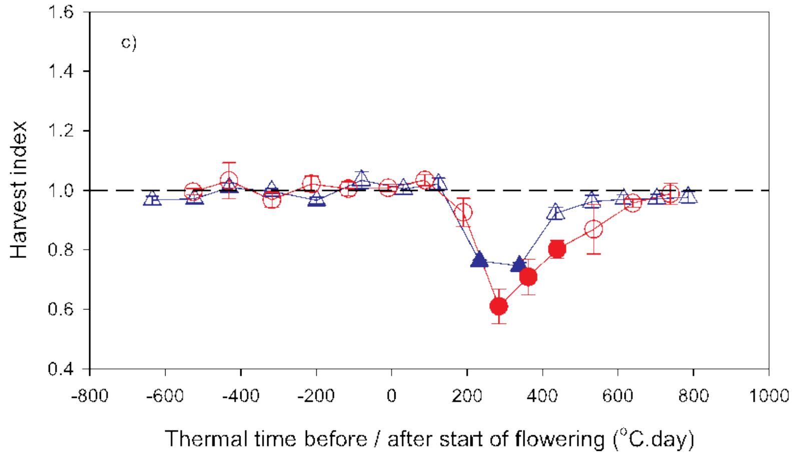

Figure 1. The impact of stress during the critical period on harvest index for canola crops sown at Wagga Wagga (triangles) and Riverton (circles). Filled symbols represent a significant difference from the control. Reproduced from Kirkegaard et al. (2018)

How do you reduce stress during the critical period?

Stresses on plants take different forms (disease, lack of water, high temperatures, low nutrition, low temperatures and pathogens). Some stresses can be controlled but most have to be avoided. In canola, the critical period for yield formation is 300°Cd after flowering. If we can identify periods within the season when the probability of frost is low, the risk of heat is low and there is a high probability of good soil water then we have the optimal time to flower and form yield (Figure 2). Simulation models are useful for identifying these periods because simulations can be run for many years beyond the average grower's life experience and can identify the optimal flowering time with a higher degree of accuracy.

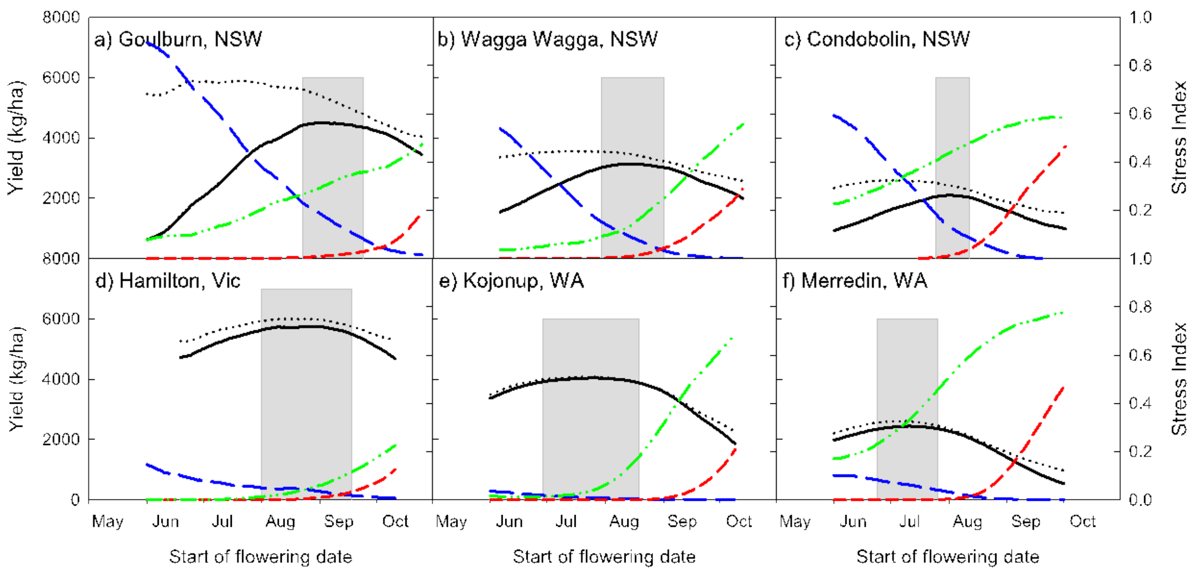

Figure 2. The optimal time to start flowering in different regions around Australia. Showing the simulated potential yield: no frost or heat limitation (black dotted), with frost or heat limitation (solid black). Frost potential (blue long dash), heat stress potential (red short dash) and water limited

potential (green dash-dot-dot). The grey box represents the optimum time to start flowering to achieve 95% of the water limited yield potential. (Reproduced from Lilley et al., 2019).

How do we get a cultivar to flower in our environment at the right time?

Understanding the developmental processes of a plant, it's phenology, allows the plants development to be predicted based on the daily temperatures and day length experienced within an area/climate. Using this knowledge allows a matching of genetics to the environment and helps ensure flowering at the correct time.

Identifying canola phenology

Plants have distinct stages of development, and these describe the phenology of the plant. The most common and easily recognised canola stages are emergence, green bud, flowering, podding and maturity (Figure 3).

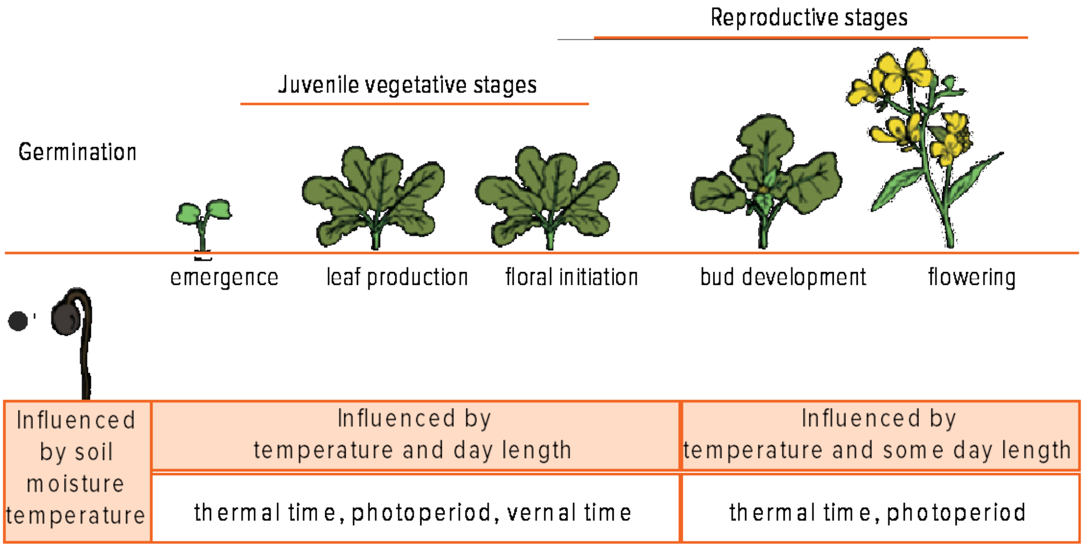

Figure 3. Growth stages for canola and the dominant environmental signals that influence growth in each stage.

Plants respond to environmental signals such as temperature to determine when they move from one developmental stage to another. At the biochemical level, this is caused by specific temperatures inducing the production of plant hormones until a critical concentration triggers the change within the plant. A simpler way to think of this is as a biological clock that accumulates average daily temperatures (day degrees) until a specific target (thermal time target) is achieved.

Why would we want to know this?

Understanding how the environment affects the growth of a plant assists in crop management and enables a grower to match the available canola cultivars to sowing times so that they start to flower at the optimal period. Flowering at this time helps reduce stress during the critical period of yield formation. In addition, many management decisions are time critical, that is, for optimum results the intervention (spray application, defoliation, stop grazing, add fertiliser) needs to occur before a plant reaches a particular growth stage. Identifying these stages can be difficult, for example, floral initiation can occur well before any visible sign appears in the plant. If the crops are grazed or stressed during this floral initiation period, then a yield penalty can occur (Kirkegaard et al 2008; Sprague et al 2014). Knowing the developmental stage of a plant can often help prevent yield loss or ensure that untimely management does not occur.

Rainfall at sowing time is generally unpredictable and may occur early or late. Understanding the phenology of different varieties allows selection of specific varieties to match the sowing time and ensure flowering occurs at the optimum time and the risk of crop loss is reduced (Figure 4).

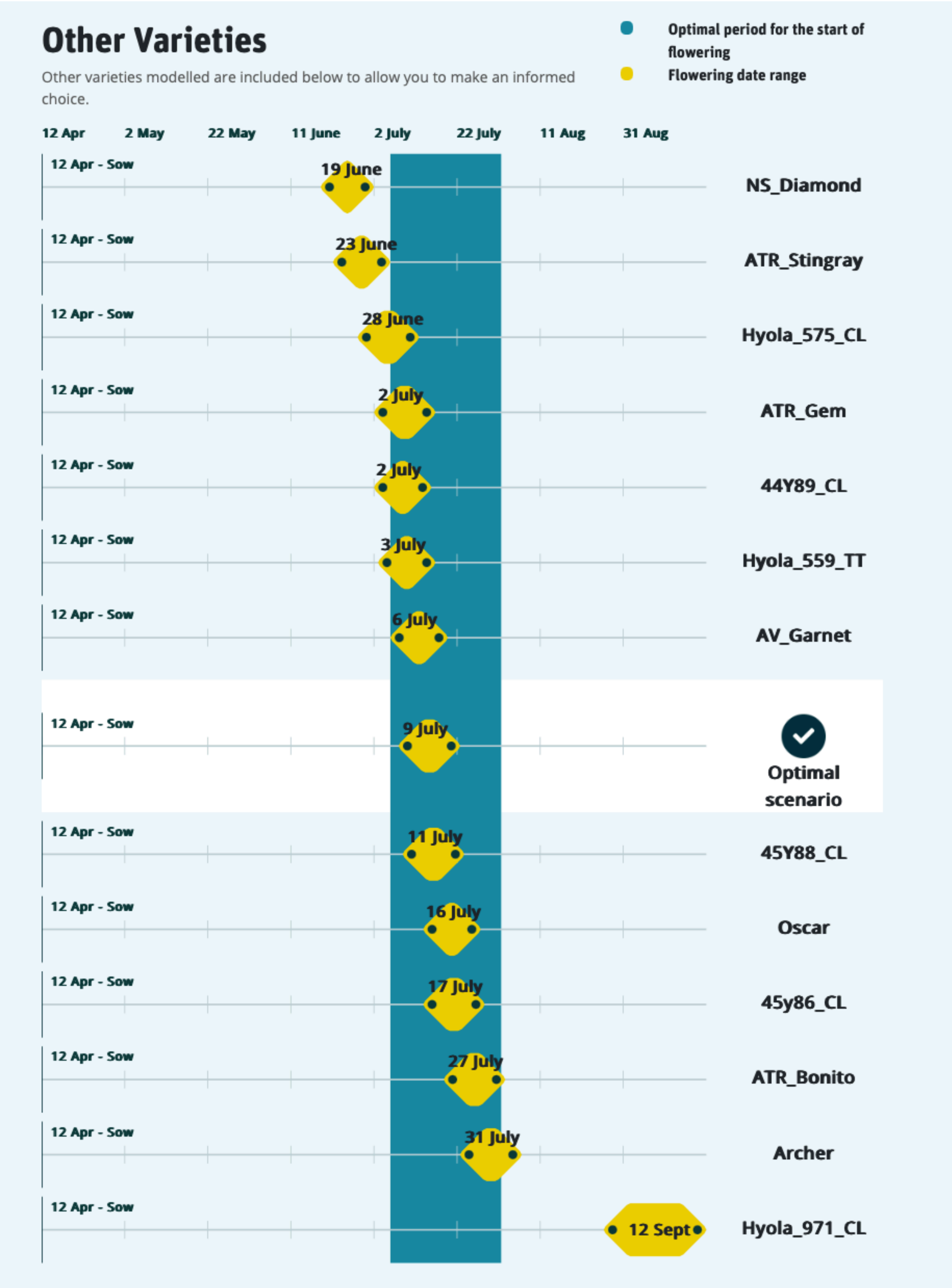

Figure 4. A screen shot from the Canola Flowering Calculator showing flowering data for several cultivars sown at Goondiwindi, Qld on 12 April. At this sowing, short season cultivars Nuseed® Diamond and ATR Stingray ⦻ start flowering before the optimal starting window, while Hyola® 575 CL is 50:50, and the slightly longer-season cultivars like Pioneer® 45Y87 (CL), Pioneer 45Y88 (CL) and Oscar⦻ start flowering at the optimal time.

Several GRDC projects have contributed to our understanding of canola flowering in the Australian environment. More recently, this work has investigated the gene combinations that produce different flowering responses. The goal is to develop a simple PCR test to predict flowering of new cultivars in any environment. While this genetics work is progressing, breeding companies are adopting the same phenological testing procedures to ensure they recommend cultivars ideally suited to each region, sowing date and purpose.

How do you calculate the phenological response for a cultivar?

Day degrees, growing degree days, degree days or thermal time are the terms used to describe the units of a plant's biological clock. They are a way of combining time and temperature into a single number. In their simplest form, day degrees are based on the average temperature recorded during a day (Figure 5). To calculate the thermal time target for a plant's development stage, the day degrees are accumulated until a specific target is reached, e.g., variety X accumulates 500-degree days between emergence and flowering.

Simple degree day calculation

$$\frac{\text{Maximum daily temperature + minimum daily temperature}}{2}$$

Date	Maximum temperature (°C)	Minimum temperature (°C)	Day degrees (°Cd)	Cumulative day degrees (°Cd)
17 May	20	6	13	13
18 May	18	2	10	23
19 May	18	4	11	34
20 May	18	4	11	45
21 May	18	2	10	55
22 May	12	10	11	66

Figure 5. Simple calculation of day degrees (average daily temperature) and accumulation of day degrees over time to calculate a thermal time target.

This example is the simplest form and assumes that the plant has a base temperature of 0°C with no growth or development occurring below this temperature. It also assumes that growth and development will continue at high temperatures (>35°C) but this is not always the case.

The simple day degree calculation can be made more complex by identifying those temperatures where plant growth and development occurs and only calculating day degree temperatures when they are within this range. For this paper we use the average daily temperature, but more information and detail on calculating thermal time can be found at: https://www.youtube.com/watch?v=t-8bwU9ke2s

For some plants, development can be described using thermal time alone, as they will flower after accumulating the same thermal time no matter where they are planted. However, canola is more complicated than this, because in addition to accumulating thermal time, it has two other mechanisms — vernalisation and photoperiod, that influence the time to flowering. The combination and interaction of these three mechanisms complicate the process of estimating when canola crops will flower.

Photoperiod (day length)

Photoperiodism describes the response of plants to increasing or shortening day lengths. Long day plants (canola) respond to increasing day length by reducing the thermal time required to flower.

For example, if it takes an accumulated total of 800-degree days to flower during a 12-hour daylight day it would take only 700-degree days if there are 16 hours of daylight. However, in Australia, canola is generally grown with <12-hour daylengths, so daylength does not influence flowering in most commercial crops.

Vernalisation

Vernalisation is described as low temperature promotion of flowering (Salisbury and Ross, 1969). It is similar to photoperiod, in that vernally sensitive cultivars require less thermal time to flower when grown in a cold environment. However, there are two types of vernalisation 'facultative' and 'obligate'. Facultative vernalisation is when canola grown in cooler climates require less thermal time to flower than when grown in warmer environments. Obligate vernalisation occurs in winter canola and works like a switch with the plants remaining in a juvenile or vegetative state until about 13 days of vernal time have accumulated (this is 13 days with an average temperature of 2°C or 52 days at 12°C). Obligate vernalisation is the mechanism that keeps plants dormant during European winters, or in Australia make this type of canola good for forage or as a dual-purpose crop. Once the obligate vernalisation trigger occurs, the plant behaves similarly to a spring type often displaying a facultative vernal response to additional cold.

How do we know this?

By studying the climate of different regions, we can build a set of key environments to test for vernal responses in canola cultivars (Figure 6).

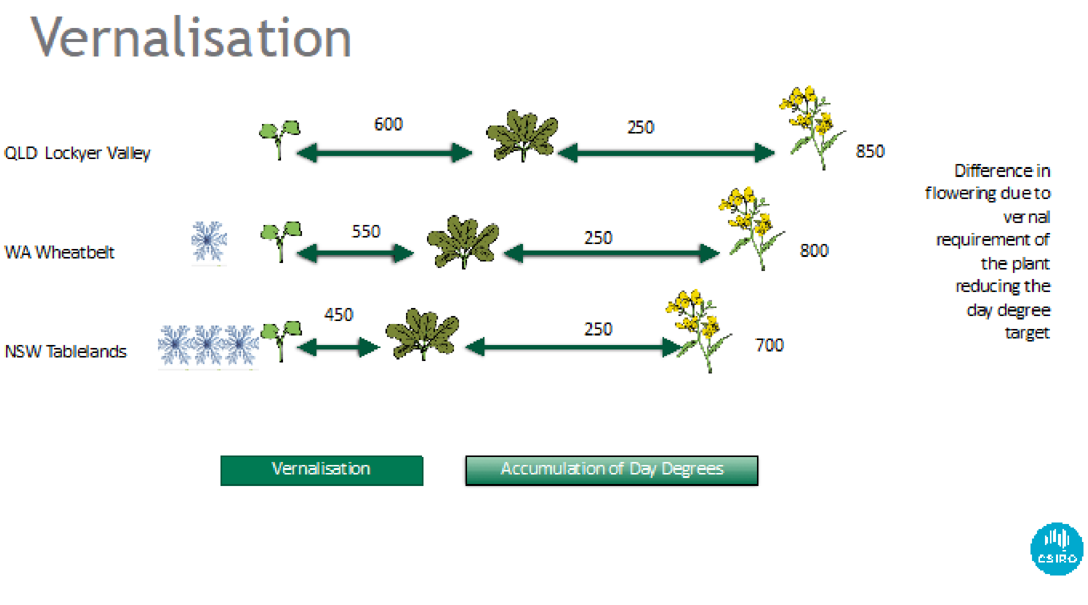

Figure 6. The influence of different rates of vernal accumulation from three sites across Australia on canola flowering time. Cooler regions require less thermal time than warmer regions to achieve flowering.

By strategically choosing sowing dates and sites that accumulate thermal and vernal time differently, we can calculate how each cultivar will behave in any environment (Figure 7). This selection of sites extends from the very cold extremes of the eastern tablelands, to areas with minimal cold, to capture all of Australia's canola growing regions.

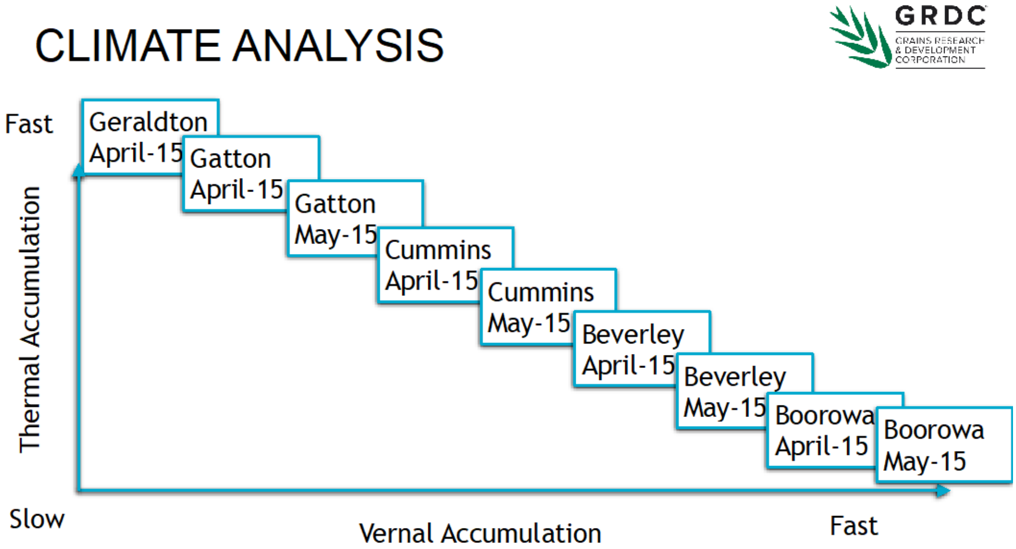

Figure 7. A selection of sowing dates and sites used to characterise the vernal to thermal ratio for Australian canola cultivars.

CSIRO's GRDC funded canola genetics project (Optimising Canola Production in Diverse Australian Growing Environments: CSP1901-002RTX) has used this approach to examine more than 300 different cultivars from around the world. The results demonstrate it is possible to identify different vernal responses (Figure 8).

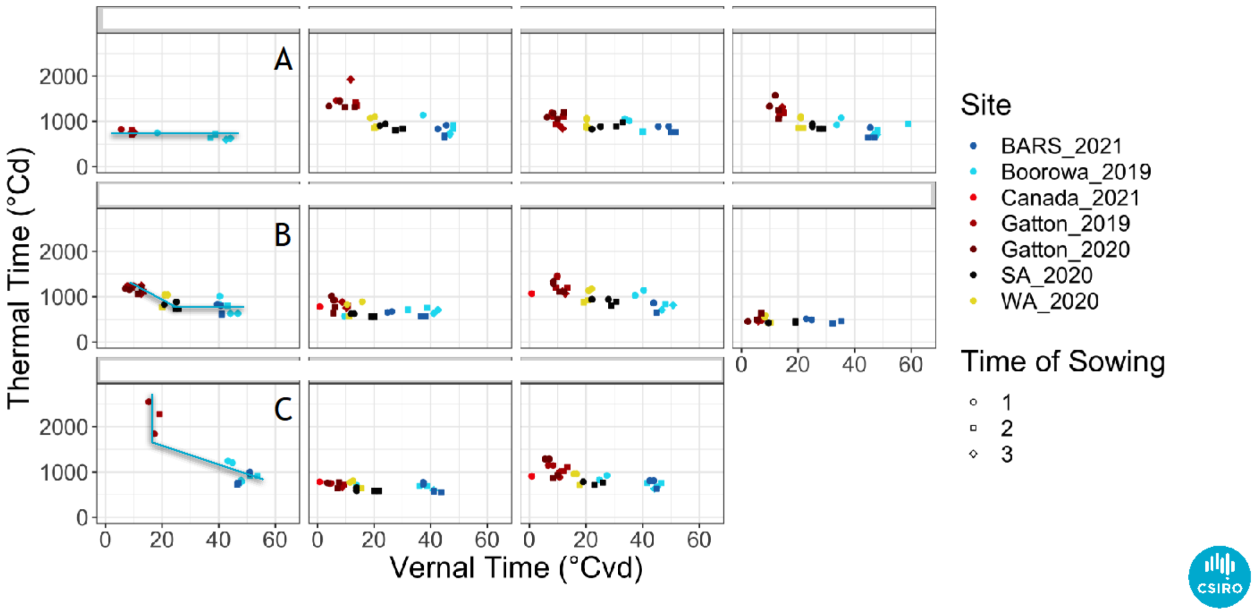

Figure 8. Data from the canola genetics project CSP1901-002RTX detailing three different vernal responses: A. no vernal response, B. facultative vernal response C. obligate vernal response.

Conclusion

Determining a cultivar's phenological characteristics suitable for simulation in APSIM by using the traditional approach of field-based assessment in a range of environments, as described here, is expensive and time consuming. As a result, few current or newly released varieties are ever listed or included within flowering support systems, such as the flowering calculator. At best new cultivars are compared to old cultivars at a few sites and a best guess is applied.

The ability to predict a cultivars time of flowering in many environments, helps refine management decisions (e.g., variety selection, sowing time, fop or dim sub clas herbicide timing and nitrogen application timing) and reduces potential yield gaps. Over the last 5 years GRDC and CSIRO have been working to match the phenological parameters required by APSIM canola to gene combinations. The results reported in the next paper (Dillon 2023, Optimisation of canola phenology in diverse Australian growing environments using genomics), demonstrates a new approach to determining a cultivars phenological response. Based on the success of this approach a new GRDC-CSIRO project (CSP1901-002RTX) will deliver a new flowering predictor within the next 12 months. This predictor will work like the canola flowering calculator and will include wheat and barley.

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Root architecture - Impacts on late season crop development to improve yield and yield stability under water-stress.

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Key words

late deep root development, growth, senescence, wheat varieties, phenotyping, drought tolerance, crop adaptation

Take home message

- Late season water-stress occurs in most seasons at most locations in Australian cropping regions
- Increased late, deep root development can be advantageous to yield where deep soil moisture is available
- Phenotyping in the field is inefficient for many reasons. Improving the efficiency and reliability of non-field phenotyping is required as differences observed in seedlings or small plants are often not replicated in the field
- A system of phenotyping in 1.5m tubes was developed to reliably study post-heading root development
- Differences between genotypes were observed in well-watered conditions, but differences were much greater when a moderate water-stress was applied post heading
- Differences in late, deep root development can be repeatably detected in this non-field system
- The growth and senesce pattern of roots after heading differ among genotypes
- Results obtained using this method can be used to identify candidate breeding parents for improved drought adaptation and to direct later field-based assessments.

Introduction

Late season water-stress occurs in the majority of seasons and at most cropping locations in Australian wheat cropping regions (Chenu *et al.,* 2013). Improved access to water late in the season is particularly beneficial for wheat crops under late season water-stress, as accessing a relatively small amount of subsoil water can have a major impact on grain yield (Kirkegaard *et al.*, 2007). Wheat crop simulations have shown that additional water used after anthesis can be converted to grain with an efficiency of up to 60 kg ha^{-1} mm^{-1} (Manschadi *et al.*, 2006). Similar results were observed in field experiments (Kirkegaard *et al.*, 2007). Thus, wheat genotypes with greater root length density at depth can improve the water availability for the crop, by improving the rate of water uptake or increasing the amount of water that can be extracted from the soil when water is available at depth (Manschadi *et al.*, 2006; Kirkegaard *et al.*, 2007).

The aim of this study was to characterise post-heading wheat root development over time, in well-watered and water-stressed conditions. The root system of two wheat cultivars were examined at key stages from heading to maturity in well-watered conditions and in a range of post anthesis water stress treatments. A system of 1.5 m polyvinyl chloride (PVC) tubes was developed using Mace and Scout as test genotypes. The system was later used to investigate differences between seven wheat genotypes both above and below-ground in response to water stress right through to physiological maturity.

Materials and methods

Plant material

Two wheat cultivars were chosen to test the phenotyping system. Firstly, Maceⓓ which is adapted to the western and southern cropping regions in areas reliant on small bouts of in-season rainfall and has a wide seedling seminal root angle. To contrast with Maceⓓ, the genotype Scoutⓓ was chosen as it is adapted to southern regions often with deeper soils and has a narrower seedling seminal root angle.

Growing conditions

Experiments were conducted in 1.5m long PVC tubes of 90 mm diameter in an outdoor open area during the winter growing season at the Queensland Department of Agriculture and Forestry (DAFQ), Lesley Research Facility in Toowoomba, Queensland, Australia (latitude 27.5598° S, longitude 151.9507° E, altitude 691 m) (Figure 1). Plump seeds of uniform size of each genotype were selected for sowing. Seed was sourced from spaced increase rows with full irrigation grown at Warwick, Queensland in 2017 (28.21°S 152.10°E, 480 m). Three seeds of each genotype were sown in each tube at a depth of 2 cm. Plants were thinned to one vigorous seedling per tube following emergence.

Seeds were sown in a packed soil which had first been airdried and passed through a 2 mm sieve. To ensure non-limiting nutrient supply, 2 gm L^{-1} of Osmocote® fertilizer containing trace elements (N 15.3% P 1.96%, K 12.6%) was added to the soil mix. The soil was watered to field capacity at the start of each experiment.

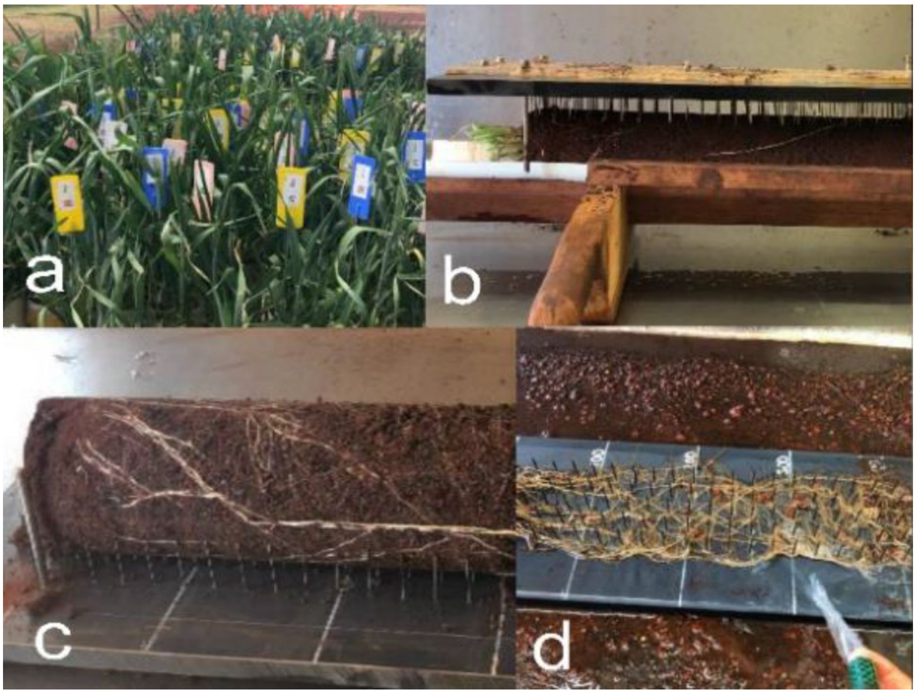

Figure 1. Plants growing in the PVC tube system in an open area in Toowoomba in southern Queensland (a); soil removed from split tubes mounted on the nail board prior to root washing (b) and (c); removal of soil from the nail board by washing (d).

Experimental treatments (TMT) were denominated by the experiment number followed by 'WW' for well-watered, 'MDE' for moderate drought early in grain filling, 'MDM' for moderate drought mid-grain filling, or 'SD' for severe drought from head emergence to maturity (Table 1). Growth stages of individual replicate plants were monitored, and watering withheld between the required developmental periods. Water withholding periods were determined according to the Zadoks decimal growth stage for individual tubes (Zadoks et al., 1974) (Table 1).

Table 1. Experiment characteristics, including the experiment identifier (ID), treatment name (Tmt), the developmental stages (Zadoks decimal growth stages) between which irrigation was withheld (water deficit period; WD period), average number of days from sowing to anthesis and maturity, and yield per plant (g) at maturity (Z92) for Mace and Scout. Values for days to anthesis and maturity as well as grain yield per plant are the mean and standard error for eight replicates.

ID	Tmt*	Water withholding period**	Genotype	Sowing	Anthesis (Z65) (days)	Difference (days)***	Maturity (Z92) (days)	Difference (days)	Yield (Z92) (g plt-1)	Difference (g)
Experiment 1 2020	E1-WW	none	Mace	4/08/2020	77± 0.9	6	129±0.8	2	16±1.5	-2
			Scout		83± 0.8		131±0.9		14±1.5	
	E1-MDE	60-71	Mace	4/08/2020	75±0.9	5	117±0.8	16	7±1.6	9
			Scout		80±0.8		133±0.9		16±1.8	
	E1-MDM	71-81	Mace	4/08/2020	78±0.9	7	117±0.8	14	8±1.8	4
			Scout		85±0.8		131±0.9		12±1.5	
Experiment 2 2021	E2-WW	none	Mace	24/08/2021	68±1.9	6	106 ±1.9	4	12±0.4	1
			Scout		74±2.2		110 ±2.2		13±0.5	
	E2-MDE	60-71	Mace	24/08/2021	65±1.9	10	96±1.9	23	8±0.4	6
			Scout		75±2.2		119±1.9		14±0.4	
Experiment 3 2019	E3-SD	50-92	Mace	4/07/2019	79±0.8	7	115±0.78	5	2.5±0.19	0.5
			Scout		86±0.8		120±0.78		3±0.19	

*Experimental treatments (Tmt) were denominated by the experiment number followed by 'WW' for well-watered, 'MDE' or 'MDM' for moderate drought early- and mid-grain filling, 'SD' for severe drought from head emergence to maturity.
** Period of withholding watering is indicated by the Zadoks decimal growth stage from when watering was discontinued followed by the stage when watering was recommenced.
***Differences were calculated as the mean value for Mace subtracted from that of Scout.

Plant measurements

Phenological Zadok's decimal growth stages were recorded regularly throughout the experiments (Zadoks *et al.,* 1974). Plants were harvested at heading (Z50), early grain filling (Z75) and at maturity (Z92). Shoots were dried for 72 hr at 70˚C before recording dry biomass. For each harvest, to maintain the root distribution, roots were washed and recovered on a nail board, with nails spaced every 30 mm (Figure 1 b, c, d). The soil was washed from between the nails using a jet of water. Root sections were excised at 10 cm intervals for measurement of dry root biomass. The root biomass was measured following drying as per the shoot samples. Root length density was measured using a WinRhizo Regular 2019 image analysis system.

Design and analysis

For each experiment, a randomized complete block design was used with eight replicates per cultivar for each treatment, a replicate being a single plant in a tube.

Analysis of variance (ANOVA) was performed using a linear mixed model approach in the R platform (v3.2.5; R Core Team 2019). A Student–Newman–Keuls (SNK) test was used to compare means for genotypes and treatments, with a significance level of 0.05.

Results

Moderate water stress increased differences in time to maturity as well as grain yield per plant

Moderate water-stress imposed by withholding water for approximately seven days increased differences between genotypes in the time between sowing and maturity (E1-MDE, E1-MDM and E2-MDE, compared to E1-WW and E2-WW respectively, Table 1). This appeared largely due to water-stress induced senescence in Maceⓓ resulting in shortening of the period to maturity of Maceⓓ while Scoutⓓ was little changed. This differential change in the period to maturity was also evident in the differences for grain yield per plant (Table 1). In contrast, a severe stress imposed from heading to maturity (over 40 days) adversely affected both genotypes similarly (E3-SD, Table 1). Severe water-stress tended to greatly reduce the period to maturity for both genotypes as well as the yield per plant.

Differences in shoot and root biomass, were highlighted under moderate water-stress

Genotypic differences in total plant biomass at maturity also tended to be greatest for moderate water-stress treatments (E1-MDE, E1-MDM and E2-MDE, Fig. 2). Differences were larger for shoot biomass, but the smaller values for total root biomass tended to follow a similar trend. With severe water stress, values of all three traits were greatly reduced compared to well-watered conditions, and they differed little between genotypes (E3-SD, Fig. 2)

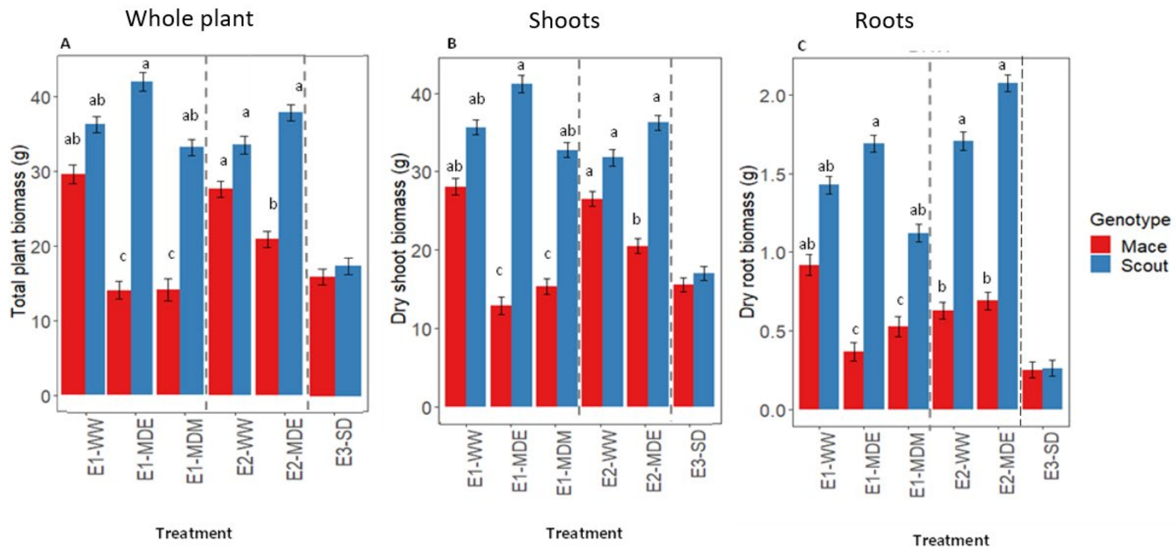

Figure 2. (A) Dry biomass at maturity (Z92) of wheat genotypes Maceⓓ and Scoutⓓ for the whole plant, (B) shoots and (C) roots in different soil water status treatments in experiments E1, E2 and E3 (Table 1). Means that are significantly different (P<0.05) between Scoutⓓ and Maceⓓ within each experiment are shown by different letters above the bars. Error bars represent the standard error of the mean (n=8). The dotted lines separate the three different experiments for which analysis of variance was performed separately.

Water-stress treatment affected the root distribution differently between genotypes

In well-watered treatments, Scoutⓓ had slightly more roots at most depths than Maceⓓ but differences tended to be small (E1-WW, E2-WW, Figure 3 A). For Maceⓓ under moderate water-stress conditions, root length density at all depths below 40 cm tended to be less than that for well-watered plants (E1-MDE, E1-MDM and E2-MDE, Figure 3 A). In contrast, for Scoutⓓ root biomass of plants exposed to moderate water-stress tended to be similar to, or greater than, that of well-watered plants (E1-MDE, E1-MDM and E2-MDE, Figure 3 A). However, both genotypes had similarly low biomass at all depths when exposed to severe water-stress (E3-SD, Figure 3)

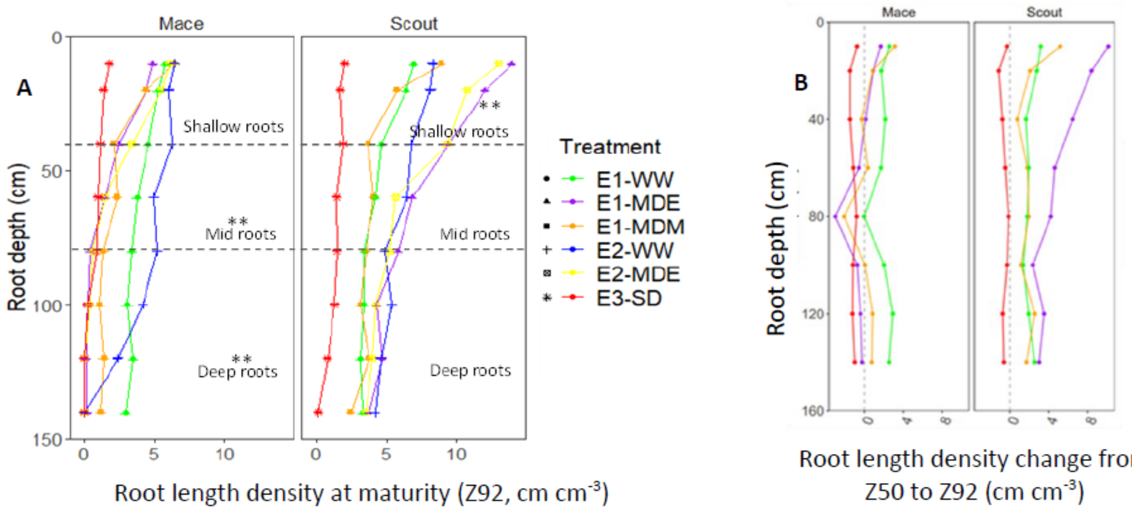

Figure 3. (A) Root length density (cm cm-3) at maturity of Mace⦶ and Scout⦶ for different depths (0 - 150 cm). The horizontal dotted lines represent partitions between shallow (0 to 40 cm), mid (60 to 80 cm), and deep root (100 to 140 cm) layers. Asterisks indicate differences between treatments for total shallow, mid or total deep layer root length density (P<0.01). (B) Differences in the root length density between heading (Z50) and maturity (Z92) for different depths for Experiment 1 only. The vertical dotted line highlights a value of zero representing no change between stages.

The differences between genotypes in root length density at maturity are likely due to the changes from heading (Z50) to maturity (Z92) (Figure 3 B). For Mace⦶, the root length density increased between Z50 and Z92 at most depths only for the well-watered plants (E1-WW, Figure 3 B). For the moderately water-stressed treatments, there were only small changes from Z50 to Z92 (E1-MDE and E1-MDM, Figure 3 B). In contrast for Scout⦶, root length density tended to increase to a similar degree, or for the E1-MDE possibly even a greater degree, for moderately stressed treatments compared to the well-watered (Figure 3 B). For the severely water-stressed plants, the root length density tended to decrease for both genotypes for most depths between Z50 and Z92 (E3-SD, Figure 3 B).

Differences at individual depths were pooled for three larger soil layers, shallow, mid, and deep layers of 50cm each, as shown in Figure 3 A. Examination of the differences in root biomass in these larger layers indicates similar differences to those observed for other traits. The differences between genotypes are most clearly expressed in the moderately water-stressed treatments (E1-MDE, E1-MDM and E2-MDE, Figure 4). In contrast, there was little difference between genotypes in either the well-watered, or severely stressed treatments (E1-WW, E2-WW, E3-SD, Figure 4). Thus, it appears important to impose a moderate, but not severe water-stress treatment in order to enhance differences between genotypes in root adaptation to water-stress.

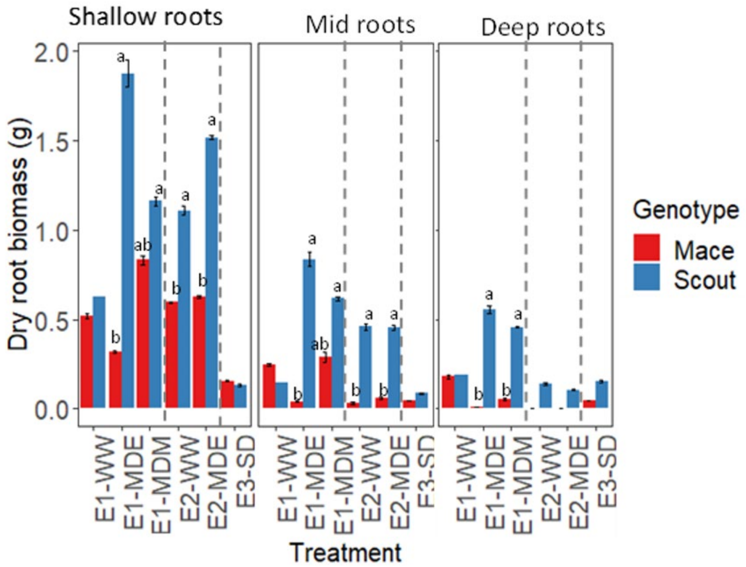

Figure 4. Partitioning of dry root biomass from mature plants (Z92) of Mace⦶ and Scout⦶ for shallow (0 to 50 cm), mid (60 to 100 cm), and deep (100 to 150 cm) soil layers. Different letters indicate significant differences between means for genotypes (P<0.05). The dotted lines the three different experiments for which analysis of variance was performed separately for each experiment.

Major differences in root development are occurring post heading

Having determined that the genotypic differences in root adaptation to water-stress were highlighted when a moderate post-flowering water-stress is applied, another experiment was conducted where all plants were moderately stressed and measurements taken at three different growth stages. In this instance seven genotypes were examined (Figure 5).

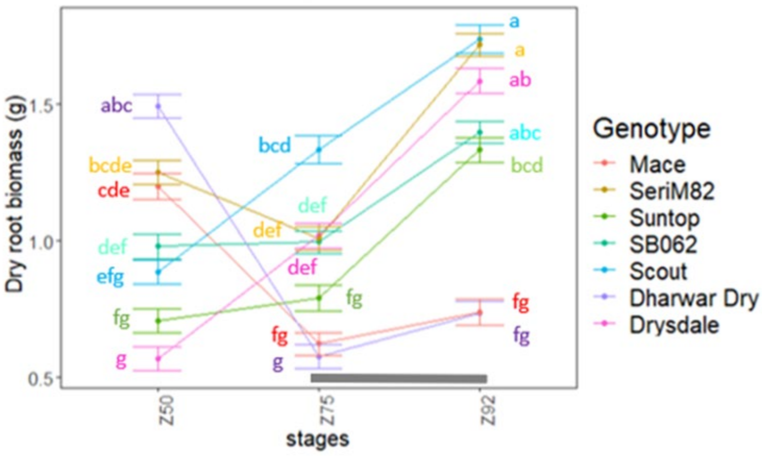

Figure 5. Total dry root biomass (g) of seven wheat genotypes under well-watered conditions at heading (Z50), mid grain-filling (Z75) and at maturity (Z92) after a late moderate water-stress. The horizontal bar indicates the period when watering was withheld to impose a mild water stress. Means that are significantly different (P<0.05) between genotypes within each developmental stage are shown by different letters above the bars. Error bars represent the standard error of the mean (n=8). Analysis of variance was performed together between each stage.

When the dynamics for total root biomass from heading (Z50) to early grain filling (Z75) and then to maturity (Z92) were examined, three groups of genotypes were elucidated (Figure 5). Scout⦶ and

Drysdale formed a first group which tend to start with a relatively lower root biomass than other genotypes at Z50 but then exhibited increased biomass at both Z75 and Z92. Suntop⦶, SB062 and SeriM82 formed a second group which tended to have intermediate root biomass at Z50, change little by Z75 but then increase rapidly between Z75 and Z92. In contrast to both of these groups, the group containing Mace⦶ and Dharwar Dry tended to have higher root biomass at Z50 but this then decreased sharply up to Z75 and remained low between Z75 and Z92 (Figure 5).

The tendency to increase root biomass post-flowering, is likely linked to improved adaptation to water-limitation in environments where water is available deep in the soil late in the season. The tendency for roots to senesce post-flowering may reflect an adaptation to reduce the growth period of roots and conserve photosynthate for grain filling in environments where deep water is not usually present.

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Novel seed traits - An update on recent R&D

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Key words

breeding, climate resilience, seedling establishment and growth, weed competitiveness

GRDC codes

CSP00182, SLR2103-001RTX, DAQ2104-005RTX, CSP1907-001RTX

Take home messages

- The long-term climate trend is for increasing summer rain and later autumn sowing breaks throughout the Australian wheatbelt. Long coleoptiles and hypocotyls will permit deeper sowing of winter crops into summer-stored subsoil moisture allowing timely, earlier germination, and crop growth to occur under conditions optimal for maximising water productivity.
- Breeding improved establishment, which together with greater early vigour, should increase weed competitiveness to aid in weed and herbicide management, and increase nutrient uptake/nutrient-use efficiency. Greater biomass with higher vigour should also facilitate the breeding of crop varieties for later sowing in frost-prone regions or where dry sowing and double-knock weed control strategies are commonplace.
- Methods developed in assessment of seedling vigour in wheat are being translated into canola and other crops to hasten the identification of new genetics and speed the delivery of improved crop varieties for changing climates.

Aims

To identify and validate traits contributing to timely and reliable seedling emergence and greater seedling root and shoot growth.

Translate learnings in genetic improvement of seedling establishment and growth in wheat to other crops in order speed delivery of new crop varieties with improved adaptation to changing climates.

Background

The seed contains all the necessary nutrients, sugars, and primordia for the first 3–4 weeks of seedling growth. All components are necessary in optimising coleoptile (or hypocotyl) and shoot and root growth, highlighting that seed quality sets the potential for establishment and early growth of the crop. Environmental challenges including competition by weeds, reduced soil moisture and high temperature, chemical and physical soil constraints, and sowing depth can act to limit this potential to reduce plant numbers and, where extreme, result in crop failure. Genetic variation is available to meet these challenges, and tools are being developed to assist breeders in the release of new crop varieties that, together with improved systems knowledge, will improve early crop growth, particularly with increasing climate variability.

This update paper highlights current research in genetic understanding to improve seedling growth and particularly increased emergence and establishment, and early leaf and root development. Presented examples are focused on wheat and include translation of learnings from wheat to adoption in other crops.

Improved wheat establishment

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

Changing weather patterns are associated with proportionally greater summer rainfall and increasingly later sowing breaks (Flohr et al. 2021; Scanlon and Doncon 2020). There is increasing interest in deep sowing into subsoil moisture (at depths up to and exceeding 10cm) to better utilise sowing opportunities after summer and early autumn rainfall and ensure earlier germination and establishment (Rich et al. 2021; Flohr et al. 2022). However, the shorter coleoptiles and hypocotyls of many current crop varieties limit sowing depths to less than 10cm and commonly as shallow as 3–5cm. High-throughput phenotyping methods have been developed and fine-tuned to screen global germplasm and identify genetic sources for use in breeding. At the same time, recognition of the critical importance of characteristics in the seed in improving seedling establishment and early growth has focused efforts in assessment of global germplasm in breeding greater shoot and root vigour.

The long coleoptile Mace⫽ experimental line (‘Mace18’), containing a new *Rht18* dwarfing gene, established well at sowing depths of 120–140mm (up to 80% of 40mm control depth) across southern, eastern and western Australia in 2020, 2021 and 2022 (for example, see Figure 1). Establishment with deep sowing of the experimental line Mace18 was as good as the older tall, long coleoptile wheat variety Halberd. Coleoptile lengths were measured at lengths of 120mm+. By contrast, the shorter coleoptile of commercially available Mace⫽ reduced establishment with deep sowing (30–40%). The new AGT variety Calibre⫽ also emerged well with deep sowing compared to Mace⫽ and Scepter⫽ (Figure 1). Grain yields were significantly (P<0.01) greater for deep-sown Mace18 in 2020 and 2021, and we are awaiting yield data in 2022 at up to 10 sites throughout Australia. Crop modelling analysis of previous research and grower data suggests an 18-20% increase in wheat productivity with improved establishment when deep-sowing particularly when targeting early-to mid-April sowing dates (Zhao et al. 2022).

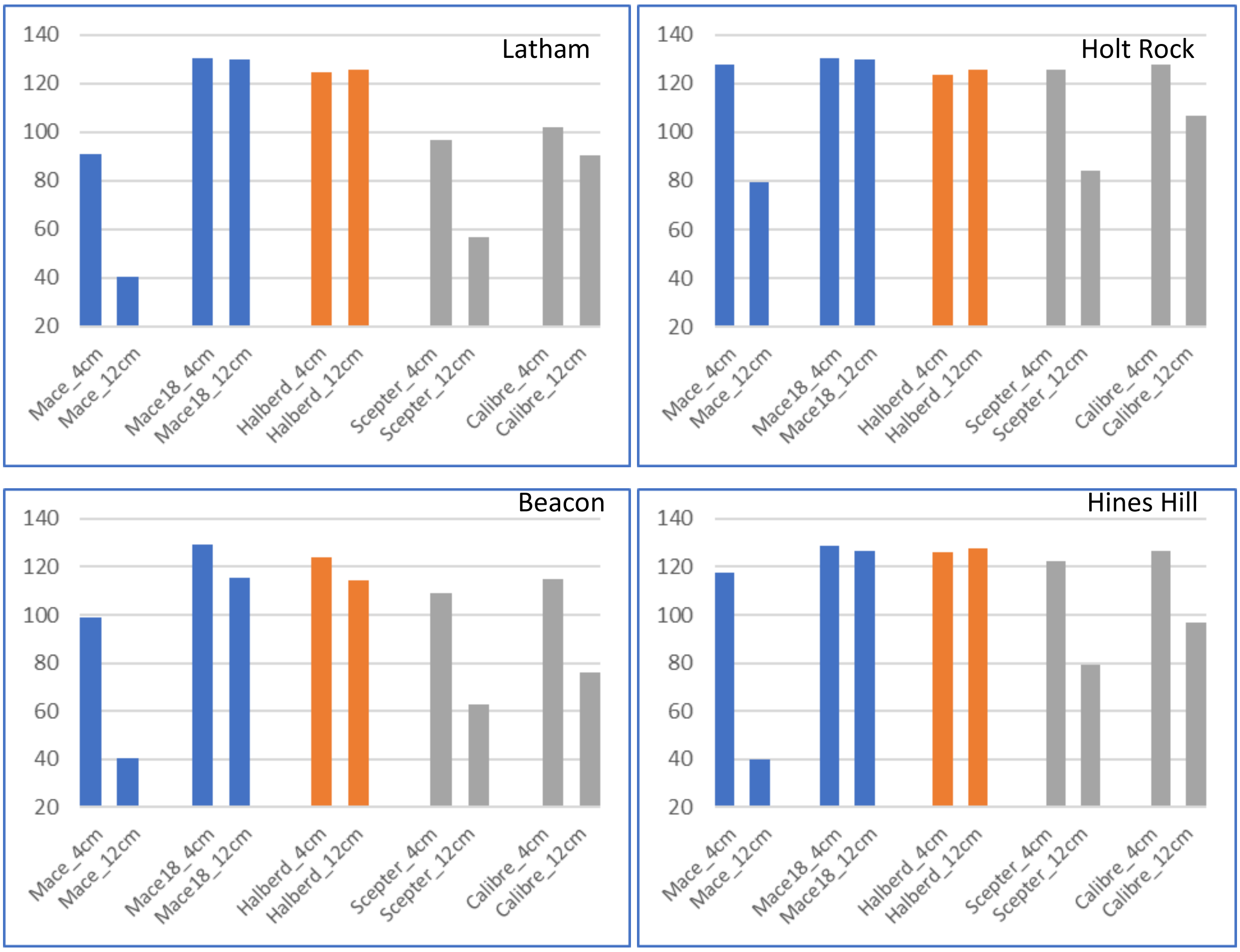

Figure 1. Mean number of plants/m² (at 200°Cd) at four WA sites in 2021 for shallow-sown (4cm) and deep-sown (12cm) Mace⦶ *Rht2* and *Rht18* NILs ■, tall, long coleoptile variety Halberd ■, and commercial *Rht2* dwarfing gene varieties Scepter⦶ and Calibre⦶ ■. Lsds were 8, 16, 6 and 6 plants per m² for Latham, Holt Rock, Beacon and Hines Hill, respectively.

Improved canola establishment

Poor establishment of canola (*Brassica napus* L.) is a widespread problem in Australia and globally with an average 50% or less of germinable seeds successfully establishing (McMaster et al. 2019). New laboratory-based, screening methods were adapted from wheat for high-throughput assessment of hypocotyl length. Figure 2(a) shows significantly ($p<0.05$) longer hypocotyls in three overseas canola varieties compared with representative Australian varieties. As in wheat, validation of laboratory conditions was needed to confirm performance with deep sowing in the field. Figure 2(b) summarises emergence data for Boorowa (one of four sites) in 2021 for the best Australian and overseas canola varieties under laboratory conditions. At the 50mm sowing depth, the three longest hypocotyl overseas varieties had significantly ($p<0.05$) higher emergence rates than the best Australian variety. As in wheat, rapid laboratory-based screening methods appear effective in identifying varieties with improved establishment potential. Experimental data from 2022 confirm these field-based results are repeatable.

Similarly, preliminary results indicate genetic variation for greater mesocotyl length among oat gene breeding germplasm (Tanu et al. 2023). As for wheat and canola, the potential exists in breeding oats with improved establishment when deep-sowing. As oats are the only winter cereal possessing a mesocotyl, sowing deeper than wheat maybe possible but requires validation.

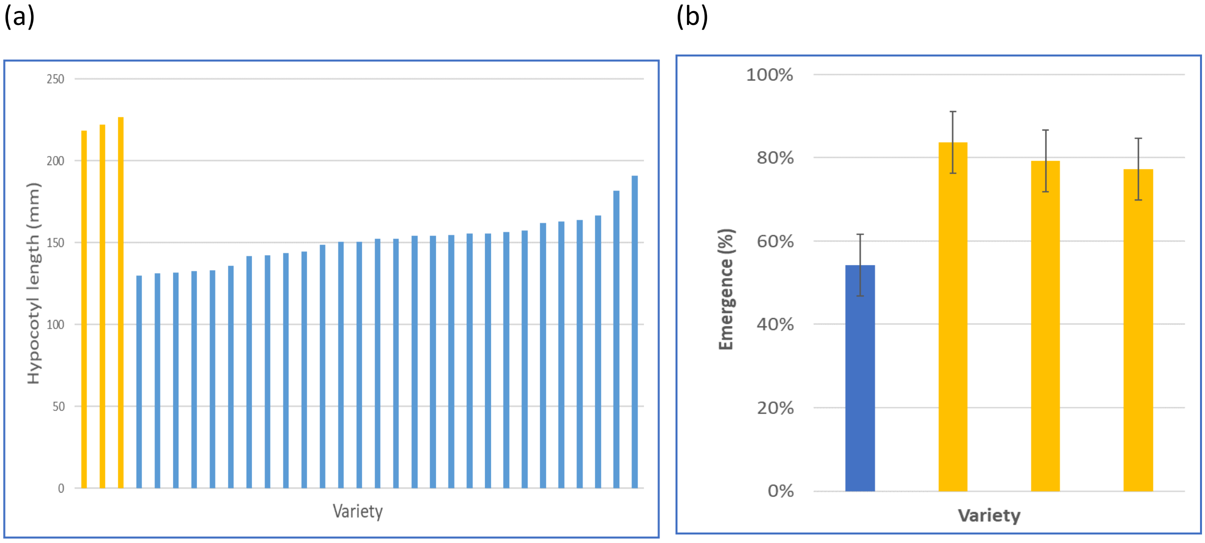

Figure 2. (a) Laboratory-based hypocotyl length for three selected overseas canola accessions (yellow) and 28 Australian varieties (blue) (Lsd = 25mm); and (b) percentage seedling emergence with deep-sowing (5cm) in the field for the best overseas long hypocotyl accessions (yellow) and best Australian canola variety (blue).

The laboratory-based methods and physiological understanding developed over three decades in wheat are being translated and modified accordingly to fast-track breeding in other crops. It is predicted that crop varieties with potential for deep-sowing will be available across most crops in the next decade to aid in de-risking poor establishment with predicted changes in the amount and timing of Australian rainfall and increasing soil temperatures.

High early vigour for improving performance with late sowing

Reductions in April–May rainfall have been mirrored by a shift in increasing rainfall later in the season (Cai et al. 2012). Growers are therefore faced with the decision to sow dry and risk poor germination. Additionally, double-knock herbicide strategies, soil amelioration, double-cropping, and pest and disease control all take considerable time to complete at the beginning of the season. The option to sow later in the season would provide more time to remediate soils and implement necessary weed control strategies. However, later sowing is tightly linked to growth under cooler temperatures, in turn reducing crop biomass and grain number to reduce yield.

New high early vigour genetics bred over 30 years at CSIRO has shown promise in rapid growth after emergence, even when sown later in the season. Figure 3 summarises grain yields at Wagga Wagga in 2021 for experimental high vigour breeding lines (CW17#66-35, CW18#58-B11 and LCH9396) and commercial varieties at two sowing dates. Later sowing reduced time to flowering from an average 133 to 107 days ($p<0.001$), and reduced grain yields (yet still exceeded 5t/ha). The experimental high vigour lines (‘CW_’) achieved the same higher yields as the more vigorous commercial varieties Condo⦶ and Vixen⦶ despite not being selected for grain yield. Of the different plant traits measured, the strongest association with grain yield in the later sowing was with increased plant height, greater early biomass and ground cover (Green et al. 2023). These high vigour genetics have been delivered and are being used in commercial breeding programs.

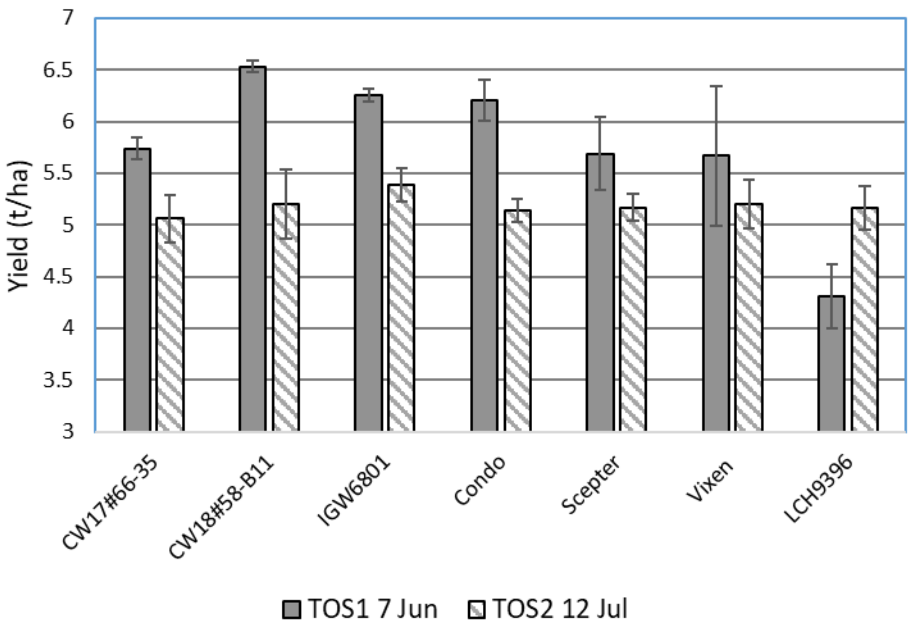

Figure 3. Grain yields of selected wheat lines sown on two sowing dates (TOS) at Wagga Wagga in 2021. Closed horizontal bars represent standard errors. Lsd (Genotype) = 0.75t/ha, Lsd (TOS) = 0.11t/ha, Lsd (Genotype × TOS) = 1.07t/ha.

Greater seedling vigour to increase crop competitiveness

Herbicide resistance, together with the high cost of pre-emergent herbicides, represent a substantial cost to Australian growers. Yield losses of up to 25% are sometimes reported where weed control is inadequate, while carryover of weed seed can present a major cost in subsequent crops while increasing risk with herbicide resistance with already limited chemical control options. Older crop varieties were very effective in competing with weeds. They were taller and produced greater leaf area early in the season to compete with weeds for light, while there was indication of their ability to also compete effectively below-ground (Hendriks et al. 2022).

Figure 4 summarises the significant ($p<0.05$) reduction in ryegrass biomass in high early vigour (HV) selected Wyalkatchem⦶ and Yitpi⦶ derivatives carefully assessed in seedling pouches. The influence on wheat vigour in reducing ryegrass growth was consistent at moderate (635 plants/m^2) and high (1270 plants/m^2) ryegrass densities, and whether growth of the ryegrass was competing above- or below-ground with the wheat. The suppression of ryegrass growth by the high vigour lines was more than two-fold the suppression of ryegrass growth by the low vigour parents. The results in this controlled laboratory assessment are consistent with field observations currently being analysed (P. Hendriks unpublished data).

Conclusions

The seed contains all the necessary machinery to assure the first 3–4 weeks of seedling growth. The potential for excellent establishment and early growth can be massively enhanced with the right genetics and high quality seed. Seed quality is determined by conditions through seed growth, harvest and storage, and can be readily assessed with germination and vigour testing.

Current research into genetic control of coleoptile and hypocotyl growth, and seedling shoot and root vigour are highlighting the potential for new crop varieties to be more resilient with changes in climate. Together with improved climate modelling and agronomy, new genetics will support opportunities in breeding for system resilience to climate change while reducing risk in weed and nutrient management. Learnings from wheat are being translated into other crops, thereby fast-tracking the breeding and farming systems requirements with the new genetics.

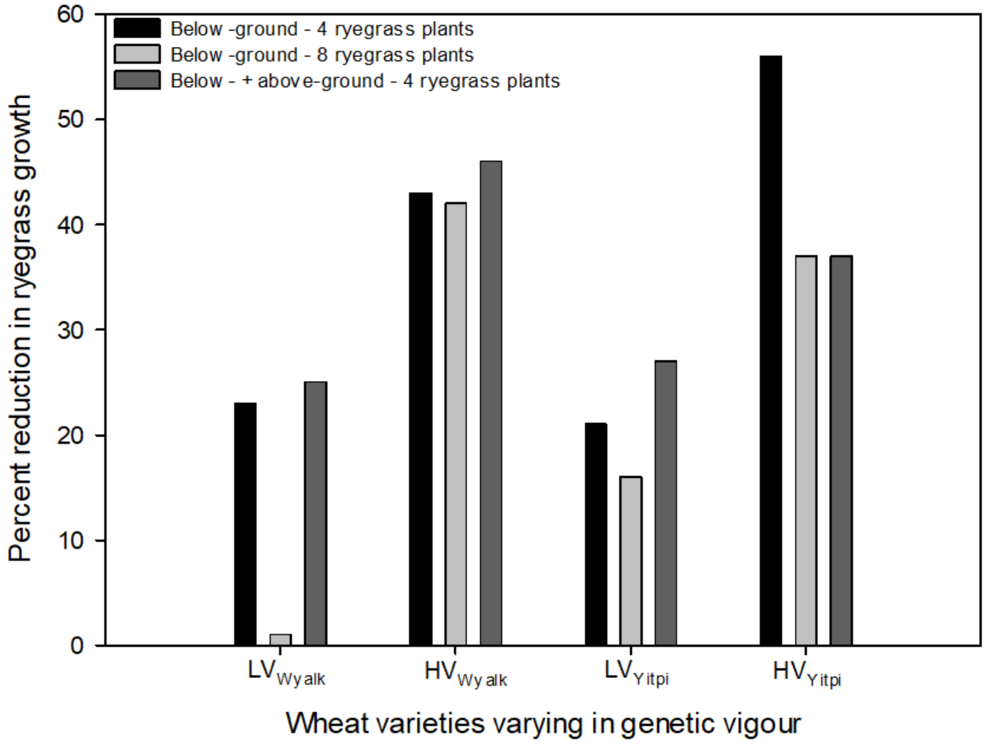

Figure 4. Reduction in ryegrass growth (biomass) for low vigour (LV) wheat varieties Wyalkatchem⊕ and Yitpi⊕ and their high vigour (HV) bred derivatives when assessed for below-ground competition in seedling pouches containing four or eight ryegrass seedlings and with above- and below-ground competition with four ryegrass seedlings. The four and eight plants correspond to 635 and 1270 ryegrass plants/m^2. Differences between high and low vigour varieties for ryegrass biomass was statistically significant ($p<0.05$) for all treatments.

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

Spatial soil constraint diagnosis using remote sensing data overlaid with soil data, for more informed management decisions about infield variation

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Key words

soil constraints, climate, in-crop rainfall, EVI

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Take home message

- There are various agriculture management options available to growers faced with soil constraints. To make informed decisions and apply the most appropriate option, growers need information about which areas of their paddocks are most impacted and whether climate influences the spatial variation of soil constraints
- Previous studies have found that soil constraints such as salinity can have a larger impact on crop growth in years with low in-crop rainfall. Conversely, soil sodicity can impact soil structure and give rise to waterlogging in years with high in-crop rainfall
- This study focused on freely available remote sensing data to study historical patterns of yield variation and thereby provide growers with useful information about variation within their paddocks
- Findings from this study will be important for further research into the drivers of yield variation and for underpinning software (e.g. ConstraintID http://constraintid.com.au) (Dang et al., 2022; Orton et al., 2022) that can use remote sensing data to design targeted sampling plans and overlay remote-sensing data with soil data, for understanding reasons for consistent spatial variation of crop yields within fields.

Introduction

Soil constraints limit plant growth and grain yield in Australia's grain-cropping regions, with the nature of the impact dependent on climate. In seasons with low in-crop rainfall, soil constraints can reduce yield by limiting soil water storage, and crop water uptake. Conversely, soil constraints can exacerbate waterlogging in seasons with high in-crop rainfall. When moderate in-crop rainfall is experienced, soil constraints may only have a minimal impact on yield. Therefore, spatial yield variation in dry and wet years might show a stronger correlation with the spatial variation of soil constraints compared with average rainfall years.

Based on the assumption that different patterns of spatial yield variation (within fields) between wet and dry years are related to the spatial variation of different soil constraints, it might be possible to detect the impact of different soil constraints from yield data collected over many growing seasons. However, the availability of long-term archives of yield monitor data is limited, thus restricting the detection of soil constraints using this approach. A valuable surrogate for yield can be derived from remote-sensing data, which offer excellent time series and spatial information (Cai et al., 2018; Semeraro et al., 2019). Therefore, this study used vegetation indices from a series of images around peak biomass (the average of the enhanced vegetation index, EVI) to approximate the spatial variation of yield among different climate years (Bai et al., 2019; Semeraro et al., 2019; Zhao et al., 2020). As a result, when the average EVI is compared with soil constraints data, there might be potential to detect the different impacts of soil constraints in different climate years.

The general hypothesis in this work is that we might expect in the dryer years:

(i) more consistent patterns of within-field spatial variation of crop growth (due to a common dominant driver); and

(ii) stronger correlations between soil constraints that limit the plant extraction of soil water and the average EVI.

Meanwhile, for wet years, we might also expect consistent growth patterns ,but perhaps different patterns to those exhibited in dry years. These patterns might reflect correlations between EVI and soil constraints causing waterlogging (e.g., sodicity or compaction).

Finally, in years with average in-crop rainfall the soil's ability to store plant available water would not be so important, and other factors (e.g., pests/diseases) might be the more important drivers of variation of crop growth across the field. In these moderate climate years, we might not see a consistent spatial variation of crop growth or such significant correlations between EVI and the constraints across the field.

In this study, we used data from five fields from across Australia′s northern grain-growing region, with sizes ranging from 10 to 200 ha. These fields were selected in earlier work (Dang et al., 2010a; Dang et al., 2010b; Dang et al., 2011a; Dang et al., 2008; Dang et al., 2011b; Dang & Moody, 2016) during which soil sampling was conducted.

The questions addressed in this work were:

- Is there evidence that remote sensing data from years with low in-crop rainfall are best for indicating areas impacted by soil salinity constraints?
- Is remote sensing data from years with high in-crop rainfall best for indicating areas affected by soil sodicity constraints?

If evidence of the benefits of analysis by wet or dry years is found, then similar analyses could readily be incorporated into tools that use remote sensing data to help growers diagnose areas of their fields affected by soil constraints, such as ConstraintID (http://constraintid.com.au).

Calculating an index to represent the spatial variation of crop yield for each year

This work used 30-m pixel resolution satellite imagery from Landsat collected between 1999 and 2019. Three bands of each satellite were used, representing the blue, red, and near-infrared (NIR) portions of the electromagnetic spectrum, to calculate the enhanced vegetation index (EVI; Huete et al., 2002). This index has been used in previous work (Ulfa et al., 2022a, 2022b) and showed a reasonable correlation with crop yields in the study region. Some images were incomplete due to partial cloud coverage or the scan line corrector issue with Landsat 7. Only images with at least 75% coverage of a field were included. For incomplete images with ≥75% coverage, gaps were filled by regression kriging.

This study used EVI, averaged over a window from 64 days before until 64 days after the date of the peak of the field-median EVI. Furthermore, we filtered this series of images by only including those for which the field-median EVI was at least 60% of the peak of the field-median EVI (to avoid including imagery with very low vegetation cover). We calculated the average from these filtered images, which we refer to from hereon as the average EVI for each year. The result of this step was, for each field, a stack of average EVI raster map layers (one layer for each year).

Detecting years to be included in the ensuing analysis

For some years, a crop might not have been sown, while for other years, the remote-sensing data might be insufficient to provide a confident spatial representation of crop growth. We defined a series of heuristics to detect the years to be included in the subsequent analysis. For each field, we calculated the field-median EVI for all available dates of imagery to compile a time series of field-median EVI for each year and checked that:

(i) there were at least five available dates in a certain year
(ii) the maximum field median EVI in a year was greater than 0.25
(iii) the maximum field-median EVI was between mid-June and the end of October (indicative of the peak biomass for a winter crop
(iv) the field-median EVI both before and after the time of the peak was at some point less than half of the maximum field-median EVI (an indication of a reasonably pronounced growth curve), and
(v) the data from a growing season spanned at least a 120-day interval.

Determining in-crop rainfall

Daily rainfall data for each field was extracted from the nearest cell of the 5-km gridded dataset, obtained from SILO (Scientific Information for Land Owners), a database of Australian climate data (https://www.longpaddock.qld.gov.au/silo/ (accessed 16 July 2021)). We used the period from 5 months before to 3 months after the peak EVI for calculating the in-crop rainfall. Each growing season was classified into one of three classes (dry, moderate, or wet; Table 1). This classification was made to keep an equal number of years within each of the categories to enable statistical comparisons.

Table 1. In-crop rainfall classification for each year and field.

Fields	Dry years	Moderate years	Wet years
1	2002, 2004, 2006, 2009, 2018	2001, 2005, 2011, 2015, 2017	2003, 2007, 2008, 2010, 2016
2	2002, 2004, 2006, 2009, 2019	1999, 2001, 2003, 2005, 2017	2007, 2008, 2010, 2011, 2016
3	2002, 2013, 2017	2000, 2003, 2006	1999, 2007, 2012
4	2006, 2009, 2012, 2013	2003, 2005, 2014, 2015	2004, 2011, 2016, 2017
5	2002, 2005, 2017	2003, 2007, 2014	1999, 2004, 2010

Assessing relative growth index consistency within a certain in-crop rainfall year classification

We tested whether there was evidence of distinct patterns of spatial variation for dry, moderate or wet years. The assessment used an index called the relative growth index (RGI) to represent the spatial variation of crop growth within a field in a given year. To calculate the RGI, the pixels in a growing season's average EVI map were ranked, and these pixel rankings were standardized to the range 0–100; thus, the RGI represented the 'good' and 'bad' performing parts of the field for a given year.

A statistical test was then applied to the RGI values from all years in a subset (i.e. all dry years, all moderate years, or all wet years) to assess whether there was evidence of a pixel showing 'consistently good' or 'consistently poor' growth (relative to the field average). This test was applied for each pixel in turn. Then, a 'consistency index' (CI) was calculated as the percentage of pixels in the field classed as either consistently poor or consistently good. This CI can range from 0, if the maps in a subset of years all showed different patterns of spatial variation, to 100, if the maps in a subset all showed identical patterns of spatial variation.

Another statistical procedure (called bootstrapping) was applied to determine whether the CI for a particular field and subset of years (in-crop rainfall class) was larger than might be expected 'by chance'. We deemed a subset of years potentially interesting—with evidence of a distinct pattern of spatial variation in the particular group of years—if the actual calculated CI was larger than the 95th percentile of the bootstrapped CI values.

Results

Remote sensing data indicating climate-specific impacts of soil constraints

Overall, from the five fields analyzed, there is no distinctive result among years classified as dry, moderate, and wet (Table 2). Based on the in-crop rainfall class, three fields (Fields 2, 4 and 5) have the largest consistency index (CI) during moderate rainfall and two fields (Fields 1 and 3) in wet years. The bootstrapping analysis revealed that only in Field 1 in wet years was the CI larger than should be expected 'by chance'. This suggests that for Field 1 in wet years, there might be something driving spatial variation of crop growth that impacts differently compared to its impact in moderate or dry years.

Table 2. Consistency index in different climate years based on in-crop rainfall. Bold values indicate marginally significant adjusted p values ($p < 0.1$).

Fields	Dry	Moderate	Wet	Bootstrap 95% percentile
Field 1	22.73	16.67	**44.31**	36.00
Field 2	23.40	42.55	36.17	44.18
Field 3	75.26	47.69	75.46	82.29
Field 4	16.43	22.59	22.16	37.76
Field 5	12.43	27.03	12.57	34.58

The distribution of the consistent pixels within each of the five fields is presented using colour coding, where dark and medium pixels are the areas with consistently low (mean RGI <50) and high (mean RGI >50) ranks among years in the same in-crop rainfall class (Figure 1). For Field 1, the field with a greater than expected CI in wet years, the westerly and easterly sides of the field showed consistently poor growth in wet years, while the central part of the field showed consistently good growth in wet years, which was not evident in the moderate or low rainfall years.

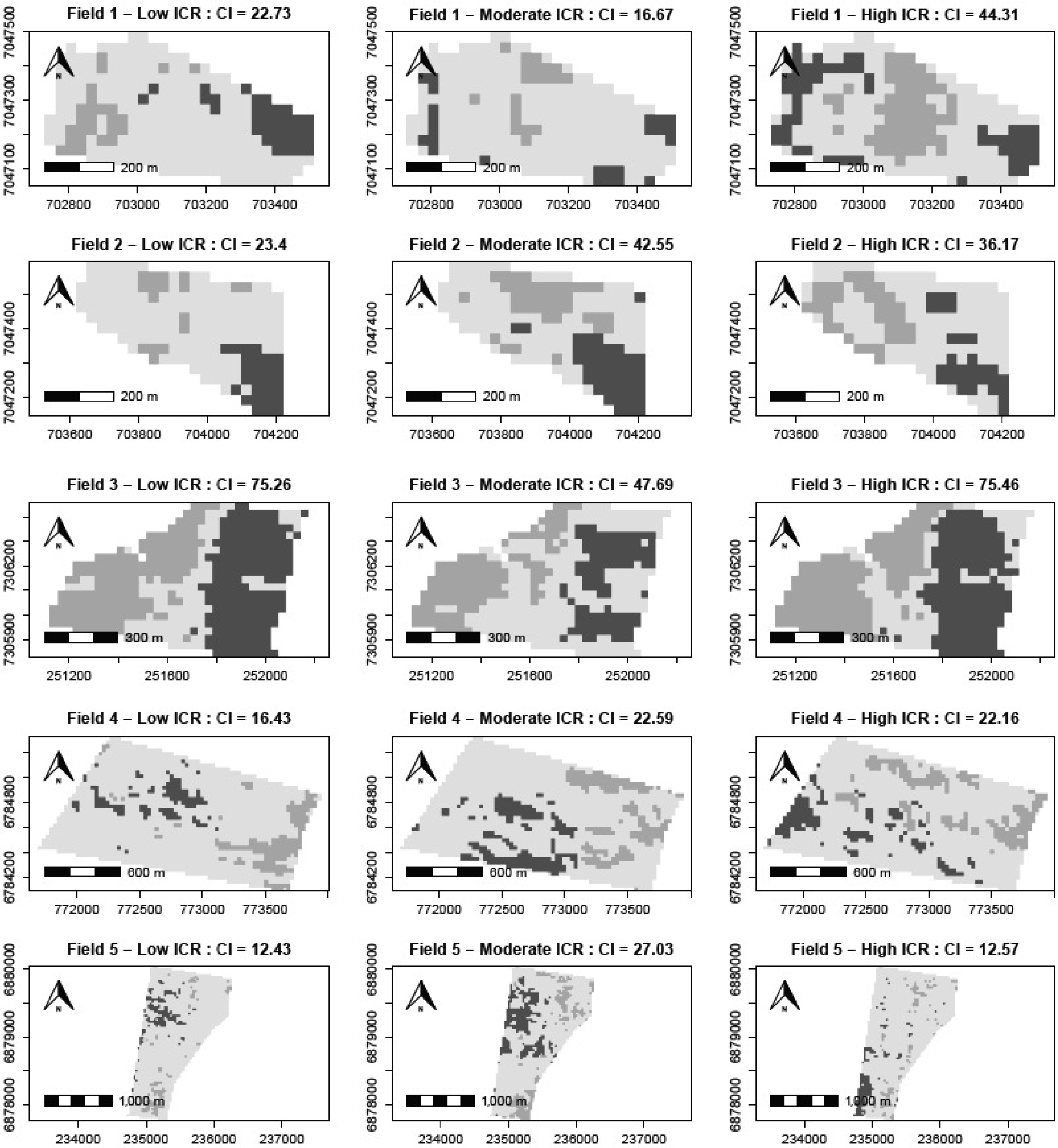

Figure 1. Consistency maps for all five fields in low, moderate and high in-crop rainfall (ICR) years, medium = consistently high, dark = consistently low, light = inconsistent/moderate.

Comparing remote-sensing data with data on soil constraints

Since the remote sensing data analysis indicated that Field 1 exhibited a significantly higher than expected consistency of variation in wet years (albeit marginally significant at $p<0.1$), soil data from the field were used to investigate this variation. Further, the soil exchangeable sodium percentage (ESP) data were used for this analysis because soil sodicity is expected to impact crop growth most in wet years. These soil constraint measurements were collected in previous work (Dang et al., 2010a) taken between April–May 2009 from nine soil cores across the field.

The soil ESP data (an indicator of soil sodicity) for different soil depths were plotted against the average EVI data from dry (red points), moderate (green points) and wet years (red points; Figure 2). This revealed that only the subsoil data (>0.3 m) showed a relationship, where the higher the ESP, the lower the average EVI (i.e. subsoil sodicity was related to poorer crop growth). For the topsoil, there was no such evident pattern, indicating that topsoil sodicity is not an important driver of yield variation in this field. Furthermore, when comparing the slope of a linear regression line (Figure 2) between average EVI and ESP for wet (blue/upper line), moderate (green/middle line), and dry years (red/lower line), the wet and moderate year regressions have steeper (negative) slopes than dry years (apart from in the topsoil). These relationships agree with what might be expected of sodic soils (stronger effects of sodicity in wet years (Armstrong et al., 2015; Gardner et al., 1992; Gill et al., 2008; Weil & Brady, 2017)).

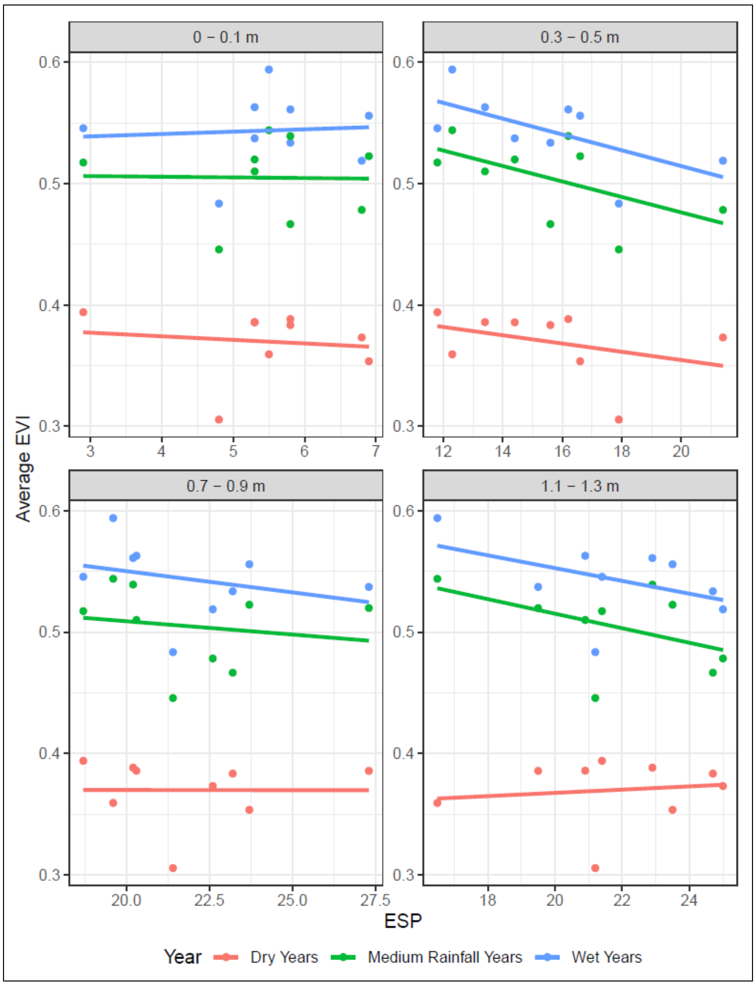

Figure 2. The relationship between average EVI and soil ESP for four soil depths at field 1 for dry (red/lower), moderate (green/middle), and wet (blue/upper) years.

Summary

In this work, we investigated the potential of remote-sensing imagery to help diagnose the impacts of soil constraints in different climate years. The results showed that one out of five fields investigated showed a distinct pattern of spatial variation associated with wet (high in-crop rainfall) years. The soil data in this field also indicated higher subsoil sodicity was associated with poorer crop growth, particularly during the wet years. These findings agreed with the hypothesis that sodicity could impact crop growth, particularly when abundant rainfall leads to issues with soil structure, poor water infiltration leading to waterlogging.

We envisage that in the future, the concept in this work would be useful for underpinning software such as ConstraintID (http://constraintid.com.au). This software enables growers to easily work with a large history of remote sensing data to identify consistently good and consistently poor growing areas within paddocks and help design targeted soil sampling plans. If a grower suspects that the within-field variation of crop growth changes between years with high and low in-crop rainfall, then they can select, for instance, only the dry years to identify the consistent variation. Besides, the software also enables growers to overlay the remote-sensing data with soil data, providing useful information to diagnose reasons for spatial variation of crop yields within fields.

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Concurrent session – Mental health and finding farm profit

Looking after yourself to look after your clients in challenging times

Mary O'Brien, Are you bogged mate?

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Notes

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

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Notes

Early risers session - in paddock decision-making on fungicide intervention

Notes

Fall armyworm: impact by crop, management strategy and resistance

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Take home message

- Pre-flowering defoliation caused by fall armyworm (FAW) in maize for a prolonged period and during later vegetative crop stages, resulted in significant yield reduction
- In most maize and sorghum production areas, FAW activity is low in spring and increases as the summer progresses. Early planted crops have largely avoided significant FAW damage, and this has been an effective strategy for minimising spraying and potential yield loss
- Like *Helicoverpa armigera*, FAW has a strong capacity to develop insecticide resistance. An integrated management approach, and strategies to minimise selection pressure on FAW populations, will be critical for effective and economically sustainable management of this pest.

Introduction

Australian agricultural industries are now into the third summer season of monitoring and managing Fall armyworm (FAW) since its arrival in Australia in early 2020. Whilst just three seasons of data may seem inadequate for drawing conclusions compared with the 40+ years of R&D on *Helicoverpa*, for example - it has been imperative that impacted industries, growers and advisors are provided with practical information on how they can best monitor and manage FAW to minimise crop losses. This is not to say that the working rules of thumb being communicated to industry are without empirical basis, they have their foundations in ongoing research outcomes from local trials, consultation with overseas researchers, and Australian grower/agronomist experience.

What is presented in this paper is key information that will assist in understanding FAW behaviour in crops and the regions, and best-bet management strategies that will be refined as there is more research and experience with this new pest.

FAW activity

The most accessible data on FAW activity in different regions comes from the network of pheromone traps being operated by Queensland Department of Agriculture and Fisheries (QDAF) staff, agronomists and growers.

Important in interpreting the data presented in these graphs is that moth activity is a function of host availability (attractive crops in the ground where traps can be placed), night-time temperatures suitable for moth activity and moth abundance. In 2020-21 there were traps across Qld and NSW. In

2022-23, there is data from Qld only. A selection of trap data is presented here to illustrate key points.

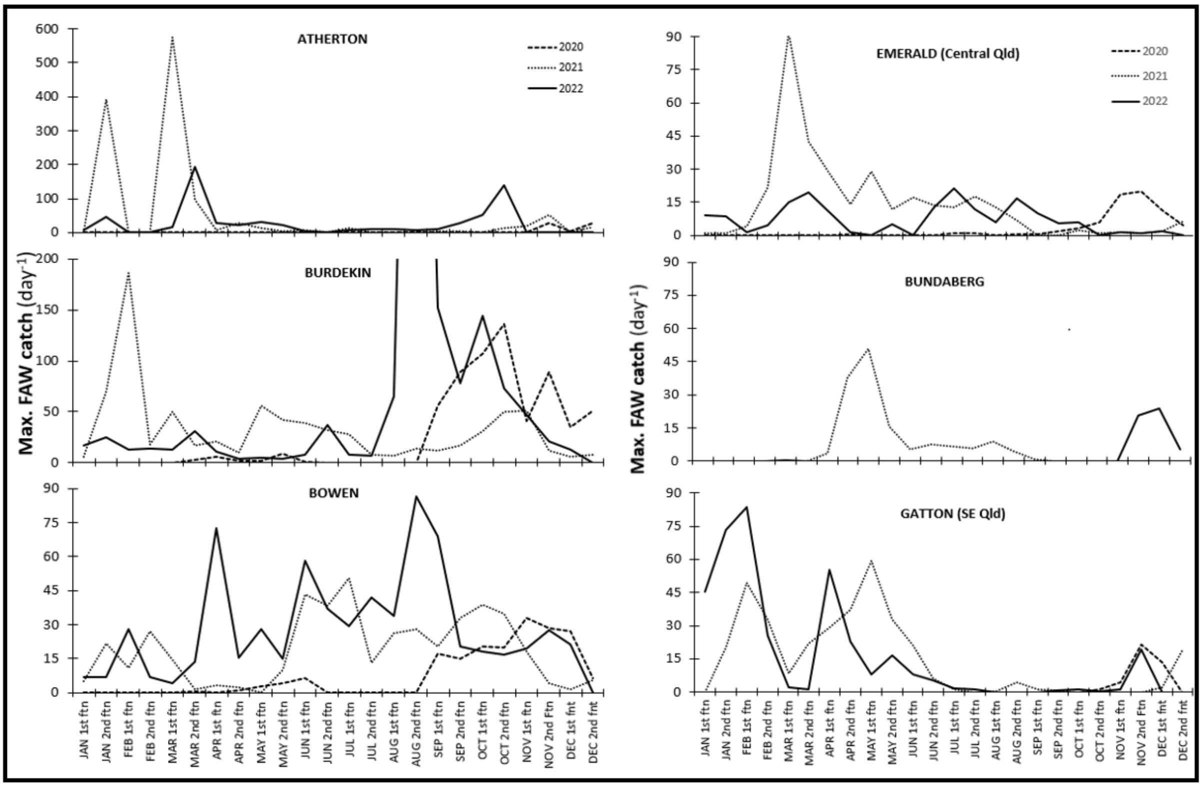

Figure 1. Summarised pheromone trap data from representative locations from North Qld (Atherton, Burdekin, Bowen) to Central Qld (Emerald, Bundaberg) and southern Qld (Gatton) for three seasons 2020-2022. Trap catch data is presented as the maximum daily catch for each fortnight throughout the year. Note the different scale (y axis) for northern and central/southern regions.

Key points to note from the figure below (Figure 1) are:

1. The level of activity in North Qld (Atherton, Burdekin, Bowen) is higher and more persistent throughout the year than it is in central and southern regions
2. Periods of very low to no activity are recorded in all regions, driven by an absence of hosts and/or cooler conditions
3. All regions experience a peak in moth activity/abundance in spring and summer
4. Periods of rainfall suppress moth trap catches.

Susceptible crops that avoid the periods of highest FAW activity (late spring – summer) have experienced significantly lower levels of damage in most districts. For example, maize crops sown in Sept-Oct on the Darling Downs have largely escaped FAW infestations and required no insecticide treatment. In contrast, crops sown in Dec-Jan are subjected to damaging infestations from early vegetative stages, requiring spraying to ensure establishment and protect from yield loss. There is anecdotal evidence of local population build up to higher densities where there are successive crop plantings (spring and then summer) in a local area, or on individual farms.

Development of economic thresholds for FAW in maize and sorghum

GRDC has invested in research to investigate the relationship between FAW infestation and impacts on yield for sorghum and maize. This research is a collaboration between QDAF, UQ-QAAFI and Cesar Australia and is in its second year. The aim of this research is to identify the growth stages most susceptible to yield loss as a result of FAW infestation, in order to inform management decisions. Ultimately the project will make available to industry a tool that will allow growers and agronomists to forecast the potential loss based on agronomic factors and FAW impacts (APSIM simulation) for pre-anthesis (tasselling) crop stages. Additional studies on direct feeding damage to reproductive structures and grain will contribute to thresholds for the reproductive stages.

In field trials, maize and sorghum were sown at the Gatton and Ayr research stations in 2021-22 and naturally infested with FAW. When the crops had three fully expanded leaves (V3), FAW was controlled in plot at either the V6, V8, V10 or V12 growth stage, then all plots were maintained FAW free from V12 until harvest. Crop development, canopy light interception, FAW infestation and yield components were monitored throughout the growing season.

An example of the results being generated include the following findings for irrigated maize. Natural FAW infestations of a maize crop at Gatton in 2022 with 8 to 12 expanded leaves showed 25 to 30% yield losses. Yields were correlated with the extent of FAW defoliation quantified as the fraction of intercepted photosynthetically active radiation (fiPAR) at anthesis and the population density of fertile plants. The effects of FAW infestation during the canopy expansion and growth stage on yields could be simulated in APSIM by attenuating model co-efficient for the potential largest leaf size until fiPAR matched observed values.

This means that yield loss was either a result of direct FAW feeding on immature leaves, indirectly through limiting photosynthate supply to developing leaves, or both, resulting in reduced total canopy size. Reduced fertility due to direct effects of FAW feeding or shading of FAW stunted plants by neighbouring plants was a secondary contribution to yield loss. However, it is unclear if crop stage sensitivity is consistent across genotypes of different maturity groups, or crops growing at different rates relative to FAW.

There are clear differences in the overall impact of FAW defoliation on maize and sorghum, but both crops have shown reductions in yield trials.

Insecticide resistance in Australian FAW and strategies to reduce the risk to effective chemistry.

In 2020-21, NSW DPI (Dr Lisa Bird) undertook a benchmarking insecticide toxicity study on FAW populations from across Australia and compared the performance of insecticides on FAW and *Helicoverpa armigera*. The results of this study showed that Australian FAW populations were moderately resistant to carbamates (Group 1A) and highly resistant to synthetic pyrethroids (Group 3A). There was no evidence of resistance to insecticides in Groups 28 (e.g. chlorantraniliprole, Vantacor®), 5 (spinosyns, e.g. SuccessNeo®) or 6 (emamectin benzoate, e.g. Affirm), but a natural tolerance to Group 22A (indoxacarb, e.g. Steward®). The full results of the baseline study are published (Bird et al., 2022).

The results of this baseline study have proven to be consistent with the field experience. Control failures have been reported where carbamates (e.g., methomyl) and synthetic pyrethroids have been used. Whilst there are current permits in place allowing use of these products, their use is not recommended. Application of the Groups 28, 5, 6 have been highly efficacious, and initial indications from the 2022-23 resistant monitoring (testing incomplete at Jan 2023) suggest no shift in susceptibility to these actives in Queensland populations tested.

Ongoing monitoring of Australian FAW populations will be critical in the early detection of resistance development, making it more likely that changes in insecticide use can be implemented in a timely manner to prevent rapid product failure. Whilst overall use of insecticides is low in the grains industry, the insecticides of importance in managing FAW are also registered for the control of *Helicoverpa* and several other insect pests in grain and horticultural crops, increasing the risk of resistance development through incidental exposure. The potential for FAW moths to move between regions, possibly taking resistance genes with them, heightens the importance of monitoring populations from across Australia.

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The Queensland Government has invested in a rapid response to support industries impacted by FAW (2020-23). This investment supports research, insecticide resistance monitoring (2022-23), extension and skills development for industry and researchers. The Cotton Research and Development Corporation (CRDC) provided financial support for the FAW resistance benchmarking study undertaken by NSW DPI.

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Resources/References

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Summer crop choice in northern farming systems – impacts on root lesion nematode, charcoal rot, AMF and winter cereal crop pathogen levels

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Take home message

- Summer crop choices are complex and should include consideration of their relative impact on pathogens and beneficial soil biota such as arbuscular mycorrhizae fungi (AMF)
- Mungbean resulted in the greatest increase in AMF populations but also elevated disease risk for charcoal rot and the root lesion nematode (*Pratylenchus thornei*) compared with sorghum, cotton, maize, sunflower and millet
- Summer crops generally reduced Fusarium crown rot risk for following winter cereal crops but variation appeared to exist in their relative effectiveness
- Maize, cotton, sorghum and mungbean appear to be potential alternate hosts for the winter cereal pathogen *Bipolaris sorokiniana* (common root rot), while sunflower does not appear to be a host
- Quantification of individual summer crop choices on pathogen levels has highlighted potential areas requiring further detailed investigation to improve management of these biotic constraints across northern farming systems.

Introduction

Crop choice decisions often involve trade-offs between different aspects of farming systems. In particular, crop choice should consider the need to maintain residue cover, soil water and nutrient availability, and managing pathogen inoculum loads using non-host crops to avoid or reduce risk of problematic diseases (e.g., Fusarium crown rot). This is increasingly challenging as many cropping systems face evolving diseases and weed threats. Hence, understanding how different crops impact on these aspects is critical.

With limited winter rotation crop options in the northern grains' region, summer crops offer advantages as break crops within cropping sequences. Incorporating a mix of summer and winter crops allows variation in herbicide and weed management options, often also serving as disease breaks within the system. For example, sorghum is known to be resistant to the root lesion nematode *Pratylenchus thornei* (*Pt*), allowing soil populations to decline. However, the increasing use of summer crops in many regions, has seen an increase in the frequency of other diseases (e.g., charcoal rot caused by the fungus *Macrophomina phaseolina*). Similarly, using long fallows to transition from summer to winter crop phases can induce low levels of beneficial arbuscular mycorrhizae fungi (AMF) populations associated with long-fallow disorder. In this paper, we interrogate the data collected from northern farming systems research sites over the past 6 years to examine how different summer crop options impact on levels of both pathogen and AMF populations within farming systems.

What was done?

Seven research sites were established in 2015 to test a range of different farming systems in different environments across northern NSW, southern and central Qld. Over the life of the project, the team has sampled and analysed soil (0-30 cm) using the PreDicta® B quantitative PCR (qPCR) DNA analysis to examine how pathogens and other soil biology have varied over a range of crop sequences. A specific PreDicta® B test panel targeted at quantifying a wide range of pathogens important to the northern grains region has been used throughout the project. Here we have looked specifically at the impact of summer crops grown in these crop sequences to calculate the extent of change in DNA populations of pathogens and AMF associated with crop choices. It should be noted that populations are what have naturally developed within each system at the various sites and were not artificially inoculated.

Data from site-crop combinations where a particular pathogen or AMF was not present or below testing detection limits was excluded, as this does not provide a useful indication of the propensity of a crop choice to impact a particular pathogen or AMF population. PreDicta®B data from soil samples collected at sowing and after harvest of each summer crop were used to calculate relative changes or multiplication factor for populations over their growing season for the various summer crop rotation options. This multiplication factor highlights the extent of increase (>1.0), maintenance (=1.0) or decrease (<1.0) in pathogen levels following growth of different summer crops.

What did we find?

Root lesion nematodes

Root lesion nematodes (RLN, *Pratylenchus* spp.) are microscopic plant parasites which feed on crop roots. Two important species are known to infect crops in eastern Australia, namely *Pratylenchus thornei* (*Pt*) and *P. neglectus* (*Pn*). *Pt* is known to be the more important species in higher clay content soils in northern NSW and Southern Qld while *Pn* is generally more prevalent in lighter soil types in south-eastern Australia. *Pn* generally feeds and causes root damage in the top 15 cm of soil whilst *Pt* can feed and damage roots down the entire soil profile. Root damage restricts water and nutrient uptake from the soil causing yield loss in intolerant winter cereal and chickpea varieties. Only *Pt* densities were prevalent at high enough densities across northern farming system sites to examine the effect of summer crop options on soil *Pt* populations.

Summer crops are known to vary in their susceptibility to *Pt* with sorghum, cotton, millet and sunflower considered moderately resistant-resistant (MR-R). Maize is considered susceptible-MR (S-MR) whilst mungbean is S-MRMS (https://grdc.com.au/resources-and-publications/all-publications/factsheets/2019/root-lesion-nematode-northern) . The range in resistance ratings can relate to differences between varieties. Our results support these general findings. Mungbean resulted in the highest average increase in *Pt* populations, whilst sorghum favoured the lowest population increases (Table 1).

Table 1. Effect of summer crop choice on *Pratylenchus thornei* soil populations

	Sorghum	**Mungbean**	**Cotton**	**Maize**	**Sunflower**	**Millet**
Multiplication factor*	1.4	8.3	3.2	2.0	3.4	5.0
Range	0.2 - 6.6	4.0 - 21.3	0.8 - 13.7	1.4 - 2.8	3.2 - 3.7	4.0 - 6.0
No. observations	31	20	10	5	3	2

* multiplication factor highlights the extent of increase (>1.0), maintenance (=1.0) or decrease (<1.0)

Charcoal rot (Macrophomina phaseolina)

Charcoal rot, caused by the fungus *Macrophomina phaseolina*, is primarily a disease of summer crops including sorghum, maize, cotton, mungbean and sunflower in northern NSW and Qld. Infection causes light brown lesions on crowns and roots and results in increased lodging and/or premature plant death when stress associated with dry weather occurs late in the growing season. *M. phaseolina* has a wide host range of more than 500 weed and crop species including winter cereals.

Table 2. Effect of summer crop choice on *Macrophomina phaseolina* (charcoal rot) soil populations

	Sorghum	Mungbean	Cotton	Maize	Sunflower	Millet
Multiplication factor*	9.5	150.0	20.8	7.2	28.9	3.9
Range	1 - 27	5 - 1191	1 - 117	4 - 11	6 - 50	2 - 6
No. observations	23	23	9	4	3	2

* multiplication factor highlights the extent of increase (>1.0), maintenance (=1.0) or decrease (<1.0)

All six of the summer crops grown increased average *M. phaseolina* populations by between 3.9 to 150.0 times demonstrating the known wide host range of this fungal pathogen (Table 2). However, considerable differences were evident between the various summer crop options with mungbean elevating populations 5 to 40 times more than the other crops (Table 2).

Arbuscular mycorrhizae fungi (AMF)

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

There are two PreDicta® B qPCR DNA assays for AMF with combined results from both assays presented. It is important to remember that in contrast to all the other pathogen assays outlined, AMF is a beneficial fungus, so higher multiplication factors are good within a farming system context.

Table 3. Effect of summer crop choice on arbuscular mycorrhizae fungi (AMF) soil populations

	Sorghum	Mungbean	Cotton	Maize	Sunflower	Millet
Multiplication factor*	3.5	26.8	10.7	5.7	12.0	7.2
Range	0.4 - 12.4	2.2 - 61.5	1.8 - 32.0	3.4 - 8.0	6.3 - 17.6	6.5 - 7.9
No. observations	41	22	10	4	3	2

* multiplication factor highlights the extent of increase (>1.0), maintenance (=1.0) or decrease (<1.0)

Mungbean resulted in the highest average increase in AMF populations, whilst sorghum was the lowest (Table 3). Interestingly, even though millet was grown as a short cover crop twice within these farming systems, it resulted in around a 7-fold increase in AMF populations. Hence, millet may be a good option for restoring ground cover over summer and AMF populations which both decline following extended dry conditions.

Fusarium crown rot (Fusarium spp.*)*

Two PreDicta® B qPCR DNA assays detect genetic variants of *Fusarium pseudograminearum* with a separate third combined test detecting *F. culmorum* or *F. graminearum*. All three *Fusarium* species cause basal infection of winter cereal stems resulting in Fusarium crown rot and the expression of whiteheads when heat and/or moisture stress occurs during grain filling. Fusarium crown rot has increased in northern farming systems with the adoption of conservation cropping practices which include the retention of standing winter cereal stubble. Yield impacts however are sometimes offset by the higher levels of plant available water often available to the plant during grain fill in such systems when compared to tilled systems. The *Fusarium* spp. which cause this disease can survive 3-4 years within winter cereal stubble depending on the rate of decomposition of these residues. Recent research from PhD student Toni Petronaitis has also highlighted that inoculum levels can increase during fallow and non-host crop periods, with saprophytic vertical growth of the pathogen inside standing stubble under wet conditions. Inoculum within standing winter cereal stubble can then potentially be redistributed across a paddock with shorter harvest heights of break crops such as chickpeas. Hence, changes in Fusarium crown rot DNA levels may not represent actual hosting of the pathogen, rather they potentially include inoculum dynamics associated with saprophytic growth and/or redistribution of winter cereal stubble inoculum during harvest. DNA data for all three tests were combined for this interpretation to provide an overall level of *Fusarium* spp. DNA.

Table 4. Effect of summer crop choice on *Fusarium* spp. (Fusarium crown rot) soil populations

	Sorghum	Mungbean	Cotton	Maize	Sunflower	Millet
Multiplication factor*	1.7	2.9	0.4	0.5	-	-
Range	0.03 - 10.3	0.4 - 9.7	0.1 - 1.0	0.2 - 0.8	-	-
No. observations	19	8	3	2	-	-

* multiplication factor highlights the extent of increase (>1.0), maintenance (=1.0) or decrease (<1.0)

Limited observations were available to support conclusions on the relative effect of summer crops on *Fusarium* spp. associated with Fusarium crown rot. However, cotton and maize appeared most effective at reducing inoculum loads (Table 4). Results were more variable with sorghum and mungbean, but both generally reduced or only moderately increased Fusarium crown rot inoculum levels. Inoculum dynamics associated with saprophytic growth of *Fusarium* spp., potential redistribution during harvest of summer and winter break crops and the role of grass weed hosts appears worthy of further investigation to improve management of this disease across farming systems.

Common root rot (Bipolaris sorokiniana)

Bipolaris primarily infects the sub-crown internode of winter cereal crops causing dark brown to black discolouration of this tissue referred to as the disease 'common root rot'. Common root rot reduces the efficiency of the primary root system in susceptible wheat and barley varieties resulting in reduced tillering and general ill-thrift in infected crops. This disease has increased in prevalence across the northern region over the last decade with the increased adoption of earlier and deeper sowing of winter cereals which exacerbates infection. There is little information on the effect of summer crop options on *B. sorokiniana* levels within Australian farming systems. One international study from Pakistan determined that millet, sorghum, mungbean and maize were hosts of *B. sorokiniana*, whilst sunflowers were a non-host (Iftikhar et al. 2009). Similar research has not been conducted in Australia.

Table 5. Effect of summer crop choice on *Bipolaris sorokiniana* (common root rot) soil populations

	Sorghum	Mungbean	Cotton	Maize	Sunflower	Millet
Multiplication factor*	3.9	2.6	6.8	7.4	0.04	-
Range	0.5 - 9.6	0.3 - 9.3	0.3 - 12.0	na	na	-
No. observations	12	6	3	1	1	-

* multiplication factor highlights the extent of increase (>1.0), maintenance (=1.0) or decrease (<1.0)

Although limited observations were available to support conclusions on the relative effect of summer crops on *B. sorokiniana* populations, the data appears to support the only previous study of host range from Pakistan (Iftikhar et al. 2009). Mungbean, sorghum and maize appeared to generally increase populations, whilst sunflower considerably decreased levels of this pathogen (Table 5). Cotton, which was not included in the Pakistan study, also appears to generally increase *B. sorokiniana* soil populations (Table 5). These results indicate that the role of summer crops need to be considered when managing common root rot in northern farming systems. Further research is required to confirm the relative host range of this increasingly important pathogen.

What does it all mean?

Summer crop choice remains a complex balancing act but this research has highlighted some of the impacts on pathogen and AMF populations. For example, mungbean had the largest increase in beneficial AMF levels but had the negatives of elevating charcoal rot and *Pt* risk compared with the other summer crop options examined. Mungbean also did not appear to be as effective at reducing Fusarium crown rot risk for subsequent winter cereal crops compared with other summer crop options where data was available. The underlying reasons behind these apparent differences requires further investigation of Fusarium crown rot inoculum dynamics with a farming systems context.

These northern farming systems experiments have further highlighted the potential differential role of summer crop species as alternate hosts of the common root rot pathogen *Bipolaris sorokiniana*, supporting an overseas study. The use of qPCR within these experiments is unique in that it allows the relative changes in pathogen or AMF levels associated with various summer and/or winter crop choices to be quantified. This is more valuable than simple presence/absence data, in that it allows growers and their advisers to understand and manage potential changes in disease risk within their paddocks to limit impacts on profitability.

References

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Using zinc phosphide to control wild house mice

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Take home messages

- Mice are not as sensitive to zinc phosphide (ZnP) as was first reported in studies in the 1980s
- 2mg of ZnP is required on each grain to deliver a lethal dose to a 15g mouse
- Grain bait mixed at 50g ZnP/kg wheat is significantly more effective than bait mixed at the previously registered rate of 25g ZnP/kg wheat
- Reducing background food could be critical to achieving effective bait uptake
- Timely application of ZnP grain bait at the prescribed rate is vital for reducing the impact that mice have on crops at sowing
- Strategic use of bait is more effective than frequent use of bait.

Background

The content of this paper relates primarily to the GRDC investment, *Determining the effectiveness of zinc phosphide rodenticide bait in the presence of alternative food supply*. Growers were reporting concerns regarding the effectiveness of commercially prepared zinc phosphide (ZnP) wheat-based baits. In response, we conducted three experiments to examine the efficacy of ZnP bait. The initial experiment set out to identify a more attractive bait substrate, but the results of this work identified unexpected questions regarding the sensitivity of mice to ZnP. The second experiment re-assessed the acute oral toxicity of ZnP for wild house mice. The results of this work showed a significant difference between the previously reported LD_{50} of 32.68mg ZnP/kg body weight and our re-calculated LD_{50} of 72–75mg ZnP/kg body weight. We then quantified the efficacy of the higher lethal dose (~2mg ZnP per grain) compared to the registered rate (~1mg ZnP per grain) in a field trial. The results suggest that a kill rate of >80% could be achieved 90% of the time for the higher rate compared to the registered rate for which an 80% kill rate would be observed only 20% of the time. These results are helping to inform how and when growers and agronomists manage mice in cropping systems in Australia.

Experiment 1 - Effects of background food on alternative grain uptake and zinc phosphide efficacy in wild house mice.

The initial trial to determine what was driving the reduced efficacy of the bait sought to test potential new bait substrates that might be more attractive to mice.

Experiment 1a - Two choice grain preference

Mice were held on a background food type (barley, lentils or wheat) and then offered the choice of an alternative grain type (malt barley, durum wheat or lentils) for five nights. Mice displayed a strong preference towards cereal grains, with a slight preference towards malt barley.

Experiment 1b - Toxic bait take against different background grains

Mice were held on a background food type (lentils, barley or wheat) then offered ZnP-baited grain (25g ZnP/kg grain) for three consecutive nights. Mice consumed toxic bait grains regardless of bait substrate although background food type had a strong influence on the amount of toxic bait consumed. Most of the mice in this experiment consumed what was considered to be a lethal dose, however the mortality rate was significantly lower than expected (Table 1) (Henry et al. 2022). Furthermore, animals that consumed toxic grains and didn't die, stopped eating toxic grains (that is, became averse).

Table 1. Percentage mortality from ZnP bait (25g ZnP/kg grain) and the average number of toxic grains consumed for each background food type on night one of the study (Henry et al. 2022).

Background food	n	Mortality (%)	Toxic grains eaten (av.)
Lentils	30	86	7.3 ± 2.5
Barley	30	53	4.5 ± 2.9
Wheat	30	47	2.1 ± 1.6

Bait substrate key results

Mortality was not as high as expected in mice that consumed toxic grains. The development of aversion was rapid although its duration is unknown. These results identified questions relating to the sensitivity of mice to ZnP (Henry et al. 2022). Had we been selecting for mice that were less sensitive to ZnP through frequent application of bait over a 20-year period? Or were mice just less sensitive to ZnP than had been reported in the past?

Experiment 2 - Acute oral toxicity of zinc phosphide: an assessment for wild house mice (*Mus musculus*)

This experiment re-assessed the acute oral toxicity of ZnP for wild house mice using an oral gavage technique, where known doses of ZnP were delivered directly into the stomachs of mice. The responses of three different groups of mice were assessed and compared: (1) wild mice from an area where ZnP had been spread frequently (exposed), (2) wild mice from an area where ZnP had never been used (naïve), and (3) laboratory mice (Swiss outbred). The proportion of mice that died at each dose was used to calculate a dose-response curve for each of the groups of mice (Figure 1) (Hinds et al. 2022).

Acute oral toxicity key results

The results showed no significant differences in the sensitivity of any of the groups of mice to ZnP, indicating that there has been no selection for tolerant mice in areas where mice had frequent exposure to ZnP. However, there was a significant difference between the previously reported LD_{50} of 32.68mg ZnP/kg body weight (Li and Marsh 1988) and our re-calculated LD_{50} of 72–75mg ZnP/kg body weight. These results mean that 2mg of ZnP/grain is needed instead of 1mg of ZnP/grain to kill a 15g mouse (Hinds et al. 2022).

Lab – Swiss outbred

LD_{50} = 79.18 ± 6.24mg ZnP/kg

Naïve wild mice

LD_{50} = 72.11 ± 9.09mg ZnP/kg

Exposed wild mice

LD_{50} = 75.22 ± 4.39mg ZnP/kg

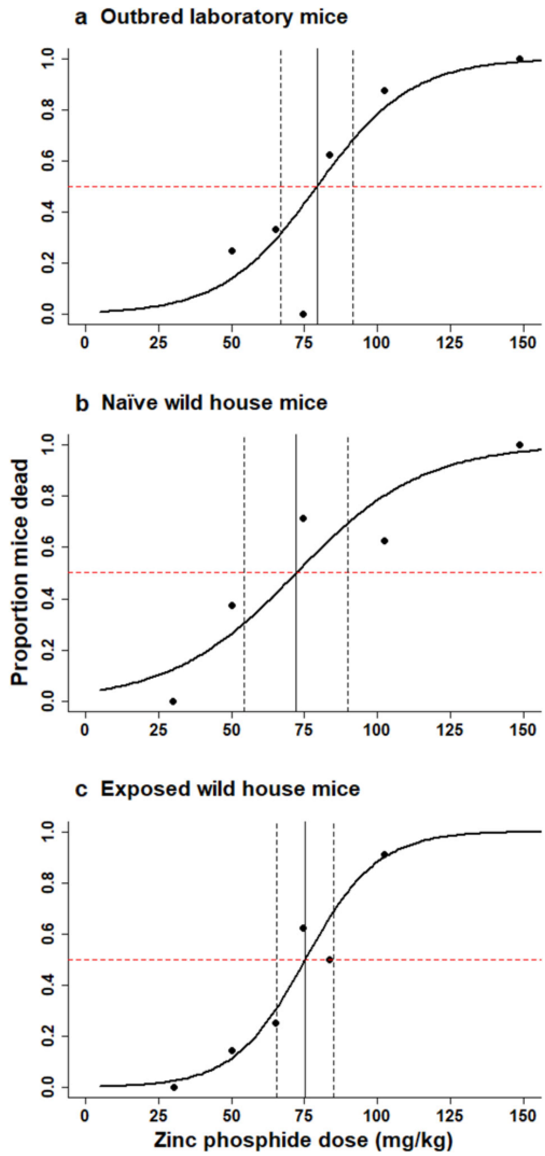

Figure 1. Proportion of mice dying after oral gavage with different ZnP concentrations (mg ZnP/kg body weight). Calculated dose response curves for (a) outbred laboratory mice, (b) naïve wild house mice, and (c) exposed wild house mice. Horizontal dashed line represents 50% mortality; vertical solid line equates to LD_{50} value; vertical dashed lines represent standard error for the LD_{50} estimate. N>four animals per test dose, with a mix of males and females (Hinds et al. 2022).

Experiment 3 - Improved house mouse control in the field with a higher dose zinc phosphide bait.

This experiment addressed the efficacy of the two different bait types, ZnP25 (25g ZnP/kg bait, ~1mg ZnP/grain) applied at 1kg bait/ha and the new formulation, ZnP50 (50g ZnP/kg bait, ~2mg ZnP/grain), applied at 1kg bait/ha.

Nine sites were selected on farms in the area surrounding Parkes in central NSW, three un-baited control sites, three sites baited with ZnP25 (25g ZnP/kg bait), and three sites baited with ZnP50 (50g ZnP/kg bait). All sites were trapped prior to baiting to establish population sizes and then again after baiting to determine changes in population.

Field trial key results

Baiting with ZnP50 led to a median reduction in mouse numbers of >85%. Modelling showed that under similar circumstances, using the ZnP50 formulation should deliver >80% reduction in population size most (>90%) of the time. In contrast, the current registered bait (ZnP25) achieved approximately 70% reduction in population size, but with more variable results. We would be confident of getting an 80% reduction in population size only 20% of the time if using the currently registered ZnP25 bait under similar field conditions (Figure 2) (Ruscoe et al. 2022).

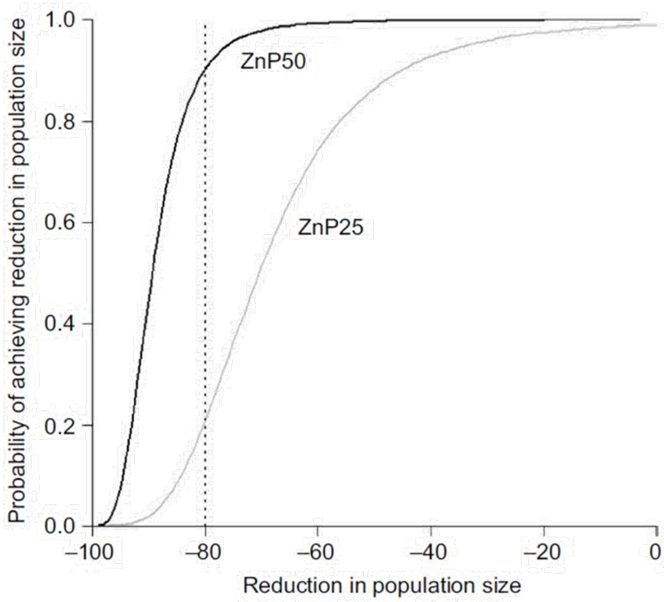

Figure 2. The probability of achieving a certain reduction in population size or better by using the ZnP50 bait (solid black line) and the ZnP25 bait (solid grey line). The dotted vertical line shows that there is a ~90% chance of getting a >80% reduction in population size by using ZnP50, but only a 20% chance of achieving that outcome by using ZnP25 (Ruscoe et al. 2022).

Conclusion

- Mice are not as sensitive to ZnP as was first reported in studies in the 1980s.
- 2mg of ZnP is required on each grain to deliver a lethal dose to a 15g mouse.
- ZnP grain bait mixed at 50g ZnP/kg wheat is significantly more effective than bait mixed at the previously registered rate of 25g ZnP/kg wheat.

Future research

Substantial grain loss, pre- and post-harvest is common in zero and no-till cropping systems. In 2022, it was estimated that $300 million worth of grain (GRDC project code GGA2110-001SAX) was left on the ground post-harvest in WA alone and reports of losses of 1t/ha are not uncommon (pers. comm). Bait spread at 1kg/ha equates to approximately three toxic grains per square metre. If there have been losses of 1t/ha, equivalent to about 2200 grains per square metre, finding a toxic grain becomes a game of hide and seek for mice (Figure 3). Understanding the role that background food plays in the uptake of ZnP bait will be critical to achieving effective mouse control.

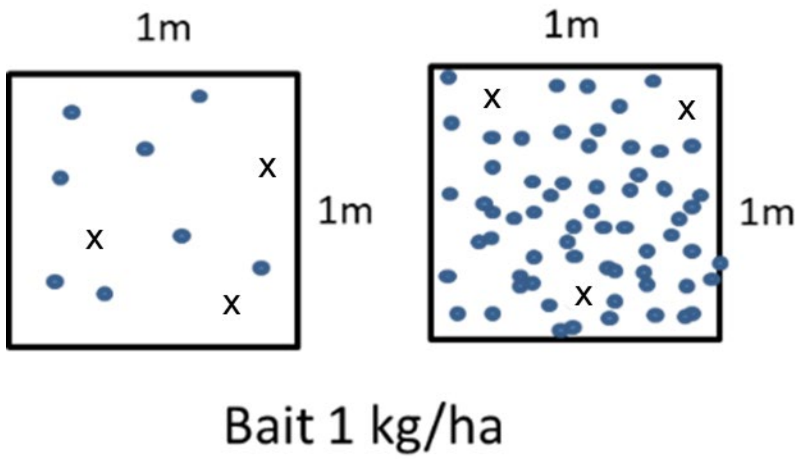

Figure 3. Representation of detectability of toxic grains at different levels of background food. The dots represent grains and crosses represent toxic grains.

Acknowledgements

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

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Concurrent session – weeds

New pre-emergent herbicides – how are they performing?

Christopher Preston, School of Agriculture, Food & Wine, The University of Adelaide

Key words

crop safety, pre-emergent herbicide, solubility, annual ryegrass, dry sowing

Take home messages

- Understanding the properties of pre-emergent herbicides and soil types is essential for the effective use of pre-emergent herbicides
- Crop damage most often occurs in soil types with low organic matter or where the herbicides are not adequately separated from the crop seed
- Less soluble pre-emergent herbicides are generally safer to use for dry sowing.

Understanding pre-emergent herbicide behaviour

Annual ryegrass control is becoming increasingly reliant on pre-emergent herbicides due to the increasing frequency of resistance to post-emergent herbicides. Pre-emergent herbicides are more complex to use compared to post-emergent herbicides. There are a number of factors that need consideration for successful use of pre-emergent herbicides. These include: behaviour of the herbicide, soil type and organic matter content, rainfall patterns prior to and after application of the herbicide, seeding system and crop tolerance.

Table 1 provides the relative behaviour of recently registered pre-emergent herbicides and compares the newer products to existing products. The key factors are water solubility and binding to soil (K_{oc}). The more soluble a herbicide is, the further it will move through the soil with each rainfall event. On the other hand, higher binding to soil components will reduce herbicide movement.

Table 1. Behaviour of some pre-emergent herbicides used for grass weed control

Pre-emergent herbicide	Trade name	Solubility (mg L^{-1})		K_{OC} (mL g^{-1})	
Carbetamide	Ultro®	3270	Very high	88.6	Medium
S-Metolachlor	Dual Gold®, Boxer Gold®*	480	High	226	Medium
Metazachlor	Tenet®	450	High	45	Low
Cinmethylin	Luximax®	63	Medium	300	Medium
Bixlozone	Overwatch®	42	Medium	400	Medium
Prosulfocarb	Arcade®, Boxer Gold®*	13	Low	2000	High
Propyzamide	Edge®	9	Low	840	High
Triallate	Avadex® Xtra	4.1	Low	3000	High
Pyroxasulfone	Sakura®, Mateno® Complete*	3.5	Low	223	Medium
Aclonifen	Mateno® Complete*	1.4	Low	7126	High
Trifluralin	TriflurX®	0.2	Very low	15,800	Very high

*Boxer Gold contains both prosulfocarb and S-metolachlor, Mateno Complete contains aclonifen, pyroxasulfone and diflufenican

Solubility and binding need to be considered in relation to soil type and rainfall events. All herbicides will tend to move further in soils with a high sand content, due to the larger gaps between the soil particles. The main soil component responsible for herbicide binding is organic matter. Herbicides will bind less to soils with low organic matter and will be more mobile.

Rainfall is a key factor in herbicide performance. Low rainfall after herbicide application will not activate the less soluble herbicides, while high rainfall after application can move the more soluble herbicides further into the soil, resulting in crop damage. Whether the soil is dry or contains moisture at application will also influence herbicide movement. Herbicide movement through the soil will always be greater for a given rainfall size, regardless of herbicide solubility, if the soil is dry compared to a soil with moisture in the top few cm. Differences in environment between years means that pre-emergent herbicide efficacy and crop safety can vary.

Inherent crop tolerance is the ability of the crop to tolerate the herbicide if the herbicide reaches the crop seed, roots or coleoptile. Crop tolerance to pre-emergent herbicides is improved through the use of knife-point, press-wheel seeding systems that throw herbicide treated soil out of the crop row and onto the inter-row. The less inherent tolerance a crop has, the more important it is to keep the herbicide away from the crop seed. Where soil types or environmental conditions provide a greater risk of crop damage, sowing the crop deeper may mitigate some of the risk. Where a rate range is available on the label, using the lower rate in lighter soil types or higher risk situations can also reduce crop damage. Crop competition is an important component of effective pre-emergent herbicide performance. The crop will reduce seed set of survivors and later emerging weeds. Therefore, damaging the crop with pre-emergent herbicides to obtain extra weed control can be counterproductive.

New pre-emergent herbicide registrations and characteristics

Carbetamide (Ultro®) Group 23

This herbicide provides grass weed control in pulse crops. Despite its high solubility, most pulses (except chickpeas) have high inherent tolerance. This means there is little danger of crop damage in the tolerant pulse crops. In lighter soil types, high rainfall can move the herbicide too far and reduce the length of control provided.

Cinmethylin (Luximax®) Group 30

Luximax is registered for the control of annual ryegrass, barley grass and silver grass in wheat (not durum wheat). Its higher solubility means that it has provided high levels of control of annual ryegrass, particularly when there is less rainfall after sowing. However, moderate solubility and moderate binding to organic matter have resulted in crop damage where heavy rainfall has occurred after sowing, even on heavier soil types. Cinmethylin is safest to use when the soil profile is close to full prior to application.

Bixlozone (Overwatch®) Group 13

Overwatch is registered for control of annual ryegrass, silvergrass and some broadleaf weeds in wheat, barley, canola, field peas and faba beans. Overwatch is not as mobile as Luximax due to lower solubility and higher binding. However, in conditions when the soil is dry at application and there is heavy rainfall after sowing, crop damage can occur. Damage is greatest on barley crops, whereas other crops are more tolerant.

Metazachlor (Tenet®) Group 15

Tenet is registered for control of annual ryegrass, several other grasses and some broadleaf weeds in canola. The higher solubility of metazachlor and low binding have resulted in crop damage with the highest label rate of Tenet, particularly where there is high rainfall after sowing. The lower rate generally provides insufficient control of annual ryegrass. In TT canola, a lower rate of Tenet can be mixed with triazine herbicides. This provides effective control of annual ryegrass with generally good crop safety. Tenet also has an early post-emergent registration mixed with clethodim. The high solubility of metazachlor means little rainfall is required to activate the herbicide. However, control of ryegrass will be best when applied at the 2-leaf stage.

Mateno® Complete (a mixture of pyroxasulfone, aclonifen and diflufenican) Groups 15, 32 and 12

This herbicide can be used for control of annual ryegrass and some other grass weeds in wheat (not durum wheat) and barley. When used pre-emergent, control and behaviour will be similar to Sakura as all the components have low solubility. Rainfall is required after application to activate the herbicide. The aclonifen and diflufenican components of the product will improve control of other grass weeds compared with Sakura. Mateno Complete also has an early post-emergent registration at a similar timing to Boxer Gold. This provides the opportunity to extend annual ryegrass control and to control some broadleaf weeds. The lower solubility of the herbicides in Mateno Complete compared to Boxer Gold means more rainfall after application is required to activate the herbicide. This means the early post-emergent application of Mateno Complete will be most useful in higher rainfall regions.

What are the best products for dry sowing?

Using pre-emergent herbicides with dry sowing is challenging as there is no way of predicting when and how much rainfall will occur at the break. A long period between sowing and getting sufficient rainfall to activate the herbicides can lead to some herbicide losses and a shorter period of persistence after the crop emerges. Of more concern is where there is a large rainfall event to start the season. As the soil is dry, large rainfall events will move the herbicides further into the soil profile, increasing the risk of crop damage.

As with all other uses of pre-emergent herbicides, soil type, soil organic matter, herbicide behaviour and seeding system need to be considered when choosing an appropriate pre-emergent herbicide. In terms of herbicide behaviour, trifluralin remains the ideal pre-emergent herbicide when dry sowing. It has low water solubility and binds tightly to organic matter (Table 1). This means it has less chance of moving far enough into the soil to cause crop damage. Herbicides with high water solubility and more mobility in soil, such as Tenet and Luximax, are not suited to dry sowing.

The other aspect of dry sowing is managing the risk of the herbicides not activating in time to control weeds. This is most likely to happen with low solubility herbicides like Sakura and Mateno Complete. A way to manage this is to mix with a herbicide that needs less rainfall to activate, such as trifluralin or Avadex® Xtra. Trifluralin requires less moisture as it works as a gas and turns into a gas on contact with water. Avadex Xtra is absorbed by the coleoptile rather than the roots, so does not need to be moved as far through the soil.

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Imazapic and diuron availability and toxicity in different soils

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Key words

Residual herbicides, imazapic, diuron, toxicity threshold, bioavailability

GRDC code

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Take home message

- Herbicide residue levels can be measured in soil, but to interpret what soil analysis results mean for the subsequent crop, information about crop toxicity thresholds, and soil-specific herbicide availability is needed.
- An approach has been developed to derive toxicity thresholds and predict herbicide availability in different soils to provide a prediction of safety for cropping.
- Soil analysis for herbicide residues is not a replacement for using herbicides according to label requirements.
- Additional ground truthing of this proof-of-concept research across a wider range of soil types and environments will strengthen the predictions.

Background

Residual herbicides are an important tactic for the extended control of weeds in Australia's northern grain region (NGR) cropping systems. The use of residual herbicides, for both fallow and in-crop weed control, has increased in recent years, with up to 45% of the cropped area routinely receiving a pre-emergent herbicide application (Llewellyn et al. 2016). This increase is largely in response to an observed increase in resistance to glyphosate in difficult to control summer weeds including feathertop Rhodes grass, flaxleaf fleabane, common sowthistle and awnless barnyard grass. The persistent nature of residual herbicides can cause damage to subsequent, susceptible crops. This is a key consideration in northern region farming where both summer and winter crops can be grown.

While residual herbicide labels clearly state plant back periods for susceptible crops, the duration of persistence can extend beyond label claims, based upon the environment in which the herbicide exists. External factors such as rainfall, temperature and soil type all affect the duration of a residual herbicide (Figure 1). There have been cases where residual herbicides in prolonged hot and dry environments have persisted beyond the label recommended time for safety, and damage of the subsequent crop has occurred. Herbicide labels are legally binding documents, and the purpose of this research was to explore extended herbicide persistence, not to shorten the plant back.

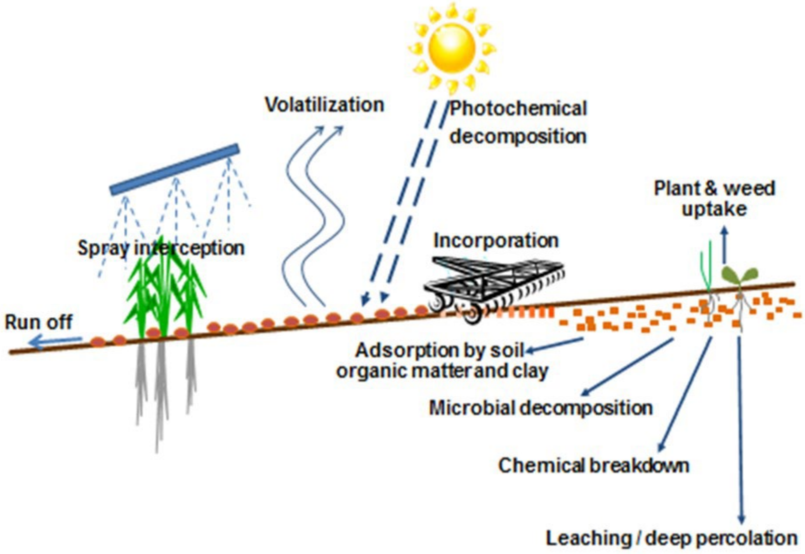

Figure 1. Interactions, loss and breakdown pathways of soil applied herbicides (Source: Congreve, M. and Cameron, J. 2019).

There are limited useful approaches to accurately predict the safety of cropping after the application of a residual herbicide. Commonly, a soil sample is submitted to determine how much herbicide is present. However, a soil test will only provide information on the total amount of herbicide present but will not tell how much herbicide is available to the plant. Furthermore, a soil test will not provide information on whether the amount of herbicide present will cause damage to the subsequent crop.

To address this issue, proof-of-concept research has been conducted toward developing a tool to assist in decision making for safe re-cropping post residual herbicide use. This research has been conducted on two test herbicides, imazapic and diuron. Both herbicides can persist in the soil for lengthy periods (12 – 24 months) at levels that can impede the growth of winter (e.g. barley, wheat, chickpea) and summer (e.g. maize, sorghum, mungbean) crops (Fleming et al. 2012).

Laboratory research has been conducted on:

- determining toxicity thresholds for imazapic and diuron on commonly grown summer and winter crops, and
- predicting the bioavailability of these herbicides across a range of soils.

A toxicity threshold is the amount of herbicide above which plant damage will occur. The threshold can be set at any percentage of damage and an ED (Effective Dose) value identified. For example, an ED_{20} value will be the concentration of herbicide resulting in 20% reduction in growth. Bioavailability is the amount of herbicide available to the plant and will differ for different soil types. By having a knowledge of both toxicity threshold and bioavailability (exposure), a prediction of safety can be determined for a specific soil type and crop (Figure 2).

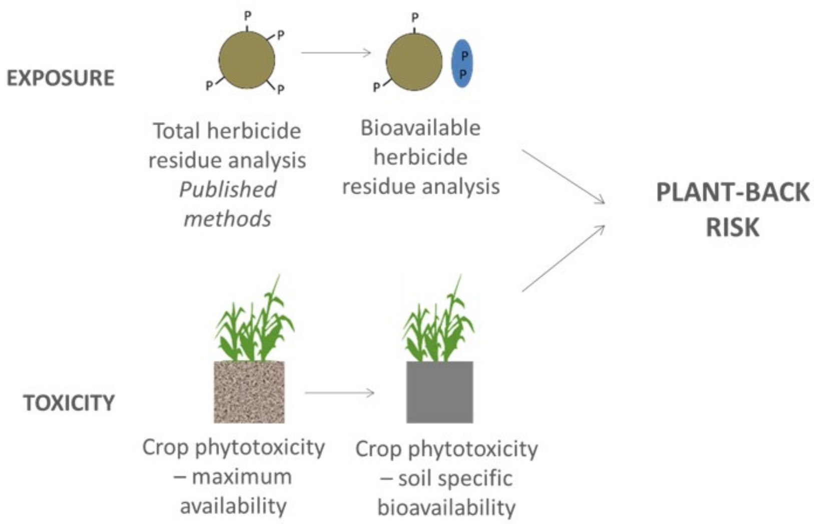

Figure 2. Framework to improve prediction of plant-back risk.

Through this research an approach to determine both crop toxicity thresholds and herbicide bioavailability for soil applied, pre-emergent herbicides has been developed. This information can be used to develop a decision support tool for residual herbicides.

Methods and results

Bioavailability

Herbicide bioavailability differs between soil types as the amount of herbicide bound to the soil (sorption) will differ. In a soil with greater sorption, less herbicide will be available to the plant. Sorption is quantified by the sorption coefficient (known as K_d), which is defined as the proportion of bound (unavailable) herbicide divided by the proportion of soluble (bioavailable) herbicide. A low K_d indicates the herbicide is more available.

Physicochemical properties can be used to determine a soils K_d value. Soils can be characterised by wet chemistry methods in a laboratory to determine factors such as pH, soil carbon, and organic matter, however, this process is very time consuming. An alternative method of characterising soils is via using mid-infrared reflectance (MIR) spectrum, which is relatively cheap and quick. MIR spectroscopy is a technique that uses a beam of MIR light through the sample and measures transmission and absorption of the light (Su and Sun, 2019). MIR integrates information about the soil's texture, carbon content and mineralogy. Together these characteristics can explain most of the variation in herbicide sorption and therefore bioavailability.

Diuron and imazapic K_d values of 42 different soils were determined via laboratory sorption experiments covering the range of soil types typically encountered in the NGR. Each soil was also scanned using MIR, and the MIR spectra calibrated against the laboratory-determined K_d value (Figure 3). It was confirmed MIR spectra were an accurate approach for prediction of K_d values.

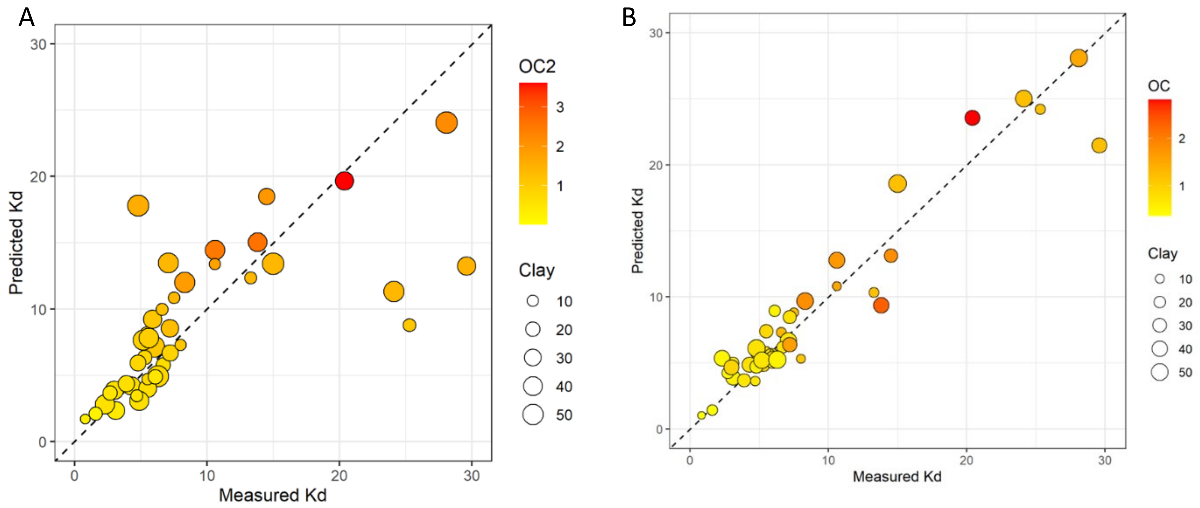

Figure 3. Measured versus best-fit predictions of soil sorption coefficients for diuron for 42 contrasting soils from the northern grains regions. A) using wet chemistry, B) using MIR. The dashed line represents a perfect prediction.

These sorption models can be used to characterise other soils and predict their K_d. Accurate prediction of herbicide sorption to soil, combined with knowledge of herbicide residue level in the soil, should allow for site-specific phytotoxicity risk assessment.

Toxicity thresholds

For this pilot study, the lower concentration levels of imazapic and diuron that cause crop damage were determined via seedling bioassays on key summer (including maize, mung bean, sorghum) and winter (including barley, wheat, chickpea) crops (Figure 4). The bioassays were carried out on washed river sand as a negligible sorption control (i.e. negligible herbicide sorption due to low organic carbon and clay). Shoot and root biomass were measured to determine toxicity thresholds (Figure 5).

Determining potential for herbicide damage via this proposed approach for other herbicides will require establishment of baseline dose response curves for each specific combination of herbicide x crop.

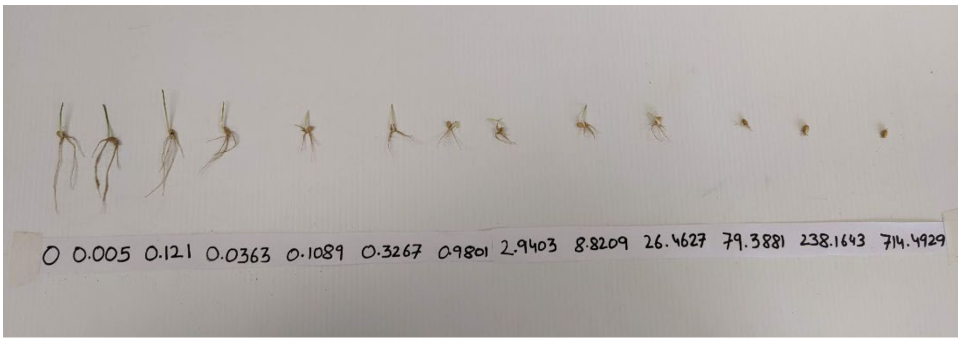

Figure 4. Imazapic dose response for wheat grown in river sand. Shoot and root length and biomass were determined.

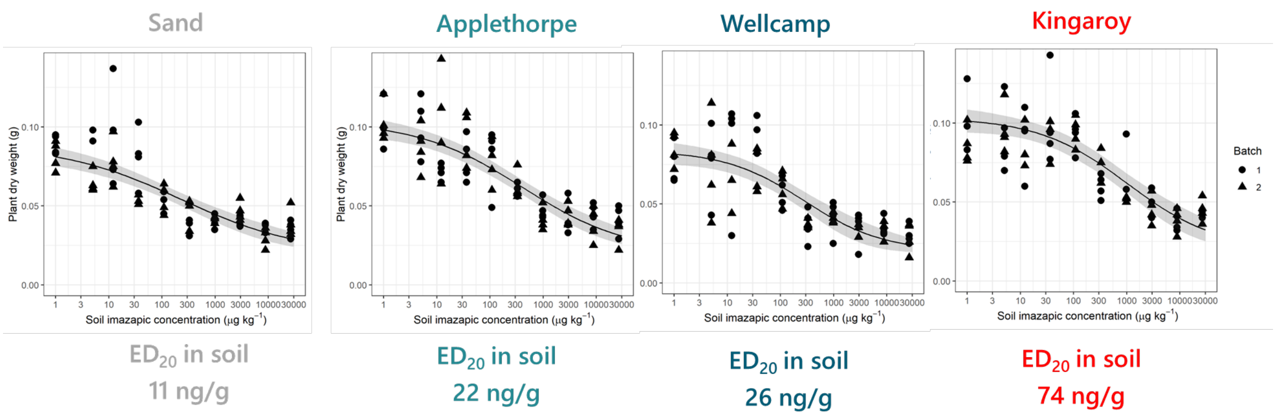

Figure 5. Imazapic dose-response curves for wheat growing in different soils and the ED_{20} value for dry weight biomass for each soil. X-axis = Soil imazapic concentration (g kg^{-1}) and Y-axis = Plant dry weight (g).

Secondly, bioassays were carried out on an additional three soil types (Table 1) to assess the effects on crop growth (phytotoxicity) (Figure 5) and to compare herbicide sorption (K_d) characteristics. The three soils were from Kingaroy (clay loam), Applethorpe (sandy loam) and Wellcamp (clay). Each soil had different characteristics (pH, organic carbon and clay content) influencing the capacity for herbicides to bind and therefore their availability to plants. By measuring plant damage and by extracting and quantifying herbicide residues from the soil, we were able to validate predictions in bioavailability.

Table 1. Physicochemical properties and sorption coefficients (K_d) for imazapic and diuron for four contrasting soils. Where OC = Organic carbon and CEC = Cation exchange capacity. Soils with a higher clay fraction tend to have a higher CEC.

Soil	OC (%)	pH	CEC (cmol⁺/g)	Clay (%)	Imazapic K_d	Diuron K_d
Sand	0.01	6.6	0.5	0.5	0.01	1.5
Applethorpe	0.59	6.1	4.1	5	0.17	3.3
Wellcamp	1.5	7.8	72	39	0.50	20.7
Kingaroy	1.8	5.1	18	20	2.19	18.0

Relationship between sorption and phytotoxicity

The sorption of imazapic and diuron differed between each other and between different soil types (Table 1). For imazapic, the K_d values were generally <1 indicating a high proportion of imazapic will reside in the soil solution in most soil types (i.e. available for plant uptake), rather than being bound to soil particles. Sorption of imidazolinone herbicide is known to be highly influenced by soil pH (and hence label plant backs increase in acidic soils). This was confirmed in this study where imazapic sorption was greater in the highly acidic soil from Kingaroy. The K_d values for diuron are much higher than for imazapic. This demonstrates that diuron is bound to soil to a greater extent than imazapic and is therefore generally less mobile and less available for plant uptake, especially in soils with higher organic carbon.

The relationship between sorption and phytotoxicity was determined by plotting ED_{20} and ED_{50} values against the K_d values determined for each herbicide and for each of the four soil types outlined in Table 1 (Figure 6).

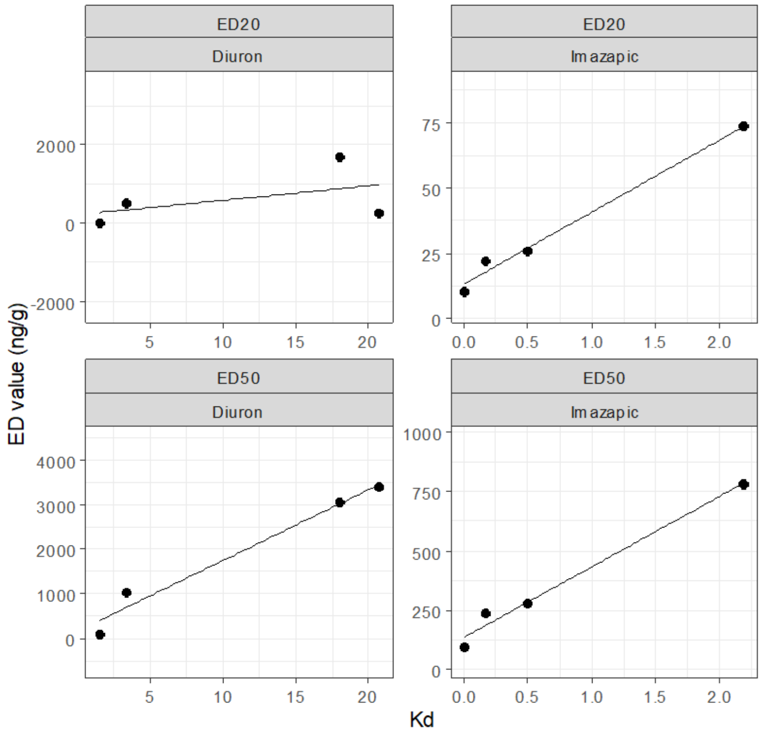

Figure 6. Relationship between K_d and toxicity threshold values (ED_{20} and ED_{50}) to wheat for diuron (left) and imazapic (right) for four different soil types. The individual points on each graph represent the four soils (K_d x ED) and the line represents the fit. The closer the points are to the line, the better the fit and model.

Imazapic thresholds for 20% and 50% shoot biomass reductions (i.e. ED_{20} and ED_{50}) were both significantly correlated with the soil K_d value. In contrast, for diuron, the ED_{50} but not the ED_{20} was significantly correlated to the K_d.

Relationships between K_d and crop tolerance have potential to allow for estimation of phytotoxicity thresholds in different soil types, if the K_d and tolerance to the specific crop are known. Evaluation of more soils will strengthen the model. Based on our work, prediction of K_d values through either wet chemistry determination or MIR should allow a reasonable estimation of soil specific toxicity thresholds.

Conclusion

Through this proof-of-concept research we have developed a framework to derive crop toxicity thresholds and predict K_d values, and therefore herbicide availability. The information produced can be used in decision making to minimise crop loss. Potentially a traffic light tool (safe - green, caution – yellow, high risk - red) could be developed from the data to indicate safety for recropping, where soil K_d and residual herbicide remaining are available.

The framework for predicting herbicide plant-back damage is outlined in Figure 7. In this framework, a soil sample is analysed using either wet chemistry or MIR and this identifies the total herbicide concentration and also information required to identify K_d using the sorption model (Figure 3). A calculation of K_d, the bioavailability model (Figure 6) and dose response curves (Figure 5) can be used to identify a soil specific toxicity threshold (eg ED_{20}). This ED value can then be compared with the measured soil herbicide concentration and risk for crop damage predicted.

While imazapic and diuron were used in this pilot study, baseline dose response curves (e.g. ED_{20} values in sand for each crop type) would need to be established for any other herbicide x crop combination.

Herbicides with low K_d values have the potential for increased mobility in the soil. This may require soil samples for residue determination to be collected from varying soil depths.

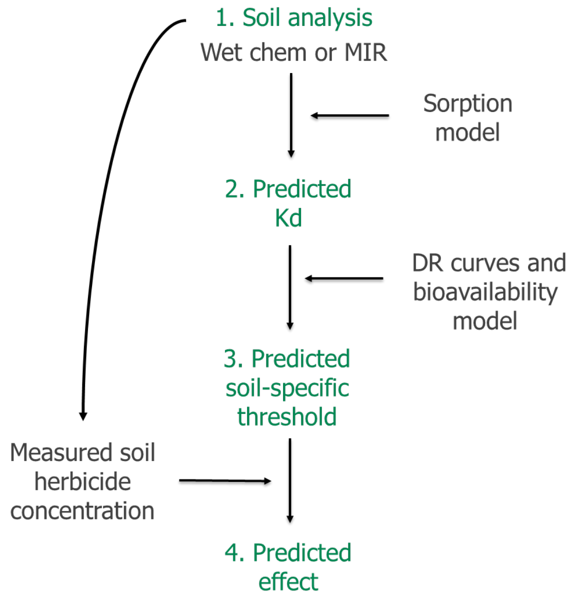

Figure 7. Framework for predicting herbicide plant-back damage potential. DR = Dose response.

The framework is adaptable to other pre-emergence herbicides and other herbicide-crop combinations, provided the baseline crop x herbicide tolerance data is generated. To make the predictions of risk more reliable, additional laboratory evaluation across a wider range of soil types is recommeded. Additional information from field trials would also provide insight into whether the damage measured in the laboratory results in yield loss.

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Regulatory challenges for new pesticide technologies - Green-on-Green optical spot sprayer technologies - herbicide tolerance trait stacking

Rohan Rainbow, Crop Protection Australia

Key words

OSST, green-on-green, optical sprayer, pesticide regulation, GMO herbicide tolerance, HT trait stacking

Take home message

- Rural Research and Development Corporations, machinery manufacturers and pesticide companies will need to work together to deliver an effective outcome to support the APVMA in delivering effective green-on-green optical spot spraying technology (OSST) regulation determinations
- Strategic herbicide tolerance (HT) issues are currently managed through informal ad-hoc discussion by the peak industry bodies through informal consultation with herbicide registrants and breeders
- Key issue is the strategic deployment of the finite resource of potential HT traits, both GM and non-GM to maximize the long-term sustainable use of the technology within a farming systems context
- There is a need for a formal industry feedback mechanism into the regulatory process beyond the initial consultation period during regulatory assessment to manage strategic farming systems issues.

Background

Weed control is one of the major costs to crop production and a major determinant of crop and pasture rotation and management. The impact can be very specific to particular weed problems in different crop and pasture production systems, and these can differ greatly across regions. The economic costs of weeds to Australian producers are also a key driver of practice change, as is the importance of managing herbicide resistance to sustain viable agricultural production. New herbicide, and precision application technologies, plus plant genetic solutions, contribute to the tools available to industry. The rapid advancement of some of these technologies and stacking of herbicide tolerance technologies presents some challenges to the regulatory framework needed to best support industry in the future. Green-on-green spray technology is on the precipice of widespread commercialisation, but will growers be able to realise its potential without significant investment and delivery of registered pesticide label registrations? Crop phytotoxicity, environmental and residue studies will potentially need to be assessed under different criteria from traditional Good Agricultural Practice (GAP) studies, which is what is currently reflected on pesticide labels.

Optical spot spray technologies and permits for use

Industry use of optical camera spot spray technology (OSST) for use in fallow has been widely adopted in Australia. Today the technology is considered industry best practice for fallow weed management, both in reducing herbicide costs, but also in ensuring there are no weed escapees which result in the increased risk of herbicide resistant weed patches in paddocks.

The origins of OSST using NIR reflectance for fallow weed management actually started in Australia in the mid-1980's but was commercialised following North American investment. The Grains Research and Development Corporation (GRDC) invested in a project with the New South Wales

Department of Primary Industries (NSW DPI) over 10 years ago to establish an industry Australian Pesticides and Veterinary Medicines Authority (APVMA) permit, for legal use of a range of herbicide products with OSST. This permit was held by Crop Optics Australia, the then Australian Agent for WeedSeeker spraying systems. This APVMA permit 'PER11163' expired in February 2019. Following considerable negotiation, Grain Producers Australia (GPA) today holds an APVMA permit PER90223 for the legal use of optical Green-on-Brown OSST, for the use of a range of herbicides for summer weed control. In addition, Nufarm Australia has registered a number of herbicide products for use with Green-on-Brown optical camera spot spray technologies.

Technology development of crop sensors, including OSST is accelerating (Rainbow, 2022). There is a significant commercial focus on Green-on-Green optical camera technologies for spot spraying of weeds within a growing crop, combined with the existing Green-on-Brown capability (Figure 1). The European company *Bilberry* has been first to market with Green-on-Green detection of broadleaved weeds such as radish, turnip, blue lupin, thistle or capeweed in wheat, barley and oat cereals. In addition, drone weed mapping solutions such as *Single Shot* for aerial weed detection have also been developed. These enable planning for weed control options to be managed separately prior to the spray operation.

	Availability	Green on Brown	Green on Green
Weed Seeker & Weed Seeker 2 (Owned by Trimble)			
WeedIt & Weed-It Quadro (Licenced by Nufarm-Croplands in Aust/NZ)			
SenseSpray (AgTechnic)			
Bilberry (Licenced to Agrifac, Dammann, Miller and Goldacres Australia)			
Bosch – SmartSprayer (Investment by BASF – licenced to Amazone, Stara & AGCO)			
Carbon Bee –SmartStriker (licenced to Kuhn, Berthoud)			
Greeneye Technology (Investment by Syngenta)	*Availability in Australia unknown*		
John Deere - See and Spray (Includes IP from John Deere owned Blue River Technologies, plus includes University of Southern Queensland IP with previous investment by SRA, CRDC & HIA)			*See & Spray Ultimate* Limited USA Release 2023
AutoWeed (James Cook University IP - Previous investment by Sugar Research Australia)	*Limited availability*		
Agerris- VIIPA (University of Sydney IP – Previous investment by Hort Innovation Australia)	*In development*		
Agrointelli (incorporating RoboWeedMaPS fitted to Robotti platform)	*In development*		
Ecorobotics (Investment by BASF)	*In development*		

Figure 1. Green-on-Brown and Green-on-Green OSST*
*information based on publicly available information October 2022

Regulatory challenges for Green-on-Green OSST

The potential of Green-on-Green OSST to use new chemistry or higher rates to kill weeds in crop, also opens up the risk of off-label chemical use as the specific technology use is not currently specified on pesticide labels. One of the options being discussed by some optical sprayer developers and users of Green-on-Green in-crop OSST, is the potential use of existing registered herbicides at higher than registered rates, or, in some cases, using broader spectrum herbicide products in crops for which they are not currently registered for use in. This concept has also been previously trialled by a number of groups using Green-on-Brown sprayers but with mixed results. A very real potential industry risk posed by Green-on-Green OSST if used in this way, is potentially exceeding maximum residue limits (MRLs) in resulting crop grain or fodder product, or residues being detected in crops the following season.

As international trade and pesticide MRL compliance becomes more complex, today more than ever, there is a need for increased industry management and efficiency in managing pesticide access and trade risks. There is a need for a broad industry discussion on options on how this can be best managed in the future, particularly with the new risks presented from the introduction of new technologies, such as Green-on-Green OSST.

The APVMA regulates crop, animal and human safety, plus risks to the environment, to the point-of-sale. Green-on-Green OSST will require a re-consideration of absolute crop-safety requirements due to the opportunity for new models of herbicide application in-crop. This becomes a difficult consideration for the regulator as to what constitutes crop safety and acceptable risks of crop loss. In addition, the risks from concentrated product use of higher herbicide rates when using Green-on-Green OSST could result in a difficult quantification of cumulative or concentrated plant and grain residue levels, depending on what percentage of a crop field is sprayed.

The current regulatory framework for chemical label extensions to maximise the efficacy and efficiency of Green-on-Green OSST is a time consuming and costly process, which will discourage many pesticide manufacturers, particularly for older generic herbicide products. An unclear regulatory pathway for Green-on-Green OSST will likely stifle investment and slow the commercialisation of new technology in the small Australian market.

While pesticide companies are well aware of the opportunity that Green-on-Green OSST presents, the challenge is the cost of closing the regulatory gaps and delivering a legally registered label outcome for use by producers. It will take industry cooperation on addressing regulatory requirements to capture the potential widespread use of Green-on-Green OSST, while protecting Australia's trade markets and ensuring food safety standards and MRL compliance for end users. To provide cost effective registration of new products using Green-on Green OSST, there is a need to develop a geospatial OSST risk assessment model which would be used in submission of an Item 25 risk assessment to the APVMA. The in-crop OSST risk assessment model could be made commercially available to pesticide registrants to support regulatory assessment of new herbicide products. For this to be successful, industry producers, their respective Rural Research and Development Corporations, machinery manufacturers and pesticide companies will need to work together to deliver an effective outcome to support the APVMA in delivering effective Green-on Green OSST regulation determinations.

Challenges for herbicide tolerance trait stacking

A report by Rainbow (2020) commissioned by the Office of the Gene Technology Regulator (OGTR) considered the current and potential future farming systems changes, environmental risks and impacts, including the impact on producer practices of the use of cultivars with multiple genetically modified organism (GMO) herbicide tolerance traits. The report outlines an understanding of current and future potential risks from resulting farming systems change through production of genetically modified (GM) crops with multiple herbicide tolerance traits. It provides a rationale for the OGTR to consider whether some form of guidance or industry advice might be appropriate to address the issues outlined in the report.

Extending multiple HT traits into a stack would potentially enhance future positive change to farming systems, particularly if the technology offers additional timing during the crop growth period to provide effective weed control or weed seed set control, while enabling effective crop competition with weeds. The report suggests that the most critical functions of GM crop HT traits risk assessment are adequately managed with the current regulatory processes in place with the OGTR, FSANZ and APVMA.

There is however a requirement for the broad value chain of industry stakeholders to discuss the complex strategic issues resulting from commercial investment in GM and non-GM HT stacking in the commercial landscape and its impact on farming systems. This includes herbicide resistance management and resulting international trade of agricultural product (Figure 2). There is also a requirement for a formal industry feedback mechanism into the regulatory process to manage strategic farming systems related issues, rather than consideration of individual trait or herbicide issues. It is also clear that there is both a requirement and opportunity for improved strategic guidance on crop HT stewardship for volunteer crop control.

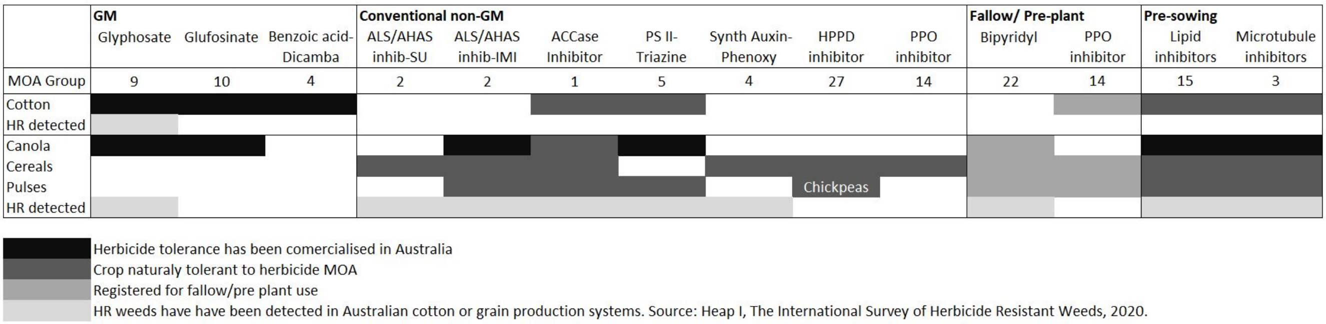

Figure 2. Herbicide resistance reported in Australian cotton and grain crops compared with current registered herbicide options in GM and non-GM crops (Rainbow, 2020).

A key issue identified in this review is the strategic deployment of the finite resource of potential HT traits, both GM and non-GM, to maximize the long-term sustainable use of the technology within a farming systems context with flexible crop rotation choices. A detailed producer survey of imidazolinone (IMI) HT volunteer control issues is warranted to further understand the reported issues associated with HT crop production and to provide insight on potential producer strategies to mitigate the issues that have been arising. Managing non-GM IMI tolerant cereal crop volunteers is becoming an increasing issue with so many crops now tolerant to IMI herbicides, including wheat, barley, canola, lentils, sorghum and maize. The issues experienced with IMI HT crops provides some insight on potential risks of volunteer management where multiple HT traits are stacked into a single crop, as the complexity of volunteer management will be potentially amplified. Additionally with multiple stacked HT traits, selection pressure for herbicide resistant weeds will be increased if all the additional modes of action technology options are utilised in one season, reducing best practice herbicide rotation options to avoid repeat use of the same mode of action in subsequent seasons. Consideration of the broader strategic issues associated with farming systems management and the integration of multiple HT traits requires a more formal process for reaching industry consensus on stewardship, particularly in the grains industry

The need for formal leadership and expert industry input

A key gap identified in the OGTR review is the need for a formal industry feedback mechanism into the regulatory process to manage strategic farming systems change related issues, rather than consideration of individual traits or herbicide use issues. A key missing link is the integration and regulation of outcomes from commercial breeding programs. It is also clear that there is both a need and opportunity for improved strategic regulatory guidance on crop HT stewardship for volunteer crop control and ensuring that product meets trade and market requirements. There are a number of options proposed which include formal expert industry input to support both the regulatory process and deliver effective technology stewardship outcomes for industry.

There has also been considerable discussion around the potential role of the cross agricultural industry National Working Party for Pesticide Applications (NWPPA) in facilitating industry coordination on guiding the introduction of Green-on-Green OSST and producing science-based evidence on how potential risks can be managed, to the APVMA regulator. As new pesticide technologies emerge, there is clearly a need for national leadership and expert input to help navigate their regulation and stewardship.

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Crop competition effects on weeds and crops – key trends from six years of research in the northern region

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Crop competition, sowthistle, chickpea, faba bean, row spacing, crop density

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Take home message

- There is convincing evidence that increased faba bean or chickpea crop competition due to narrower row spacing (23 – 25cm row spacing) and/or increased crop density (30 plants/m^2) reduces sowthistle growth and seed production.
- Importantly in most instances, narrower row spacing and increased plant density of faba bean and chickpea crops did not have a negative impact on grain yields. In situations where resources (e.g. water) were not limiting, more competitive crops were often higher yielding.
- The impact of different cultivars on sowthistle growth, sowthistle seed production and crop yield were not consistent for either faba bean or chickpea across trials and is likely a reflection of differences in cultivar adaptation to specific environments.

Background

In-crop weed control in the northern grain region (NGR) is heavily reliant on herbicides. However, this practice is not sustainable due to resistance. Herbicide resistance is becoming more common and is predicted to increase if there is an ongoing reliance on herbicides for weed control. To prevent further resistance, and for herbicides to remain an important tactic for weed control, a combination of chemical and non-chemical weed control tactics is required.

An often overlooked weed management strategy is the use of agronomic management for more competitive crops. Increased crop competition can be achieved by narrowing row spacing, increasing plant density or the use of more competitive crop species and cultivars. A competitive crop is able to compete against weeds to reduce weed growth (biomass) and seed production. While this general principle is commonly known, a 2015 review of data in Australia (Widderick *et al* 2018) revealed a lack of data for the key crop:weed combinations of the NGR.

As such, research was undertaken to quantify the effects of growing competitive crops for the following scenarios:

- Pulse crops (winter and summer),
- Sorghum, and
- Early emerging summer weeds in winter crops (wheat and chickpea)

This paper summarises results from the winter pulse (faba bean and chickpea) research conducted across 6 years and multiple sites and implications for growing competitive crops as a weed management tactic.

Methodology

Over the 2016 to 2021 winter growing seasons, replicated field trials were established across the NGR at three locations (Narrabri, Wagga Wagga and Hermitage) to provide data on crop competition across different seasons and sites. The impact of crop row spacing, crop density, cultivar and a combination of row spacing and crop density was measured on weed growth (biomass), weed seed production and crop yield.

At each site, common sowthistle were established either with the crop by sowing weed seeds, or by transplanting weeds into the crop. Exact crop and weed densities were established in fixed quadrats from which weed and crop measures were taken. To measure weed growth and seed production, destructive samples were taken. Crop yield was also measured at each trial. No herbicides were applied in the crops and background non-target weeds were manually removed.

For chickpea and faba bean, the row spacings compared were 23/25cm and 46/50cm (differences due to available planting equipment). For chickpea, the crop densities compared were 15 and 30 plants/m^2, and for faba bean 20 and 30 plants/m^2. Cultivar comparison for chickpea included PBA Boundary⒫, Kyabra⒫, PBA Seamer⒫ and PBA Slasher⒫, and for faba bean PBA Warda⒫, PBA Samira⒫, PBA Nanu⒫ and PBA Marne⒫..

The seasons encountered during the research ranged from severe drought to flooding. In drought seasons, supplementary irrigation was applied. In some cases, crop establishment and survival was greatly impacted by the season and any compromised data has been excluded from analyses.

The research produced a large quantity of data with a total of 49 winter crop trials. To establish key trends in data, a combined trial analysis across sites and seasons was undertaken. Separate analyses were done for each agronomic factor (i.e. row spacing, crop density and row spacing × crop density) and each crop. For these analyses, separate 'environments' were considered and compared. Within each year and location, an environment was where both levels of the crop agronomy were present. For example, when investigating narrow versus wide row spacing, trial H19 at Hermitage in 2019 included 12 environments (3 cultivars x 2 crop densities x 2 sowthistle densities). By pooling data in this way, we have been able to assess the impact of different agronomic factors (row spacing and/or crop density) over a range of different growing conditions.

When significant interactions between crop agronomy and environment occurred, a summary of pair-wise comparisons between the levels of crop agronomy practice (narrow vs wide row spacing, low vs high crop density, poor vs high competition) within each environment was undertaken using t-tests (i.e. a subset of least significant difference comparisons) to investigate trends in response to crop agronomy.

Results

Faba bean

A more competitive faba bean crop, due to narrower row spacing (23/25cm) and/or increased crop density (30 plants/m^2), consistently reduced sowthistle growth (biomass) and seed production, while maintaining grain yields in most cases. The greatest impact was evident when faba bean was grown at both a narrower row spacing and increased density where reduction in sowthistle growth and seed production were not only more frequent, but greater (Table 1). Our research showed an inconsistency in results relating to faba bean cultivar.

Table 1. Impacts of different agronomic factors in faba bean on sowthistle biomass, sowthistle seed production and faba bean yield. Agronomic factors: Row spacing – Narrow = 23/25cm vs Wide = 46/50cm; Crop density – Low = 20 vs High = 30 plants/m^2; Row spacing × crop density – Poorly competitive = 50cm + 20 plants/m^2, Highly competitive = 25cm + 30 plants/m^2; Cultivars – PBA Warda⦹, PBA Nasma⦹, PBA Samira⦹, PBA Nanu⦹ and PBA Marne⦹.

Agronomic factor	Sowthistle biomass	Sowthistle seed production	Faba bean yield
Row spacing (55 to 68 environments from 9 to 11 trials)	Narrow row spacing reduced sowthistle biomass. • Reduction in 87% of environments* (6 – 83% biomass reduction) • Significant reduction in 44% of environments (35 – 83% biomass reduction)	Narrow row spacing reduced sowthistle seed production. • Reduction in 87% of environments* (3 – 85% seed reduction) • Significant reduction in 24% of environments (36 – 71% seed reduction)	Narrow row spacing resulted in a significant increase in faba bean yield.^
Crop density (36 to 48 environments from 3 or 4 trials)	High crop density reduced sowthistle biomass. • Reduction in 83% of environments* (8 – 74% biomass reduction) • Significant reduction in 33% of environments (37 – 74% biomass reduction)	High crop density reduced sowthistle seed production. • Reduction in 77% of environments* (3 – 95% seed reduction) • Significant reduction in 23% of environments (44 – 89% seed reduction)	Increased crop density resulted in a significant increase in faba bean yield.^
Row spacing × crop density (28 to 34 environments from 10 or 11 trials)	Highly competitive faba bean reduced sowthistle biomass (Figure 1). • Reduction in 97% of environments* (4 – 87% biomass reduction) • Significant reduction in 60% of environments (47 – 87% biomass reduction)	Highly competitive faba bean reduced sowthistle seed production (Figure 2). • Reduction in 90% of environments* (12 – 95% seed reduction) • Significant reduction in 53% of environments (45 – 95% seed reduction)	Highly competitive faba bean maintained or increased crop yield (Figure 3). • Significant increase in yield at 25% of environments (15 – 43% yield increase) • No change in yield at 71% of environments • Significant reduction in yield at 4% of environments (21% reduction in yield)
Cultivar	Inconclusive results, likely due to cultivar adaptation to different environments.		

* - includes both statistically significant and non-significant reductions.
^ - Statistical main effect across environments.

Row spacing x crop density effect

Sowthistle biomass

Highly competitive faba bean, combining narrow row spacing (23/25cm) with high crop density (30 plants/m^2), resulted in a lower sowthistle biomass in all but one environment (Figure 1).

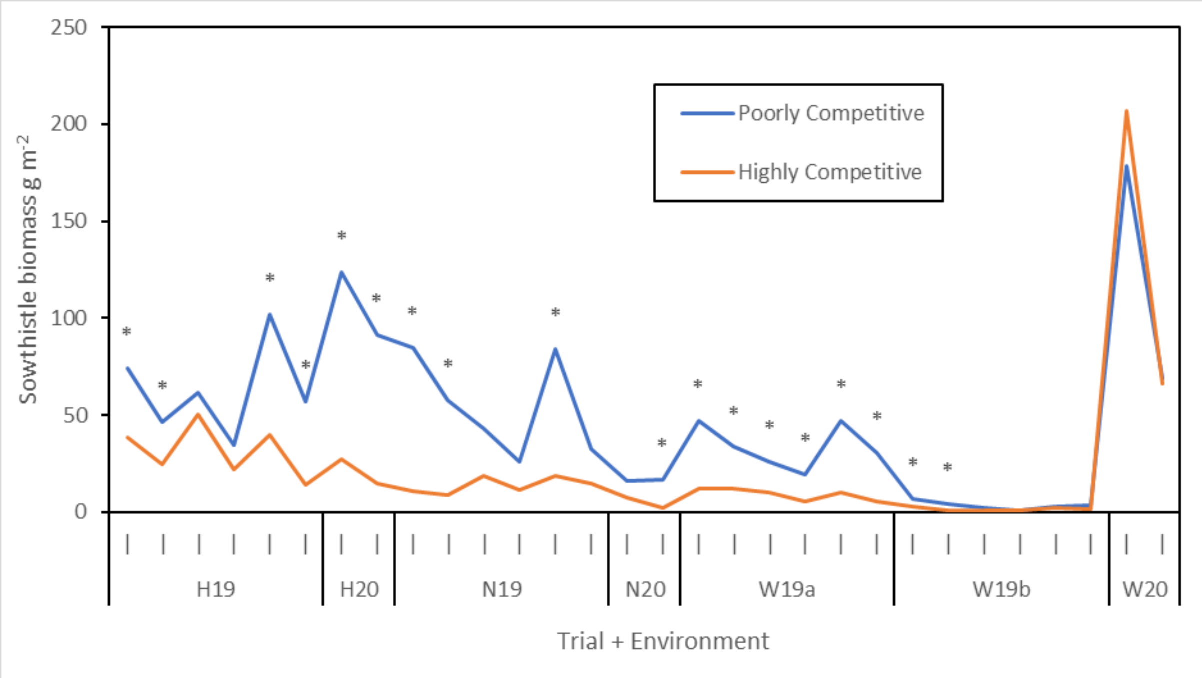

Figure 1. Impact of faba bean row spacing × crop density on sowthistle biomass production. Where Poorly competitive = 46/50cm row spacing and 20 plants/m^2, Highly competitive = 23/25cm and 30 plants/m^2, * = significant difference. The x-axis represents both the trial (location – H=Hermitage, N=Narrabri or W=Wagga Wagga) and year, and the 'Environment' represented by 'I' is a combination of faba bean cultivar and sowthistle density.

Sowthistle seed production

The seed production of sowthistle was reduced in a highly competitive faba bean crop (23/25cm row spacing and 30 plants/m^2) in all but three environments (Figure 2). For these three environments, the difference was significant in only one environment where production was high compared to other environments. At this site (W20) the 2020 growing season was favourable with the growing season rain (April to October) very close to the long-term average.

Faba bean yield

Growing faba bean at the highly competitive configuration of 23/25cm row spacing and 30 plants/m^2, either maintained or increased faba bean yield in all but three environments (Figure 3). For these three environments, this reduction in yield was significant for one environment where yield was high for both competition treatments compared to other environments.

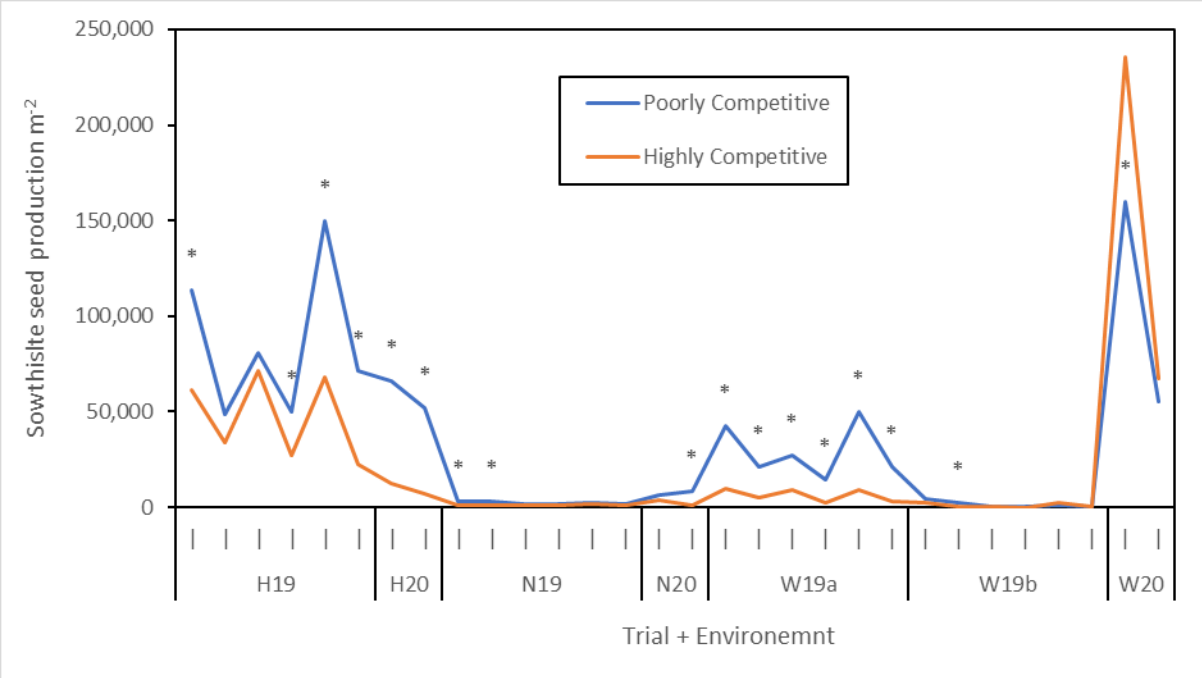

Figure 2. Impact of faba bean row spacing × crop density on sowthistle seed production. Where Poorly competitive = 46/50cm row spacing and 20 plants/m^2, Highly competitive = 23/25cm and 30 plants/m^2, * = significant difference. The x-axis represents both the trial (location – H=Hermitage, N=Narrabri or W=Wagga Wagga) and year, and the 'Environment' represented by 'I' is a combination of faba bean cultivar and sowthistle density.

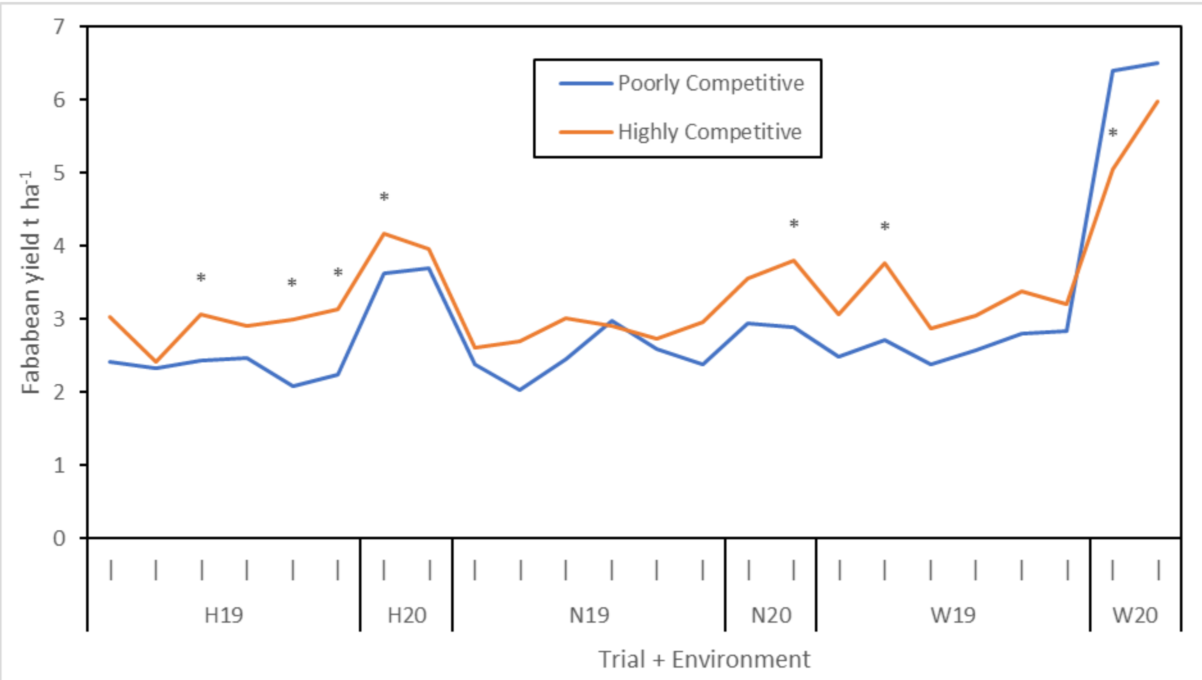

Figure 3. Impact of faba bean row spacing × crop density on faba bean yield. Where Poorly competitive = 46/50cm row spacing and 20 plants/m^2, Highly competitive = 23/25cm and 30 plants/m^2, * = significant difference. The x-axis represents both the trial (location – H=Hermitage, N=Narrabri or W=Wagga Wagga) and year, and the 'Environment' represented by 'I' is a combination of faba bean cultivar and sowthistle density.

Chickpea

A more competitive chickpea crop, due to a narrower row spacing (23/25cm) resulted in a reduction in sowthistle biomass but had no effect on sowthistle seed production (Table 2). Chickpea grain yields were either maintained or increased at this narrower row spacing. An increased chickpea density from 15 to 30 plants/m^2, resulted in a reduction in sowthistle growth (biomass) and seed production and an overall increase in chickpea yield. When narrow row spacing and increased crop density were combined, sowthistle biomass and seed production were reduced to a greater degree than either alone, and yield was maintained in most cases. Our research showed an inconsistency in results relating to chickpea cultivar.

Table 2. Impacts of different agronomic factors in chickpea on sowthistle biomass, sowthistle seed production and chickpea yield. Agronomic factors: Row spacing – Narrow = 23/25cm vs Wide = 46/50cm; Crop density – Low = 15 vs High = 30 plants/m^2; Row spacing × crop density – Poorly competitive = 46/50cm + 15 plants/m^2, Highly competitive = 23/25cm + 30 plants/m^2; Cultivars – PBA BoundryΦ, KyabraΦ, PBA SlasherΦ, and PBA SeamerΦ.

Agronomic factor	Sowthistle biomass	Sowthistle seed production	Chickpea yield
Row spacing (41 to 49 environments from 9 or 10 trials)	Narrow row spacing reduced sowthistle biomass.^	No difference between narrow and wide row spacing across environments.	Yield maintained or increased with no evidence of yield reduction due to narrow row spacing. • No difference in yield at 90% of environments. • Significant yield increase at 10% of environments (19 – 193% yield increase)
Crop density (28 to 36 environments from 5 or 6 trials)	High crop density reduced sowthistle biomass. • Reduction in 92% of environments* (3 – 74% biomass reduction) • Significant reduction in 36% of environments (37 – 74% biomass reduction)	High crop density reduced sowthistle seed production. • Reduction in 88% of environments* (5 – 74% seed reduction) • Significant reduction in 27% of environments (39 – 74% seed reduction)	High crop density resulted in a significant increase in chickpea yield.^
Row spacing × crop density (19 to 23 environments from 7 or 8 trials)	Highly competitive crop reduced sowthistle biomass (Figure 4). • A reduction in 91% of environments* (13 – 84% biomass reduction) • A significant reduction in 44% of environments (40 – 84% biomass reduction)	Highly competitive crop reduced sowthistle seed production (Figure 5). • Reduction in 83% of environments* (7 – 85% seed reduction) • Significant reduction in 30% of environments (39 – 85% seed reduction)	Yield maintained or increased with little evidence of yield reduction due to a highly competitive crop (Figure 6). • No difference in yield in 63% of environments. • Significant yield increase in 26% of environments (11 – 154% yield increase) • Significant yield reduction in 11% of environments (20-30% yield reduction).
Cultivar	Inconclusive results, likely due to cultivar adaptation to different environments.		

* - includes both statistically significant and non-significant reductions.
^ - Statistical main effect across environments.

Row spacing x crop density effects

Sowthistle biomass

Highly competitive chickpea grown at 23/25cm row spacing and density of 30 plants/m^2, reduced the biomass of common sowthistle in all but one environment compared to chickpea grown at the wider row spacing of 50cm and density of 15 plants/m^2 (Figure 4). In this environment, the sowthistle biomass was large for both competition treatments compared to most other environments.

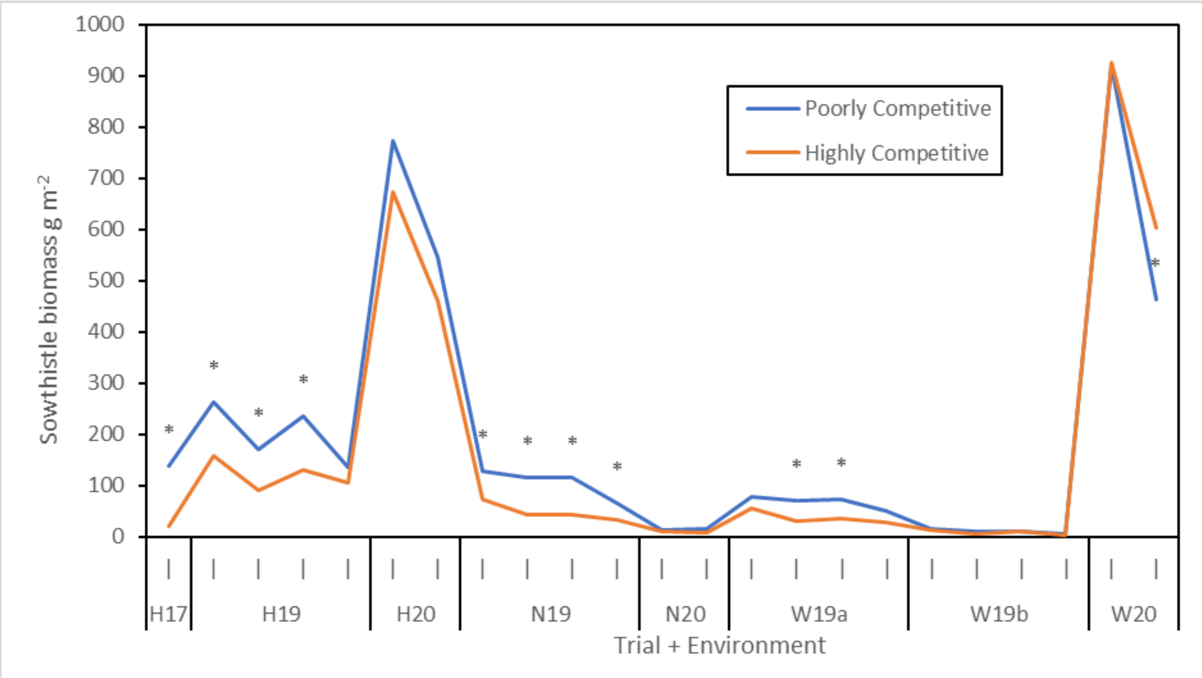

Figure 4. Impact of chickpea row spacing × crop density on sowthistle biomass production. Where Poorly competitive = 46/50cm row spacing and 15 plants/m^2, Highly competitive = 23/25cm and 30 plants/m^2, * = significant difference. The x-axis represents both the trial (location – H=Hermitage, N=Narrabri or W=Wagga Wagga) and year, and the 'Environment' represented by 'I' is a combination of chickpea cultivar and sowthistle density.

Sowthistle seed production

Competitive chickpea grown at a row spacing of 23/25cm and a density of 30 plants/m^2 reduced seed production of sowthistle in all but four environments (Figure 5). In only one of these environments was this difference significant and in this environment the sowthistle seed production was great in both competition treatments and generally greater than other environments.

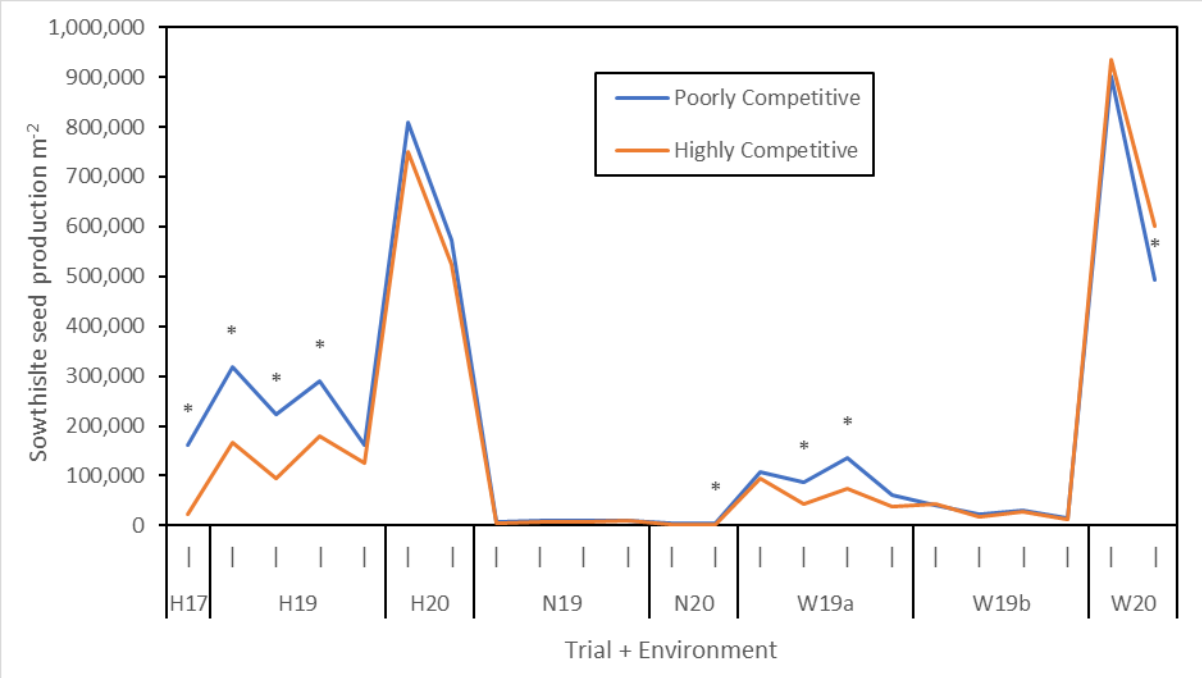

Figure 5. Impact of chickpea row spacing × crop density on sowthistle seed production. Where Poorly competitive = 46/50cm row spacing and 15 plants/m^2, Highly competitive = 23/25cm and 30 plants/m^2, * = significant difference. The x-axis represents both the trial (location – H=Hermitage, N=Narrabri or W=Wagga Wagga) and year, and the 'Environment' represented by 'I' is a combination of chickpea cultivar and sowthistle density.

Chickpea yield

A competitive chickpea crop at a row spacing of 23/25cm and a density of 30 plants/m^2, maintained chickpea grain yield in most environments and increased grain yield in 5 environments (Figure 6). In contrast, in only 4 environments was there a decrease in crop yield in the highly competitive crop, and in only 2 of these environments was the yield reduction significant.

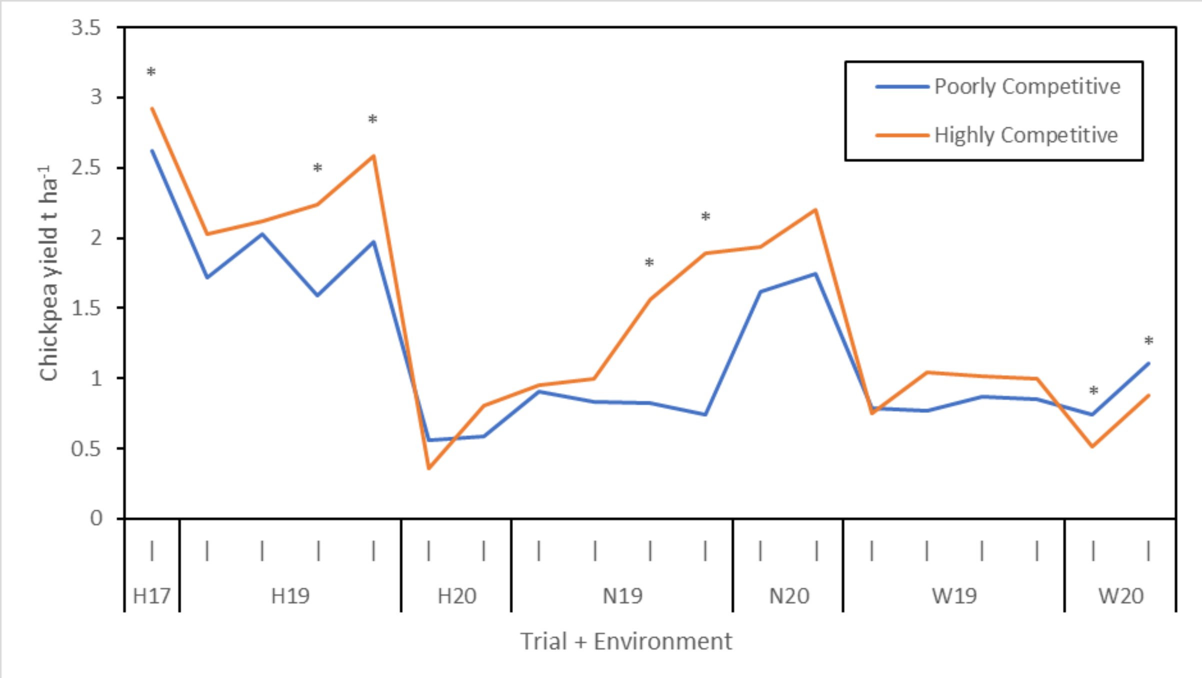

Figure 6. Impact of chickpea row spacing × crop density on chickpea yield. Where Poorly competitive = 46/50cm row spacing and 15 plants/m^2, Highly competitive = 23/25cm and 30 plants/m^2, * = significant difference. The x-axis represents both the trial (location – H=Hermitage, N=Narrabri or W=Wagga Wagga) and year, and the 'Environment' represented by 'I' is a combination of chickpea cultivar and sowthistle density.

Discussion

Growing a competitive faba bean or chickpea crop at a narrow row spacing (23/25cm) and/or increased crop density (30 plants/m^2) is likely to reduce in-crop growth (biomass) and seed production of common sowthistle. Favourably, these competitive crop configurations maintained crop yield in most environments, and in some environments resulted in significant yield gains. In a minority of environments, competitive crop configurations resulted in crop losses. A more competitive crop will require more resources (e.g. water) in order to retain or increase crop yield and grain quality.

Reducing sowthistle growth via a competitive crop takes the reliance off herbicides for in-crop weed control. In reality, herbicides (either pre- and/or post-emergence) will be applied in crop. A competitive crop will provide complimentary weed control and reduce the growth and seed production on any survivors of herbicide treatment, thus preventing weed spread and persistence. This is important for keeping weed densities low and also for preventing the spread of herbicide resistance, should these survivors possess resistance.

One of the barriers to adopting competitive crops is the required change in machinery, especially for narrow row spacing. Our research has shown an increased crop density, which doesn't require machinery change, can provide competitive advantages against weeds that equal the effects of narrowing row spacing. However, combining a narrow row spacing with an increased crop density provided the greatest weed suppression advantages in our research.

To spread yield loss risk, grow competitive crops when resources are likely to be plentiful or only in select paddocks rather than the whole property. A competitive crop may be used as a replacement for in-crop herbicides if weed densities are low, or in a situation of high weed density, combining a competitive crop with pre- and post-emergence herbicide will minimise weed survival and seed production.

Our research has shown little consistency in effect of different faba bean and chickpea cultivars. This is not surprising given the adaptability of different cultivars to different growing environments. Although there may be weed control gains through cultivar selection, the gains achieved through narrow row spacing and increased crop density are likely to surpass those of changing cultivar.

Reference

Widderick M, Lemerle D, Taylor C, Johansen C, Hashem A, Osten V, Cook T, Bell K, Storrie A (2018). *Research priorities for weed suppression by crops in Australia*. In: Proceedings of 21st Australasian Weeds Conference, Sydney, NSW. Pp 133-136. http://caws.org.nz/old-site/awc/2018/awc201811371.pdf

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

Grain farm sustainability

Alan Thomson, Hitachi Aust

What contribution do mungbeans make to soil nitrogen?

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Key words

mungbean, nitrogen fixation, nitrogen uptake, grain yield, soil nitrates

GRDC code

DAQ1805-003RTX mungbean agronomy

Take home message

- There is limited grain yield response to applied nitrogen in the fallow prior to planting mungbeans
- Increasing nitrate supply in the top 60cm of the profile reduces the amount of nitrogen that is fixed from the atmosphere
- Mungbeans are a net consumer of soil nitrates when the nitrogen fixation rate is less than 55% of total nitrogen uptake by the plant.

Introduction

Mungbean (*Vigna radiata*(L.) Wilczek) is one of the main summer pulses grown on the Australian eastern seaboard and has provided strong cash prices over the last decade. Traditionally, mungbean has been sown as a rotational cash crop that is thought to also contribute nitrogen to the farming system and help reduce reliance on fertiliser nitrogen and mineralised nitrogen from organic sources.

In more recent times the prices for mungbeans has highlighted that strong gross margins could be generated from the crop, and it has become a dedicated cash crop in our farming system. Hence in more recent times, research emphasis has been on increasing the productivity of the crop in our environment. Nutrition is a key area to develop higher levels of production in this crop, within this area nitrogen (N) has been long overlooked as a potential source to enhance production because of the plants' nitrogen fixing properties.

Over the 2020 and 2021 summer seasons, the Mungbean Agronomy project ran a series of trials examining the grain yield response and nitrogen fixation impacts of applying a range of N rates in the fallow prior to planting mungbeans.

Experimental outline

2020 season

A trial site was established at the Central Queensland Smart Cropping Centre (CQSCC) near Emerald, which had a wheat cover crop planted for the winter of 2019. This crop was planted without any fertiliser and taken through to harvest to reduce the amount of N in the profile.

After wheat harvest, the site was set up for 64 plots (4m x 24m) in a randomised block design. Treatments applied were as follows:

1. No N applied (0N)
2. No N applied and no inoculation at planting (0N-IN)*

3. No N applied plus double starter rate at planting (0N+2ST)
4. 30 kg N/ha applied (30N)
5. 60 kg N/ha applied (60N)
6. 90 kg N/ha applied (90N)
7. 120 kg N/ha applied (120N)
8. 150 kg N/ha applied (150N)

*All treatments except treatment 2 (0N-IN) have inoculant applied at planting through water injection.

**All N treatments (4 to 8) were applied after wheat harvest on the 25 November. N was applied as urea dissolved in water solution and sprayed onto soil surface between standing stubble rows. Soil profile was too dry and hard to use banding applications. Site was irrigated the following day (26 November) after N applications with 100mm.

***Treatments were doubled up to make two separate trials situated side by side. One trial received supplementary irrigation the other remain in a dryland scenario. Four replicates of eight treatments in each trial making a total of 64 plots for the site.

The whole site was irrigated again starting on the 16 December with another 100mm application by travelling boom irrigator. The site received 217mm of rainfall from the start of January through to planting on the 14 February. Average plant available water content (PAWC) at planting was 120mm (1.2m profile).

The whole site was planted with Jade Au at a seeding rate of 30 seeds/m². Non-nodulating soybeans were hand planted into each plot on 17 February in area of ~1 m². These soybeans were used as the contrast species for ^{15}N isotope analysis of natural abundance testing at peak biomass.

Measurements

- Soil cores were taken for nutrition testing after wheat harvest, at planting and after mungbean harvest. Additional soil cores were taken for gravimetric assessment at planting and at harvest.
- Predicta®B testing was conducted after planting
- Plant establishment counts
- Light interception measurements were taken prior to flowering, at flowering and after flowering
- Dry matter (DM) cuts were taken at peak flowering, peak biomass and 90% black pod. Peak biomass samples were used for ^{15}N assessment. The non-nodulating soybean quadrats were also cut at the same time. The maturity cuts taken at 90% black pod were used for hand harvest assessments
- Dates for 50% flowering, 50% black pod and 90% black pod were recorded for each plot
- Final grain yields obtained via plot harvester.

The irrigated trial was given one application of 50mm by travelling boom on the 24 March (post-flowering). In crop rainfall on 6th March meant the first irrigation prior to flowering was not required.

2021 season

A trial site was established at the CQSCC in early June 2020. This experiment was set up in a similar structure to the previous season (2020) with the addition of two long fallow (LF) treatments. These treatments were set up in early June prior to wheat planting, with one treatment receiving 60 kg N/ha applied on 50 cm bands in the top 10 cm and the other treatment had no N applied as a control for the long fallow (LF60, LF0). The rest of the trial site was planted to a wheat cover crop over the winter of 2020. This crop was planted without any fertiliser and taken through to harvest to reduce the amount of N in the profile.

After the wheat harvest, the rest of the treatments were applied (Table 1) on 19 November with the same configuration as the long fallow treatments. Trial design was a randomised block design with the eight treatments randomised within each replicate with four replicates in total. Each plot was 4 m wide by 24 m long and the whole trial was repeated so that one trial could be managed as a dryland trial and the other would have overhead irrigation applied to create a higher yield demand on the treatments.

Table 1. List of treatments for the N response trial

8 treatments:	**No.**	**Name**
Long Fallow + zero N	1	LF0N
Long Fallow + 60N	2	LF60N
Short Fallow + Cover crop +zero N	3	CC0N
Short Fallow + Cover crop +zero N, No inoculant*	4	CC0N-Nil Inoc
Short Fallow + Cover crop +30N	5	CC30N
Short Fallow + Cover crop + 60N	6	CC60N
Short Fallow + Cover crop + 90N	7	CC90N
Short Fallow + Cover crop + 120N	8	CC120N

*All treatments except treatment 4 have inoculant applied at planting through water injection

**N treatments were applied either in June 2020 (treatment 2) or after wheat harvest on the 19 November 2020 (treatments 5 to 8). N was applied as urea between standing stubble rows with a double disc opener into the top 5 cm of the surface profile. Site was irrigated with 100 mm on the 25 November with overhead sprinklers on a travelling boom.

***Treatments were doubled up to make two separate trials situated side by side. Four replicates of eight treatments in each trial making a total of 64 plots for the site.

The whole site was irrigated again starting on the 7 January 2021 with another 100 mm application by travelling boom irrigator. The site received 240 mm of rainfall from the 26 November 2020 through to planting on the 24 February 2021. Average plant available water (PAW) at planting was 132 mm (1.2 m profile).

Whole site was planted with Jade-AU at a seeding rate of 30 seeds/m². Non-nodulating soybeans were hand planted into each plot on 25 February in area of ~1 m². These soybeans were used as the contrast species for ^{15}N testing at peak biomass.

The irrigated trial was given two applications of 40 mm each by travelling boom on the 31 March and the 14 April. Both trials received 90 mm of in-crop rainfall.

Measurements:

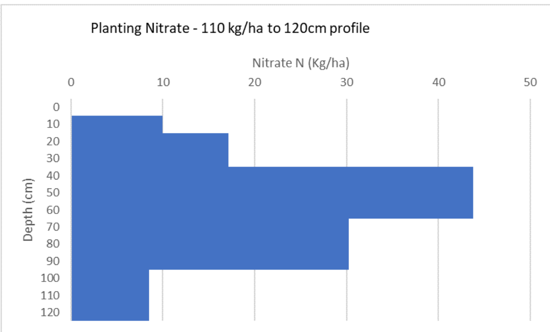
- Soil cores were taken for nutrition testing after wheat harvest, at planting and after mungbean harvest. Additional soil cores were taken for gravimetric assessment at planting and harvest
- Predicta®B testing was conducted after planting and at harvest
- Plant establishment counts
- Light interception measurements were taken prior to, at and after flowering
- Dry matter cuts were taken at peak flowering, peak biomass and 90% black pod. Peak biomass samples were used for ^{15}N assessment. The non-nodulating soybean quadrats were cut at the same time. The maturity cuts taken at 90% black pod were used for hand harvest assessments
- Dates for 50% flowering, 50% black pod and 90% black pod were recorded for each plot
- Final grain yields were obtained via plot harvester.

Results

The data from these trials have similar trends, so for the benefit of this paper the results are presented together, however the statistical analysis was done separately for each trial.

In both trials the starting nitrates were measured at planting in the zero N treatments (CC0N) and despite efforts to reduce the starting N by growing a wheat cover crop over the preceding winter; mineralisation rates proved to be higher than normal in the 2020 trial. This trial had 110 kg N/ha at planting to a depth of 120cm with a large proportion of this N being in the 30-60cm layer (Figure 1). The 2021 trial had 77 kg N/ha at planting to a depth of 120cm, with most of this N evenly distributed down the profile (Figure 1).

The 2020 trial had a very high mineralisation rate (68 kg N/ha over 3 months) leading up to planting, while the 2021 trial had a more normal mineralisation rate (21 kg N/ha over 3 months) which would not be unusual in most commercial paddocks.



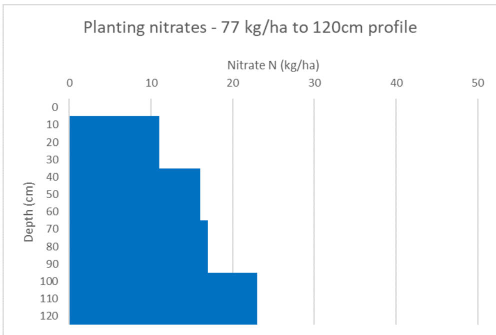


Figure 1. Average of planting nitrates distributed down the profile for the 2020 trial (left) and the 2021 trial (right).

The grain yield in the 2020 trial showed no significant differences in grain yields (Table 1). This means that none of the applied N rates increased grain yield any more than those treatments that had no N applied (0N, 0N-in, 0N+2ST). The mean yields across the treatments (0.6 – 1.3 t/ha) were considered low by commercial standards and the amount of starting nitrate at planting could have already met the modest crop demands.

The grain yields from the dryland trial in 2021 (Figure 2) did show some significant differences between selected treatments. Most notable was a ~180 kg/ha difference between the CC30N treatment and all the other treatments that received N (CC60N,CC90N,CC120N and LF60N) in the dryland trial. There was also a ~200 kg/ha difference between the two zero treatments (LF0N, CC0N) and the rest of the applied N treatments.

While these differences are statistically valid, the gross margin outcomes suggest that these differences are not worth pursuing. An outlay of $162/ha for 130 kg/ha of urea ($1250/t) will return $200/ha in extra mungbean yield ($1000/t). This amounts to a $38/ha return on the extra fertiliser applied. The other factor is that this marginal response seems to be only relevant to a crop that is yielding ~1.5 t/ha or better, as there was no response in the previous season where yields were less than 1 t/ha.

The use of irrigation in season 2021 increased the general yields across all treatments (Figure 2), however the only significant yield improvement to N application was in the CC120N treatment which was 214 kg/ha better then the CC0N treatment. This trial result would lead to a $111/ha loss in relation to applying 120 kg N/ha as urea.

Table 1. Mean mungbean grain yields recorded for both hand harvested and machine harvested measurements in the 2020 N trial.

Treatments	Dryland		Irrigated	
	Machine harvest grain yield (kg/ha)	Hand harvest grain yield (kg/ha)	Machine harvest grain yield (kg/ha)	Hand harvest grain yield (kg/ha)
0N	573	983	1069	1295
0N + 2ST	577	895	1012	1199
0N -in	660	1041	941	1418
30N	681	1046	1130	1398
60N	607	936	1045	1538
90N	711	1034	1019	1408
120N	670	1164	934	1349
150N	612	922	1013	1229
Trial means	637	1003	1021	1354
SE of means	60	100	195	153
$LSD_{0.05}$	n.s.	n.s.	n.s.	n.s.

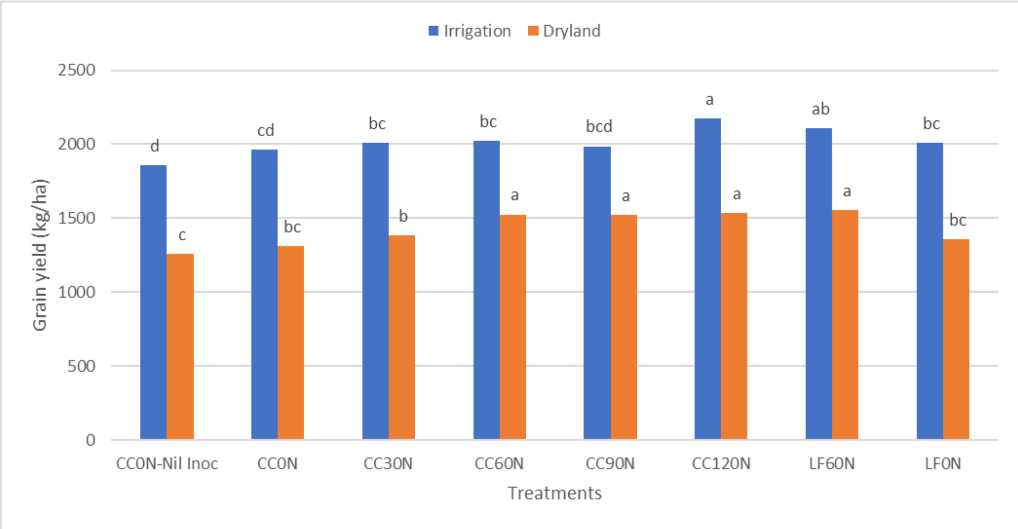


Figure 2. Mean mungbean grain yields recorded for machine harvested measurements in the 2021 N trial. LSD have been generated separately for the irrigation (128.7) and dryland (97.9) trials. Means with same letters are not significantly different at the P=0.05 level.

The yield data from both the 2020 and 2021 trials would suggest that mungbean grain yields are generally not responsive to applied rates of N. This means that either the crop is fixings its own N and does not rely on soil nitrates, or that in both these trials the level of soil nitrates at planting was enough for total crop uptake. The third option is that the crop uses a combination of both soil nitrates and fixed N via rhizobia interaction, to meet its N needs and can compensate using either source during the season without impacting on yield.

To define this issue further, N fixation was measured in both trials through the ^{15}N isotope natural abundance process using non-nodulating soybeans as the comparison species.

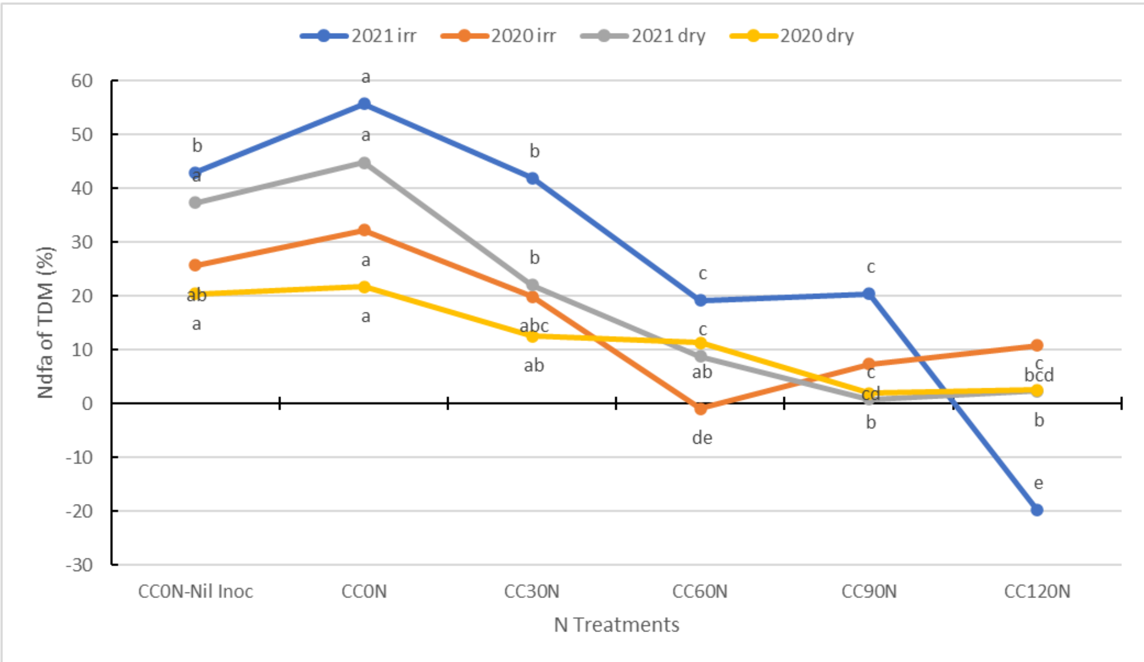


Figure 3. Mean % values of total N uptake in above ground total dry matter (TDM) that can be attributed to nitrogen derived from atmosphere (Ndfa) fixed by symbiotic rhizobium bacteria. These measurements have been taken from both irrigated and dryland trials across the 2020 and 2021 seasons. Means with the same letters are not significantly different at the P=0.05 level.

The percentage of nitrogen derived from atmosphere (Ndfa%) in total dry matter (TDM) measurements (Figure 3) shows a similar pattern across all four trials. Despite the amount of soil nitrate that was present at planting in both years, the crop clearly nodulated and fixed the maximum amount of N in the CC0N (control) treatments. The proportion of fixed N in these controls varied from 20-30 % of TDM in 2020 increasing to 45-55 % in 2021 (Figure 3). This may reflect the fact that the 2021 crop had starting nitrates of 77 kg N/ha which was 33 kg N/ha less then the previous trial in 2020. It could also be a symptom of a higher yielding crop.

The most common factor of all four trials is that the Ndfa% in TDM decreases as nitrate supply increases from N application. In most cases the percentage of Ndfa reduces to less then 10% once the application rate reaches 60 kg N/ha or more. The only exception to this was the irrigated trial in 2021 where the grain yields exceeded 2 t/ha and the Ndfa% remained at 20% for both 60 and 90 kg N/ha applied (Figure 3). This may have been because the plant was feeding a larger biomass.

In three out of the four trials there is a linear regression between increasing N applied and decreasing rate of Ndfa% (linear regression not shown). The reduction in Ndfa% has a direct impact on the amount of 'free' N (atmospheric sourced N) which is being incorporated and retained in the soil profile after the crop is harvested. The lab analysis of TDM (Figure 4) and grain (Figure 5) shows how much total N is taken up by the crop irrespective of what the Ndfa% is.

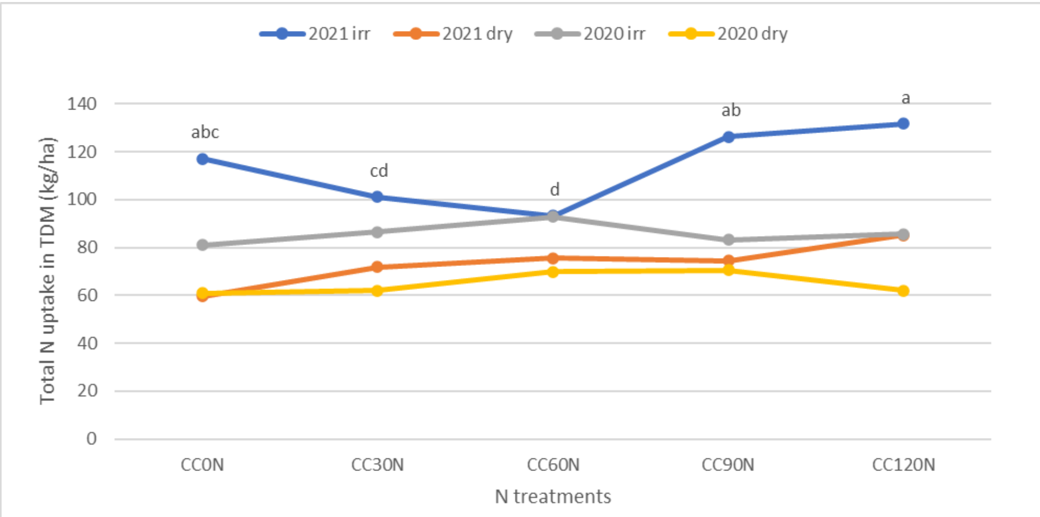


Figure 4. Mean values for the total amount of N taken up in TDM across the five main N rates in each of the four trials. Means with the same letter are not significantly different at the P=0.05 level. Means without letters have no relative significant differences within the data set.

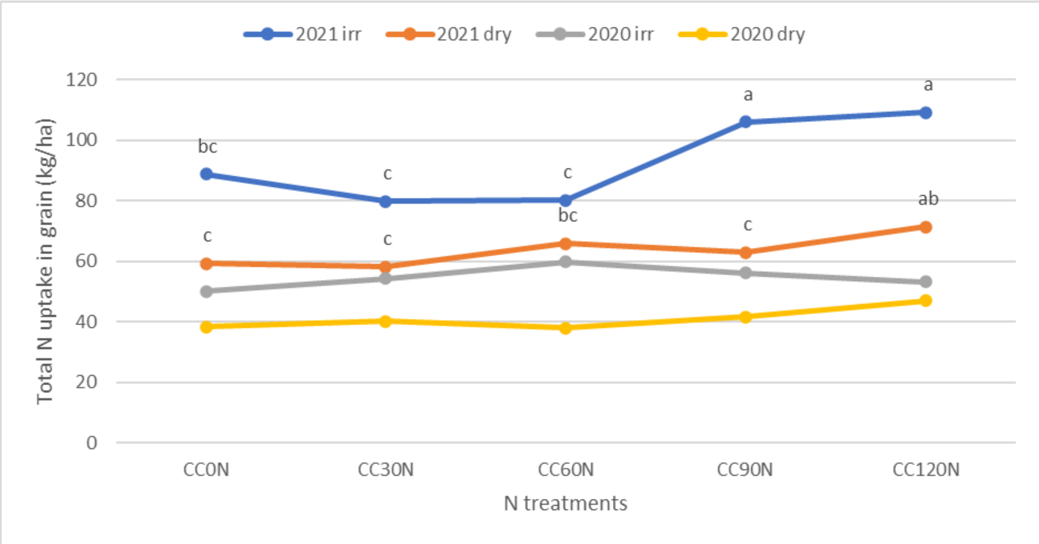


Figure 5. Mean values for the total amount of N taken up in grain across the five main N rates in each of the four trials. Means with the same letter are not significantly different at the P=0.05 level. Means without letters have no relative significant differences within the data set.

The amount of N taken up by the plant in TDM (Figure 4) is not responding to increasing levels of applied N except in the irrigated trial in 2021. The proportion of this crop N uptake in TDM that ends up in the grain is also consistent across N treatments (Figure 5). These two pieces of data can be combined into a N harvest index (Figure 6) which reinforces the consistency in the proportion total N uptake which is distributed to the grain regardless of the amount of N applied (Figure 6). What is surprising about this data is how high this harvest index is, particularly in the 2021 trials. In most situations, the plant is only returning 10-20% of its total N uptake back in residual stubble in the 2021 season. In the 2020 season that proportion increased to 30-40% across all N treatments.

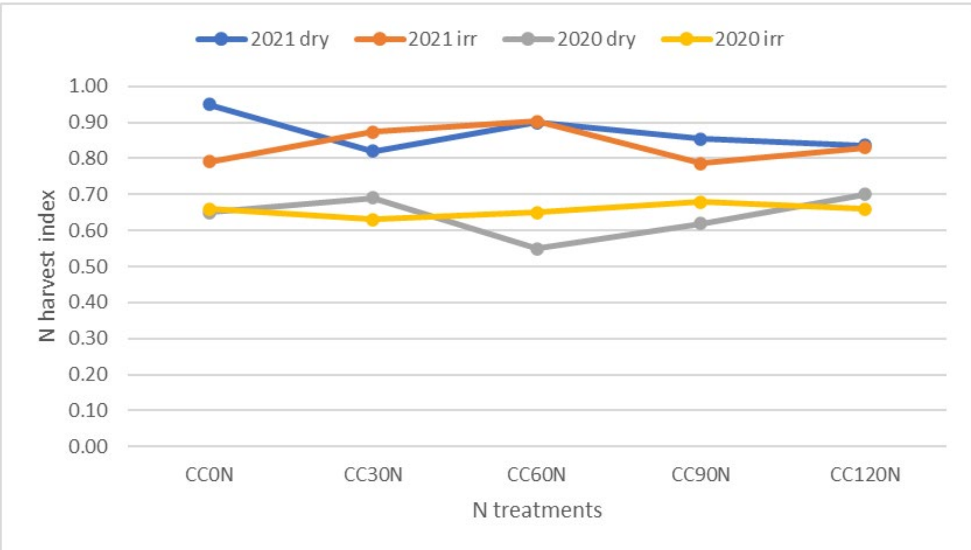


Figure 6. Mean values for the N harvest index calculated across the five main N rates in each of the four trials. Means without letters have no relative significant differences within the data set.

The proportion of N remaining in the residual stubble of the plant after harvest has a direct effect on the amount of Ndfa that is being returned to the soil profile as new N or 'free N'. Using the Ndfa% and the grain and TDM uptake lab results, a calculation can be made on how much Ndfa is remaining in the residual stubble (Figure 7). The amount of Ndfa being returned to the soil profile is quite small. Even in the control treatments (CC0N) where the amount of fixation was at its highest, the maximum amount of Ndfa being contributed is 14 kg N/ha or less. In the dryland trials that number is closer to 2-4 kg N/ha.

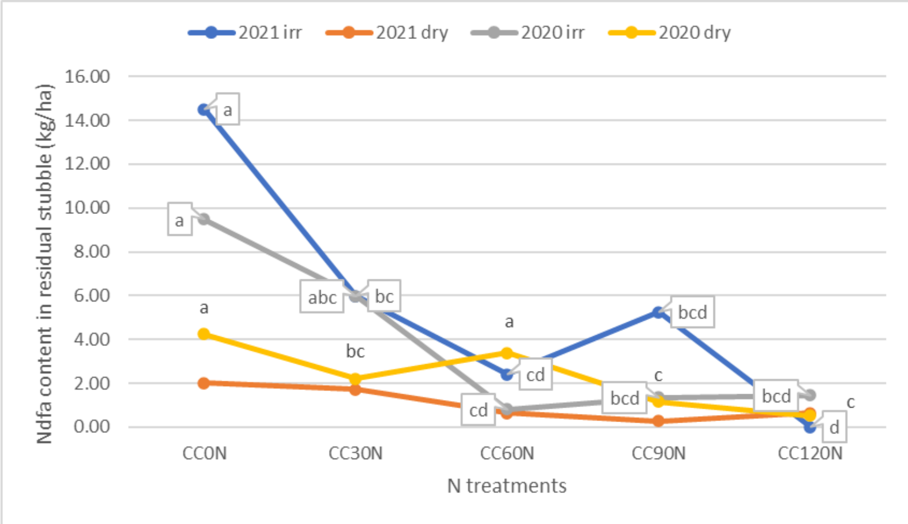


Figure 7. Mean values for the amount of Ndfa remaining in residual stubble after the crop has been harvested. These calculations have been made across the five main N rates in each of the four trials. Means with the same letter are not significantly different at the P=0.05 level. Means without letters have no relative significant differences within the data set.

The amount of Ndfa being returned in stubble needs to be compared to the amount of soil nitrates that are being exported off the paddock in grain. Using the Ndfa% for TDM and applying this proportion to both grain and residual stubble, a calculation can be made on whether the crop is a net contributor or a net consumer of the original pool of soil nitrate that was present at the start of the crop. In all four trials across the two seasons, the calculated data shows that the mungbean crop was a net exporter of soil nitrates (Figure 8). The net amount exported depends on the amount of soil nitrates present at the time of planting and this follows a general linear trend (Figure 8 linear regression not shown). This data shows a range of between 20 – 60 kg nitrates/ha is exported from the soil profile, although the 2021 irrigated trial shows this removal rate can be as high as 130 kg N/ha (Figure 8).

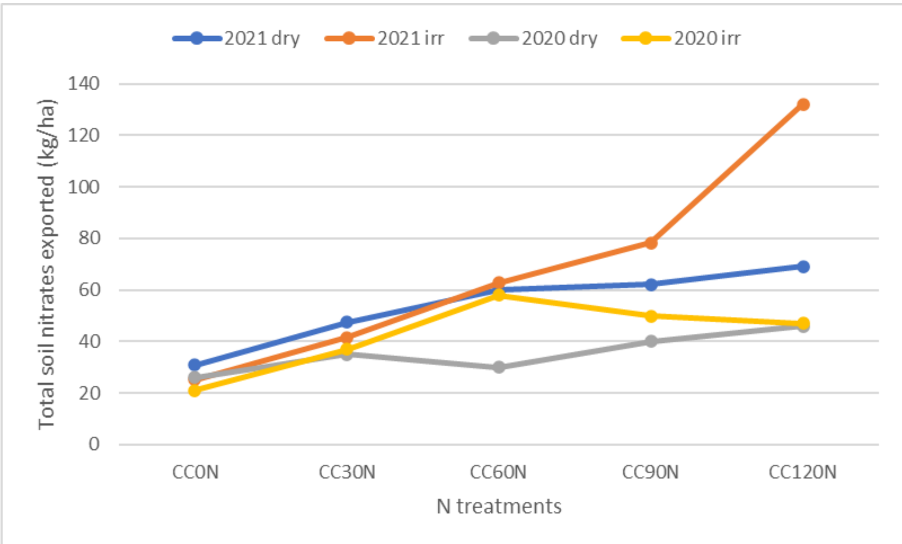


Figure 8. Mean values for the amount of soil nitrates that are exported from the field in grain. These calculations have been made across the five main N rates in each of the four trials. Statistical analysis has not been done on these calculations.

The amount of nitrate in the profile at planting impacts the amount of N exported from the field. The 2021 trials included two long fallow scenarios where plots were left fallow for 15 months prior to planting (wheat 2019 to mungbean 2021). One of these fallow treatments had 60 kg N/ha added eight months prior to planting. The nitrates measured at planting from these two fallow scenarios (Table 2) shows a considerable increase in soil nitrate levels compared to the CC0N and CC60N treatments that had a much shorter fallow (3 months).

The nitrate level in the long fallow 0N treatment was equivalent to the CC60N treatment (60 kg N/ha applied in a short fallow, not shown) and the nitrate levels for the long fallow treatment with 60 kg N/ha applied in June 2020 was equivalent to the CC120N treatment (120 kg N/ha in a short fallow, not shown). These two long fallow scenarios are not uncommon in our current farming systems so the amount of nitrates that are exported off the paddock (Table 2) by mungbeans in these treatments has some commercial validity.

Consistent with the data presented already in relation to N application rates, the long fallow treatments exported similar amounts of soil N off the paddock as those short fallow treatments that had equivalent starting soil nitrates at planting (Table 2, CC60N and CC120N).

The total amount of soil nitrates exported off the paddock by a mungbean crop is worth considering when trying to mange the N supply for the farming system as whole. It could also be critical to understand what layers of the profile where most of those nitrates have been extracted from. Soil testing after harvest of these trials shows data on where the distribution of N is in the profile after a mungbean crop is harvested. The 2021 soil profile data (Figure 9) shows a distinctive trend across a selection of N treatments in both the irrigated and dryland trials. These soil tests are showing that the 0-10cm, 10-30cm and the 30-60cm layers have less than 5 kg of nitrate /ha in both the irrigated and dryland trials. This is compared to the 11 – 16 kg of nitrate/ha that existed at planting (Figure 1) plus the 30 – 60 kg N/ha that was applied in those respective treatments (CC30N, CC60N). This distribution reflects where the mungbean root system is most active in relation to nutrient uptake and this could be strongly related to water access. This could indicate that the more nitrate contained in the top 60cm of the soil profile, the less requirement it has for fixation.

Table 2. Comparison of mean profile nitrates recorded at planting of selected short fallow and long fallow treatments in the 2021 trial. Calculated figures for the amount of soil nitrate exported from these treatments.

Treatment category	**Year**	**Nitrates at planting (kg/ha)**	**Nitrates exported (kg/ha)**	
			Dryland	**Irrigated**
Short fallow 0N	2020	110	26	21
Short fallow 0N	2021	77	31	25
Long fallow 0N	2021	134	67	85
Long fallow 60N	2021	196	75	90

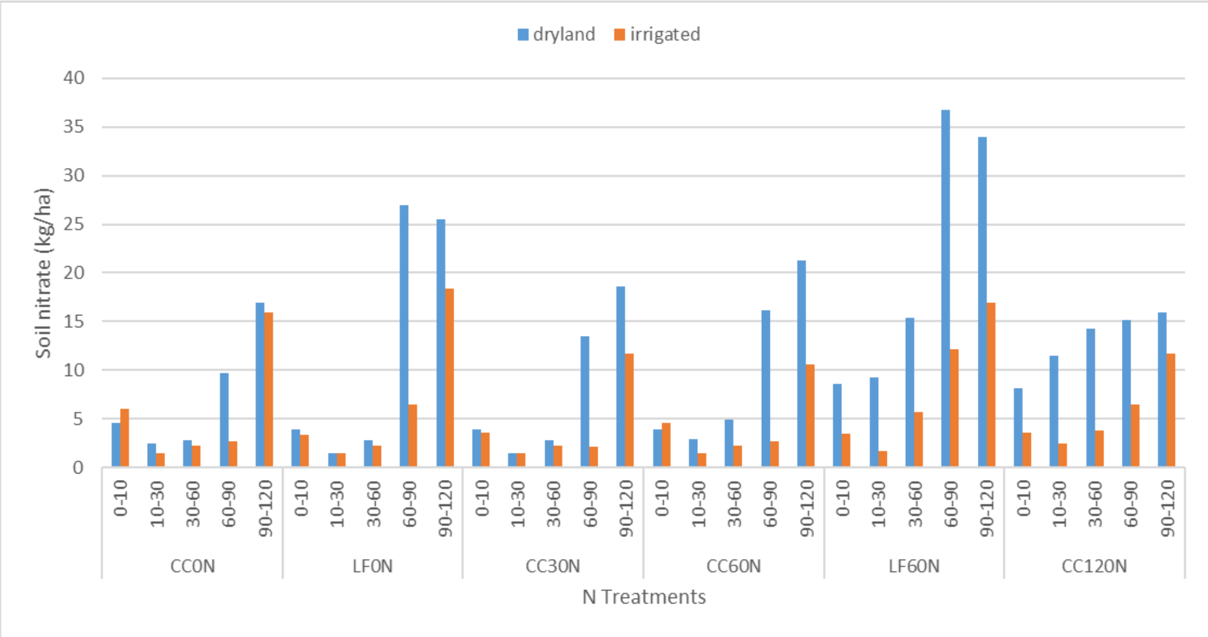


Figure 9. Distribution of mean nitrates across tested layers of the profile within selected N treatments in the 2021 trial site.

The irrigated treatments show much lower nitrate levels remaining after harvest in the 60-90cm layer than in the dryland trial indicating that the irrigation trials were more efficient at taking up nutrient from this layer. The ability of a mungbean crop to extract more water from deeper layers (potentially more nutrients) when supplementary irrigation is used is a characteristic that has been noted in previous time of sowing trials in Central Queensland. There is no clear explanation for this observation.

The soil profile data also shows that as the nitrate supply is increased (LF60N and CC120N), the proportion of soil nitrate remaining in the soil after harvest increases, particularly in the dryland trial. This could mean the higher level of N supply is surplus to the crops requirements and its yield is being restricted by other limitations such as soil water supply or weather factors.

Summary

It is clear from the data presented that pre-applying nitrogen to mungbean crops will not promote better yields unless soil profile levels are very low which may occur in a back-to-back double cropping scenario (not tested in this project) but not under normal broadacre conditions where a six-month fallow is common between crops.

It is also clear from the data that the rate of N fixation from the atmosphere is considerably influenced by the level of soil nitrates in the profile and particularly in the top 60cm of the profile. The Ndfa % can vary depending on natural mineralisation rates, with the 0N treatments across the four trials ranging from 20% to 55%, with higher Ndfa% occurring in the higher yielding crops.

The proportion of N that is exported off the paddock in grain can range from 60 – 90 % of total plant uptake. This means the ability of the mungbeans to contribute Ndfa to the soil profile is compromised and in most cases is reducing the level of soil nitrate in the system that will be available for the next crop. These field trials have shown that mineralisation rates prior to planting and changes in N harvest index are critical components that impact on the amount of fixed N which is returned in stubble.

The specific factors governing changes in the N harvest index are not clear from this work, however, on a broader scale there seems to be a seasonal influence. Natural mineralisation rates can also be quite variable from season to season which makes it hard to predict.

The main issue with mungbean being a net consumer of soil nitrates, is that it puts greater pressure on the organic matter fraction of the soil to continue to mineralise nitrates, if non-organic fertiliser is not used to meet the deficit. While mungbeans do not respond directly to N fertiliser rates, they can be a net consumer of the soil nitrate pool which in-turn can affect the long term N fertility status of the farming system. Growers will need to compensate N fertiliser rates for the following crop to cover for the potential N deficit created by the mungbean crop.

Acknowledgments

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The author would also like to recognise the considerable technical officer support provided by Peter Agius and Penny Borger in the management and field data collection that was required for these trials.

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Managing phytophthora in chickpeas – soil type and seed treatment effects on yield

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Key words

Phytophthora root rot, metalaxyl, seed treatment, yield loss prediction.

GRDC codes

DAN00213, BLG215: Implementation of PRR management via improved variety resistance

Take home message

- To reduce the risk of phytophthora root rot (PRR) losses in chickpeas, pre-planting preparations are the key as there are currently no methods of in-crop control
- Pre-planting preparations include:
  - Paddock risk assessments based on susceptible crop and weed history, topography, soil type, PRR inoculum measurement, and floodwater history
  - Variety choice based on chickpea PRR resistance rating
  - Use of seed treatment – metalaxyl only provides up to 8 weeks protection
- In-crop PRR yield losses can be estimated using an online spreadsheet tool, the estimated level of loss can be used determine crop economic viability.

Phytophthora root rot in chickpeas

Causal species

Phytophthora root rot (PRR) of chickpea is caused by *Phytophthora medicaginis*. The description of the species causing PRR of chickpeas has undergone a number of name changes. Briefly, in 1931 the species *Phytophthora megasperma* was described, but due to the wide host range that this species covered it was later reclassified using a forma specialis structure. For example, in the 1980's the identity *Phytophthora megasperma* f. sp. *medicaginis* described the species pathogenic to chickpeas and lucerne. Finally, in 1991 the forma specialis structure was abandoned and from isolates pathogenic to legumes within the original *Phytophthora megasperma* identity, three species (*P. medicaginis*, *P. sojae* and *P. trifolii*) were identified as separate species with other isolates demonstrating a broad host range remaining as *Phytophthora megasperma.*

In 2020 through the development of improved molecular based diagnostic tests another Phytophthora species was also detected in chickpea root and paddock soil samples. The test detects a group of five phytophthora species in the *Phytophthora megasperma* clade. Tests of soil from chickpea crops showed that this second Phytophthora species is widespread from northern NSW through to southern Queensland. To date results indicate that this pathogen is only weakly pathogenic to chickpea causing a yellowing of the root system. However, its ability to cause a disease complex by co-infection with *P. medicaginis* requires further investigation.

Biology

The first description of PRR of chickpea in Australia was recorded near Toowoomba, Queensland in 1979. Phytophthora root rot of is a soil- and water-borne disease with inoculum surviving between host crops as oospores and chlamydospores. If a susceptible host is present and conditions are conducive, oospores germinate to produce mycelium and zoospores. In saturated soils the pathogen can rapidly multiply and release large numbers of zoospores. The movement of zoospores can occur through the capillary action of water between soil pores and they can swim short distances. Zoospores and mycelium often infect host roots resulting in multiple infection points that can cause severe disease. When frequent late winter and spring rain occurs, the pathogen can multiply quickly on chickpea roots and by the time foliage symptoms are visible, the population on the roots will have already peaked. Infection can occur at any growth stage and the pathogen only infects living plant cells.

Oospores can survive in the soil for at least 5 years. An inoculum survey of chickpea paddocks in northern NSW and southern Queensland in 2013 and 2014 indicated that the pathogen is widespread, with 33% of chickpea paddocks in this region testing positive for the pathogen (Bithell el al. unpublished results).

Symptoms and ideal climatic conditions

Symptoms of PRR of chickpea include: wilting; yellowing (chlorosis) and drying of the foliage; decay of the lateral roots and lower portion of the tap root; dark brown to black tap root lesions, in some cases extending to ground level; and plant death. Symptoms can occur a week or more after a heavy rain event. Taproot lesions may completely encircle the tap root and just above ground level the infected stem tissue shrinks, a distinctive symptom described as girdling or as a canker.

Symptoms are often first observed in low lying (e.g., upper sides of contour banks) or compacted areas of paddocks where water pools after heavy rainfall and soil moisture content is high. The amount of rainfall over the rest of the season will determine the level of inoculum spread in surface water from the infected to uninfected areas. Root-to-root spread of the disease can also occur between neighbouring plants.

The presence of above ground symptoms of PRR can be delayed, but if plants with PRR infected roots become stressed, foliage symptoms can rapidly appear. A change in climatic conditions from mild, to hot and dry can also lead to foliage symptoms appearing quickly, as damaged, infected roots cannot provide sufficient water to the plant when evaporative demand is high.

Substantial yield losses (up to 70%) can occur for chickpea varieties with the highest PRR resistance ratings when conditions are highly favourable to disease development (high inoculum loads, poorly drained soils and high rainfall). Yield loss in chickpea is greatest in seasons with above average rainfall, however only a single saturating rainfall is needed for infection.

Which crops or weeds are hosts of PRR inoculum?

Phytophthora medicaginis can infect and multiply on a large number of legume hosts, especially pasture legumes, such as medics and lucerne. Testing of medicago, lotus, sulla, sesbania and some Vicia species, such as woolly pod vetch has shown they are all PRR disease hosts and will increase phytophthora inoculum in a paddock. Medic species, such as burr medic, snail medic and barrel medic are common weeds to cropping areas. If these weeds and/or volunteer chickpea plants are present in break crops or in fallows, PRR inoculum could rapidly multiply, increasing the risk of PRR to following chickpea crops.

Testing of other pulse crops including faba bean, albus and narrow leaf lupin and mungbean showed they were not effective hosts of PRR. Lentils were shown to be highly susceptible to PRR.

Paddock risk assessment

Paddock history

Any paddocks where chickpeas have shown PRR symptoms in the previous 5 years would be considered a high risk of developing the disease in a conducive season (Table 1). Paddocks that have not grown chickpeas or other PRR susceptible crops or pasture legumes would be considered low risk.

Even though a paddock may have never had a PRR susceptible crop such as lucerne or chickpea grown in it, chickpea crops have been lost to PRR due to medics hosting the pathogen. A paddock history PRR risk assessment should include presence of PRR host plant populations. Paddocks with a recent (within the last 5 years) pasture history are high risk.

Table 1. Paddock risk identification summary

Low risk paddock	• PRR disease symptoms have not been observed in previous chickpea crops • Soil samples taken in chickpea crops are PRR negative in PreDicta® B test. • No PRR susceptible hosts present in break crops • No recent floodwater over the paddock.
High risk paddocks	• PRR symptoms have been observed in previous chickpea crops • Soil samples taken in any prior season are PRR positive in PreDicta® B test. • PRR susceptible non-crop hosts such as medics present in recent years • Floodwater over the paddock from a neighbouring infected paddock or regions where PRR is present.

Topography and soil type

The topography or paddock aspect, along with soil type influences the risk of PRR. Paddocks with heavy clay soils (vertosols) with low lying areas, are poorly draining, prone to waterlogging and/or surface flooding would be considered high risk if inoculum is present and conditions favour PRR. High risk areas include the high side of contour banks, compacted soil or soil with shallow hardpans.

Paddocks with free draining soils are at a lower risk of severe PRR as the pathogen requires soil saturation to multiply and for the infection to spread.

Under very wet conditions entire paddocks can be affected. Floodwaters can carry and deposit PRR inoculum in silt and crop debris from infected paddocks to previously clean paddocks, changing the PRR risk level of that paddock.

Inoculum measurement

The PreDicta® B test can measure PRR inoculum levels in the soil only in some circumstances due to difficulty in effective sampling and results requiring careful interpretation.

Survey results have shown that the most reliable time to detect PRR is in the chickpea crop, rather than in the crop following chickpea. In-crop experiments and surveys showed that even at chickpea harvest, the PRR populations were lower than 3 months earlier when PRR foliage symptoms were evident. This is because most of the inoculum produced by the infected plants breaks down quickly leaving only low concentrations of widely and unevenly dispersed oospores. This dispersed PRR inoculum is difficult to sample and detect reliably. An experiment comparing phytophthora presence at chickpea harvest compared with post-harvest, showed that PRR detection was unreliable within 4 months of harvest (Bithell el al. unpublished results).

The implications of PRR inoculum decay and a dispersed distribution for PRR disease risk predication can be summarised as:

1. A positive detection in soil samples collected from a chickpea crop means that PRR is present and in future seasons, if conditions are conducive, then chickpeas in this paddock will have a high risk of developing PRR
2. If the test is based on break crop paddock samples, results need to be interpreted with some caution as reliable detection of PRR in break crops is difficult, as outlined above. For test results from break crops, a nil detection of *PRR* does not mean the risk is low. Detecting any level of PRR in samples from a paddock makes it high risk of developing PRR if conditions are conducive.

Variety selection and metalaxyl seed dressing

Once growers have selected their paddocks based on the PRR risk, varietal choice should be considered. Following changes in chickpea PRR variety rating methods to yield loss responses, there are currently only two levels of varietal PRR resistance ratings, susceptible (S) and very susceptible (VS).

The two main chickpea diseases in NSW and Queensland are ascochyta blight (AB) and PRR. The recently released CBA Captain⏀ has a moderately susceptible (MS) rating to AB and susceptible (S) rating to PRR, currently the highest level of resistance available for AB and PRR. Both PBA HatTrick⏀ and PBA Seamer⏀ have an S rating for PRR, and S and MS-S rating to AB, respectively.

In high-risk paddocks, do not plant VS or S-VS varieties, such as Kyabra⏀, PBA Boundary⏀ or PBA Drummond⏀. Unfortunately, all kabuli varieties are very susceptible to PRR.

Metalaxyl seed dressing, which is registered for *Phytophthora megasperma* not *Phytophthora medicaginis,* can be applied after the application of other seed dressings such as thiram. All seed dressings need to be applied before rhizobia inoculation. Metalaxyl provides protection for approximately 6 to 8 weeks after sowing.

In 2021, four experiments at different sites evaluated metalaxyl seed treatment's ability to reduce PRR yield loss of chickpea. At three sites with low-moderate PRR disease pressure, the minimum reduction in yield loss of a metalaxyl seed treatment was ~ 1 t/ha of grain (Table 2). The importance of soil type to the potential for PRR losses was also demonstrated by the largest losses occurring on the heaviest soil types.

The Piallamore experiment, the fourth site, was not flat and following heavy rains in September and October, water ran diagonally through approximately 50% of the plot areas. The floodwater carried *P. medicaginis* inoculum from PRR inoculated plots to other plots. Large areas of control plots had plants die from PRR and areas of Phytophthora and metalaxyl treated plots that received the runoff water also quickly developed severe PRR disease. The metalaxyl seed treatment did not provide protection against yield loss from PRR, results are not presented as analysis was not possible due to flooding effects and inoculum movement between treatments (data not shown).

Table 2. Grain yield (t/ha) at three 2021 experimental sites of PRR inoculum applied (+PRR) or no PRR inoculum applied (-PRR), and metalaxyl seed treatment (+MET) or no metalaxyl (-MET). Yield is the average of three varieties (CBA Captain⊕, Kyabra⊕ and PBA Seamer⊕) and an advanced breeding line CICA1328. LSD and *P* values presented, * = *P*<0.05. In crop rainfall ranged from 360 to 350 mm.

Site	Trangie: grey vertosol		Trangie: red chromosol		ACRI, Narrabri brown vertosol	
PRR/MET treatment.	-PRR	+ PRR	-PRR	+ PRR	-PRR	+ PRR
- MET	4.03	1.33	3.60	2.68	2.37	1.38
+ MET	3.85	2.84	3.58	3.66	2.26	2.29
LSD	0.542*		0.195*		0.394*	
LSD[1]	0.396*		0.141*		0.279*	

[1]LSD for same level of phytophthora, ie. only -PRR or only +PRR comparisons

These findings indicated that if severe PRR disease does not occur following the period of protection early season protection provided by metalaxyl seed treatment can protect yield. If there are prolonged wet periods after the six to eight week period of protection then metalaxyl seed treatments cannot be expected to reduce PRR yield losses.

PRR yield loss estimate tool

A spreadsheet yield loss tool has been developed to estimate the potential yield losses of chickpea varieties with different levels of resistance to PRR grown on different soil types. The tool will be available for use online through the NSW DPI website.

Six assumptions were made to exclude non-PRR factors when predicting chickpea yield:

1. plant establishment
2. seed quality
3. other pest and disease issues
4. timing of primary PRR infection
5. sowing dates, and
6. effects of other yield constraining biotic constraints.

The user is required to input background agronomic data including target chickpea yield, plant density, monthly rainfall to date, paddock size, and area of confirmed symptomatic PRR affected plants. Two PRR yield loss tool spreadsheets were provided: one for a black vertosol and one for a grey vertosol.

The spreadsheet tool requires the selection of the appropriate spreadsheet based on soil type, confirmation of PRR symptoms and the availability of the agronomic data for the paddock in question. In the first section of the tool, the proportional yield loss for PBA Seamer⊕ (with the assumption made that the performance of PBA Seamer is able to be extrapolated to varieties with the same resistance rating, such as CBA Captain⊕ and PBA HatTrick⊕) could be predicted by inputting the estimated rainfall to harvest, the area of the paddock affected by PRR and the expected yield of the non-diseased area in the same paddock. Proportional yield loss estimates were calculated from the yield loss relationships estimated for PRR inoculated chickpea, under combined rainfall and irrigation, that were developed from experiments in 2018 and 2019 at the Hermitage Research Station, Qld. For each yield estimate an upper and lower range of the predicted yield value was calculated based on an approximate 95% confidence interval.

In the second section of the tool, crop input management costs and a nominated grain price could be submitted to provide estimates of the value of grain from the PRR affected area, relative to the non-affected area of the paddock. Using estimated input costs up to harvest, the value of grain from the PRR affected area minus input costs was also calculated.

To evaluate how representative the yield loss estimates from the 2018 and 2019 Hermitage experiments were, proportional yield loss results due to PRR were compared to those from the 2021 Trangie grey vertosol experiment. Estimation of the level of proportional yield loss due to PRR was selected rather than absolute yields, as the absolute yield of a variety will be expected to differ among sites due to environmental and management effects.

Comparison of PRR affected yields in terms of proportional yield loss (yield loss of Phytophthora inoculated treatment relative to non-Phytophthora inoculated treatment) indicated that PRR proportional yield loss across the three experiments differed for CICA1328 (Fig. 1). But for PBA Seamer⦶ proportional yield losses between the Hermitage 2019 and Trangie 2021 experiments were relatively similar at approximately 55 to 60%. Although there were only a small number of data sets to compare, results for proportional yield loss predictions for PBA Seamer⦶ showed some promise at estimating the range of proportional PRR yield loss with the tool.

The second section of the yield loss tool, by use of forecasted crop input management costs and a nominated grain price, could provide estimates of the value of grain from the PRR affected area, relative to the non-affected area of the paddock. The PRR data sets that the tool was based on had a lowest observed PRR affected yield of approximately 1.25 t/ha; at this production level estimated income from PRR affected yields were higher than the forecasted yield losses.

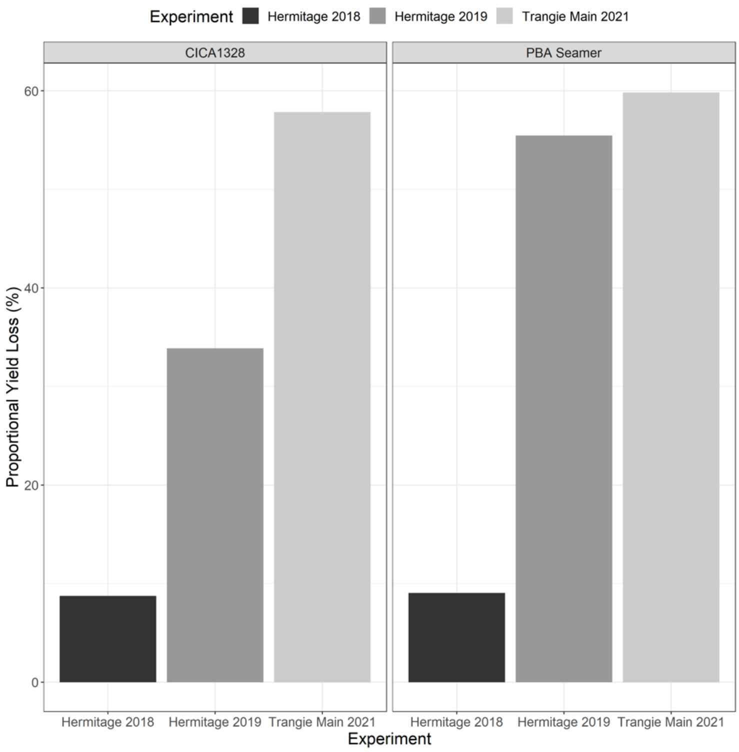

Figure 1. Plots of the proportional (%) grain yield loss for *Phytophthora medicaginis* inoculated CICA1328 (left panel) and PBA Seamer⦶ (right panel) from experiments conducted at the Hermitage Research Station in 2018 on a grey vertosol, Hermitage Research Station in 2019 on a black vertosol and at Trangie Research Station in 2021 on grey/black vertosol.

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Desiccating mungbeans - is windrowing an alternative?

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GRDC code

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Take home message

- Windrowing mungbeans is a viable alternative to chemical desiccation with no serious yield impact, less overall harvest losses and improved grain quality
- Windrowing may be an option in the following situations: multiple flushes of pods, hard to kill vigorous plants, pending wet weather, heavy powdery mildew infestation, accessing markets with low glyphosate maximum reside levels and growing for seed &/or sprouting
- Windrowing is not an option in the following situations: uneven ground, predicted very large amounts of rainfall, no windrowing machinery and very wet soil.

Background

Currently Australian mungbeans are chemically desiccated prior to harvest to aid in dry down of the crop to facilitate mechanical harvest. It is estimated that 90 - 95% of the crop is desiccated with glyphosate. Glyphosate is recommended to be applied when pods are black or brown (label instructions vary). Timing of desiccation is critical to ensure maximum dry down whilst minimising chemical residue in the seed. With the improvement in mungbean varieties resulting in more vigorous plants, desiccation has become increasingly problematic. Often growers struggle harvesting mungbean crops due to the moisture remaining in the stem after desiccation causing problems. Stem sap can cause seed coat staining which results in downgrading grain quality. As a result, growers have resorted to increasing rates of herbicides.

The mungbean industry must be ready to adapt if needed to meet market specifications as export markets becoming increasingly sensitive to pesticide maximum residue limits (MRL's). To further complicate this, international markets are amending their MRL's in very short time frames – often too slow for the industry to respond. Residues of glyphosate in mungbeans are already affecting the acceptance of Australian mungbean in some export markets. With over 90% of Australian mungbeans exported, options for alternative harvest practices that do not use crop protection products was deemed as a priority by the national industry body, the Australian Mungbean Association (AMA), in their current strategic plan.

The Mungbean Agronomy Project supported by the Queensland Government Department of Agriculture and Fisheries, the Grains Research and Development Corporation and the Australian Mungbean Association undertook research assessing the potential of mechanical desiccation of mungbeans, also known as swathing/windrowing, as an alternative to chemical desiccation. A series of commercial scale trials were implemented in 2022 which built on small plot trials conducted in 2021. Windrowing is the mechanical process of swathing or cutting the crop to form the mungbeans into a windrow which is placed onto the ground. Several days later the windrow is harvested by a header with a specialised pick-up front designed to harvest the crop off the ground. The 2021 trials successfully showed that mechanical desiccation of mungbeans was a viable method. This paper explores the results from the 2022 commercial scale trials.

Methods

15 trials were implemented, however only 12 had complete data sets due to rain. More trials were planned, however unseasonably high rainfall limited the final number. These trials were situated across southern Queensland and northern New South Wales.

Two treatments were used throughout this trial: windrowing (Figure 1) and glyphosate (Figure 2) desiccation.

Figure 1. Windrowed mungbeans

Figure 2. Chemically desiccated mungbeans

The trials established on each growers' property were unique for every paddock to best cater for the grower's unique machinery configuration (control traffic systems) (Table 1). As a result, each trial varied in size and sample amounts, however where possible several samples were taken for each treatment to account for as much variability as possible. Treatments were assessed via a range of parameters including grain yield, plant moisture at desiccation and harvest, and grain losses.

Grain losses were measured at various stages, using a variety of techniques, at the implementation of the treatments.

- Pre-harvest losses – Measured from the point of desiccation to just prior to harvest in the glyphosate desiccated crops only. Hessian bags were placed around the base of the mungbeans prior to chemical desiccation which captured falling seed until harvest. This measurement was assessing shattering losses during dry down.
- Swathing losses – Measured at the time of swathing (cutting). This was done using 50 x 50 cm quadrat randomly placed in the swathed area with mungbean seeds collected and weighed. This measured the losses resulting from the swathing of the crop such as shattering at the comb.
- Header losses – Measured at the time of harvest using a harvest loss system known as a Bushels Plus (Primary Sales Australia). The tray was attached to the header on the rear axle and triggered during harvest of both windrow and glyphosate treatments. This assessed loss out of the rear of the header.
- Comb losses –Measured at the time of harvest for glyphosate only treatment using hessian bags placed in the paddock. The header harvested directly over these and the seed which was on the bags after harvest was collected and weighed. This measurement assessed losses such as shattering at the reel.
- Total losses – Measured after harvest using 50 x 50 cm quadrat which was placed directly where the windrow was harvested and in a similar position in the paddock for glyphosate desiccation. This measure assessed overall losses for both treatments throughout the whole period of the crop through to after harvest. This was an independent measure.

Note: losses were extremely variable across the paddock hence were very difficult to measure accurately hence the data presented is only indicative.

Grain quality and glyphosate residue level in the seed (MRL) were also assessed.

Results

The results show that mungbeans via windrowing is a viable method (Table 1).

Table 1. Summary of results from 12 growers which had complete datasets for the respective treatments.

	Glyphosate			**Windrow**		
	Minimum	Maximum	**Average**	Minimum	Maximum	**Average**
Days to harvest from desiccation	8	16	**11**	5	16	**9**
Plant moisture at harvest (%)	19	47	**31**	13	27	**19**
Pre-harvest losses (kg/ha)	7	52	**22**	-	-	**-**
Swathing losses (kg/ha)	-	-	**-**	1	212	**58**
Yield (t/ha @12% moisture)	1.00	4.2	**2.13**	1.2	4.1	**1.95**
Header losses (kg/ha)	1	28	**10**	6	67	**18**
Comb losses (kg/ha)	15	161	**100**	-	-	**-**
Total losses (kg/ha)*	74	328	**153**	14	192	**67**

*Measured as an independent variable

Yield

On average, windrowed mungbeans showed a small yield penalty compared to glyphosate desiccated mungbeans (1.95 t/ha versus 2.13 t/ha) (Table 1), but this relationship was not consistent across all trials. Some crops achieved higher yields when windrowed, indicating the viability of the management practice when correctly implemented. The crop yields across these trials varied widely; from 1 to 4 t/ha. Although the lowest crop yield was 1 t/ha, it still had a relatively high biomass.

Days to harvest from desiccation

When directly comparing windrow and glyphosate desiccation across 12 grower sites with complete data sets, windrowing mungbeans had the benefit of a shorter period to harvest by at least three days (Table 1). Due to trial and harvest logistics, harvesting of the windrow didn't occur at the optimal time in several cases. The majority of the windrows could have been harvested within the 4–7-day window, potentially halving the time to harvest compared to glyphosate desiccation. The earlier harvest with windrowing was possible due to the rapid dry down of plant material; windrowed plant moisture was 19% at harvest compared to glyphosate which was 31% (Table 1). This was also a similar trend in the 2021 small plot trials at DAF Hermitage research station (data not shown). Three days post windrowing the plant moisture had almost halved and continued a rapid decline. It wasn't until 14 days after desiccation that glyphosate treatments reached a similar plant moisture level compared to windrowed treatments.

Grain losses

Grain losses were measured at various times across the process from desiccation to harvest (Figure 3 and 4). Total losses (measured as an independent variable) were lower in windrowed mungbeans compared to glyphosate desiccated mungbeans (Table 1). Average loss for windrowed treatments was 67 kg/ha compared to 153 kg/ha for glyphosate desiccated mungbeans. The highest loss of 328 kg/ha for glyphosate desiccation was a result of delayed desiccation due to rain.

Swathing (i.e. the process by which the mungbeans were cut and thrown into a windrow) losses for windrowed treatments measured the loss which occurred during the swathing process (Figure 4). Results showed a loss of 58 kg/ha on average and ranged from 1 to 212 kg/ha (Table 1). The swathing losses between sites varied due to weather conditions and swathing machinery. The trials with lower swathing losses were achieved by swathing when conditions were more conducive i.e., when the mungbean pods were still slightly soft in hand. When these conditions were met, swathing losses were below 30 kg/ha. The highest swathing loss of 212 kg/ha was recorded in a trial on a flood irrigated furrow system. The mungbean plants were leaning over into the furrow and the swather wasn't set up correctly (with crop lifters) to capture these pods which were below the machine's sickle bar. When removing this site from the results, the average swathing losses reduce to 43 kg/ha.

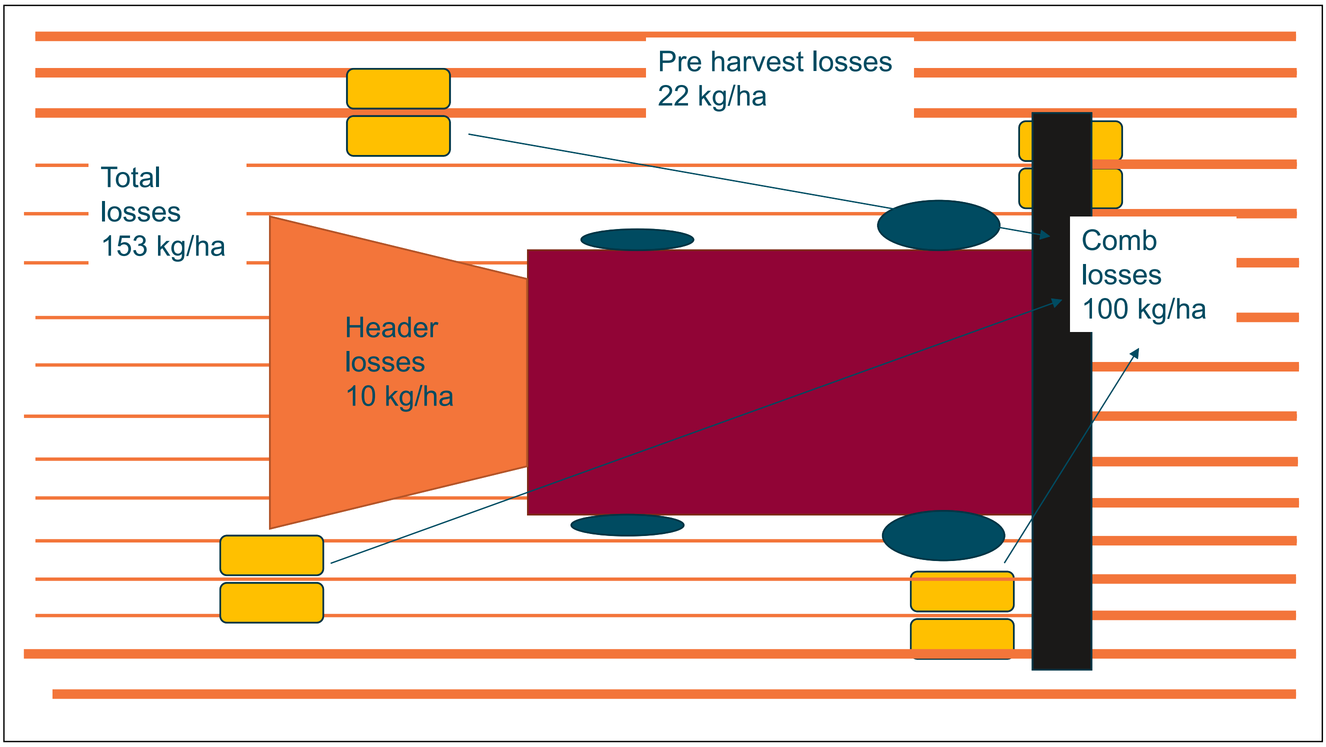

Figure 3. Diagram of harvest losses when harvesting glyphosate desiccated mungbeans

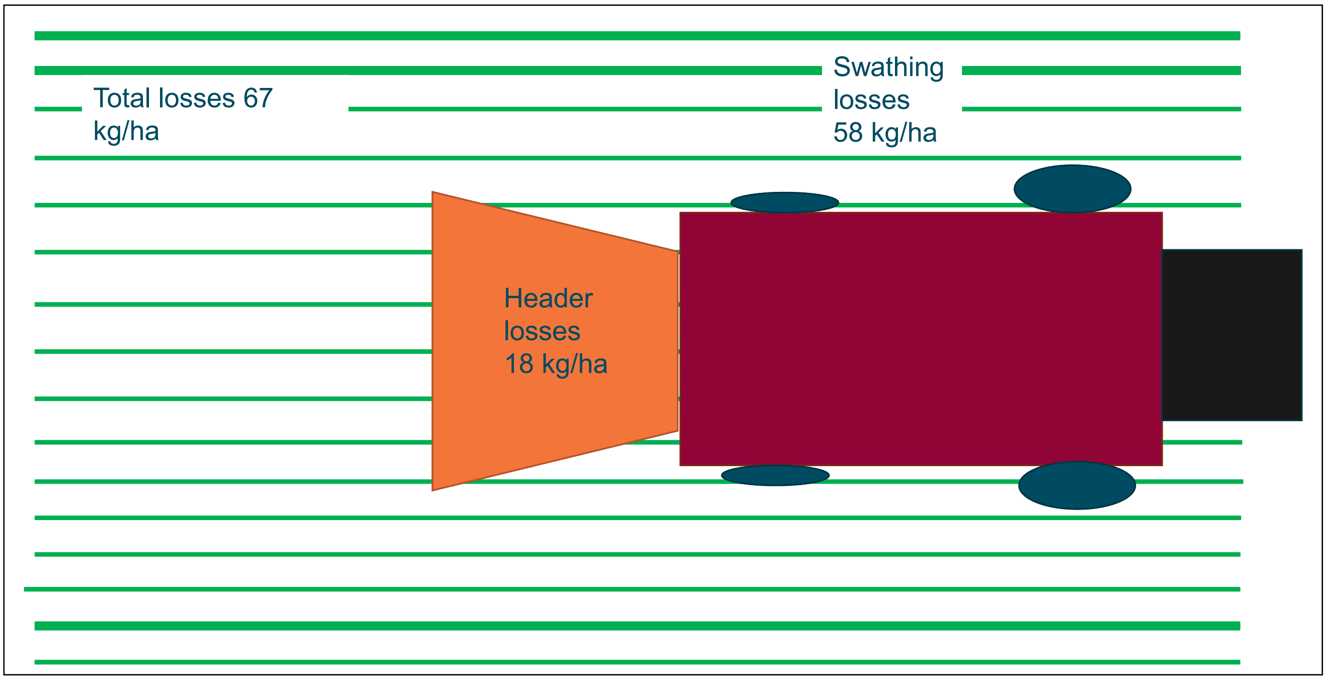

Figure 4. Diagram of harvest losses when harvesting windrowed mungbeans

Grain quality

Mungbean grain quality was variable, however, most trials were manufacturing grade and above(Figure 5, Table 2). Generally windrowed crops achieved higher quality levels (10 out of 15 higher and 2 out of 12 with the same). These trials showed that moderate falls of rain on the windrowed treatments, no more then 25- 50 mm, didn't have a serious impact on mungbean quality and harvestability. There was rain of approximately 15 mm in two crops (MungGrower001, 003) and in both cases the windrowed treatment had better quality mungbeans. However, extreme weather events of more than 100 mm, resulted in complete loss of the windrowed mungbeans and severe quality downgrades for both treatments (MungGrower002). In the case of MungGrower013, 014 and 015, windrowing enabled the crop to be harvested before rain due to faster dry down and no withholding periods resulting in a large increase in quality (Figure 5). Mungbeans deemed below manufacturing (BM) made this level due to large amounts of rain e.g., more than 100 mm post desiccation.

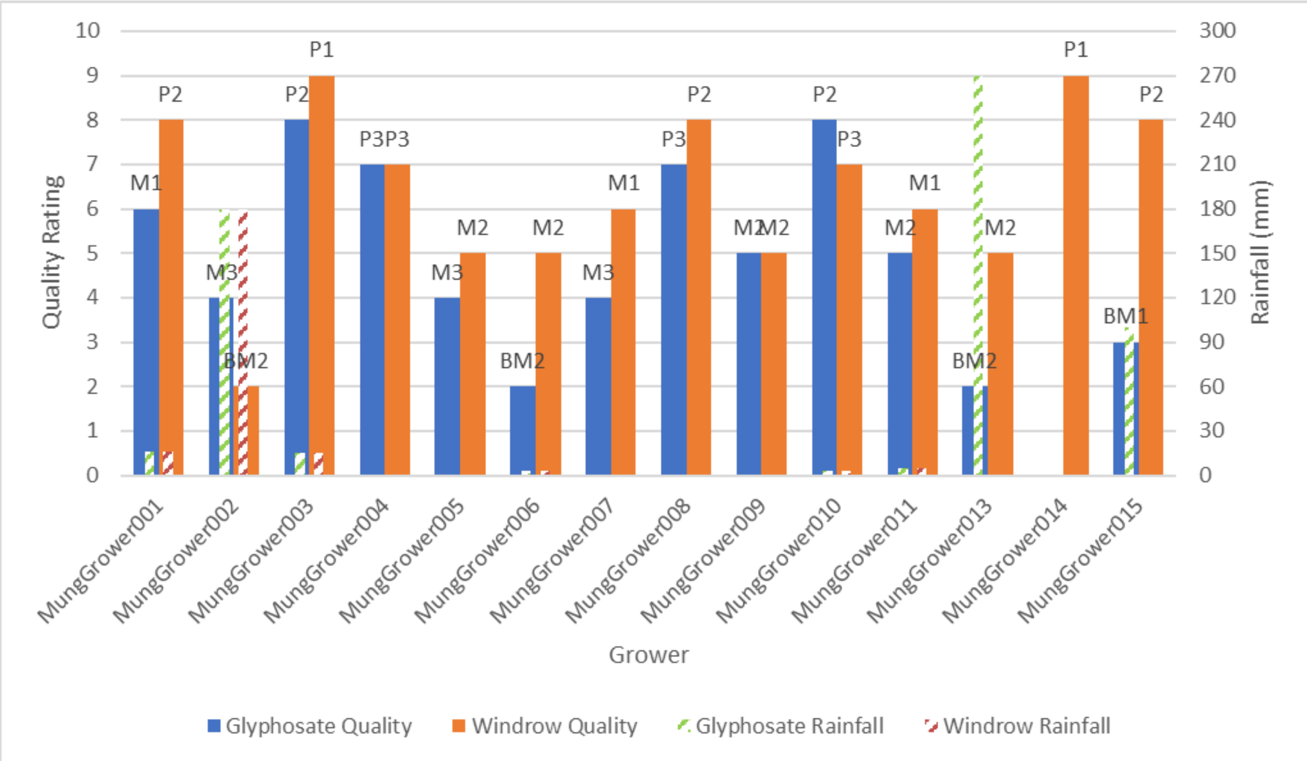

Figure 5. Quality rating for glyphosate and windrowed mungbeans. Dashed bars represent rainfall between desiccation and harvest. Letters and number on top of bar represent grain quality rating.

Table 2. Grain quality rating scale conversion table from commercial code to number code.

	Rating scale	No. rating scale
P=Processing	P1	9
	P2	8
	P3	7
M=Manufacturing	M1	6
	M2	5
	M3	4
BM = below manufacturing	BM1	3
	BM2	2
	BM3	1

Glyphosate desiccated treatments were tested for glyphosate residue in the harvested seed. All samples recorded glyphosate, however, all were under the Australian maximum reside level (MRL) of 10 mg/kg (Figure 6). Individual countries set their own MRLs. For example, Taiwan currently has the lowest MRL of 2 mg/kg. Only two crops recorded over this MRL (MungGrower008 and 013), 5 mg/kg and 2.7 mg/kg respectively. MungGrower008 most likely had a higher percentage of green and immature pods at the time of glyphosate desiccation resulting in translocation of this chemical into immature seeds.

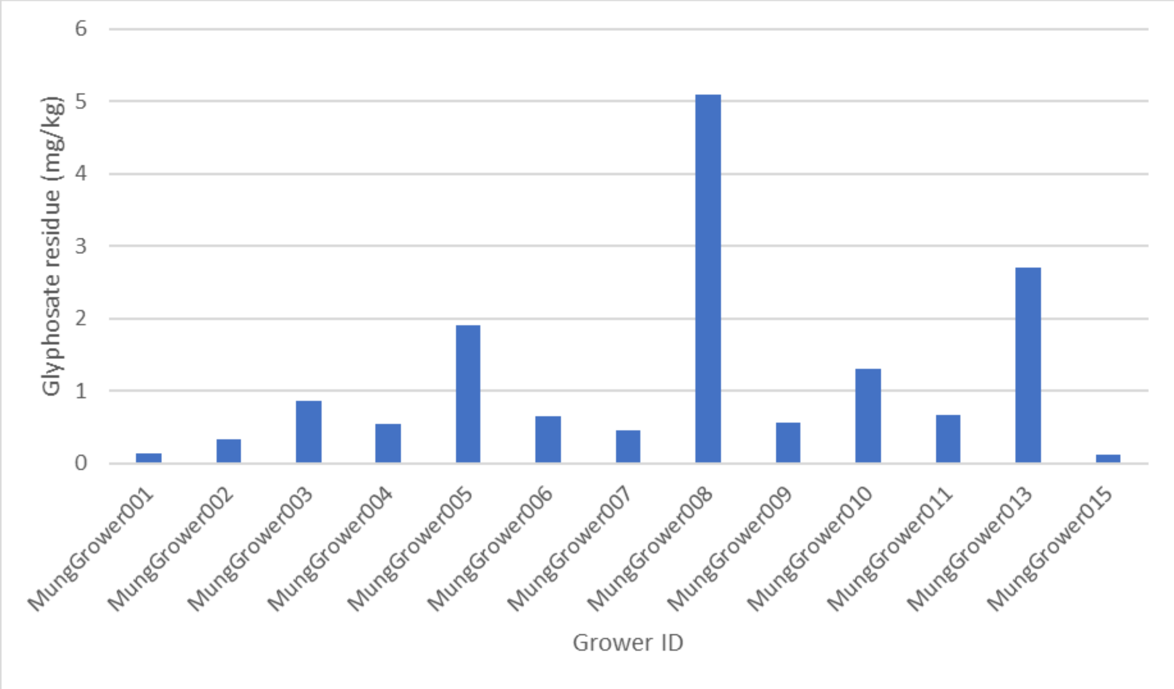

Figure 6. Mungbean grain desiccated with glyphosate residue levels (mg/kg)

Gross margins

Partial gross margins were calculated comparing the cost of implementation of the treatments (Table 3):

- Glyphosate 570 g/L (highest label rate of 1.7 L/ha)
- Windrowing
- Diquat 200 g/L (highest label rate of 3 L/ha)

These calculations indicate that windrowing mungbeans costs approximately $13/ha more than glyphosate desiccation, however, half the cost of a full label rate of diquat. Considering seed crops and crops for the sprouting market are recommended to be desiccated with diquat (as glyphosate reduces germination) – windrowing may be an option purely based on profitability.

Table 3. Cost estimates for mungbean desiccation

Treatment	Costs 2022
Glyphosate 1.7L/ha	$29.20
windrowing	$42.05
diquat 3L/ha	$83.40
2022 Assumptions: 12 m Swath, 7 km/hr Swathing speed, $14/L glyphosate, $26/L diquat, 36 m boomspray, 15 km/hr spraying speed, $1.8/L fuel.	

Further, an increase in quality of the mungbeans e.g. from manufacturing to processing would increase the price paid by marketers by $50 to $100/t. Considering these crops were on average over 2 t/ha this represents a large increase in gross margin, more than covering the extra cost of windrowing.

Conclusions

Growers can have the confidence to successfully harvest their mungbean crops by windrowing. Windrowing has two major benefits over glyphosate desiccation; faster dry down and no potential glyphosate residue. Other benefits of windrowing include potential for earlier desiccation and harvest, easier threshing, no sap staining, and better grain quality. The results of these on-farm commercial strip trials also showed that there are fewer overall losses from windrowed mungbeans, and yield is similar to glyphosate desiccated mungbeans.

However, windrowing mungbeans involves more costly operations with two slower passes (swather and header). The requirement for specialised machinery is a major limitation to windrowing. Swathers and pickup fronts are not common pieces of machinery in Queensland; hence this is the biggest barrier to adoption of mungbean windrowing in Queensland. In NSW, it is suspected that this would be less of a barrier due to more availability of this specialised machinery which is also used for canola harvesting.

Mungbean regrowth post windrowing could add to the cost as a post-harvest spray. However, depending on rainfall patterns, a post-harvest fallow spray is likely to be required regardless. Participating growers in these trials felt that they would rather spray regrowth post windrow harvest compared to desiccating mungbeans with glyphosate, as there was no risk of chemical translocation to the seed. Spraying regrowth mungbeans also gives far greater flexibility to use herbicides with various modes of action.

Timing of harvest operations and harvester set-up is critical to minimising harvest losses across both techniques. Timing windrowing is not as critical as it is for chemical desiccation as there is no risk of chemical translocation. It is recommended that windrowing occur when ~90% of the pods have reached physiological maturity. The mungbean crop needs to be cut earlier in the day when pods are 'doughy' in hand or crop isn't as mature. If the pod is crispy and shattering in hand i.e., late in the afternoon, this will result in high swathing losses.

Growers need to be aware of the rapid dry down of windrowed mungbeans and time pickup accordingly. This research was carried out in relatively mild conditions from April to June. If mungbeans were windrowed in hotter summer conditions, for example January and February (30ºC plus days), dry down could be as short as 2-3 days. Harvest losses may be reduced by picking-up early in the morning whilst there is still moisture on the crop. If the crop is too dry, harvest losses can be significant. In comparison there is a withholding period of seven days prior to harvest of glyphosate desiccated mungbeans.

Once the mungbean crop has been swathed and put into a windrow, it can tolerate small amounts of rain, of up to ~50mm. In contrast, large amounts of rain and very wet ground can result in mould and reductions in yield and quality. Growers also need to be aware of ground surface moisture which can result in the swather or pick-up front also harvesting smalls clumps of dirt. This will directly impact mungbean quality.

Spraying glyphosate earlier than recommended prior to physiological maturity, may result in translocation of the chemical to the seed. This translocation to immature seeds will result in detectable levels in these seeds which may have implications for marketing. Ensure you discuss with your marketer prior to desiccation. Minimise glyphosate seed residues by accurately assessing physiological maturity and not desiccating immature crops.

It is still uncertain how successful windrowing would be in low biomass crops, as this research was conducted on crops with high biomass.

Mechanical desiccation may be an option in situations when:

- Multiple flushes of pods
- Hard to kill vigorous plant
- Pending wet weather (i.e., in 7-14 days)
- Heavy powdery mildew infestation when glyphosate can't be taken up by the plants
- Accessing market with low glyphosate MRL e.g., Taiwan
- Desiccating crops for seed &/or sprouting market.

Mechanical desiccation is not an option in situations when:

- Uneven ground e.g., flood irrigated mungbeans with large furrows can result in very high losses. Set-up needs to be seriously considered to minimize losses
- Very large amounts of rainfall are predicted
- No machinery available
- Very wet soil as this will result in wheel tracks and compaction

Acknowledgements

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'Which won where': AMMI and GGE Biplot approach for genotype × environment interaction on yield stability of pigeonpea [*Cajanus cajan* (L.) Millsp.]

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Keywords

Pigeonpea, yield stability, GGE biplot, environment

Take home message

The presence of variety (genotype) (G) × environment (E) interaction (G × E) influences production decision making on issues such as time of sowing, location, and selection of varieties. Identifying appropriate varieties and their fit to a particular growing environment would minimise environmental stress and thereby maximise productivity.

Abstract

High yield potential and yield stability are the most desirable genetic characteristics for commercial pigeonpea genotypes. The growing environment greatly influences crop growth, leading to substantial variations in yield. Therefore, understanding genotype and its interaction with environment is critical in the development of genotypes with yield stability. Three pigeonpea genotypes were compared for grain yield in seven environments created by different sowing dates at the University of Queensland. Additive mean effects and multiplicative interaction (AMMI) and GGE biplot were used to analyse the genotype-by-environment interaction (G × E).

Grain yields varied widely across the time of sowing with a mean of 2.7 t / ha. Additive mean effects and multiplicative interaction (AMMI) and GGE biplot were used to analyse the genotype-by-environment interaction (G × E) and found highly significant environment (87 %) followed by genotype (11 %) and G × E effects (2 %) on grain yield. The genotype 'Quest' was the highest yielding followed by 'ICP 14425' and 'QPL 1001'. The analysis revealed that 'ICP 14425' consistently performed well in all the environments and was thus considered as the most stable genotype compared to 'Quest' and 'QPL 1001'. 'QPL 1001' performed moderately well in all the environments. However, 'Quest' performed better in the environments associated with sowing dates of 6/12/2017, 9/01/2018 and 20/12/2018 whereas the better sowing environments for 'ICP 14425' were sown on 16/02/2018, 10/10/2018 and 15/11/2018. The outcome of this study has implications for assessing the genotypic adaptation to subtropical environments where photoperiod exceeding 13 h and maximum temperatures reaching > 40°C between latitude 20°S - 30°S. The interaction between genotype, maturity class and growing environment are critical in optimising grain yield in pigeonpea.

Introduction

Pigeonpea is an important tropical legume widely grown in semi-arid regions of the Indian subcontinent, Africa, and Caribbean Islands. Total world production is 4.3 million tons from 5.3 million ha with an average productivity of 0.8 t/ha. India is the largest producer and consumer followed by Myanmar, Malawi, Kenya, and Uganda (Chand et al., 2014, Kyu, 2016, Tiwari, 2016). It is often intercropped with maize or grown in mixed cropping systems and it plays an important role in production and income for subsistence farmers (Hogh Jensen, 2007). A study conducted in Ghana indicated that pigeonpea-maize rotations increased maize yield by 75 - 200 % (Adjei-Nsiah, 2012). In another study where pigeonpea was grown in resource poor soils without inputs produced a reasonable grain yield of 2.5 t/ha (Snapp, 2003). Though, the yield potential of Cajanus cajan is high, it is generally not realized due to biotic and abiotic stresses. Changing environmental conditions along with genotypic characteristics and interaction between environment and variety, might cause large variability in crop yield.

Environments differ in their range of photoperiod and temperatures which can impact crop growth and reproductive development. Various climatic conditions because of global warming and subsequent climate change have considerable impact on rainfall pattern and hence on crop yield (Joshi, 2011). Pigeonpea is a native drought tolerant legume and well adopted to several environments in semi-arid tropics (Saxena, 2008). It is a deep-rooted crop and capable of extracting water from more than 150 cm depth. The capacity to extract soil water from depth is one strategy for mitigating the impacts of climatic uncertainty (Odeny, 2007). Rapid flowering in pigeonpea is triggered by shorter day lengths. Phenological development specially time of flowering can have significant effect on dry matter production and harvest index (Chauhan, 1998).

The major constraint to greater production has been that of low yields (Padi, 2003). However, recent studies have revealed a higher yield potential in Queensland, Australia (Rachaputi et al., 2018) and farmers perceive this as one of the summer legume option for Northern Queensland due to its financial and rotational benefits. The major challenge in pigeonpea development has been to develop stable high-yielding varieties with resistance to environmental stresses (Chauhan, 1998). Varietal interaction with growing environment, are critical in determining yield. Incorporating pigeonpea into Northern cropping systems could bring benefits including a new summer legume for the rotation with associated nitrogen fixation. Rhizobia associated with pigeonpea roots are capable of fixing 41 - 280 kg ha-1 of nitrogen (Tripathi et al., 2018., Udensi and Lkpeme, 2012).

The presence of genotype (G) × environment (E) interaction (GEI) influences decisions on issues such as time of sowing, location, and selection of varieties. Understanding and exploiting GEI is the key to increase the agricultural productivity and the basis for successful breeding to develop stable varieties for diverse environments.

The objectives this study are: (i) Understand G × E interaction effects (ii) Evaluate genotypic stability under different environments, (iii) Identify most prodcutive environments (iv) Analyse the role of environmental factors on G × E interaction effects.

Statistical analysis

Grain yield (t/ha) was the only measured variable in this research. Analysis of variance (ANOVA) was performed to assess the genotypic, environmental and GEI effects. With the presence of a significant GEI in the data, research outcomes were evaluated for adaptability and yield stability using AMMI and GGE Biplot models using 'R' statistical programming language version: 4.0.3.

Two important statistical technique, AMMI (Additive Main-Effects and Multiplicative Interaction) and GGE Biplot were effectively used by many researchers to evaluate GEI (Chauhan, 1998, Neisse et al., 2018, Santos et al., 2019, Simtowe, 2012, Yau, 1995). AMMI model uses analysis of variance and principal component analysis for better understandings of GEI, it causes and consequences (Neisse et al., 2018), whereas,GGE Biplot considers both additive main effetcs and multiplicative interaction effects. AMMI separates G from GEI and Biplots provides simple graphical analysis for better understanding. Both AMMI and Biplot depend on principal component analysis (PCA) since multi-dimensional data are difficult to represent using Biplots.

Material and methods

The experiments were conducted at the horticulture research farm of The University of Queensland Gatton Campus. Varieties were assigned to sub-plots in three replicates in a randomised manner. The plot size was 2.4 m (width) × 4 m (length) and consisted of eight rows spaced at 0.5 m. Plant to plant distance within a row was 15 cm.

The experiment was laid out as a split-plot design with eight dates of sowing, as the main plots and three varieties as subplots (Table.1). The sowing date of 3/11/2017 (affected by water logging) and 13/03/2018 (affected by frost) were excluded from analysis.

The research site had sorghum grown in the previous season. The research site was rotary hoed twice to a depth of 15 cm. Basal fertiliser 'Incitec Pivot Fertilisers®', 'CK-88' (N:P:K:S = 15.1:4:11.5:13.6) was applied 30 days before planting (200 kg/ha).

Table 1. Details of field experiments conducted in season 2017/18 and 2018/19 at the University of Queensland's Horticultural Research Farm at Gatton, Queensland.

Season	Sowing date	Genotypes
2017/2018	3/11/2017	Quest, QPL1001 & ICP 14425
	6/12/2017	
	9/01/2018	
	16/02/2018	
	13/03/2018	
2018/2019	10/10/2018	Quest, QPL1001 & ICP 14425
	15/11/2018	
	20/12/2018	

Plots were inoculated with 'Nodule-N®' immediately after sowing by adding inoculum + water suspension (10 g/5 L water). A drip irrigation system was set up using 'T' tapes (Rivulis®, 340 LPH/100 m at 0.55 BAR) and irrigated weekly in summer (Nov to March) and reduced to fortnightly from April to June. A pre-emergent herbicide (*Pendimethalin 440 EC*) was applied within 48 hours of sowing, followed by mechanical weeding as necessary. When 80 % of pods turned brown, plants from 2 m^2 were harvested at ground level and mature pods were separated and dried at 35 °C in a well-ventilated oven for seven days. Dried pods were threshed into seeds, and seed weight recorded.

Results and discussion

Environmental characterisation

Maximum and minimum air temperatures, photoperiod and in-crop rainfall varied due to different sowing dates. The monthly mean air temperature was consistently lower in season 2018/2019 as compared to 2017/2018. The highest pre-flowering mean maximum temperature was recorded in 20/12/2018 with 34.5 °C, whereas the post-flowering maximum temperature (33.3 °C (Table 2)) was highest for the 15/11/2018 sowing date. The in-crop rainfall varied between sowing dates. In season 2017/2018, the crop received a significantly higher average rainfall of 681.6 mm distributed throughout the experimental growing season as compared to the 2018/2019 which received a low 297.2 mm (Table.2). The highest cumulative incident radiation from emergence to maturity in 2017/2018 and 2018/2019 was 2862 and 2249 MJ/m^2, respectively (Table.2).

Table 2. Seasonal growing season changes in cumulative growing season day degree (GDD), daily mean, minimum and maximum temperatures, diurnal temperature variation, photoperiod, rainfall and solar radiation in seasons 2017/2018 and 2018/2019 for pigeonpea sown at specified dates in the field experiments conducted at the University of Queensland, Gatton Campus.

Sowing date	GDD (°Cd)	T_m (°C)	T_{min} (°C)	T_{max} (°C)	PP (Hrs)	Rainfall (mm)	Radiation (MJ/m²)
6/12/2017	1943	24.3	18.5	31.4	13.4	356.6	2862
9/01/2018	1683	22.4	16.6	29.6	13.1	287.8	2512
16/02/2018	1259	19.3	13.6	26.5	12.6	273.0	2045
13/03/2018	994	17.6	11.3	25.4	11.4	62.2	1916
10/10/2018	2027	25.0	17.8	32.6	13.6	223.2	2238
15/11/2018	1610	25.8	19.0	33.2	13.5	172.0	2249
20/12/2018	1987	24.7	18.1	32.0	13.3	181.4	1875

† 'T_m' = Mean temperature, 'T_{min}' = minimum temperature, 'T_{max}' = maximum temperature, 'PP' = Photoperiod, 'Environment' = time of sowing, 'GDD' = Cumulative Growing season day degrees.

AMMI analysis

The AMMI conjoined analysis of variance for yield (t/ha) showed a significant genotypic (G) and environmental (E) main effect as well as interaction effects (G × E) (***P < 0.001 and ** P < 0.01) with a low coefficient of variation of 10.9 % (Table.3). The significant G × E confirmed the differential performance of pigeonpea varieties across different environmental conditions, as reported by Laxman et al. (1990) and Chauhan (1998).

The results confirmed that further analysis could be proceeded with based on the presence of G × E. The first two principal components (PC1 and PC2) were significant with P < 0.01. PC1 explained 84.3 % of the variability; the proportion attributed to PC2 was 15.7 %. Thus, PC1 and PC2 together explained total variability (100 %). The other principal components were insignificant and considered as noise and pooled with residuals. The biplot (Figure.1) was plotted against PC1 and yield.

Table 3. Analysis of variance of yield of pigeonpea varieties and sum of squares decomposition and their level of significance at (***P < 0.001 and **P < 0.01)

Source of variation	Df	SS	MS	F-value	Pr (>F)
Environment (E) (87 %)	5	59.89	11.9	216.5	< 0.001***
Replicate (E)	15	0.83	0.05	0.8	0.70NS
Genotype (G) (11 %)	2	2.95	1.47	20.4	< 0.001***
G × E (2 %)	10	2.38	0.23	3.3	< 0.01**
PC1 (84.3 %)	6	2.11	0.35	4.8	<0.01**
PC2 (15.7 %)	4	0.39	0.09	1.4	< 0.01**
Residuals	30				
Grand Mean (t/ha)	2.8				
CV (%)	10.9				

Genotypes and environments closer to the center have smaller G × E. It shows that the mean grain yield of the varieties can be ranked as Quest > ICP 14425 > QPL 1001. Among these varieties, ICP 14425 was the more stable variety than Quest and QPL 1001 because it lies closer to the first principal component, which explains most of the variability (84.3 %) (Figure.2).

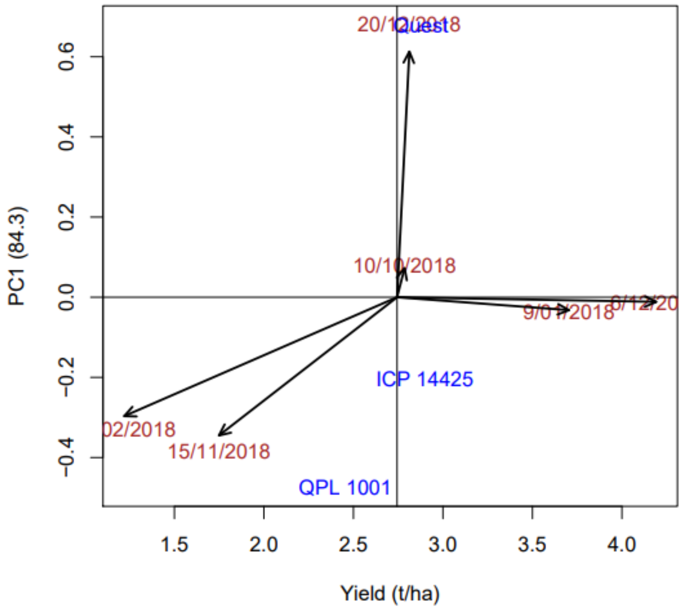

Figure 1. AMMI biplot for (PC1 vs Yield) for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

The environment with the highest yield was 6/12/2017 and followed by 9/01/2018. The yield obtained from the 6/12/2017, 09/01/2018, 10/10/2018 and 20/12/2018 sowing environments were greater than the mean yield across the environment. The lowest-performing sowing environments were 16/02/2018 and 15/11/2018 (Figure.1).

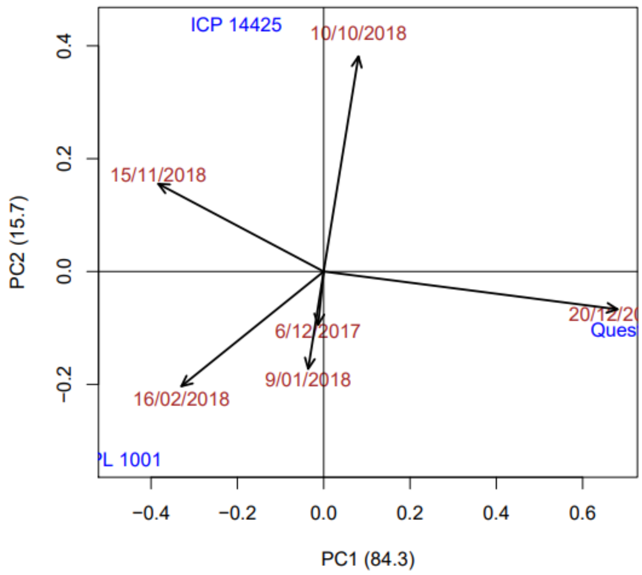

Figure 2. AMMI biplot for (PC1 vs PC2) for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

The most stable environments corresponded with the sowing dates were 6/12/2017, 9/01/2018 and 10/10/2018 (Figure.2). Adaptation of genotypes to various environmental conditions appears associated with different sowing dates. For instance, ICP 14425, an indeterminate type, is more stable than Quest and QPL 1001, which are determinate types. Chauhan (1998) also found differences in the adaptation of determinate and indeterminate varieties. The presence of indeterminateness might provide greater environmental plasticity allowing the crop to be a better fit for a wider range of environments.

GGE Biplot analysis

Since PC1 and PC2 explained 100% of total variability among other principal components, these two components were used to visually represent the data. When characterising the environments according to the genotypic performances, the most stable sowing environment for these genotypes was 16/02/2018, followed by 09/01/2018 and 6/12/2018 since these environments fell within the concentric rings of the biplot (Figure.3). On the other hand, the environments 15/11/2018, 10/10/2018 and 20/12/2018 were relatively less stable and 20/12/2018 was the least stable environment.

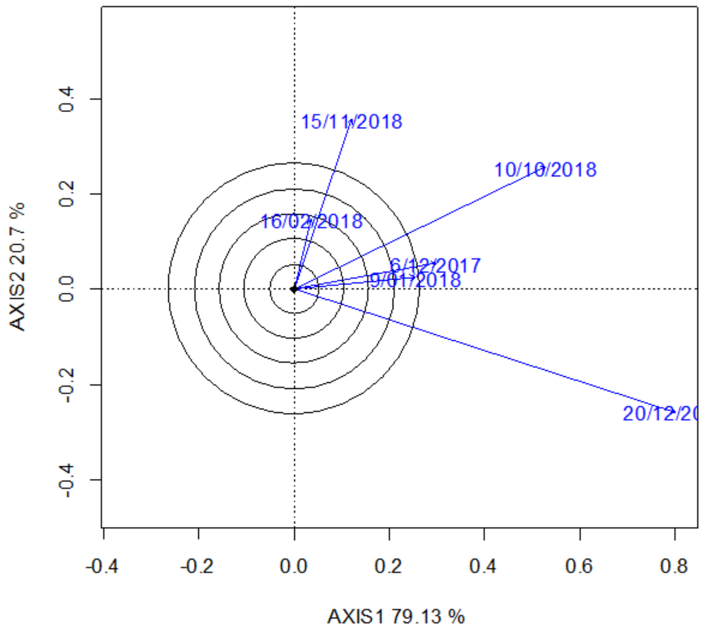

Figure 3. AMMI biplot for environmental characterisation for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

The “Which won Where” plot allowed visual grouping of environments based on G × E on yield. The vertices of the triangle comprise genotypes and six environments which were clustered into three mega environments (Figure.4).

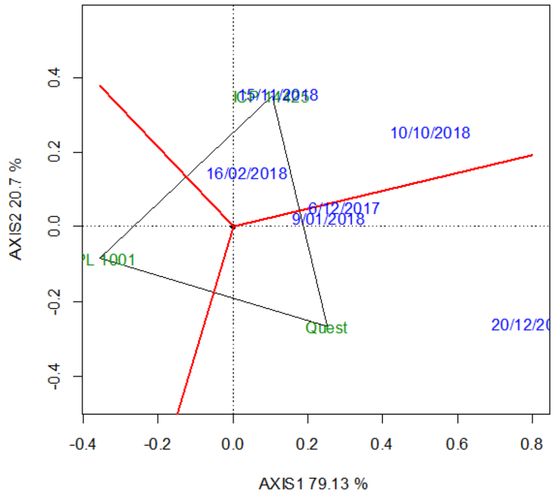

Figure 4. “Which won where/What” GGE biplot for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E)

As for relative performances across environments, variety Quest was in the vertex of the mega-environment formed by 6/12/2017, 9/01/2018 and 20/12/2018 indicating that this variety had the highest yield in these environments. Similarly, variety ICP 14425 was the best variety in the mega-environment formed by 16/02/2018, 10/10/2018 and 15/11/2018. However, variety QPL 1001 was in a region with no allocated environment, which means it performed relatively lower in all the environments, perhaps be due to its genetic potential. The model allows individual genotypes to be assessed for their relative yield performance in each environment and unique temperature and photoperiod regimes (Figure.4).

The “Mean vs Stability” GGE biplot (Figure.5) allowed the evaluation of varieties by their yield and stability characteristics. The blue circle in the middle represents the mean environment, an ‘ideal’ environment created on coordinated means of all the environments. The green line with the arrow indicates the mean environmental axis and the direction in which the arrow points to a higher mean yield. The second axis represents genotypic stability, where the varieties closer to the origin are more stable (Neisse et al., 2018).

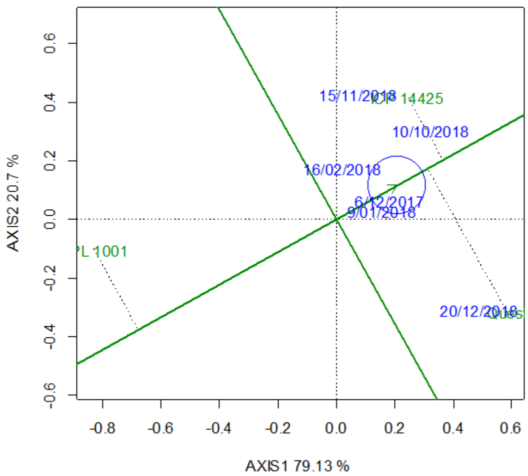

Figure 5. “Mean vs stability” GGE biplot for the pigeonpea yield (t/ha) of multi-sowing agronomy trial with three varieties (G) and six environments (E).

According to Figure.5, the mean yield of the varieties was QPL 1001 < Genotypic Mean < Quest < ICP 14425. Among the three varieties, ICP 14425 was the most stable and Quest was the most unstable variety. The instability in Quest was due to its good performance at the 20/12/2018 time of sowing compared to the other sowing environments, whereas ICP 14425 constantly performed in all the environments. Results indicated that the varieties with the highest yield potential were not always most stable, particularly in challenging seasons.

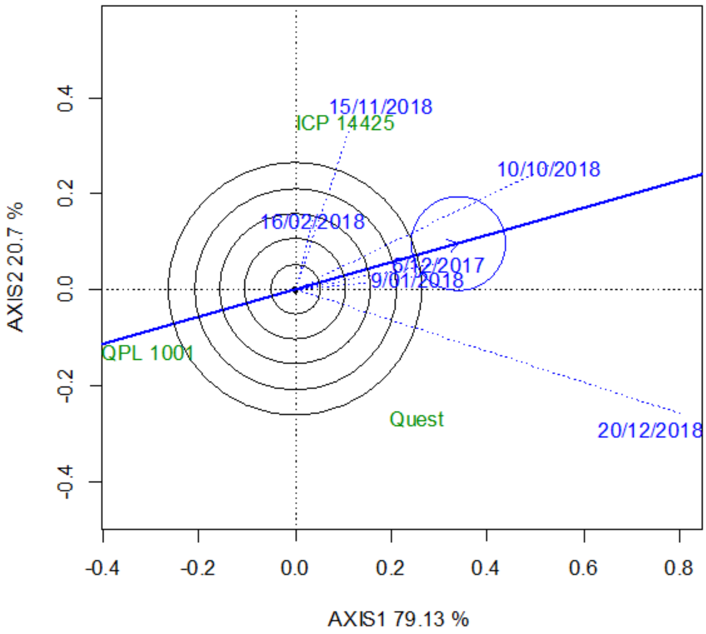

Figure 6. “Discriminativeness vs representativeness” GGE biplot for the environments.

The “discriminativeness vs representativeness” GGE biplot evaluates the environments to identify superior varieties for a mega-environment. In the present analysis, environments with shorter vectors (16/02/2018, 6/12/2017 and 9/01/2018) discriminate less for varieties, and all the varieties tend to perform equally in those environments (Figure.6). On the other hand, the sowing environments 15/11/2018, 10/10/2018 and 20/12/2018 had long vectors and high discriminativeness for varieties. Alternatively, an environment with a smaller angle with a mean-environment axis has higher representativeness. Therefore, the sowing environments 6/12/2017 and 9/01/2018 had a shorter vector and narrower angle than other environments and should be recommended as highly productive and stable environments for tested varieties.

Comparing AMMI and GGE biplot analysis, AMMI retained 84.3 % and 15.7 % for PC1 and PC2, and GGE biplot retained 79.13 % and 20.7 %, respectively. The sum of total variation retained by both PC1 and PC2 was similar. This result was consistent with other studies performed by Hongyu *et al*. (2015) and Neisse *et al.* (2018). The GGE biplot explains only a fraction of the total variability, there is a possibility to evaluate a variety as stable if its variability is not significantly explained by both principal components.

Conclusion

The combination PCA and GEE biplot analysis allowed environments to be analysed based on their unique temperature and photoperiod regimes and assess the relative performance of individual genotypes across growing environments. The analysis revealed that ICP 14425 constantly outperformed in all the environments and was considered as the most stable genotypes compared to Quest and QPL 1001. QPL 1001 moderately performed in all the environments. Alternatively, the environments 6/12/2017 and 9/1/2018 were highly productive and stable environments for these genotypes.

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Future Farm – the potential value in data-driven N decisions

Brett Whelan, Andre Colaco and the Future Farm team

Key words

nitrogen, machine learning, data-driven decisions, precision agriculture

GRDC code

9176493: Future Farm Phase 2: Improving farmer confidence in targeted N management through automated sensing and decision support.

Take home message

- Current methods for calculating in-season nitrogen requirements based on a single sensor and simplistic agronomic decision frameworks can match the performance of good farmer management decisions at the uniform field-rate level
- The way to improve the accuracy and profitability of nitrogen rate decisions when the uniform-rate decisions are near optimal is by increasing the spatial resolution of management
- Empirical, multivariate, data-driven methods for predicting the site-specific, economically optimum nitrogen application rate (EONR) have potential to successfully increase the spatial resolution of decisions and reduce the error and increase profitability of fertiliser management (~$50/ha in this study)
- Data availability is critical to enable data-driven prediction methods and increase profitability. On-farm experimentation (OFE) is a critical enabler of these data-driven decision tools as they allow the automated collection of large digital datasets of crop response to applied nutrients that are needed to train the algorithms. Such OFE should be adopted as a core element of farm business operation to support decision optimisation
- Farm businesses that collect and maintain relevant production response and resource data will be able to push closer towards season- and site-specific economically optimum operations.

Introduction

Future Farm is a research program combining skills from CSIRO, USYD, USQ, QUT and AgVIC. It aimed to re-examine and improve the way in which on-farm soil and crop sensors, and digital data from elsewhere, could be used to improve decisions about input management and explore automation of the process from data acquisition, through analysis, to the formulation and implementation of decision options. The research focused on nitrogen application decisions, but the concept could be applied to any rate-based inputs (e.g., lime, gypsum and other nutrients).

Methods

A program of on-farm experiments (OFE) was established at sites across the three GRDC regions that were designed to document the local yield and protein response to applied nitrogen. The trials included three application rates: a zero (or reduced) nitrogen rate, a farm decision nitrogen rate, and a high nitrogen rate that ensures nitrogen should be non- limiting. The nitrogen rate treatments were placed adjacent to each other in strips or plots and the treatments were applied to run through zones of predetermined potential management classes in each field site (Figure 1). Data was gathered from the OFE in-season and the harvest data from the OFE was used to evaluate and compare the benefits of a range of different methods that the team designed that use digital data from a range of sources (Appendix 1) to ultimately predict the N requirement in different agro-ecological zones across Australia.

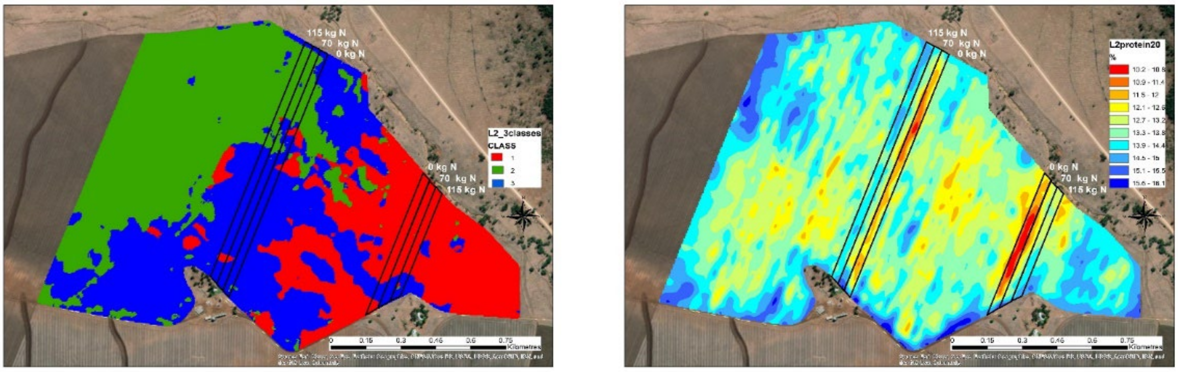

Figure 1. An example of a field trial layout (left) and grain quality data (right) for a site in Northern NSW.

Assessment of nitrogen recommendation models

The assessment process was designed to provide a comparison between the average ability of the different methods designed by the team to predict nitrogen requirement across the sites, in terms of both average accuracy and average profitability. The assessment process also allows the developed methods to be compared against the current farm decision approach (a whole-paddock uniform rate decision) and also against a number of currently used 'benchmark' methods. A number of simple methods for predicting nitrogen requirement using Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge (NDRE) indices calculated from ground-based Crop Circle sensors (CC) and satellite systems (Sentinel) have also been included. These provide an evaluation of a digital, single sensor approach to N estimation. In all, 15 different models were produced and tested, however Table 1 shows the models employed in the final comparison process.

Yield and protein data were obtained from the OFE using commercially-available, harvester-mounted yield and protein sensors. A regression analysis was performed between applied N rates and the harvest data (grain yield and protein) along the length of the trial strips, fitting a quadradic model to the response data using a moving window approach (Figure 2). This process provided site-specific functions at a 10 m scale for each site (site-specific management analysis) which could then be aggregated up to an average response function for each potential management class where possible (potential management class analysis) or an average single response function for the whole paddock (whole-paddock uniform management analysis).

From these functions the economically optimal N rate (EONR) was calculated as the rate that maximised partial profit (harvest income minus expenditure on N fertiliser). The harvest income was calculated based on the average grain price between 2018 and 2020 adjusted for protein premiums based on Table 2. The EONR is regarded here as the ultimate nitrogen application rate decision against which all the recommendation and benchmark methods were compared. The comparison was made in terms of the prediction accuracy of each method (root mean squared error, RMSE) and also the resultant partial profit. The partial profits for the different prediction methods were obtained by inserting the nitrogen recommendations from each into the respective partial profit response functions for each site.

The results of the comparative assessment are tabulated in Table 3 where the methods are ranked on normalised partial profit (NPP) achieved. The NPP is the partial profit achieved for each prediction method normalised against the EONR partial profit values for each site at the different management scales. In Figure 3, each method is plotted based on the average achieved across all sites for RMSE and

NPP. The results are only shown here for the site-specific and whole-paddock management levels to enable a clearer view of the comparison.

Table 1. Methods included for in-season prediction of nitrogen requirement.

Label	**Approach**	**Description**
EONR	Ex-post reference	Observed N rate that maximised partial profit.
Max yield	Ex-post reference	Observed N rate that maximised grain yield.
Farmer	Benchmark method	Farmer decision for application rate.
Simplified mass balance	Benchmark method	A mass balance calculation from publicly available water-limited yield potential data, used as a standard commercial agronomist comparison.
Yield prediction (LM)	Digital method based on yield prediction	Inspired by the 'Nitrogen fertilisation optimisation algorithm', a mass balance back calculation from estimated yield using NDVI and a simple linear regression model.
Yield prediction (RF)	Digital method based on yield prediction	As per 'Yield prediction (LM)' but using multiple variables and a Random Forest model for yield prediction instead of the linear regression.
Response function (NDVI CC)	Digital method based on crop response prediction	Inspired by the Crop Circle (CC) approach, the N rate that maximised the Crop Circle NDVI based on a mid-season response function of vegetation index vs N rate.
Response function (NDRE CC)	Digital method based on crop response prediction	As per 'Response function (NDVI CC)' but using NDRE instead of NDVI.
Response function (NDVI Sent)	Digital method based on crop response prediction	As per 'Response function (NDVI CC)' but using Sentinel 2 data instead of Crop Circle.
Response function (NDRE Sent)	Digital method based on crop response prediction	As per 'Response function (NDVI Sent)' but using NDRE instead of NDVI.
N sufficiency (MV)	Digital method based on N sufficiency	N sufficiency approach based on machine vision data.
DD (data abundance)	Digital method based on an empirical, data-driven approach	Data-driven model; the site and season conditions at which the model is validated are well represented in the data used to build the model
DD (data limited)	Digital method based on an empirical, data-driven approach	Data-driven model; the site and season conditions at which the model is validated are not well represented in the data used to build the model

Figure 3 shows that as accuracy in prediction of nitrogen required increases (decreasing RMSE), partial profit increases, but the rate of increase diminishes as the methods become more accurate. This result reflects the often 'flat' profit response to applied N around the optimum rate which can limit the improvement in profitability through greater accuracy. However, while the rate of increase in NPP slows, the increase in accuracy means an application rate closer to target is more often achieved, bringing a commensurate decrease in the risk associated with N management. Thus, reducing the error improves the chance of getting the management decision correct (or less chance of making an incorrect decision) and increases farmer confidence in the decision. Better targeting of nitrogen application rates to optimum also has implications for minimising potential environmental impact.

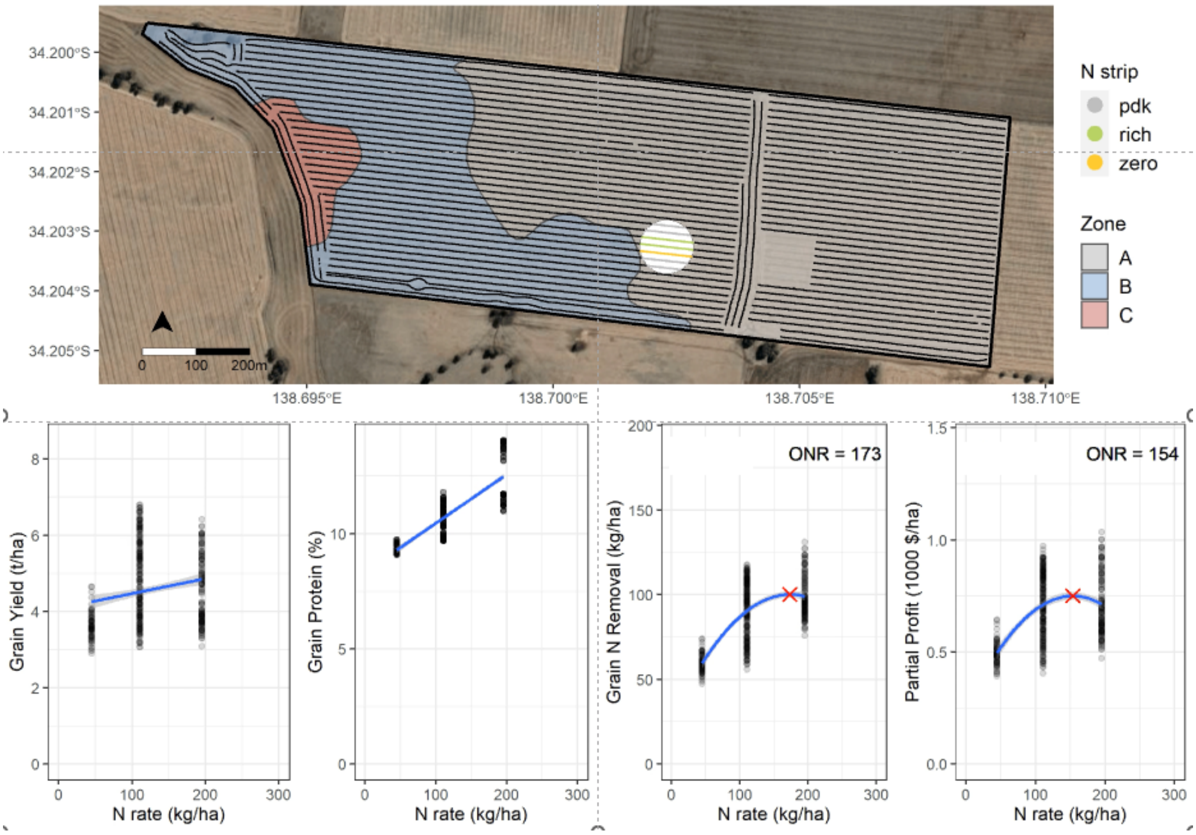

Figure 2. An example of the moving window regression analysis at one point along a strip trial at a site in SA.

Table 2. Average grain grade and nitrogen prices applied in partial profit analysis.

Item	Grade	Grain protein (%)	Adjustment	Price (AUS $/t)
Wheat	ASW1	< 10.5	0.85	261.80
Wheat	APW1	10.5 – 11.5	1 (base)	308.00
Wheat	H2	11.5 – 13	1.05	323.40
Wheat	H1	> 13	1.1	338.80
Barley	Malting	9 – 12	1 (base)	300.00
Barley	Feed	< 9 or >12	0.92	277.00
Urea (46% N)	-	-	-	500.00

The best future farm method was the data-driven model (DD data abundance), which represents a situation where a database is available for fields that provides information on past OFE and production response and associated environmental data that encompasses the variation in production that can be achieved in that field. This method succeeds in providing better estimates than the average farm- based decision (farmer) at all management scales. At the whole-field uniform and site-specific management scales, the DD (data abundance) can improve NPP by 2% ($14/ha) and 5% ($47/ha) respectively, over the average Farmer method (Table 3; Figure 3).

Table 3. Results of the comparison of methods for predicting N requirement along with benchmark methods for comparison. Methods ranked on normalised partial profit achieved.

Method	Scale	RMSE (kg/ha)	Normalised partial profit (NPP)	NPP $1000/ha max
EONR	Site-specific	0.0	1.00	1000
DD (data abundance)	Site-specific	15.6	0.99	990
Max yield	Site-specific	35.6	0.97	972
DD (data abundance)	Uniform	34.5	0.96	960
EONR	Uniform	34.5	0.96	959
Max yield	Uniform	40.2	0.95	948
Farmer	Uniform	42.8	0.94	943
Resp func (NDVI Sent)	Uniform	48.6	0.93	930
Yield prediction (RF)	Uniform	44.0	0.93	928
N sufficiency (MV)	Uniform	42.1	0.93	927
Yield prediction (RF)	Site-specific	44.0	0.93	926
Yield prediction (LM)	Uniform	44.7	0.93	926
Yield prediction (LM)	Site-specific	44.8	0.93	926
N sufficiency (MV)	Site-specific	44.4	0.92	922
DD (data limited)	Uniform	45.8	0.91	913
Simplified mass balance	Uniform	46.2	0.91	910
Resp func (NDRE Sent)	Uniform	57.0	0.91	909
DD (data limited)	Site-specific	46.0	0.91	907
Resp func (NDVI CC)	Uniform	48.3	0.90	897
Resp func (NDRE CC)	Uniform	51.0	0.88	884
Resp func (NDVI Sent)	Site-specific	56.6	0.87	870
Resp func (NDRE Sent)	Site-specific	63.6	0.86	859
Resp func (NDVI CC)	Site-specific	55.9	0.85	851
Resp func (NDRE CC)	Site-specific	56.9	0.85	846

The farmer recommendation is on average 2% ($14/ha) lower in NPP than the average uniform EONR (Table 3). All the farmers involved in the project were skilled in using Precision Agriculture technologies in farm management and the result here confirms that they were very good at calculating nitrogen requirement for the seasons under study. Aside from the top performing (DD data abundance) method, a number of the other digital mechanistic sensor-based methods (e.g., 'Yield prediction (RF)', 'Response function (NDVI Sent)' and 'N sufficiency MV') approached within 1% ($13 - $16/ha) of the Farmer decision level of average profit and accuracy at the uniform application scale (Table 3; Figure 3). The response function approach was sensitive to the type of input data, that is, some combinations of vegetation indices and their data sources may match a profit response function better than others.

For the fields in this study, the sensor-based response function that most resembled the final profit function was the one derived from Sentinel 2 NDVI. Since Sentinel data can be accessed for free, the fact that it out-performed the methods which used proximal crop sensors represents an important result for farmer adopters of such PA technologies. The 'N sufficiency' method, a less common sensor-based approach, had a similar performance to the 'yield prediction' methods.

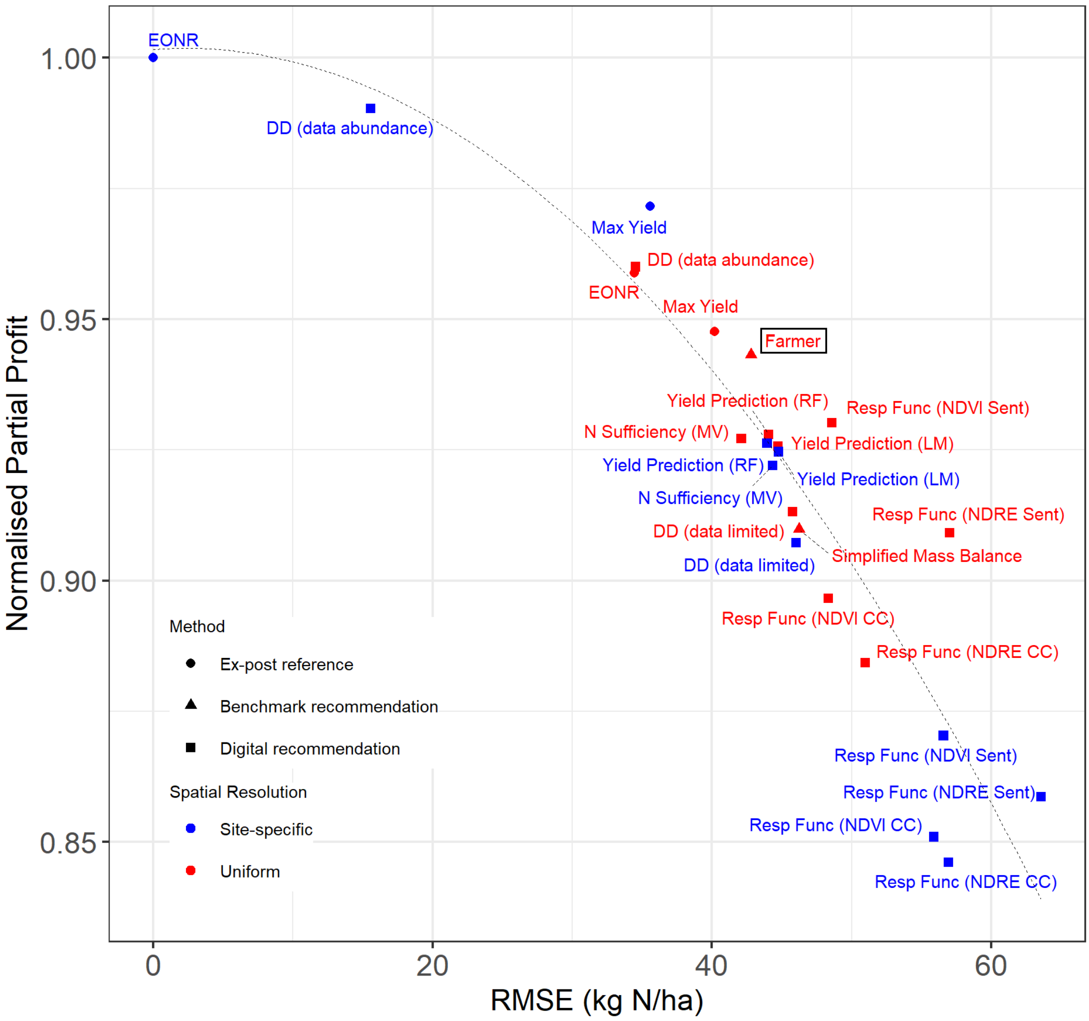

Figure 3. Profitability (y axis) verses accuracy (x axis, root mean squared error) of methods for N recommendation averaged across trial sites at uniform and site-specific management scales. All relevant sites utilised.

However, apart from the DD (data abundance) approach, all the other methods performed worse on average when implemented at the site-specific scale as compared to the unform application scale (Figure 3) because of their larger recommendation error. In some cases, using the methods to calculate a uniform application rate reduced the error substantially, suggesting that methods in which the recommendation error is expected to be large are better implemented as the average for the field instead of site-specifically.

The variables that proved of most importance for the DD (data abundance) method were the Sentinel NDVI from each N strip, historic yield monitor data, accumulated rainfall to GS31 and the historic NDRE (95th percentile). For the mechanistic models that predicted yield in order to calculate a nitrogen recommendation rate, the most important variables were historic yield monitor data, accumulated rainfall to GS31, Sentinel NDRE at GS31 from all strips and historic NDRE (5th percentile). From this it is clear that information derived from the OFE are crucial for these prediction methods.

The average results shown in Figure 3 also suggest that. Moving towards a more site-specific nitrogen management approach may be more achievable in all locations using an approach that includes more information that is able to describe the range of site and season variables that impact the response to nitrogen.

Conclusions

From assessing these varied model types over multiple sites in five States, it appears the farmers in this study are operating near the optimum management level at the uniform paddock scale, for the seasons included, and they would need to move towards site-specific decisions using a data-driven approach with more data in order to improve the accuracy and profitability of nitrogen requirement decisions. The methods built here require further development and testing. However, the data-driven approach with increasing levels of OFE data for directly predicting ONR appears to be a promising target methodology for improving site-specific decisions. Using the methodology at the uniform paddock scale would also be a viable approach to improve uniform management decisions on farms where uncertainty in decisions at that level remain high.

The data-driven approach relies on data availability to ensure the method performs at its optimum. Its success at all management scales in this assessment provides a significant pointer towards a future where farm businesses that collect and maintain relevant production response and resource data will be able to push closer towards season- and site-specific economically optimum operations.

A system in which farmers share OFE data across larger communities may also play a crucial role in building the necessary database for empirical DD approaches. Improvements can be gained as soon as more OFE data is collected and made available from farms. However, as formalised OFE is an exception rather than a rule across farming operations, this means it is not an approach that can currently be employed by every farmer.

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Appendix 1. List of variables available for use in digital N recommendations.

Group	Variable	Description	Source	Spatial scale	Timing of collection
Field history	Historic yield (on-farm)	Average yield from previous 3 to 4 years of wheat and barley crops	Onboard yield monitoring	Site-specific (interpolated at 5 m pixels)	Previous seasons
Field history	Yield potential	Water limited yield potential (t/ha) at the local level	Yield Gap Australia – CSIRO	Field-scale	Previous seasons
Field history	Historic yield (public)	Historic average yield	ABARES	Field-scale	Previous seasons
Field history	Historic crop indices	5^{th} and 95^{th} NDRE percentiles from historic imagery	Landsat 8	Site-specific (30 m pixels)	Previous seasons
In-season crop sensing	Vegetation indices	NDVI and NDRE	Crop Circle sensor	Site-specific (point data along the strips)	GS-31
In-season crop sensing	Vegetation indices	NDVI and NDRE	Sentinel 2	Site-specific (10 m pixels)	GS-31 (nearest image to the Crop Circle sensing date)
In-season crop sensing	Machine Vision features	NGRDI, NRBDI and canopy cover	RGB camera	Site-specific (point data along the strips)	GS-31
Soil/ landscape	Soil bulk density	Soil bulk density at the top 0.3 m layer	ASRIS	Field-scale	-
Soil/ landscape	Soil clay content	Soil clay content at the top 0.3 m layer	ASRIS	Field-scale	-
Soil/ landscape	Soil pH	Soil pH (CaCl2) at the top 0.3 m layer	ASRIS	Field-scale	-
Soil/ landscape	Gamma radiometry	U^{238}, Th^{232} and K^{40} radiometry from airborne gamma-ray spectrometric survey	Radiometric Grid of Australia	Site-specific (100 m pixels)	-
Soil/ landscape	Aspect, hill shade and slope	Landscape attributes from digital elevation model	Digital Elevation Model of Australia	Site-specific (30 m pixels)	-
Weather	Evapotranspiration	Total evapotranspiration	MODIS	Field-scale	Between sowing and GS-31
Weather	Phase and amplitude	Model parameters (phase and amplitude) of a sinusoid function fitted to a land surface temperature dataset	MODIS	Field-scale	-
Weather	Degree days	Summed daily mean temperatures	BOM	Field-scale	Between sowing and GS-31
Weather	Rainfall	Total daily rainfall, and accumulated since sowing, aggregated into weekly intervals	BOM	Field-scale	Between sowing and GS-31
Weather	Maximum temperature	Summed daily maximum temperature, and accumulated since sowing, aggregated into weekly intervals	BOM	Field-scale	Between sowing and GS-31

Is it time to challenge current nitrogen strategies, tactics and rules of thumb?

Chris Dowling, Back Paddock Company

Key words

N pools, organic, efficiency, strategy, spread, drill

Take home message

- After a run of high-yielding years and wetter than normal soil conditions post-harvest for the coming season, we are likely to see soil mineral N reserves low, soil stored water at maximum capacity, crop residue levels higher than usual, recycling of nutrients from partially and unharvested crops, and minimal fertiliser nitrogen movement into the soil profile. These add up to a challenging situation in a cropping system that would typically expect greater than 50% of crop N to be sourced from mineralisation, some stored mineral N reserves distributed down the soil profile, and some movement of fertiliser N into the profile from the pre-sowing application
- In seasons and situations where there is a significant change in the balance of crop N sourced from organic, soil mineral and fertiliser N pools, caution is needed in determining seasonal N fertiliser requirements based on general rules of thumb, particularly as the crop N uptake efficiency is 50%
- Most current N management strategies are limiting the maintenance or growth of organic C and N reserves by not replacing the contribution from annual mineralisation in N budgets. A more strategic approach that concentrates on soil N management rather than crop N requirement may be more suitable to achieve both crop productivity and soil fertility goals
- With the seasonal conditions this year, the logistics of getting N applied will necessitate fertiliser N being applied in ways that would not usually be considered due to a higher risk of loss or lower efficiency. Even with the current high N fertiliser prices in highly N-responsive situations, insufficient N will likely cost more than losses and lower the efficiency of alternate application strategies.

Organic vs different fertiliser N sources

In managing crop N requirements for the last 30 years, there has been widespread reliance on simple N budgets that, in essence, treat all sources of N available to the crop, soil N depth distribution and fertiliser application strategies equally. But is accepting equality of N supply still the best approach , or is it computational expediency that, for the most part, has served its purpose and now it's time for a closer look at a more informed approach??

At a gross functional level, plants acquire N from the soil dominantly via the mineral pool, which in turn is topped up by the plant residue (labile), the 'old' organic matter (humic), and fertiliser where the supply from other sources is adjudged to potentially limit yield and produce quality (Figure 1).

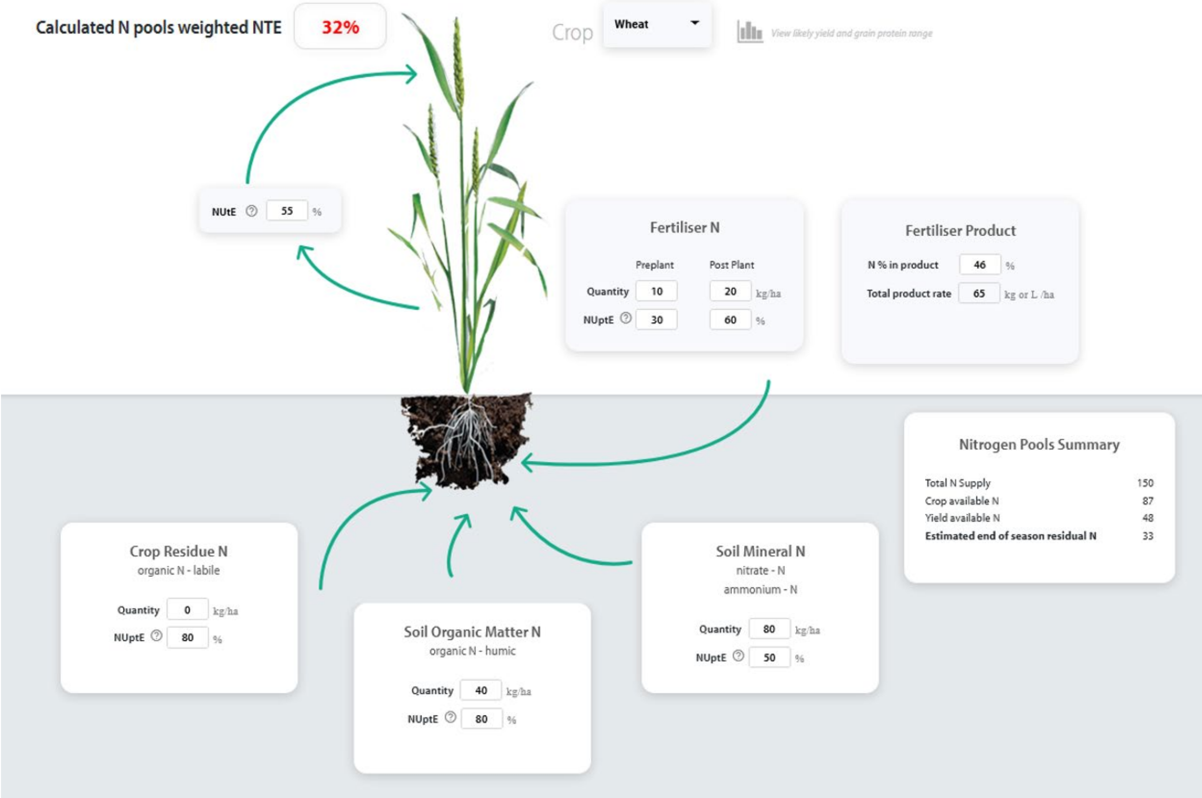

Figure 1. Representation of a soil N supply pool scenario with differing N quantity/N uptake efficiency contributions to plant N supply and potential grain yield and protein outcomes (image from Back Paddock Opterra N Pools Calculator).

The science says not all crop N supply pools are the same, differing in the quantity of N supplied and efficiency of crop uptake being impacted by characteristics of the N forms that make up the source pool (Table 1). Significant N supply pool balance changes affect crop N supply and may significantly affect seasonal fertiliser N requirement. This explains why many soils in their virgin state and after highly productive legume pasture ley can supply the entire crop N requirement based on the quantity and efficiency of supply and why similar amounts of N supplied as fertiliser are unable to reach the same yields and grain protein outcomes. It may also factor in the 'better than expected' N responses following canola and pulse crops for the quantity of N available. The relative uptake efficiency from the different soil N pools often explains the difference. While recent research suggests that the net soil N gain from pulse crops may be large (Brill et al. 2022; Kirkegaard et al. 2021), minimal and even negative (Sands et al. 2022), the faster rate of N turnover from these residues with lower C/N ratios and higher uptake efficiency can significantly influence yield and quality in the following crop (Kirkegaard et al. 2021).

Where the crop N supply quantity is heavily skewed toward the higher or lower uptake efficiency pools, there is a significant change from the widely adopted 'average' crop N efficiency (50 %, commonly represented as crop N demand equals 2 x removal) that the "standard" N budget may significantly over or underestimate the crop fertiliser N requirement.

Table 1. General range short-term crop uptake efficiency of N from 4 major supply pools by cereals.

Major soil N supply pool (and crude working definition)	General crop uptake efficiency in cereals	Characteristics
Humic OM – contribution from sources more than 3 seasons after incorporation to thousands of years old (Baldock 2019)	70 – 90%	• Largest organic N pool with a regular slow turnover rate of ~2% of total soil organic N annually • Losses via erosion; not subject to leaching, denitrification or volatilisation • Converted to crop-available mineral forms based on favourable soil temperature and moisture conditions • Highest efficiency where most of the contribution is released in-crop • If released during a fallow, it becomes part of the soil mineral N pool and is potentially vulnerable to multiple N loss pathways.
Labile OM – contributed from crop residues with less than 3 seasons of mineralisation (Peoples et al. 2017)	70 – 90%	• Variable size organic N pool based on quantity and quality (C/N ratio) of plant and animal residues returned • Losses dominantly via erosion; not subject to leaching, denitrification or volatilisation • Converted to crop-available mineral forms based on favourable soil temperature and moisture conditions • Net annual contribution depends on the outcome of net mineralisation/immobilisation processes • Legume residues provide up to 30% of total N in residual DM in the following season (Peoples et al. 2017). Some studies suggest that canola residues can perform similarly • Highest efficiency where most of the contribution is released in-crop • If released during a fallow, it becomes part of the soil mineral N pool and is potentially vulnerable to multiple N loss pathways.
Soil profile mineral N – nitrate and ammonium below 10 cm at sowing (Bell et al. 2010)	50 – 70%	• Variable size mineral N pool is based on a combination of residual mineral N from previous crops and N mineralised in the previous fallow • Losses dominantly via leaching and denitrification • Uptake efficiency is affected by N depth relative to rooting depth, soil water and constraints distribution • Quantity available below 60 cm may be limited by root density but is crucial in seasons where the soil profile above has dried.
High concentration, rapidly mineralisable fertiliser N (Daniel et al. 2018) – • applied in the fallow and at sowing • applied in crop	 • 0 – 40 (70[1])% • 20 – 60%	• Highest annual uptake efficiency when applied into an active root system • Lowest annual efficiency when lost during fallow and if stranded in dry soil above the active rootzone for a significant period • If not lost during a fallow, it can become part of the residual soil N for the following crop at up to 2 x higher efficiency than the year of application • Losses dominantly via volatilisation, leaching and denitrification.

[1] Wimmera

For the future, rebuilding soil capacity to supply the majority (>70 %) of crop N requirements from higher-efficiency, low-risk soil sources must be considered a priority to help dampen the adverse effects of seasonal weather extremes and increased agricultural market volatilities (e.g., urea price and commodity price variance) by regenerating soil nutrient supply plasticity (soil contribution more when it is wet and less when it is dry).

Nitrogen – strategies for building the pool and reducing losses

Research suggests that implementing best cropping practices may have, at best, halted the decline in soil organic carbon and nitrogen stocks in continuous cropping systems; however, in most cases, they are still declining. Fundamentally this means that in the long term, the conversion of available rainfall to plant biomass is less effective than previous land uses they are being compared to. To emphasis this point it is worth understanding that estimates of total soil N decline in continuously cropped soils indicate that total soil N haves every 23 (+/- 12) years (Angus and Grace 2017).

The Yield Gap project has identified that across most areas of Australia, the lack of nitrogen is a primary factor in not reaching seasonal and long-term water-limited yield potential (average 40 %) (Hochman and Horan 2018) and, by inference, soil C and N return to the soil in plant residues during grain production.

This issue brings into sharp focus the basis for determining appropriate crop N supply strategies. Current strategies are primarily based on using organic matter mineralised N (contributed to fallow mineral N and mineralised in crop) to minimise the fertiliser N requirements. While this may be a sound short term financial strategy (i.e., targeting optimum economic yield annually), from a longer term view and soil nutrient resource perspective, it can only lead to further declines in organic C and N if the long-term aggregate rate of addition of N for a rotation is less than crop N removal + annual mineralisation and losses.

e.g., Annual average grain N removal of rotation = 71 kg N/ha

- 2 x wheat @ 4t/ha @ 11.5% protein = 160 kg N/ha
- 1 x canola @3 t/ha @ 23% protein = 110 kg N/ha
- 1 x barley@ 5t/ha @10.5% protein = 85 kg N/ha
- 1 x chickpea @ 2.5 % @ 24% protein + N fixation = 0 kg N/ha

Soil total N (0 – 10 cm) = 0.1 % (OC% ~1.2)

Annual humic mineralisable N = 2% of soil total N% = $0.1 \times 10{,}000 \times 1.3 \times 0.02 \approx 26$ kg N/ha

Minimum long-term annual N addition rate ~97 kg N/ha + seasonal N loss adjustment (15%?)

Some alternative approaches for consideration include:

- N strategy based on long-term crop + annual humic mineralisation replacement
- Replacement N based on long-term removal rates and strategic use of legume ley pasture (40 %) in mixed farming and pulse N
- N bank – N rate strategy based on long term crop available water
- N pools weighted budget + humic mineralisable N.

Use the greater of the above long-term minimum rate approaches and seasonal pools weighted N budget rate?

Spread urea or drill it in?

The answer to the question as to whether it is better to spread or drill urea can fall either way depending on factors such as physical soil conditions, soil chemistry, crop residue loads, beneficial or adverse effects of soil disturbance and application efficiency (including equipment and skilled labour) and cost. An individual situation should be evaluated on its merits considering the prevailing conditions. Table 2 highlights some pros and cons associated with each application method. The choice should also consider which method is most likely to promote the majority of mineral N in the 15 – 40 cm soil layer by crop establishment in summer dominant rainfall areas and other areas that rely significantly on stored soil water for crop production reliability.

Table 2. Pros and cons of spreading or drilling urea

	Pros	**Cons**
Spread	• Logistically, generally more efficient field coverage • Generally lower operator skill level required • Uses multi-purpose equipment • May avoid soil moisture loss associated with soil disturbance • Avoid potential plant establishment effects if urea is drilled at sowing. • Wider application window and conditions.	• Potentially high volatilisation losses, if not incorporated or not treated with a volatilisation inhibitor • Higher yield impacting immobilisation "losses" in high crop residues (5 kg/t compensation when residue volume >5 t/ha) • Calibration and spread pattern can be variable.
Drill	• Potential to delay mineralisation of urea/ammonia (slow release) from some application configurations. • Deeper application (>15 cm) may be less prone to stranding • Can be multi-tasked where soil disturbance is required for other purposes.	• If too shallow in wet alkaline soils, volatilisation losses can be higher than spread. • Potential for higher N_2O emissions during nitrification.

What does a systems approach look like?

We must develop practical long-term strategies and ensure strong alignment with short-term tactics when considering systematic restoration of the soil's nutrient-based production capability.

Some of the primary considerations for the long-term management of soils in the sub-tropical grains industry include:

- All nutrients have residual value when not taken up due to crop water deficit, positional unavailability or erosion
- Uptake efficiency of residual nutrients can be many times greater than freshly applied, if not lost during a fallow due to redistribution within the soil profile
- Reporting of single-year crop uptake efficiencies and profitability for nutrients is misleading where there is yield active residual value
- Plan to manage nutrients for a rotation first, then by crop
- Using nutrient removal is not an appropriate short or long-term application rate for all soils, nutrients and situations
- Monitoring soil nutrient and grain nutrient content trends and balance are essential for long-term management
- Soil phosphorus and potassium strategies need to include the 10 – 30 cm layer in sub-tropical Vertosols

- As seasonal and nutrient cost variability becomes more extreme, soil nutrient-based production plasticity becomes more important to help stabilise costs and income
- Nitrogen mineralised from organic matter annually may need to be added to, not deducted, from crop requirements to arrest further soil organic carbon and nitrogen decline.

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