GRAINS RESEARCH UPDATE

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

Southern Series Livestream

Volume 2

February 22, 23, 24

#GRDCUpdates

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2022 GRDC Grains Research Update Series Livestream convened by ORM Pty Ltd.

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GRDC Foreword

2022 GRDC Grains Research Updates Foreword

On behalf of the Grains Research and Development Corporation (GRDC), I am pleased to welcome you to the 2022 Update series for the southern grain growing region.

Unfortunately, once again, the COVID-19 pandemic has impacted GRDC's ability to host this Update series across a face-to-face setting, but I can assure you, the latest research and information that's expected to be presented won't be diminished by the online platform.

GRDC's updates are focused on building the profitability of grain growers by delivering regionally relevant, strategic information that they can use to improve their practices and become more efficient and innovative on farm.

During the updates, you'll hear from our presenters about the cutting edge research, development and extension (RD&E) that GRDC has invested in to assist growers in making better, more informed management decisions and to adopt new farming practices and technologies.

With a global push to reduce greenhouse gas emissions, GRDC has identified significant opportunities and challenges for the grains industry and farming businesses. Determining how best to manage a shift in climate will be a highlight at this year's update, with a range of topics on the agenda.

Our first session will provide up to date research on assessing a farming system's greenhouse gas footprint and the key points growers need to consider regarding their footprint at a farm gate level. The presentations will also investigate the trending topic of carbon sequestration and highlight the pros and cons of soil carbon farming that growers can consider.

The series will also provide more hands on, practical information to help growers assess their management practices and identify where they could make changes to continue lifting their productivity and profitability.

Topics will include management of pests, weeds and disease, the latest in precision agriculture, soil and nutrition management and advancements in pulses and canola.

I trust that these updates will provide a wealth of knowledge to you as a member of the grains industry and arm you with useful information, networks, and contacts to improve your enterprise for the coming season and into the future.

The GRDC has an extensive network that aims to support growers, so please make the most of these online events and take advantage of the questions and answer sessions. While I know communicating over the computer can be difficult, we've worked to ensure our Updates allow participants a direct avenue to industry experts - so don't be afraid to participate.

The success of our Updates depends upon local support, and we are grateful to our suppliers, grower groups and presenters who have taken the time to help develop such a high-class series.

I sincerely hope you enjoy the 2022 Update series and thank you for supporting the GRDC.

Southern Region Panel Chair,

John Bennett

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GRDC SOUTHERN Grains Research Update Series

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FEBRUARY 2022 LIVESTREAM PROGRAM

NB. All times are Australian Eastern Daylight Savings Time (AEDT).

Program Day 4 – Disease and pest update

Tuesday 22 February, 9am AEDT

Start time	Finish time	Topic	Presented by
9:00	9:05	**Welcome/Introduction to day four**	*GRDC Representative*
9:05	9:35	**Powdery mildew in wheat - how to best manage**	***Sam Trengove,*** *Trengove Consulting*
9:35	10:05	**Keeping fungicide resistance in check**	***Tara Garrard,*** *SARDI*
10:05	10:35	**Canola diseases - key considerations for this season**	***Steve Marcroft,*** *Marcroft Grains Pathology*
10:35	11:05	**Rust resistance - new pathotypes to be aware of**	***Robert Park,*** *University of Sydney*
11:05	11:20	*Morning Tea Break*	
11:20	11:50	**Regionally based control measures for Septoria**	***Grant Hollaway,*** *Agriculture Victoria*
11:50	12:20	**Is your blue green aphid strategy on target?**	***Paul Umina,*** *CESAR*
12:20	12:50	**Minding the 'good guys' - impact of insecticides on key beneficial organisms**	***Robert McDougall,*** *CESAR*
12:50	13:20	**Managing what is bugging you this season**	***Lizzy Lowe,*** *CESAR*
13:20	13:30	*Close and evaluation*	*GRDC Representative*

The WeedSmart Big 6

Weeding out herbicide resistance in winter & summer cropping systems.

The WeedSmart Big 6 provides practical ways for farmers to fight herbicide resistance.

How many of the Big 6 are you doing on your farm?

We've weeded out the science into 6 simple messages which will help arm you in the war against weeds. By farming with diverse tactics, you can keep your herbicides working.

Rotate Crops & Pastures

Crop and pasture rotation is the recipe for diversity

- Use break crops and double break crops, fallow & pasture phases to drive the weed seed bank down,
- In summer cropping systems use diverse rotations of crops including cereals, pulses, cotton, oilseed crops, millets & fallows.

Increase Crop Competition

Stay ahead of the pack

Adopt at least one competitive strategy (but two is better), including reduced row spacing, higher seeding rates, east-west sowing, early sowing, improving soil fertility & structure, precision seed placement, and competitive varieties.

Implement Harvest Weed Seed Control

Capture weed seed survivors

Capture weed seed survivors at harvest using chaff lining, chaff tramlining/deckir chaff carts, narrow windrow burning, bale direct or weed seed impact mills.

Stop Weed Seed Set

Take no prisoners

- Aim for 100% control of weeds and diligently monitor for survivors in all post weed control inspections,
- Crop top or pre-harvest spray in crops to manage weedy paddocks,
- Consider hay or silage production, brown manure or long fallow in high-pressure situations,
- Spray top/spray fallow pasture prior to cropping phases to ensure a clean start to any seeding operation,
- Consider shielded spraying, optical spot spraying technology (OSST), targeted tillage, inter-row cultivation, chipping or spot spraying,
- Windrow (swath) to collect early shedding weed seed.

WeedSmart Wisdom

Never cut the herbicide rate – always follow label directions
Spray well – choose correct nozzles, adjuvants, water rates and use reputable products,
Clean seed – don't seed resistant weeds,
Clean borders – avoid evolving resistance on fence lines,
Test – know your resistance levels,
'Come clean. Go clean' – don't let weeds hitch a ride with visitors & ensure good biosecurity.

Mix & Rotate Herbicides

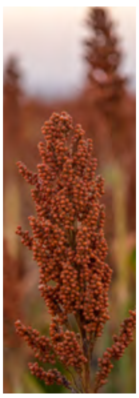
Rotating buys you time, mixing buys you shots.

- Rotate between herbicide groups,
- Mix different modes of action within the same herbicide mix or in consecutive applications,
- Always use full rates,
- In cotton systems, aim to target both grasses & broadleaf weeds using 2 non-glyphosate tactics in crop & 2 non-glyphosate tactics during the summer fallow & always remove any survivors (2 + 2 & 0).

Double Knock

Preserve glyphosate and paraquat

- Incorporate multiple modes of action in the double knock, e.g. paraquat or glyphosate followed by paraquat + Group 14 (G) + pre-emergent herbicide
- Use two different weed control tactics (herbicide or non-herbicide) to control survivors.



Fungicide resistant wheat powdery mildew – management and resistance testing

Sam Trengove[1], Stuart Sherriff[1], Jordan Bruce[1], Fran Lopez Ruiz[2] and Kejal Dodhia[2].

[1]Trengove Consulting; [2]Centre for Crop and Disease Management, Curtin University, Perth.

SAGIT project code: TC120

Keywords

- wheat powdery mildew, fungicide resistance

Take home messages

- Varietal resistance plays an important role in managing wheat powdery mildew. The variety Grenade CL Plus⏀ (MS) had less powdery mildew infection in the untreated than Chief CL Plus⏀ and Scepter⏀ (SVS) treated with a two-spray fungicide strategy.
- Wheat powdery mildew resistance mutation frequency increased from 2019 to 2021. In the northern Yorke Peninsula region in 2019, more than half the paddocks surveyed had no group 11 QoI (strobilurin) resistance mutation, whereas in 2021, all 30 paddocks sampled had some level of resistance mutation with the median resistance frequency increasing from 0 to 19%.
- Group 11 QoI resistance mutation has been detected at lower levels in the central Yorke Peninsula and Mid North regions in 2021.
- In a fungicide product trial, the application of group 11 QoI fungicides increased the frequency of resistance mutation from 19% in the untreated control to 48.5% on average across QoI treatments.
- The presence of group 11 resistance mutations meant that the performance of group 3 + 11 fungicide mixtures was generally not any better than the straight group 3 (DMI triazole) fungicides.
- Group 7 SDHI fungicides did not provide any additional control to the standalone group 3 DMI fungicides when applied in product mixtures. This is due to poor efficacy of group 7 fungicides on wheat powdery mildew, with no resistance to this fungicide group identified in these powdery mildew populations.
- Mutation at Cyp51 is a gateway mutation that infers reduced sensitivity to the group 3 DMI fungicides is likely, though the actual mutations conferring resistance are not known. High frequency of the Cyp51 mutation has commonly been encountered at trial sites, yet the group 3 DMI fungicides are currently providing the best fungicidal control, albeit incomplete control.

Background

Wheat powdery mildew (WPM) has been documented to cause up to 25% yield loss in Australia (https://grdc.com.au/news-and-media/newsletters/paddock-practices/protecting-cereal-crops-from-powdery-mildew). Wheat varieties that are commonly being grown have poor varietal resistance, with many having ratings of susceptible to very susceptible (SVS), and only a few varieties rated as moderately susceptible to susceptible (MSS) or moderately susceptible (MS). The most common wheat variety grown in the northern Yorke Peninsula area has been Scepter⦶, which has a SVS rating. Consequently, there is a heavy reliance on foliar fungicides for WPM control. Fungicide options for WPM and other diseases have relied heavily on the DMI group 3 (triazole) products such as tebuconazole and epoxiconazole, and these are the basis of many fungicide mixes, putting pressure on resistance development. In more recent years, there has also been increasing use of the QoI group 11 (strobilurin) actives in mixtures with DMI fungicides in products such as Amistar Xtra® (azoxystrobin + cyproconazole), but control from these fungicides has been variable due to QoI resistance developing in some of the same populations. New generation fungicides which contain a group 7 (SDHI) active ingredient, such as Aviator Xpro and Elatus Ace, were expected to provide improved control of WPM, particularly WPM populations with reduced sensitivity or resistance to group 3 DMI and 11 QoI fungicides. However, findings from 2020 indicate the group 7 SDHI actives have poor efficacy on WPM, with most of the control from these fungicides being derived primarily from the group 3 DMI mix partner (Trengove et al 2021). In terms of fungicide resistance risk the DMI group 3 are medium risk, whilst the SDHI group 7 and QoI group 11 fungicides are medium-high and high risk for development of fungicide resistance (AFREN Fungicide Resistance Workshop), (FRAC Code List ©*2021).

Trials were initiated in 2020 and 2021 as part of SAGIT project TC120 to better understand best practice management of WPM given emerging fungicide resistance issues.

Method

Five trials were established in 2020 (Trengove et al 2021) and six in 2021. Each of the trials had a particular focus and the main varieties used (excluding the variety trial) were Scepter⦶ and Chief CI Plus⦶ in 2020 and Chief CI Plus⦶ in 2021. The focus of the 2021 trials were:

1. Varietal resistance and post emergent fungicides
    - o Four varieties with disease ratings for WPM ranging from MS to SVS and four fungicide strategies, plus two new lines with no fungicide applied.
2. Pre-emergent fungicides
    - o Six pre-emergent fungicides +/– post emergent fungicide.
3. Post-emergent fungicides
    - o A range of post emergent fungicide treatments applied at the full label rate at both, GS32 and GS39. Fungicide rates are described in Appendix 1.
4. Fungicide timing
    - o Fungicide applied at four timings (GS14, 32, 39 and/or 71) in 10 timing combinations.
5. Fungicide sequencing
    - o A trial focused on controlling resistant powdery mildew using 12 combinations of pre-emergent and post emergent fungicides from a range of fungicide groups.
6. Fungicide coverage
    - o A trial investigating the application rate of two fungicides and a control treatment and two water application rates 100 and 200L/ha.

Each trial was a randomised complete block design with three replicates and plots were 10m * 1.5m. Post emergent fungicide treatments were applied using 015110 pre orifice nozzles in 100L of water.

The 2021 trials were located at a site on a sand hill north of Bute, northern Yorke Peninsula, where WPM has been frequently observed. Nearby sites were identified in a 2019 survey with reduced sensitivity to group 3 DMI and resistance emerging to group 11 QoI fungicides. This paper will only present results from the variety and product trials established in 2021 at this site.

Powdery mildew assessments were made during the growing season using either a canopy score of 0 – 5 (0 = no infection, 1 = low infection, 2 = low-moderate infection, 3 = moderate infection, 4 = high infection, 5 = severe infection) or pustule count on specific plant parts. Where pustules merged, an individual pustule was counted as an area of 2mm2. WPM samples were collected from the fungicide product trial on Sept 27 and inserted into a nucleic acid preservation buffer (NAP buffer) to prevent the degradation of the DNA during transport. Three samples were collected per plot, with two WPM infected leaves included in each sample. These were submitted to the Centre for Crop and Disease Management (CCDM) for fungicide resistance testing.

A survey of WPM was collected from the northern Yorke Peninsula (NYP – 30 paddocks), central Yorke Peninsula (CYP – 11 paddocks) and Mid North (MN – 10 paddocks). Agronomists working in these regions supplied location details of WPM infections. Sampling was performed on Sept 23 and 24. Several WPM infected leaves were collected from each location and inserted into the NAP buffer as above. These were submitted to CCDM for resistance testing.

In the NYP region, the 2021 season was characterised by a dry start and late May break, followed by a wet early winter period (Figure 1). The region then experienced a dry late winter and early spring. Wheat powdery mildew developed later in the 2021 season compared with 2020. WPM infection was observed to develop through the latter part of August as the crop approached GS39, whereas in 2020 infection occurred from GS14 in late June. Different seasonal conditions likely explain the differences in disease development between these years.

WPM spores germinate best at high levels of humidity (>95%) with a temperature range of between 10 to 22°C. Disease development will rapidly decline when temperatures exceed 25°C and humidity lowers however spores can still germinate when humidity declines below 50% due to their high moisture content. Under higher rainfall or free moisture conditions (i.e., rainfall) the moisture can both wash the spores from the leaves or inhibit spores from germinating by causing them to burst (Cunfer 2002; Te Beest et al. 2008).

Results and discussion

Varietal resistance to wheat powdery mildew

Varietal resistance is an important part of powdery mildew management. A total of six varieties were included in this trial in 2021 with a range of resistance levels to determine the benefit of varietal resistance and its interaction with fungicide use. The varieties included Grenade CL Plus⏀ (MS), Mace⏀ (MSS), Scepter⏀ (SVS) and Chief CL Plus⏀ (SVS). Scepter⏀ and Chief CL Plus⏀ were both chosen as they have commonly been grown in the area and field observations indicate that Chief CL Plus⏀ may be more susceptible than Scepter⏀, despite both being rated SVS. Two new lines, Calibre (RAC2721) rated S and IGW6683 with provisional rating of R were also included although no fungicide treatments were applied to these. This was to test their ratings against the WPM population at this site and known commercial cultivars.

Powdery mildew build-up occurred late in the 2021 winter, however, varietal resistance played an important role in the level of infection in the crop canopy (Figure 2). For the four main varieties, increasing the rating from SVS (Chief CL Plus⏀) to MS (Grenade CL Plus⏀) reduced the number of pustules on the leaf flag -1 (F -1) by 96%. Calibre⏀ incurred less

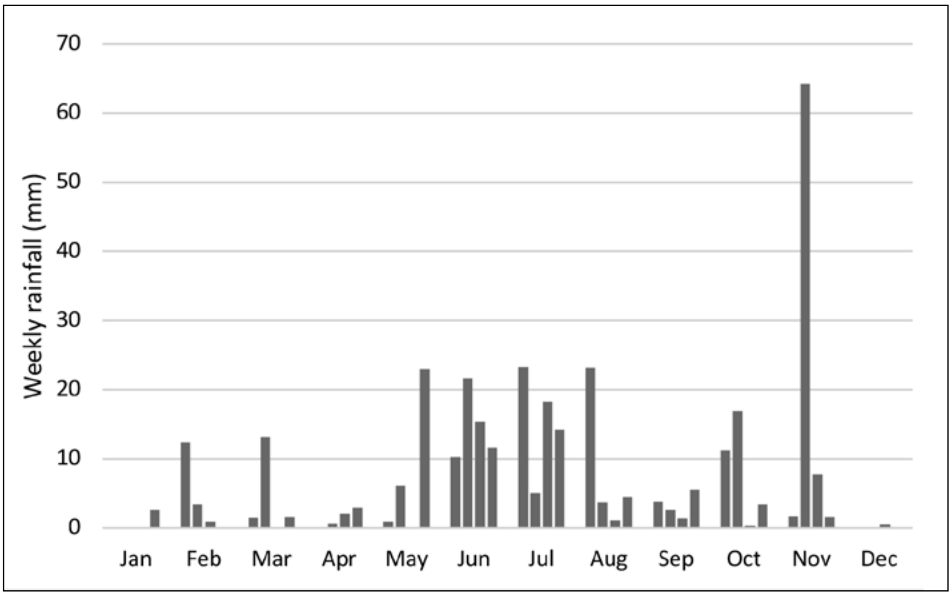


Figure 1. Weekly rainfall at Bute in 2021. April to October rainfall 234mm, 2021 annual rainfall 346mm.

WPM infection than expected given its resistance rating, with results at this site placing it between the MS and R varieties, rather than its current S rating. However, WPM has large genetic diversity, with many different pathotypes likely to be encountered across the cropping regions, meaning that varietal resistances can perform differently depending on which pathotype is present. In accordance with its R rating, IGW6683 performed very well at resisting WPM infection. No WPM infection was recorded on this variety at all, except in one small 4m² hotspot in the 3rd replicate of the trial. In this hotspot infection was observed with average canopy score of 1.5, but no infection on the F -1 on September 22. Tara Garrard and Hugh Wallwork (SARDI) collected a sample of this isolate for culturing and testing in the glasshouse, with their results indicating that where this pathotype is dominant IGW6683 is likely to perform more like an SVS, rather than R. This example highlights the scale of genetic diversity that can be encountered in the field.

Varietal resistance has a significant effect on fungicide performance and their importance. In the variety Chief CL Plus⁽ᴰ⁾, which was shown to have the highest level of susceptibility to WPM, a one spray strategy (Amistar Xtra 800mL/ha applied at GS39) did not significantly reduce the canopy score and the district practice treatment (Epoxiconazole125 500mL/ha# applied at GS32 followed by Amistar Xtra 800mL/ha applied at GS39) reduced the infection score to 1.9 (low-moderate) (Figure 3). Scepter⁽ᴰ⁾ was less susceptible to this WPM population, with the single spray strategy reducing the canopy score of infection from 2.2 (low-moderate) to 1.3 (low). This was equivalent to the district practice treatment. In comparison, the variety tested with the best currently available resistance, Grenade CL Plus⁽ᴰ⁾, had a lower canopy score in the nil fungicide treatment than the other varieties that were treated with a two-fungicide strategy, as did Calibre⁽ᴰ⁾ and IGW6683.

 # The label rate of epoxiconazole for control of WPM is 250mL/ha, 500mL/ha was used due to the expected presence of group 3 fungicide reduced sensitivity and to align the active ingredient loading with other products.

The level of powdery mildew in the canopy was lower than the previous year, but some effect on grain yield was still apparent (Figure 4). Grain yields for Chief CL Plus⁽ᴰ⁾, Scepter⁽ᴰ⁾ and Mace⁽ᴰ⁾ increased by 0.6-0.7 t/ha (11-13%) through the application of fungicide whereas in the more resistant variety Grenade CL Plus⁽ᴰ⁾ there was no yield response. In 2020 the yield response in Chief CL Plus⁽ᴰ⁾ was also 0.7t/ha (17%), but at a lower yielding site this was a larger relative increase.

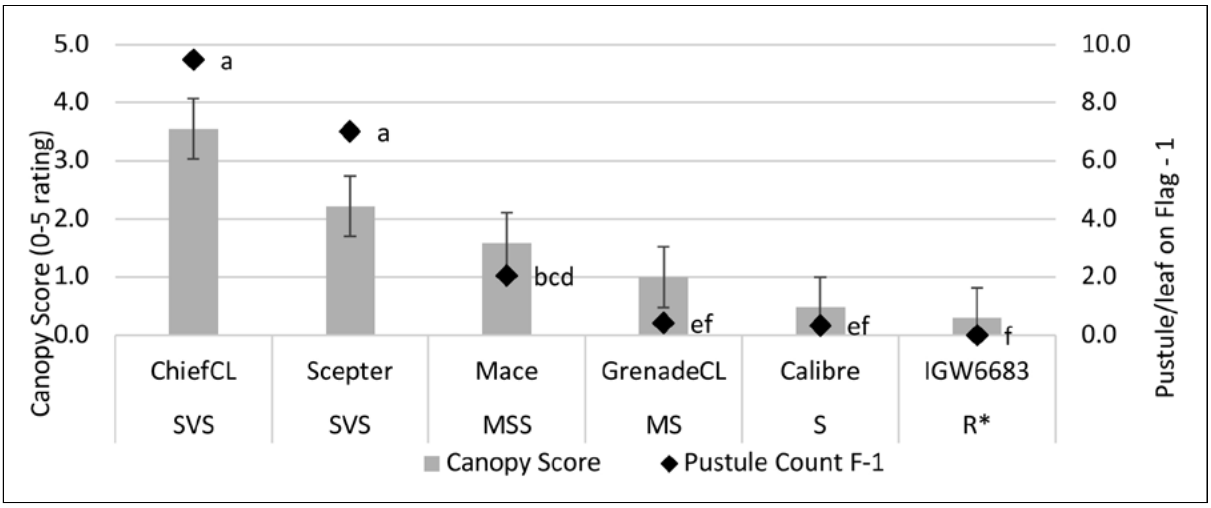


Figure 2. Powdery mildew canopy score (0 = no powdery mildew, 5 = severe infection) and pustule count on F-1 (number of pustules on the leaf flag – 1) for the nil fungicide treatments in the variety * fungicide trial at Bute 22/9/2021. Letters denote significant differences between pustule count (Pr(>F) = <0.001) and error bars show LSD 0.05 for canopy score.

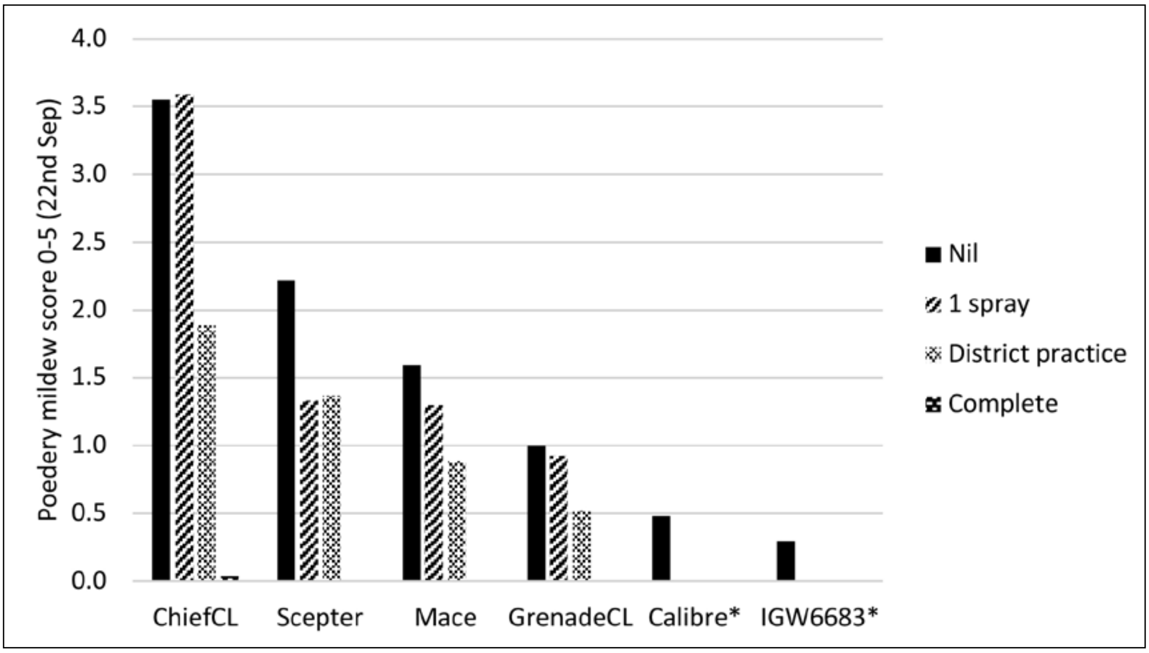


Figure 3. Powdery mildew canopy score (0 = no powdery mildew, 5 = severe infection) in the variety * fungicide trial at Bute 22/9/2021 (Pr(>F) = 0.001, LSD 0.05 = 0.2). Nil = no fungicide, 1 spray = Amistar Xtra 800mL/ha applied at GS39, District practice = Epoxiconaxole125 500mL/ha# applied at GS32 + Amistar Xtra 800mL/ha applied at GS39, Complete = complete control. *Calibre and IGW6683 only received Nil treatment.

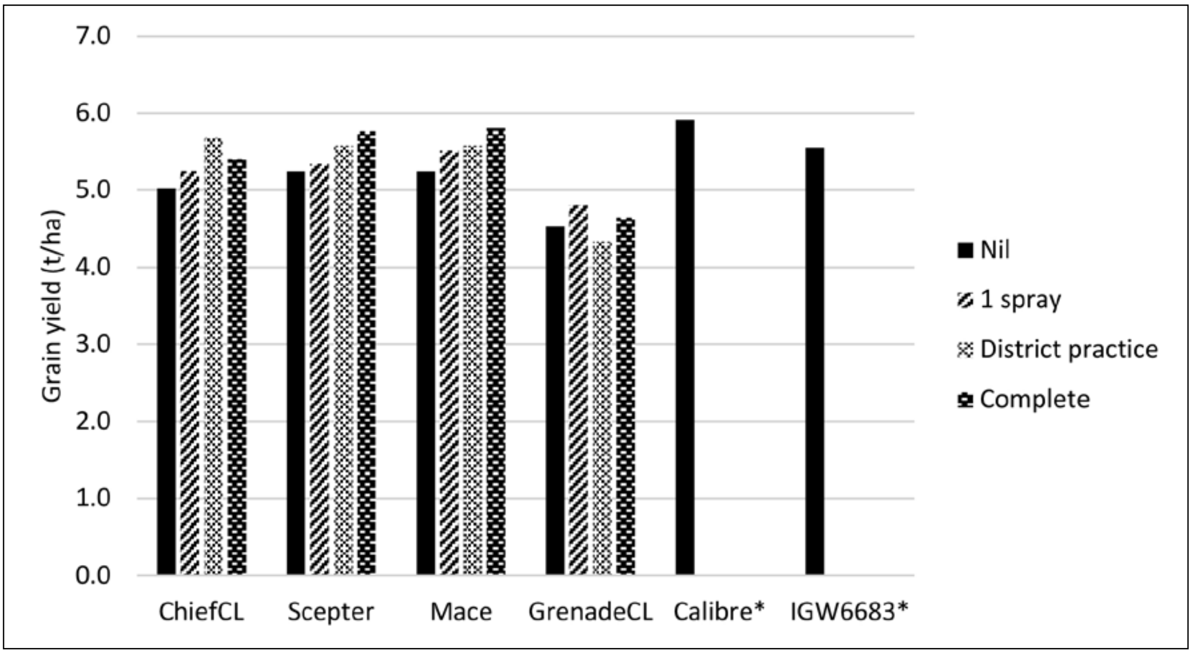


Figure 4. Grain yield (t/ha) for the variety * fungicide trial at Bute 2021 (Pr(>F) = 0.001, LSD 0.05 = 0.51). Nil = no fungicide, 1 spray = Amistar Xtra 800mL/ha applied at GS39, District practice = Epoxiconaxole125 500mL/ha# applied at GS32 followed by Amistar Xtra 800mL/ha applied at GS39, Complete = complete control. *Calibre and IGW6683 only received Nil treatment.

Wheat powdery mildew fungicide resistance and post-emergent fungicide performance

Wheat powdery mildew fungicide resistance was confirmed on the northern Yorke Peninsula (NYP) in 2019. The frequency of the gateway mutation at Cyp51, which is used as a resistance marker due to its association with the presence of other mutations conferring reduced sensitivity to the Group 3 DMI fungicides, ranged from 2.2 to 99.5%, while the group 11 (QoI) resistance mutation was up to 57.5% in one paddock, but with more than half of tested paddocks with no QoI resistance mutation (Table 1). A second survey was conducted in 2021 and the geographical spread of mutations associated with fungicide resistance on the central Yorke Peninsula (CYP), NYP and the mid north (MN) was assessed (Figure 5). For the NYP, CYP and MN the average level of the QoI resistance mutation was 32.6, 11.9 and 10.2% respectively with a large range in frequencies in each of the areas (Table 1). It shows that there has been a significant increase in the frequency of this mutation on the NYP since the first survey in 2019. All paddocks tested in this region now record at least a low level of the resistance mutation, and the median has increased from 0 to 19%. This is consistent with QoI resistance

Table 1. Average, median, minimum and maximum frequency of the G143A mutation in the wheat powdery mildew strobilurin (QoI) target Cytb tested using ddPCR for the samples collected from paddocks across the central Yorke Peninsula (CYP), northern Yorke Peninsula (NYP) and the mid north of SA (MN).

Area	# of samples	Average frequency (%)	Median Frequency (%)	Minimum frequency (%)	Maximum frequency (%)
NYP 2019	17	13	0	0.0	57.5
NYP 2021	30	32.6	19.2	1.7	89.5
CYP 2021	11	11.9	4.6	0.6	38.3
MN 2021	10	10.2	0.8	0.0	89.7

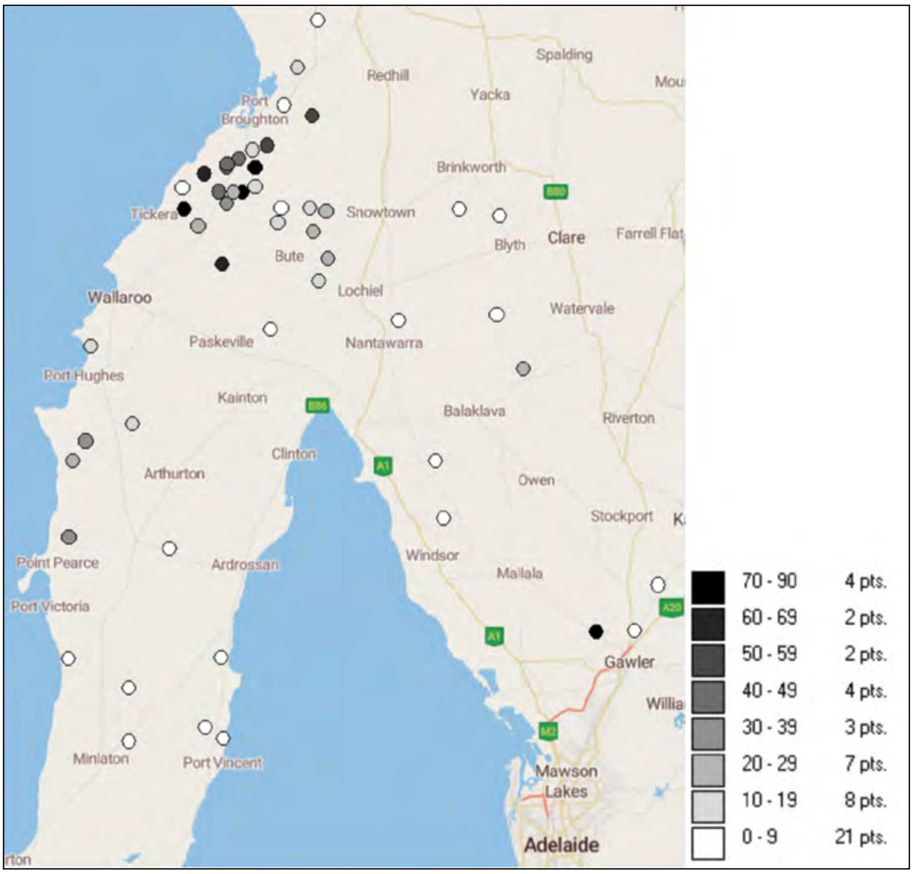


Figure 5. Sample locations and frequency of the G143A mutation in the wheat powdery mildew strobilurin (QoI) target Cytb tested using ddPCR for the samples collected for paddocks across the central Yorke Peninsula, northern Yorke Peninsula and the mid north of SA in 2021, number of points in the legend show number of paddocks sampled in that range.

development in other pathogens, where once resistant individuals have been selected, resistance development occurs quickly with ongoing QoI fungicide selection pressure. The analysis of the NYP samples revealed a higher frequency of the resistance mutation compared with nearby regions, and this is consistent with anecdotal observations from agronomists where WPM control has been more difficult in this region. Frequencies of the QoI resistance mutation in 2021 on the CYP and MN is more comparable with the levels on the NYP in 2019. These results demonstrate where the CYP and MN might be in two years' time with ongoing QoI fungicide use. There is a large amount of variability within each region too, as shown by the range from minimum to maximum between paddocks, this may possibly be explained by fungicide applications within individual paddocks, however not all data is currently available for this analysis.

At the 2020 trial site SE of Bute there was low level of the QoI resistance mutation, in the untreated control with 0.5% frequency. The application of Tazer Xpert, containing QoI fungicide azoxystrobin increased the frequency of the resistance mutation to 9.2% (data not shown). However, the effect of QoI application was inconsistent at this site in 2020, with other QoI treatments having no effect on increasing resistance frequency. In contrast, at the 2021 trial site north of Bute, the untreated had 19% QoI resistance frequency (Figure 6). The application of any fungicide treatment containing a group 11 QoI increased the resistance mutation frequency significantly, to an average of 48.5%. As expected, the application of group 3 DMI and group 7 SDHI fungicides did not affect the frequency of the QoI resistance mutation.

At the 2021 trial site, the application of fungicide did not have any impact on the frequency of the gateway mutation at the DMI target Cyp51. The frequency averaged across four selected treatments, including untreated, was 87%. In comparison the average frequency at the 2020 trial site was 70%. However, due to the limitation with this target, it is not possible to say which of these samples had isolates which may have caused any field failures, as only the gateway mutation is detected, not the mutation(s) actually conferring resistance.

The presence of fungicide resistance and reduced sensitivity will have a significant impact on fungicide performance. In 2020, the group 3

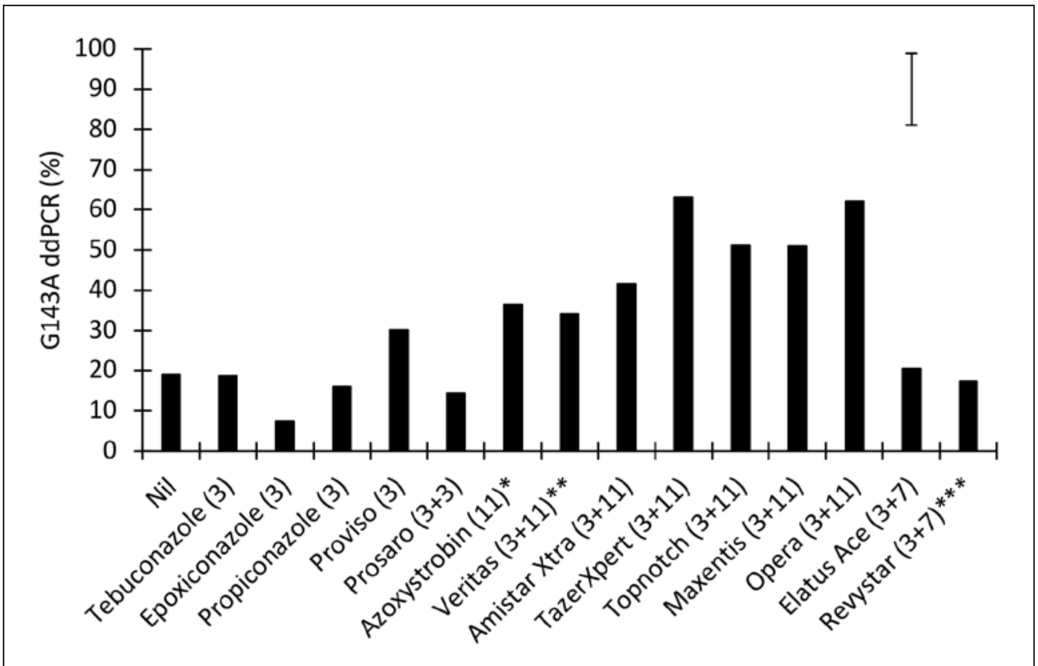


Figure 6. Frequency of the G143A mutation in the wheat powdery mildew Cytb (strobilurin resistance) for a subset of samples collected from the 2021 fungicide product trial using the NAP buffer method. Bar shows LSD 0.05.

* *Straight azoxystrobin (not registered) was included for research purposes in the post-emergent fungicide trial to evaluate the individual fungicide group performance.*

** *Veritas is not currently registered for the control of Powdery Mildew in wheat. It has been included at the maximum label rate for other wheat foliar disease control.*

*** *Revystar is not currently commercially available, registration is pending.*

fungicides ranged in performance from 15 – 73% control of WPM on the leaf, flag – 1, and group 3 + 11 mixtures ranged from 73 – 84% control (Figure 7). Straight azoxystrobin (not registered) was included for research purposes in the post emergent fungicide trial to evaluate the individual group performance, and this produced 64% control. By contrast, the relative performance of these fungicides tended to be poorer in 2021, particularly for treatments containing the QoI fungicide azoxystrobin. The group 3 DMI control ranged from 0 – 62%, and 41 – 67% control from the group 3 + 11 mixtures (Figure 7). Control from the straight azoxystrobin treatment was only 15% in 2021. The general decline in performance from treatments containing the group 11 azoxystrobin can be attributed, at least partly, to the increasing frequency of the QoI resistance mutation at this site. It is likely that the ongoing use of this fungicide group will continue to increase the resistance frequency in the future.

Fungicide resistant mutations in WPM are widespread in SA, it is therefore important to make assessments of individual fungicides in context of the resistance status at the site. However, it is also important to consider that powdery mildew is a population, and the population can shift with use of different fungicides.

At this site in 2021, of the group 3 fungicides, epoxiconazole had the poorest efficacy, not being significantly better than the untreated control for pustule number on the leaf, flag -1 (F -1) (Figure 8). This is a similar result to 2020 (Figure 7). Of the other group 3 fungicides, tebuconazole, propiconazole, and Proviso (prothioconazole) performed similarly to each other, reducing the canopy score to an average of 2.0. The fungicide Prosaro, effectively contains a full label rate of prothioconazole and half rate of tebuconazole, the effect of this is additive with Prosaro producing the best control of the straight group 3 treatments, with a canopy score of 0.9 although this difference did not occur in the F -1 pustule number (Figure 8).

Of the group 3 + 11 mixtures, Veritas, Amistar Xtra, Tazer Xpert, Topnotch and Opera all performed similarly with an average canopy score of 2.1, which is no better than the straight group 3 DMI performance. Opera contains the group 11 fungicide pyraclostrobin applied at 85g ai /ha at full label rate##. Veritas delivers 76 gai/ha azoxystrobin when applied at the full label rate**. The other three have azoxystrobin applied between 120 and 160g ai/ha at full label rate. This indicates that pyraclostrobin is performing in a similar manner to azoxystrobin. The fungicide Maxentis (prothioconazole + azoxystrobin) had the greatest efficacy in terms of

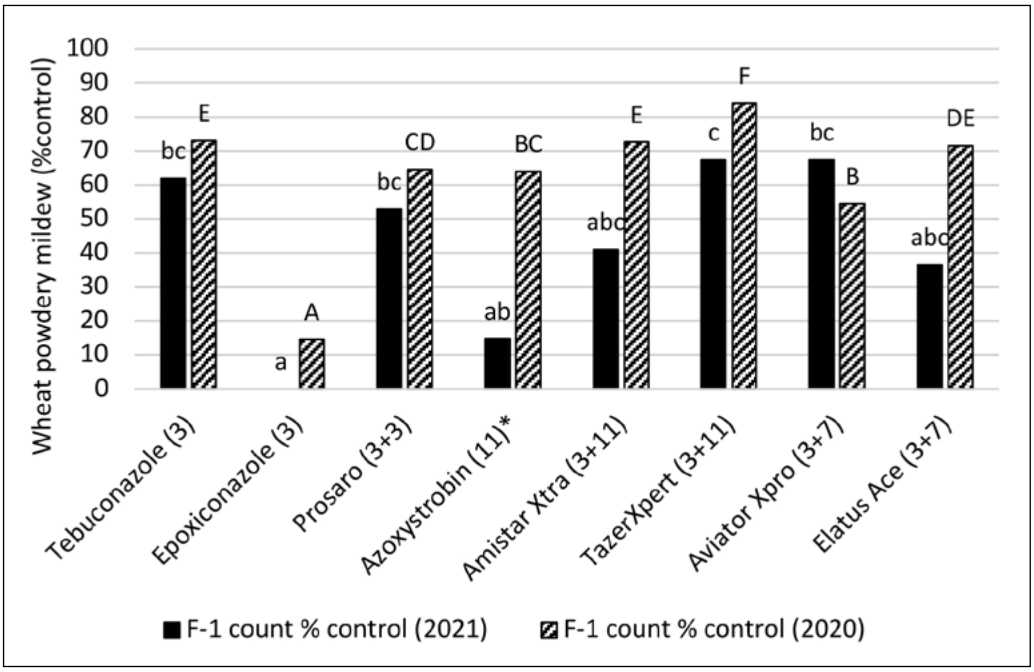


Figure 7. Flag-1 pustule percent control for the post emergent product trial in years 2020 and 2021 at Bute. Statistics performed using log10(1+count) transformation, lower and upper letters represent significant differences for the 2021 and 2020 data, respectively.

canopy score, but it is not clear why this occurred as prothioconazole did not perform better than the other group 3 fungicides.

The label rate of Opera for control of WPM is 500mL/ha, 1000mL/ha was used due to the expected presence of group 3 fungicide reduced sensitivity and to align the active ingredient loading with other products.

*** Veritas is not currently registered for the control of Powdery Mildew in wheat. It has been included at the maximum label rate for other wheat foliar disease control.*

The next generation of fungicides include the new group 7 (SDHI) active ingredients. In both years, 2020 and 2021, these fungicides performed in a similar manner to the straight group 3 fungicides. In both years a straight group 7 active ingredient (not registered) was included in the trials and performed poorly (data not presented). This indicates that the group 3 mix partner in these new fungicides is providing the control of powdery mildew and further development of group 3 reduced sensitivity will reduce the efficacy of these products also.

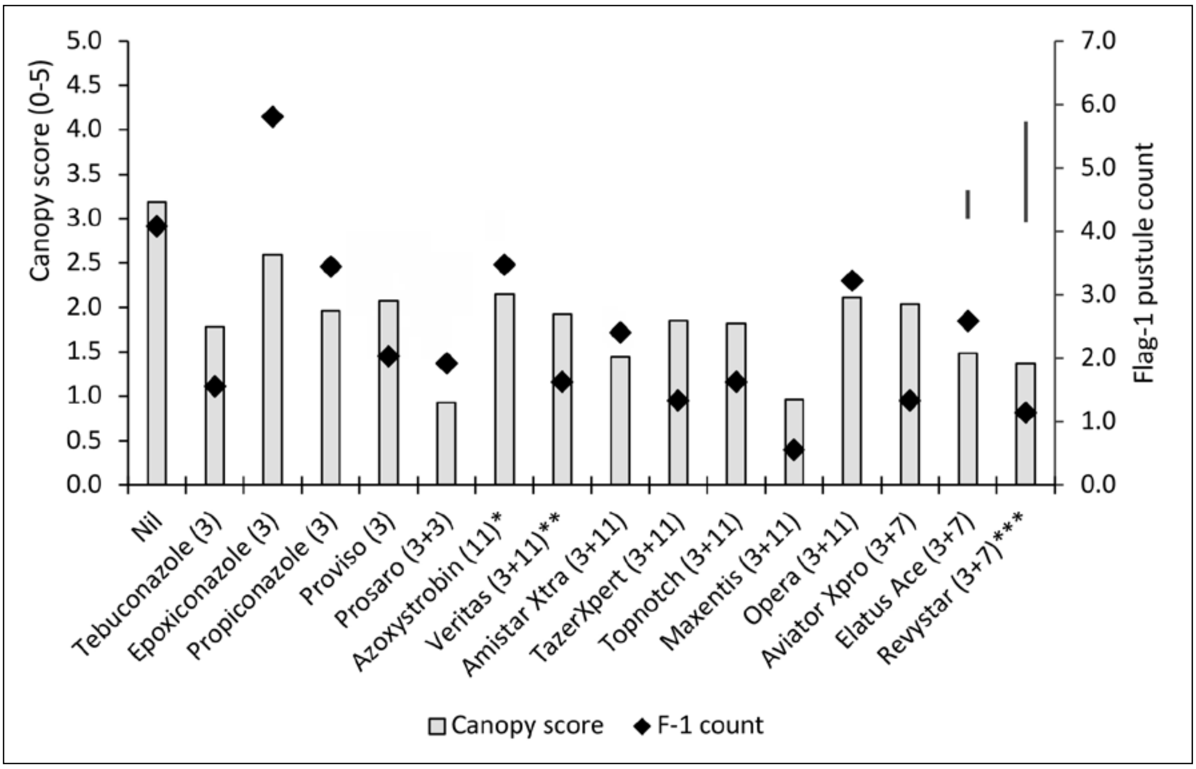


Figure 8. Canopy score and F-1 pustule count for the post-emergent fungicide trial at Bute 2021 assessed on Sept 22. Pr(>F) = <0.001 for both and LSD (0.05) = 0.3 (left) and 1.6 (right) for the canopy score and F-1 pustule count, respectively.

* Straight azoxystrobin (not registered) was included for research purposes in the post-emergent fungicide trial to evaluate the individual fungicide group performance.

** Veritas is not currently registered for the control of Powdery Mildew in wheat. It has been included at the maximum label rate for other wheat foliar disease control.

*** Revystar is not currently commercially available, registration is pending.

Appendix 1. Fungicide treatments applied in trials in 2021 including application rates and active ingredient loading. Application rates were based on the maximum labelled rate for wheat for the control of any disease, not just powdery mildew. Products labelled with * are not registered in wheat.

Product	Rate applied in trials (mL or g per ha)	Active	Group	ai (g/ha)
Nil			0	
Tebuconazole430	290	Tebuconazole 430g/L	3	124.7
Epoxiconazole800	78	Epoxiconazole 800g/kg	3	62.5
Propiconazole 550	230	Propiconazole 550g/L	3	126.5
Proviso 250EC	250	Prothioconazole 250g/kg	3	62.5
Prosaro	300	Prothioconazole 210g/L	3	63.0
		Tebuconazole 210g/L	3	63.0
Azoxystrobin 800*	200	Azoxystrobin 800g/kg	11	160.0
Veritas	630	Tebuconazole 200g/L	3	126.0
		Azoxystrobin 120g/L	11	75.6
Amistar Xtra	800	Cyproconazole 80g/kg	3	64.0
		Azoxystrobin 200g/L	11	160.0
TazerXpert	2000	Epoxiconazole 31.25g/L	3	62.5
		Azoxystrobin 80g/L	11	160.0
Topnotch	600	Propiconazole 200g/L	3	120.0
		Azoxystrobin 200g/L	11	120.0
Maxentis	600	Prothioconazole 100g/L	3	60.0
		Azoxystrobin 133g/L	11	80
Opera	1000	Epoxiconazole 62.5g/L	3	62.5
		Pyraclostrobin 85g/L	11	85.0
Aviator Xpro	500	Prothioconazole 150g/L	3	75.0
		Bixafen 75g/L	7	37.5
Elatus Ace	500	Propiconazole 250g/L	3	125.0
		Benzovindiflupyr 40g/L	7	20.0
Revystar	750	fluxapyroxad 50g/L	7	37.5
		mefentrifluconazaole 100g/L	3	75

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FRAC Code List ©*2021: Fungal control agents sorted by cross resistance pattern and mode of action (including coding for FRAC Groups on product labels), Fungicide Resistance Action Committee

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 SAGIT, the authors would like to thank them for their continued support. The input during this project from Michael Brougham, Hugh Wallwork, Tara Garrard and Nick Poole is gratefully acknowledged.

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

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Keeping fungicide resistance in check and managing septoria tritici blotch in the low rainfall zone and medium rainfall zone

Tara Garrard.

SARDI.

GRDC project codes: CUR1905-001SAX, UOA2003-008RTX, DJP2104-004TRX

Keywords

- Fungicide resistance, net form net blotch, septoria tritici blotch, spot form net blotch.

Take home messages

- Surveys for fungicide resistance are ongoing and agronomists are encouraged to notify SARDI of any suspect cases and submit samples for testing. Updated information is available from SARDI and the AFREN website.
- The efficacy of specific DMI actives where resistance is detected is currently not well understood and is an emerging issue that needs to be monitored.
- 2021 was not a conducive season to septoria tritici blotch (STB) development at the low rainfall zone (LRZ) and medium rainfall zone (MRZ) trial sites. No fungicide sprays were required to prevent yield losses and work in this area is ongoing.

Background

The Australian grains industry now has several cases of fungicide resistance in cereal foliar diseases that are either currently affecting or threatening South Australian growers. Additionally, there are fungicide resistance cases interstate that are likely to show up in South Australia in the near future. Up-to-date advice about the current Australian fungicide resistance situation, as well as management strategies, provides SA growers with the required tools to work with resistance in our systems.

Currently, the main concerns in South Australia are succinate dehydrogenase inhibitor (SDHI) and demethylation inhibitor (DMI) resistance to net form net blotch and strobilurin and DMI resistance in wheat powdery mildew. Strobilurin resistance has now also been detected in wheat septoria tritici blotch (STB) in South Australia, but current prevalence is thought to be localised to the Millicent region in the South East.

Interstate, the other fungicide resistance concerns are SDHI (WA) and DMI (WA and VIC) resistance to spot form net blotch and DMI resistance to barley powdery mildew in WA, QLD, NSW, VIC and TAS.

The Australian Fungicide Resistance Extension Network (AFREN) consists of regional plant pathologists, fungicide resistance experts and communications specialists. This grouping coordinates the provision of up-to-date information and advice as the fungicide resistance situation changes in Australia.

In addition to fungicide resistance tracking and more general management advice, more research is required to understand the specifics of the resistances present. For example, current DMI resistance testing often only uses tebuconazole as an indicator molecule for the DMIs. More thorough testing using the actives used by growers would add significantly greater value. In some instances, further testing is done using plate cultures. Whole plant or in-field testing would further our understanding of resistances and product efficacies relevant to growers. In South Australia for wheat powdery mildew, SAGIT have funded Trengove Consulting to conduct some of this in-field work in the Bute area, where the disease and fungicide resistance are having substantial impacts. Further information on this work will be published in a separate GRDC update paper by the respective authors.

An integral part of managing fungicide resistance is reducing unnecessary fungicide applications and using fungicides in a more targeted approach. Understanding which seasons are conducive to disease development that causes yield loss is an important tool in this decision making. The first year of data on the septoria tritici blotch trials in South Australia have been included in this paper as they demonstrate a non-conducive season for disease development in low and medium rainfall zones.

GRDC have invested in the research on septoria tritici blotch of wheat in the low and medium rainfall zones in the Southern Region (GRDC project: DJP2104-004TRX). Agriculture Victoria and SARDI are working together with input from FAR Australia and NSWDPI to conduct this work. The research aims to better understand the disease outside of the high rainfall zone (HRZ) to enable smarter integrated disease management strategies and to lower unnecessary chemical inputs.

The integrated disease management (IDM) work in STB includes spore trapping and stubble monitoring to better understand the epidemiology of the pathogen. This monitoring requires multiple seasons of data before results can be meaningful. These data will therefore be presented in future years. Plot trials have focused on better understanding the interaction between variety disease resistance rating and yield loss, as well as optimal fungicide timing. These trials are targeted at medium and low rainfall zones.

Methods

Fungicide resistance prevalence

Data contributing to our understanding of the prevalence of fungicide resistance is obtained from the collection of diseased leaf samples sent to the Centre for Crop and Disease Management (CCDM) Fungicide Resistance laboratory for analysis. Samples are collected by growers, agronomists, and pathologists either when fungicide resistance is suspected in a paddock, or through targeted surveys. CCDM conduct the analysis for fungicide resistance by both molecular and culture phenotype methods. Sample results are reported as either lab detection (detected in lab but no evidence of field failure), reduced sensitivity (for DMIs and SDHIs only) or resistance (indicating complete fungicide resistance).

Barley net form net blotch underwent targeted surveys during 2019 when SDHI resistance was first detected on the Yorke Peninsula and samples from other regions have been sent in subsequent seasons.

Wheat powdery mildew has undergone targeted surveys through Trengove Consulting's SAGIT project in 2020 and 2021 on the northern Yorke Peninsula.

In 2021, CCDM confirmed the detection of strobilurin resistance to wheat septoria tritici blotch in the Millicent area and put an open call out for STB samples in the 2021 season.

Septoria tritici blotch IDM

Results in this report will focus on the yield loss by variety trials. These trials will be run for the three years of the project, but only the first year of trials have been completed so far.

Six varieties were selected based on their disease resistance ratings to STB. Ratings for stripe rust and powdery mildew were taken into consideration as well. Varieties and STB resistance ratings are listed in Table 1.

Table 1: Varieties and STB disease resistance ratings used in 2021 yield loss by variety trials.

Table 1. Varieties and STB disease resistance ratings used in 2021 yield loss by variety trials.

STB Rating	Variety
SVS	Impala⚬
S	Scepter⚬
MSS	Hammer CL Plus⚬
MS	LRPB Lancer⚬
MRMS	Orion⚬
MR	Sunlamb⚬

Trials were designed by Statistics for the Australian Grains Industry (SAGI) South and included disease-inoculated plots and disease-controlled plots to develop plus and minus disease for each variety. Trials included six replications and were blocked by disease treatment, plots were 10m x 1.5m. In South Australia, trials were located at Hart Field Site and Booleroo Centre.

Plus-disease plots were inoculated at seedling and mid tiller stages using a conidial suspension in water applied as a spray. Fungicides were applied to minus-disease plots at GS 31 and 39. The GS 31 spray consisted of Elatus Ace (250 gai/L propiconazole + 40 gai/L benzovindiflupyr) @ 500mL/ha and GS 39 epoxiconazole (500 gai/L) @125mL/ha. Disease assessments were conducted at flowering time by assessing percentage of disease severity on each leaf of 10 plants/plot. Trials were harvested and yield values calculated based on harvest weight/plot. Preliminary single site statistical analysis was conducted with Genstat 20th Edition.

Results and discussion

Fungicide resistance prevalence

Fungicide resistance is now prevalent across all grain growing states in Australia as can be seen in Figure 1. This figure demonstrates which states have recorded fungicide resistance and the associated crop, disease and fungicide group. The legend also indicates if the detection is lab, reduced sensitivity or complete resistance. In cereal crops, South Australia has now detected fungicide resistance to barley net form of net blotch in SDHIs and DMIs, wheat powdery mildew in strobilurins and DMIs and wheat septoria tritici blotch in SDHIs and DMIs.

Barley net form net blotch (NFNB)

In 2019, SDHI fungicide resistance to barley net form net blotch was detected on the southern Yorke Peninsula in the Minlaton area. Targeted surveying by CCDM and SARDI determined the resistance to be prevalent throughout the mid and southern Yorke Peninsula. Additionally, DMI resistance was detected in many of the samples, identifying the presence of dual fungicide resistance. The SDHI resistance was detected from the use of fluxapyroxad as a seed treatment. In the paddock of original detection, the crop had been barley for the previous two years with fluxapyroxad used as a seed dressing in both years.

Since 2019, SDHI resistance has been detected in multiple locations on the Eyre Peninsula, in the Mid North and the South-East regions of SA. At the end of the 2021 growing season, SDHI resistance had also been detected in the North-West of Victoria. There are currently three separate mutations present causing the SDHI resistance in NFNB, indicating there are multiple separate occurrences of resistance development.

Although the current testing for DMI resistance to NFNB is confined to tebuconazole in laboratory tests, field reports from affected paddocks indicate commonly used chemistries such as propiconazole and prothioconazole are still effective. Further field research on individual actives within the DMIs for their efficacy to NFNB would be beneficial to industry.

Wheat powdery mildew

Strobilurin fungicide resistance to wheat powdery mildew is prevalent on the northern Yorke Peninsula in the Bute area and has now been detected around Cummins on the Eyre Peninsula, as well as near Naracoorte in the South-East. Laboratory detections

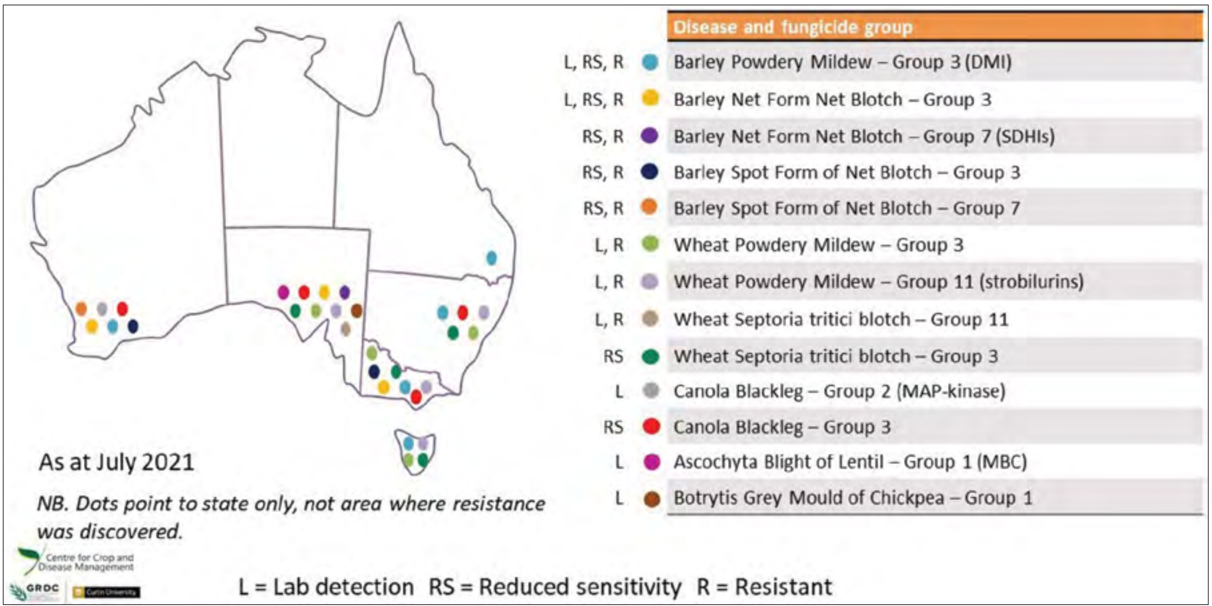

Figure 1. Prevalence of fungicide resistance across Australia in grain crops. Figure produced by AFREN.

for DMI resistance have also been recorded in these areas. These detections are based on what is known as a gateway mutation that has been associated with reduced sensitivity, although on its own it does not confer much resistance.

Wheat septoria tritici blotch

Previous surveys by NSWDPI conducted in 2016 and 2017 identified the prevalence of a resistance mutation in the Cyp51 gene in the pathogen. Results of the survey found the mutation to be present in a high proportion of crops sampled in SA, VIC, TAS and NSW. The mutation significantly reduces the efficacy of DMI fungicides such as tebuconazole, propiconazole and flutriafol.

The occurrence of DMI resistance in STB has also favoured the use of SDHIs and strobilurins. These chemistries are prone to higher levels of resistance arising from a single mutation as opposed to the stepwise mutations seen in DMIs. At the beginning of the 2021 growing season, the CCDM confirmed that there had been a detection of strobilurin resistance in STB in the Millicent region of SA in 2020. This was only a single detection that was taken from a plot at a trial site and was not the result of an in-field failure.

Given the significance of losing this chemistry, CCDM put out an open call for samples in the 2021 growing season to assess whether the mutation was more widely distributed. As of December 2021, CCDM have not detected the mutation elsewhere and the current risk is thought to be confined to the lower South-East region of SA. Growers in this region are advised to avoid the use of strobilurins for STB control in 2022.

Barley spot form net blotch (SFNB)

In Western Australia, DMI resistance in spot form net blotch has been present for several years. In 2020, SDHI fungicide resistance in SFNB was also detected in WA. The resistance has currently not been detected outside of WA and at this stage, SA growers should be aware the resistance has developed but need not be concerned for the 2022 season.

Barley powdery mildew

Resistance to DMIs in barley powdery mildew is now present in every state of the grain growing regions other than South Australia. Currently in SA, DMIs are still very effective at controlling barley powdery mildew to the extent that SARDI have had no reports of the disease in recent years. This reduces the chance of the resistance developing independently in the state and the main cause for concern is interstate resistant strains entering SA.

Fungicide resistance management

Managing fungicide resistance will continue to play an increasingly important role in on-farm decision making as the situation develops in Australia. Growers need to have a good understanding of the disease pressures in their area, as well as any fungicide resistance present or posing a major threat of entering their region.

Fungicide resistance develops when a fungus is repeatedly exposed or over-exposed to the same mode of action group. (No, fungicide resistance occurs all the time and is simply correlated with the population size of the pathogen (See COVID). It is the repeated exposure to the same selection

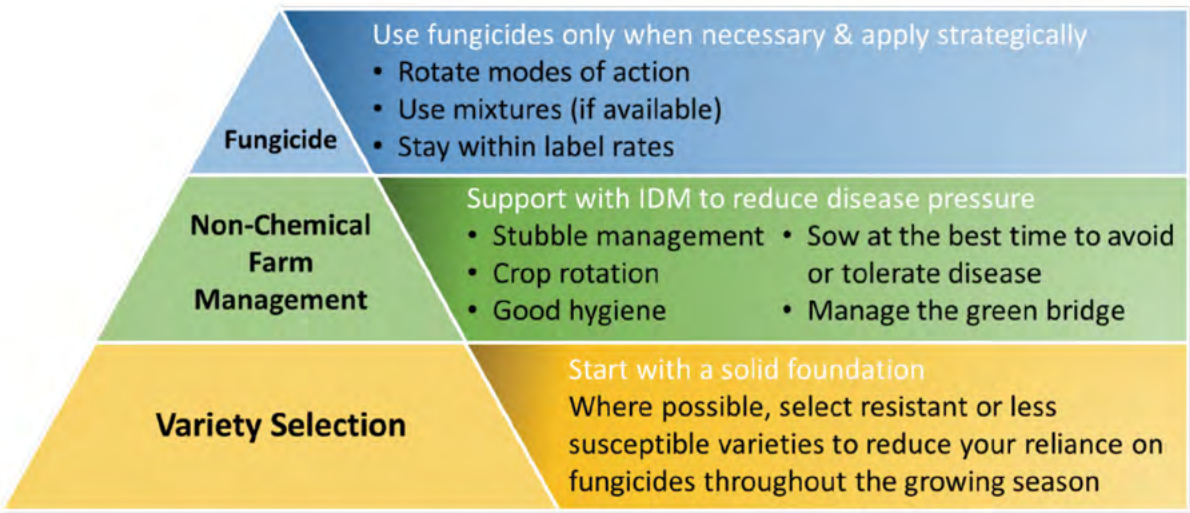

Figure 2. Fungicide resistance management pyramid produced by AFREN.

pressure that determines whether a mutation survives and the rate at which it multiplies). Therefore, fungicide resistance management is focused on reducing the over-exposure, managing disease with other strategies, as well as reducing the chances of additional cases of fungicide resistance developing.

The implementation of integrated disease management is the core of this approach. Figure 2, developed by AFREN, summarises how disease management decision making should be weighed up. The largest emphasis should be placed on variety selection as varieties that contain some level of resistance to the disease provide the strongest and most economical protection.

Following this, non-chemical farm management should be considered and appropriate IDM strategies for your farming system implemented. It is important to note that many endemic diseases such as net blotches, STB and powdery mildew are stubble borne and stubble retention systems in combination with the use of susceptible varieties heavily contribute to high inoculum loads.

Once these factors have been considered and appropriate strategies implemented, then fungicide management should be the last consideration. Fungicide use should be targeted and only used when necessary, rotate modes of action and only use the same active once per season, and use mixtures where possible.

Once fungicide resistance is present within a paddock, it may not be apparent in the first one to two seasons and the affected active may continue to be effective at a paddock scale. Pathogens causing diseases such as net blotch, powdery mildew and STB can reproduce sexually. When fungicide resistance first affects a paddock, it may only be present in a small percentage of the pathogen population, allowing the rest of the sensitive pathogen population to respond to the fungicide. It can take two or more years for the resistant portion of the population to become the dominant portion and for field failure of the fungicide to be observed.

Septoria tritici blotch IDM

Conditions at both Booleroo Centre and Hart Field Site were not conducive for extensive disease development in the 2021 growing season. As a result, disease levels were barely detectable at the Booleroo site and at Hart, the SVS variety Impala had only 11.3% disease (Tables 2 & 3).

Mean yields at the Hart site were numerically higher in the minus-disease (fungicide treated) plots than in the plus-disease (disease inoculated) plots (Figure 3). However, preliminary statistical analysis found no significant differences. The Booleroo mean yields were very variable and minus-disease plot yields were numerically slightly lower than plus-disease plot yields in all varieties except Impala (Figure 4). There were no significant differences in yields at the site.

These trials provide growers with an example of STB disease development in low and medium rainfall zones, how disease development alters depending on variety rating and associated yield losses. In the 2021 season, conditions were not conducive to disease development at these locations and resulted in no significant yield losses. This is important data to inform decision making, as in 2021, fungicide sprays would not have been economical in these areas as yield losses were not significant.

These trials are also being run at medium and low rainfall sites in Victoria. It is expected that after three years of trials, there will be multi-environment data that is able to give growers information about which seasons are conducive for STB yield losses.

Table 2. STB mean disease severity of whole plants at Hart Field Site in 2021.

Rating	Variety	Mean disease severity %	
		+ Disease	- Disease
SVS	Impala⟮D⟯	11.3	0.0
S	Scepter⟮D⟯	8.7	0.0
MSS	Hammer CL Plus⟮D⟯	2.2	0.0
MS	LRPB Lancer⟮D⟯	1.7	0.0
MRMS	Orion⟮D⟯	1.1	0.0
MR	Sunlamb⟮D⟯	0.1	0.0

Table 3. STB mean disease severity of whole plants at Booleroo Centre in 2021.

Rating	Variety	Mean disease severity %	
		+ Disease	- Disease
SVS	Impala⟮D⟯	0.09	0.00
S	Scepter⟮D⟯	0.11	0.00
MSS	Hammer CL Plus⟮D⟯	0.00	0.00
MS	LRPB Lancer⟮D⟯	0.00	0.00
MRMS	Orion⟮D⟯	0.02	0.00
MR	Sunlamb⟮D⟯	0.02	0.00

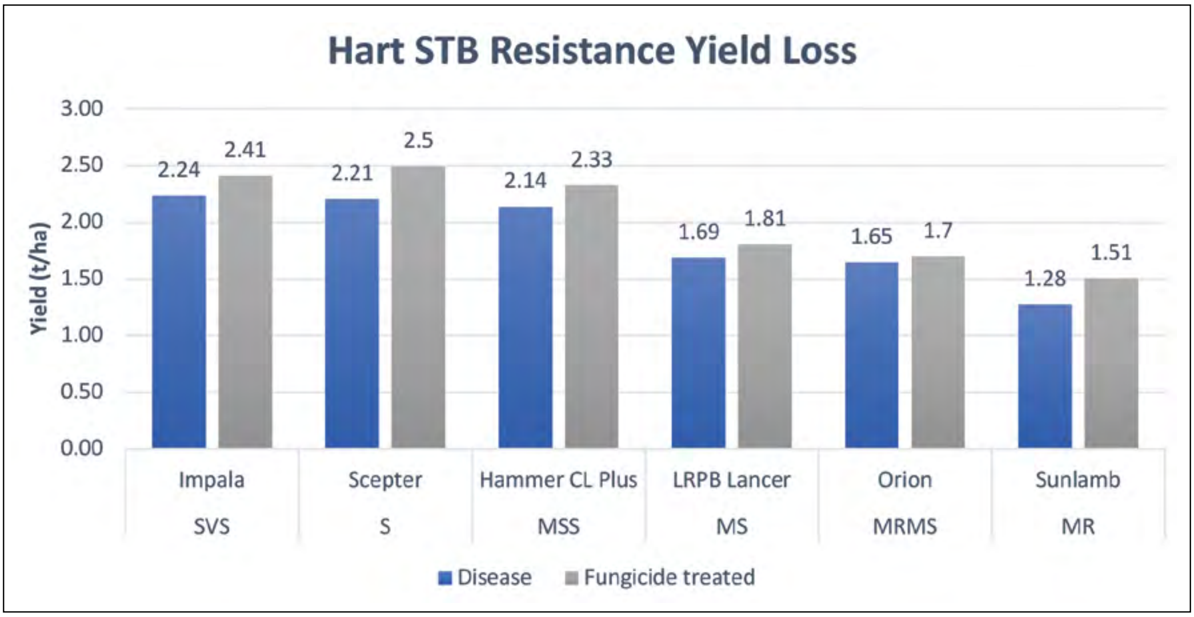

Figure 3. Mean yield losses associated with STB at Hart Field Site in 2021, no significant differences were detected.

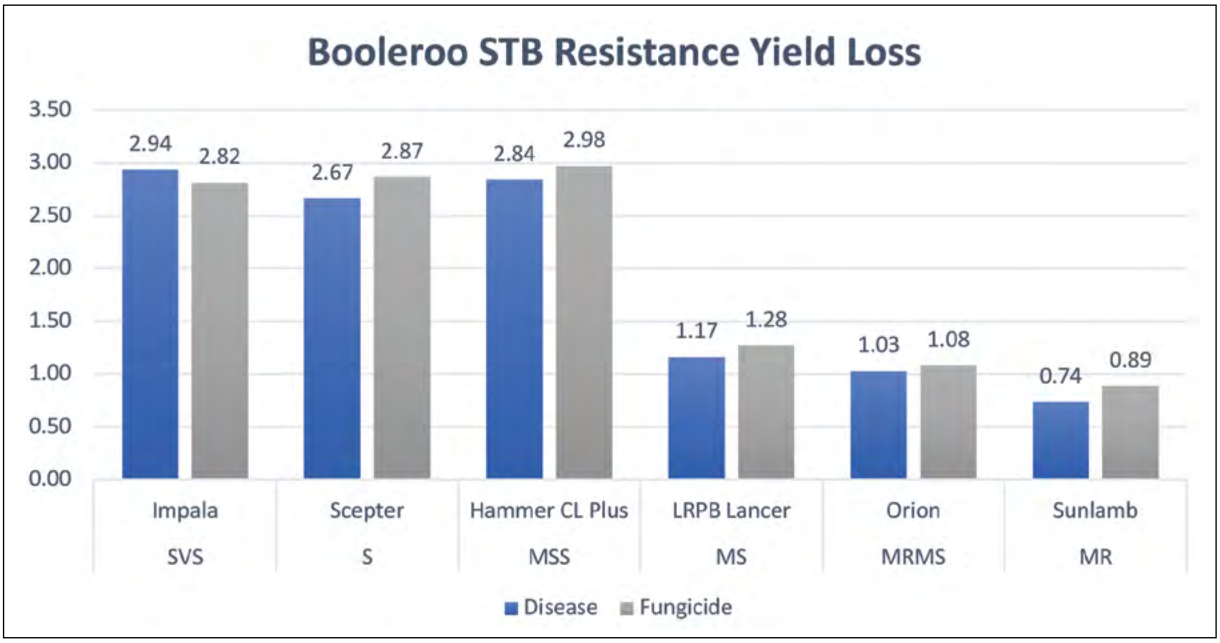

Figure 4. Mean yield losses associated with STB at Booleroo Centre in 2021, no significant differences were detected.

Conclusion

IDM plays a crucial role in fungicide resistance management and a better understanding of how endemic diseases interact with our environment. This paper provides growers and advisers with up-to-date information on which fungicide resistances are present in South Australia, as well as which interstate resistances are currently posing threats. Resistances of most concern in South Australia are NFNB resistance to SDHI and DMIs, wheat powdery mildew resistance to strobilurins and STB resistance to DMIs.

Growers can manage fungicide resistance by knowing which resistances are present in their region, selecting varieties with genetic resistance, using IDM strategies and strategically applying fungicides. Fungicide applications should be limited to spraying only when necessary, avoiding actives if they are resistant in your region, rotating modes of action, only using any one active once per season, and using mixtures where possible.

Septoria tritici blotch field data from the 2021 growing season showed that, at the low and medium rainfall sites tested, seasonal conditions were not conducive for enough disease development to result in significant yield loss, even in SVS and S varieties. Further years of data will better develop our understanding of which years provide conducive disease development so that fungicide use can be targeted to these seasons.

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The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the authors would like to thank them for their continued support. The authors would also like to acknowledge the rest of the AFREN team and the Fungicide Resistance team at CCDM as well as collaborators on the STB project including Agriculture Victoria, FAR Australia, Hart Field Site Group, Upper North Farming Systems, Birchip Cropping Group and AgXtra.

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

Cereal variety disease guide 2021 (https://www.pir.sa.gov.au/__data/assets/pdf_file/0005/384998/Cereal_Variety_Disease_Guide_2021.pdf)

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

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Will increased canola density change blackleg and/or sclerotinia management decisions?

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GRDC project codes: UOM1904-004RTX, UM00051, CSP00187, MGP1905-001SAX, DAN 00177, UM 0051, BLG 206

Keywords

- blackleg, canola, stubble management, sclerotinia .

Take home messages

- Increased canola area will result in increased canola stubble in subsequent years and therefore increased blackleg spore density.
- Spore density can (but not always) result in increased disease severity.
- Increased canola stubble area and the increased area sown to canola will reduce the ability of growers to maintain a 500m buffer between one-year-old stubble and current crops.
- Stubble quantity rather than stubble management has the largest effect on blackleg disease.
- Seasonal conditions will influence whether crown canker or upper canopy infection (UCI) will be more important and potentially warrant control. It will be rare to have severe forms of both versions of blackleg in the same year.
- Crown canker years occur from late sowings, resulting in plants remaining as seedlings during the winter infection period.
- Upper canopy infection years will likely result from early sowing times resulting in plants commencing flowering in late July/early August. Early flowering will result in increased infection and will provide the fungus with more time to cause damage prior to harvest.
- The canola industry is likely to become more reliant on fungicides due to increasing canola production (inability to avoid canola stubble).
- The decision to use a fungicide is not clear cut. You must first understand the disease risk profile of your crop.
- Prior to sowing, use the BlacklegCM decision support tool to identify high risk paddocks and explore management strategies to reduce yield loss.
- Fungicide application for upper canopy infection is a separate decision-making process from crown canker control. Upper canopy infection fungicide application can result in very variable yield returns. You must understand your risk before applying a fungicide.
- Outbreaks of sclerotinia stem rot are sporadic and dependent on the growing season conditions. Saturated canopy conditions for more than 48 hours during flowering favour the development of the disease.
- Current and adjacent paddocks with histories of sclerotinia disease in broadleaf crops over the last four years are a good indicator of potential risk for this season's crop.
- The frequency of canola or lupin in a paddock is very important in determining the risk of a sclerotinia outbreak, as these crops are very good hosts for the disease and can quickly build up levels of soil-borne sclerotia.
- Foliar fungicides for management of the disease are best applied at 20–30% bloom (15-20 flowers off the main stem) for main stem protection.

Increased canola density will increase blackleg inoculum (spore density). However, inoculum is just one factor that is responsible for disease and disease does not always result in yield loss

Every hectare of canola that you grew in 2021 is now canola stubble. The blackleg fungus survives and reproduces on canola stubble, therefore more stubble results in more blackleg-causing spores. Blackleg is caused by a sexually reproducing pathogen. Individual isolates of the blackleg fungus that have attacked the same plant will survive within the plant and then, on the subsequent canola stubble in the following season, these isolates will mate using the stubble as an energy and structural source. All blackleg fungal isolates are one of two mating types and can only mate with a different mating type. Post-mating, sexual fruiting bodies will appear on the external surface of the canola stubble. The blackleg fungus requires moist conditions for mating and subsequent reproduction. Therefore, this process will occur after the break of the season when the stubble stays moist for a considerable period. Typically, spores will be released from the sexual fruiting bodies once the stubble has stayed moist for 3 weeks. If looking at stubble with a magnifying glass, the fruiting bodies that are still developing look like mountains and fruiting bodies that are releasing spores look like volcanoes. Once the fruiting bodies are developed, they will release spores every time it rains for the rest of the growing season.

As long as stubble stays intact, it will release blackleg fungal spores within the growing season. We have measured spore release in canola stubble for up to four years. However, the blackleg fungus will release fewer spores as the stubble and the fruiting bodies age, that is, one-year-old stubble produces more spores that two-year-old stubble, and so on. The main driver, however, is stubble quantity. Spore release per piece of stubble multiplied by stubble quantity (t/ha) will determine the number of spores that are available to infect your crop. Previous work showed that approximately 99% of spores originate from the previous year's crop, that is, older stubble produced fewer spores and has less stubble to harbour the disease.

What about stubble conservation

Previous work measured the effect of raking and burning stubble and we even measured spore release after bush fires. We found that deliberate stubble destruction could reduce spore production by 50% but we were unable to measure any reduction in disease severity. There was still enough spores in the raked and burned stubble to drive disease, that is, spores were not the limiting factor. However, it needs to be noted that the raked and burned stubble was still producing vastly more spores per hectare than two-year-old stubble.

Do modern practices of interrow sowing and full stubble conservation change management decisions

Prior to inter-row sowing, canola stubble was knocked down each year via various tillage practices. The stubble lying in contact with the soil, stayed moist during the growing season and released blackleg fungal spores with each rainfall event. Stubble which was two or three years old produced very few spores, so they were highly unlikely to add to the annual disease severity. However, recent work has shown that stubble that remains standing in modern farming practices stays dry, is not developing sexual fruiting bodies at the same rate as the lying down stubble, and therefore, releases fewer spores but the release is later in the growing season.

But how does stubble conservation and interrow sowing impact on disease

During 2021 we undertook experiments comparing disease severity caused by a range of stubble treatments (Figure 1) representing one-year-old stubble or two-year-old stubble that was either lying or standing and with different stubble quantities (low or high). For each stubble treatment, two times of sowing was undertaken to allow for crown canker development (late sown) or upper canopy infection (early sown).

Impact of stubble treatment on crown canker infection

As expected, the earlier sown plants had significantly less crown canker (internal infection), as indicated by average internal infection scores, than the later sown plants, irrespective of stubble treatment (Table 1). For the later sown plants, neither stubble load nor stubble type had any significant impact on disease level with average internal infection ranging between 75.9–92.5%.

Crown canker severity significantly differed across the stubble treatments for the earlier sown plants (Table 1). Significantly more disease was observed in both the standing and lying, high load, one-year-old stubble treatments compared to all others. No significant differences were seen between any standing and lying treatments belonging to the same stubble load. For the high stubble load treatments,

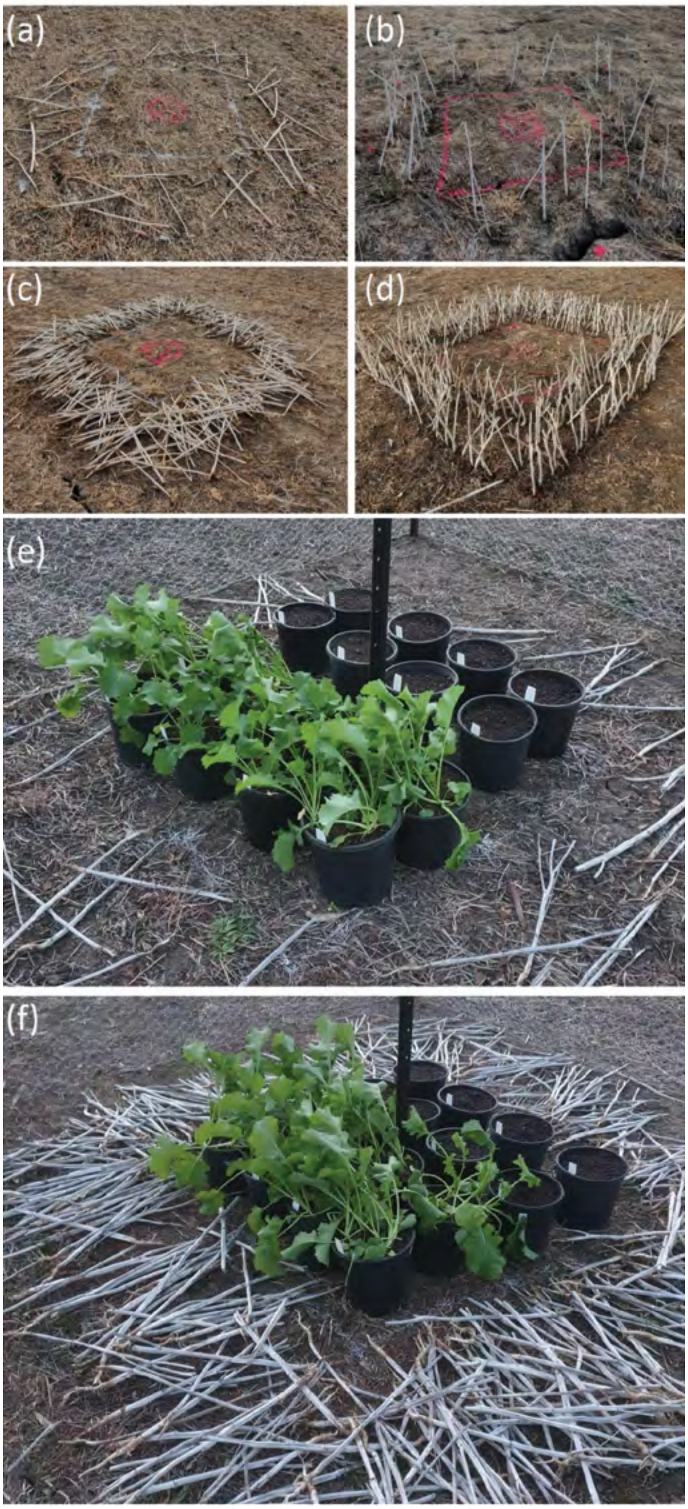

Figure 1. Set up of stubble and plants at Riverside. (a-d) Stubble was set up as either lying (a and c) or standing (b and d) and with either low (a and b) or high (c and d) stubble load. (e-f) Plants were sown in pots at two different times to allow capture of both upper canopy infection (early sown) and crown canker (late sown) infection.

one-year-old stubble caused significantly higher levels of disease than the two-year-old stubble.

Taken together, the data suggest that later sowing leads to more significant crown canker compared to early sowing and that stubble load, rather than stubble orientation, has a significant impact on crown canker disease severity. Stubble age, irrespective of stubble orientation, has a significant impact on disease severity but only at high stubble density.

Impact of stubble treatment on upper canopy infection (UCI)

As expected, the earlier sown plants had significantly higher upper canopy infection severity compared to the later sown plants. Very low levels of upper canopy infection were detected in the late sown plants, as expected, with no significant differences between any treatments.

Similar to the crown canker situation, stubble load had a significant effect on disease severity across all stubble treatments for the early sown plants (Table 1). The impact of stubble orientation did cause some significant differences, but only at the low stubble density. Standing one-year-old stubble caused significantly larger stem lesions (34.5cm) compared to the lying one-year-old stubble (8.3cm) at low density, however no differences were detected in branch infection. Similarly, the standing two-year-old stubble caused significantly larger stem lesions (20.4cm) compared to the lying two-year-old stubble (9.6cm). Again, no difference in branch infection was observed.

These data again support the previous findings that earlier sowing times lead to significant levels of upper canopy infection compared to late sowing times. Furthermore, stubble load has a significant impact on disease compared to stubble age or orientation. Stubble orientation did impact the levels of stem lesion infection when stubble was at low density loads.

What does all this mean for stubble management?

- Avoid one-year-old stubble, that is, keep the 500m isolation rule from the previous year's crop. In this experiment, stubble quantity (high) had significantly higher disease severity for both crown canker and UCI.
- Two-year-old stubble will still produce inoculum and disease but the difference between treatments is minor, therefore the management of two-year-old stubble is probably not warranted.
- The largest effect is time of sowing. Early sown crops get UCI whilst late sown crops are safe from UCI. However, early sown crops are safe from crown canker but late sown crops are vulnerable to crown canker.

Your crop is unlikely to get both crown canker and upper canopy infection (UCI) in the same year, therefore you need to know which form of the disease you need to manage this year.

Findings over the past few years have indicated that most years will be defined as a crown canker or UCI year, but rarely both. In most regions, 2021 was a crown canker year. That is, as an agronomist, you will be managing for either crown canker or UCI. The risk is determined by the timing of sowing (germination).

Table 1. Effect of sowing time, stubble type and stubble load on crown canker (internal infection) and upper canopy infection (stem lesion length and percentage brown branches). Values within the same disease parameter with the same letter indicate no significant difference ($p<0.001$). Spore release was also determined from all stubble types and relative proportions determined by comparing total spore numbers to the one-year-old, lying, high load stubble.

Stubble parameters			Disease severity parameters						Spore release	
			Internal infection (%)		Stem lesion length (cm)		Branch infection (%)			
Stubble age	Stubble orientation	Stubble load	Early sown	Late sown	Early sown	Late sown	Early sown	Late sown	Total spore release	Relative to one-year-old, lying, high stubble (%)
One-year-old	Lying	High	49.8^{c}	85.6^{ab}	81.0^{a}	1.7^{c}	56.7^{a}	4.5^{d}	1.9E+08	100.0
		Low	24.4^{de}	80.6^{ab}	8.3^{c}	0.3^{c}	27.2^{b}	3.0^{d}	1.9E+06	1.0
	Standing	High	54.4^{c}	84.7^{ab}	67.6^{a}	0.4^{c}	69.1^{a}	10.9^{cd}	1.0E+08	55.3
		Low	21.3^{e}	85.9^{ab}	34.5^{b}	1.9^{c}	31.6^{b}	4.8^{d}	1.0E+06	0.6
Two-year-old	Lying	High	36.6^{d}	80.6^{ab}	9.6^{c}	1.3^{c}	32.1^{b}	2.2^{d}	9.1E+07	48.4
		Low	37.5^{d}	75.9^{b}	7.0^{c}	0.0^{c}	17.4^{c}	3.6^{d}	9.1E+05	0.5
	Standing	High	34.7^{de}	92.5^{a}	20.4^{b}	2.2^{c}	26.0^{b}	8.0^{d}	7.4E+07	39.4
		Low	32.5d^{e}	89.4^{ab}	6.7^{c}	1.9^{c}	14.2c^{d}	4.9^{d}	7.4E+05	0.4

Crown canker

Severe crown canker is most likely to develop when plants are infected during the early seedling stage (cotyledon to fourth leaf). The driving factor for seedling infection is the length of time that the plant is exposed to blackleg infection while in the seedling stage. Therefore, the risk of seedling infection, which leads to crown cankers, is very variable from season to season. Once plants progress past the fourth leaf stage, they are much less vulnerable to crown canker. That is, older plants will still get leaf lesions, but the pathogen is less likely to cause damaging crown cankers as the fungus cannot grow fast enough to get into the crown. Typically, plants sown early in the growing season (April) will develop quickly under warmer conditions and progress rapidly past the vulnerable seedling stage whereas, plants sown later (mid-May) will progress slowly and remain in the vulnerable seedling stage for an extended period.

Upper canopy infection (UCI)

UCI occurs when the plants become reproductive early in the growing season, typically when crops commence flowering in late July/early August. This results in cool moist conditions which are conducive for infection events but also allows enough time for the pathogen to cause tissue necrosis prior to harvest. That is, flower and branch infection (UCI) can occur at any time, but it only results in yield loss if it occurs early in the season. This is because the pathogen must grow from the infection point to within the vascular tissue of the plant where the necrosis occurs, causing yield loss. In 2021, crops that commenced flowering in September in many cases did get UCI but the infection did not progress to the vascular tissue and no yield losses resulted.

Management for increased canola intensity

If you have increased canola production, it is almost certain that you have also increased blackleg severity, however you need to determine if increased blackleg severity will also result in an increased yield loss. If your current farming system has low levels of disease, a small to moderate increase in disease will not be yield-limiting. However, if your crops already have some level of yield loss, increased disease severity will increase the yield loss.

- Know your region – high canola intensity and high rainfall = high risk. One in four-year rotations and 500m isolation between this year's crop and last year's stubble reduces risk. Monitor crops for both UCI and crown canker so that you know if you need to retain or change practices.
- Distance to canola stubble – crops sown adjacent to one-year-old stubble will have the highest amount of disease, so maintain a 500m buffer if possible.
- Cultivar resistance – cultivars rated R-MR or above have very low risk of developing crown cankers. MR will develop cankers but only if grown under high disease severity, for example canola/wheat/canola in high rainfall. See www.grdc.com.au/resources-and-publications/all-publications/publications/2020/blackleg-management-guide
- Pathogen population – if you've grown the same cultivar for a number of years and disease severity is increasing, then you sow a cultivar from the same resistance group, you will be at a higher risk of crown cankers.
- Understand the seasonal risk based on sowing/germination timing – are you managing for crown canker or UCI?
- Fungicides – use the BlacklegCM App to determine potential economic returns for fungicides for crown canker.
- Fungicides for UCI – if your crop has blackleg symptoms and commenced flowering in late July/early August, it is more likely to benefit from a fungicide application. Later flowering crops are unlikely to have yield losses. Cultivar resistance to UCI is effective but we do not yet have a reliable cultivar screening system. If your cultivar has had major yield increases from 30% bloom fungicide applications in previous years, it is likely to be susceptible and benefit from fungicide application.

How does sclerotinia develop?

The complexity of the disease cycle of sclerotinia stem rot results in disease outbreaks being sporadic compared to other diseases. There are several key stages that must be synchronised and completed in order for plant infection to occur. Weather conditions must be suitable for the pathogen at each stage. These stages of development include:

- Softening and germination of soil-borne sclerotia
- Apothecia development and release of ascospores

- Infection of petals by air-borne ascospores
- Senescence of infected petals in the presence of moisture and subsequent stem infection

Weather conditions during flowering play a major role in determining the development of the disease. The presence of moisture during flowering and petal fall will determine if sclerotinia stem rot develops. Dry conditions during this time can quickly prevent development of the disease, hence even if flower petals are infected, dry conditions during petal fall will prevent stem infection development.

What are the factors that drive the development of sclerotinia stem rot (Figure 2)

- ***Frequency of sclerotinia outbreaks.*** The past frequency of sclerotinia stem rot outbreaks in the district can be used as a guide to the likelihood of sclerotinia developing this season. Paddocks with a recent history (last 5 years) of sclerotinia outbreaks are a good indicator of potential risk, as well as those paddocks that are adjacent. The frequency of canola and lupin in the paddock can also increase disease risk. Canola and lupin are very good hosts for the disease and can quickly build up levels of soil-borne sclerotia.
- ***Commencement of flowering.*** The commencement of flowering can determine the severity of a sclerotinia outbreak. Spore release, petal infection and stem infection have a better chance of occurring when conditions are wet for extended periods, especially for more than 48 hours. Canola crops which flower earlier in winter (late June—July) are more prone to disease development and exposure to multiple infection events.
- ***Spring rainfall.*** Epidemics of sclerotinia stem rot occur in districts with reliable late winter and spring rainfall and long flowering periods for canola. These provide long periods of canopy wetness necessary for the disease to develop, at least 48 hours or more. Overnight dews generally don't trigger epidemics of the disease.

Key points for low-medium rainfall districts

- Compared to high rainfall districts, serious outbreaks of sclerotinia stem rot will be highly sporadic, once in every 5–7 years, often in years of above average rainfall.
- Background levels of sclerotia are likely to be much less, due to less frequent outbreaks of the disease, reducing disease pressure.

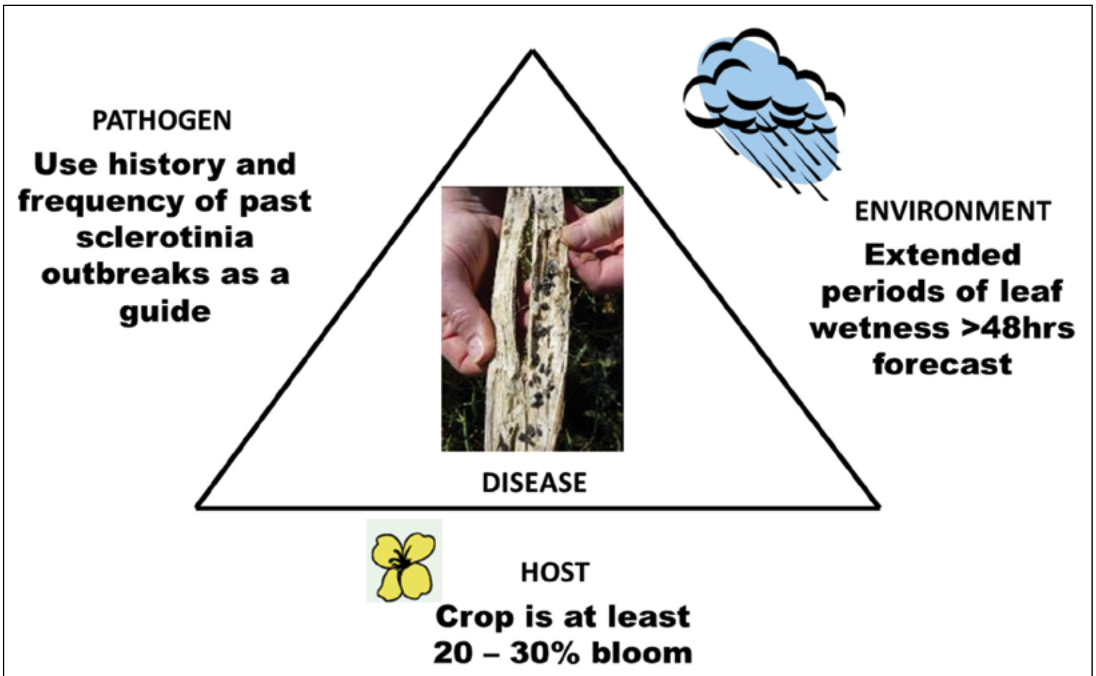

Figure 2. Host, pathogen and environmental factors that drive the development of sclerotinia stem rot.

- Shorter flowering periods for canola reduces the opportunity for the disease to develop to damaging levels and crops canopies are less bulky.
- The intensity of canola in the system is often less, reducing high disease risk situations from high inoculum loads.

Pre-sowing sclerotinia management

Crop rotation

- Rotate canola once in every 4—5 years to reduce build-up of sclerotia.
- Incorporate lower-risk crops into the crop rotation, for example, cereals, field pea and faba bean.
- Separate last year's canola stubble and new seasons' crops by at least 500m.
- Ascospores spread within 100m to 400m of the apothecia.

Burning

- Burning of stubbles and windrows will kill some sclerotia but will not greatly reduce the risk of disease.

Clean seed

- Always use seed free of sclerotia where possible.
- Grade retained seed for sowing to remove sclerotia if in doubt.
- Grain receival standards allow a maximum of 0.5% sclerotia in the sample.

Variety selection

- There are no Australian canola varieties with known resistance to sclerotinia. Some differences may be observed in the level of stem rot in some seasons. This is likely to be related to the timing of flowering and infection events.

Crop management

- Always follow the recommended sowing time and seeding rate for your region.
- Early maturing varieties sown early can be prone to developing stem infection due to the earlier commencement of flowering when conditions are wet for prolonged periods.
- Once flowering starts, the crop becomes susceptible to infection and prolonged exposure to infested senescent petals means greater chance of stem infection.
- Bulky crop canopies can retain more moisture and are conducive to the development of stem infections.
- Wider row spacing or reduced seeding rates can increase air-flow through the canopy, reducing moisture retention and potential for infection.

Use SclerotiniaCM app (see useful resources) to determine the most appropriate management strategies for your district.

Post sowing sclerotinia management — fungicide application

- Use foliar fungicides to prevent early stem infection via infested petals.
- Always use fungicide products that are currently registered in Australia.
- Timing of foliar fungicide application is more important than choice of fungicide product in reducing potential levels of stem infection.
- Foliar fungicide application is most effective before an infection event.
- Application of foliar fungicide at 20—30% bloom stage is most effective in reducing main stem infection and most yield loss by protecting early petals from infection and penetration of fungicide product into the crop canopy to protect potential infection sites from falling petals.
- Multiple foliar fungicide applications may be needed in high-risk-disease districts with a high yield potential. Applications at both 10—20% and 50% bloom provide critical early and follow-up protection from multiple infection events.
- Use high water rates (at least 100L/ha) to achieve good coverage and penetration into the canopy.
- Foliar fungicides generally have an active life of two to three weeks. The protection provided may wear off during the critical infection period or where crops have an extended flowering period. A single fungicide application too early may be ineffectual.

- Foliar fungicides will have no effect on managing basal infections, as this occurs below the soil surface and beyond the activity of foliar fungicides.

Always

- Determine disease risk as your crop enters the flowering period.
- Assess bloom stage, seasonal conditions and weather forecasts to identify the potential risk to your crop.
- Identify how many consecutive wet days are forecasted as the crop commences flowering and the week ahead, especially consecutive wet days of 48 hours or more.
- Monitor crops for disease development and identify the types of infection. Basal and main stem infections cause the most yield loss.

Useful resources

BlacklegCM App for iPad and android tablets

Blackleg management guide (www.grdc.com.au/resources-and-publications/all-publications/publications/2020/blackleg-management-guide)

Canola: the ute guide (https://grdc.com.au/resources-and-publications/groundcover/ground-cover-issue-27/canola-the-ute-guide)

Marcroft Grains Pathology (https://www.marcroftgrainspathology.com.au)

NVT Australia () https://www.grdc-nvt.com.au/login

NSW DPI Winter Crop Variety Sowing Guide (Disease updates, variety resistance, fungicide products) (https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/winter-crop-variety-sowing-guide)

ScleotiniaCM App for iPad and android tablets

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Wheat stripe rust epidemic in 2021 – learnings for 2022

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Keywords

- fungicide management, varietal resistance, head infection, green bridge.

Take home messages

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

Why was there a problem in 2021?

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

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

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

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

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

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

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

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

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

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

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

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

Has the stripe rust pathogen changed again in 2021?

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

What crop stage do these disease ratings relate to?

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

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

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

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

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

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

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

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

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

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

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

Stripe rust management

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

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

Does knowing the pathotype change my in-season management?

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

Will APR be enough?

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

Table 1. Stripe rust rating for Beckom$^{\phi}$, Scepter$^{\phi}$ and Vixen$^{\phi}$ depending on the pathotype present

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

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

When do I pull the trigger on fungicide applications?

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

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

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

Is the aim for the plant to be rust free?

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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Cereal disease update 2022

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Keywords

- fungicide resistance, net form of net blotch, septoria tritici blotch, stripe rust.

Take home messages

- Proactive disease management, which combines options such as variety selection, paddock selection and appropriate fungicide use, provides proven sustainable and economic control of cereal diseases.
- Septoria tritici blotch, an important disease in HRZ, caused yield loss in highly susceptible varieties in field trials in the MRZ (Wimmera) but not the LRZ (Mallee) during 2021. Fungicides did not provide an economic increase in grain yield in either environment.
- Cereal rusts (especially wheat stripe rust) are likely to be very important during 2022 due to increased carry over of rust on volunteers growing over summer because of La Niña conditions in eastern Australia. A proactive strategy to manage cereal rusts in 2022 is essential.
- An increasing range of decision support apps to assist with in-crop disease management are available for free. These apps assist with decisions around in-crop fungicide application.
- Development of fungicide resistance is increasing in cereal pathogens but can be slowed through the adoption of integrated control strategies and prudent use of fungicides.

Background

Implementation of proactive strategies for the control of cereal diseases can prevent avoidable losses when seasonal conditions are suitable for disease. This paper provides an update on the latest research regarding cereal diseases for Victorian growers.

Septoria in wheat

Septoria tritici blotch (STB) (*Zymoseptoria tritici*) is a damaging disease of wheat with large losses known to occur in susceptible cultivars in high rainfall cropping zones (HRZ) of Victoria and South Australia. However, the impact of STB on yield in the medium (MRZ) and low rainfall cropping zones (LRZ) in Victoria and South Australia is less understood, even though this disease has become common in these regions. This increase in STB prevalence is associated with increased use of cultivars susceptible to STB and stubble retention practices. There is much uncertainty about the impact and control of this disease in medium and low rainfall zones.

To determine the impact of STB in Victoria and South Australia's MRZ and LRZ, GRDC is supporting a new investment in research led by Agriculture Victoria, in partnership with the South Australia Research and Development Institute. This investment will investigate the epidemiological conditions required and the impacts of STB in these regions to inform disease management decisions.

In Victoria, seven field experiments were conducted during 2021: three each in the MRZ (Longerenong) and LRZ (Watchupga, with Birchip Cropping Group) and one experiment in the HRZ (Hamilton) of Victoria to understand the conditions that suit the disease progression, study the impact of STB on wheat with different resistance ratings and identify optimal timing for fungicide application during seasons at risk. Similar experiments are occurring in South Australia.

Conditions critical for STB development and spread

At three locations in Victoria (LRZ, MRZ and HRZ), susceptible wheat inoculated with infected stubble were grown. The plots were monitored for disease development and a Pessl weather station (courtesy of ADAMA) collected climatic data that influences disease progress including temperature, relative humidity, precipitation, and leaf wetness.

STB severity was different in each of the three locations. As expected, disease development was greatest in the HRZ and least in the LRZ (Figure 1). The three locations showed different weather conditions (Table 1). Low maximum temperatures combined with high growing season rainfall distributed evenly across the season and larger periods of leaf wetness at Hamilton provided ideal conditions for STB progress and the potential for maximum impact (Table 1). Conditions at Longerenong and Watchupga were only partially or not conducive respectively for STB development and wheat varieties with moderate resistance grown in these conditions are likely to escape the yield losses.

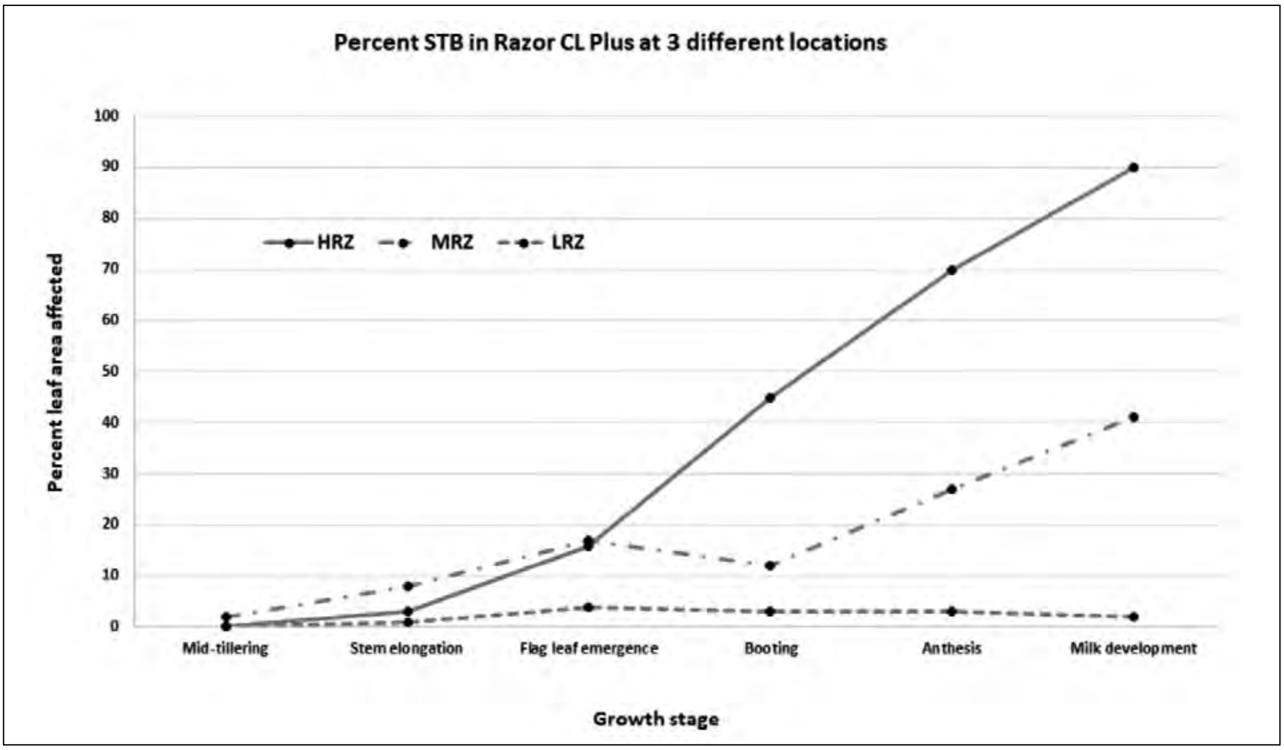

Figure 1. STB severity (% leaf area affected) across time in wheat (cv. Razor CL Plus⁽ᵖ⁾, susceptible to STB) at three different locations in Victoria during 2021.

Table 1. Summary of weather at three locations in Victoria during the 2021 growing season.

Location	Growing season (April to October)			
	Total rainfall (mm)	Mean leaf wetness (hrs/day)	Mean maximum temperature (°C)	Mean number of rain days/month#
Watchupga (LRZ)	172	10	19	11
Longerenong (MRZ)	262	7	17	14
Hamilton (HRZ)	419	20	15	18

#A rainy day is defined as a day with a rainfall of at least 0.1mm or more rainfall.

Yield loss due to STB

Two yield loss experiments, one each at Longerenong (MRZ) and Watchupga (LRZ), were conducted during 2021. Each experiment had six commercial wheat varieties with different resistance/susceptibility to STB, and six replications of plus and minus disease treatments (inoculated with infected wheat stubble) applied in a split plot design.

Good levels of STB developed at the Longerenong site (MRZ) in the susceptible varieties Scepter$^{\phi}$ (S) and LRPB Impala$^{\phi}$ (SVS) which caused 8% and 7% of yield loss, respectively (Table 2). This was due to suitable conditions during the season for the disease to progress with above average rainfall during the spring that supported infection of the top three leaves during grain fill, but also shows that partial resistance can provide adequate disease suppression in this environment.

In contrast, conditions were not conducive for STB at Watchupga (LRZ) where only low levels of STB developed and yield loss was not measured, even in the susceptible varieties Scepter$^{\phi}$ and LRPB Impala$^{\phi}$ (Table 3).

Relative STB severity in each variety corresponded with resistance status at both locations. The suppression in STB levels in the partially resistant varieties demonstrates that avoiding susceptible varieties in these regions should be adequate to manage STB.

Fungicide timing for STB management

Two experiments, one each at Longerenong (MRZ) and Watchupga (LRZ), were conducted to determine the optimal fungicide timing for STB control. Six replications of six fungicide treatments consisting of either single or combinations of seed and/or foliar applied fungicide and an untreated control (UTC) were applied to a susceptible variety, Scepter$^{\phi}$ (S). As limited disease developed at the low rainfall site, only the results from Longerenong will be discussed here.

At Longerenong, all fungicide treatments reduced STB severity compared to the UTC, but the early applications of seed only or a single spray at Z31 were not as effective as any of the three treatments that included a fungicide application at Z39 (Table 4).

Table 2. Septoria tritici blotch severity (% leaf area affected) and grain yield of six wheat varieties at Longerenong, Victoria with high (Max) and low (Min) disease, during 2021.

Variety	Rating	Disease severity (% leaf area affected)						Grain yield (t/ha)		Yield loss (%)
		29-Jul, Z25-31		31-Aug, Z37		25-Oct, Z69-75				
		Max.c	Min.	Max.	Min.	Max.	Min.	Max.	Min.	
Sunlamb$^{\phi}$	MR	0	0	5	2**	0	0	5.2	5.1	-
Orion$^{\phi}$	MRMS	1	0	1	1	8	0**	5.2	5.3	-
LRPB Lancer$^{\phi}$	MS	1	1	7	4**	6	0**	5.6	5.8	-
Hammer CL Plus$^{\phi}$	MSS	2	1*	12	7**	11	0**	5.3	5.3	-
Scepter$^{\phi}$	S	2	1**	24	12**	49	1**	6.2	6.8**	8
LRPB Impala$^{\phi}$	SVS	2	1**	27	14**	56	5**	5.3	5.8**	7

***=statistically significant at 1% lsd; *=statistically significant at 5% lsd, ns=not significant at 5%. a Max. = Maximum disease; Min. = Minimum disease.*

Table 3. Septoria tritici blotch severity (% leaf area affected) and grain yield of six wheat varieties at Watchupga, Victoria with high (Max) and low (Min) disease, during 2021.

Variety	Rating	Disease severity (% leaf area affected)						Grain yield (t/ha)	
		28-July, Z25-31		2-Sep, Z39-49		06-Oct, Z61-71			
		Max.a	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Sunlamb$^{\phi}$	MR	0	0^{ns}	1	0^{ns}	0	0^{ns}	3.0	3.2^{ns}
Orion$^{\phi}$	MRMS	0	0^{ns}	0	0^{ns}	1	1^{ns}	2.7	3.0^{ns}
LRPB Lancer$^{\phi}$	MS	0	0^{ns}	2	1**	1	0**	2.7	2.5^{ns}
Hammer CL Plus$^{\phi}$	MSS	0	0^{ns}	4	2**	2	1**	2.8	3.0^{ns}
Scepter$^{\phi}$	S	1	0^{ns}	9	3**	4	1**	3.0	3.2^{ns}
LRPB Impala$^{\phi}$	SVS	1	0**	10	4**	4	2**	2.9	2.8^{ns}

***=statistically significant at 1% lsd; *=statistically significant at 5% lsd, ns=not significant at 5%. a Max. disease = Maximum disease; Min. disease = Minimum disease.*

Table 4. Septoria tritici blotch severity (% leaf area affected) and grain yield of wheat (cv. Scepter(D) (S)) in response to different fungicide treatments in the Victorian medium rainfall zone (MRZ), Victoria during 2021.

Treatment	Active ingredient	Disease severity (% leaf area affected)			Grain yield (t/ha)
		29-July, Z31*	31-Aug, Z37*	25-Oct, Z73#	
Seed	Fluquinconazole	1[a]	13[a]	34[c]	6.0
Foliar at Z31	Benzovindiflupyr + Propiconazole	2[b]	13[a]	17[b]	6.1
Foliar at Z31 and Z39	Benzovindiflupyr + Propiconazole at Z31 and Epoxiconazole at Z39	2[b]	13[a]	1[a]	6.2
Seed and Foliar at Z39	Fluquinconazole as seed + Epoxiconazole at Z39	1[a]	11[a]	3[a]	6.2
Foliar at Z39	Epoxiconazole	2[b]	23[b]	3[a]	6.1
Untreated control	-	2[b]	23[b]	52[d]	6.1
P		0.00	<0.001	<0.001	0.47
lsd (0.01)		1.14	2.72	4.65	ns

*Means with one letter in common are not significant. *Average of single plot assessments; #Average of the top three leaves of ten tillers per plot.*

Although fungicide application reduced STB severity significantly, no significant yield benefit was observed with any of the fungicide treatments (Table 4).

These trials showed that fungicide applications may not be economical in either the LRZ or MRZ during years with below average to average rainfall conditions. Economical returns may be possible, particularly in the MRZ should above average rainfall conditions occur, and the fungicide strategy will need to reflect seasonal conditions.

Cereal rust

The risk from cereal rusts (stripe rust, leaf rust and stem rust in wheat, leaf rust in barley and crown rust and stem rust in oats) is expected to be very high during 2022. Growers should adjust their rust management strategies to reflect this risk and avoid losses associated with cereal rusts.

Historically, rust pressure is highest in seasons following wet summers that support the widespread growth of volunteer cereals that enable rust to survive and build up over summer (often referred to as the “green bridge”). Following higher levels of rust in cereal crops in eastern Australia compared with recent years, and the late spring and early summer rainfall events in NSW and parts of Victoria, along with predicted La Niña conditions, we expect high rust levels in 2022.

Cereal rusts can only survive from one season to the next on living plant material, which is why rust is more important in seasons following a green bridge over summer. Cereal rusts do not survive on seed, stubble or in the soil.

Another consideration is that cereal rusts are dispersed by wind across very large distances. This means that a widespread green bridge in another area, such as NSW, can increase the risk for Victorian crops and this needs to be considered in management plans.

Strains of stripe rust and disease ratings

Surveillance of cereal rust strains (pathotypes) by the University of Sydney provides us with good information on the strains of rust affecting cereal crops nationally. This knowledge of the strains present nationally is critical for the development of resistance ratings that are published in annual disease guides.

In recent years, there have been changes in the relative prevalence of the strains of stripe rust in eastern Australia. The two stripe rust strains first detected in Australia in 2017 (the 239 strain) and 2018 (the 198 strain) have now become the dominant strains, each representing about 40% of the population, replacing the “Western Australian” family of strains (134) which were dominant since 2003. The ratings in the Agriculture Victoria Cereal Disease Guide (Agriculture.vic.gov.au/cereal-disease-guide) represent the worst case rating for these three strains. Resistance ratings for varieties against each of these individual strains can be found on the NVT website (https://nvt.grdc.com.au/). Unfortunately, it is not possible to predict which strains will dominate in any season, and rapid testing to determine strains is not possible. Therefore, monitoring of crops is still an important component of disease management.

The University of Sydney’s rust surveillance team provides a map of cereal rust strains during the season on the web (see link under “useful resources”). This service is useful for an idea of strain distribution nationally. It takes about 3 weeks from when a sample is collected to when these results are available.

Cereal rust management for 2022

All rusts of cereal crops (stripe rust, leaf rust and stem rust in wheat, leaf rust in barley, and crown rust and stem rust in oats) will most likely require proactive management in 2022 due to increased risk compared to recent years. The summer rain, associated with the La Niña, will support carry over of rust spores on volunteer cereals growing over summer, and combined with the susceptibility of many cultivars, contribute to the heightened risk. It is therefore important that growers take the following steps to reduce their risk:

- Remove the green bridge (volunteer cereals) by mid-March
- Use a current cereal disease guide to revise resistance ratings as there have been many changes due to new strains
- Where possible, avoid susceptible varieties
- Develop a fungicide management plan
- Download the StripeRustWM App for iPads and tablets to support with wheat stripe rust management (see below).

Fungicide resistance in Victoria

Resistance to fungicides is becoming an increasing threat to cereal crops across Australia. The status of resistance to fungicides in important cereal diseases is summarised in Table 5 and is based on work by the Fungicide Resistance Group (FRG) at the Centre for Crop and Disease Management (CCDM at Curtin University).

Following are the latest findings on fungicide resistance in Victoria:

Barley net blotches

On the South Australian Yorke Peninsula during 2019, a mutation in the net form of net blotch (NFNB) pathogen was identified that conferred field resistance to SDHI (Group 7) fungicides which includes key actives such as fluxapyroxad and bixafen. Limited testing during 2021 detected this mutation in six barley samples from Victoria suggesting that this resistance may be widespread across the southern region (Table 6). Mutations in NFNB that confer reduced sensitivity (partial resistance) to SDHI fungicides were also common in the Victorian samples.

A mutation that confers reduced sensitivity to the DMI (Group 3) fungicides was also common in

Table 5. Fungicide resistance and reduced sensitivity cases identified in Victorian and South Australian wheat and barley crops.

Disease	Pathogen	Fungicide Group	Status[A]	Industry implications
Barley powdery mildew	*Blumeria graminis* f.sp. *hordei*	3 (DMI)	Lab detection	May see some reduced efficacy in field. Field resistance detected in WA
Wheat powdery mildew	*Blumeria graminis* f.sp. *tritici*	3 (DMI)	Field Resistance	Some Group 3 DMIs will be ineffective in field
		11 (QoI)	Field Resistance	Group 11 fungicides ineffective
Barley net-form of net blotch	*Pyrenophora teres* f.sp. *teres*	3 (DMI)	Reduced sensitivity	Expect to see reduced field performance with time
		7 (SDHI)	Field resistance (SA) Lab detection (Vic)	Increasing occurrences of field failure expected
Barley spot-form of net blotch	*Pyrenophora teres* f.sp. *maculata*	3 (DMI)	Lab detection	Products still effective but will decline as resistance develops
		7 (SDHI)	Not detected	Field resistance detected in Western Australia but not eastern Australia
Wheat septoria tritici blotch leaf blotch	*Zymoseptoria tritici*	3 (DMI)	Reduced sensitivity	May see some reduced efficacy in field
		11 (QoI)	Field resistance (SA)	Two detections in SA during 2020, but not detected in 23 locations across Victoria and South Australia in 2021

*[A]**Lab detection** - Measurable differences in sensitivity of the pathogen to the fungicide when tested in the laboratory. Detection of resistance in the lab can often be made before the fungicide's performance is impacted in the field; **Reduced sensitivity** – Some reduction in fungicide performance which may not be noticed in the field. Serves as a warning that resistance is developing in the pathogen. Increased fungicide rates as per registered labels may be necessary. **Field Resistance** - Fungicide fails to provide an acceptable level of control of the target pathogen at full label rates.*

Table 6. Mutations associated with resistance and reduced sensitivity to demethylase inhibitor (DMI, Group 3) and succinate dehydrogenase inhibitor (SDHI, Group 7) fungicides detected in net blotch samples from Victoria and South Australia in 2021.

Location	State	Disease present	DMI Reduced Sensitivity		SDHI Resistance	SDHI Reduced Sensitivity	
			Promoter lindel	F489L	*PtSdhC*-H134R	*PtSdhD*-D145G	*PtmSdhC*-N75S
			SFNB	NFNB	NFNB	NFNB	NFNB
n/a	Vic	NFNB+SFNB	-	+	+	-	-
Banyena	Vic	NFNB	-	+	+	-	+
Banyena	Vic	NFNB	-	+	+	-	+
Minyip	Vic	NFNB+SFNB	-	+	+	+	-
Minyip	Vic	NFNB+SFNB	-	+	+	-	-
Horsham	Vic	NFNB+SFNB	-	+	-	-	-
Horsham	Vic	NFNB	-	+	+	+	-
Minlaton	SA	NFNB+SFNB	-	+	-	-	-
Minlaton	SA	NFNB+SFNB	-	-	-	-	-
Minlaton	SA	NFNB+SFNB	+	-	-	-	-
Minlaton	SA	NFNB+SFNB	-	-	+	-	+
Minlaton	SA	SFNB	-	-	-	-	-

the limited testing conducted on Victorian NFNB samples during 2021 (Table 6). Previously, this mutation was observed in NFNB from the Yorke Peninsula of SA and is associated with reduced sensitivity to DMI compounds. These types of mutations provide an early warning that the pathogen is accruing mutations that will eventually enable the pathogen to be resistant to the fungicide.

Within the spot form of net blotch testing, a mutation that confers partial resistance to DMI (Group 3) fungicides was identified in South Australia but not Victoria. This mutation has been detected in Western Australia since 2016 and is associated with reduced sensitivity to some DMI compounds. This detection in eastern Australia provides an early warning that practices are required to slow the development and spread of fungicide resistance.

Septoria tritici blotch

Based on studies conducted several years ago by NSW DPI, it is known that reduced sensitivity (partial resistance) to the triazole (DMI, Group 3) fungicides is well established within the Victorian STB pathogen population. Work is required to establish the current status of resistance to these fungicides in Victoria.

The finding of resistance mutations to strobilurin fungicides (QoI, Group 11) in two Septoria tritici samples collected in South Australia during 2020 was very concerning for growers in the southern region. In vitro testing of these isolates showed a 200-fold increase in resistance to azoxystrobin compared with the susceptible strain. Fortunately, testing of 32 samples collected from Victoria, Southern Australia and New South Wales during 2021 did not detect this mutation suggesting that this mutation is still at a low prevalence. However, this re-enforces the need to adopt strategies to protect the limited range of fungicides that we have available (see below).

Wheat powdery mildew

Resistance to both DMI (Group 3) and QoI (Group 11) fungicides has been detected in Victoria. Analysis of samples from seven paddocks in north-east Victoria were all positive for the mutation associated with resistance to QoI fungicides. This means there will be increasing occurrences of field failure in areas prone to powdery mildew and where susceptible varieties are grown.

Fungicide resistance management

There are five strategies that growers can adopt to slow the development of resistance in pathogen populations and therefore extend the longevity of the limited range of fungicides available:

- **Avoid susceptible crop varieties.** Where possible, select the most resistant crops suitable and/or avoid putting susceptible crops in high-risk paddocks
- **Rotate crops.** Avoid planting crops back into their own stubble or adjacent to their own stubble
- **Use non-chemical control methods to reduce disease pressure.** Delaying sowing, early grazing are examples of strategies that can reduce disease pressure

- **Spray only if necessary and apply strategically.** Avoid prophylactic spraying and spray before disease gets out of control
- **Rotate and mix fungicides/mode of actions.** Use fungicide mixtures formulated with more than one mode of action, do not use the same active ingredient more than once within a season and always adhere to label recommendations.

For more information on the management of fungicide resistance consult the "Fungicide Resistance Management Guide" available from www.afren.com.au

Apps to support in-crop disease management decisions

Apps are available to assist in making decisions around disease management in crop. The apps use models that produce predictions based on information on variety resistance rating, plant growth stage, yield potential and the presence of disease inoculum. The model predictions are compared and validated with field trial data to ensure accuracy and reliability. The models were developed by DPIRD and GRDC with input from AgVic. The apps are available free from the Apple App Store and Google Play.

StripeRustWM App

The StripeRustWM App is available to download on tablets. The app can support decision making around fungicide use for stripe rust management during the season. The app uses information that is specific to a local area or paddock to improve accuracy. Comparisons to field trials have demonstrated a high level of accuracy and reliability.

YellowSpotWM App

The YellowSpotWM App was released during 2021 and is available to download on tablets and smartphones. Its predictions are being developed in line with data from the 2021 season, ready for the 2022 growing season. This app will support in-crop fungicide decisions.

NetBlotchBM App

The NetblotchBM tool will be tested during 2022 and the app will be released during 2023 to help support in-crop fungicide management decisions for the spot and net forms of net blotch in barley. If you would like to help with testing of NetBlotchBM, please contact Anna Hepworth (anna.hepworth@dpird.wa.gov.au), or any of the lead authors of this paper.

Conclusion

In the absence of proactive disease control, yield losses due to diseases can be greater than 20%. The risk from rust diseases is likely to be greater with a wet summer (La Niña) supporting volunteer cereals that carry rust inoculum from one season to the next. It is, therefore, important that plans are developed to effectively manage cereal diseases this season. Disease management plans should consider paddock and variety selection and, where the risk warrants it, the proactive and prudent use of fungicides that avoid overuse to protect their longevity.

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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Useful resources

Agriculture Victoria cereal disease guide (agriculture.vic.gov.au/cereal-disease-guide)

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

Field Crop Diseases Victoria (https://extensionaus.com.au/ fieldcropdiseasesvic1/)

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Understanding the magnitude and spread of insecticide resistance in bluegreen aphids *(Acyrthosiphon kondoi)*

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Keywords

- aphids, carbamates, insecticide resistance, organophosphates.

Take home messages

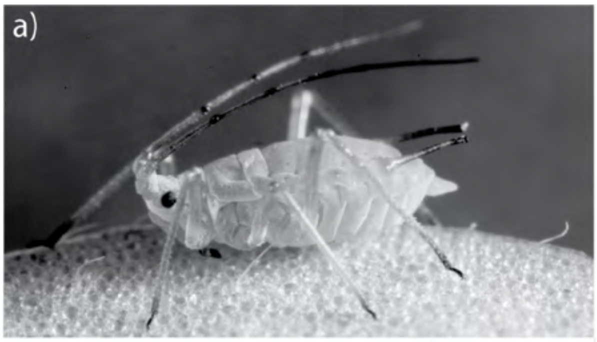
- The bluegreen aphid (BGA; A*cyrthosiphon kondoi*) is a widespread pest of lucerne, pastures and grain legumes.
- Reports from growers and preliminary research suggest some field populations of BGA could be evolving resistance to current insecticides registered for BGA control in Australia.
- Research is underway to determine if control failures following insecticide applications targeting BGA is due to insecticide resistance.
- If BGA has evolved insecticide resistance, growers will require new management strategies to be developed so they can confidently protect their crops from this pest.

Background

Bluegreen aphids (BGA; *Acyrthosiphon kondoi*; Figure 1a) are widespread pests in Australian crops of lucerne, pastures, and grain legumes (Bailey 2007; Clouston et al. 2016; Edwards 2001). Typically, BGA are most abundant during spring, but they can also be problematic in autumn and winter (Figure 1b; Humphries et al. 2012; Lodge and Greenup 1980). BGA cause both direct and indirect damage to crops (Valenzuela and Hoffmann 2015). Direct damage to crops occurs through feeding – mostly on upper leaves, stems and terminal buds (Bailey 2007) – which removes essential nutrients from plants, causing stunted growth, leaf curling and leaf drop. BGA also indirectly damage crops in two ways. Firstly, BGA secrete honeydew on plants which can facilitate secondary fungal growth, ultimately inhibiting photosynthesis and decreasing plant growth (Bailey 2007). Secondly, BGA can spread plant viruses, including cucumber mosaic virus (CMV) and bean yellow mosaic virus (BYMV)(Garran and Gibbs 1982).

Results and discussion

In the past, growers have successfully protected their crops from BGA by spraying organophosphate and carbamate-based insecticides that efficiently control these aphids. However, over the last few years, we have received reports from multiple growers and agronomists in New South Wales and South Australia that have experienced poor control of BGA with these commonly used insecticides (Table 1). Our preliminary investigations suggest these populations may be evolving resistance to organophosphates, Chemical control failures can occur due to a number of reasons, for example spray application issues, low quality chemical and/or environmental reasons. Therefore, further research



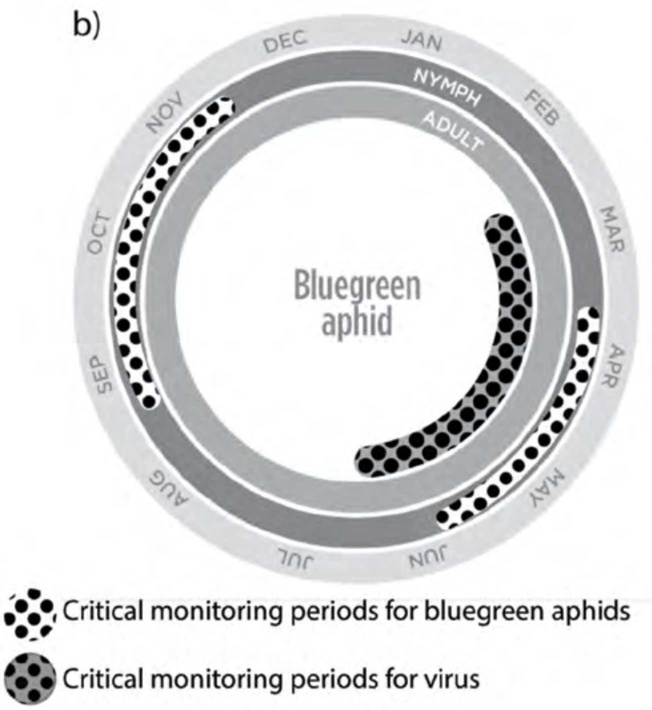


Figure 1. a) Bluegreen aphid adult (non-winged). Photo by Andrew Weeks, Cesar Australia. **b)** Lifecycle, critical monitoring and management periods for the bluegreen aphid.

is required to confirm whether reported control failures are due to evolved insecticide resistance versus other factors.

While the evolution of insecticide resistance is a reasonably common occurrence in some aphid pests (for example, green peach aphids; Myzus persicae), to our knowledge, insecticide resistance has not occurred in BGA previously. Therefore, these reports might constitute the first cases of resistance for BGA globally. We will commence a study in January 2022 (funded by AgriFutures) to quantify chemical tolerances and characterise target gene variation in field populations of BGA. Firstly, we will use laboratory-based bioassays to determine whether BGA populations from key cropping areas in NSW and SA have evolved resistance to organophosphate and carbamate-based insecticides. We will quantify how resistant these populations are by comparing their chemical tolerances to a susceptible BGA population. If these populations are resistant, we will then investigate the heritability of resistance (for example, does the resistance persist over multiple aphid generations). Additionally, we will characterise variation in the target gene, ace (acetylcholinesterase), to determine if any known resistance mutations have evolved in this gene. We will present preliminary results of our bioassays at the February GRDC Grains Research Update.

If our research confirms BGA populations have evolved insecticide resistance, developing updated BGA management approaches must be prioritised to ensure growers can protect their crops from future outbreaks. Such management approaches may involve the registration of new insecticides for BGA, new cultural and biological methods to help

Table 1. Recent reports of bluegreen aphid insecticide control failures.

State	Approximate location	Date first reported	Crop	Insecticides used
NSW	Forbes	Aug 2019	Clover	chlorpyrifos, omethoate, pirimicarb
NSW	Combaning	Jun 2020	Lucerne	omethoate
NSW	Canowindra	Oct 2020	Lucerne	chlorpyrifos, omethoate, pirimicarb
SA	Wanbi	Sep 2020	Lucerne	chlorpyrifos, omethoate
SA	Willalooka	Dec 2020	Lucerne	chlorpyrifos
SA	Keith	Jan 2021	Lucerne	chlorpyrifos, alpha-cypermethrin
SA	Laffer	Mar 2021	Lucerne	chlorpyrifos
SA	Jamestown	Nov 2021	Lucerne	omethoate

growers control BGA populations, and better guides to help monitor and identify BGA within lucerne and grain crops.

Conclusion

While confirmation is required, the anecdotal evidence suggests BGA populations may be evolving some level of resistance to insecticides. In turn, growers may lack a sustainable method of protecting their crops from BGA outbreaks into the future. Upcoming research will rigorously test whether resistance has evolved in BGA populations collected from NSW and SA. As such, we request any information that growers and agronomists can provide on experienced BGA control failures, including details on location, crop type, and insecticide usage.

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 thank the many growers and agronomists, as well as SARDI, for freely providing information about chemical field failures involving BGA. Thanks also to those that have sent BGA samples to our laboratory for testing. AgriFutures has committed funding to explore BGA resistance in 2022.

Useful resources

Bluegreen aphid information and identification guides on pestnotes (https://cesaraustralia.com/pestnotes/aphids/bluegreen-aphid/)

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Bluegreen aphid information and identification guides on PestNotes (https://cesaraustralia.com/pestnotes/aphids/bluegreen-aphid/)

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The impact of insecticides and miticides on beneficial arthropods in Australian grains

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Keywords

- biological control, broad-spectrum insecticide, integrated pest management, selective insecticide.

Take home messages

- A guide has been developed outlining the non-target impacts of insecticides and miticides commonly used in grains on natural enemies of grain crop pests.
- There is great diversity in the impact that these chemicals can have on natural enemies.
- This research has confirmed that many active ingredients considered to be 'soft' or 'selective' have low impacts on beneficials, even under laboratory conditions.
- Our testing revealed that some species demonstrated unexpected tolerances towards active ingredients typically considered to be broad-spectrum products (for example gamma-cyhalothrin).
- Consulting this guide will allow growers to make more informed choices about which active ingredients to use when controlling pests within their crops while preserving natural enemies.

Background

Insecticides and miticides are the primary tool by which Australian grain growers control pests within their crops, with a focus on prophylactic use of broad-spectrum chemicals such as organophosphates and synthetic pyrethroids (Umina et al. 2019). While these are generally effective at preventing yield losses, a downside of the widespread use of these chemicals is the potential for non-target effects (Overton et al. 2021). Some of the organisms that can be inadvertently impacted by pesticides include those which can themselves act as agents of pest control, primarily arthropods that serve as predators and parasitoids of pest organisms (Overton et al. 2021). This can lead to situations where the application of insecticides results in secondary pest outbreaks due to killing off organisms that were providing biological pest control services, with these beneficial organisms and the services they provide often not noticed until they are lost (Naranjo et al. 2015).

While there is a growing awareness of the benefits that these biological control agents can play as part of Integrated Pest Management (IPM) programs, uncertainty surrounding the impact of pesticides on these agents can make IPM programs difficult to implement. To help tackle this issue, guides have been produced for both the cotton (CRDC and Cottoninfo 2021) and horticultural industries (Hort Innovation 2020) in Australia which outline how commonly used insecticides and miticides can affect biological control agents. This has allowed growers and agronomists to make more informed decisions about what chemicals to use in pest control, in particular promoting the use of chemistries that can provide sufficient pest control without compromising locally abundant predators and parasitoids. While these two guides represent a valuable data source, industry differences in the chemicals used, maximum registered field rates, growing environments and key pests mean that a guide specific to the grains industry is required to provide the best possible guidance to growers and advisors. This paper outlines the process of producing this guide and presents our initial findings. A more detailed version of the guide will be available online from early 2022 and updated regularly as more data is collected.

Methods

To determine the impact of insecticides and miticides on natural enemies, we exposed organisms representing key beneficial groups to chemicals in a series of standardised laboratory assays, following protocols developed by the International Organisation for Biological Control (Hassan et al. 1985). Using a Potter Tower, we sprayed Petri dishes with selected chemicals at a rate per cm2 proportional to the labelled application rate per hectare. Chemicals used were selected based on consultation with growers and chemical industry representatives regarding what active ingredients are most commonly used to control invertebrate pests in Australian grains. Chemicals were generally tested at 100% and 10% of the maximum registered field rate (MRFR) within Australian grain crops according to the APVMA (APVMA 2021), unless application rates less than 10% of MRFR are commonly used, in which case this lower rate was tested along with the 100% rate.

After the spray deposits dried (30-60 minutes), individuals from arthropod species representative of key beneficial groups were placed in Petri dishes and mortality was monitored over the next 48-72 hours, depending on species. In accordance with IOBC protocols, we used vulnerable lifecycle stages when conducting testing, with juveniles used in assays on predatory species and adult stages used for testing of parasitoids. The chemicals and arthropods used are shown in Table 1.

Each time an assay was conducted, in addition to the chemicals of interest, we also tested mortality rate of organisms exposed to a “negative” control (water) and a “positive” control – a highly toxic industry standard consisting of either an organophosphate (chlorpyrifos or dimethoate) or a synthetic pyrethroid which was expected to be particularly toxic. Gamma-cyhalothrin was initially used as the representative synthetic pyrethroid, however, a number of assays showed lower than expected mortality rates of organisms exposed to this chemical (see results), so we later switched to bifenthrin.

Arthropods were primarily obtained from the commercial suppliers Biological Services™ and Bugs for Bugs™. However, as hoverflies, spiders and snout mites are not commercially available, we used a combination of field collections and laboratory rearing of these groups to obtain individuals of appropriate life stages for assays.

Results and discussion

A simplified summary of the findings from our assays, along with data from comparable studies from the academic and grey literature, is shown in Table 1. This work is ongoing, and this table should be considered a snapshot of the data available at the time this paper was prepared (Jan 2022) rather than a definitive final document.

This data gives growers options for selecting chemical control for key pests with fewer toxic effects on beneficial predators and parasitoids. In situations where monitoring for beneficials is not feasible, and knowledge of the beneficials present in the local environment is limited, growers can select the overall least toxic chemical from the list that is effective against the target pest. Where growers are able to monitor for important local beneficial species, more nuanced selections can be made. Though difficult to directly quantify, the preservation of pest controlling organisms can have a range of economic benefits to growers, including costs saved due to a reduced need for insecticide application, avoidance of secondary pest outbreaks and a decrease in the likelihood that insecticide resistance will evolve in pest populations (Horne et al. 2008).

These data support the claims around a number of active ingredients marketed as being ‘soft’ or ‘selective’ as having less acute toxic effects on beneficial organisms. These include afidopyropen and flonicamid, which are selective against aphids, and chlorantraniliprole, which is selective against lepidopteran larvae. All resulted in relatively low mortality rates in the majority of the beneficial species tested. Also showing very low levels of harm to beneficials were the two biological pesticides tested, Bt (*Bacillus thuringiensis*) and NPV (nucleopolyhedrovirus), both of which are pathogens of lepidopteran larvae and had minimal impacts on almost all species tested.

While most of our findings were consistent with the international literature and were within expected

Table 1. Impact of insecticides and miticides on beneficial arthropods in Australian grains. Note that some rankings cover several categories of toxicity due to variation amongst species in a group or between studies. Toxicity ratings are based on IOBC protocols, with a rating of L representing <30% mortality, M 30-80%, H 80-99% and VH >99% mortality. Chemicals are listed in descending order from least to greatest overall toxicity when averaged across all organisms tested.

Active Ingredient	Mode of Action	Rate chemical was applied (g/ha a.i.)	Ladybird Beetles	Rove Beetles	Hoverflies	Aphid Parasitoids	Lepidopteran larval parasitoids	Egg parasitoids	Predatory bugs	Lacewings	Predatory Mites	Spiders
Bacillus thuringiensis	11A	1700	L	L		L	L-M	L	L	L-M	L	L
Chlorantraniliprole	28	24.5	L	L	L	L	L-M	L-M	M	L-VH	L	L
NPV	31			L		L		L		L	L-M	L
Flonicamid	29	50	L-M	L	L	L	L-M	L-H	L-M	L	L-M	M
Afidopyropen	9D	5	M-H	L	L	L	L-M		M	L	L-M	L
Paraffinic oil		1584	L	L		L-M	L-M	L	L-M	L	L	L
Indoxacarb	22A	60	L-M	L		L-VH		L	L-VH	L-M	L-VH	L
Pirimicarb[1]	1A	75	L	L	VH	L-VH	L-M	VH	L	L	L-M	L
Emamectin benzoate	6	5.1	L	L	L	M-H	VH	L	M-VH	L	M	L-M
Pirimicarb[1]	1A	500	L-M	L	L-VH	M-VH	M	VH	L-M	L	L-M	
Abamectin	6	5.4	H	L		M-H		L-VH	VH	L-M	L-VH	L-M
Sulfoxaflor[2]	4C	50	L	L		M-VH		L-M	H-VH	L-M	L	L
Spinetoram	5	36	L-M	L		H-VH		M	M-VH	M-VH	L-H	L
Thiodicarb[3]	1A	281.25	H-VH	M		M-VH	L-M		M-H	L	L	L-M
Diafenthiuron	12A	300	H-VH	L		M-VH	VH	L-VH	L-VH	L	M-VH	L
Methomyl	1A	450	VH	VH		VH	M	VH	VH	VH	H-VH	VH
Synthetic Pyrethroids	3A	various	L-VH	L	L	L-VH	L-VH	VH	H-VH	L-VH	L-VH	L-VH
Organophosphates	1B	various	M-VH	VH		M-VH	VH	VH	L-VH	L-VH	L-VH	L-VH

[1] – Pirimicarb has been included twice due to large variations that exist in the MRFR for its use in different crops.

[2] – While Sulfoxaflor is registered at rates of up to 100 g/Ha a.i. for Greenhouse Whitefly, this is an infrequent pest so we have focused here on the more industry relevant rate of 50 g/Ha a.i.

[3] – While Thiodicarb is registered at higher rates for the control of Helicoverpa in maize, such control is often not economical, and thus we have focused here on the more industry relevant rate used in pulse crops.

toxicity rating categories, a few results stand out as being novel. Rove beetles and hoverflies appear to be tolerant of a number of chemicals that produce high mortality rates in other species (Table 1). As the rove beetle individuals used (*Dalotia coriaria*) were obtained from a commercial supplier (Bugs for Bugs™), it is possible their behaviour may not be typical for the group. However, the hoverflies (*Melangyna viridiceps*) used were the first-generation offspring of wild caught individuals collected from a variety of habitats, including parks and gardens around Melbourne and agricultural fields in Western Victoria. This species of hoverfly may be inherently tolerant of commonly used insecticides and miticides, and thus represent a promising candidate for IPM programs, given that their larvae are voracious aphid predators (Soleyman-Nezhadiyan and Laughlin 1998). However, as hoverflies are not currently produced commercially in Australia, promotion of these predators would have to rely on conservation biological control, rather than augmentative measures.

The broad range in mortality rates shown for a number of groups of organisms in response to synthetic pyrethroids (SPs) was unexpected, as chemicals in this group are generally considered broad spectrum insecticides. The majority of low mortality results from this group were for exposure to gamma-cyhalothrin. Initially this was the only SP tested against most groups of organisms – the response of species that showed low susceptibility to gamma-cyhalothrin should be characterised for other SPs in future research, to determine if these results apply only to gamma-cyhalothrin or to SPs more generally.

Conclusion

This guide will allow grain growers and advisors to make informed choices about the chemicals they use in pest control programs. Selective insecticides such as flonicamid, afidopyropen, chlorantraniliprole and biopesticides are low risk options for the treatment of aphids and caterpillars. Where these options are not viable, local knowledge of the predatory and parasitic arthropods common in an area may allow growers to select chemicals that are less toxic to these natural enemies.

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. Further, we would like to thank the many chemical company representatives and researchers who provided consultation when deciding what active ingredients and beneficial arthropod groups should form the focus of this research. Thanks also to those chemical companies who freely provided chemical samples and advice.

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Cesar Australia

https://cesaraustralia.com/pestfacts/

Cotton Info

https://www.cottoninfo.com.au/sites/default/files/documents/Cotton%20Pest%20Management%20Guide%202021%20LR-2.pdf

AUSVEG

https://ausveg.com.au/biosecurity-agrichemical/crop-protection/#IPM

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TOP 10 TIPS

FOR REDUCING SPRAY DRIFT

01 **Choose all products in the tank mix carefully**, which includes the choice of active ingredient, the formulation type and the adjuvant used.

02 **Understand** how product uptake and translocation may impact on coverage requirements for the target. Read the label and technical literature for guidance on spray quality, buffer (no-spray) zones and wind speed requirements.

03 **Select the coarsest** spray quality that will provide an acceptable level of control. Be prepared to increase application volumes when coarser spray qualities are used, or when the delta T value approaches 10 to 12. Use water-sensitive paper and the Snapcard app to assess the impact of coarser spray qualities on coverage at the target.

04 **Always expect** that surface temperature inversions will form later in the day, as sunset approaches, and that they are likely to persist overnight and beyond sunrise on many occasions. If the spray operator cannot determine that an inversion is not present, spraying should NOT occur.

05 **Use weather forecasting** information to plan the application. BoM meteograms and forecasting websites can provide information on likely wind speed and direction for 5 to 7 days in advance of the intended day of spraying. Indications of the likely presence of a hazardous surface inversion include: variation between maximum and minimum daily temperatures are greater than 5°C, delta T values are below 2 and low overnight wind speeds (less than 11km/h).

06 **Only start spraying** after the sun has risen more than 20 degrees above the horizon and the wind speed has been above 4 to 5km/h for more than 20 to 30 minutes, with a clear direction that is away from adjacent sensitive areas.

07 **Higher booms increase drift**. Set the boom height to achieve double overlap of the spray pattern, with a 110-degree nozzle using a 50cm nozzle spacing (this is 50cm above the top of the stubble or crop canopy). Boom height and stability are critical. Use height control systems for wider booms or reduce the spraying speed to maintain boom height. An increase in boom height from 50 to 70cm above the target can increase drift fourfold.

08 **Avoid high spraying speeds**, particularly when ground cover is minimal. Spraying speeds more than 16 to 18km/h with trailing rigs and more than 20 to 22km/h with self-propelled sprayers greatly increase losses due to effects at the nozzle and the aerodynamics of the machine.

09 **Be prepared** to leave unsprayed buffers when the label requires, or when the wind direction is towards sensitive areas. Always refer to the spray drift restraints on the product label.

10 **Continually monitor** the conditions at the site of application. Where wind direction is a concern move operations to another paddock. Always stop spraying if the weather conditions become unfavourable.
Always record the date, start and finish times, wind direction and speed, temperature and relative humidity, product(s) and rate(s), nozzle details and spray system pressure for every tank load. Plus any additional record keeping requirements according to the label.

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

Managing what might bug you this season

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GRDC project codes: CES1904-002RTX, UOM1906-002RTX, CES2001-001RTX, CES2010-001RXT, CES00003, UOA1805-018RTXpeach

Keywords

- green bridge, green peach aphid, insecticide resistance, Russian wheat aphid.

Take home messages

- Our research update provides information and management solutions for growers and advisors on key grains pests which may cause issues this year.
- In 2022, the mild wet weather is likely to increase green bridge risk which can allow some pests to persist over summer and become problems for establishing crops.
- Increasing insecticide resistance is an important consideration for pest management decisions in grain growing regions this year.
- We discuss research updates and management for pests, including Russian wheat aphid (RWA), green peach aphid (GPA) and redlegged earth mite (RLEM).
- Tools and services available to help manage pests include resistance testing for RLEM and GPA; a threshold calculator for the RWA; and a hatch timing tool and severity risk calculator for RLEM.

Background

The ability to efficiently respond to insect pest threats will be paramount to the Australian grains industry in 2022. One of the most important considerations for the grains industry is the increasing need to improve the way insecticides are used in order to reduce the evolution of resistance and protect beneficials. Integrated pest management (IPM) provides guidance on sustainable practice and is most effective when management actions are supported by the understanding of local conditions, on-the-ground information about pest biology, and access to effective alternatives to pesticide use. In this presentation we will:

- provide information on how key grain pests are likely to respond to conditions in 2022
- explore management considerations in response to rising insecticide resistance
- provide information on tools and services that may help growers and advisors stay on top of pest problems this year.

Climate outlook and green bridge risk in 2022

Insect pests are often seasonal, and each species' potential impact on farming systems is influenced by a range of environmental factors. Similar to the conditions seen last year, we are likely to have a mild, wet summer in 2022. The recent switch to La Niña in the Asia Pacific region has meant very wet summers compared to the years prior. Data from the Bureau of Meteorology predicts that rainfall from January to March is likely to be above median for east coast NSW, eastern Victoria and areas near the

NSW-Victoria border. Rainfall and temperatures for Victoria and southern NSW from March to May are not expected to vary significantly from the average. Wet conditions are likely to support above average crop and pasture production through summer. However, it may also have substantial implications for the emergence and persistence of pests. A wetter than average summer means that much of the vegetation that would normally dry out, die off or fail to germinate may flourish throughout the warmer months, providing the opportunity for a so-called 'green bridge' to grow between winter cropping seasons. The green bridge is plant material, crop volunteers and weeds growing between cropping seasons, that creates habitat for pests and diseases to persist and thrive. These out-of-season plants allow pests to move from one season's crop to the next, which can be especially damaging to establishing winter grains crops at the early growth stages. Although green bridges can provide good conditions for beneficials early in the season, they can also be reservoirs of crop diseases and are host to many key pests such as slugs, snails, the diamondback moth, and a range of aphids, including the RWA and the GPA.

Insecticide resistance in Australia

Insecticide resistance is a growing problem for the Australian grains industry. Reliance on a select number of chemical options for management of key insect grain pests has created strong selection pressure that drives the evolution of resistance. Resistance reduces the number of effective insecticide options available and places additional selection pressure on the remaining chemical actives as growers begin to utilise these alternative insecticides more regularly. Modelling work, undertaken by Cesar Australia as part of a GRDC integrated pest management investment for the southern region, has identified specific pests at high risk of evolving future resistances. Pests on this list include species that are already known to exhibit resistance, as well as additional key grain pests that currently are not known to be resistant. The evolution of further resistance in grain insect pests could prove both costly and complex for growers' pest management regimes (Maino et al. 2018a). Importantly, a substantial amount of research on insecticide resistance in key grain pests has been undertaken in the last few years and resources have been developed to help grain growers and advisors manage the risks of resistance. Currently, four major grain pests are known to have widespread resistance to multiple insecticides: cotton bollworm (Helicoverpa armigera), diamondback moth (Plutella xylostella), green peach aphid (Myzus persicae, GPA) and redlegged earth mite (Halotydeus destructor, RLEM). Several other minor grain pests, including silverleaf whitefly (Bemisia tabaci), two spotted mite (Tetranychus urticae), western flower thrips (Frankliniella occidentalis) and onion thrips (Thrips tabaci), have also recorded resistance to insecticides in Australia. Here, we present recent findings relating to the current status of insecticide resistance in GPA and RLEM, including the development of resistance management strategies for these species.

Results and discussion

The green bridge risk and Russian wheat aphid

For most grain growing regions in Australia, Russian wheat aphid (RWA) populations grow within cultivated crops over the winter, disperse into 'over-summer' refuges, and then re-disperse back into emerging crops during an autumn migration. Crop damage occurs when RWA migrate into crops during establishment in high numbers. Conditions in the previous growing season and the intervening summer determine the risk of establishment at crop emergence. Russian wheat aphids cause problems when conditions during the previous spring support successful migration from mature cereal crops onto summer hosts and when over summer conditions allow populations to survive in high numbers. Conditions during autumn will also affect the ability of the RWA to migrate into emerging crops, especially if an early break will create a growth flush of its main host, barley grass (van Helden et al. 2021). Importantly, RWA persistence in green bridges is associated with moderate temperatures of below 20°C, low to moderate available soil moisture (5% in top 0-10cm), with migration occurring when daily maximum temperatures exceed 24°C (Ma and Bechinski 2009). It is important to note, however, that a higher presence of RWA in some green bridge areas does not necessarily mean they will move into crops. Yet, the higher refuge risk does serve as a timely reminder to plan green bridge management and to monitor establishing crops for movement of RWA into paddocks.

Russian wheat aphid management

The ability of RWA to migrate and cause damage is strongly influenced by the green bridge, therefore ongoing control includes eliminating refuge volunteer cereals and grasses in fallows and other areas before sowing. Prophylactic seed treatments are rarely justified. Later planting of winter cereals can delay and reduce early infestations, and agronomic practices to promote crop vigour and dense canopy growth can help to inhibit RWA populations and reduce their impacts. In some circumstances, chemical control may be required. Researchers from SARDI and Cesar Australia have developed a calculator to assist growers and advisors to decide whether spraying for RWA is economically justified (van Helden et al. 2022). This action threshold calculator considers dynamic factors, including the cost of control, cereal market price and aphid numbers. It can be used between GS30 (start of stem elongation) and GS50 (start of head emergence), although monitoring is recommended at GS30. This calculator is the culmination of field trial data collection and analysis over two winter cropping seasons (2018-2019) in south-eastern Australia.

Predicting redlegged earth mite hatch dates and severity risk

The RLEM is another pest common in Australian grain growing regions that is strongly influenced by climatic conditions. Redlegged earth mites enter diapause over summer, emerging as the weather becomes more favourable. Early-season management, therefore, relies strongly on the timing of hatching of summer diapause eggs. Previous research indicates that RLEM eggs in south-eastern Australia hatch after 5mm of rain over 5 days, followed by 10 days of mean temperatures below 16°C (McDonald et al. 2015). This knowledge has allowed us to use weather data (maximum/minimum temperatures and rainfall) to predict when RLEM populations will hatch in different regions each season. Most of Victoria and southern NSW would normally expect to see egg-hatch starting in mid-April. However, with a wet and cooler than average start to the season in many regions, the RLEM prediction models are showing earlier than average hatching dates. A cool start to the season could also create a false break, causing RLEM eggs to hatch but fail to develop, if conditions do not continue to be suitable (for example, in a warm, dry autumn or if there is not adequate food available). The RLEM hatch timing tool has been developed through a GRDC investment (CES2010-001RXT) with contributions from CSIRO, Cesar Australia, the University of Melbourne, and the Department of Primary Industries and Regional Development (DPIRD) to estimate the timing of egg hatch in different locations depending on local climate conditions. The hatch timing tool assists decision making by predicting when eggs will hatch in autumn, which is a key indicator of when to increase crop monitoring.

Best management practice of RLEM involves using Timerite® in the previous season to limit the number of diapause eggs produced in spring. If it is suspected that RLEM may become a problem, growers and advisors can use the severity risk assessment tool featured in the 'Redlegged earth mite: best management practice guide', created by Cesar Australia, Birchip Cropping Group and SARDI. Several factors need to be taken into consideration when using this tool to predict whether the RLEM may become a problem in a paddock, including:

- the type of crop last year
- the type of crop this year
- the extent of broadleaf weed cover in the paddock
- the presence of the species in previous years
- the spray history of the paddock.

A series of questions in the risk assessment tool can be used to assist growers and advisors in weighing up these factors to calculate a 'RLEM risk-rating' for individual paddocks. Recently, through the project 'Future options for the control of RLEM in Australian grain crops' (CES2010-001RTX), the project team has developed an online, interactive risk calculator based on this best practice guide.

Redlegged earth mite insecticide resistance

Control of RLEM is largely reliant on three registered chemical classes: neonicotinoids (as seed dressings), synthetic pyrethroids (SPs), and organophosphates (OPs; as foliar insecticides). Continued use of this limited set of agrochemical options in Australia has resulted in resistance issues (Umina 2007, Arthur et al. 2021). Redlegged earth mite populations resistant to either SPs or OPs, or both, are now present across large areas of Western Australia and parts of eastern Australia. This includes confirmed resistance in multiple populations from South Australia in 2017 and a recent detection in Victoria (Maino et al. 2018b). Cesar Australia is offering a screening service to test for RLEM insecticide resistance within South Australia, Victoria, NSW and Tasmania. The screening is at no-cost for Australian grain growers and advisors, thanks to GRDCinvestment. We are particularly interested in hearing from growers and advisors who have either experienced recent or past chemical control failures or have paddocks that are frequently impacted by RLEM and have required spraying. This service is playing a key role in detecting resistance before it becomes widespread and is assisting in the identification of best control options for growers. During the 2022 season, we will be undertaking field collections of RLEM for resistance screening, so please get in touch if you would like us to collect RLEM from your area.

Insecticide resistance in green peach aphid

The green peach aphid (GPA) is a widespread pest across Australia and is common in many broadacre crops, broadleaf pastures, and horticultural crops. Insecticide resistance in GPA is a major threat to canola and pulse production in Australia. There are diminishing chemical options available to growers, and the functional diversity, prevalence, and severity of resistances encountered in the field is increasing. Importantly, GPA can transmit over 100 plant viruses, which drives many of the insecticide applications targeted at this pest. While resistance issues and regulatory pressures are removing older chemistries from use, new mode of action chemistries — which are increasingly costly to develop, register and apply, and slow to market — are also at risk. This is evidenced by the recent finding of sulfoxaflor resistance evolving in parts of Western Australia. As part of a previous GRDC investment (CES00003), we developed bioassay methodologies and generated baselines for GPA to sulfoxaflor. This allowed us to efficiently investigate the chemical control failures experienced in Western Australia and thus inform industry in a matter of a few weeks (as opposed to six months or more). Current GRDC investment (CES2001-001RTX) is undertaking research to track resistance evolution and map distributions of insecticide resistances in GPA populations across Australia. The project aims to characterise seasonal and regional patterns between GPA host preference, GPA migration, insecticide resistant GPA, and turnip yellows virus dispersal. We will also develop baseline sensitivity data for new chemicals and update the GPA Insecticide Resistance Management Strategy (IRMS) in line with new research. Updating the IRMS will enable more effective management of GPA and support more sustainable use of chemical options. As for RLEM, Cesar Australia also offers a resistance testing service for GPA. We would like to strongly encourage grain growers and advisors across Australia to report any observations of potential insecticide failures.

Green peach aphid and TuYV transmission

Turnip yellows virus (TuYV; formerly known as beet western yellows virus) is primarily spread by the GPA, which has a very high (96%) transmission efficiency. Once acquired, the virus is carried within the aphid for its entire lifecycle and transmitted to healthy plants during feeding. TuYV is difficult to manage because chemical treatments do not work post-infection, as they do with fungal diseases. Therefore, prevention of infection via monitoring and control of GPA is the best defence. Mild temperatures in March and April provide optimal conditions for GPA to multiply and potentially spread TuYV from volunteer canola and brassica weeds to this season's crops. The virus is also thought to be more prevalent in wetter than average years because of the increased risk of aphids entering seedling crops from green bridges. Therefore, growers and advisors will need to be aware of GPA in 2022, especially considering the insecticide resistance issues discussed above.

A proactive approach to manage GPA is essential for limiting the impact of TuYV. DPIRD and Cesar Australia are currently testing an early warning system to support proactive management of TuYV epidemics in Australian canola crops. As part of the program, agronomists throughout Western Australia, Victoria and southern NSW deploy sticky traps which are regularly sent to DPIRD where captured aphids are tested for TuYV using a rapid and sensitive RNA detection technique. The project also includes leaf sampling when the canola crop is at GS30 (stem elongation) to assess levels of virus infection. The project deployed sticky traps at 16 locations in Victoria and southern NSW in 2021 (Figure 1). A high prevalence of the virus was detected in aphids caught on sticky traps in 2021, with large numbers of aphids (including GPA) caught, and TuYV detected in the crop at 10 of the 16 sites tested (1% to 86% infection). In 2020, TuYV was detected at all 13 locations tested (1% to 58% infection).

Insecticide resistance management

Insecticide resistance management strategies have been developed for the four main resistant grain pests as well as a number of best management practice guides that provide information on applying integrated pest management practices in the field, including for cotton bollworm, diamondback moth, GPA and RLEM. To give growers and advisors easy access to up-to-date and relevant information, we are developing a new online platform called AgPest (being developed under AGPIP). This website will provide a central portal through which existing resources can be accessed as well as provide access to new decision-aid tools for management of insecticide resistance in grains. The platform will host up-to-date information on known resistant pests, maps that display known resistances across Australia, resources on beneficial insect stewardship

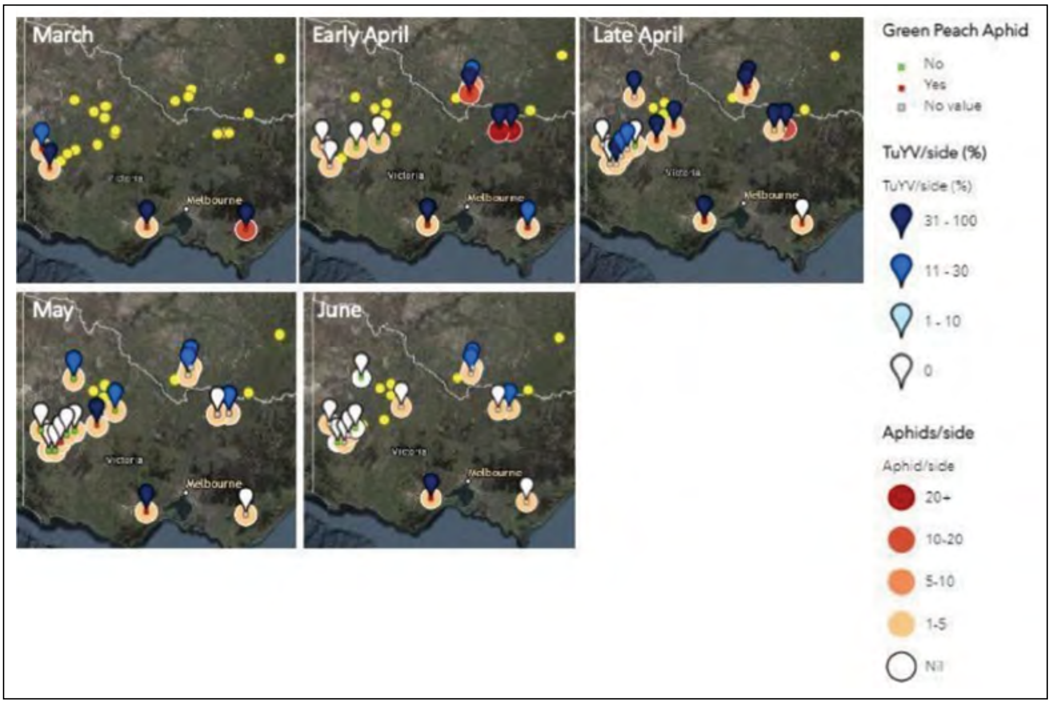

Figure 1. Site location and density by month of turnip yellows virus and GPA detected across 16 sites in Victoria in 2021.

(including information on insecticide toxicities for different natural enemy species) and access to resistance management resources.

Conclusion

Some important factors to be considered heading into 2022 are the green bridge harbouring pests over summer and the rising levels of insecticide resistance in key crop pests. The use of timely monitoring and pro-active management of risk factors can help to keep pests below threshold levels and reduce the need for extensive chemical control. If you need to identify pests or suspect resistance in any of the at-risk pests mentioned above, you can contact the Cesar Australia PestFacts south-eastern team for more information.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the authors would like to thank them for their continued support. The TuYV work was funded by DPIRD Boosting Grains Science Partnerships project 2019SP02. AGPIP is a collaboration between the Pest & Environmental Adaptation Research Group at the University of Melbourne and Cesar Australia. The program is a co-investment by the Grains Research and Development Corporation (GRDC) and the University of Melbourne, together with in-kind contributions from all program partners. We also thank all of our project partners including South Australian Research and Development Institute (SARDI), Department of Primary Industries Research and Development (DPIRD), Queensland department of agriculture and fisheries (QDAF) and NSW department of primary industries (NSW DPI).

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Pest Facts south-eastern (https://cesaraustralia.com/pestfacts/)

How well will Russian wheat aphid cross the green bridge this season? (https://cesaraustralia.com/pestfacts/russian-wheat-aphid-green-bridge-2021/)

Redlegged earth mite best management practice guide – Southern (https://grdc.com.au/resources-and-publications/all-publications/publications/2020/redlegged-earth-mite-best-management-practice-guide-southern)

Redlegged earth mite hatch timing tool (https://cesaraustralia.com/resources/redlegged-earth-mite-hatch-timing-tool/)

Redlegged earth mite seasonal risk estimate (draft version) (https://cesaraustralia.shinyapps.io/rlemseasonalrisk/)

Turnip yellows virus early warning system (https://www.agric.wa.gov.au/canola/turnip-yellows-virus-early-warning-system)

Insecticide resistance in the southern region: current status, future risk and best management practices (https://grdc.com.au/insecticide-resistance-in-the-southern-region)

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FEBRUARY 2022 LIVESTREAM PROGRAM

NB. All times are Australian Eastern Daylight Savings Time (AEDT).

Program Day 5 – Improved nutrition and soil management

Wednesday 23 February, 9am AEDT

Start time	Finish time	Topic	Presented by
9:00	9:05	**Welcome/Introduction to day five**	*GRDC Representative*
9:05	9:35	**Protein mapping – getting more bang for your buck**	***Edward Scott,*** *Field Systems*
9:35	10:05	**Long term Nitrogen management strategies: implications for productivity, profit and sustainability**	***James Murray,*** *Birchip Cropping Group*
10:05	10:35	**An informed approach to phosphorus management**	***Sean Mason,*** *Agronomy Solutions*
10:35	10:50	*Morning Tea Break*	
10:50	11:20	**Clearing your headspace and the lockdown blues**	***Don Elgin,*** *Australian athlete*
11:20	11:50	**Liming & acidity - the economics of 'rule of thumb' applications**	***Lisa Miller,*** *Southern Farming Systems*
11:50	12:00	**New knowledge & practices to address subsoil acidity**	***Ruby Hume,*** *University of Adelaide (PhD Candidate)*
12:00	12:30	**Amelioration strategies for sandy soils - picking the best tool for your situation**	***Therese McBeath,*** *CSIRO*
12:30	12:40	*Close and evaluation*	*GRDC Representative*

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Protein mapping – getting more bang for your fertiliser buck

Edward Scott.

CropScanAg Solutions.

Keywords

- Grain protein concentration, nitrogen, protein mapping, variable rate

Take home messages

- Wheat grain protein concentrations of less than 11.5% generally indicate that nitrogen (N) supply was insufficient for a crop to meet its water limited yield potential.
- If this 'rule-of-thumb' is applied across a landscape, a spatially referenced wheat grain protein concentration map is analogous with an 'N adequacy' map.
- This layer can be used in conjunction with targeted deep N soil sampling as a basis for site-specific N inputs to reduce both instances of yield loss due to N undersupply and adverse environmental/economic consequences associated with N oversupply.
- Research conducted in 2019/2020 across five paddocks (511.4ha) in southern NSW supported the use of wheat protein mapping as a basis for site-specific N.

Introduction

Fertiliser prices have put the use of variable rate technology front and centre of input decisions for the 2022 season. Nitrogen is a dynamic nutrient in the environment, and as such, grower confidence in utilising the right precision ag information to support the variable rate decision making has been of high importance. The use of cereal grain protein mapping as part of site-specific N fertilisation strategy has shown promising results as a valuable precision ag layer for improved decision making. By using grain protein as an indicator, fields can be assessed to where yield gains can be achieved. Results will be presented from paddock scale research conducted in 2019-20 by EM Ag Consulting that examined relationships between soil mineral nitrogen (SMN) levels and grain protein concentration across five paddocks in southern/central NSW.

Theoretical background to cereal grain protein based site-specific N

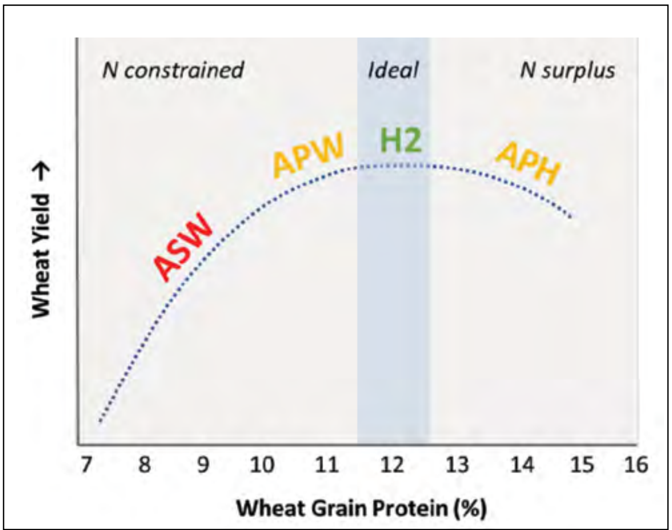
For many decades it has been recognised that a consistent relationship exists between cereal grain yield and cereal grain protein concentration according to N supply (for example, Russell 1963). This relationship consists of increasing grain yield and protein concentrations with greater N supply up to a certain point, after which grain yield begins to plateau while protein concentration continues to increase. At very high N levels, a decline in yield often occurs (Holford et al. 1992).

The point at which N supply has been optimised for maximum grain yield is termed the 'critical grain protein concentration' and is around 11.2–12.0% in most Australian hard white wheats through studies conducted in southern/central NSW (Brill et al. 2013; Sandral et al. 2018) and South Australia/Victoria (G. McDonald, review published in Unkovich et al. 2020).

While critical grain protein concentrations will vary between varieties and across seasonal conditions (Fowler 2003), a simplified 'rule-of-thumb' interpretation under favourable (non-drought) conditions can be summarised as:

- protein <11.5% = insufficient N supply to meet yield potential
- protein 11.5–12.5% = adequate/optimum N supply to achieve yield potential

- protein >12.5% = surplus N to crop requirement, possibly some yield penalty (Figure 1).



Figue 1. A generalised representation of the relationship between yield and grain protein concentration in wheat with increasing N supply. Labels refer to grades in the Australian wheat classification system.

If we apply this rule-of-thumb spatially across a management area grown to a single wheat variety, a georeferenced map of wheat protein concentration is analogous to an 'N adequacy' map, that is, it serves to distinguish areas of the paddock that had insufficient, ideal or surplus N according to their site-specific yield potentials.

Ground-truth soil testing at the start of the following season can be used to test this assumption and quantify out-of-season mineralisation. A good approach to determining the placement of soil tests is to divide the paddock into zones based on combinations of yield and protein results from the previous harvest. This process provides useful insights into not only N dynamics but also where non-N related constraints may warrant further investigation. These concepts are summarised in Table 1.

A major advantage of a protein-based variable rate (VR) N approach over currently available alternatives is that it combines both the supply and demand elements of the N balance equation. For example, low protein areas within a paddock may occur either due to low N supply (for example, differences in carryover N, mineralisation, fertiliser inputs) OR higher yield potential (for example, due to the dilution of protein by higher yield; Simmonds 1995). Regardless of which factor is responsible (or both), the management decision will involve increasing N rates in the following season.

In this sense, the protein layer is also accounting for temporal variability of N dynamics by providing a retrospective assessment of the **whole season**, net N balance, rather than a 'snapshot in time' as occurs with data layers such as spectral indices or grid soil mapping.

Table 1. Within-paddock combinations of cereal yield, protein attributes and their properties.

Classification	Interpretation	Residual N levels	Action
High Yield/ High Protein	• Optimum scenario • Yield potential achieved, no major limitations • This area of the paddock may have higher mineralisation potential	Likely moderate to high, however soil test to confirm (particularly if crop N demand was higher than budgeted)	Determine rates based on soil test results and according to high yield potential
High Yield/ Low Protein	• Sub-optimal N management • Yield could have been even higher • N deficiency likely occurred later in the season, as sufficient N was available to produce biomass/tillers • Could indicate 'tired' areas with lower mineralisation potential (e.g., historically high N removal/low SOM)	Likely low (assume post-harvest residual SMN was negligible, so levels are dependent on out-of-season mineralisation)	Increase N rates relative to paddock average in following season/s to support higher yields and build SMN
Low Yield/ High Protein	• Non-N related problem • Further N additions would **not** have increased yield • If protein is **very** high, yield penalties from oversupply of N likely occurred • Most commonly related to lack of moisture supply (for example, shallow or hostile subsoils, around trees), however may be another constraint such as pH, P	Likely high (mining of N may be advised to reduce yield penalties associated with N oversupply)	If the constraint cannot be amended, reduce N inputs relative to paddock average permanently to match lower yield potentials
Low Yield/ Low Protein	• Sub-optimal N management • Yield potential was not met • It is unclear if other constraints exist that would continue to limit yield with higher N inputs • If N deficiency is the primary cause, SMN was likely low for the whole season	Likely low	Start by increasing N to determine the non-N constrained yield potential, then manage according to results

Another advantage is the benefit afforded by the plant providing an indication of N adequacy according to the conditions it experienced, that is, the **plant available** N. This circumvents a limitation of soil testing where mineral N may be present within the profile however the plant may not be able to access it (for example, if subsoil hostilities prevent root access). In a similar manner, if subsoil conditions are favourable and the plant is able to access deeper SMN, this will be reflected by the plant's protein concentration however may be missed by an arbitrary soil sampling depth cut-off.

Getting started

Many growers have access to yield maps, and with an increase in growers having an on-combine grain analyser, these growers have access to quantity and quality metrics across their fields which can support subsequent crop fertiliser decision making.

A protein based site-specific N strategy might be a good approach for a grower if they:

- are predominantly located on soil types not prone to losses (that is, free draining with good nutrient holding capacity) and
- have within-paddock variability in factors such as texture/CEC/OC%/PAWC, productivity (N removal) and/or management histories (for example, amalgamated paddocks, previous inputs).

At present, the cost of a harvester mounted grain analyser is approximately AUD $25,000 + GST and installation (Next Instruments 'CropScan 3300H' unit). This cost will be spread over a number of seasons. The unit can also be removed and reinstalled if a new harvester is purchased. There will also be costs related to data management and interpretation if the grower cannot or does not wish to do this themselves.

After completing the first harvest, a good strategy is to pick a few of the most variable paddocks to focus on. If a grower isn't comfortable implementing a VR application straight away, they may prefer to use N-rich and/or N-poor strips to test the impact of variable N rates on their soils. If doing so, strips should be designed so they pass through several zones (for example, low/high protein, soil types, management histories). Paddocks being cropped to a second cereal crop (for example, wheat on wheat) will be of most value for reviewing the results of strip trials and/or the success of VR N applications.

Setting rates

Due to fluctuations that occur in critical grain protein concentrations between seasons and some varieties, start-of-season soil sampling will remain an essential step to determining actual N rates. Soil sampling will also act as a ground-truthing step to test assumptions regarding patterns of carryover SMN and to test any unusual areas.

Where consistent protein zones are present, soil sampling should cover off on each of the major protein/yield combinations (see Table 1), aiming to get an idea of the paddock average and the spread (range) of SMN values.

Over a number of seasons, implementing this strategy should reduce the spatial variability of protein concentrations, ideally converging around 11.5–12.5% if the base rates chosen have been appropriate. It is likely that the most 'bang for buck' to be gained implementing this strategy will occur in the early stages, by eliminating very low (highly constrained) and very high N zones.

It is important to remember that in paddocks where yield potential varies greatly due to factors other than N (for example, relatively fixed factors such as PAWC), a successful outcome will not be where yield becomes even, but rather where yield is optimised in all areas according to their site-specific yield potentials.

In all cases, ongoing monitoring of cereal protein per cent results and annual deep soil sampling should serve as constant feedback to ensure N decision-making approaches are performing well.

Results and discussion

A snapshot of the 2019/2020 research project undertaken across five sites in southern NSW by FarmLink Research is presented. The research sought to examine within-paddock N variability patterns and test assumptions around the correlation of SMN with various parameters, including protein concentration. Selected findings are presented below. The full research report can be accessed at http://www.farmlink.com.au/project/nitrogen-variability (Moffitt 2021).

Considerable within-paddock variability of start-of-season (Feb–Mar 2020) SMN was observed at four of the five sites, where the range of values (max – min) was greater than 140kg N/ha, and the standard deviation was greater than 20kg N/ha (Table 2). At the fifth site (Ardlethan), where the average SMN

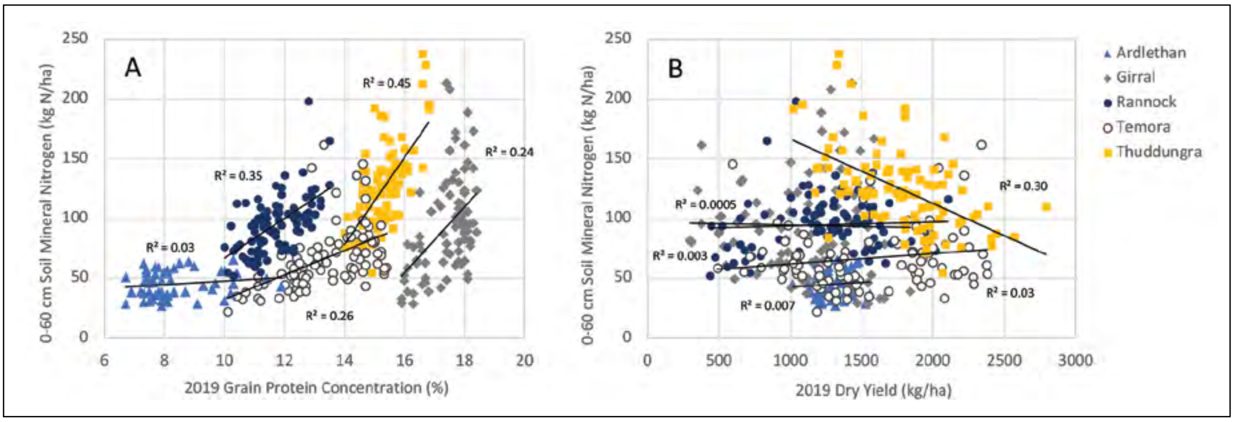


Figure 2. 0-60cm oil Mineral N (kg N/ha; sampled Feb–Mar 2020) versus 2019 cereal harvest results, (a) Grain Protein Concentration and (b) Dry Yield. (Girral = barley, rest = wheat). Each point represents one grid site (n = 425).

was much lower (46kg N/ha ± 11kg N/ha SD), the range of SMN was 43kg N/ha.

When examining the relationship between start-of-season (Feb–Mar 2020) SMN and various other attributes, 2019 grain protein per cent displayed the most consistent and strongest correlation compared to all other layers examined (Figure 2a). This consistently positive relationship was significant at four out of the five sites.

Importantly, at each of the four significantly correlating sites, areas of the paddock with the lowest protein per cent coincided reasonably well with areas of low SMN.

Previous management history appeared to be a key driving factor of N variability for at least three sites, with noticeable differences observed between areas that were previously fenced separately, despite some of these changes being made up to 15 years prior.

Across the five sites, there was a general trend of increasing strength of correlation between SMN and protein per cent as the average SMN level increased. This may be explained by considering that N supply levels have to be high in comparison to N demand in order for there to be substantial residual (carryover) SMN. If crop demand is much higher than supply, SMN may be drawn down across the paddock and residual N will be correspondingly low. In this situation, protein per cent may still vary, as overall N supply may have differed spatially throughout the season.

Due to the uncertainty around this result, a strip trial experiment was implemented in 2020 to explore whether the grid soil mapping results or 2019 protein per cent layer would have been the best basis for site-specific N in 2020. The site was grown to a second season of wheat, with 80kg/ha urea applied as a flat rate and two 160kg/ha urea N-rich strips applied at 140m width.

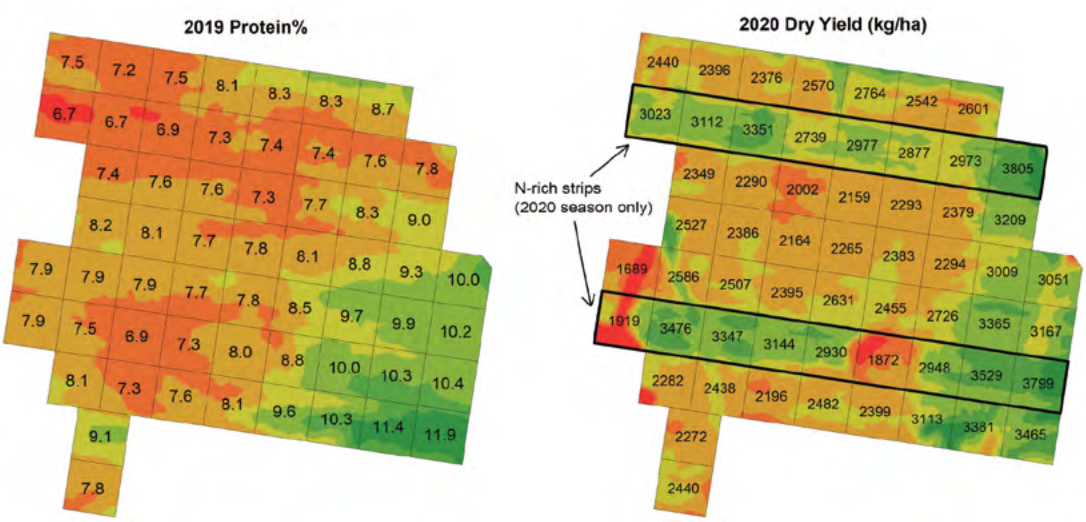


Figure 3. 2019 wheat (cv. Lancer⁽ᵈ⁾) grain protein (left) and 2020 wheat (cv. Spitfire⁽ᵈ⁾) dry yield at Ardlethan, with locations of N-rich strips shown. Note the greater yield response to additional N in areas of lower 2019 protein per cent.

Results demonstrated a significant positive correlation between 2019 protein per cent and 2020 protein per cent for both the N-rich strip areas (n = 15, r = 0.81, P<0.001) and non N-rich strip areas (n = 40, r = 0.73, P<0.0001; Figure 3a). A significant positive correlation was also observed between 2019 protein per cent and 2020 yield for the non N-rich strip areas (r = 0.83, P<0.0001; Figure 3b) while no significant correlations were observed between 2020 start-of-season SMN and 2020 yield or protein.

An average yield increase of 564kg/ha and protein increase of 1.7% was observed for the N-rich strip cells when compared to their immediately adjacent non N-rich cells.

These results suggest that given a fixed N budget, applying additional fertiliser to the lowest protein per cent areas of the paddock would have produced the greatest overall yield increase. Therefore, it appears that the adoption of a VR N strategy in 2020 based on the 2019 protein per cent pattern would likely have resulted in a more profitable outcome at this site than using grid soil mapping results or management zones where soil tests were used to directly determine rates.

Conclusions

The results of this project and experiences working with growers collecting and utilising harvester protein data have demonstrated that considerable potential exists for protein-based site-specific N strategies to drastically improve N management in our cropping systems, when used in conjunction with annual soil sampling and an appropriate N rate calculation method.

The success of protein-based site-specific N strategies appears to be linked to the major advantage of this approach whereby the crop itself indicates the N adequacy it experienced over the sum of the whole season. This circumvents many of the challenges of site-specific N management which have either limited the quality/efficacy of some VR N approaches (that attempt to provide simple solutions to a complex problem) or have limited the uptake of other VR N approaches (that are too complex/laborious to be practical). The high spatial resolution of this data and relatively low cost when compared to alternative approaches (for example, intensive soil sampling) is another major advantage.

While protein maps cannot be used to guide N management decisions in the season of their collection, this method should be considered more of a 'whole-system' approach to N management, with the aim of incrementally building (and/or mining) background SMN levels to match site-specific yield potentials across the farming operation over a number of seasons. This approach has considerable synergy with the concept of 'N banking' (Hunt et al. 2021; Meier et al. 2021) which aims to decouple N input decisions from seasonal demand by 'topping up' N levels each year to a pre-defined target that would be considered non-limiting in most seasons.

By using these two methods in conjunction (on soils that are not prone to losses), growers are armed with a simple, yet targeted strategy to both reduce/eliminate areas of yield loss due to N deficiency and reduce instances of N oversupply which are environmentally, agronomically and economically undesirable. This approach also has logistical benefits in that N rates and VR input maps can be determined/created quite early in the season (following the return of deep N soil test results). This has obvious benefits for financial budgeting and planning however also means that these decisions can be made well ahead of time rather than at a potentially stressful period before a rain event if relying on mid-season remotely sensed imagery, for example.

Given the immense potential productivity and environmental benefits of improved site-specific N management, considerable scope exists for follow up research to address the abovementioned challenges and explore the applicability of these methods in other regions and soil types.

Acknowledgements

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Managing N fertiliser to profitably close yield gaps

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Keywords

- nitrogen fertiliser, soil organic matter, yield.

Take home messages

- Making fertiliser N decisions based on Yield Prophet® Lite or an environmentally appropriate N bank target maximises profit, slows soil organic N decline and prevents accumulation of excessive mineral N.
- N decisions based on 50% Yield Prophet® probability or 125 kg/ha N bank strategy apply more N (60-80 kg/ha) are over $100/ha per year more profitable than the district average N rate (21-30 kg/ha N).
- The most profitable strategies all have neutral to positive N balances (more N applied in fertiliser than removed in grain) indicating soil organic N is not being mined.
- High urea prices anticipated for 2022 will reduce profit and optimal N rates. Growers can offset this by using alternative sources of N e.g. planting a higher area of legumes (grain, hay, pasture, brown manure) and using organic wastes (manure, compost, biosolids) where available and cost effective.

Background

Australian wheat yields are only half what they could be for the rainfall received (Hochman et al. 2017). Nitrogen (N) deficiency is the biggest factor contributing to this yield gap. This is also likely to be true for other non-legume crops (barley, canola and oats) and this reduces farm profitability. Alleviating N deficiency would increase national wheat yields by 40% (Hochman and Horan 2018).

On farms with no legume pastures, most of the crop N supply must come from N fertiliser. Grain legumes do not provide enough N to support yield of subsequent crops at the intensity at which they are currently grown. N fertiliser is a costly input and use of it increases cost of production and value-at-risk for growers. Growers fear that over-fertilisation will result in 'haying off', which reduces both yield and quality. There is also concern that overapplied fertiliser not used by crops is lost to the environment by leaching, volatilisation and denitrification. Consequently, efforts are made to match N fertiliser inputs to seasonal yield potential. This is difficult in southern Australia due to uncertainty of seasonal forecasts for rainfall at the sowing. The difficulty in matching N supply to crop demand and a tendency for growers to be conservative in their N inputs is the cause of the large proportion of the yield gap.

In 2018, BCG and La Trobe University commenced a multi-year field experiment to evaluate the potential for different N management systems to profitably close the yield gap and slow organic matter decline. The year 2021 was the fourth season of the experiment.

Aim

To evaluate different N management systems designed to profitably close the yield gap due to N deficiency and slow soil organic matter decline.

Paddock details

Location: Curyo, Victoria

Crop year rainfall (Nov-Oct):	2018: 200 mm
	2019: 368 mm
	2020: 358 mm
	2021: 241 mm
GSR (Apr-Oct):	2018: 138 mm
	2019: 149 mm
	2020: 221 mm
	2021: 197 mm
Soil type:	Sandy loam top-soil with clay content and calcium carbonate increasing with depth
Paddock history:	2017: Lentil

Trial details

Crop type/s:	2018: wheat cv. Scepter⌀
	2019: canola cv. Hyola 350 TT
	2020: wheat cv. Scepter⌀
	2021: barley cv. Spartacus CL⌀
Treatments:	Refer to Table 1
Seeding equipment:	Knife points, press wheels, 30cm row spacing
Sowing date:	2018: 14 May
	2019: 29 April
	2020: 16 May
	2021: 14 May
Replicates:	Four
Harvest date:	2018: 15 November
	2019: 15 November
	2020: 21 November
	2021: 25 November

Trial inputs

N fertiliser:	Refer to Table 2 for nitrogen fertiliser applications in 2020 and 2020 BCG Season Research Results (pages 122 to 128) for results from 2018, 2019 and 2020. All nitrogen fertiliser has been top-dressed as a single application of urea during winter.
Starter fertiliser:	2018: Urea @ 35kg/ha at sowing (host grower management)
	2019: Granulock® Z @ 60 kg/ha at sowing
	2020: Granulock Z @ 60 kg/ha at sowing
	2021: Granulock Z @ 60 kg/ha + triple superphosphate @ 35 kg/ha at sowing

The experiment was kept free of weeds and disease as per current best practice management.

Method

A multi-year experiment using a randomised complete block design was established in 2018 to evaluate the performance of different N management systems. There were four different systems being tested:

- Matching N fertiliser to seasonal yield potential (Yield Prophet® and Yield Prophet Lite, YP)
- Maintaining a base level of fertility using N fertiliser (N banks, NB)
- Replacing the amount of N removed in grain each year with fertiliser in the next season (replacement)
- Applying national average N fertiliser rate (45 kg/ha) each season (national average, NA)

All systems were compared to a nil control to which only starter fertiliser was applied (7kg N/ha per year). (7 kg N/ha per year). Within the Yield Prophet® and N bank systems, there were additional treatments targeting different yield potentials (Table 1). In the Yield Prophet treatment prior to 2021, water limited potential yield was determined at different levels of probability and the amount of N required to achieve these yields applied assuming a requirement of 40 kg N /ha N per t wheat yield and 80 kg N /ha per t canola yield (Figure 1). From 2021

Table 1. Nitrogen management systems and treatments used in the experiments.		
System	Treatment	Description
Nil	Nil	No nitrogen applied other than in starter fertiliser
Replacement	-	Amount of N removed in grain applied as fertiliser N in the following season
National average	-	National average N fertiliser (45 kg/ha N) applied each season (Angus & Grace, 2017)
Nitrogen banks (kg/ha N)	100	Soil mineral N + fertiliser = 100 kg/ha N
	125	Soil mineral N + fertiliser = 125 kg/ha N
	150	Soil mineral N + fertiliser = 150 kg/ha N
Yield Prophet probabilities	100%	Yield with lowest yielding season finish on record (decile 1 in Yield Prophet Lite)
	75%	Yield with lower yielding quartile season finish (decile 2-3 in Yield Prophet Lite)
	50%	Yield with median season finish (decile 4-7 in Yield Prophet Lite)
	25%	Yield with higher yielding quartile season finish (decile 8-9 in Yield Prophet Lite)

onward, Yield Prophet® Lite was used in a similar way. For the N bank treatments, there were different target levels of N fertility (N banks). N fertiliser rate in these treatments were calculated as the N bank value minus soil profile mineral N (kg/ha) measured prior to sowing.

Gross margins were calculated for the four years of the experiment using values from the 2021 SAGIT Gross Margin Guide assuming medium rainfall and 5 year average prices (SAGIT 2021).

Results and interpretation

2018-2020 results

Please see 2020 BCG Season Research Results (pages 122-129) for results from the 2018- 2020 growing seasons.

2021 Results

After 2 years of the experiment, there were large differences between treatments in soil mineral N measured prior to sowing in 2021 (Table 2). There was a strong positive relationship between 3-year N balance (fertiliser applied minus N removed in grain in 2018-2020) and soil mineral N measured (Figure 2). On average, 76% of fertiliser N applied 2018-2020 that exceeded grain removal was available as mineral N prior to sowing in 2021. This is consistent with N recovery measured in 2019 and 2020. Yield Prophet 50% and 25% treatments had the highest mineral N reflecting very high fertiliser N applications made in 2020. N in these treatments would have been at risk of larger losses over summer compared to treatments with less mineral N. All N bank treatments had lower mineral N in 2021.

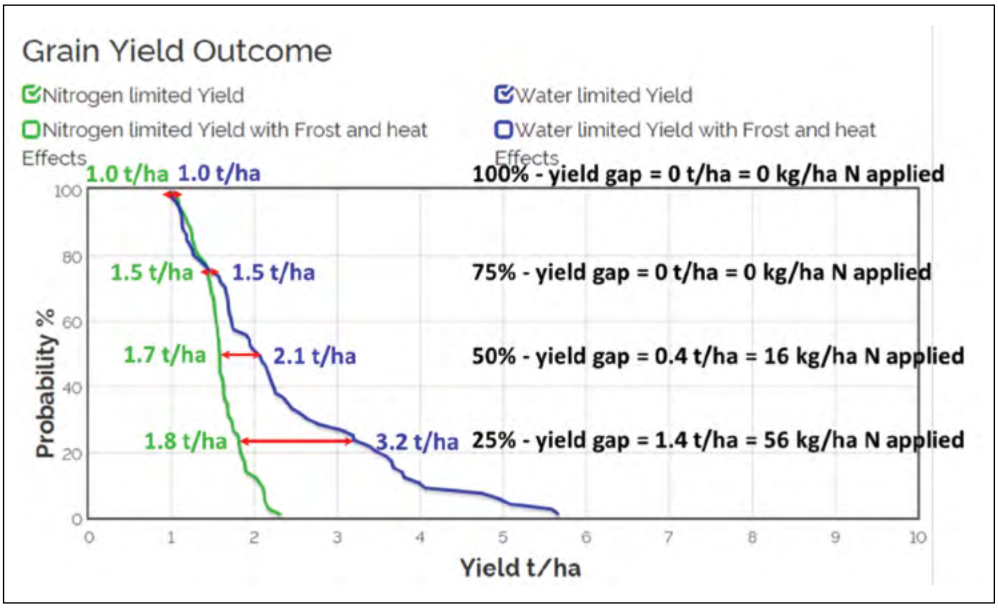

Figure 1. An example from 2018 of how Yield Prophet is used to determine water limited potential yield given probabilities of different season yield outcomes, and how this is used to calculate a yield gap and N fertiliser rate required to close the yield gap.

Table 2. Soil mineral N measured prior to sowing, top-dressed N, crop N supply, barley grain yield, protein and gross margin for different treatments in the experiment in 2021.

System	Treatment	Soil mineral N (kg/ha)	Top dressed N (kg/ha)	N supply (kg/ha)	Yield (t/ha)	Protein	Gross margin ($/ha)
Nil	Nil	26	0	33	1.1	10.0	-$113
Replacement	-	48	50	105	2.3	10.7	$77
National average	-	41	45	93	2.2	10.4	$62
Nitrogen banks (kg/ha N)	100	34	59	100	2.3	10.8	$64
	125	57	61	125	2.4	11.6	$83
	150	67	76	150	2.6	12.2	$105
Yield Prophet probability	100%	38	0	45	1.1	10.3	-$113
	75%	46	0	53	1.7	10.7	$17
	50%	131	0	138	2.1	11.0	$104
	25%	108	8	123	2.4	12.2	$158
Sig. diff.		<0.001	-	<0.001	<0.001	<0.001	-
LSD (P=0.05)		24	-	20	0.2	0.7	-

Despite the relatively dry growing season (only 129 mm rain or decile 1 up to 28 September), grain yield, protein and gross margin increased relative to N supply (Table 2). The highest yielding treatment was the 150 kg/ha N bank treatment which had the most fertiliser N in 2021, but the most profitable treatment was the Yield Prophet 25% treatment which had high rates of fertiliser in 2020 (128kg N/ha), a lot of which carried over as mineral N in 2021 and thus only 8 kg N/ha fertiliser N was applied.

4-year averages

Comparison of the different systems over the four years of the experiment shows that the Yield Prophet 50% and N bank 125 kg/ha N treatments were most profitable, with several other treatments achieving similar levels of profit. All these treatments, on average, had more fertiliser N than the district average of 21—30 kg N/ha (Norton 2016) or national average of 45 kg/ha (Figure 3). Assuming the district average N application is 30kg N/ha, the non-linear function suggests that the Yield Prophet 50% and N bank 125 kg/ha treatments, on average, returned ~$100/ha per year more profit than the district average.

The two most profitable treatments also had a neutral to slightly positive 4-year partial N balance (N applied in fertiliser minus N offtake in grain, Figure 4), indicating that soil organic N is not being mined. This contrasts to the Nil control with a 4-year N balance of -89 kg/ha N which, based on the soil C:N ratio at the site of 9.7, suggests ~863 kg/ha of soil organic carbon was lost during the experiment.

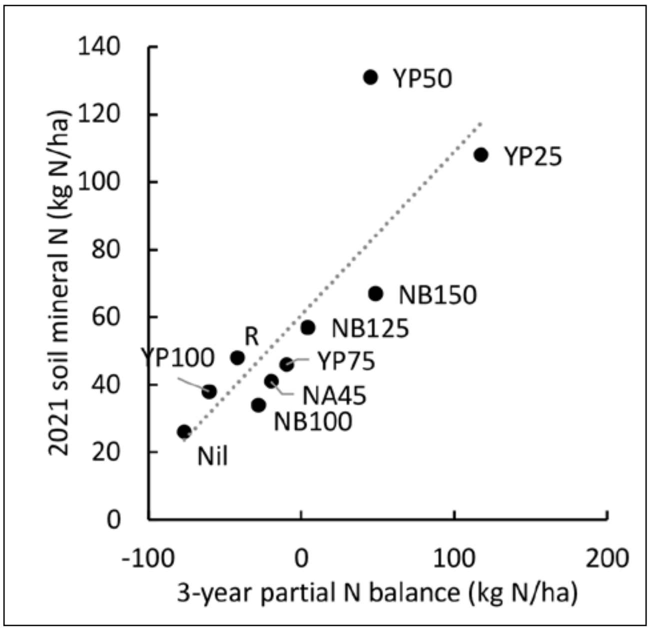

Figure 2. The relationship between 3-year N balance (2018-2020) and soil mineral N measured prior to sowing in 2021. The linear regression is fitted by least-squares regression to the positive N balance values only and is of the form $y = 0.48x + 60.60$, $R^2 = 0.69$.

The grains industry is understandably concerned about what high urea prices will mean for farm profitability and N strategies in 2022. Figure 5 shows the 4-year average N rate and gross margin for this experiment, assuming either a urea price of $550/t (as used in Figure 3) or $1100/t with all other costs and prices held constant, profit will be reduced at high urea prices and the most profitable urea rate reduces in this example from 73kg N/ha to 61kg N/ha.

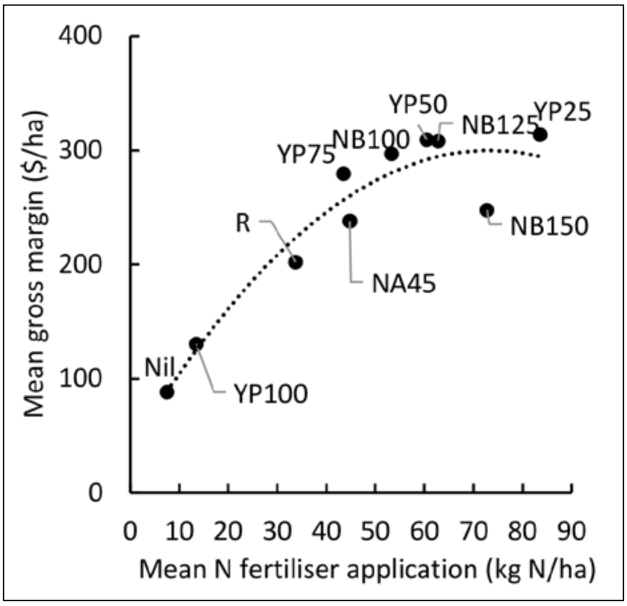

Figure 3. The relationship between mean 4-year fertiliser application and mean 4-year gross margin for the different treatments. The quadratic function fitted by least-squares regression is of the form y = -0.05x2 + 7.16x + 37.51, R^2 = 0.90.

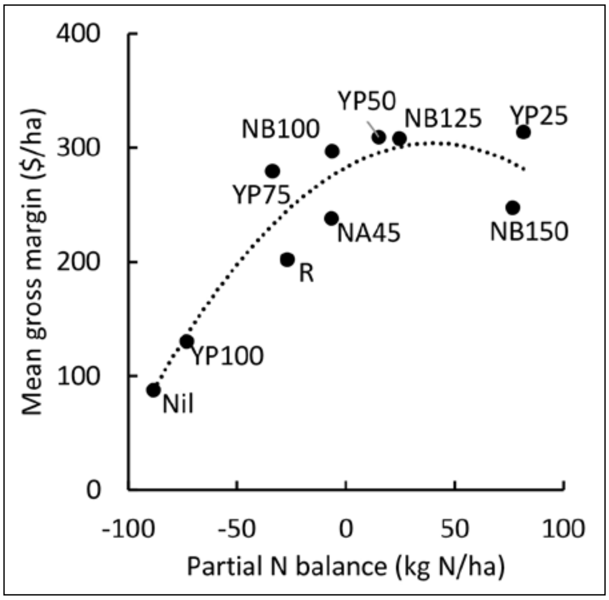

Figure 4. The relationship between 4-year partial N balance and 4-year mean gross margin for the different treatments. The quadratic function fitted by least-squares regression is of the form y = -0.01x2 + 1.05x + 282.74, R^2 = 0.84.

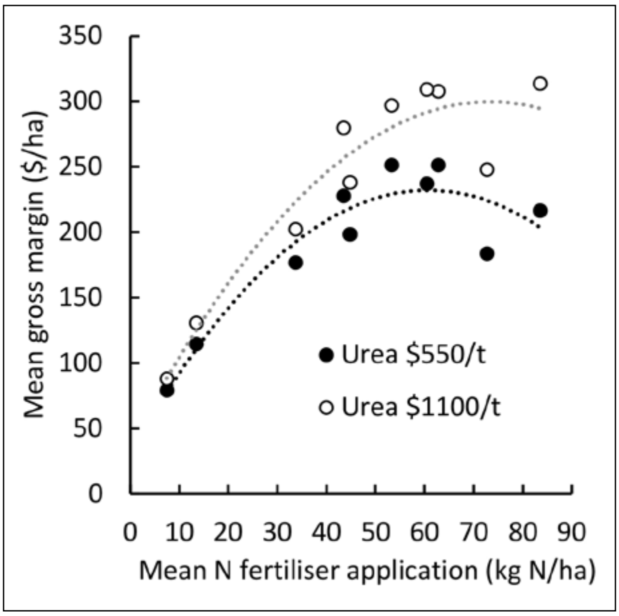

Figure 5. The relationship between mean 4-year fertiliser application and mean 4-year gross margin for the different treatments assuming a urea price of either $550/t or $1100/t. The quadratic functions fitted by least-squares regression are of the form y = -0.05x2 + 7.16x + 37.51, R^2 = 0.90 for $550/t and y = -0.05x2 + 6.61x + 31.64, R^2 = 0.88 for $1100/t.

Commercial practice and on-farm profitability

Growers should soil test and use an environmentally appropriate fertiliser N management strategy such as Yield Prophet Lite or N banks to maximise profits. In this experiment, profit has been maximised at much higher rates of fertiliser N (60—80 kg N/ha N or 130—174 kg/ha urea per year) than is usually applied in the district (21—30 kg N/ha or 46—65 kg/ha urea). Long term profitability is likely to be increased by growers being less conservative with N fertiliser applications, particularly for those consistently achieving cereal grain proteins of less than 11.5% (namely, APW or ASW wheat). Growers in low rainfall regions with heavy textured soils can be confident that the majority of applied N not used in year of application will remain in the soil profile for use in subsequent seasons.

The most profitable treatments in this experiment had neutral to slightly positive N balances, indicating a 'win-win-win' where profits are maximised, soil organic N is not mined, and excessive mineral N is not accumulated that is then susceptible to losses. Growers should check the long-term N balances of their paddocks to ensure soil organic N is not being mined. A spreadsheet to do this is available here at:

https://www.bcg.org.au/understanding-crop-potential-and-calculating-nitrogen-to-improve-crop-biomass-workshop-recording/

High urea prices in 2022 are a legitimate concern given the strong reliance of continuous cropping systems on synthetic N fertiliser for high yields and profits. Growers can offset this price rise by using alternative sources of N e.g. increasing planted area of legumes (grain, hay, brown manure or pastures), particularly in paddocks that return a low soil N test and would require substantial fertiliser N inputs if planted to non-legume crops. Growers with good access to organic wastes (manures, composts, biosolids) can substitute these for N fertiliser. Always test N content of organic wastes prior to application to ensure they are cost effective in comparison to synthetic fertilisers and that an agronomically appropriate rate of N (and other nutrients) is being applied.

Acknowledgements

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An informed approach to phosphorus management in 2022

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GRDC project code: PROC9176604

Keywords

- phosphorus availability, phosphorus economics, replacement phosphorus.

Take home messages

- Opportunities are available for reformed phosphorus rates under high fertiliser prices, but background knowledge is key.
- Gross margin analysis with phosphorus application rates is sensitive to soil available P, yield potential, fertiliser, and grain prices.
- On phosphorus responsive soil types, return from fertiliser (P) investment is normally greatest and most stable with cereal phases.

Background

Fertiliser prices for phosphorus (P) inputs have more than doubled since those used for the start of the 2021 season and for a three-year rolling price average. Currently, these high fertiliser prices are coupled with high grain prices which offsets potential decreases in partial gross margins, but in the current global scenario, there is high uncertainty if grain prices will hold until the end of 2022. Higher inputs costs will naturally generate a mindset of simply reducing these input rates, but it is important to have background knowledge supporting these decisions so yield returns aren't compromised. Combined with high fertiliser prices there have been the observations that P replacement programs have resulted in mining of phosphorus in some soil types. This paper aims to outline gross margin scenarios under a range of fertiliser and grain prices which could be vastly different to those set up in previous seasons. Importantly, the gross margin analysis will be performed using a range of different background P levels, soil type characteristics and yield potentials. Identification of likely paddock responsiveness and the variability in that response across the paddock is important. Several tools are available to assist with this determination which will be explained.

Method

Through various research projects across the last 10 years, both Agronomy Solutions and Trengove Consulting have obtained over 50 replicated field trials across the broadacre regions of South Australia, with most of them within the last 5 years (>40). Most of these trials have assessed wheat and barley responses to P applications across a range of soil types x climate years, but we have also been gaining valuable information on pulse P requirements. This dataset is highly valuable to assess gross margin scenarios under a range of conditions and the accuracy of various data layers in predicting P requirements.

Typically, a response parameter is used when assessing grain yield relationships from a range of increasing P applications using relative yield, which compares the yield of the nil treatment with the maximum yield obtained as determined through curve fitting analysis. For this paper, we have used the P rate which is associated with the greatest partial gross margin (PGM) return when factoring in fertiliser prices and returns from grain yields. We have used this dataset to test the accuracy of various data layers in predicting PGM under current conditions and, from the most accurate data layers, looked at the effect of changing fertiliser to grain price ratios for expected 2022 scenarios. Determination of PGM has used recent price trends of MAP at $1250, Wheat (APW) at $400 and Barley (F1) at $295. This field trial dataset is concentrated in the Yorke Peninsula and Mid North regions of South Australia but is applicable to wider regions where soil types vary in alkalinity within paddocks driven by the presence of carbonates. Widespread data from the recently completed GRDC-funded project (PROC9176604) has been utilised to provide an indication of current P levels across the broadacre cropping region of SA and the potential impact of decreasing P rates in response to high fertiliser prices.

Results and discussion

Current soil P levels

Reviewing the large soil test database from PROC9176604 reveals the overall P status of the broadacre cropping regions of SA and VIC. Over 1300 surface samples were collected in 2019 and 2020 with both Colwell P and DGT P levels placed in deficient, marginal, and sufficient categories (Table 1) built on published data (Moody 2007, Mason et al 2010). The PBI value for each site was used to determine a critical Colwell P position and the Colwell P value then compared to this target. DGT P critical levels of 60µg/L for wheat were established in Mason et al. 2010 and have continued to be stable with incorporation of a substantial amount of field trials post 2010. As a summary, there was some discrepancy between the two tests, but over half (52%) of sites were above critical DGT levels and as much as 73% of sites were sufficient in P using Colwell P. It is assumed that sites with soil P levels lower than the critical value or range will result in a yield penalty if no P is applied. Using soil test results to make a P recommendation for the sites sampled shows that there are 83% for Colwell P and 73% for DGT of sites that require <10kg P/ha to maximise yields. The high proportion of sites with low requirements for P provides opportunities in 2022 for identification of soil types where residual P is adequate and lowering P rates won't generate yield penalties.

Site soil characteristics driving recent P responses

The intensive field trial dataset produced by Trengove Consulting from 2019 to 2021, where 33 replicated field P response trials have been established on various soil type x NDVI/grain yield zones, is a powerful tool to test previously reported data layers (Colwell P, DGT P) as an accurate guide for P requirements, but also other accessible data layers which might assist P decisions moving forward. Of the 33 sites, 64% recorded non-significant ($p>0.05$) responses to applied P (Table 2), which is in line with the broader analysis reported in Table 1. Of the 12 responsive sites, at current prices, the average P rate required to maximise PGM was 20kg P/ha, which highlights the continued importance of identification of P responsive soil types. Responsive soil types are characterised by soil pH ($CaCl_2$) between 7.5-7.8, higher PBI values (P retention) driven by the presence of soil carbonate and low comparative NDVI values (Table 2). These broad averages support recent opinions that replacement P programs must incorporate a soil P retention factor which can have a greater influence on residual P availability compared to P offtake through crop yields.

Relationships between P rates at maximum PGM and several data layers were used to assess the applicability of soil data layers for accurately determining where reducing P inputs in 2022 may not be a profitable approach. Of the soil P tests alone, DGT P ($R2 = 0.71$) was superior at splitting apart profitable high P rates at current prices and sites where reduction in P rates would not cause a decrease in PGM. This data set highlights the importance of including PBI with Colwell P interpretation. In this case, we have simply divided the Colwell P value at each site by the PBI value obtained to create an index value which greatly improved Colwell P interpretation ($R^2 = 0.73$ from

Table 1. Soil P test results (Colwell P and DGT P) through the southern broadacre cropping region sampled in 2019 and 2020 placed in deficient, marginal, and sufficient categories with associated determinations of required P rates to maximise yields.

		Deficient		Marginal	Sufficient
		>10kg P/ha	5-10kg P/ha	0-5kg P ha	
Colwell P	Number of sites	218	72	68	970
	% Split	16	5	5	73
DGT P	Number of sites	367	163	113	685
	% Split	28	12	9	52

Table 2. Summary of soil characteristics averaged across the 12 significant ($p<0.05$) responsive P sites compared to 21 nonresponsive sites through Yorke Peninsula and Mid-North regions of SA. PGM was calculated based off MAP at $1250, Wheat (APW) at $400 and Barley (F1) at $295.

Response category	Number of sites	P rate at max PGM (kg/ha)	pH ($CaCl_2$)	Colwell P (mg/kg)	PBI	DGT P (ug/L)	Colwell P/PBI	pHnNDVI
Significant (response to P)	12	20	7.56	28	91	26	0.42	9.3
Non-significant (No response to P)	21	0.3	6.61	45	60	94	0.91	6.6

R^2 = 0.44). Using Colwell P alone as a relatively cheap data layer for intensive sampling strategies (for example, grid sampling) will add confusion and should be avoided unless a PBI measure is made at similar intensities.

The most accurate combined data layer to provide a P rate requirement for max PGM was an index of the soil pH and NDVI near GS30 across different zones within a paddock (Figure 1). The index simply divides soil pH with the NDVI normalised to the paddock average outlining that relatively high soil pH coupled with low NDVI values in a zone will generate higher index values and a high likelihood of higher P requirements. In association with higher soil pH coupled with poor early vigour will be the presence of soil carbonate, higher PBI values and lower residual P. The index is yet to be tested on soil types where high PBI is driven by other soil attributes such as Al or Fe, where there is a tendency of soil pH to be <6 in these soils (for example, ferrosols on Kangaroo Island). For these areas, a normalised NDVI index alone could be appropriate.

Partial gross margin analysis for fluctuating fertiliser and grain prices

While there is some clarity with fertiliser prices for the 2022 season, there is difficulty in predicting the grain price when it comes to locking in prices towards the end of 2022. At current grain prices, the identification of P responsive sites as outlined previously still pays but what happens if grain prices fall? Using an accurate data layer (DGT P or pHnNDVI), we can present the influence of changing fertiliser and grain prices on optimal P rates for max PGM (Table 3). Based off 2021 fertiliser prices as a

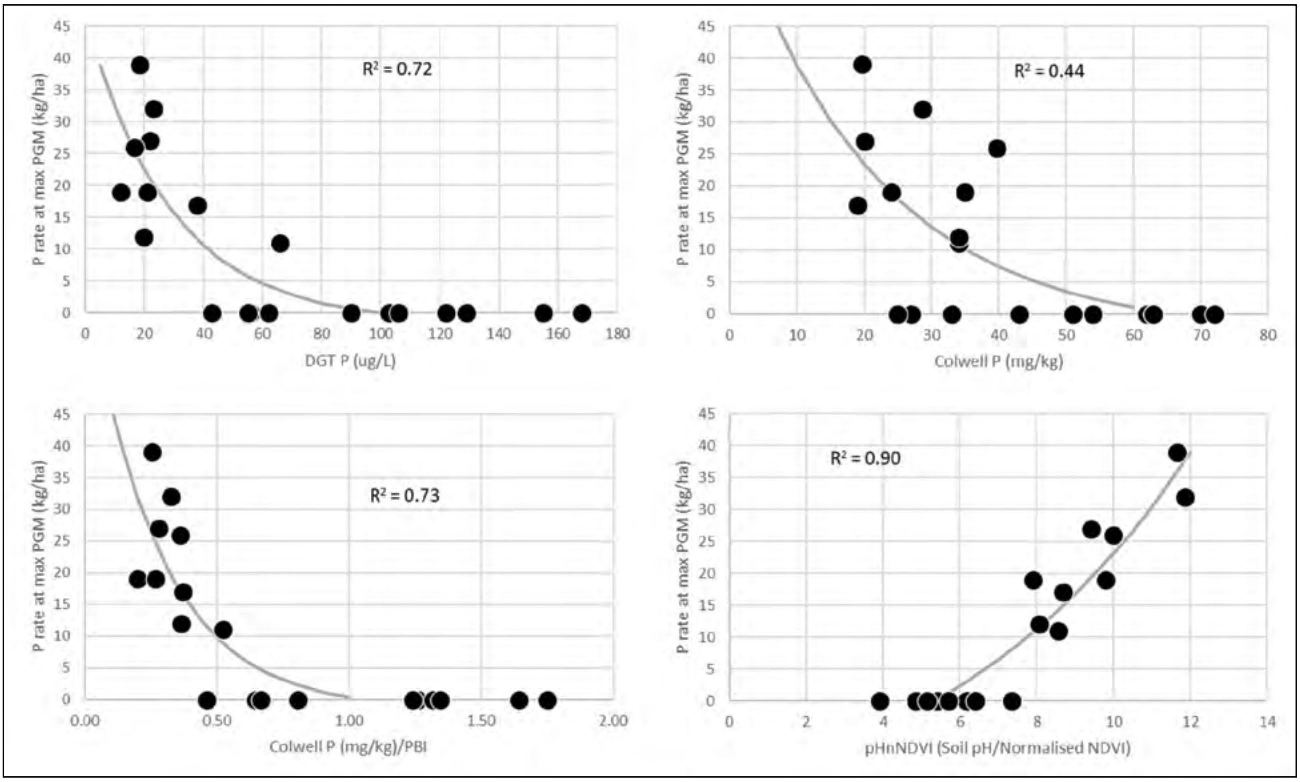


Figure 1. Relationships between the P rate associated with max PGM for P response trials (2019-2021) with DGT P, Colwell P, Colwell P/PBI and pHnNDVI.

Table 3. Sensitivity analysis of optimal P rates required for max PGM (kg/ha) for moving MAP prices at three decile grain prices (1, 5, 9) using either the pHnNDVI index or DGT P as a guide of deficiency (see Figure 1). Grain price deciles from 2010 onwards, source: Mercado.

Decile 1 Grain prices: Wheat (APW1) - $214t, Barley (F1) - $165

MAP ($/t)	pHNNDVI					Soil DGT P				
	4	6	8	10	12	>150	100	50	30	<20
$500	0	3	11	19	28	0	4	16	28	40
$750	0	1	7	13	19	0	3	12	21	30
$1000	0	1	5	10	14	0	2	9	16	24
$1250	0	0	4	7	10	0	1	7	12	18
$1500	0	0	3	5	7	0	1	5	9	13

Decile 5 Grain prices: Wheat (APW1) - $275t, Barley (F1) - $230

MAP ($/t)	pHNNDVI					Soil DGT P				
	4	6	8	10	12	>150	100	50	30	<20
$500	0	5	16	26	36	0	6	20	34	47
$750	0	2	10	18	25	0	4	15	26	38
$1000	0	1	7	13	19	0	3	12	21	31
$1250	0	1	6	10	15	0	2	10	18	25
$1500	0	1	4	8	12	0	2	8	14	21

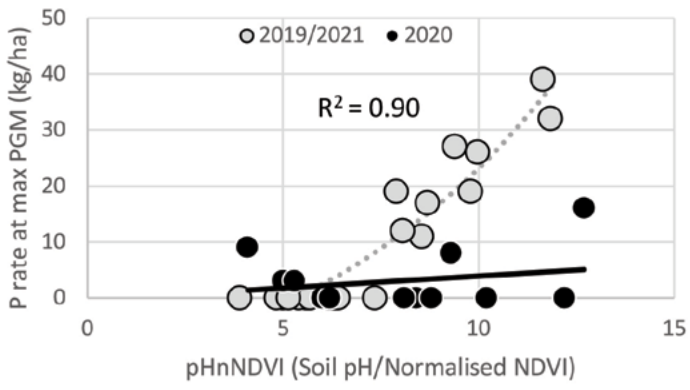
Decile 9 Grain prices: Wheat (APW1) - $332t, Barley (F1) - $293

MAP ($/t)	pHNNDVI					Soil DGT P				
	4	6	8	10	12	>150	100	50	30	<20
$500	0	8	20	31	42	0	9	23	37	51
$750	0	3	12	21	31	0	5	18	31	44
$1000	0	2	9	16	24	0	3	14	25	36
$1250	0	1	7	13	19	0	3	12	22	31
$1500	0	1	6	11	16	0	2	10	18	26

comparison and expected 2022 prices, this analysis suggests economic P rates will be slightly less than half of that required in 2021.

Opportunities for 2022 – Time of Sowing (TOS)

Recent SAGIT funded project (AS216) outlined the effect of TOS on P requirements through trials established on P responsive sites between 2017 and 2018 due to the prevalence of earlier sowing times. Results outlined that if adequate soil moisture was present at April sowing times, P rates can be reduced dramatically without any impact on yield. This benefit diminished if either low moisture was prevalent in April or sowing times moved to mid-May and beyond, with June sowing times producing uneconomic linear but relatively flat responses. Under high soil moisture and warm temperatures, crop root systems develop effectively and therefore exploration of residual P is high, placing less reliance on fertiliser P inputs. Diffusion rates of P in these conditions are also optimised. Data from Trengove Consulting supports this theory, as the 2020 field trial data set revealed a lower pHnNDVI with optimal P rate relationship (Figure 2). With early May sowing, the high soil moisture present due to favourable early rainfall meant the early TOS effect was present (Table 4). This is a potential option for 2022 if wet conditions in April prevail.



Site	Year	Rainfall to May (mm)	Rainfall for April (mm)
Koolunga	2019	13	4.4
Bute	2019	9.1	3.2
Brinkworth	2020	180	64
Bute	2020	119	67
Kybunga	2020	154	78
Crystal Brook	2021	29	2.6
Spalding	2021	43	4.4
Hart	2021	42	10

Figure 2 and Table 4: Influence of high rainfall and high soil moisture at the 2020 sites compared to 2019 and 2021 and the impact of lower P requirements at P deficiency indices.

Alternative sources of P

With higher fertiliser P prices, there is a natural tendency to look at alternative sources of P at associated lower costs if they are available. For products that need broadcast application (for example, chicken litter, biosolids) the efficiency of P in these products if applied alone range from approximately 20-50% of the same amount of MAP applied with or below the seed. Due to limited movement of P in soils, particularly those prone to deficiency, the broadcast approach without incorporation can limit root accessibility for that current year. These alternative sources of P should be used in conjunction with an amount of applied P banded. For all other sources of fertiliser P, it is advised to check the chemistries of the product and seek trial information of product performance before use.

Conclusion

High P fertiliser price is currently slightly offset by high grain prices, but with uncertainty if these grain prices will continue into 2022, it is advised to revise P applications in 2022 due to major impacts on optimal P rates required to maximise gross margins. Several data layers are available to assist with identifying areas where P rates can be safely cut back and those that will still return a profit with increased grain yields through adequate P applications.

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Lime application and soil acidity – the economics of current rules of thumb

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Southern Farming Systems.

GRDC project code: SFS1811-001OPX

Keywords

- economics, lime, soil acidity.

Take home messages

- Use LimeAssist calculator to analyse the economic benefits of lime application, help calculate lime rate requirements and estimate the time for re-application.
- Current 'rules of thumb' widely used for lime recommendations are likely to cause subsoil acidity deep in the soil profile that can be costly to treat.
- Improvements in treatment and management of soil acidity can come from monitoring your own soil pH changes over time to determine acidification rates and responses to lime rather than reliance on rule of thumb applications.

Background

While soil scientists recommend treatment of soil acidity with lime to maintain the soil asset, agronomists aim to remove a range of constraints to crop production, and economists advise growers to make investment decisions based on maximising economic returns. In addition, growers can also have different goals depending on their stage of life, such as winding up or winding down operations. All of this can make advice giving and decision making complex.

However, a commonality between all these sources of advice is that agriculture causes acidity and sooner or later, liming will be necessary to correct that acidity. The difficult decision is when to prioritise liming over other inputs, especially when grower's funds are limited. Advice is easy to give when funds are not limited, but this is rarely the case. Most often lime is competing with fertiliser and other inputs.

Advisors grapple with: do I address fertiliser constraints or apply lime? With some advisors, lime generally takes a back seat to fertiliser inputs and advice is often: apply lime when you can afford it. However, a neutral soil pH is essential for good root growth and effective uptake of fertilisers. Ignoring the need for lime will only decrease the effectiveness of fertilisers and other inputs.

Fertiliser usually provides a quick visual response, but the benefits of lime may not always be seen in the first year or not be large enough to be noticeable. In most cases, liming is about maintenance of soil pH, stopping yield losses and having options to sow many different crop species, rather than just acid tolerant ones. Growers can be disappointed if benefits are not seen immediately and think that the lime hasn't worked. Lime application is considered expensive to apply (freight being the major cost) and it should be considered a capital cost, and so, returns are spread over a long period of time which makes calculation more difficult.

This paper discusses economics of liming and a new tool called LimeAssist to help producers and advisors make lime decisions based on calculation of net present value (NPV) using a discount flow model.

Impacts of soil acidity and lime

Despite investigation into alternative soil acidity amendments, lime remains the most effective ameliorant to increase soil pH (Li 2021).Advisors may need to justify to growers that acidity is limiting their crop production and that the benefits of liming outweigh the costs. This is especially true now as soil pH (CaCl2) targets have changed from 5.0/5.2 at 0-10cm to above 5.5 (about 5.8 measured in water) to avoid subsurface or subsoil acidity developing.

There are commonly known benefits to correcting soil pH with lime applications such as the increase in root growth and uptake of nutrients and water, reduction in aluminium and manganese toxicity, increase in availability of nutrients (especially phosphorus), and maintenance of soil biological functions. However, there are some less commonly promoted benefits. Condon et al. (2021) reports that soil acidity stress increases susceptibility to biological and environmental stresses like waterlogging, herbicide injury and disease.

Yield benefits from liming have been measured in a range of crops through paddock trials in the high rainfall cropping zone (HRZ), where the yield differences from limed and untreated plots using a randomised and replicated design. The mean results are graphed against known soil pH and mean responses are shown in Figure 1. The response curves are for surface application of lime in minimum till systems, ameliorating acidity in the top 10cm.

At present SFS does not have a large dataset on the benefits incorporation of lime to develop a separate response curve. However, trials in other areas show that the incorporation of lime generally increases the speed of the yield increase (in eight trials versus four trials) with an average yield increase of 4% compared to surface lime application in the first three years. In ideal conditions, lime might move approximately 2cm per year, and will take five years to reach 10cm. Incorporating lime will amend the top 10cm, and therefore, yield increases are likely occur for up five years until surface lime catches up.

SFS trials have indicated that subsoil acidity at 10-20cm can also reduce yields by 3 to 4% (unpublished trials). These results are similar to those recorded at other regional locations as part of the subsoil acidity project (Li 2021).

Historical trends for lime applications

In the HRZ, the rule of thumb for lime application has been to apply 2.5t/ha about every 10 years. This rule of thumb was developed in the Acid Soil Action program in the late 1990s, about 20 years ago. Researchers who were involved at the time, indicated that rate and frequency was decided more on what they thought growers would apply rather than what was necessarily needed. While rules of thumb are good communication aids, the danger is they can become outdated as farming practices change or become inaccurate as advances in scientific understanding of different scenarios improves - both apply with soil acidity and liming. Common rules of thumb are shown in Table 1 along with their relevance today.

Ideally advisors/growers should look to develop their own rules of thumb for acidification rates and lime rates for their typical soil types and farming systems. Growers can do this by monitoring changes

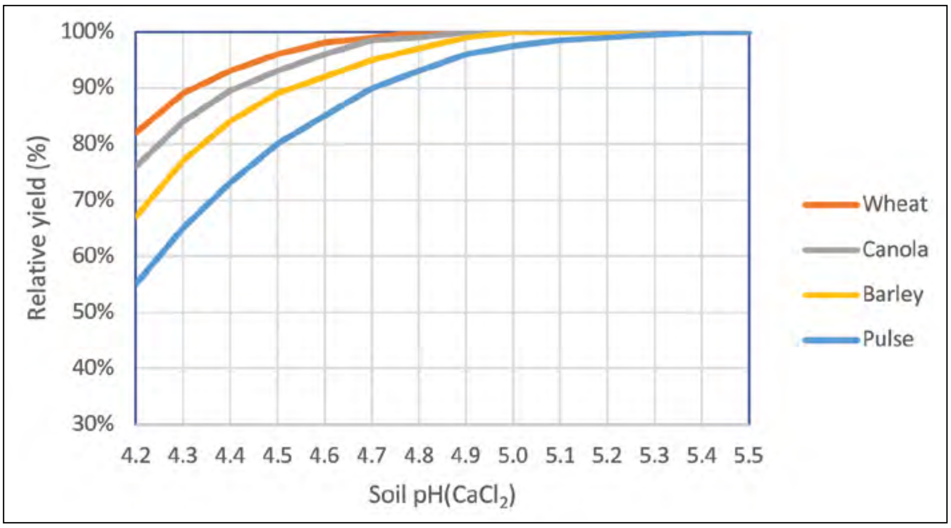

Figure 1. Mean relative yield by crop type as measured in SFS trials in HRZ.

Table 1. Common liming rules of thumb developed several decades ago and their relevance today.

Common rules of thumb/messages	Relevance and likely consequence
Apply 2.5t/ha of lime about every 10 years.	Outdated. Crop yields and use of nitrogen fertiliser has increased acidification rates and not enough lime has been applied to counteract this, leading to an increase in soil acidity. Also higher rates of lime (e.g. 3-4 t/ha) and/or more frequent applications are recommended where pH is very low and the soil has a high buffering capacity, especially if trying to correct subsurface acidity.
Lime isn't economic unless pH is less than 4.5 or lucerne is being grown.	Outdated and incorrect. Most crops go in and out of stress depending on seasonal conditions and can be affected by pH < 5.5, especially most pulses (Condon et al. 2021). Also at pH<5.5 subsurface soil receives no lime and becomes increasingly acidic.
Need to apply greater than 1t/ha to be economic.	Relevant. Minor applications of lime have been shown to cause little improvement in pH change (Scott et al. 1999).
Lime should be incorporated.	Relevant. Lime incorporation has long been the advice but was dismissed with trend towards minimum till. Re-emerged as an issue with identification of acid bands in the subsurface even where lime was topdressed at low rates.
Proactive, preventative management of topsoil pH with regular lime addition remains the most cost-effective solution for addressing subsoil acidity.	Relevant. This was the conclusion of the 'Innovative approaches to managing subsoil acidity in the southern grain region' project, GRDC project code: DAN00206 (Li 2021). Incorporation of lime can also speed up lime movement.

in pH over time following liming (acidification rate) and calculate how much lime (t/ha) is needed to change soil pH by 1 unit, 2 years after liming (soil pH buffering capacity) or have it measured by a laboratory. Alternatively, the LimeAssist online tool can help estimate lime requirements.

LimeAssist - new online tool

LimeAssist is a new lime decision tool designed to help advisors and growers calculate the economic returns from lime applications. It uses a simple discount cash flow model, which is the best analysis to use when evaluating lime benefits and costs over time. An Excel version of the economic calculator was first developed by Kerry Stott, an economist at Agriculture Victoria, which was then converted into an online version by the Centre for Excellence in Research Digital Innovation (CeRDI) team at Federation University.

It currently contains yield response curves to soil pH for wheat, canola, barley and pulses (faba bean and peas) (see Figure 1). In March 2022, acid sensitive and acid tolerant pasture response curves will be added. At this stage, the calculator only runs the economics of treating the surface soil (0-10cm) due to insufficient data to confidently calculate the yield penalty of deeper acidity. While other similar calculators exist in other states, this one is based on yield responses and acidification rates in the high rainfall zone of the southern cropping region, including southwest Victoria, Gippsland, SE of South Australia, Kangaroo Island and Tasmania.

LimeAssist is available at URL https://limeassist.sfs.org.au/, and will be accessible through links in SFS, McKillop Farm Management and Kangaroo Island Productivity groups who have provided yield response data.

Using LimeAssist

The tool contains four steps to work through. Each step contains instructions and information buttons give explanations of what different input cells require and tips on use. The results can be saved, so that data are available for later use.

Step 1. Paddock information notes

The calculator caters for variable rate liming decisions, where one zone or multiple paddock zones can be selected. An estimation of soil pH buffer capacity is made based on organic carbon and clay content of soil and is used to calculate the pure lime rate required to achieve the desired pH change (target pH — current pH). The equation used to do this was developed by Aitken et al. (1990) and utilised by National Heritage Trust Australia (2001) in the National Land and Water Audit 2001 report. However, the equation used overestimates the lime requirement for hydrosols or ferrosols and so, results in these soil types should be treated with caution. Soil texture can be used to infer clay percentage which utilises relationships measured by Rab (2019). By inserting a farm delivery address, lime delivery costs can be calculated.

Step 2. Calculate lime costs notes

A lime supplier map helps identify nearby or convenient lime quarries and shows their measured moisture content and neutralising value. The contact details of the supplier are given, so the lime price can be obtained. A freight return distance cost calculation is provided at 10 cents/km/t. This distance and many of the default inputs can be overridden if required. The time frame of the analysis can be selected or left at the default period of 5 years. Likewise, discount and inflation rates can be overridden or left at the default settings of 7% and 2.2%, respectively. A summary of lime requirements is generated and shows the actual lime cost, delivered and spread.

Step 3. Calculate benefits notes

To calculate benefits, crop details need to be included (i.e. crop type, expected yield and price). If an acid tolerant crop was to be used other than wheat, such as lupins, oats or triticale, then select wheat. If another acid sensitive crop was used, then select barley or pulses (faba bean, field peas). Other than yield improvements, lime residual value (unused lime at the end of the analysis period) is calculated and valued. There is a lag time built into the lime responses so that benefits occur in the year following liming and peak in year two, where maximum pH change occurs before starting to fall as lime is used.

Step 4. Economic analysis notes

A graph of the cumulative net cash flow with inflation over the analysis period is generated and this shows the year where break even occurs. Two graphs show pH change over time with and without liming. These can be used to interpret where the pH falls below the trigger for re-liming, commonly 5.5. A summary of returns is given including the net present value and a modified internal rate of return. Selecting the full economic model provides further additional details on changes in yield and pH over time. More information on the discount flow analysis used or the soil technical relationships can be found in Stott et al. (2019) or in the calculator notes section.

Conclusions

Old ‘rules of thumb’ developed several decades ago but still widely used for lime recommendations may be inadequate and are likely to cause subsoil acidity deep in the soil profile. Improvements in treatment and management of soil acidity can come from monitoring your own soil pH changes over time to determine acidification rates and responses to lime rather than reliance on rule of thumb applications.

LimeAssist provides an easy way to calculate economic benefits of liming that can be used in helping to decide to lime or prioritise paddocks. The calculator does contain assumptions, and therefore decisions need to be made in conjunction with soil monitoring. The calculator makes it easier for an individual farm to develop its own rules of thumb, which should lead to improved soil acidity management.

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Detection of lime in acidic soils using mid infrared spectroscopy

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GRDC project code: UOA1905-01RTX

Keywords

- acidic soil, lime, mid infrared spectroscopy.

Take home messages

- Acidification of surface and subsurface soils is increasing in South Australia due to increasing productivity and use of fertiliser nitrogen.
- Soil pH is often highly variable within a paddock and requires detailed monitoring for effective management.
- Infrared spectroscopy technology may reduce the labour and soil analysis costs of assessment across paddocks and down the soil profile, improving precision management of soil acidification.
- Detection and prediction of inorganic carbon with can be used to measure agricultural lime in soils and to monitor lime movement, assisting with management of acidic soils.
- Infrared spectroscopy is a viable alternative to traditional laboratory methods.

Background

This work details PhD research undertaken as part of the GRDC-supported project, 'New knowledge and practices to address topsoil and subsurface acidity under minimum tillage cropping systems of South Australia' (Acid Soils SA), which aims to generate new information regarding lime movement and its effectiveness when applied to different soils and environments in modern farming systems. The focus of this component is the use of novel spectroscopic methods to improve the identification and management of soil acidification.

South Australia's (SA) cropping zone is becoming increasingly affected by soil acidity, particularly in productive cropping rotations with high yields and high nitrogen fertiliser inputs. If left untreated, soil acidification can lead to reduced crop yields, particularly for acid sensitive, high-value crops such as legumes. Acidification of soils in the subsurface, generally between 5 and 15cm below the soil surface, is increasing in farming systems and, similarly to surface acidity, is detrimental to crop productivity (Tang et al.2013; Whitten et al. 2000).

The most commonly used treatment for soil acidification is the addition of agricultural lime, which increases soil pH and reduces exchangeable aluminium concentrations, and consequently increases crop yields (Conyers et al. 2003; Scott et al. 2000). Liming is generally most effective in the acidic soil layer where it is applied, and so surface acidity can be managed via topdressing liming materials. Mapping of pH has proved useful in identifying the distribution of pH at the soil surface and enabling targeted lime applications, but measuring and treating subsurface acidity and stratified acid layers is often more challenging, and these issues are often not detected with current soil testing methods. While some research has explored ameliorating subsurface acidity by using high surface lime rates or incorporating lime into subsurface layers, the effectiveness of these approaches to increase the soil pH at depth is often more difficult and costly to measure. There is a need for improved cost-effective methods to measure pH changes at small spatial distances and to monitor lime movement in the soil profile without undertaking extensive laboratory-based soil testing, which is often time-, energy- and cost-intensive.

Soil analysis has begun to move from complex laboratory physical and chemical analytical procedures towards more rapid and simple spectroscopic methods that have the potential to be effective in the field. A common spectroscopic method for the measurement of multiple soil properties is infrared (IR) spectroscopy. Infrared spectroscopy utilises radiation in the 700–25000nm wavelength region (near infrared (NIR): wavelength 700–2500nm, wave number 14000–4000cm^{-1} and mid infrared (MIR): wavelength 2500–25000nm, wave number 4000–400cm^{-1}) of the electromagnetic spectrum (Soriano-Disla et al. 2014). There is a relationship between the chemical composition of a sample and the spectrum measured in the IR region, whereby samples with different chemical compositions will have different infrared spectra (Janik et al. 1998; Viscarra Rossel et al. 2006). Infrared spectroscopy works on the principle that the absorbance or reflectance values reported by a spectrometer do not directly measure an element but instead measure the various bonds associated with that element within the IR spectrum. The content of an element is then inferred by the relationship developed in the chemometric model. Infrared spectroscopy offers minimal sample preparation and rapid scan time. It is relatively easy to use and has the potential to analyse soil properties in real-time.

Of relevance for the management of soil acidification is the potential of IR spectroscopy to detect and quantify carbonate (used interchangeably with ‘lime’ for the purposes of this paper) present in soil, and to trace the dissolution and/or movement of lime down the soil profile. Carbonates have distinct spectral features in the IR region and can be readily identified and quantified. While IR spectroscopy has been used to measure naturally occurring carbonates in soils (generally present at concentrations >>1%), this method has not been explored in an agricultural context, where lime is applied to acidic soils and generally present at concentrations <<1%. This research explores the ability of mid infrared spectroscopy to measure low concentrations of lime in acidic soils, and to combine this information with other soil properties, to improve management of subsurface acidity.

Methods

The initial stages of this work were to develop a method to detect agriculturally relevant concentrations of lime in soil using MIR spectroscopy measurements in the laboratory. Based on current recommended liming rates, it was hypothesised that carbonate concentrations of less than 1% would need to be detectable for this technology to be useful in management of soil acidification. In order to achieve this, predictive models were established to measure carbonate concentrations of soil from spectral data. Acidic soil samples that had been limed were dried and sieved (<2mm) and fine ground (<0.1mm) before MIR spectra were obtained. Carbonate concentration was measured using a pressure calcimeter method, and partial least square regression (PLSR) models were derived from the MIR spectra and reference calcimeter data for the prediction of carbonate content. Details of this method are provided in Hume et al. (2022).

This new method is now being applied to a number of field trials that have been established as part of the Acid Soils SA project, to measure the concentration of undissolved lime in the soil profile. Each trial site comprises four replicate blocks containing trial treatments with various lime sources, rates and incorporation methods. Intensive soil sampling was undertaken at a number of the trial sites whereby soil cores were collected from selected treatments within each replicate block at depths of 0-5cm, 5-10cm and 10-20cm. Treatments selected for sampling were those with different rates of lime (2t/ha, 4t/ha and 6t/ha) and different lime application methods (surface applied or incorporated with a tyned cultivator to 10cm).

The soil samples were analysed with traditional laboratory methods to determine pH ($CaCl_2$) and exchangeable aluminium levels, and also scanned with a lab-based MIR spectrometer. The MIR carbonate prediction method (Hume et al. 2022) was used to measure concentrations of undissolved lime in the soil at these sites. Preliminary results are provided for one trial site (Sandilands, Yorke Peninsula, South Australia — loamy sand with ironstone gravel over red clay) and further data for other trial sites is currently being processed.

Results and discussion

Carbonate prediction at agriculturally relevant concentrations

Figure 1 depicts the predictive capability (relationship between laboratory measured and MIR-predicted carbonate content) of the MIR method. The R^2 value of 0.735 confirms the potential of this method for the prediction of carbonate content in acidic soils that contain additions of lime.

The data in Figure 2 provides an example of potential application of this MIR method to detect carbonate in an agricultural context. Two soil profiles, one limed and one un-limed, collected from a trial site used in the acid soils project (Wirrabara, South Australia — sandy loam over brown clay) are presented with predicted carbonate concentrations at 25mm intervals. The limed soil was treated in 2015 with a surface application of lime at a rate of 6t/ha, and the presence of lime down to approximately 100mm can clearly be detected. This highlights the potential of this method as a tool for monitoring lime presence and movement in acidic soils.

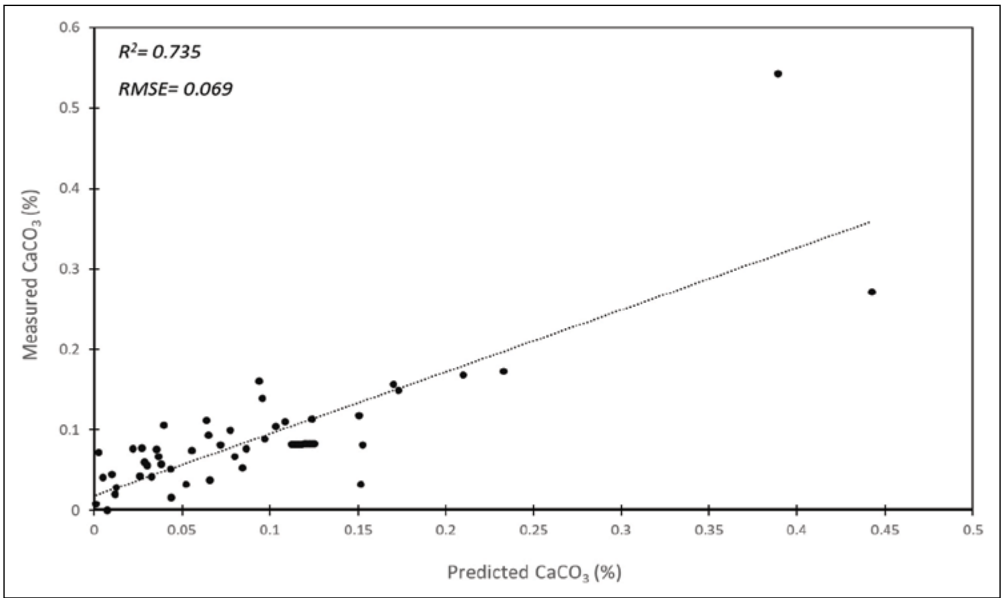

Figure 1. Carbonate predictive validation results showing predicted carbonate versus measured carbonate (%) of field collected soils (acidic soils treated with lime) in the MIR spectral ranges 2560-2460cm^{-1}.

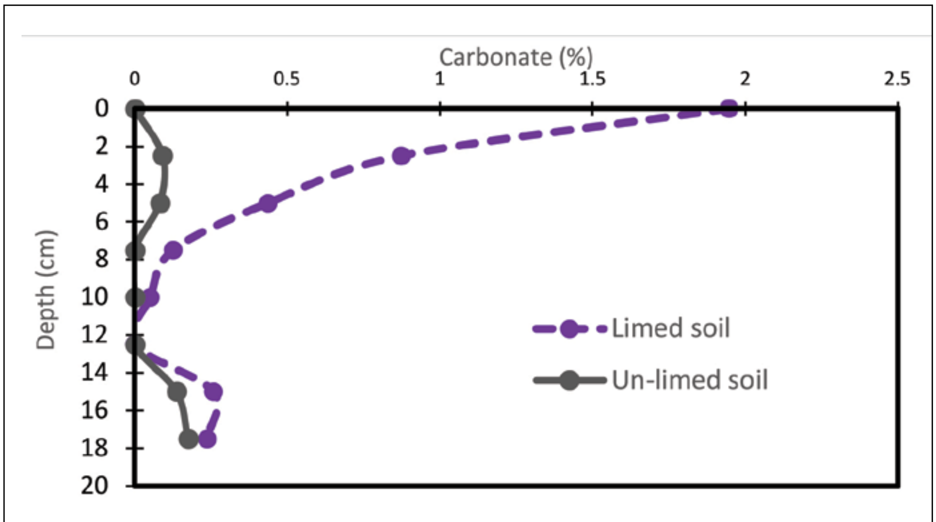

Figure 2. Example of application of the MIR method to detect carbonate in a soil profile at the Wirrabara trial site for an un-limed and a limed soil. The limed soil was treated with surface applied lime at a rate of 6t/ha in 2015.

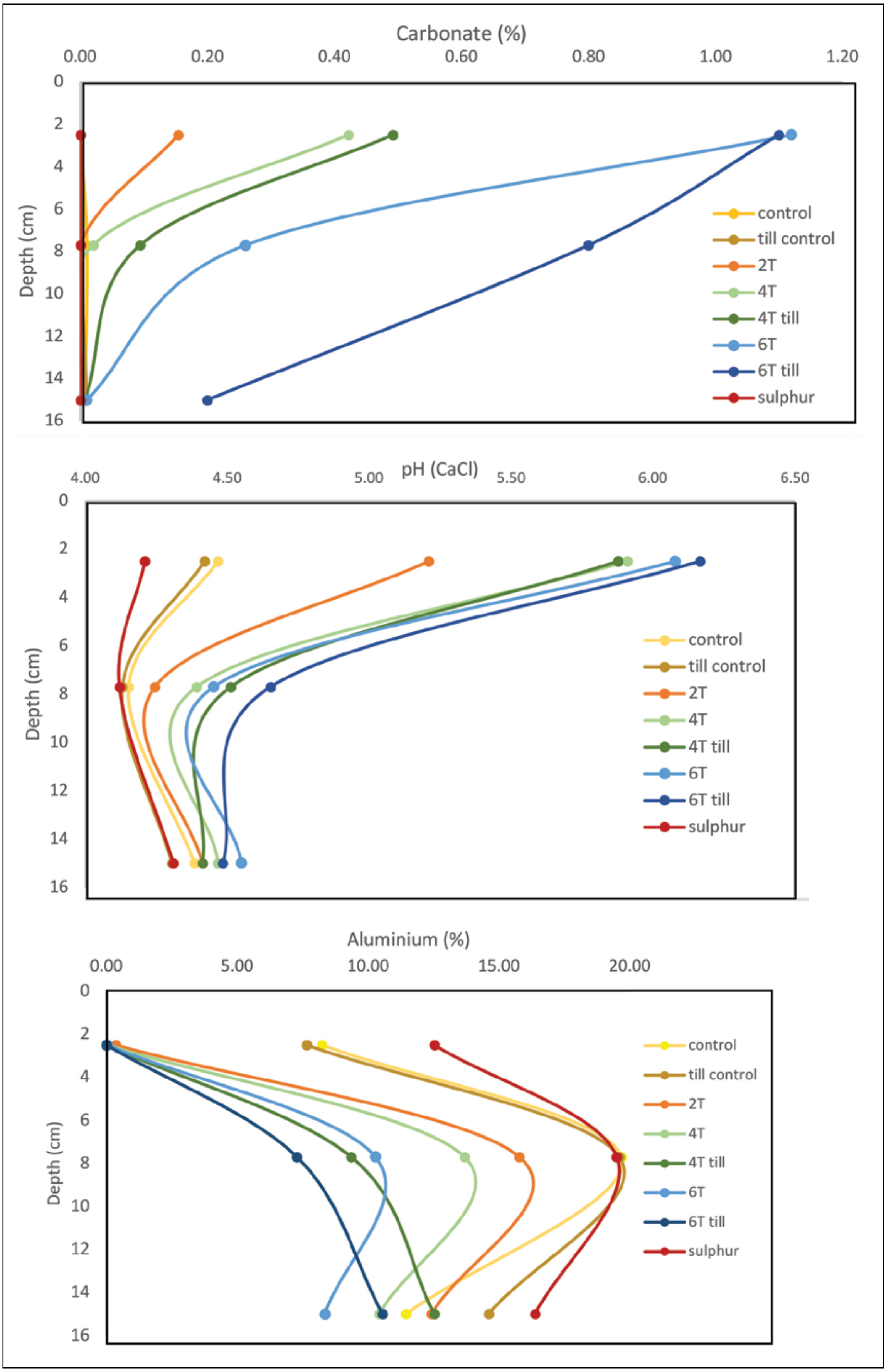

Figure 3. Soil carbonate content, pH and aluminium content (measured in 2021) in relation to lime rate and incorporation treatments with lime at Sandilands trial site. Loamy sand with ironstone gravel over red clay. Soil was limed in 2019 at rates of 2, 4 and 6t/ha and lime was surface applied or incorporated with a tyned cultivator to 10cm (till).

Application of method at field trials

Figure 3 depicts the 2021 carbonate concentrations of soils collected from the Sandilands trial site which was treated in 2019 with lime at rates of 2, 4 and 6t/ha, and either surface applied or incorporated with a tyned cultivator to 10cm. An elemental sulphur treatment is also included to mimic continued acidification of the soil. This figure highlights where undissolved lime is located in the soil and, when combined with other information about each treatment (such as pH and Al), gives an indication about the efficacy of the treatments at remediating the soil acidity.

Conclusion

This study provides a proof of concept for the use of MIR spectroscopy to measure low concentrations of carbonate additions to soil. The use of this method in soils that have been limed may enable the measurement of carbonate content and detection of carbonate movement in acidic soils at fine spatial scales. By measuring lime movement through acidic soils, we propose that MIR spectroscopy undertaken in controlled laboratory conditions will be useful in the monitoring and management of soil acidification in agricultural settings. Currently, this method is being utilised to measure carbonate concentrations in various trial sites established under the soil acidity SA project. It provides valuable information about the movement of lime and may be useful in ensuring that sufficient lime is applied to remediate acidity in subsurface layers.

The applicability of infrared spectroscopy under field conditions is yet to be demonstrated for this purpose, but previous studies have highlighted the capabilities of portable IR devices for accurate prediction of other soil properties such as organic C, pH, CEC and clay/sand content. As hand-held IR technology improves and costs decrease, this approach offers an appealing option where intensive soil sampling is required for effective management.

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 authors are grateful for the help of the Les Janik (formerly of CSIRO) for advice with spectral analysis, Prof. Michael McLaughlin (University of Adelaide) for provision of spectroscopic equipment, and Brian Hughes and Andrew Harding (PIRSA) for project support and advice.

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Ameliorating sandy soils to overcome soil constraints and improve profit

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Keywords

- hard-setting, ripping, soil constraints, water repellence.

Take home messages

- Most of the sandy soils we have worked with have a physical constraint to crop root exploration and water use. New insights into the nature of the physical constraints suggest that both hard-setting and compaction processes are important.
- Water repellence is a common constraint and, if severe, may present issues even when physical constraints are addressed.
- Yield responses to ripping depths of less than 40cm have proven unreliable.
- Analysis across our validation sites have shown that the net present value of the investment in amelioration is most dependent on the yield response but is also sensitive to cost assumptions and grain prices.
- A whole of farm case study based on an Ouyen farm demonstrated that while the profit is positive in response to amelioration of sands, the returns are lower than achieved at the plot-level when farm-level cost and benefit factors are considered.
- Major drivers of farm-level profit include investment costs and proportion of cropped land responsive to amelioration.
- Recent responses to ripping using inclusion plates with high inclusion capacity suggest that we may be able to offer strategies that produce similar yield benefits and possibly longevity to full profile mixing (for example, spading), and which also leave the soil surface with less erosion-risk.

Background

Crop water-use and yields on sandy soils are commonly limited by a range of soil constraints that reduce root growth. Constraints can include a compacted or hard-setting layer preventing root proliferation, a water repellent surface layer causing poor crop establishment, soil pH issues (both acidity and alkalinity) and/or poor nutrient supply. The aim of the Sandy Soils project is to increase crop water use in underperforming sandy soils in the Southern cropping region by improving the diagnosis and management of constraints. Growers are experiencing a range of outcomes in response to amelioration of deep sands. Understanding the constraints, appropriate amelioration tools and a set up that will best address the constraints are critical to success. A profit-risk analysis can help growers and advisers think through the relevant components of the costs, the expected response and financial risks associated with amelioration of deep sands. This paper focuses on high soil disturbance interventions (deep ripping, spading and inclusion ripping) that require specialised machinery to break up compacted or hard-setting layers.

Method

Constraint identification

The key measurements for constraint identification include water repellence (water drop test), soil strength (penetration resistance) or bulk density, pH and soil nutritional status. A summary of these constraints for the validation program sites is given in Table 1. The grower guide for identifying constraints is currently available via Fraser (2020) and is being developed for inclusion in a web-based app. Further to this effort, there has been a post-doctoral project examining the nature of the physical constraints in sandy soils. This study has focused on the measurement of bulk density (compaction) and soil strength under drying soil water conditions (hard setting) (da Silva et al. 2021). Tests have also been completed to identify if cementing (irreversible hardening) was an important physical constraint at these sites. A simple test for cementing is demonstrated in this video link (https://youtu.be/ZNIv7VpH0e0).

Testing amelioration techniques

A range of research experiments were established across the low to medium rainfall environments of the southern region with sites categorised according to their primary soil constraints identified (Table 1). Experiments for the research program were established between 2014 and 2019, while a broader validation program was established between 2019 and 2021, including a range of deep ripping (30-60cm deep), spading, inclusion ripping and/or inversion ploughing approaches, with/without additional amendments (fertiliser, N-rich hay, chicken manure, clay). All experiments monitored the effects of amelioration on crop growth and yield, while the research program had a further set of more detailed soil and crop measurements. It is only possible to present a subset of data in this paper, so we have focused on the effects of ripping depth on yield and economic response utilising the validation program data (2019-2020).

Economic analysis

Utilising 2019 and 2020 grain yields from the validation program, the discounted cashflow response to amelioration was evaluated for cost:benefit outcomes in response to ripping depth, utilising ripping costs provided by grower and industry consultation ($60-105/ha depending on ripping depth), 5-year average grain prices from the Gross Margin Guide (wheat (APW) five-year price was $294/t, SAGIT et al. 2021) and a discount rate of 6%. The sensitivity to cost of investment, grain prices, yield and discount rate was also analysed by comparing the base scenario to variations in these factors. The cash flow outcome is presented here as the net present value (NPV). The investment is worth undertaking if NPV is positive as it reflects that the present value of the future cash flow is bigger than the initial investment.

Further to this effort, several case study farms were developed in collaboration with Pinion Advisory Pty Ltd. Using results from the validation trial at Tempy, an Ouyen case study farm was developed to evaluate deep ripping as a 'farm investment project'. The assumptions included dividing the farm into three classes of land and predicting the level of amelioration response for each class over a 3-year period. Of the 4,792ha cropping area, it was assumed that 30% would be ripped across a 6-year program (240ha/year), an $80,000 ripper would be purchased, and the farm would upgrade their tractor, with 30% of the tractor use assigned to ripping.

Optimising spading and deep ripping operations

The work to date (Ucgul et al. 2019) has developed new insights on how spading and inclusion ripping machinery are best set-up and used. The incorporation by spading of a surface-applied amendment or the mixing of a constrained sublayer achieves variable levels of mixing uniformity within the profile, which is a function of speed, depth and spader design. The mixing by spading process is cyclical rather than continuous and controlled principally by the spading 'bite length'. The uniformity of mixing is greatly improved under dual-pass, low-speed (3km/h) spading, which can reduce the time to crop response from lime incorporation, relative to very delayed and diluted response with surface-applied lime. The high cost and greater erosion risks of high uniformity mixing requires caution and careful adoption where justified.

A lower risk profile-amelioration method consists of inclusion plates fitted behind deep ripping tines which promote the natural inclusion of the top layer into the loosened profile. Substantially enhanced inclusion capacity can be obtained when operating in loose, flowable top-soil conditions with optimised plate design and set-up, such as the plate upper-edge length and its lower-edge depth of reach. However, greater inclusion capacity correlates with increased power requirements and rougher surface finish. Pilot work has also revealed great potential for maximising the inclusion capacity under active inclusion systems that can also leave the surface finish 'seeder-ready'. Active inclusion includes the use of twin plates that funnel topsoil into the inclusion zone. Early on-farm and commercial adoption of some of these ideas demonstrate the demand for improved deep ripping solutions. Two separate experiments at Younghusband (near Mannum) established in 2020 and 2021 have directly compared spading with inclusion ripping and ripping. The inclusion ripping treatments at this site have taken advantage of the knowledge to optimise the set-up of the inclusion plates.

Results and discussion

Constraint identification

Of the 19 validation sites, 12 have a severely constrained layer for soil strength and the remainder have a moderate constraint. Ten of the sites also have moderate to high water repellence (Table 1), while three also have issues of acidity, and 11 have problems with poor nutrient supply.

Hard setting and compaction can both contribute as physical constraints restricting root growth and exploration. Hard setting is a natural, moisture driven and reversible process, where particles become bound together as the soil dries. This increases soil strength and makes it more difficult for roots to grow. Compaction is a physical process where soil particles are packed together more tightly with reduced porosity because of external forces, such as machinery trafficking. Cementing is also a naturally occurring process, but unlike hard setting, it is irreversible when exposed to water because particles are chemically bound (through cementing agents). The difference between these

Table 1. Summary of constraint scores (0 = low, 1 = moderate, 2 = high)* at validation program sites including repellence measured as water drop infiltration time, presence of a physically constrained layer measured as penetration resistance, acidity measured as pH water, and soil nutrient status.

Research Site_Year Established	Repellence	Physical strength	Acidity	Nutrients
Physical constraints and low inherent nutrition				
Koolonong_19	0	2	0	1
Buckleboo_19	0	2	0	1
Karkoo_19	0	1	0	1
Sherwood_19	0	2	0	1
Monia Gap_19	0	1	1	1
Cummins_19	0	2	1	1
Walpeup_20	0	2	0	0
Telopea Downs_20	0	1	0	0
Taplan_20	0	2	0	0
Water repellence, physical constraints and low inherent nutrition				
Alawoona_18	2	1	0	1
Warnertown_19	1	2	0	0
Kybunga_19	1	2	0	0
Tempy_19	1	2	0	0
Wynarka_19	2	2	0	1
Mt Damper_19	1	1	0	1
Malinong_19	2	2	2	1
Younghusband_20	2	2	0	1
Wharminda_21	2	1	0	1
Coombe_21	2	1	0	0

**Repellence as water infiltration time: 0 = <5s, 1 = 5-240s, 2 = >240s; physically constrained layer as penetration resistance: 0 = <1.5Mpa, 1 = 1.5-2.5Mpa, 2 = >2.5Mpa; acidity as pH water: 0 = >6.5, 1 = 6-5.5, 2 = <5.5; and nutrients: 0 = sufficient, 1 = marginal, 2 = deficient measured through lab-based soil test reporting and inclusive of N, P, K, S, Zn, Mn, Cu status.*

physical constraints is likely to be important for understanding how crops respond to amelioration, and how long the benefits will last. The four sites that we were able to access in 2020/21 did not classify as having a cementing layer, but they did have a hard setting layer that is prone to becoming extremely hard (>3.5MPa, restricting all root penetration) with very small reductions in soil water content (just 4% w/w, from 9% to 5% w/w) (da Silva et al. 2021). This is likely to be a critical issue in low rainfall environments. We will continue to explore this hard setting response across a broader range of sites and contrast the process under different amelioration strategies.

Yield and economic response to ripping at validation sites (two-year response)

In line with the presence of physical constraints at many sites, most scenarios have been responsive to ripping, particularly to depths greater than 40cm (Figure 1). The most consistent responses have been generated at depths of 50cm, with an average discounted NPV of $247/ha (Figure 1).

As the database consolidates to combine both the validation and research program datasets, the confidence in the optimal depth for yield and economic benefit will improve.

The discounted cash flow analysis to derive NPV depends on discount rate, treatment cost, grain prices, and grain yield response (that is, the difference in yield between treated and control plots). Information on cost and prices were obtained from various published sources and expert opinion. However, our findings are sensitive to changes in cost and prices. For this reason, sensitivity analysis is presented along with a base case scenario in Figure 2. As expected, our analysis suggests that the yield response is a key driver of the ripping NPV outcome. A 25% increase in the yield response increased NPV by $16-249/ha. The NPV was less sensitive to cost (which ranged from $60-105/ha) with a $28-47/ha reduction in NPV with 50% cost increase, while a 25% reduction in grain price (base price $294/t) generated a $2-256/ha reduction in NPV (Figure 2).

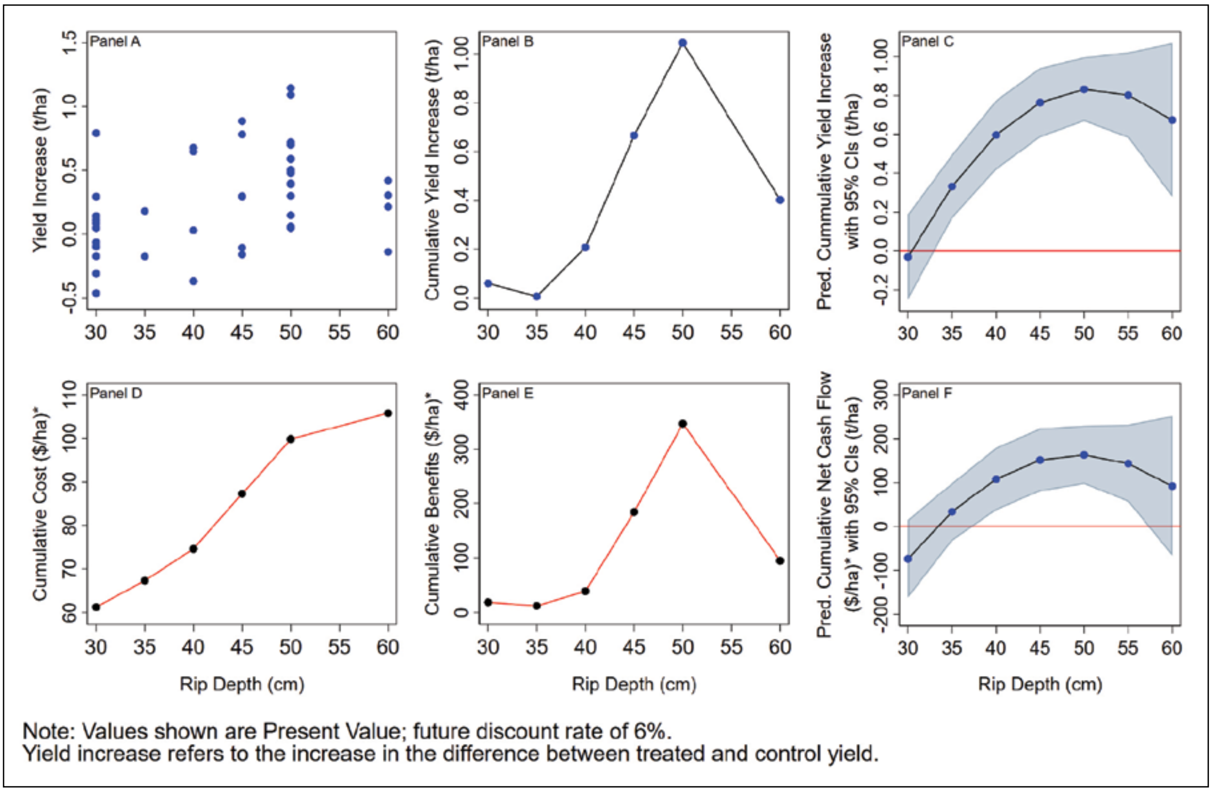

Figure 1. Panel A plots the yield increase (that is, the difference between treated and control yield) at various ripping depths. Panel B is the average 2-year cumulative yield response to each ripping depth. A non-linear regression of this relationship is shown in Panel C, where the shading represents the confidence interval and shows that there is less data for analysis at 60cm depth. Panel D and E show average cumulative discounted costs and benefits of different ripping depths. Panel F shows the cumulative discounted net cash flow mirrors the curvilinear yield relationship as given in Panel B and C. These relationships will continue to consolidate as the database accumulates the research program and 2021 yield data.

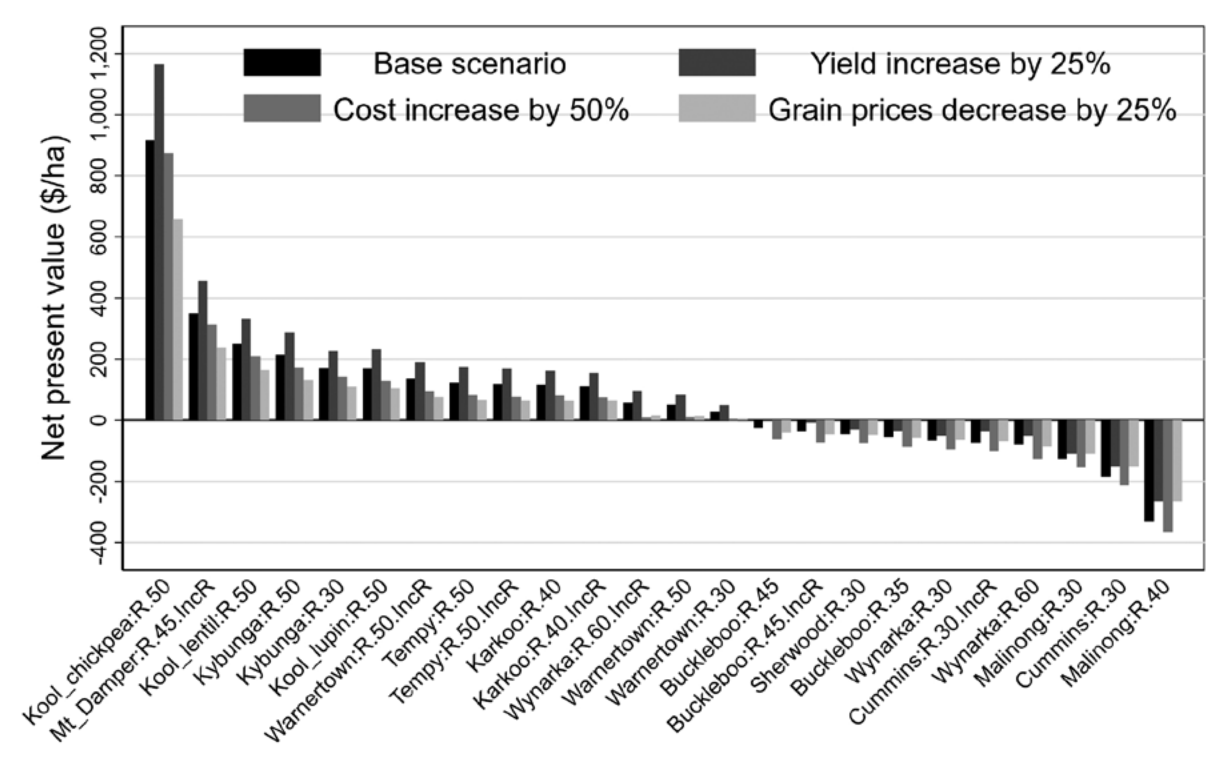

Figure 2. Sensitivity analysis of ripping net present value response base scenario compared with an increase in ripping cost (+50%), a decrease in grain prices (-25%) and an increase in yield response +25%). Each column on the figure represents a site x treatment response value. The baseline scenario has a wheat price of $294/ha (but other crops are represented as per label), ripping costs of $60-105/ha dependent on ripping depth and yield benefits ranging from -0.5-1.0t/ha.

Using the Ouyen case study farm example, the net present value of the investment was predicted to be $55/ha with a payback period of approximately 6 years. This case study involved purchasing a tractor (with partial attribution of tractor use to ripping) and ripper. In addition, only a portion of land was assumed responsive to ripping and able to be treated in any one year. Exploration of the sensitivity of the case study outcomes to assumptions suggested the purchasing options (ripping investment cost), level of crop responsiveness in land area, longevity of response (assumed here to be 3 years) and selection of crop sequence are all highly sensitive factors influencing the return on investment. However, it is consistently the case that analysis at the farm-level reveals a lower level of predicted return than simple extrapolation from plot-scale data.

Optimising cost and crop response to inclusion ripping

Given the importance of the yield response and managing the cost of the deep ripping investment, we have several sites at which optimisation of the deep ripping operation is examined. This includes the design of the ripper set up (for example, wing attachments), tine spacing and operational speed through to modification of the ripper for inclusion to allow for multiple constraints to be addressed simultaneously. The process of inclusion allows for repellency to be addressed to some degree because topsoil is included into deeper soil layers, diluting the repellency in the surface, but also redistributing organic matter and nutrients in the topsoil layer. At the same time, the soil physical constraint is addressed. Recent results from Younghusband (Figure 3) suggest that inclusion ripping may provide a useful alternative to spading with reduced erosion risk and a more seeder-ready finish. Year-1 wheat yield benefits in 2020 (decile 7) were 1.9t/ha from enhanced inclusion-ripping (modified 60cm long plates, at 60cm ripping depth) compared with a 1.1t/ha benefit for deep ripping alone (control yield 2.8t/ha).

In 2021 (decile 1), residual year-2 barley yield benefits from inclusion ripping maintained a 1.1t/ha gain compared with a 0.4t/ha benefit for deep ripping alone which was equivalent to the soil wetter

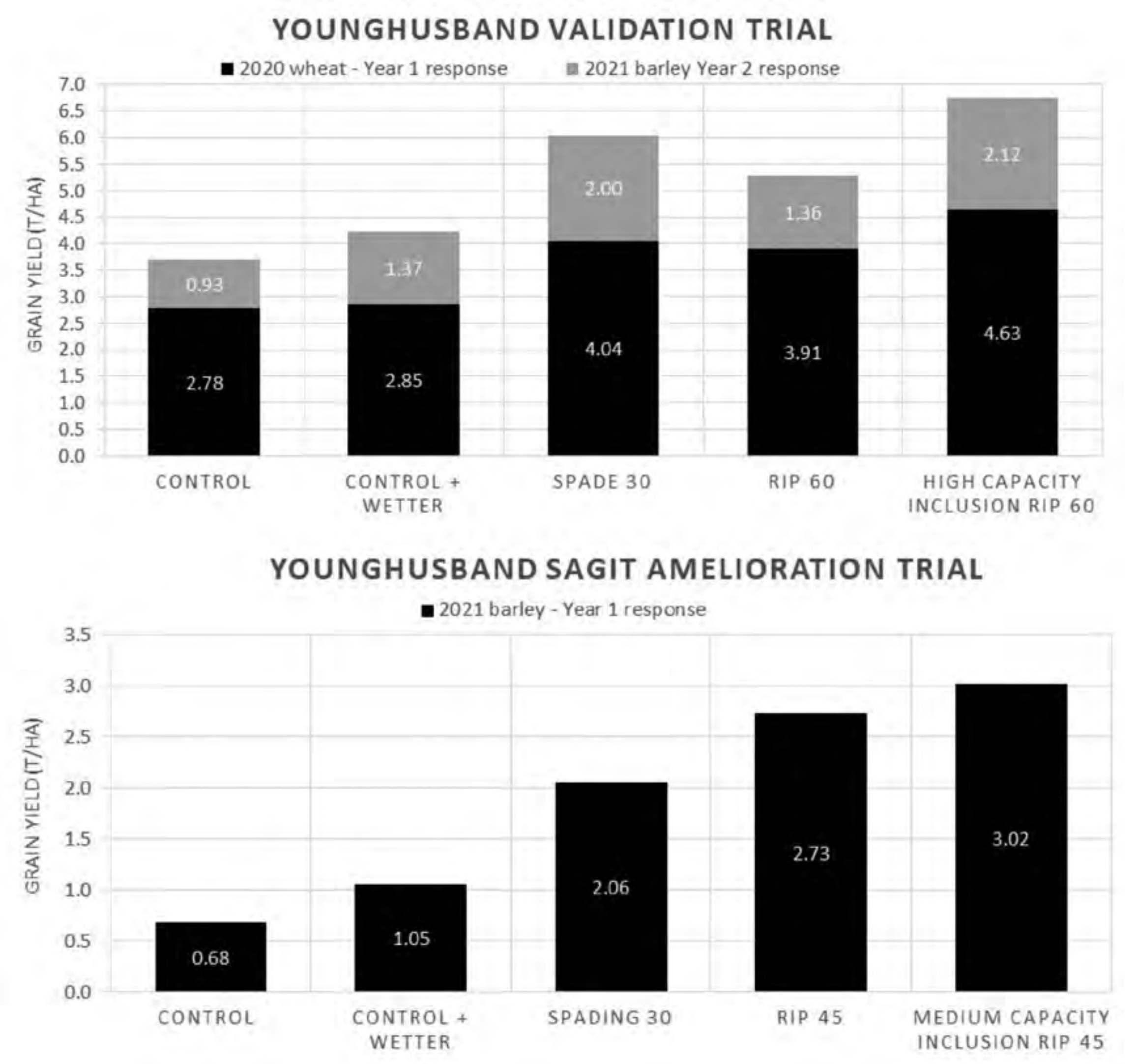

Figure 3. (Top) Comparison of cereal yield responses to deep ripping (60cm), spading (30cm) and inclusion ripping (60cm) at Younghusband in 2020-2021 for the validation trial and (bottom) Year-1 barley responses to dep ripping (45cm), spading (30cm) and inclusion ripping (45cm) at an adjacent trial in 2021.

treatment (control yield of 0.9t/ha). In both years, a spading treatments to 30cm depth yielded +0.1t/ha and +0.6t/ha above the deep ripping only treatment, respectively. A year-1 response of +2.0t/ha to deep ripping at 45cm and +2.3t/ha to inclusion ripping at 45cm was concurrently obtained at an adjacent trial (Figure 3) in 2021. The rapid reduction in response to ripping in year-2 compared with the magnitude of year-1 responses suggests there may be limited longevity for ripping alone treatments at the site, which may relate to the impact of a hardsetting layer.

Although inclusion ripping may appear an attractive option over spading, anecdotal variability in topsoil inclusion and crop responses alongside elevated running costs can pose challenges for reliable return on investment. Experiments in WA and SA Mallee sands have shown higher draft requirements (+24% to +40%), reduced workrate (-24%), and extra fuel use (+3.7L/ha) with baseline inclusion ripping technology compared to ripping alone (Parker at al. 2019). Further work in SA (Ucgul et al. 2020) has shown that higher power requirement is primarily influenced by how deep the lower plate edge is set relative to the deep ripping point, with draft increase of up to 80% possible. High draft may not always correlate with higher inclusion capacity, which is influenced by speed and plate length. The optimisation of inclusion ripping has not yet been fully explored and remains an area of research in high demand from growers trying to manage sands with the combination of physical and repellency constraints.

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 thank the technical teams who deliver the experimentation for the Sandy Soils Project. We thank Pinion Advisory for their role in the analysis and development of farm case studies. This research has been enriched by preceding research trials, the significant contributions of growers and consultants across the Southern region, and the support of the GRDC and SAGIT (for the Younghusband 2021 site). GRDC project CSP00203 research and validation activities are a collaboration between the CSIRO, the University of South Australia, the SA Government Department of Primary Industries and Regions SA, Mallee Sustainable Farming Inc., Frontier Farming Systems, Trengove Consulting, AgGrow Agronomy, AIREP, and MacKillop Farm Management Group.

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FEBRUARY 2022 LIVESTREAM PROGRAM

NB. All times are Australian Eastern Daylight Savings Time (AEDT).

Program Day 6 – New technology & high rainfall zone agronomy

Thursday 24 February, 9am AEDT

Start time	Finish time	Topic	Presented by
9:00	9:05	**Welcome/Introduction to day six**	***GRDC Representative***
9:05	9:35	**Canopy management for better yields**	***Kenton Porker,*** *FAR Australia*
9:35	10:05	**Reducing the effects of waterlogging on yield**	***Malcolm McCaskill,*** *Agriculture Victoria*
10:05	10:15	**Emerging research on water logging tolerance in barley varieties**	***S M Nuruzzaman Manik,*** *University of Tasmania (PhD candidate)*
10:15	10:45	**An integrated approach to ryegrass control in higher rainfall environments**	***Chris Preston,*** *University of Adelaide*
10:45	11:00	*Morning Tea Break*	
11:00	11:10	**Hyperspectral remote sensing & rapid assessing for wheat crops**	***Andrew Longmire,*** *University of Melbourne (PhD Candidate)*
11:10	11:40	**Precision to decision – have we explored all the options? Lessons learned from the future farm project**	***Brett Whelan,*** *University of Sydney*
11:40	11:50	**Use of remote and proximal sensing to guide yield predictions**	***Ian Marang,*** *University of Sydney (PhD Candidate)*
11:50	12:20	**New technology and automation – what's on the horizon?**	***Jacob Humpal,*** *University of Southern Queensland*
12:20	12:30	*Close and evaluation*	***GRDC Representative***

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Crop canopy management to achieve higher yields in the better seasons — lessons from hyperyielding and irrigated crop agronomy

Kenton Porker[1], Nick Poole[1], Tracey Wylie[1], Ben Morris[1], Tom Price[1], Kat Fuhrmann[1], Darcy Warren[1], Aaron Vague[1], Max Bloomfield[1], Greta Duff[2], and Rohan Brill[3].

[1]Field Applied Research (FAR) Australia; [2]Southern Farming Systems; [3]Brill Ag..

GRDC project codes: FAR2004-002SAX, FAR1906-003RTX

Keywords

- canopy management, feed winter genetics, plant growth regulators (PGR), waterlogging .

Take home messages

- Canopy management techniques should aim to maximise crop growth during the critical period of grain number formation and improve harvest index (conversion of biomass to yield).
- Slower developing feed cultivars express their improved yield potential in the wetter and milder seasons. Consider the feed price spread and yield differential.
- Slower developing genetics typically produce more biomass and have greater yield potential. Interventions such as grazing improve harvest index (HI) but come at the expense of reduced final biomass and thus, yield is rarely increased.
- Irrespective of development type and other management, disease management is one of the key drivers of improving yield and HI in wetter seasons, achieved by both improved genetic resistance and strategic fungicide application.
- Fertile soils in the high rainfall zone (HRZ) limit the ability to manage yield and early biomass production with applied nitrogen in wetter environments. Mineralised N timing, and other canopy management factors, such as plant growth regulators (PGR) and fungicides, are equally or more important.
- Principles of canopy management also apply to irrigated scenarios, however the nitrogen rates required to achieve irrigated canola yields of greater than 4t/ha are not as high as dryland budgets would suggest.
- Minimum durum protein requirements of 13% to achieve DR1 can be met with attention to nitrogen management in irrigated scenarios.
- Canopy management benefits of PGR and fungicides extend beyond the growing season and limit pre-harvest yield losses (lodging, brackling, head-loss) and improve harvest logistics.
- Waterlogging tolerance of barley compared to wheat is poor in wetter seasons, however earlier sowing and slow developing cultivars increase the chances of improved yield recovery.

Hyperyielding crops research

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

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

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

While canopy management techniques can improve harvest index, they should not come at the expense of reduced final biomass. For example, grazing (mowing) spring and winter wheats at Gnarwarre, Victoria in 2020 increased harvest index (HI) but yields were not increased due to lower biomass (Figure 1). This trend was also observed at other hyper yielding experiments in NSW and SA. Spring wheats that achieved similar final dry matters

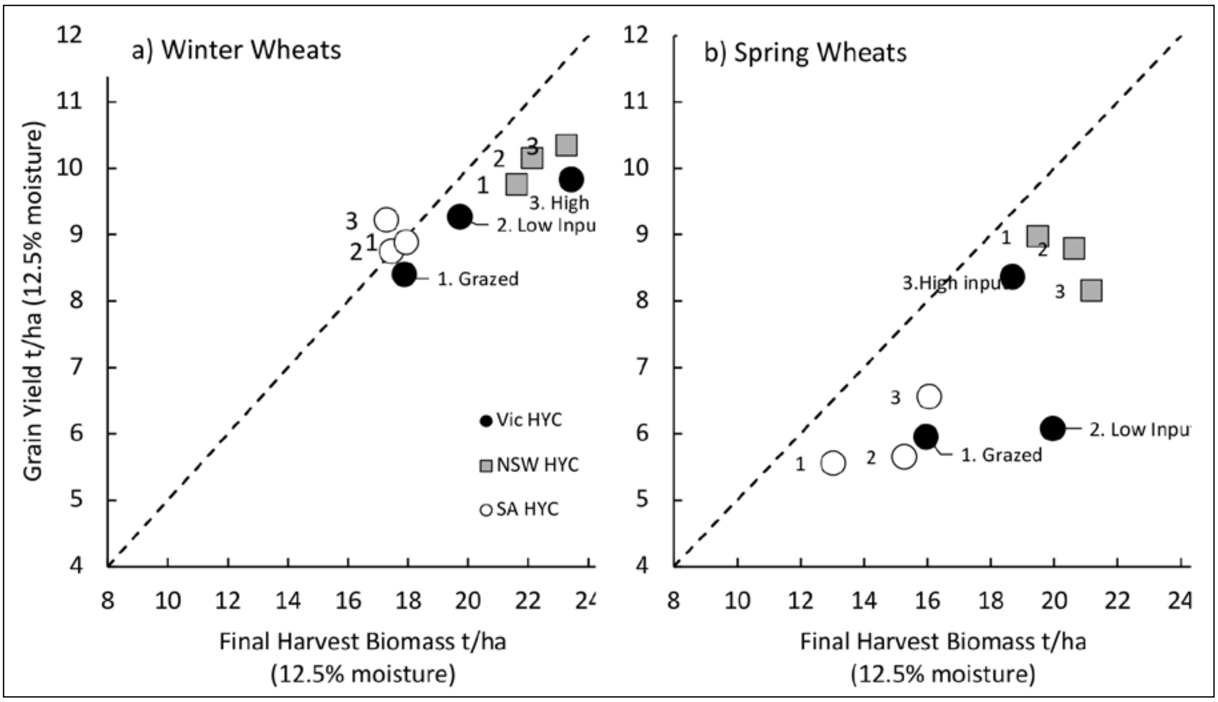

Figure 1. Relationship between dry matter and grain yield (t/ha) across a: Winter wheats (RGT Acrocc and Anapurna), and b: Spring wheats (Scepter⍉ and Trojan⍉) at three different management levels, grain only 2. low and 3. high input systems, and 1. grazed systems in 2020 at Wallendbeen NSW, Millicent SA, and Gnarwarre Vic. The dotted line represents aspirational yields that are possible with a harvest index of 50%. The key differences between low and high input are the addition of a PGR, and extra nitrogen (~20—40kg), and one extra fungicide. Grazing simulated by mowing prior to GS30. Management details for Victoria in this example can be found on the FAR Australia website.

as winter wheats yielded lower (lower HI) due to reduced light interception in the critical period from developing under sub-optimal conditions (early) and reduced green leaf area in upper canopy (increased disease infection).

Optimising irrigated grains research

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

Two years of irrigated canola and durum research

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

Durum research at Finley over the last two years (Tables 2 and 3) illustrated much lower available soil N reserves in the 2021 season compared to 2020: 232kg N/ha in the soil profile (0—90cm) following fallow in 2019, compared to 146kg/ha over the same depth in 2021 following canola. Consequently, DBA Vittaroi⫶ gave no significant yield response to applied N fertiliser (urea 46% N) at levels between 10–350kg N/ha in 2020, with yields ranging from 6.93–7.43t/ha. By comparison, yields in 2021 were between 4.87–6.74t/ha , with no significant yield response to N application above 100kg N/ha.

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

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

However, it required another 100kg N/ha of applied fertiliser (200kg N/ha total) to increase protein above 13%, the minimum required to achieve DR1 quality when applied N was split between GS30 and GS32 (pseudo stem erect & second node). However, in a separate experiment, it was illustrated that when N timing was delayed until GS32 and GS37 (flag leaf visible), a protein of 13.4% was achieved with no more 100kg N/ha of applied nitrogen (Table 3) and no loss of yield. (data not shown).

Hyper yielding research: achieving high yields from the better seasons

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

The wet 2021 season and HYC research has highlighted that the increased yield potential of feed wheats and winter barley is expressed in the better seasons and exceeds current commercially available milling wheats and malt barley cultivars. While it is possible to grow higher yield of feed wheats and barley, they need to be profitable. The durum example above shows it is possible to achieve high yields and higher proteins with N management and highlights possibilities to make the most of quality price spreads with management. The HYC results below demonstrate the milling wheats are capable of yielding 8t/ha and milling grade with adequate disease control, whereas feed winter wheats are achieving yields of ~ 11t/ha and greater in the same experiments. It must be noted in southwestern Victoria and in the lower South East of South Australia, milling wheats have often achieved lower yields, and failed to meet milling grades from earlier sowing. Figure 2 below can be used to determine how much higher feed wheats need to yield across

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

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

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

	Nitrogen application rate									
	0kg/ha N		100kg/ha N		200kg/ha N		300kg/ha N		Mean	
Nitrogen timing	Protein %		Protein %		Protein %		Protein%		Protein%	
PSPE & GS30	10.9	-	12.4	-	13.8	-	15.0	-	13.0	b
GS30 & GS32	10.6	-	12.5	-	13.7	-	15.0	-	13.0	b
GS32 & GS37	10.9	-	13.4	-	15.3	-	16.4	-	14.0	a
Mean	10.8	d	12.8	c	14.3	b	15.5	a		

N timing	Lsd	0.4	P val	<0.001
N rate	Lsd	0.5	P val	<0.001
N timing x N rate	Lsd	ns	P val	0.235

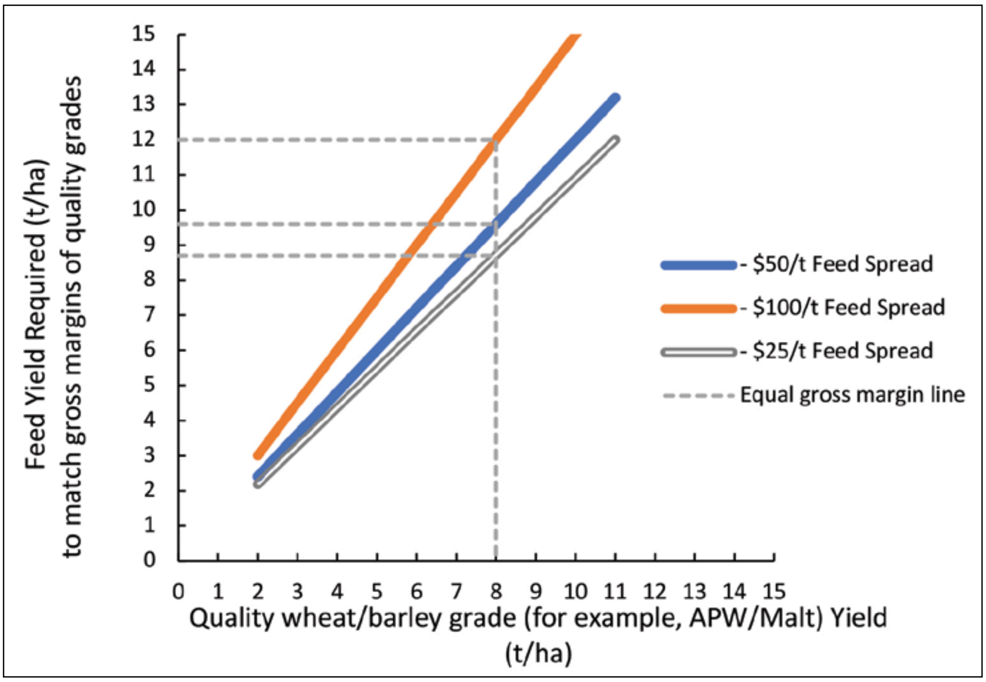

Figure 2. Relationship between the grain yield of feed cereals and quality grades required to achieve similar gross margin returns at different feed delivery price spreads (assuming quality delivery price is $300/t).

different quality grade yield potential environments to equal or exceed milling wheat gross margins. For example; at feed splits of $100 between APW and feed wheat, a feed wheat would have to yield 12t/ha (or an extra 4t/ha) to equal the gross margin of APW yielding 8t/ha (at $300/tonne delivery price). If the spread reduces to $50/t, the yield required by a feed wheat is 9.6t/ha. This assumes higher quality grades are achieved in the milling wheat. The same applies to durum in reverse: if durum attracts a $50 price premium over milling wheat, then it would only need to yield 6.2t/ha to match the gross margin of a milling wheat at 8t/ha. These yields have been achieved under irrigation in 2020 and 2021. This may be a more profitable system than chasing the extra yields of feed wheat under irrigation.

Barley is a different story, as high yields and malt can be achieved in spring barley. However, introduction of higher potential winter feed barley cultivars could raise yield expectations. The price

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

Variety		Type	Grain yield (t/ha)	
1.	Planet⑪	Two Row Malt Spring (Control)	8.0	d
2.	Rosalind⑪	Two Row Feed Spring (Control)	8.0	d
Experimental Lines[2]				
3.	AGTB0244	Two Row Spring	7.9	d
4.	Laureate	Two Row Spring	8.0	d
5.	Cassiopee	Two Row Winter	7.9	de
6.	Madness	Two Row Winter	8.7	c
7.	Newton	Two Row Winter	9.7	b
8.	Memento	Two Row Winter	8.9	c
9.	Pixel	Six Row Winter	10.4	a
10.	Visual	Six Row Winter	7.5	de
		P Val <0.001, Lsd 5% 0.64, Mean	8.10	

[1]High yielding management conditions include a robust fungicide strategy, plant growth regulators and extra N described in the flow diagram in Figure 3. [2]Lines are experimental and yet to be commercialised in Australia or receive a quality classification.

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

Feed winter barley is yet to achieve the same adoption as feed winter wheats

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

The summary of two wet seasons (three experiments) at Millicent SA, and Gnarwarre Vic of earlier sowing is below (Figure 3). A key finding was that the addition of an SDHI fungicide in

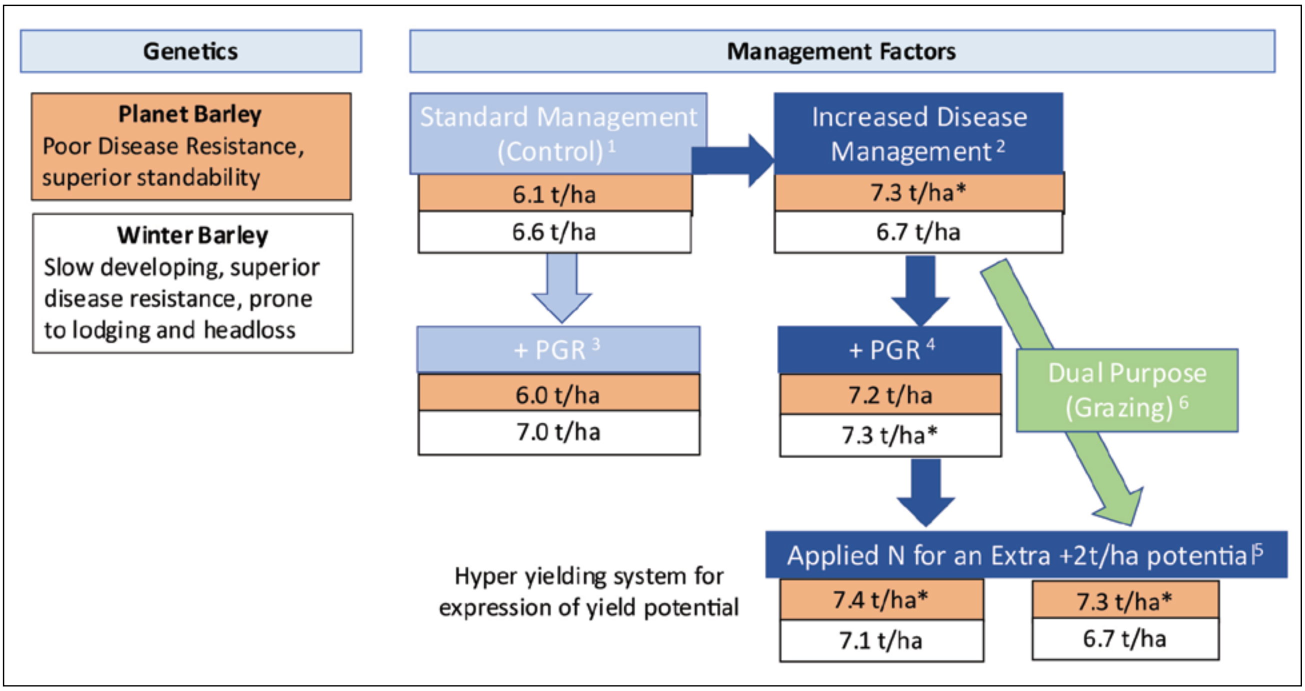

Figure 3. Mean yields and response to canopy management factors: fungicide application, plant growth regulators (PGR), nitrogen and grazing in two contrasting barley cultivars across three earlier sown experiments (~20 April) in the HRZ of SA, Vic (2020/2021).

Definitions of management factors:

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

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

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

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

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

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

the susceptible cultivar Planet⁽ᵈ⁾ increased yield by 1.2t/ha (6.1–7.3t/ha) irrespective of any other management factor. Whereas in the winter barley, yields were 6.6 and 6.7t/ha under standard and increased disease management, respectively. The addition of plant growth regulators or defoliation by grazing, or an extra 80kg of applied N did not increase yield and demonstrates in the barley variety Planet⁽ᵈ⁾, **disease management is the number one factor to achieve high yields.**

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

Disease management in better seasons is essential with higher yield potential and in wheat and barley cultivars of poorer disease resistance. Irrespective of the medium or high rainfall zone (M-HRZ), it is crucial growers and advisers consider disease management as one of the most important components of growing high yielding cereal crops in seasons with higher yield potential as highlighted in barley above.

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

- fertile soils in the HRZ limit the ability to manage yield and early biomass production with applied nitrogen in wetter environments — other techniques such as PGRs, cultivars and fungicides are more important for active management in the critical period
- canopy management benefits extend beyond the growing season – disease control and the combined application of PGRs and timely harvest ensures pre-harvest yield losses are reduced, particularly in barley (for example, head loss and brackling)
- waterlogging tolerance of barley compared to wheat is poor in wetter seasons, however earlier sowing of slow developing cultivars increases the chances of improved yield recovery post-waterlogging.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the investment of the GRDC, the author would like to thank them for their continued support. FAR Australia gratefully acknowledges the support of all of its research and extension partners in Hyper Yielding Crops project. These are CSIRO, the Department of Primary Industries and Regional Development (DPIRD) in WA, Brill Ag, Southern Farming Systems (SFS), Techcrop, the Centre for eResearch and Digital Innovation (CeRDI) at Federation University Australia, MacKillop Farm Management Group (MFMG), Riverine Plains Inc and Stirling to Coast Farmers. We would also like to thank our host growers in each state. FAR Australia gratefully acknowledges the collaboration of Irrigated Cropping Council and NSW DPI with this component of the Optimising Irrigated Grains project. We would also like to acknowledge Southern Growers Inc for providing and hosting the FAR Australia Finley Irrigated Research Centre.

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Potential strategies to reduce the impact of waterlogging on crop yields

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GRDC project codes: VGIP2A, VGIP2C, DAV00141, DAV00151

Keywords

- denitrification, dewatering crops, drainage, nitrogen.

Take home messages

- Tactical options including early sowing, early application of nutrients (preferably using enhanced fertiliser forms) or aerial application after waterlogging can improve yields and fertiliser use efficiency.
- Faba bean and wheat are relatively tolerant of waterlogging beyond the juvenile stage whereas canola appears highly sensitive at all growth stages.
- The impact of waterlogging on crop yields is often highly variable within a paddock, requiring spatially explicit management responses.
- Nitrogen requirements in parts of the paddock exposed to prolonged waterlogging are higher than in well-drained areas because of poorer crop utilisation and greater N losses (presumably via denitrification).

When and where does waterlogging occur?

Short-term perched water tables occur in most years in the High Rainfall Zone (HRZ), but the depth and duration of perched water tables is rarely measured. In a study of paddock variability conducted in 2021, the water table was within 10cm of the surface between mid-July and mid-August and included some periods when almost the entire paddock had water above the soil surface (Figure 1). Over the longer term, soil moisture data from a cropping paddock near Hamilton shows that full soil moisture profiles occur in most years between mid-July and mid-September, but may start as early as May and finish as late as mid-October in some years. Ironically, in some seasons, water shortages during grain filling in these paddocks can subsequently reduce a crop's ability to achieve expected yield potentials.

Waterlogging is not only a problem in the high rainfall zone. At three Wimmera (medium rainfall zone) paddocks monitored in 2021, periods of high water tables were recorded between mid-July and mid-August, with a brief period of a high water table at one site in October following a storm (Figure 3). These perched water tables occurred despite the deeper soil layers not fully wetting due to constrained water movement into sodic (dispersive) clay subsoils.

What changes occur under waterlogging?

While the most obvious change under waterlogging is loss of trafficability for spraying and fertilising operations, plant roots and microbes suffer shortage of oxygen (anoxia). Plant roots need oxygen to provide the energy to take up nutrients such as nitrate, which are at low concentrations in the soil water but are required at much higher concentrations within the plant. Respiration from plant roots and microbes cause the soil to rapidly become anoxic in waterlogged soil, which curtails most aerobic respiration. The nodal roots of wheat have air-conducting spaces known as aerenchyma that allow oxygen to move within the root to a soil depth of about 10cm, enabling the crop to grow and access nutrients from this layer. However, until the tillering stage, wheat plants are dependent on their seminal roots, which lack aerenchyma, for water and nutrient uptake. These roots stop growing soon after waterlogging and have limited capacity to regrow after waterlogging ceases. Severe waterlogging at this stage can lead to plant death. Faba beans have an air-filled hollow in the stem that continues into the larger roots, and appears to be capable of rhizobia nodules with oxygen. Nevertheless, faba beans are at risk of plant death if waterlogging occurs early in the plant's life.

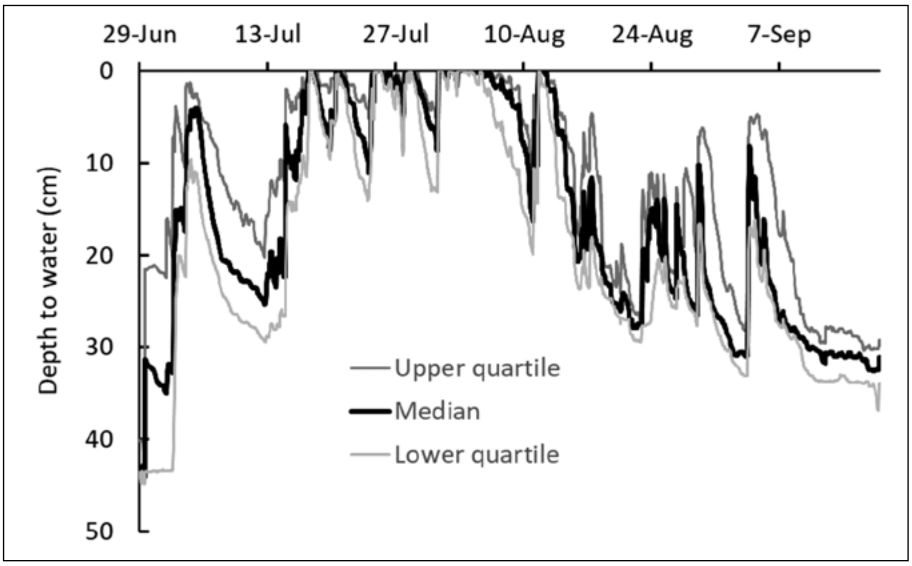

Figure 1. Depth to the perched water table at 12 monitoring positions within a paddock at Wickliffe in the HRZ during 2021.

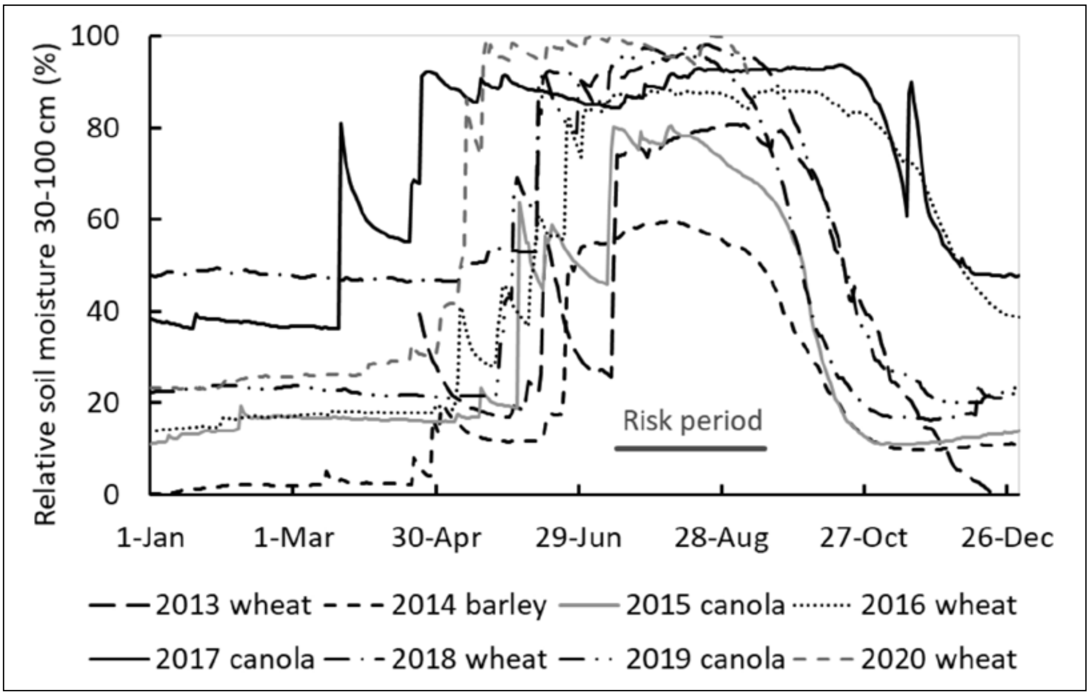

Figure 2. Seasonal changes in soil moisture in a cropping paddock near Hamilton over 8 seasons, indicating the high-risk period for waterlogging between mid-July and mid-September. Source: Agriculture Victoria soil moisture monitoring network.

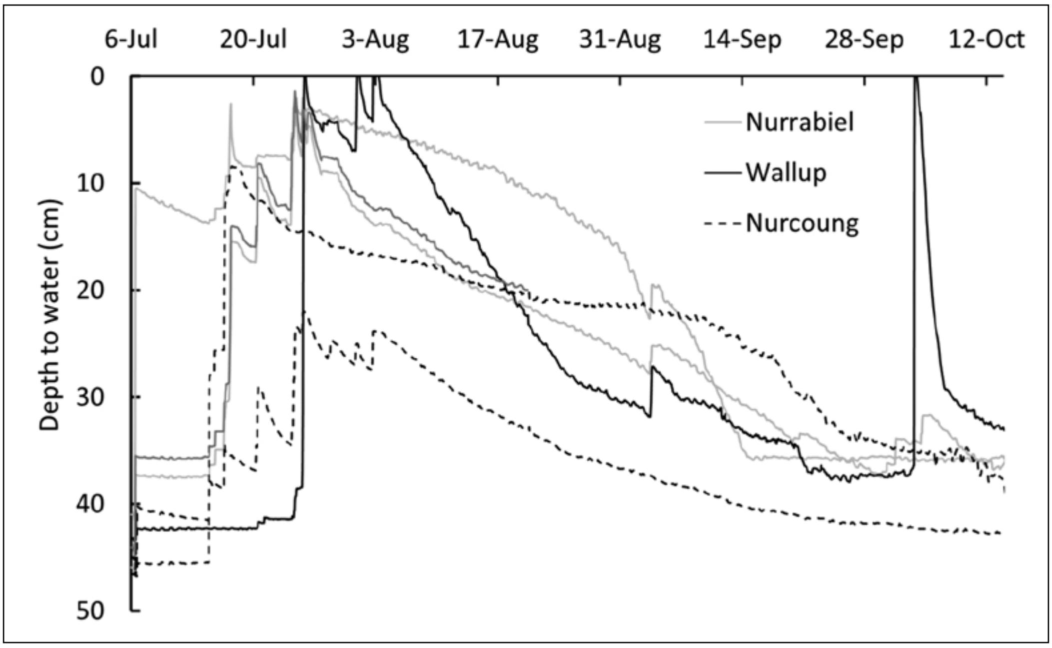

Figure 3. Depth to a perched water table in three paddocks in the Wimmera in 2021 – Nurrabiel (2 monitoring positions), Wallup (1 position) and Nurcoung (2 positions).

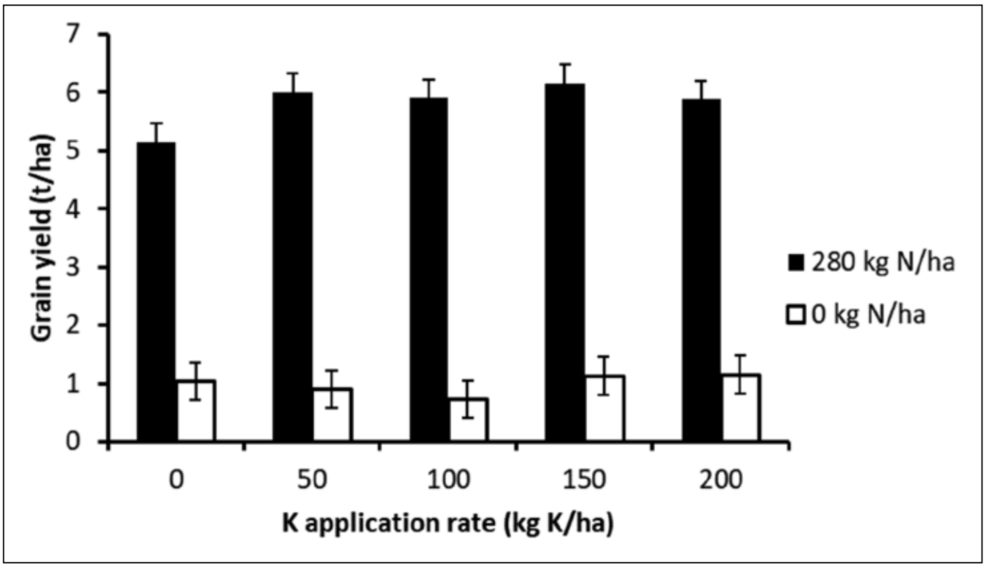

Figure 4. Response of canola to top-dressed urea and potash at Hamilton in 2016 on a site with 160mg/kg of Colwell-extractable K in the top 10cm, and 238kg/ha of KCl extractable nitrate-N in the top 60cm. Error bars indicate the 5% Lsd. Source: McCaskill et al. (2020).

Canola lacks adventitious roots and in saturated soil is entirely dependent on a thin oxidised layer of soil near the surface for its nutrient uptake. In one nutrient response experiment in 2016, we measured large responses to broadcast urea and potash despite soil tests indicating adequate quantities of plant available N and K in the soil profile (Figure 4). Raised beds provided a layer of aerated soil 5-10cm deep, below which root access was restricted due to waterlogging. This experiment shows that high canola yields are possible under prolonged waterlogging if sufficient nutrition is provided in the surface layers.

Measures to reduce this risk of nutrient deficiency include strategies that help the crop avoid waterlogging during critical growth stages by early sowing, applying N ahead of peak plant demand, particularly immediately prior to periods of high waterlogging risk, and aerial application of urea if necessary. The nitrification inhibitor ENTEC® has been shown to reduce N losses if applied well

Table 1. Percentage of 15N labelled urea (100kg/ha, applied at GS30) recovered in the wheat grain, stubble, soil and unaccounted for, presumed mostly denitrified.

	Lower slope	Mid-slope	Upper	5% Lsd
^{15}N in grain (%)	15a	38b	41b	6
^{15}N in stubble (%)	3a	7b	8b	2
^{15}N in soil (%)	23	26	25	12 (ns)
^{15}N unaccounted for (%)	59b	29a	26a	13

ahead of demand at times of high waterlogging risk (Harris et al. 2016). Potassium deficiency also needs to be assessed prior to sowing. The critical soil test value for Colwell-extractable K in the topsoil should be higher for crops at risk of prolonged waterlogging (273mg K/kg) than for crops where this risk is lower (73mg K/kg) (McCaskill et al. 2020).

Under saturated soil conditions, soil microbes change from aerobic respiration (using oxygen) to anaerobic respiration that metabolises nitrate into nitrous oxide and nitrogen gas, a process known as denitrification. Poorly drained areas therefore have higher rates of denitrification. In a 15N tracer study at Wickliffe in the HRZ, we found a higher proportion of the fertiliser N applied being unaccounted for at harvest (most of which is likely to have been denitrified) in a low-lying part of the paddock (Table 1). In the following season, low crop vigour in these poorly-drained areas became evident as areas of low NDVI on satellite images. Correcting these areas of low NDVI requires either a higher rate of N over the entire paddock, or variable rate spreading.

What is the yield penalty due to waterlogging?

Wheat yields in areas prone to waterlogging can be as much as 38% below that of well-drained areas. The size of yield loss varies substantially in time and space, so crop simulation modelling could be a useful tool to estimate losses. However, models such as APSIM currently do not yet have the capability to estimate yield loss from waterlogging. As a first step in improving model performance in waterlogged conditions, we conducted detailed measurements of wheat and faba bean crops in an experiment at Hamilton in which waterlogging was imposed through frequent irrigation for a short (17 days) or a long period (30 days) during flowering. Although there were significant effects on crop biomass (Figure 5), we only measured significant yield differences in wheat (38%), but not faba bean (Table 2). The non-waterlogged faba beans, however, were taller and suffered more severe lodging during a storm than the waterlogged treatments. Early differences in biomass may therefore not translate into increased grain yield.

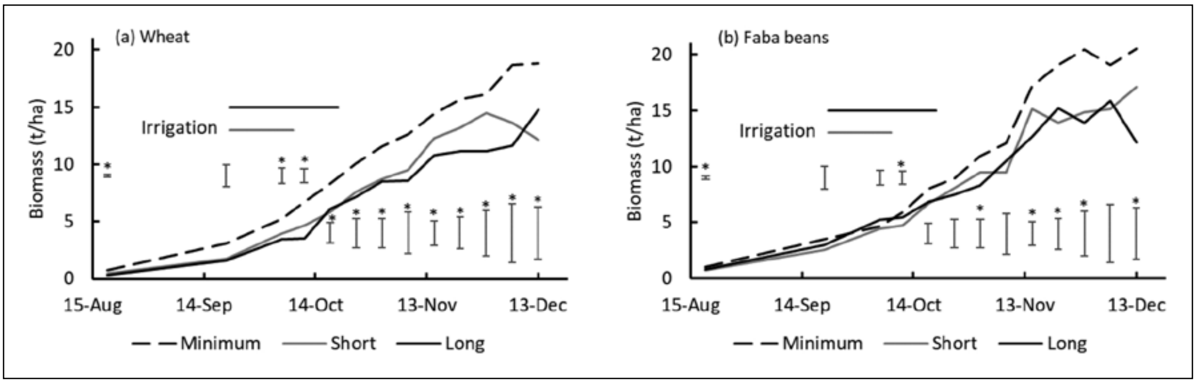

Figure 5. Above ground biomass accumulation in wheat and faba bean crops, showing the period when irrigation was imposed to create short (17 days) and long (30 days) durations of waterlogging. Error bars show the 5% Lsd and asterisks when differences were significant.

Table 2. Grain yield of wheat and canola crops exposed to short and long periods of waterlogging during flowering.

	Non-waterlogged	Short	Long	Lsd 5%
Wheat (t/ha)	8.4 b	6.8 ab	5.2 a	1.8
Faba bean	8.7 a	8.9 a	7.5 a	3.3

Self-sown crops

In some years in the HRZ, substantial falls of rain are experienced in November and December when the crop is maturing and unable to effectively utilise this soil moisture. Our field trials have shown that moisture above about 30cm is lost to soil evaporation and transpired by self-sown plants over the summer fallow period, whereas deeper soil water remains until sowing of the following winter crop, greatly increasing the risk of waterlogging. A summer dewatering crop in such years could create a buffer of dry soil that would delay the onset of saturated soil conditions for the following winter crop, so the plants are larger and better able to tolerate waterlogging. One such year was 2020. In a paddock sown to canola, the soil was moist at the time of windrowing, and the soil profile contained 94mm more water in the soil profile than when the previous crop of wheat was harvested (Figure 6). To utilise carryover soil moisture, self-sown canola was allowed to grow. However, it was unable to dry the deeper layers of the soil and did little more than utilise most of the 200mm of summer rain that fell over the fallow period. During soil coring in the paddock, we encountered a hard dry layer at about 30cm depth, below which penetration was easy. Since plant roots would have similar difficulties penetrating this layer, it may be necessary to establish plants early in the summer period before this layer dries through soil evaporation.

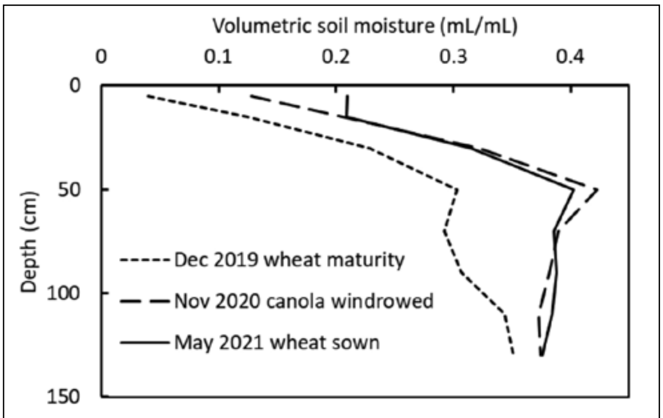

Figure 6. Soil moisture at wheat maturity in 2019, when canola was windrowed in November 2020, and when the following crop of wheat was sown in 2021. Data are averaged across 40 monitoring points.

Drainage and lucerne understorey

In Victoria, few growers have installed underground drainage for field crops. Some growers in the Cavendish area have installed underground drains on their cropping paddocks and used this in combination with an understorey of lucerne as a dewatering crop. Drainage installation costs were estimated at $1250/ha in 2016, and a 38% rate of return was calculated based on higher wheat and canola yields, and lamb finishing on lucerne during the summer (Lewis and Price 2016). Alternatively, one grower who implemented subsoil manuring reported that paddocks that previously could only grow pasture were now producing wheat yields of up to 10t/ha.

Conclusion

Wheat and faba bean are vulnerable to waterlogging early in the crop life, but in most years, have developed their nodal roots by the time waterlogging commences. These crops are subsequently relatively robust if the soil is saturated. Canola lacks roots that conduct oxygen, but nevertheless can produce good yields if sufficient nutrition is supplied into the aerated surface layers during periods of waterlogging.

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Improving waterlogging tolerance of barley varieties

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GRDC project code: UOT1901-001RTX

Keywords

- aerenchyma, *Hordeum vulgare*, hypoxia, waterlogging, yield.

Take home messages

- Waterlogging is a serious environmental factor that limits barley yield.
- A single QTL for aerenchyma formation found in a wild barley has been introgressed into commercial variety RGT Planet⦶ to produce Planet⦶+.
- The Planet⦶+ lines showed 20-50% higher yielding than RGT Planet⦶ under waterlogged conditions with no significant differences under control conditions.

Background

Waterlogging is one of the major abiotic stresses in crop production (Zhou et al. 2007). Globally, an estimated 12% of crop areas are affected by waterlogging (Manik et al. 2019). By influencing crop growth and development (Kozlowski 1997; Ren et al. 2014), waterlogging drastically reduces barley yield (Liu et al. 2020; Manik et al. 2022). Global barley production has diminished over the last two decades, decreasing from 155Mt in 2008–2009 to 142Mt in 2017–2018 (Statista, 2020; Liu et al. 2020). Part of this decline is due to increased frequency of waterlogging and susceptibility of barley to waterlogging stress damage (Byrne et al. 2022). In many contexts, improving crop tolerance to low or mild waterlogging is generally cost effective. However, under severe waterlogging, combined agronomic, engineering and genetic solutions are needed (Manik et al. 2019).

Waterlogging hinders the growth of plants by reducing the dispersal of oxygen through the pore spaces in the soil around the root zone (Drew and Sisworo 1977; Armstrong 1980). Waterlogging first affects the roots and the plant root needs an adequate supply of oxygen so as to fulfill the water and nutrient requirements of the shoots. The soil oxygen concentration should be above 10% where atmospheric concentration is 21% (Colmer and Greenway 2011). Under waterlogging conditions, oxygen demand to the root tip and to the rhizosphere is supplied by forming aerenchyma through removal of some cells of the cortex and these remove excess gases from the root and soil (Armstrong 1980; Colmer and Greenway 2011). Morphological adaptations including adventitious roots with well-formed cortical aerenchyma (Figure 1) enhance internal diffusion of oxygen from shoots to the waterlogged roots, allowing roots to maintain aerobic respiration (Armstrong 1980; Zhang et al. 2015).

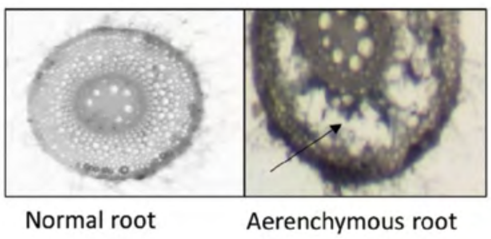

Figure 1. Barley normal root has an intact cortical region (left). The aerenchyma in barley root on the right is formed through removal of some cells or lysis of the cells in the cortex.

Our research has discovered a key gene in a wild barley genotype which contributes to root aerenchyma formation under waterlogging conditions, thus, to waterlogging tolerance (Zhang et al. 2015). The objectives of this study were to introgress the gene into commercial varieties and to examine the contribution and effect of the QTL for root cortical aerenchyma (RCA) formation under waterlogging stress to mitigate barley yield loss.

Materials and methods

The experiments were conducted in 2021 at the research station of the Tasmanian Institute of Agriculture, Launceston, Tasmania.

Planet⁽ᵈ⁾ is a high yielding commercial variety but is sensitive to waterlogging events. The waterlogging-tolerant wild barley (Tam407227) genotype was used as a donor parent to cross with Planet⁽ᵈ⁾ to develop waterlogging-tolerant lines (Planet⁽ᵈ⁾+ or P+) which have a Planet⁽ᵈ⁾ background with the waterlogging tolerance gene added.

Planet⁽ᵈ⁾, and two new Planet⁽ᵈ⁾+ lines P-17 and P-52 were sown with three replications in 1.2m x 2m field plots in a randomised complete block design. Row spacing was 0.22m and 40 seeds were sown per row, with 0.03m between seeds. The controls were sown in well-drained beds. Waterlogging treatment was started at two-three leaf stage (Figure 2) when barley suffers the most from excess water in Australia's high rainfall regions. The waterlogging treatment lasted for two months, the period that happens very often in these regions. After waterlogging treatment concluded, all plots were fully drained until harvest.

Root survival was determined based on the proportion of white adventitious roots at 30 days under waterlogging (30DT), 60 days under waterlogging (60DT) and 30 days after recovery (30DR). At crop maturity, all plants were taken for determination of grain yield and yield components (total number of spikes and 1000-grain weight). Grain quality of all the samples was analysed at the Australian Export Grains Innovation Centre, South Perth, Australia.

Results and discussion

Field performances and aerenchyma formation

Under waterlogging conditions, tolerant genotypes showed healthy and more green leaves than sensitive genotypes (Zhou et al. 2007). In this study, Planet⁽ᵈ⁾+ showed better growth characteristics in the field during waterlogging and after terminating waterlogging events (Figure 3a-3f). Aerenchyma formation is the key superior characteristic of waterlogging-tolerant barley genotypes under waterlogging events (Zhang et al. 2015; Manik et al. 2022). Under waterlogging condition, P+ formed a considerably higher proportion of aerenchyma in adventitious roots than Planet⁽ᵈ⁾ (Figure 3g-3h). There was no aerenchyma formed in adventitious root under the well-drained control conditions in both P+ and Planet⁽ᵈ⁾.

Adventitious roots

Under waterlogging conditions, adventitious root formation is one of the tolerance mechanisms in cereals (Shabala 2011). Under waterlogging conditions, P+ produced a higher proportion of healthy white adventitious roots than Planet⁽ᵈ⁾. At 30 days under waterlogging conditions, the proportion of white adventitious roots is significantly higher than Planet⁽ᵈ⁾. After 60 days waterlogging, P+ kept forming white adventitious roots. In contrast, Planet⁽ᵈ⁾ showed a slow progress in adventitious root formation. At 30DR, both genotypes started to recover by forming more adventitious roots, with P+ showing a greater ability to form adventitious roots compared to Planet⁽ᵈ⁾ (Figure 4a).

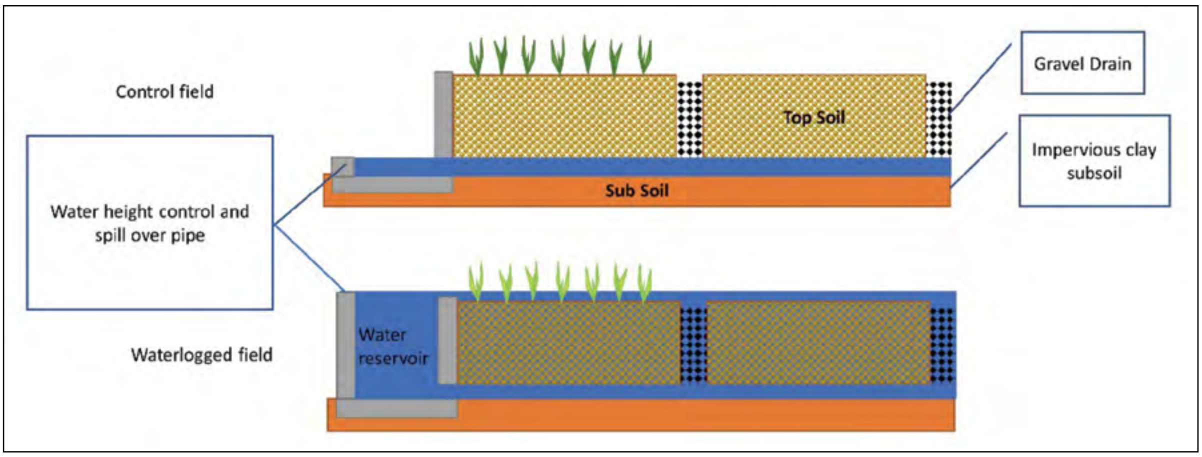

Figure 2. Layout of waterlogging and control treatment (Manik et al. 2022).

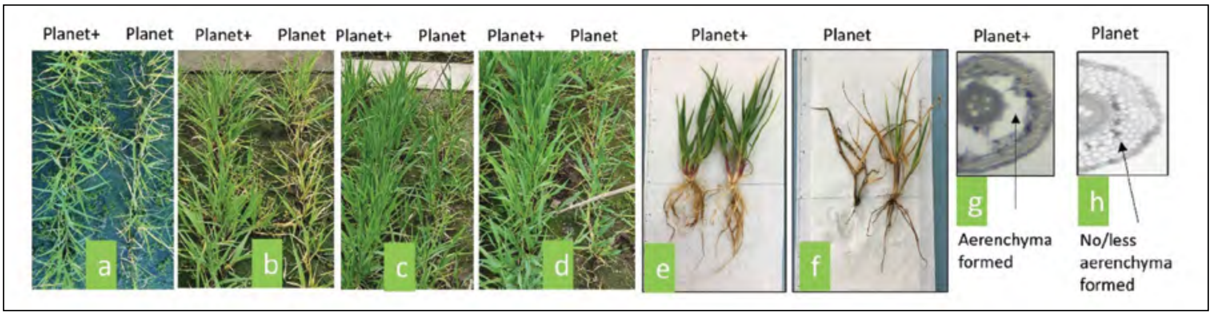

Figure 3. Left: Planet⁽ᵗʰ⁾+; right: PlanetA. a: 60 days after waterlogging; b: one week after waterlogging terminated; c: one month after waterlogging terminated; d: two months after waterlogging terminated; e: Planet⁽ᵗʰ⁾+ developed numerous adventitious roots; f: Planet⁽ᵗʰ⁾ has few/no adventitious roots; g-h: Planet⁽ᵗʰ⁾+ formed a higher proportion of aerenchyma than Planet⁽ᵗʰ⁾ under waterlogging conditions.

Crop phenology

Waterlogging hinders barley growth and delays the phenology (Liu et al. 2020). Under waterlogging conditions, P+ showed better growth attributes than Planet⁽ᵗʰ⁾. During recovery, P+ recovered earlier than Planet⁽ᵗʰ⁾, thus P+ showed earlier flowering and maturity than Planet⁽ᵗʰ⁾ (Figure 4b).

Grain yield components

Waterlogging treatments decreased barley grain yield by 30-70%. Waterlogging-tolerant genotypes produced 20-30% greater grain yield than susceptible genotypes (Liu et al. 2020; Manik et al. 2022) under waterlogging conditions. In this study, there were significant differences between P+ (P-17 and P-52) and Planet⁽ᵗʰ⁾ in grain yield and yield components under waterlogging conditions with P+ (P-17 and P-52) showing 50% higher yield than Planet⁽ᵗʰ⁾ (Figure 5a). Grain yield is highly associated with tiller (spike) number. P+ genotypes had more than a 50% higher spike count than Planet⁽ᵗʰ⁾ (Figure 5b). Thousand grain weight of P-17 is slightly lower due to the high number of spikes (Figure 5c).

Grain quality

Waterlogging affects the barley grain quality parameters (Zhou et al. 2008; Manik et al. 2022). Grain quality parameters are very important for commercialisation of barley genotypes. There was no significant difference between Planet⁽ᵗʰ⁾ and P+ in terms of grain quality parameters protein (Figure 6a), malt extract (Figure 6b), wort (Figure 6c) and diastatic power (Figure 6d) under control conditions. Under waterlogging conditions, diastatic power and protein were reduced compared to the control but malt and wort remained unchanged. There were no significant differences between P+ and Planet⁽ᵗʰ⁾ under waterlogging conditions.

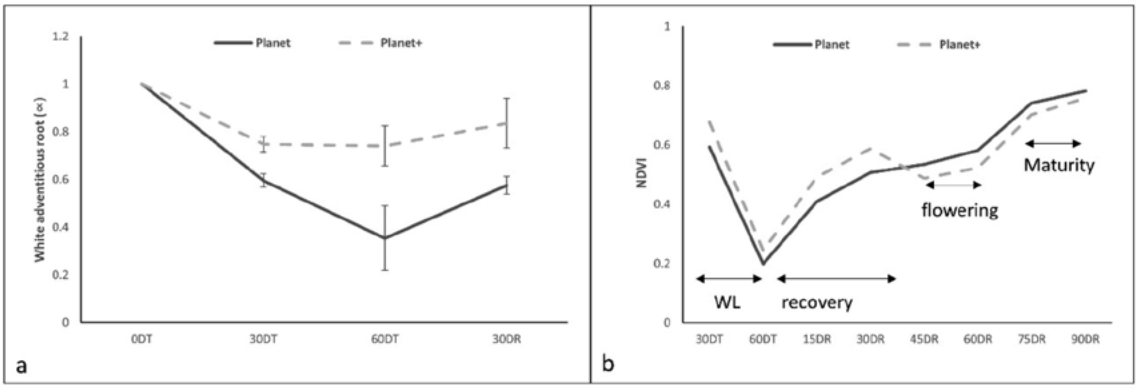

Figure 4. a: PlanetA+ produced more adventitious roots during and after waterlogging; **b:** Planet⁽ᵗʰ⁾+ showed faster recover, earlier flowering and earlier maturity than Planet⁽ᵗʰ⁾ after waterlogging events; 0DT: before starting waterlogging events, 30DT and 60DT: 30 days and 60 days under waterlogging events, respectively; 15DR, 30DR, 45DR, 60DR, 75DR and 90DR: 15 days, 30 days, 45 days, 60 days,75 days and 90 days recovery after terminating waterlogging events, respectively.

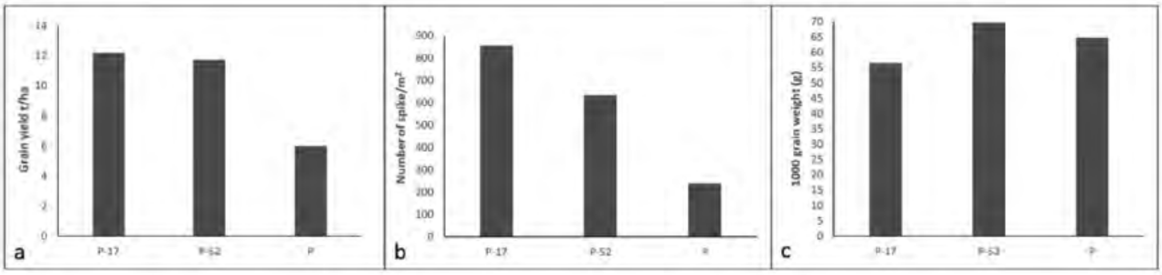

Figure 5. a: Grain yield; **b:** Number of spike/m2; **c:** 1000 grain weight. P-17 and P-52 are the P+ NILs and P is RGT Planet(d).

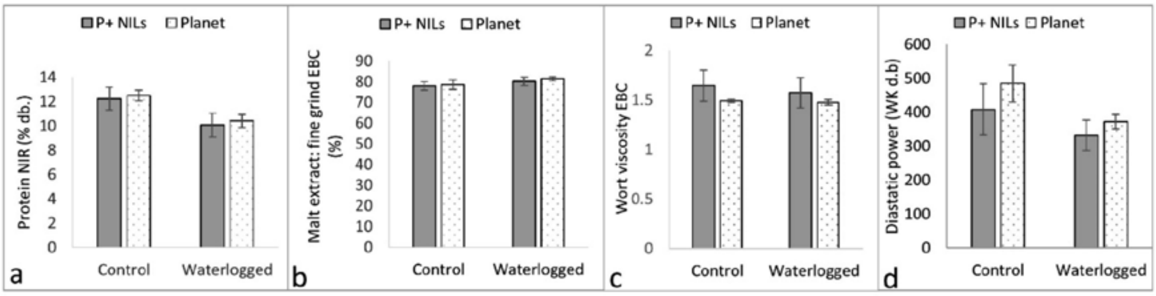

Figure 6. Grain quality parameters of P+ NILs and Planet(d); a: protein content; **b:** malt extract fine grind; **c:** wort viscosity; **d:** diastatic power.

What next?

In 2022 waterlogging tolerant lines will be assessed in field trials in Tasmania, Victoria and WA with possible release in coming years.

Conclusion

The below table (Table 1) shows that:

- under non-waterlogged conditions, no differences were identified between Planet(d)+ and Planet(d).
- under waterlogged conditions, Planet(d)+ survived better and showed a quick recovery, more tillers, earlier flowering and maturity, and more importantly, 20-60% higher yield than Planet(d).

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

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Table 1. Comparison of PlanetA and Planet(d)+ performance parameters.

	Parameters	Planet(d)	Planet(d)+
1	Crop phenology in control (non-waterlogged conditions)	Same	Same
2	Crop phenology in waterlogged conditions	Late recovery, a smaller number of tillers, late flowering and late maturing compared to Planet(d)+	Quick recovery, more tillers, early flowering and early maturing compared to Planet(d)
3	Grain yield in control conditions	Same	Same
4	Grain yield in waterlogged conditions	20-60% less yield than Planet(d)+	20-60% more yield than Planet(d)
5	Grain quality	Same	Same

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Managing annual ryegrass in the high rainfall zone

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GRDC project codes: UA1803-008RTX, SFS00032, SFS1904-003WCX

Keywords

- double breaks, harvest weed seed control, pre-emergent herbicides.

Take home messages

- Mixtures and sequences of pre-emergent herbicide are required for effective control of annual ryegrass in the HRZ.
- Harvest Weed Seed Control (HWSC) can be a valuable extra tool in the HRZ, despite more ryegrass seed shattering before harvest.
- Double breaks in rotations are the key to longer term management of annual ryegrass.
- Tactics need to be stacked each year for profitable annual ryegrass control.

Annual ryegrass is challenging to manage in the high rainfall zone

The long crop growing season of the high rainfall zone (HRZ) means that emergence of annual ryegrass is extended and late emerging annual ryegrass plants are still able to set a considerable amount of seed. In addition, there is widespread resistance to post-emergent herbicides in annual ryegrass. This means that annual ryegrass escaping pre-emergent herbicide control can easily repopulate the seed bank, maintaining high weed numbers.

Mixtures and sequences of pre-emergent herbicide are required for effective control of annual ryegrass in the HRZ

The high levels of resistance to post-emergence herbicides means that pre-emergent herbicides are the main means of annual ryegrass control in cereal crops. The extended emergence of annual ryegrass makes pre-emergence control difficult in the high rainfall zone. The use of pre-emergent herbicides as mixtures or as sequences with Boxer Gold® used early post-emergent can increase the amount of control achieved by having more persistence of the herbicides.

The introduction of new pre-emergent herbicides in recent years has offered new options for annual ryegrass control across all crops. However, the more mobile pre-emergent herbicides are more challenging to use in the HRZ. These herbicides can more easily be moved into the crop root zone resulting in crop damage, or leached out of the root zone of weeds, resulting in poor weed control. The registration of Mateno® Complete as an early post-emergent option in wheat has the potential to improve annual ryegrass control through its greater persistence in the soil compared with Boxer Gold.

Is harvest weed seed control viable in the HRZ

The long cropping seasons in the HRZ tend to result in annual ryegrass maturing and shedding substantial amounts of seed before the crop is ready for harvest. This means the efficacy of harvest weed seed control (HWSC) tactics is lower in the HRZ than in other regions (Table 1).

Table 1. Amount of annual ryegrass seed shed in HWSC trials in the HRZ prior to harvest.

Trial	2015	2016	2017
Lake Bolac, Vic	50%	31%	0%
Yarrawonga, Vic		57%	65%
Conmurra, SA		59%	65%

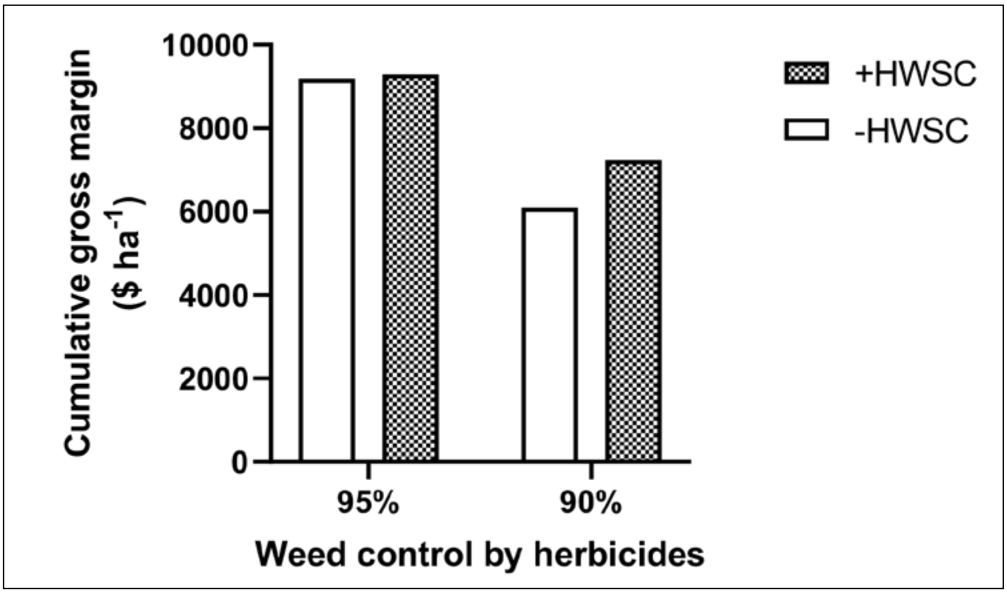

Figure 1. Cumulative income after 12 years of a simulated wheat-barley-canola rotation, with or without a weed seed impact mill (HWSC) that removes 30% of weed seeds at harvest, and with effective herbicide control (95% of weeds killed) or less effective herbicide control (90% of weeds killed).

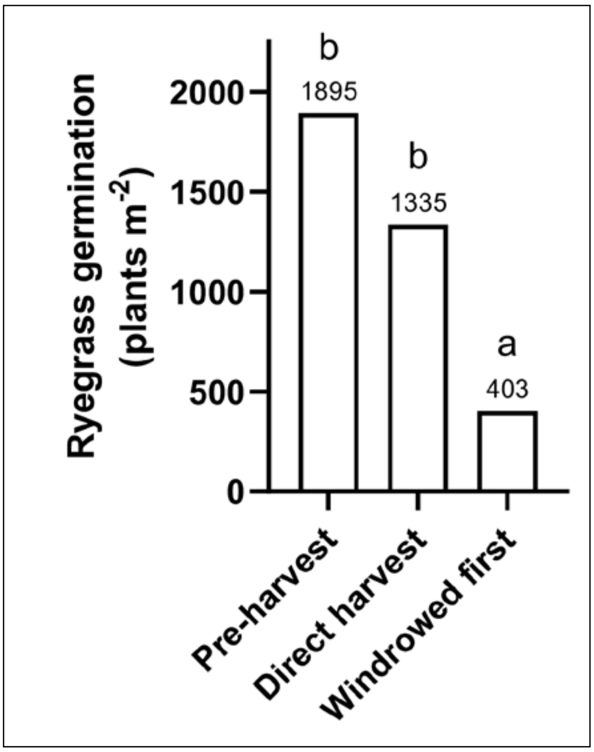

Figure 2. Annual ryegrass germination from plant and soil samples taken pre- and post-harvest at Conmurra, where direct harvest and windrowing strategies were used with an impact mill. Different letters indicate treatments that were significantly different.

However, HWSC can still have value in the HRZ, as it helps reduce weed populations for future years. Modelling of the influence of HWSC on annual ryegrass populations and the effects of weed competition with crops suggests that 30% reduction in seed inputs will be beneficial, provided that the extra costs of HWSC are less than $34/ha. The benefits may be greater if herbicide control is compromised (Figure 1).

Windrowing crops can lead to less ryegrass shedding and more seeds are able to enter the front of the header. A paddock trial at Conmurra comparing direct harvest with an impact mill to windrowing and then harvest showed that windrowing first was able to greatly reduce the amount of annual ryegrass that germinated in the next year (Figure 2). The higher biomass of crops in the HRZ also means that costs of HWSC can be higher due to slower harvest. Some growers manage this by harvesting most of the crop at the normal height and dropping the header front low when they run into patches of annual ryegrass.

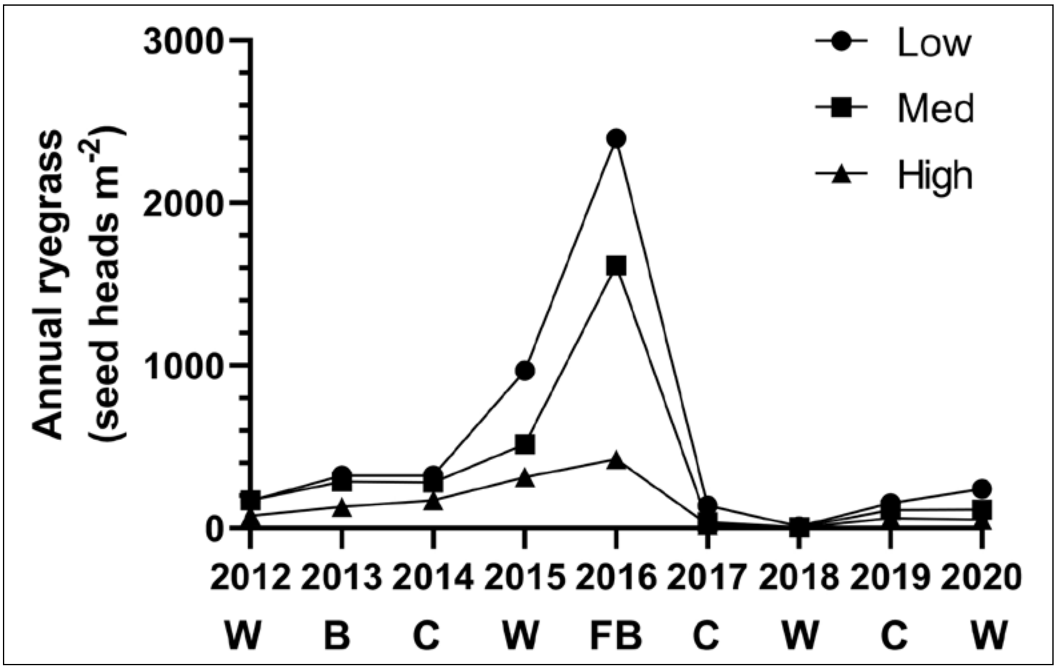

Figure 3. The mean effect of herbicide strategy on annual ryegrass seed heads/m in a nine-year trial at Lake Bolac. "W" is wheat, "B" is barley, "C" is canola, "FB" is faba beans. There are significant differences in all years except 2017.

Double breaks in rotations are the key to longer term management of annual ryegrass

As there are few effective controls for annual ryegrass in cereals in the HRZ, other than pre-emergent herbicides, break crops are an opportunity to greatly reduce annual ryegrass numbers. However, single break crops in rotations tend to just slow the rate of increase of annual ryegrass numbers. Break crops allow the use of clethodim and butroxydim as post-emergent herbicides, which still provide some level of control of annual ryegrass, and effective crop-topping. These tactics are not available in cereal crops. A double break, by reducing annual ryegrass seed set 2 years in a row has the potential to re-set annual ryegrass numbers.

This was demonstrated in a long-term trial at Lake Bolac from 2012 to 2020. This trial compared three herbicide strategies, low, medium and high cost, for the control of annual ryegrass. From 2012 to 2016 annual ryegrass increased with all three strategies. The increase in annual ryegrass numbers (as measured by seed heads at harvest) was much lower in the high cost herbicide treatment, but herbicides on their own were not effective in reducing annual ryegrass numbers. A double break of faba beans followed by canola in 2016 and 2017, where both crops were crop-topped allowed a large reduction in annual ryegrass numbers in all three herbicide strategies. These low numbers were maintained in the medium and high cost herbicide strategies through 2020.

Table 2. Yield for wheat in 2019 and faba beans in 2020 at Frances with four management strategies (MS1 to MS 4) and cumulative gross margins for the management strategies across the two years. Different letters after values in each column indicate significant differences.

Management strategy	Yield (t/ha)		Cumulative gross margin ($/ha)
	2019	2020	
MS 1	6.2 c	3.8 ab	$3,772
MS 2	6.2 c	3.5 b	$3,642
MS 3	6.7 b	3.9 ab	$3,926
MS 4	7.1 a	4.0 a	$4,072

Tactics need to be stacked each year for profitable annual ryegrass control

The Lake Bolac trial also demonstrated the value of stacking herbicide tactics. The high cost strategy was able to maintain annual ryegrass populations and, by reducing the impact on crop yield, provided a cumulative $1613/ha gross margin advantage over the low cost strategy over the 9 years of the trial.

A trial at Frances across 2019 and 2020 comparing increasing intensities of management also showed that increasing management intensity that reduces annual ryegrass numbers leads to improved profitability. In this trial, the most intensive management strategy (MS 4) provided a $300/ha cumulative gross margin advantage over the least intensive management strategy (MS 1).

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Useful resources

https://grdc.com.au/resources-and-publications/all-publications/publications/2021/managing-annual-ryegrass-in-the-high-rainfall-zones-of-victoria,-south-australia-and-tasmania

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Variability in wheat grain protein estimated from airborne hyperspectral and thermal remote sensing imagery

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Keywords

- grain quality, machine learning, remote sensing.

Take home messages

- Hyperspectral remote sensing offers powerful new tools in agriculture.
- Machine learning/AI are key to unlocking actionable information from data.
- New methods can estimate aspects of crop performance including grain protein content.

Background

Bread and durum wheat are major staple foods and receive large amounts of nitrogen (N) fertiliser, a large and risky expense for growers. Grain protein content (GPC) drives both the economic and dietary value of grain and is influenced by weather, soil and agronomic factors, but drought and/or heat can depress photosynthesis during grain filling, leading to higher GPC (Gooding et al. 2007). Header-mounted GPC monitors are becoming popular and provide large data streams, an opportunity for scientific analysis with potential benefits to growers. Early knowledge of the spatial patterns of GPC within and between paddocks could allow growers to harvest strategically for grain segregation or blending, or to adjust fertiliser applications to achieve quality benchmarks and optimise profit (Apan et al. 2006).

Because of its high spectral resolution, hyperspectral remote sensing (RS) offers vastly more information about plant condition than broadband indices. Retrieval of plant physiological traits, and stress detection, are hence vastly improved. As GPC is linked to stress, there is a sound theoretical basis to GPC estimation by hyperspectral methods. These include many reflectance indices, as well as physical modelling methods. Machine learning (ML) algorithms permit complex relationships between multiple explanatory and response variables to be modelled, and for the relative contribution of each input to model accuracy to be assessed. Because of the many parameters that can be retrieved from hyperspectral data, this is highly applicable to GPC estimation. However there appears to have been no previous study predicting GPC from airborne remote sensing at commercial scale, over consecutive years and utilising header-generated data, although smaller studies have been conducted (Rodrigues et al. 2018) We applied a ML algorithm that has not previously been applied to GPC and seldom to hyperspectral or other RS data streams.

Methods

Nitrogen (N) fertiliser treatment trials at Birchip (35.97° S, 142.82° E) and Yarrawonga (36.05° S, 145.98° E) were planted to a common wheat cultivar in 2019. Seventeen commercial paddocks (approx. 2000ha) around Kaniva (36.37° S, 141.24° E) were sown to various bread and durum cultivars in 2019 and/or 2020. At Kaniva in each of 2019 and 2020, crops were sown in May and early June and 1—3 fertiliser applications were made each year, usually as urea. Hyperspectral and thermal data were collected by sensors flown on a light aircraft over Birchip (3 March 2019), Yarrawonga (9 October 2019), and Kaniva (22 October 2019, 28 October 2020). Hyperspectral data were collected in the visible and near infrared (VNIR) domains with a Micro-Hyperspec VNIR E-Series sensor (VNIR; Headwall Photonics, Fitchburg, MA, USA), capturing 371 bands from 400—1001nm. Thermal infrared radiation (7.5—14µm) was recorded with an A655c (FLIR systems, Wilsonville, Oregon, USA). Flights at 350—400m over the plot sites gave hyperspectral pixel resolutions of 0.15—0.2m, while passes at 7000feet gave pixels of 1.0m (hyperspectral) and 1.7m (thermal) at Kaniva. Instrument calibrations were done before flights and irradiance and meteorological data were collected at ground level during airborne data capture. On the ground, leaf-clip spectroscopic measurements were taken during flights. Per-plot GPC was assessed by benchtop near infrared (NIR) spectroscopy (Crop Scan 3000B Grain Analyser, Next Instruments, Sydney Australia). Similar combine-mounted spectrometers (CropScan 3000/3300H, Next Instruments) collected GPC during harvest, with location for each record from GPS.

Regions of interest (ROI), 100m^2, were established around each of the ~50,000 GPC made available by the grower, though those intersecting paddock perimeters, dams, trees and cloud shadow were excluded. The ROI became the base experimental unit for the commercial sites. Mean radiance and reflectance spectra, and canopy temperature values were calculated from image pixels in each plot or ROI. Narrow-band reflectance indices, solar-induced fluorescence (SIF) and crop water stress index (CWSI) were retrieved from airborne data for all plots and ROIs (Table 1). Indices were also calculated from leaf clip spectra at plot scale. In addition, the leaf pigments carotenoids (Car), chlorophyll *a* + *b* (C_{a+b}) and anthocyanins (Anth) and the canopy structural traits leaf area index (LAI) and leaf inclination (LIDFa) were estimated by inverting leaf- and canopy radiative transfer models, linked as PRO4SAIL. Details of the inversion are found in Poblete et al. (2021).

A gradient boosted machine ML algorithm was used to estimate, through supervised learning, relationships between leaf and canopy traits retrieved from airborne data: indices, inverted parameters, CWSI and SIF (Table 1), and the target variable GPC. Input features were passed to a linear function to assess their contribution to GPC estimation (Chen and Guestrin 2016) and to train the model to estimate GPC. Data from each year/cultivar at Kaniva were randomly split 70:30 into training and test sets. From the training dataset, the ML algorithm learns relationships between input and response variables, then uses these to predict GPC in a test set, unseen during training. The ML algorithm was run 80 times for each combination of year and wheat type, with random splitting each iteration; this ensures the model is robust while also causing some variability in results.

Results and discussion

Plot studies

Our results from plot studies showed close associations between physiological indicators, whether calculated from reflectance or inverted, and GPC, along the induced N gradient. Relationships between physiological parameters, including C_{a+b}, Anth and PRI, and GPC, were consistently stronger than those of the structural indicators such as EVI, LAI and NDVI (not shown). This reflects work showing physiological traits' association with stress and lowered photosynthesis, as well as the lack of any physiological connection between NDVI and stress (Gamon et al. 1992; Magney et al. 2016; Suárez et al. 2008).

Commercial crops

Low rainfall in 2019 (280mm; Kaniva) compared to 2020 (443mm), affected commercial paddocks, and the 2019 conditions affected both plot sites. Accumulated rainfall from harvest 2018 to 2019 sowing was also very low (87mm) compared to the next year (164mm; Bureau of Meteorology 2021). Such conditions, especially the contrast in soil moisture, can have large effects on grain protein and were seen in the current work. Significance and effect size of GPC differences between years and wheat types were assessed by a Wilcoxon test for non-normal distributions (Bauer 1972) and in every case, Wilcoxon's $p < 0.0001$. By these tests, bread wheat had significantly higher mean GPC in 2019 than 2020 (effect size $r = 0.489$) but durum had

Table 1. Selected canopy trait quantities calculated from spectra observed with leaf clip instruments in plots at Birchip and Yarrawonga and from airborne hyperspectral and thermal imagery captured in flights over those plots and commercial wheat near Kaniva. *S = structural, P = physiological. For CWSI, VPD = vapour pressure difference. VI = vegetation index. NDVI is shown for reference.

Quantity	Abbreviation	Type*	Data source	Retrieval method	Formula / description / units	Reference
Crop Water Stress Index	CWSI	CWSI	thermal	-	$CWSI = \frac{(Tc\text{-}Ta) - (Tc\text{-}Ta)_{LL}}{(Tc\text{-}Ta)_{UL} - (Tc\text{-}Ta)_{LL}}$ where $(Tc - Ta)LL = -3.25 \cdot VPD + 3.38$	Idso (1982)
Enhanced VI (NIR)	EVI	S			EVI = 2.5*(R800-R670)/(R800+6*R670-7.5*R800)	Longmire et al. (submitted)
Normalized Difference VI	NDVI	S	airborne / leaf clip refl	VI	NDVI = (R840−R670)/(R840+R670)	Rouse et al. (1974)
Photochem. Reflectance Index	PRI	P			PRI = (R531−R570)/(R531+R570)	Gamon et al. (1992)
Solar-induced fluorescence	SIF	P	radiance	Fraunhofer line depth (FLD)	FLD2 = d-R*b, where R = (c-d)/(a-b), a = E750, b = E762, c = L750 and d = L762 (mW/m^2/nm/sr)	Plascyk and Gabriel (1975)
Chlorophyll a + b content	C_{a+b}	P				
Carotenoid content	C_{x+c}	P			µg/cm^2	Féret et al. (2017)
Anthocyanin content	Anth	P	airborne refl	model inversion		
Leaf area index	LAI	S			m^2/m^2	Verhoef et al. (2007)
Leaf Inclination Dist. Function	$LIDF_a$	S			°	

higher GPC in 2020 (r = 0.360, Figure 1). Durum GPC was higher than bread GPC in each year also, with a larger effect size in the more climatically benign 2020 (2019: r = 0.112; 2020: r = 0.564). These results suggest that GPC in durum was less affected by adverse conditions than in bread wheat and confirm higher GPC in durum.

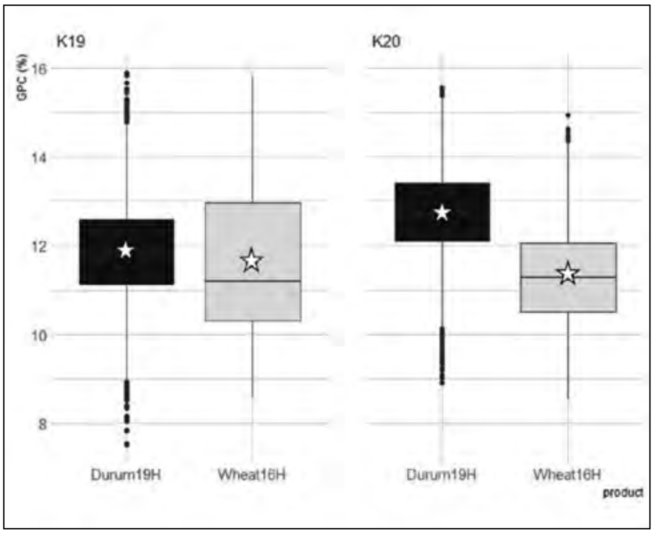

Figure 1. Grain protein content (GPC; %) by wheat type and year in commercial crops at Kaniva, Victoria in 2019 (K19) and 2020 (K20). Stars show mean GPC; all comparisons between year and wheat type means are significant (Wilcoxon's $p < 0.0001$).

Model predictive skill was assessed by coefficient of determination (R2) and relative root mean square error (rRMSE; GPC (%)). For each combination of year and product, GPC prediction in the unseen test data was best when the algorithm was fed with all sources of canopy trait information: models with CWSI, physiological and structural layers outperformed those lacking CWSI, structural measures or both. The best GPC predictions were seen in the severely droughted Kaniva 2019 bread wheat crop (R^2 = 0.80, rRMSE = 0.62; Figure 2), when CWSI contributed 69% of total predictive power. This year/crop combination also had the best skill when based on only physiological or physiological + structural inputs. Under lower drought stress, CWSI provided relatively less information to the model and predictive power was more moderate. This showed that physiological quantities were important indicators of GPC and that thermal data, despite its importance, could be excluded in such conditions without a large penalty to predictive skill. When added to physiological quantities, canopy structural measures LAI, LIDFa leaf angle and EVI strongly increased model skill, despite the low importance of each component alone. Under

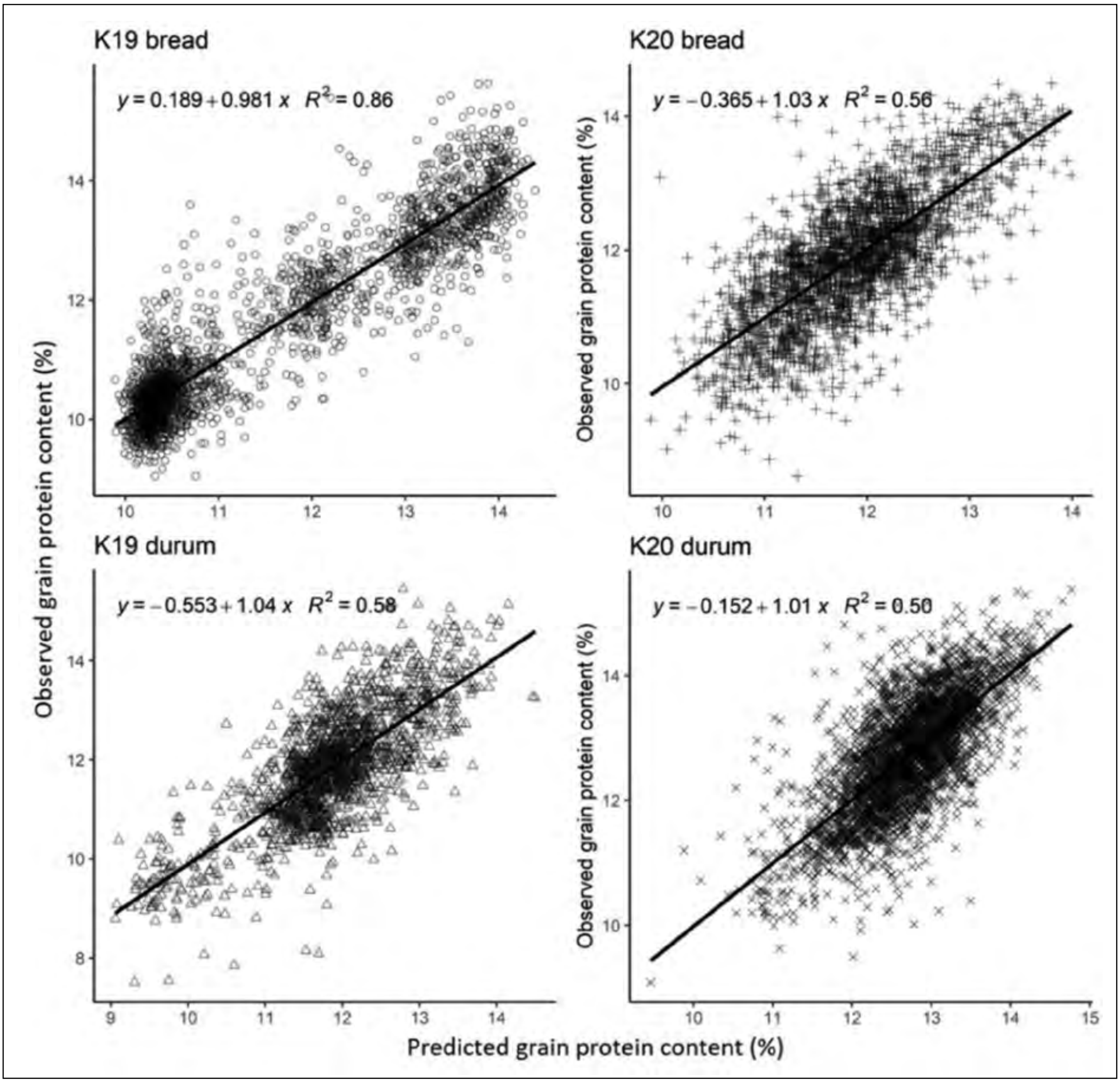

Figure 2. Observed grain protein content (GPC; %) as a function of predicted GPC in commercial bread and durum wheat crops at Kaniva, Victoria in 2019 and 2020. Discrepancies in R2 between figures and text arise because those in the text represent the mean of many model runs, while the figures are from random single runs within crop type and year.

severe stress, physiological model inputs retained some power to indicate GPC, but under moderate and low stress were of prime importance because they show lowered photosynthesis (Poblete et al. 2021; Suárez et al. 2008; Zarco-Tejada et al. 2018). These findings have identified key physiological indicators for GPC prediction and has important ramifications for the development of our methods toward practical application. This includes GPC estimation from data collected with instruments of lower spectral resolution and without thermal data, often absent from relevant satellite platforms.

Our predictive skill was similar to some previous studies of wheat GPC (Li et al. 2020; Øvergaard et al. 2013; Zhou et al. 2021), though with more robust methods, while other studies have been based entirely in experimental contexts.

Conclusion

We used machine learning to estimate GPC in commercial wheat crops and achieved best mean accuracy of $R^2 = 0.80$ between predicted and observed GPC of an unseen dataset, using a model built with thermal, physiological and structural variables. CWSI was important when crops were water stressed, but physiological measures were important in more benign conditions, and structural indicators such as LAI and NDVI were less important.

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Hyperspectral and thermal remote sensing laboratory (HyperSens) (https://fvas.unimelb.edu.au/research/groups/hypersens#home)

HyperSens – Hyperspectral Remote Sensing & Precision Agriculture Laboratory (https://blogs.unimelb.edu.au/hypersens/#tabmain)

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Better targeted, more precise fertiliser decisions as a counter to rising fertiliser prices – focussing on 3 of the 6 Rs

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GRDC project code: CSP1803-020RMX

Keywords

- decision support systems, digital agriculture, on-farm experimentation, precision agriculture.

Take home messages

- In the past decades, digital and precision agriculture technologies have been developed with the main goal of allowing traditional agronomic decision tools to be implemented at the site-specific scale in an automated fashion.
- Traditional N fertiliser recommendation frameworks have not been designed for the accuracy expected for precision nutrient management, leading to limited value of digital approaches underpinned by them.
- Novel, data-driven decision support systems based on non-mechanistic frameworks, abundant multivariate data, and on-farm experimentation can improve the accuracy and profitability of N application.
- The Future Farm team worked with top-performing growers across the country who, through comparative analyses, are proven to be very good at N-decision making. Even then, a data-driven N model developed in Future Farm resulted in a ~$50/ha improvement in partial profit over the current practices used by these growers.

Growers will be acutely aware of recent increases in fertiliser prices, largely on the back of constraints to the supply of raw materials, especially in the EU; the price of urea, for example, doubled in the period between May and October 2021 (https://www.indexmundi.com/commodities/?commodity=urea&currency=aud) and the ratio of the grain price to urea price is well over 2.5t wheat/t urea (https://www.thomaseldermarkets.com.au/inputs/market-morsel-gaslighting-fertilizer/). One way to counter this very substantial increase in the costs of production is to optimise the efficiency with which fertiliser is used –putting the **right** amount of the **right** product in the **right** place at the **right** time (the traditional '4 Rs') using the **right** equipment and, with the decision as to the right amount, underpinned by the **right** data (the '6 Rs').

The Future Farm project[3] was established to re-examine and improve the way in which digital data are used to inform decisions about input management. Its intent is to provide a way of automating the process from data acquisition, through analysis, to the formulation and implementation of decision options. The focus for the project is improvement in the efficiency and profitability of applied nitrogen (N) use and

[3]Future Farm is a co-funded collaborative project involving CSIRO, The University of Sydney, The University of Southern Queensland, Queensland University of Technology, Agriculture Victoria and the GRDC.

increased grower confidence in N decision making. In effect, Future Farm seeks to provide growers with the tools which, amongst other things, could help them address the current difficulties with fertiliser price increases. In terms of the 6 Rs, we are especially focussed on the right **amount** in the right **place** using the right **data**.

Agronomic advice and digital technologies

The conventional approach to the provision of advice, such as fertiliser recommendations, has been to use mechanistic agronomic knowledge of crop production to identify important crop and soil parameters and integrate understanding of these to underpin a recommendation or decision. In the case of fertilisation, recommendation charts based on nutrient balances or generalised response curves are examples of such an approach, even though in most instances, they translate agronomic knowledge into simplistic 'rules of thumb'. More advanced decision support systems (DSS) based on crop models, such as Yield Prophet™ and its 'parent model' APSIM, are also similarly reliant on mechanistic agronomic knowledge (for example, Figure 1a). Unfortunately, such models can be very 'data hungry' and/or reliant on things which can be difficult and expensive to measure, and which may be highly spatially variable, for example, soil water availability and soil N status. One consequence of this is that such DSS are often used with a 'best guess' set of input parameters, for example, using soil properties from a 'nearby' soil profile, which might be some distance (several km) from the paddock of interest. Another is that, presumably for reasons of trust, the 26% of growers who make use of a DSS tend, on average, to use more than two of them (Bramley and Ouzman 2018).

The advent of digital technologies, such as remote and proximal sensing, has led to a lot of effort going into sensor calibration so that some of the agronomic parameters of interest can be sensed, thereby allowing the deployment of existing decision frameworks locally and in an automated fashion (Figure 1b). However, whilst some of these sensing technologies (for example yield monitors, soil pH sensors) are straightforward to calibrate, others (for example multispectral remote or proximally sensed imagery) are not, which is no doubt why, to date and to the knowledge of the Future Farm project team, none of the traditional DSS such as Yield Prophet take sensor data as input. One reason such calibrations are difficult is the fact that many of the sensors make surrogate (as opposed to direct) measurements and so should more accurately be described as tools for **prediction** of attributes of interest rather than tools which can be calibrated. For example, the commonly used normalised difference vegetation index (NDVI), which can be obtained through remote and proximal multispectral crop sensing, is a surrogate measure of photosynthetically active biomass, which relates closely to the size and health of the crop canopy. Despite what you might see in the media or in advertisements from agronomic service providers, NDVI is not a measure of plant N status, although under some circumstances, it might be correlated with it and so can be used to predict it. So, much of the effort put into the integration of sensors into agronomic decision making has relied on the development of prediction models based on crop sensor data – for example, to provide estimates of yield potential. Fertiliser recommendations can then be based on mass balance (that is, the N rate to apply is equivalent to the difference between nutrient demand (given by the yield potential) and nutrient supply). Of course, such predictions are subject to error. It is also clear that relationships between sensed and target variables (for example NDVI vs yield potential) may be highly subject to site and seasonal variation (Colaço and Bramley 2019).

A final key issue is that, by necessity, traditional N recommendation frameworks simplify complex agronomic interactions, so that they can be easily implemented at the level of the field or farm. As such, most common fertiliser recommendation approaches have not been designed for the accuracy expected for precision nutrient management using variable rate application (VRA). Consequently, even if digitally based predictions of yield potential can be made, the resulting N recommendation may not provide much improvement (if any) if the information is implemented via simplistic mechanistic frameworks (Colaço et al. 2021). Accordingly, the common univariate approach (Figure 1c) based on a single sensor input as a surrogate estimate of N requirement should be treated with caution, and in a recent review study, evidence of this approach providing benefit over farmer practice has been equivocal (Colaço and Bramley 2018). Clearly, most agronomic decision making is not a univariate issue. Decisions as to whether to apply N mid-season, and how much to apply, are greatly affected by soil moisture (Colaço and Bramley 2019, Lawes et al. 2019) in addition to many other factors including yield and protein targets, expectations of future weather, grain prices, grower attitudes to risk, and of course, the cost of fertiliser.

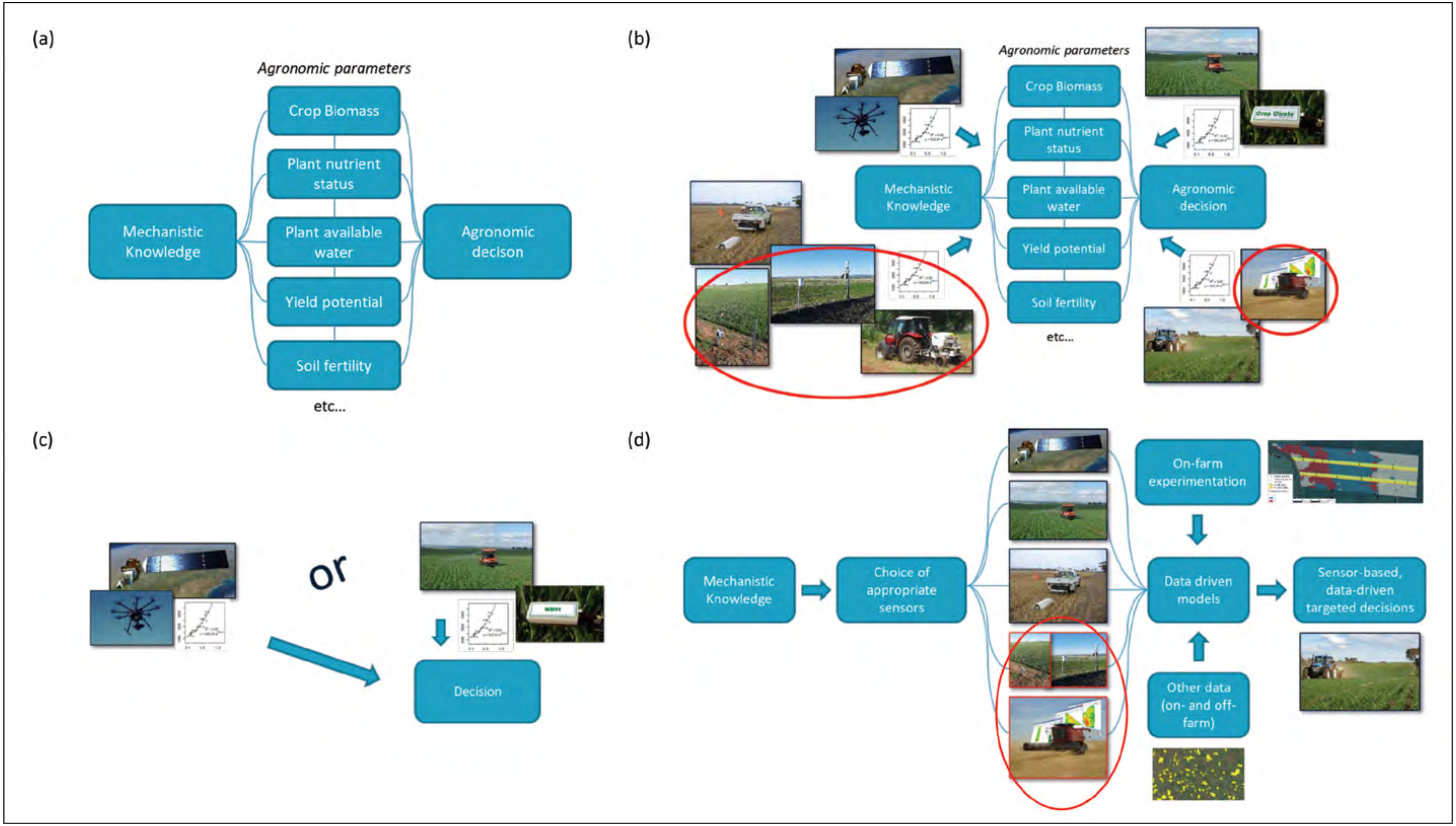

Figure 1. Pathways to a digital decision: (a) the classical approach to agronomic decision support; (b) digital tools and their typical interaction with existing agronomic decision support; (c) the simplistic univariate approach commonly used in some commercial offerings; and (d) the framework hat underpins Future Farm's data-driven approach to decision making. In (b) and (d), the circled pictures indicate that these sensors are relatively easy to calibrate. Those not circled are used for prediction of crop and soil attributes rather than absolute measurement.

A new way forward with on-farm experimentation

An alternative to the approaches described in Figure 1a-c is to use the same mechanistic understanding of crop production to identify sensors which are likely to provide useful information of relevance to agronomic problems (Figure 1d). Instead of focussing on sensor-based prediction of single crop or soil attributes, use the data the sensors provide as input to data-driven models on the basis that their digital signal is providing data of potentially useful predictive value in guiding decisions in different locations. It is implicit in Figure 1d that, in adopting this approach, the multivariate nature of the agronomic decision is recognised. Figure 1d also recognises that on-farm experimentation (OFE, for example use of N-rich and N-minus strips) is a valuable tool to aid targeting of the decision to the location where it is to be implemented. It also highlights the potential value of off-farm and publicly available data (for example, data for adjacent areas including historic yield, electromagnetic (EM) maps, imagery; and weather data) as inputs to the decision (Fajardo and Whelan 2021).

The Future Farm team recognise diversity, both in the preferences amongst growers and advisors for mechanistic versus data-driven methods, and in the data available to underpin N fertiliser decision making across the grainbelt. Accordingly, we have tackled the task of improving grower confidence in estimating N requirements for cereal growth by purposely evaluating a diverse range of methods, including the data-driven approach, for predicting N requirement (Table 1) and developing comparisons between these. It is also evident that adoption of data-driven methods cannot occur until sufficient data have been collected. Therefore, in the meantime, growers who have been less active as data gatherers may need to rely on other N recommendation methods that are less dependent on large agricultural datasets, which nonetheless can still provide benefit over traditional methods that are based on simplistic rules of thumb.

A key element of Future Farm is OFE, in this case ‘N strips’, designed to test the yield and protein response to applied N. We think that this is an essential component of optimising decision making for the simple reason that every farm and field is different. All the Future Farm OFE included three application rates: a zero N rate, a farm decision N rate (that is, the grower’s best estimate of requirement) and a high N rate that ensures N should be non-limiting. The N rate treatments are placed adjacent to each other in strips (Figure 2) and are applied to run through zones of predetermined potential management classes in each field. In addition to providing key input to the various methods used to develop an N recommendation (Table 1), our OFE was also used as the basis for calculating partial profit (harvest income minus expenditure on fertiliser) response functions using the applied N rates, yield and protein data gathered using harvester-mounted yield and protein monitors along the trials, combined with financial information reflecting average grain grade sale prices and average urea fertiliser costs.

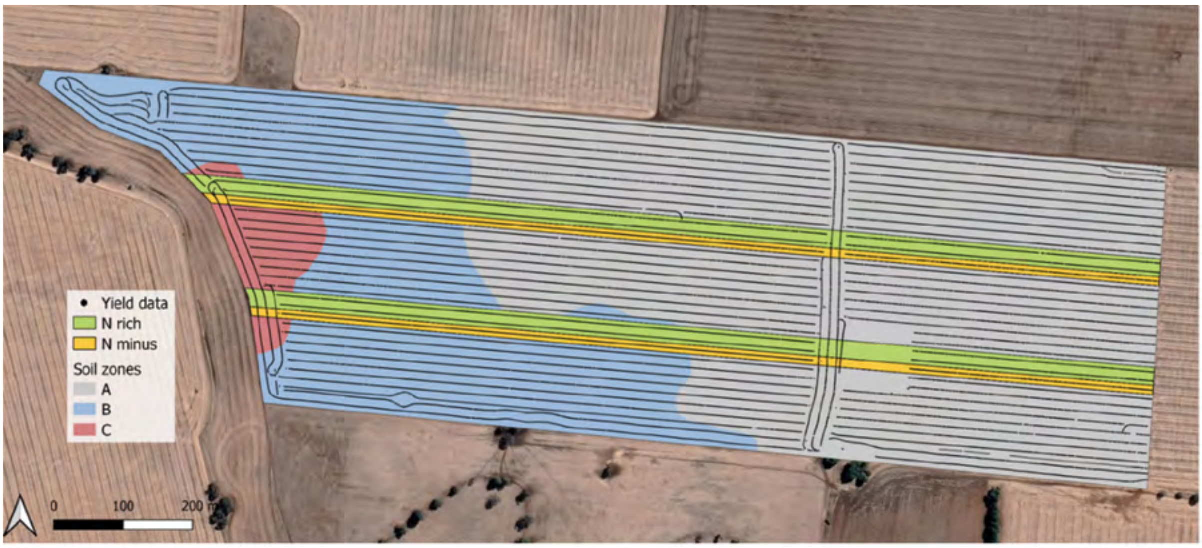

Figure 2. An example of a Future Farm strip trial, in this case, in a 64ha paddock near Tarlee, SA.

Table 1. Methods included for in-season prediction of nitrogen requirement.

Label	Description
Grower	Grower decision for application rate (that is, the host grower's chosen rate).
EONR	Observed rate that maximised partial profit (Economic Optimal N rate).
Max yield	Observed rate that maximised grain yield.
Max N removal	Observed rate that maximised grain N removal.
NDVI CC	Inspired by the Crop Circle approach, the N rate that maximised the Crop Circle NDVI mid-season on the assumption that this maximises end-of-season yield. Note that Crop Circle is a proximal sensor that works in a similar way to the Greenseeker, TopCon CropSpec and similar sensors.
NDRE CC	As per NDVI CC but using NDRE instead of NDVI.
NDVI Sent	As per NDVI CC but instead using NDVI sourced from the Sentinel2 satellite.
NDRE Sent	As per NDVI Sent but using NDRE instead of NDVI.
DD (data abundance)	Data driven model in which a range of data sources are calibrated against economic optimal N rates (EONR) using random forest regression (Figure 3). In essence, this empirical approach provides a recommendation by assessing current site and season characteristics and relating those to past conditions for which optimal N rates are known. In this data abundance scenario, 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)	As above, but in a scenario of limited data; the site and season conditions at which the model is validated are not well represented in the data used to build the model which comes primarily from other fields.
N Suff CC	N sufficiency approach based on Crop Circle sensor data. This method is based on the N dilution curve which describes the relationship between plant biomass and plant %N. A target plant %N for fertilisation is set based on estimated crop biomass and an established N dilution model.
N Suff Sentinel	As above but using Sentinel2 satellite data.
MV (yield)	A machine vision approach based on prediction of optimal N rates for yield maximisation. This uses a tractor-mounted RGB camera coupled with detailed image analytics.
MV (grain N removal)	As above but optimised against grain N removal.
Yield Resp Model	A simplified model of the yield and protein response of APSIM developed by using remote and proximally sensed data, and used to predict the EONR
Simplified mass balance	Simple mass balance calculation targeting local water-limited yield potential (Gobbett et al., 2017) and protein. Three variants are used: (a) deducts initial soil N from total N demand based on soil sampling; (b) assumes an arbitrary amount of starting soil; (c) does not account for any starting soil N.

Comparing approaches for N recommendations

The partial profit response functions were calculated at a fine scale using a moving window regression analysis along the trial strips. This provided site-specific functions at a 10m scale for each site which could then be aggregated up to an average response function for each potential management class, or to an average single response function for the whole paddock. Such an approach enables comparison of the N recommendation methods at three scales – site, management class and whole field. We did such an analysis across nine large scale trials across SA (2018-20), WA (2019-20), Vic (2018-20) and NSW (2020), generating over 1500 observations of crop response to N application. From these functions, the N rate that maximises partial profit, the economic optimum N rate (EONR), can be identified at the three different management scales. The EONR is regarded here as the ultimate N application rate against which all the recommendation methods were compared.

As seen in Table 1, in addition to the methods developed by Future Farm for deriving N recommendations based on Figure 1d, several simple methods using NDVI and NDRE indices calculated from proximal Crop Circle sensors (CC) and satellite remote sensing (Sentinel) were also included. These provide an evaluation of a digital, single sensor approach to N estimation (Figure 1c). The preliminary results (to be updated as data from more Future Farm trial sites become available) of the comparison of the various approaches are shown in Figure 4, where each method is plotted based on the average root mean square error (RMSE, that is the prediction error) and a normalised average partial profit (NPP) at each management level across all sites analysed. The partial profit has been normalised because not all the methods were applied across all Future Farm site-years. Nonetheless, costs and prices appropriate to each season (2018-20) were used to generate the results.

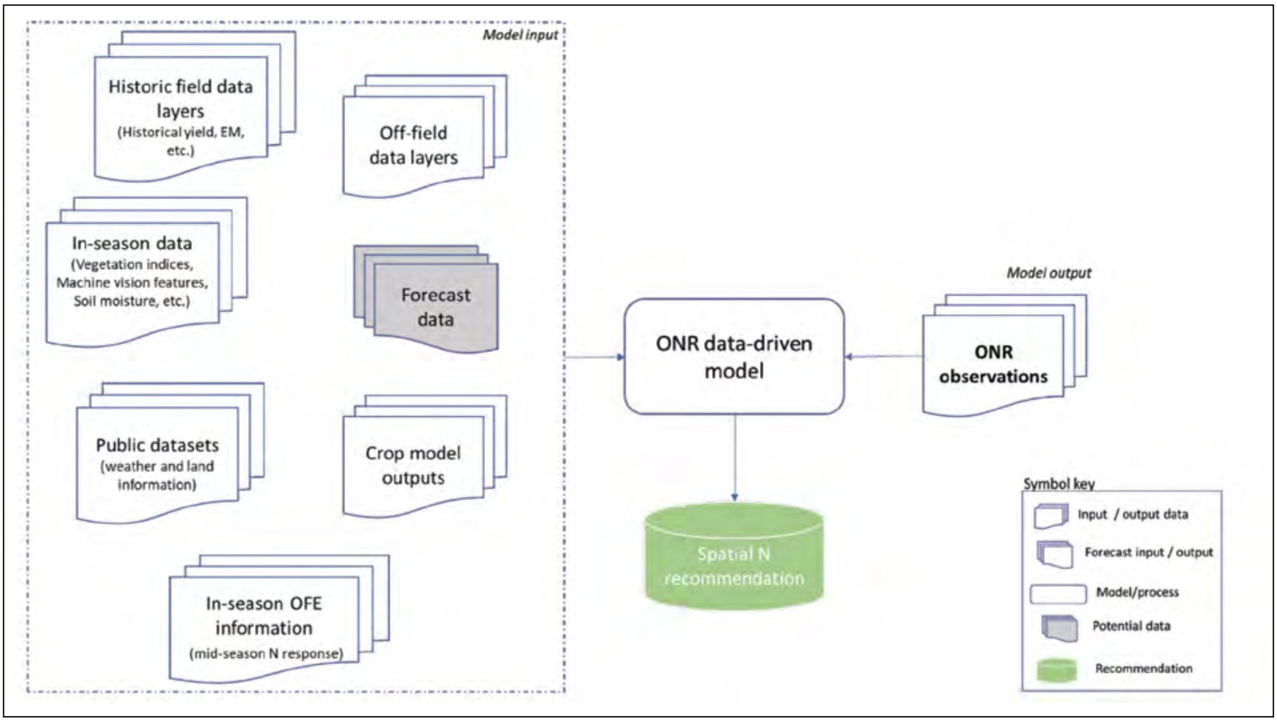

Figure 3. Workflow for an N recommendation approach based on the optimal N rate prediction by a data-driven empirical model.

The right data and higher spatial resolution lead to profitable N use

In Figure 4 the EONR calculated from the site-specific analysis is set as the 'gold standard' with a zero RMSE and a normalised partial profit equal to 1. The outcome of each proposed method is compared relative to this ultimate benchmark. One way to interpret Figure 4 is to multiply the y-axis by $1000 so that the EONR delivers a NPP of $1000/ha. Thus, for example, a recommendation derived for the whole paddock from an NDRE measurement using the Crop Circle sensor would deliver an NPP of just under $900/ha.

The analysis shows that as accuracy in prediction increases (decreasing RMSE), partial profit increases, but the rate of increase diminishes as the methods become more accurate. Such analysis could be used to assess the worth of a new technique or technology that seeks to improve accuracy compared with its cost. Note that Figure 4 includes results from three options of the 'Simplified mass balance' approach, similar to the common 'rules of thumb' decision-making processes that many growers and agronomists undertake and that this standard method had similar results to the grower practice. Results also indicate that the mass balance calculation loses performance when the accuracy of soil N information decreases (from (a) to (b) to (c)).

The grower decision approach is on average 7% lower in NPP than the optimal recommendation (EONR) at the site-specific level and only about 1% lower than the EONR at whole paddock level. This result confirms that the growers collaborating in Future Farm, who already utilise aspects of the PA philosophy, are very good at optimising their fertiliser use. In this connection, we point out that the simplified mass balance approach which gives a result very similar to that of the grower, assumes that the target yield is the water-limited yield potential. In other words, these growers have very little 'yield gap' and they should already have confidence in their N decision making. A key message from Figure 4 therefore, is that for these growers to make improvements to NPP, their N decisions need to be made at higher spatial resolution; in other words, using VRA, rather than uniform paddock management. The extent to which Future Farm might lead to increased confidence amongst other growers is unclear. However, it is of note that the decisions of our collaborating growers outperform all of the single sensor approaches (Figure 1c).

The best Future Farm method is the data-driven model with a full dataset (DD data abundance) at the site-specific level and it displays an increase of 5% over the management of our collaborating growers at paddock scale. Its use at paddock scale leads to a 1% improvement compared to the grower practice. The site-specific DD data abundance method loses slightly to EONR at the site-specific management level, but essentially matches the EONR at the management class and whole paddock resolution.

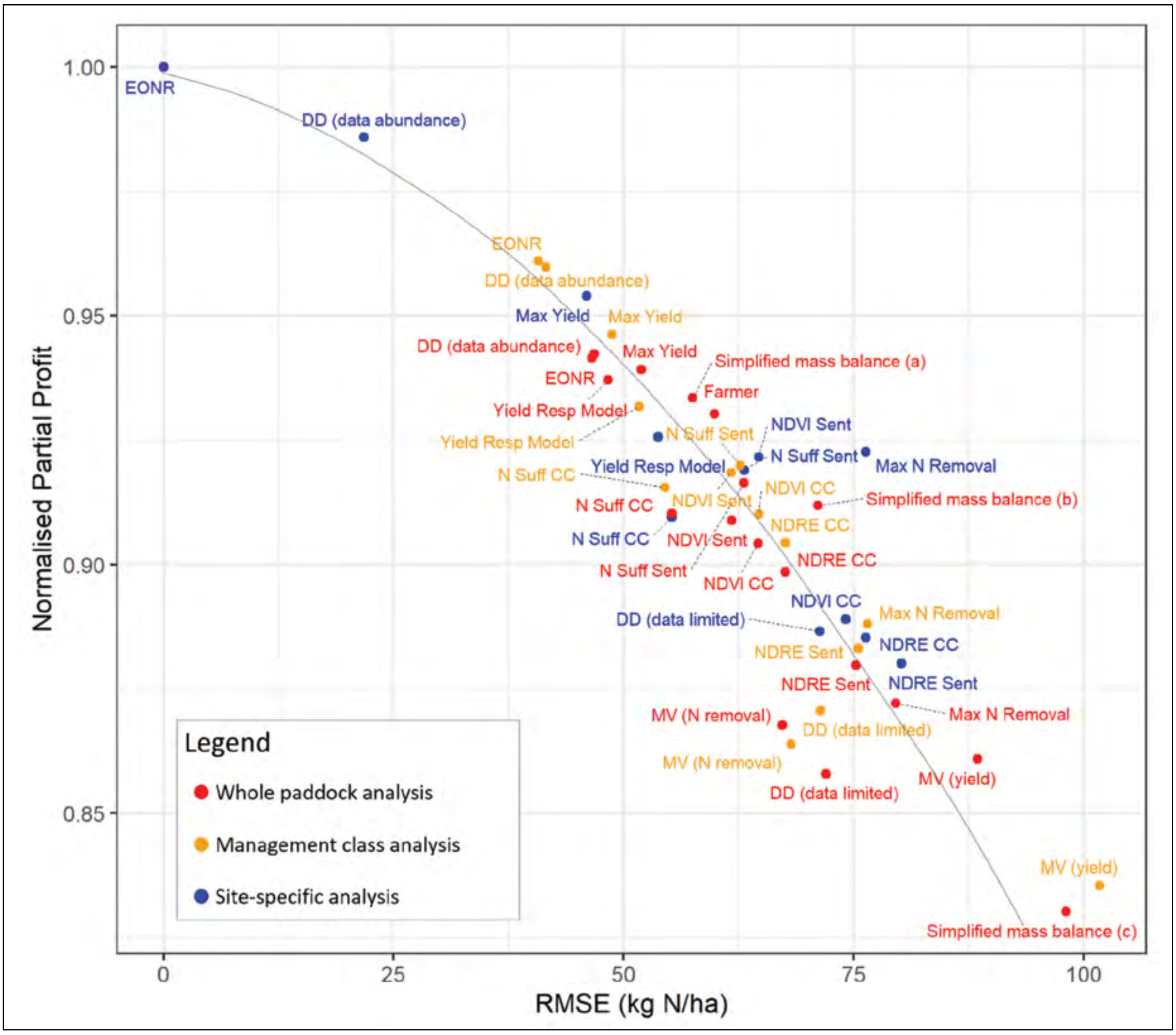

Figure 4. Profitability versus accuracy of in-season methods for N recommendations averaged across trial sites at different management scales. Method labels are defined in Table 1.

As a simple example to facilitate interpretation, a 5% improvement can reasonably translate into a $50/ha increase (using a $1000 base line for maximum NPP) which, over a 2000 ha cropping program, would mean a $100 000 gain annually. This can be regarded as a conservative number given that it is based on the high performing growers we've collaborated with in the project.

These results point toward relatively low value in a single sensor approach (for example NDVI or NDRE alone). Many of the methods that rated higher in terms of RMSE and partial profit did, however, use NDVI and/or NDRE in a more thorough analytical approach, so they do have value when combined with other data to give a multivariate input to the decision. A data-driven approach based only on limited external data is also shown here to be a low value option for predicting N requirements. This emphasises the fact that the data-driven approach has significant value only when sufficient on-farm data to support it have been acquired. This is also why there is justification during the lead-in to adopting this for using one of the more mechanistic approaches. On the other hand, most common mechanistic approaches may seek to optimise grain yield which, as seen in the graph, can offer only limited improvement over the grower practice (approximately 2%). Of course, whilst grain yield is an important component of profitability, frameworks aimed at yield maximisation do not fully accommodate other important economic considerations.

A profitable future based on OFE and the 6 Rs

Overall, from this multi-site, multi-method assessment process, it appears that the only way to improve the accuracy and profitability of our good performing growers is by increasing the spatial resolution of their management from the whole paddock scale – in other words, through the use of management zones or, better still, continuous variable rate. We make this conclusion with the caveat that this move to higher resolution is accompanied by the use of an effective N decision framework such as the DD method. The data-driven approach relies on data availability to ensure the method performs at its optimum as is evident from the comparison of the DD 'abundant' and 'limited' results. **Nonetheless, we are certain that a key element for acquiring such large datasets, and indeed improving N decision making generally, is the use of automated OFE such as the strip trials used here. There is no impediment to these being scaled out across the country and seamlessly implemented by growers every season forthwith.** There is also scope to build the required datasets at field or farm scale, amongst groups of neighbours, in local regions and wider to train data-driven decision methods, such as the one proposed here. Its success at all management scales in this assessment provides an important pointer towards a future where farm businesses that collect, maintain, and even share, relevant production response and resource data will be able to push closer towards season- and site-specific economically optimal operation. Against the background of high and rising fertiliser prices, this would be a good thing. Given also the broader push toward sustainability and reduced emissions from N fertiliser usage, it is arguably also necessary.

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. In addition to the authors, the Future Farm team comprises Jonathan Richetti, Damian Mowat and Roger Lawes (CSIRO), Mario Fajardo and Asher Bender (University of Sydney), Alison McCarthy, Anand Pothula and Craig Baillie (University of Southern Queensland), Eileen Perry, Alex Clancy and Glenn Fitzgerald (Agriculture Victoria) and Stephen Leo, Daniele De Rosa and Peter Grace (Queensland University of Technology); their valued input is gratefully acknowledged. We are also most grateful to the various growers who have provided us with fields in which to develop and test our methods – Ashley Wakefield, Ben Pratt, Bob Nixon, Ed Hunt, Jessica and Joe Koch, Mark and Sam Branson, Mark Swaffer, Rob Cole, Robin Schaeffer, Stuart Modra, Kieran Shepard and Peter Bell. Note that in addition to the GRDC Updates being held in February 2022, this article has also been prepared as input to the Precision Ag News of the Society of Precision Agriculture Australia (SPAA).

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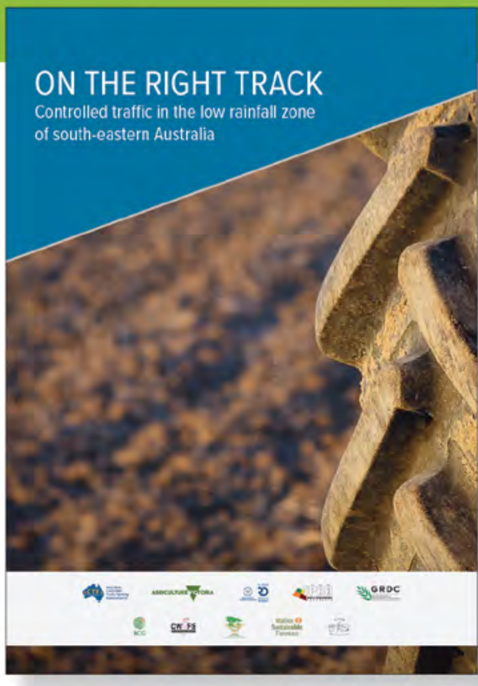

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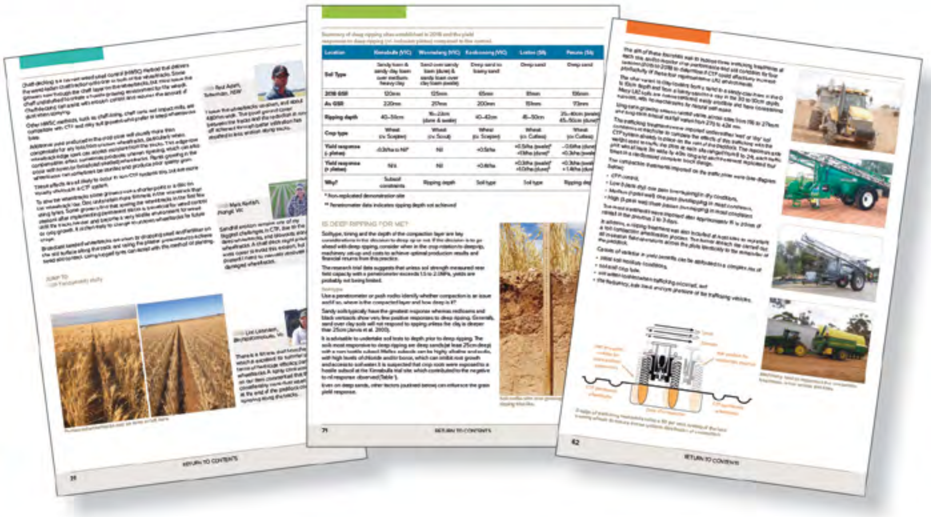

Can assimilating remote and proximal sensing observations into the Agricultural Production Simulator crop model improve wheat yield prediction accuracy without calibrating against observed yield

Ian Marang.

The University of Sydney.

Keywords

- agricultural production simulator crop model, sensing observations, wheat yield prediction.

Take home messages

- Mid-season predictions of end season crop production can be achieved by using potential yield with only a limited set of field condition observations collected remotely.
- Assimilating mid-season remote and proximal sensing observations can improve APSIM model predictions of wheat yield.

Abstract

There is increasing pressure on agriculture to deliver the food and fibre production necessary to meet the rising demand of a growing population while reducing inputs and impacts on the environment. To meet these challenges, growers need more accurate estimates of mid-season crop condition and potential yield under variable future growing circumstances. Assimilating mid-season remote sensing observations of crop status into process-based crop models can be a useful tool to provide these estimates. This project tests if assimilating remote and proximal sensing observations into the APSIM crop model can improve wheat yield prediction accuracy without calibrating against observed yield. This is achieved by using a sensitivity analysis to map the weighting from the errors between crop condition simulations and observations with the model parameters' individual impact on outputs and taking the mean of an ensemble of predictions.

Results indicate remote sensing has strong potential for sampling crop status with high spatial, spectral and temporal resolution, as seen with accurate protein concentration estimation (r^2 of 0.88 in 2020) and strong yield prediction (r^2 of 0.64 in 2019). There are substantial confounding aspects to collecting and interpreting remote sensing data, however, due to the high dependency of plant condition on factors outside the scope of observation, including interannual and intraseasonal climate and phenology variation, biotic and abiotic stresses, and viewing geometry, amongst others. These factors may be behind the lower accuracy seen in comparisons across the two years' experiments, such as protein concentration in 2019 (r^2 of 0.29) and yield prediction in 2020 (r^2 of 0.32).

Crop models are able to simulate the processes that remote sensing or statistical models cannot, but to do this they need effective parameterisation and calibration. 'Sobol' sensitivity analysis was run on the APSIM crop model using five different

block sizes with three perturbed model physics ensemble members. This generated a total of 576 000 simulations which were used to identify the relative influence of 23 parameters after their 'Sobol' confidence intervals had stabilised and reached approximately 0.05 on average. After 96 000 runs, each ensemble had stabilised and indices were reported, showing APSIM constants controlling radiation use efficiency and soil water extraction were the most influential. Cultivar parameters were the least influential across all the output variables and block sizes tested. The main effect indices were then averaged across the season and used in the crop modelling data assimilation framework. Data assimilation is a technique to check model performance against observed conditions and update the model for improved accuracy.

For use in the data assimilation framework, a group of model simulations (i.e., an ensemble) was built with small variations in the key factors that impact crop modelling prediction uncertainty: management action (four or six nitrogen fertiliser rates), observations (11 sets of weather), parameterisation (three levels of soil condition) and model structure (three examples of altered physics). These ensemble members were run over 15 iterations of the 2019 and 2020 seasons using calibrated and uncalibrated parameters, with their parameters modified between iterations using the relative errors in their predictions scaled by the sensitivity indices. Error weighting was derived from comparing predicted height growth, water extraction and yield against height growth from RGB photogrammetry, water extraction from soil moisture probes and potential yield from a statistical model. The mean of each ensemble was tested against observed yield for the year as well as APSIM performance without data assimilation. Results indicate there is strong potential for this approach, with average improvements between 7-12% of observed yield in all tests. The data assimilation framework delivered substantial improvements over both the standard run and a simple statistical model built using 12 seasons of yield data and weather from a nearby site. This project shows assimilating mid-season remote and proximal sensing observations can improve APSIM model predictions of wheat yield.

Background

Food security is an increasing concern with the rising demand from a global population projected to reach 9 billion by 2050 [1]. Exacerbating this are the large-scale impacts to growing conditions, both current and prospective, of a changing climate [2], [3]. There are a number of efforts to address the challenge of increasing production of food and fibre, including plant breeding [4], [5], more efficient and sustainable farm production methods [6], [7] and building a better understanding of food production through crop models [8]–[11]. Remote sensing is a useful tool to infer crop status at scale, but is less effective at direct numerical evaluation and prediction [12]–[14]. Crop growth models, in comparison, can be robust at prediction but are fundamentally abstract constructs that cannot accurately replicate all processes that contribute to plant production [15]. By assimilating observations of a crop mid-season, the missing aspects of these models, such as pests or disease impacts can be adjusted for and so generate more plausible estimates of plant condition and production [16].

Process-based models can be used for investigating regional or global projected changes on a macro scale, but also informing grower management action on a local level [17]. There is a wide assortment of models being used, however, most are either for use in very specific fields (for example, studies of soil organic matter processes, such as DayCent, see review by Brilli et al. 2017), or are no longer being developed and supported (such as CENTURY, see review by Jin et al. 2018). Most are based on a daily time step and involve incrementing plant biophysical condition as a function of weather forcing (for example, rainfall amount, maximum and minimum temperature), soil nutrients and moisture available for plant extraction, and selected management actions, with limits and coefficients given by genetic parameters which are related to a sown cultivar [20], [21].

Simulating soil dynamics and climate extremes are areas where models require further development [1], [18]. Additionally, most models poorly simulate grain protein content and quality parameters, possibly due to incorrect N mobilisation estimates and an emphasis on yield over other outputs [17], [22]. However, many models manage to estimate yield effectively by balancing intra-seasonal modelling errors and structural inconsistency (for example, where errors in one part of the model can be balanced out by others in different parts), suggesting model efficacy should not be judged based on a single variable [17]. One approach to overcome these modelling challenges, is to use an ensemble of models, whereby multiple instances of the same model, or multiple instances of different models are run with the same or similar forcing data and simulate the same crop [1]. This has seen increasing usage, especially in the climate change impact assessment community where ensembles of twenty or thirty models combined are common [17], [23], [24]. However, ensembles as small as two or three models have been reported to improve estimation accuracy considerably [25]. In several previous studies, the median or mean of all ensemble members had superior accuracy over any of the individual models. That's possibly because the ensemble balanced out the individual model design errors or had access to all the datasets used to calibrate the individual models by proxy, and therefore better sampled the variability of crop growth under study [1], [17], [23], [26]–[28]. Ensembles may also provide a direct estimate of the uncertainty of the prediction [29].

The objectives of this study were to test if remotely sensed crop height and soil moisture observations can be combined with a statistical model's estimate of yield from rainfall and assimilated into a process-based crop growth model, the Agricultural Production SIMulator (APSIM) to improve yield prediction. At the time this research began there were limited previous studies on assimilating remote sensing observation with APSIM. The authors coupled a radiative transfer model with APSIM outputs for use with satellite optical reflectance data to predict biomass in maize. They found that data assimilation was successful at improving the modelled biomass in most cases [42]. Another used spatial variation across a field to drive yield spatial variability [43]. In contrast, this study assimilates the predictions of a statistical model and direct observations from a UAV platform and soil moisture probes into APSIM to improve predictions of wheat yield.

Methodology

There were three main components to this project:

1 Two field trials of wheat were held (one each in 2019 and 2020) to collect remote and proximal sensing observations for assimilating into the crop model (Figure 1). The ability of remote sensing to quantify the observed crop condition and production was tested using actual and combined measures of reflectance (vegetation indices).

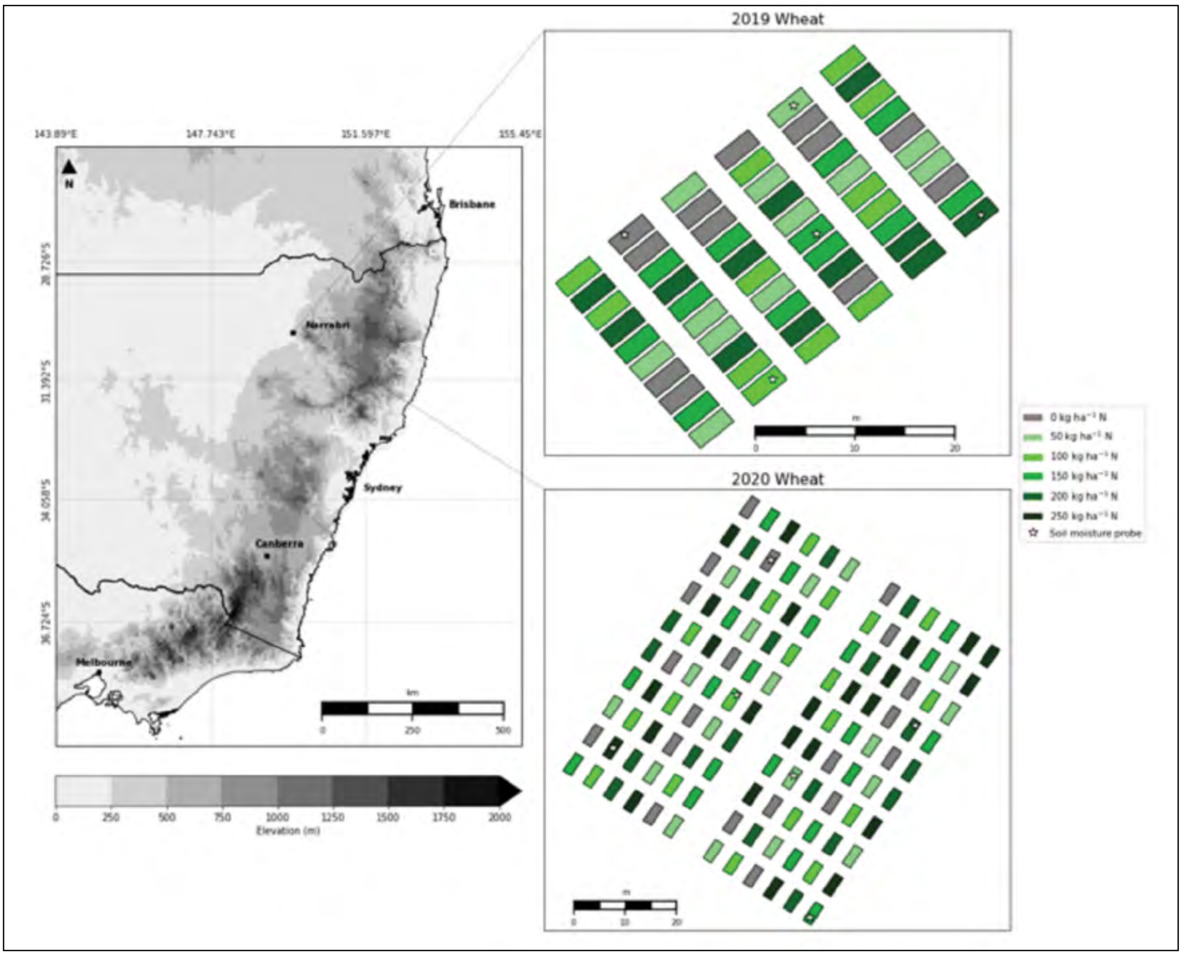

Figure 1. Regional map showing locations of 2019 and 2020 wheat experiments.

2 A sensitivity analysis was run to map the influence of twenty-three selected parameters on the crop model's output. This section identifies the key levers of model performance on the output matching the observations from the field trials.

3 A data assimilation framework was built to run the APSIM crop model iteratively over a large group (396 in 2019 and 594 in 2020) of models, each containing different combinations of estimates of weather, soil condition, model structure and fertiliser applications. The average of the group of model predictions before and after data assimilation were compared to see if in-season crop simulation and yield prediction accuracy were improved.

Four tests were run, with the APSIM DA framework (Figure 2) using calibrated and default genetic and soil parameters for 2019 and 2020 for the first run, with potential modifications in subsequent runs in response to the errors during assimilation. The iteration (i) determined when the test was complete and if the conversion factor applied to model parameters should be inverted if errors had increased.

Results

Remote sensing showed strong relationships between reflectance and thermal imagery and observed crop characteristics or end season production, but with very limited consistency between years. For example, 2019 yield prediction was strong using thermal (R2 of 0.64), but 2020 yield prediction using thermal was substantially weaker (R2 of 0.32) (Figure 3).

After data assimilation, crop condition predictions accuracy saw improvement in height estimation and above ground biomass but not so leaf area index, which had a very mixed outcome. Soil moisture and leaf N % were already very close to the observations before data assimilation (Figure 4).

Yield prediction improved in all four tests, more so in 2019 (Figure 5) as the water use efficiency model's error signal was much stronger in 2019 than in 2020 (Figure 6) due to lower in-season rainfall leading to a lower potential yield threshold.

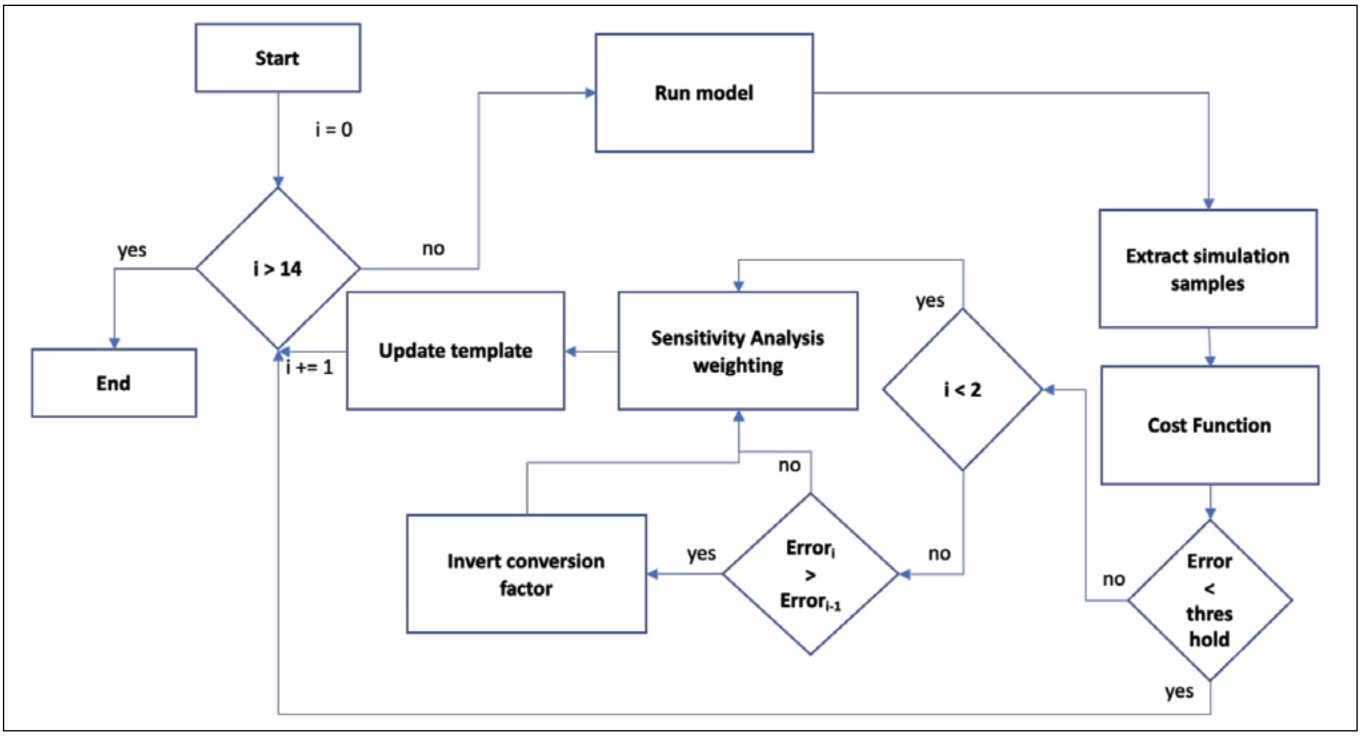

Figure 2. Data assimilation framework conceptual flowchart.

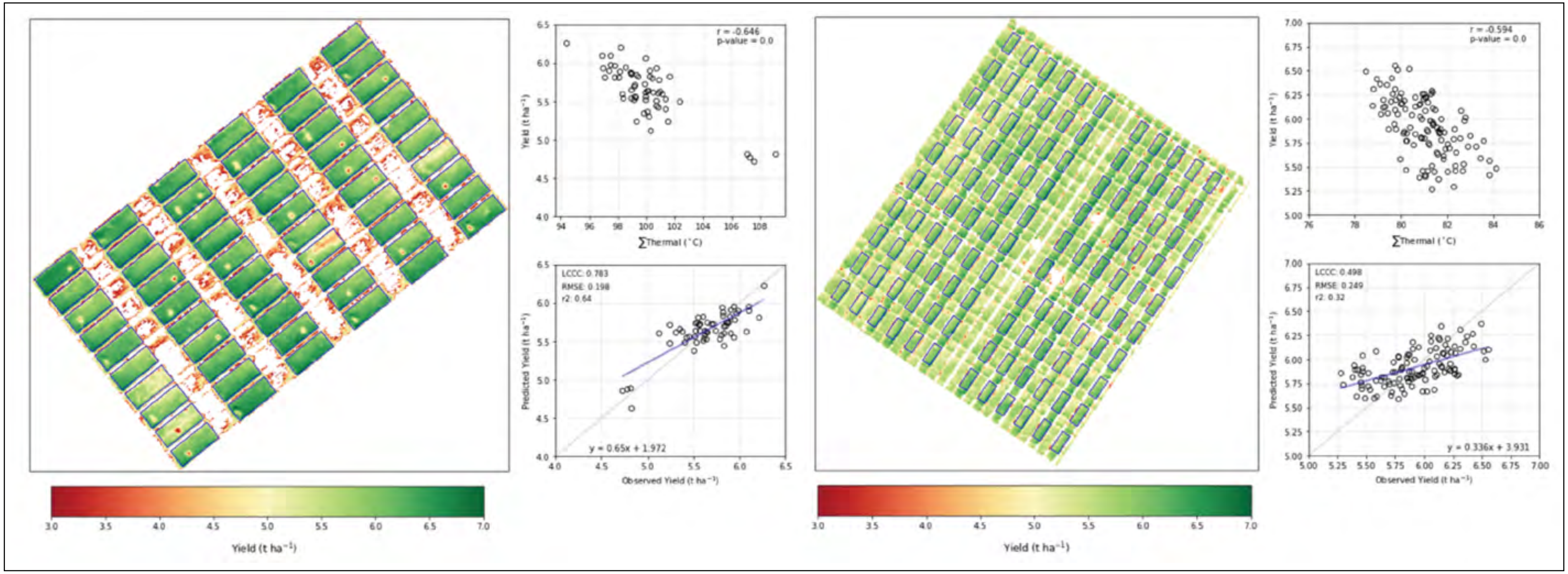

Figure 3. Sum of thermal remote sensing over four sample dates in 2019 (left) and 2020 (right) predictions of yield, note predictions <3t/ha were made null.

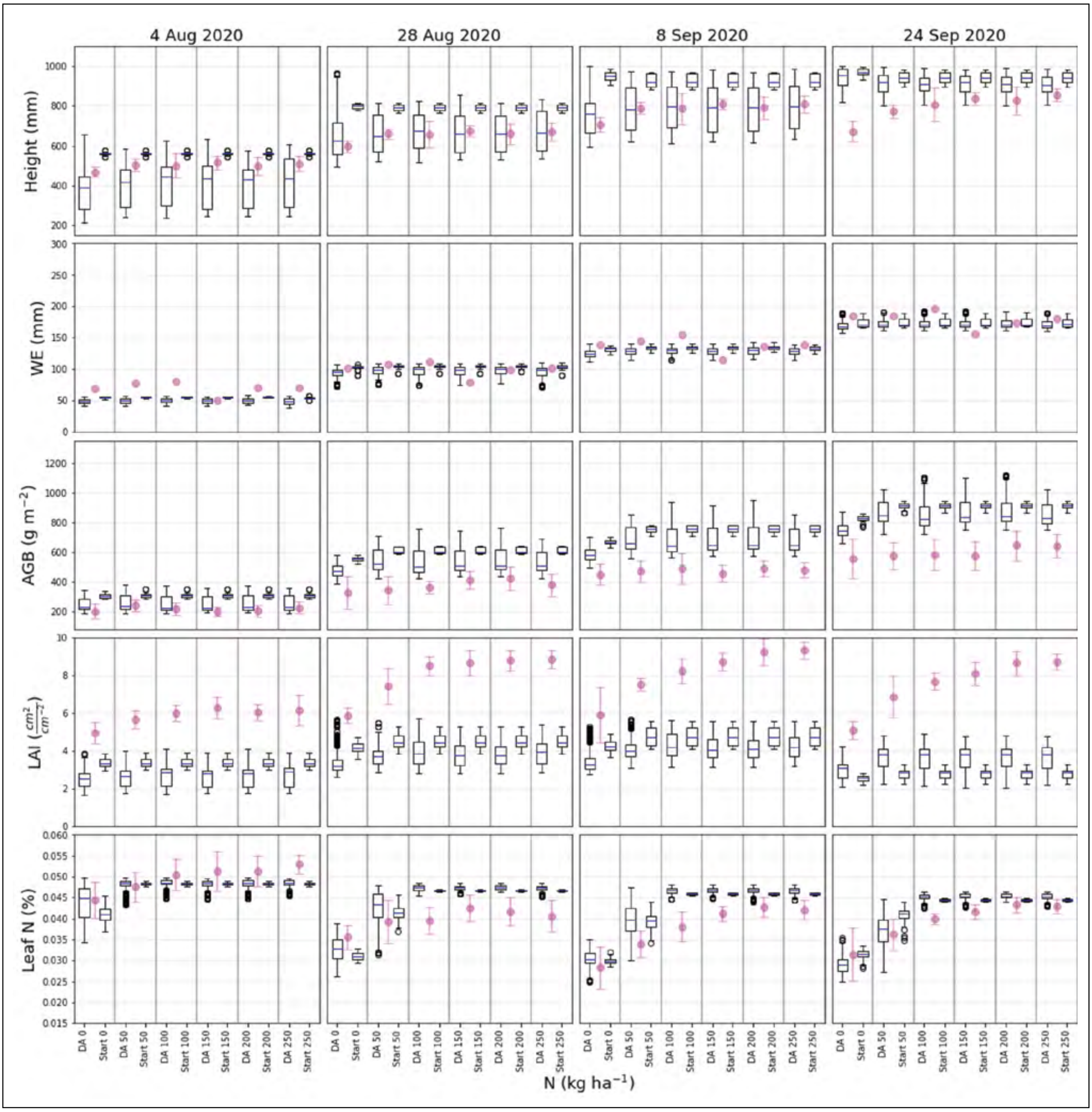

Figure 4. Crop condition performance of the standard and DA APSIM model runs for the calibrated test in 2020 for the six tested N levels and four sample dates. 'Start' in the plot refers to the model runs in only the first iteration using only the default model physics. Height is plant height; WE is water extraction, AGB is aboveground biomass; LAI is leaf area index and leaf N % is leaf nitrogen concentration. Average observed values are shown as circles with errors bars for the standard deviation. Note the water extraction was measured at a single point and so has no standard deviation.

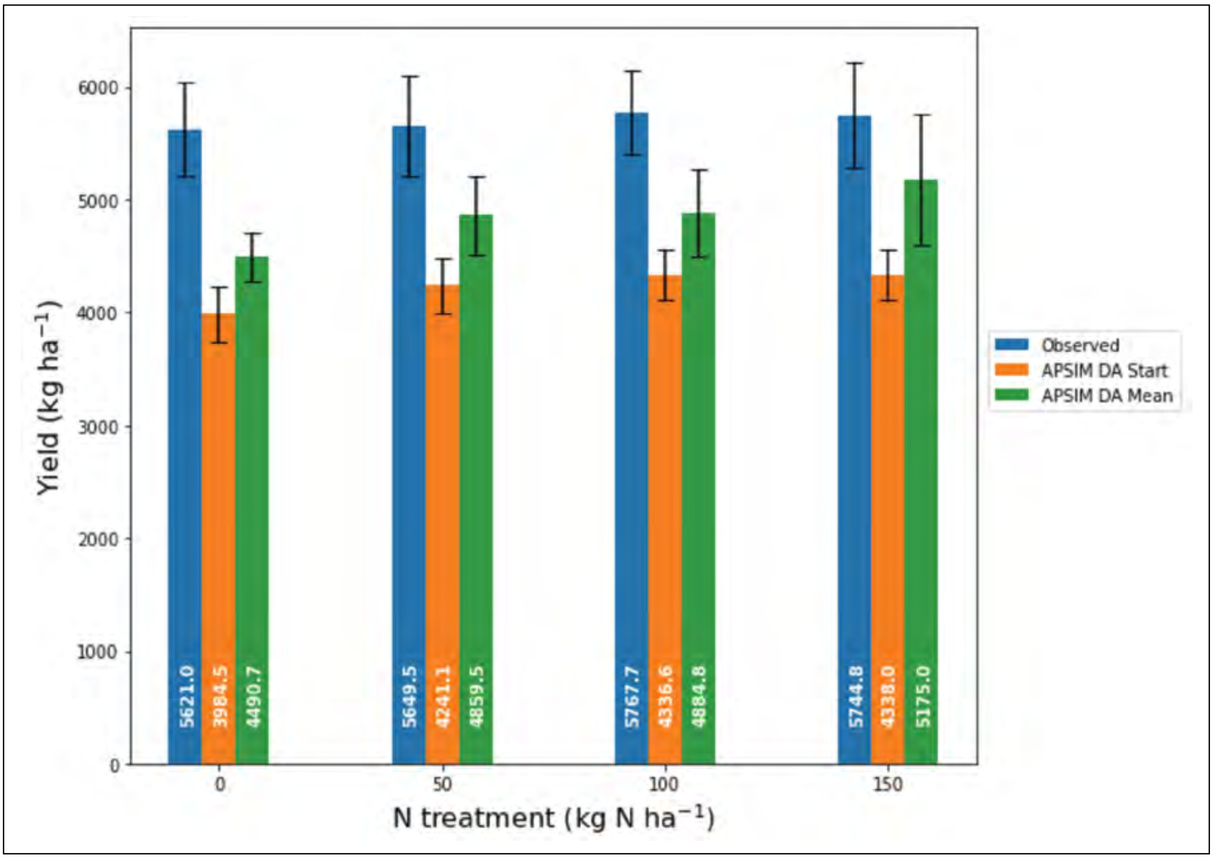

Figure 5. Yield predictions of APSIM before (using only the default physics; 'DA Start') and after data assimilation ('DA Mean') compared with average observed values in 2019. Error bars show the standard deviation and the average values are printed at the base of the columns.

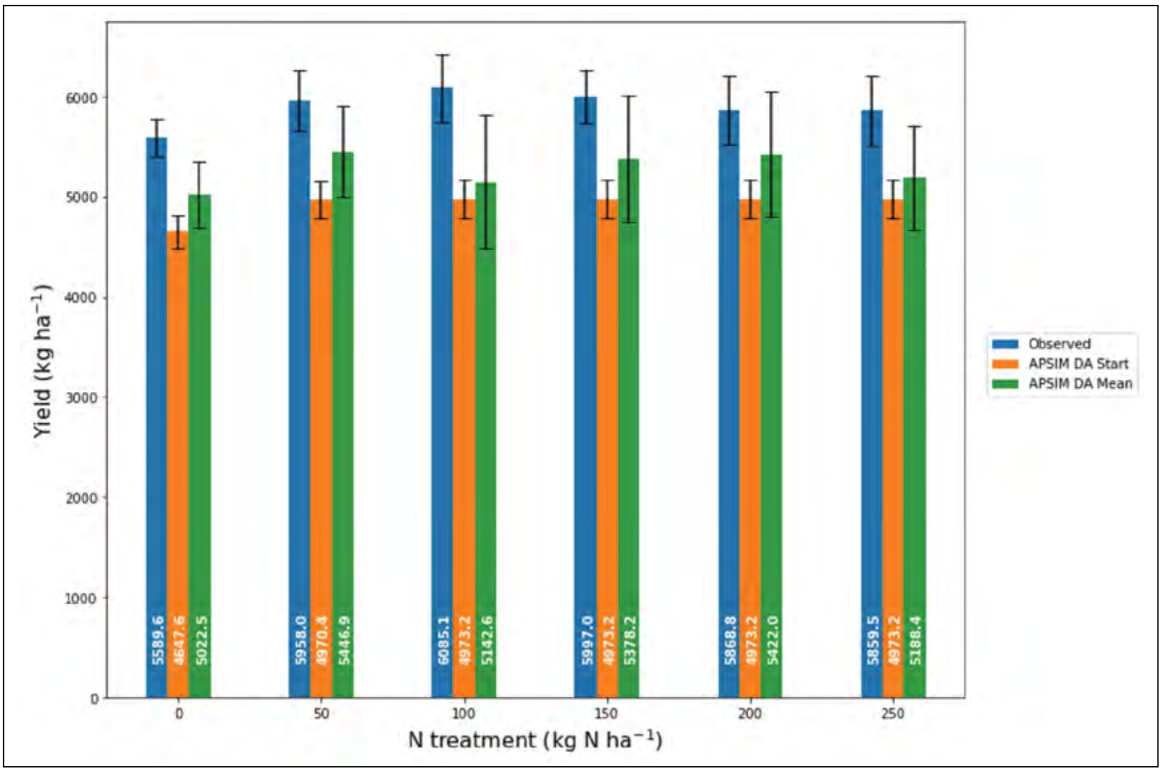

Figure 6. Yield predictions of APSIM before (using only the default physics; 'DA Start') and after data assimilation ('DA Mean') compared with average observed values in 2020. Error bars show the standard deviation and the average values are printed at the base of the columns.

Conclusion

This project consisted of two field trials of wheat, with remote sensing and soil moisture observations, complemented by in-season crop condition sampling. A sensitivity analysis was performed on the APSIM crop model to find the relative influence of each of the 23 parameters chosen from a review of the relevant literature. The sensitivity analysis results were then applied as scaling to the error weighting from comparing potential yields, and remote sensing and soil moisture observations with model predictions in a multi-model ensemble Data Assimilation (DA) framework to test if prediction fit could be improved.

The ensemble mean yield prediction after DA outperformed the standard APSIM prediction using the default physics, on average, by between 7-12% for all four tests, although, more so for 2019 than 2020. Uncalibrated tests showed larger improvements, although this was from a much lower baseline accuracy. The range of variation added through ensemble factors stretched the range of potential model states, and therefore captured more of the natural range of outcomes seen in the field. The scaling from the sensitivity analysis may have reduced the impact of parameter interactions by minimising the impact of parameters that were less influential and maximising those with higher influence. Further, the parameter weighting provided by assimilating errors in the fit between observed and predicted state variables (i.e., height growth, water extraction and potential yield) guided the model towards more realistic estimates of crop status.

While the main focus of this project was yield prediction accuracy improvement, for farmers and agronomists in-season crop condition is important for delivering better outcomes at the end of the season, as well as building confidence that the model is getting the 'right answer for the right reason'. The DA ensemble's iterative adjustment over the modelling runs resulted in mean crop condition during the season being improved over the standard in most output variables on most dates. Several key dates showed large improvements in accuracy, such as the 28 August and 8 September having near identical simulated and observed mean heights in the calibrated test in 2020, however, all dates showed improvement in height estimation. The improvements for other variables were not uniform, however, as shown by the predictions of LAI for the first through to the third sample date in 2020 being generally less accurate after the DA framework than for standard APSIM. The results for 2019 were similar, however, with slightly better results in LAI and slightly less successful height adjustment. APSIM predictions were generally strong for both the standard and DA ensemble in leaf N and water extraction.

In order to test the generality of the approach and whether a mid-season application of the DA ensemble framework was possible, neither during calibration nor the model runs did the DA framework reference actual observed yield from either year. Instead, the predicted yield during the runs were tested against the French and Schultz Water Use Efficiency (WUE) model, as a proxy for potential yield. After the data assimilation, the results were tested against observed yield (Figures 5 & 6). For the 2019 calibrated test, this was successful in improving the yield predictions. The 2020 calibrated test was predicting yield greater than the WUE model from the first iteration, due to a lower threshold from less rain having been received in-season, however, yield predictions continued to improve due to the height and water extraction assimilation. This highlights the practical application of this research for farm managers and advisers: mid-season predictions of end season crop production can be achieved by using potential yield with only a limited set of field condition observations collected remotely.

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Automation: opportunities for adoption in agriculture

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GRDC project code: USQ2006-004RTX

Keywords

- automation, autonomy, technology

Take home messages

- Automation is a stepping-stone on the path to autonomy.
- Automation reduces risk by increasing precision and repeatability.
- Opportunities for farm automation are here now.

Background

Gains in productivity are being made through increased control of inputs and through precise timing of management operations, indicating a potential use case for increased integration of automation and autonomous systems on-farm.

Original equipment manufacturers (OEMs), such as John Deere and Case IH, are primarily developing machinery with an increasing level of automation leading to full autonomy.

However, there is a lack of consumer available functionality which provides active perception and decision making to on-farm machinery. This limits the potential of the automated technologies to situations where an operator can be present, limiting operations both by the number of automation capable and equipped machines and by the number of available skilled operators.

While automated systems are widely used in agriculture today, a focus will need to be on bringing active perception and intelligent decision-making tools to automated systems, allowing for fully autonomous systems to be viable and actively adopted in agriculture. This will allow the removal of the operator, enabling operations to be completed with increased efficiency.

Fundamentals of automation for agriculture

Defining automation to autonomy

The initial step towards on-farm autonomous machinery is automation. Automation allows a machine to complete a series of functions automatically. This differs to autonomy where the machine must complete a task without human assistance while having sufficient skill to complete that task in changing environments. This difference is illustrated when looking at a machine which can be operated using an automatic guidance system on pre-defined tracks and a machine which can follow those pre-defined tracks, identify a perceived obstacle and make a decision regarding the interaction of the current operation and that obstacle (Figure 1).

Autonomy is driven by perception which can be broken down into two groups:

- Locative Perception where the machine knows something about its surroundings and its place in those surroundings.
- Task Perception where the machine knows something about what it is doing and how well this task is being done.

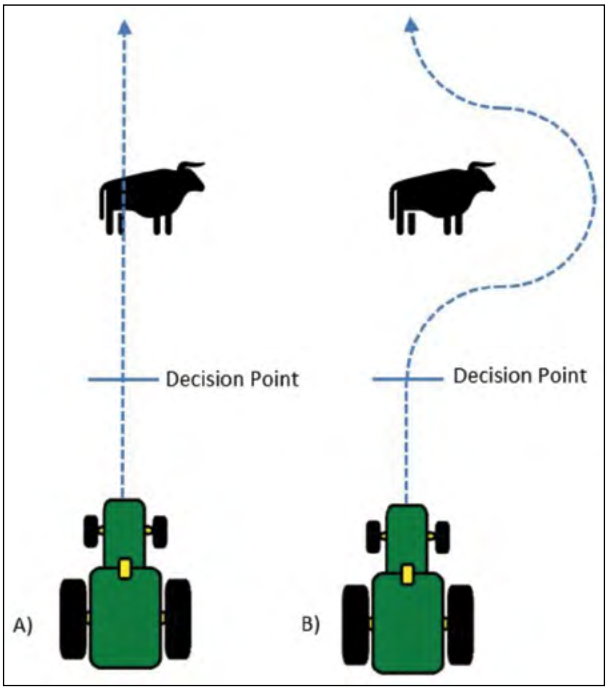

Figure 1. A) An automatic machine requiring human input to make a decision and avoid an obstacle. **B)** An autonomous machine identifying an obstacle and making a decision regarding interaction with that obstacle.

Machine objectives

The key features which enable tractor autonomy are defined in Baillie et al. (2020, 2017) and include the automated systems which work together to provide an autonomous solution, such as automated tractor guidance systems, variable rate technology (VRT), sensing and perception systems and in-field communication.

Currently, OEMs and third-party equipment manufacturers do not offer commercial autonomous navigation perception or sensing options for integration into their existing automation technology stacks. These options are presently limited to expensive, single-use technologies from high-tech start-ups. However, perception technologies currently exist within OEM and third-party technology stacks for other uses and these companies are actively investing in and exploring autonomous use cases, as evidenced by John Deere's recent acquisition of Bear Flag Robotics (John Deere, 2021a) and John Deere, Case New Holland (CNH), and Kubota's development of autonomous tractor concepts (Case IH, 2021a; John Deere, 2021b; Wilson, 2020) (Figure 2).

Current state-of-the-art

Currently, the majority of OEM and third-party provider offerings revolve around automated guidance systems and VRT, with some expansion into machine vision and perception as operator assistance tools. All major OEMs provide an option for automated tractor guidance through GPS and RTK correction systems (Case IH, 2021b; CLAAS, 2018a; Deutz Fahr, 2021; Fendt, 2021; John Deere, 2021c) as well as VRT application (Case IH, 2021c; CLAAS, 2018b; John Deere, 2021d). However, there is limited product development of perception technologies by OEMs for active obstacle avoidance. Current perception technologies developed by OEMs are focused on in-row wheel guidance and harvester optimisation.

Locative perception

CNH provides a range of sensing and perception technologies through their technology stacks with a focus on in-crop row guidance and harvester optimisation. AFS RowGuide™ provides mechanical deflection-based row guidance (Case IH, 2021d), while Cruise Cut provides laser-based harvester guidance through the detection of the crop edge (Case IH, 2021b).

Figure 2. Kubota X autonomous tractor (Topspeed Media, 2021).

CLAAS's range of sensing and perception technologies have also been developed primarily around in-crop row guidance and harvest optimisation. CLAAS provides three separate sensor-based automatic steering options for their harvesters, AUTO PILOT, CAM PILOT and LASER PILOT (CLAAS Group, 2021). CLAAS AUTO PILOT uses two mechanical deflection-based sensors to determine the position of maize rows relative to the harvester. CLAAS CAM PILOT builds on this using a stereo camera to control automatic steering in grass harvesting operations. Finally, CLAAS LASER PILOT uses a LiDAR to guide the harvester along the cut edge of cereal crops.

John Deere provides sensing options for in-crop guidance through AutoTrac TM Vision. AutoTracTM Vision uses a single frame-mounted camera using machine vision to keep sprayer wheels in between crop rows (John Deere, 2021e).

SAME Deutz-Fahr (SDF) developed Driver Extended Eyes to assist the operator in navigating machine blind spots. This technology uses an intelligent control unit to actively monitor up to six cameras, extending the view of the driver to the left and right and automatically preventing tractor movement if a human obstacle is detected by cameras (SDF Group, 2021). SDF also uses their machine vision camera technology to provide automatic trailer hitch coupling using environmental recognition to control tractor movement. These cameras actively identify the position of an implement in relation to the tractor and the control system calculates the best path for coupling to the implement, automatically performing all necessary movements (SDF Group, 2021).

Raven Precision, recently acquired by CNH Industrial (Raven Precision, 2021a), has also developed in-row guidance systems and offers the VSN® Visual Guidance Sensor, a stereo vision camera-based machine vision system which can navigate crop rows up to full canopy closure (Raven Precision, 2021b). Raven's AutoBoom® XRT uses radar and optical obstacle detection to maintain optimal spray height (Raven Precision, 2021c).

Raven Precision is on the leading edge of full on-farm autonomy with their OMNiDRIVE™ and OMNiPOWER™ systems. Raven's OMNiDRIVE™ system is an autosteer system which allows an operator to monitor and control a driverless tractor from the cab of the harvester (Raven Precision, 2021d). The autonomous tractor can return to a predetermined unloading area when the grain cart is full. Raven's OMNiPOWER™ is a self-propelled power platform which allows fully autonomous control of field tasks which can be remotely commanded and supervised. However, OMNiPOWER™ requires specially made implements and currently only supports a nutrient applicator spreader and a VRT spray system (Raven Precision, 2021e).

Task perception

CNH developed AFS Harvest Command for Case IH machines which provides automatic adjustments to the harvester in real-time as conditions change (Case IH, 2021e). CNH also provides IntelliFill™, a 3D camera-based system to detect trailer edges and monitor forage harvester filling on New Holland machines (New Holland Agriculture, 2021).

CLAAS offers variable rate harvesting control and automatic trailer filling using a 3D camera to detect trailer edges and monitor and adjust the upper grain discharge chute during cart fill (CLAAS, 2021).

John Deere also provides sensing options for automatic grain-cart filling and real-time spot spraying. John Deere's Active Fill Control controls the harvester discharge chute similar to CLAAS' system, enabling automated cart filling (John Deere, 2021f). John Deere's See & Spray™ Select uses an integrated camera and machine vision algorithms to automatically detect green plants within fallow ground, triggering a chemical application (Burwood-Taylor, 2017).

Future opportunities

As OEMs prepare for the future, they are looking towards technologies such as big data, artificial intelligence, unmanned aerial vehicles (UAVs) and electrification. CNH has produced two autonomous tractor concept vehicles to date. One tractor was a futuristic concept cab-less Case IH while the New Holland NH^{Drive} concept resembles a retrofit tractor with a cab which allows operator control. Both CNH vehicles use AI, GPS/RTK, LiDAR, radar and RGB camera sensors to run autonomously. John Deere has developed both a concept autonomous one axle electric-drive tractor and an autonomous electric-drive sprayer, both concepts were unveiled at Agritechnica 2019. The electric-drive sprayer is fully autonomous with a 30-foot boom, 560-litre spray tank, independent four-wheel steering and tracks to reduce ground pressure (Francis, 2019). John Deere has indicated that they will consider improvements to battery life, speed and autonomous filling (Real Agriculture, 2019). John Deere has actively pursued these battery improvements as evidenced by their recent acquisition of majority ownership in Kreisel Electric, a high-density, high-durability battery manufacturer (John Deere, 2021g). Autonomous filling was revealed at Agritechnica 2019 on John Deere's semi-autonomous tractor concept as part of their Automation to Autonomy core technology stack for the future of farming (John Deere, 2021b). The spray tank on this machine is capable of being filled completely automatically to reduce operator exposure to pesticides. John Deere's autonomous electric one axle tractor concept removes operating emissions and greatly reduces noise levels (John Deere, 2021b). John Deere has also developed a Command Cab, a future tractor cab concept which John Deere views as an intermediate step from automation to autonomy, integrating big data to provide a mobile command centre for the farm (John Deere, 2021b). Finally, John Deere has announced the development of a bolt-on package of hardware and software that uses machine learning to create a fully autonomous tractor which will begin production in late 2022 (Vincent, 2022). If successful, John Deere may have the first widespread, OEM developed autonomous tractor kit on the market.

Multiple manufacturers are also developing autonomous UAV spray systems. John Deere is developing an autonomous swarm drone sprayer concept. The drones are equipped with John Deere's weed identification technologies and each carry a 10.6L spray tank which is filled automatically at a field boundary station (John Deere, 2021b). Kubota is also developing pesticide spraying drones, integrating environmental data into their current decision system software and aim to optimise planting patterns through AI decision systems (Kubota, 2021). Kubota has developed a three-step roadmap to autonomy (Kubota, 2021). This revolved around Kubota's Agri Robo Tractor launch in 2017, followed by the Agri Robo Combine Harvester in 2018 under the plan. Kubota further plans to implement unmanned operation across multiple fields and enable remote monitoring of equipment travel on farm roads. While Case IH has not yet signalled anything around the development of UAV spray systems, they are actively collaborating with DroneDeploy® to provide a drone package which monitors crop health for rapid decision-making (Case IH, 2021f).

Discussion

Current OEM automation technologies enable the majority of features which are required for full machine autonomy. However, they are limited by lack of perception integration options. Major OEMs are developing autonomous concepts which incorporate AI-driven perception systems (namely LiDAR, radar, stereo cameras). Additionally, these perception technologies exist within the OEMs for other uses, such as increasing operator safety or reducing fatigue.

To determine how sophisticated autonomy enabling technologies, such as perception, need to be an operating design domain (ODD) needs to be defined. This ODD specifies what the machine will be tasked for and therefore informs the technical requirements. Currently, there is an opportunity to better define specific applications for autonomy and the ODD with the OEMs. This will allow OEMs to refine the use case and the cost benefit to farmers.

In addition to the technical impediments to autonomy, there are other barriers and, in particular, the safe operation of this equipment and where the various responsibilities exist for the technology users, dealers, service providers and manufacturers. The code of practice for autonomous machinery, led by Grain Producers Australia in collaboration with industry partners , a world first, has been developed to better define these responsibilities (GPA, TMA, SPAA, 2021).

The integration of AI-driven machine perception for navigation by OEMs into their technology stacks and the development of ODDs within these OEMs will likely be the catalyst to allow for the uptake of true on-farm automation. This will, in turn, bring regulatory and legislative attention to on-farm automation technologies and allow for regulatory requirements to begin to be seriously discussed. The Code of Practice has helped put Australian agriculture on the front food in this regard. The gradual implementation of electrification will also inform the pathway to autonomy.

Conclusion

True on-farm autonomous vehicles are limited in use as they are often developed by high-tech start-ups and are targeted towards the specialty or high-value crop markets. OEM driven machine autonomy is limited by lack of AI-driven perception integration options for autonomous navigation and the lack of defined ODDs within these OEMs. With current GPS autosteer, end-of-run sequence automation and communication capabilities, current OEM and third-party options can be integrated to make a machine which can run fully autonomously. However, OEMs put safety mechanisms in place to ensure operator presence as the current machines lack perception integration. These same OEMs are currently developing autonomous concepts but have yet to make them available to consumers, instead focusing on the development of integrated technology stacks, progressively increasing machine automation. Further hurdles to full autonomy include the lack of a direct path to market and the lack of standard regulatory requirements. An AI-driven perception technology, likely developed by an OEM or major third-party provider after the definition of an ODD, which is compatible with current technology stacks, will be the catalyst for the transition from on-farm automation to true autonomy. These developments are beginning to be seen with John Deere's announcement of a commercial autonomous kit for their 8R series tractor in January 2022 (Vincent, 2022). John Deere have defined the ODD for the specific use case, operating a chisel plow in US broadacre cropping systems and notably connected to the farmer via a smart phone to provide supervision. It is expected that the ODD will be developed as the capabilities of the technology advance and incorporate other use cases, including adoption of that technology in Australia.

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May 2021

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Based at Lawloit, between Nhill and Kaniva in Victoria's West Wimmera, John and his family run a mixed farming operation across diverse soil types. The farming system is 70 to 80 per cent cropping, with cereals, oilseeds, legumes and hay grown. He wants to see RD&E investments promote resilient and sustainable farming systems that deliver more profit to growers and ultimately make agriculture an exciting career path for young people.

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