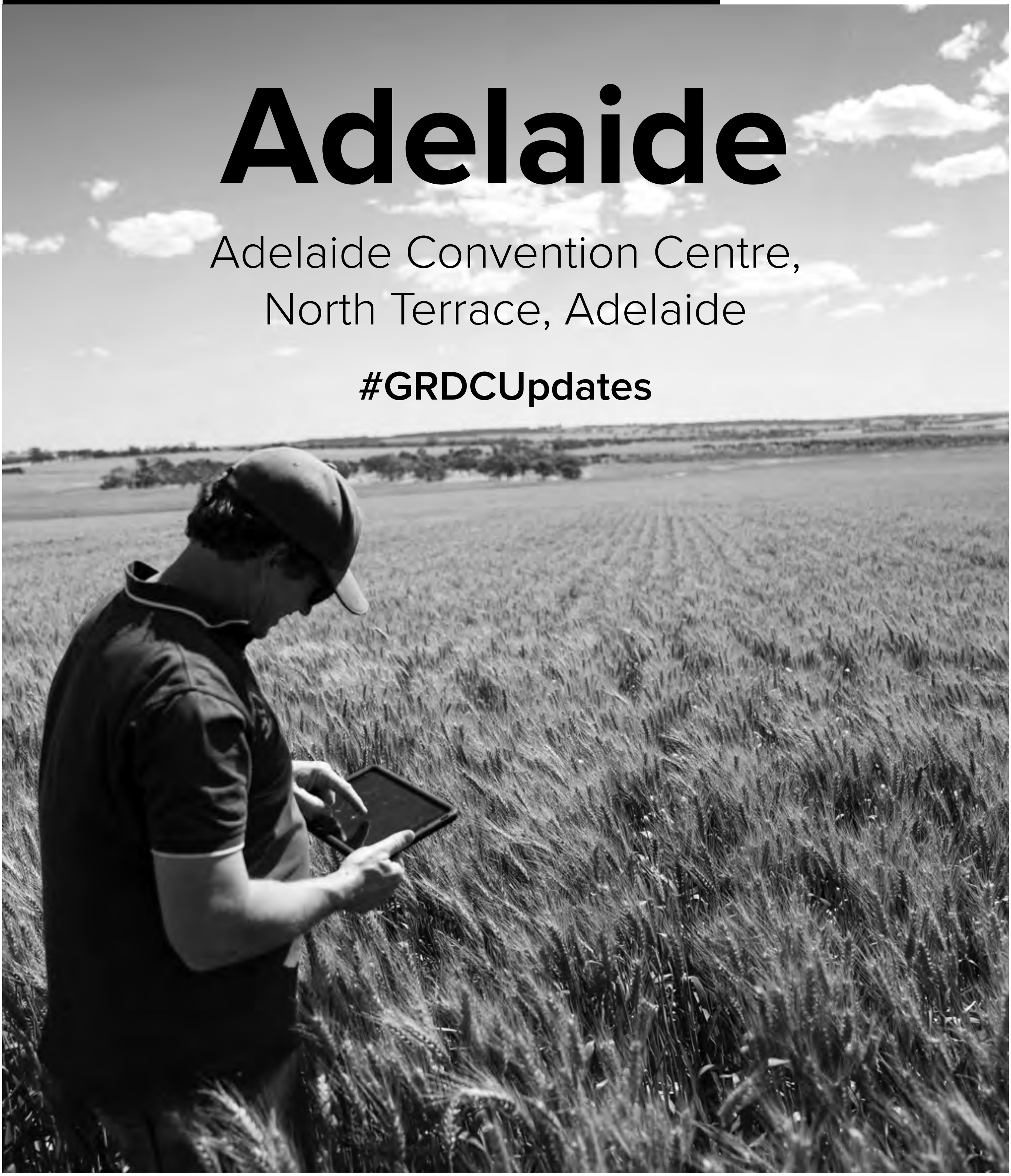
GRAINS RESEARCH UPDATE

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

Adelaide

Adelaide Convention Centre,
North Terrace, Adelaide

#GRDCUpdates



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GRDC Welcome – Adelaide Grains Research Update Proceedings

On behalf of the Grains Research and Development Corporation (GRDC), it is my pleasure to welcome you to the 2020 Grains Research Update, Adelaide.

This annual grains research, development and extension (RD&E) forum heralds the beginning of a new decade of grain production in this State.

The South Australian grains industry has certainly evolved and progressed over the past 10 years – something for which we can all be proud. Improvements in crop water-use efficiency and continual optimisation of production costs in a non-subsidised production environment have been enabled by the adoption of new technology and practices on-farm. Despite these gains, it is critical that we continue to build momentum to ensure growers remain competitive, resilient and profitable into the future.

We embark on this new decade acutely aware of the need to be innovative, responsive and aspirational in our approach to investment in grains RD&E. More of the same will simply not be good enough. Improving grower profitability, within the context of dynamic climatic, seasonal, environmental and market conditions, will require a proactive, targeted and strategic approach to research.

To this end, the GRDC is squarely focused on implementation of its 2018-23 RD&E Plan. Significant progress in the development of investment strategies aligned to the profit drivers of yield, price, costs and risk have been made for each of the 30 new Key Investment Targets (KITs). So far, 15 KIT summary strategies have been launched, with the remaining 15 to be finalised in the coming months. Each of these strategies provides a roadmap for future investment, signalling GRDC's intent to get the right balance between strategic and tactical RD&E investment.

One of the first KIT summary strategies to be developed is focused on minimising the impact of frost on grain yield and stability (KIT1.2). The need to explore new approaches is recognised and the new strategy aims to enable improved pre-season planning, more informed in-season management decisions and effective tools to address this issue. For more details about the KITs, please visit the GRDC website at https://rdeplan.grdc.com.au/objectives-and-kits/ and provide feedback via KIT@grdc.com.au.

The past 12 months has been an extremely busy period for the GRDC, not only in development of investment targets but also in the implementation of numerous exciting new investments. Underlining the breadth of the GRDC's RD&E investment portfolio is the development of a potentially transformative machine learning platform by the GRDC's Enabling Technology group. Machine learning is a powerful way to analyse data for the grains sector and this suite of investments is bringing a new cohort of research partners to the table, helping to tackle previously intractable problems.

The GRDC has also recently invested in utilising cutting-edge 'synchrotron' scanning technology (a particle accelerator that acts like a super-powered microscope), to provide further insights into interactions between root and water distribution and nutrient availability in soils (UOQ1910-002RMX,USA1910-001RTX, UOQ1910-003RTX). Only 60 synchrotrons exist in the world, and this technology brings to our grains industry a whole new research dimension that has so many potential applications.

Another series of recent blue-sky investments include several innovative new approaches to fertiliser manufacture. GRDC has partnered with CSIRO, the Australian Renewable Energy Agency (ARENA) and Orica to explore an innovative and potentially transformational hydrogen to ammonia discovery project. In a separate planned investment, GRDC is exploring new fertiliser technology aimed at cost-effectively targeting nutrient availability to plant demand through novel formulation technology and the inhibition of nitrogen-loss pathways.

An improved understanding of crop phenology remains a focus and significant research is underway to inform our understanding of phenology drivers of different crops/varieties and related management approaches. This includes an investment in a National Phenology Initiative, led by La Trobe University (ULA00011) as well as a new investment to commence this season, targeted at matching adapted pulse genotypes to soil and climate to maximise yield and profit with manageable risk (PROC-9176094).

Transformational opportunities around three-dimensional characterisation of soils and radical approaches to amelioration aiming to deliver new understandings and solutions to address multiple soil constraints are other examples of numerous new investments underway.

You will learn more about some of these investments as well as a diverse range of other advances in grains RD&E at this Grains Research Update.

This event is an important platform for building knowledge regarding the latest grains research findings, as well as raising awareness to inform tactical decision-making for the coming season. Extending this information across the industry is vital and discussing and debating how these learnings may be applied to deliver an impact on farm profit is a key outcome of the two-day program.

With a strong regional presence and outreach, the GRDC is well placed to identify and respond to key issues affecting grower profitability but this requires strong partnerships and collaboration. I encourage all of you attending this update to have your say, speak with a member of GRDC staff, panels or the broader GRDC Grower Network to discuss the GRDC's investment approach or any ideas and feedback you may have. And if you are interested in having greater involvement in grains RD&E, we would love to hear from you.

Timely access to relevant information plays a crucial role in supporting and informing growers and advisors. You'll soon be receiving details about a new subscription centre through which you can determine and control what lands in your email inbox, and we'll also be offering a new regional consolidated electronic newsletter to keep you up to date.

In the meantime, as the nation continues to deal with the enormous losses and long-term repercussions as a result of drought and recent bushfires we can only hope that the remainder of the year sees a return to 'normality'.

Best of luck with the season ahead and may the grain prices be high and silos overflowing in 2020.

Craig Ruchs

Senior Regional Manager South

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The GRDC's podcast series features some of the grain sector's most pre-eminent researchers, growers, advisers and industry stakeholders sharing everything from the latest seasonal issues, to ground-breaking research and trial results with on-farm application.

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GRDC GROWNOTES

SPRAY APPLICATION GROWNOTES™ MANUAL

SPRAY APPLICATION MANUAL FOR GRAIN GROWERS

The Spray Application GrowNotes™ Manual is a comprehensive digital publication containing all the information a spray operator needs to know when it comes to using spray application technology.

It explains how various spraying systems and components work, along with those factors that the operator should consider to ensure the sprayer is operating to its full potential.

This new manual focuses on issues that will assist in maintaining the accuracy of the sprayer output while improving the efficiency and safety of spraying operations. It contains many useful tips for growers and spray operators and includes practical information – backed by science – on sprayer set-up, including self-propelled sprayers, new tools for determining sprayer outputs, advice for assessing spray coverage in the field, improving droplet capture by the target, drift-reducing equipment and techniques, the effects of adjuvant and nozzle type on drift potential, and surface temperature inversion research.

It comprises 23 modules accompanied by a series of videos which deliver 'how-to' advice to growers and spray operators in a visual easy-to-digest manner. Lead author and editor is Bill Gordon and other contributors include key industry players from Australia and overseas.

Spray Application GrowNotes™ Manual – go to: https://grdc.com.au/Resources/GrowNotes-technical
Also go to https://grdc.com.au/Resources/GrowNotes and check out the latest versions of the Regional Agronomy Crop GrowNotes™ titles.

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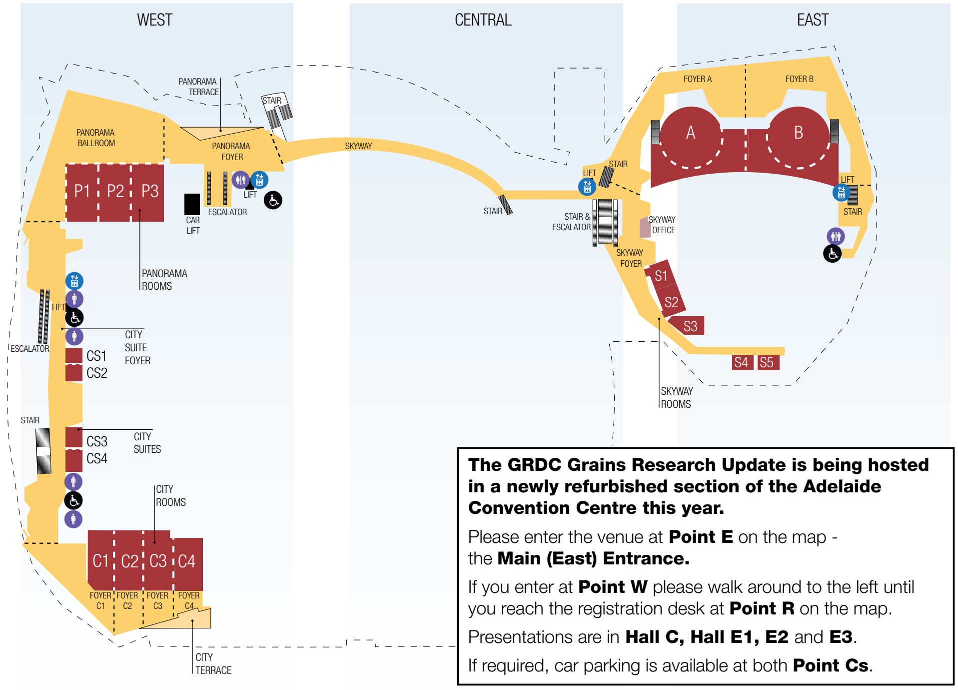
UPPER LEVEL



The GRDC Grains Research Update is being hosted in a newly refurbished section of the Adelaide Convention Centre this year.

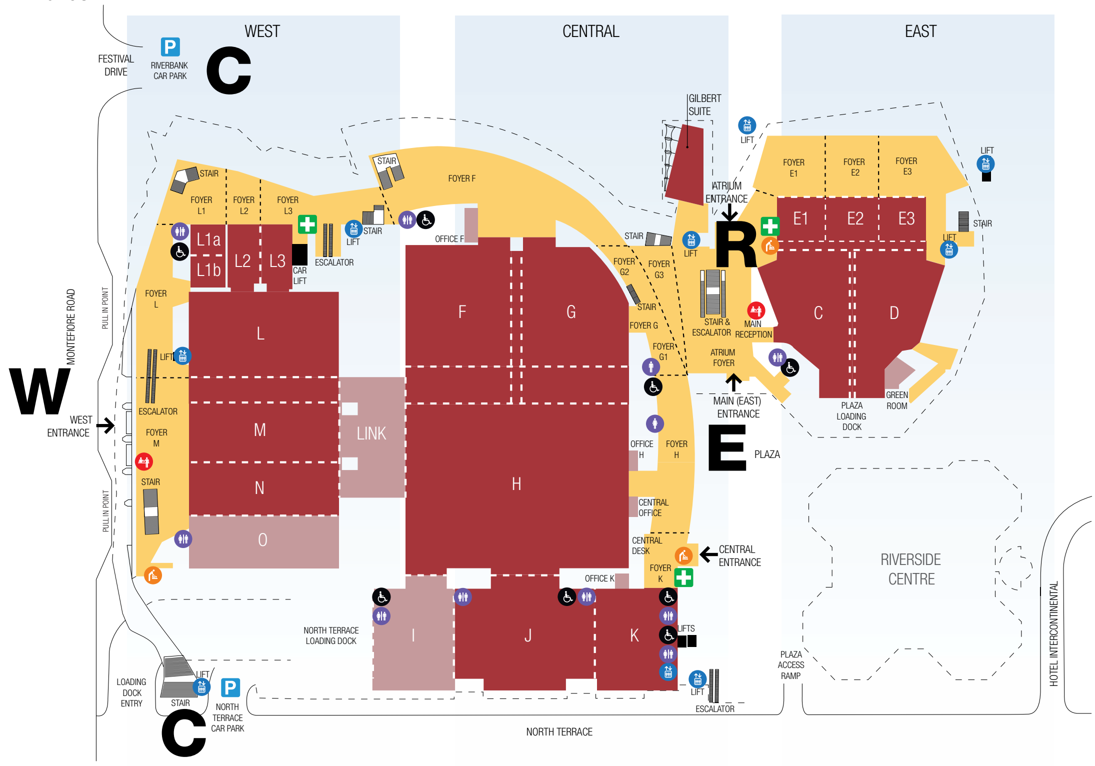
Please enter the venue at **Point E** on the map - the **Main (East) Entrance.**

If you enter at **Point W** please walk around to the left until you reach the registration desk at **Point R** on the map.

Presentations are in **Hall C, Hall E1, E2** and **E3**.

If required, car parking is available at both **Point Cs**.

GROUND LEVEL



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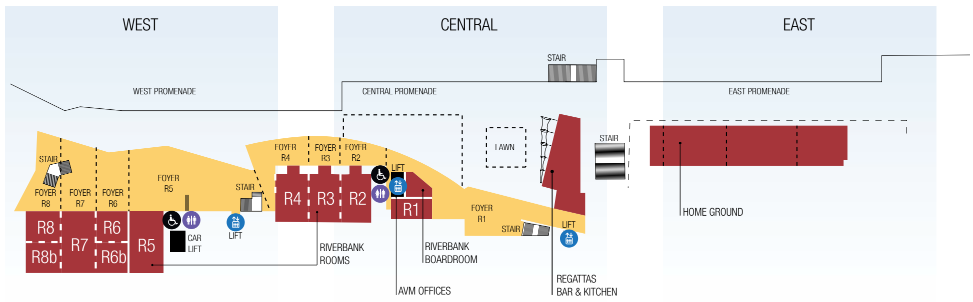

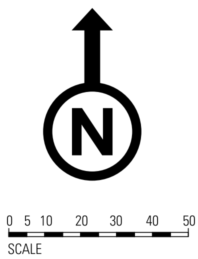

Aug 2018

GRDC Grains Research Update ADELAIDE

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FINAL SESSION

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GRDC Grains Research Update ADELAIDE

GRDC GRAINS RESEARCH & DEVELOPMENT CORPORATION

PROGRAM DAY 1 - FEBRUARY 11th

8.55 am	**Announcements**	*ORM*
9.00 am	**Welcome and GRDC update**	*GRDC representative*
9.20 am	**Australia's grain industry in 2030 - a look into the future** - P15	***Ross Kingwell,** AEGIC*
9.55 am	**New herbicides - the best integration to prolong their impact** - P23	***Roberto Busi,** AHRI*
10.30 am	**Morning tea**	

CONCURRENT SESSIONS (40 minutes including time for room change)

(R = session to be repeated)

	Hall C	Room E1	Room E2	Room E3
11.05 am	**Latest strategies in canola disease control (R)** - P31 ***Steve Marcroft,*** *Marcroft Grains Pathology*	**New pasture opportunities for low rainfall mixed farms (R)** - P41 ***Ross Ballard,** SARDI*	**The hows and whys for deep ripping sandy soils (R)** - P53 ***Brian Dzoma,** SARDI*	**A sensor-based approach to improved N decision making (R)** - P63 ***Rob Bramley,** CSIRO*
11.45 am	**Frost mitigation - investigating agronomic options (R)** - P75 ***Mick Faulkner,** Agrilink Agricultural Consultants*	**The 10 key lessons from the Optimising Canola Profitability project (R)** - P77 ***Andrew Ware,*** *EPAG Research*	**Potassium and sulphur - the known knowns and the known unknowns (R)** - P85 ***Rob Norton,*** *Norton Agronomic P/L*	**Problem weeds - management to minimise impact (R)** - P91 ***Gurjeet Gill,*** *University of Adelaide*
12.25 pm	**The health report: pulse disease update (R)** - P99, 105 and 113 ***Mohsen Khani, Sara Blake** and **Blake Gontar,** SARDI*	**Use of chemicals and residues arising** - P121 ***Gerard McMullen,*** *NWPGP*	**New pasture opportunities for low rainfall mixed farms** - P41 ***Ross Ballard,** SARDI*	**A sensor-based approach to improved N decision making** - P63 ***Rob Bramley,** CSIRO*
1.00 pm	**LUNCH**			

CONCURRENT SESSIONS (40 minutes including time for room change) (R = session to be repeated)

	Hall C	Room E1	Room E2	Room E3
2.00 pm	**New changes and future opportunities within NVT (R)** - P125 ***Rob Wheeler,*** *GRDC*	**The hows and whys for deep ripping sandy soils** - P53 ***Brian Dzoma,*** *SARDI*	**Break crop selection in low rainfall environments - one size does not fit all (R)** - P127 ***Sarah Day,*** *SARDI*	**The health report: pulse disease update** - P99, 105 an 113 ***Mohsen Khani, Sara Blake*** *and* ***Blake Gontar,*** *SARDI*
2.40 pm	**Problem weeds - management to minimise impact** - P91 ***Gurjeet Gill,*** *University of Adelaide*	**The 10 key lessons from the Optimising Canola Profitability project** - P77 ***Andrew Ware,*** *EPAG Research*	***On the couch with Roberto & Ross***	**Frost mitigation - investigating agronomic options** - P75 ***Mick Faulkner,*** *Agrilink Agricultural Consultants*
3.20 pm	**Potassium and sulphur - the known knowns and the known unknowns** - P85 ***Rob Norton,*** *Norton Agronomic P/L*	**Break crop selection in low rainfall environments - one size does not fit all** - P127 ***Sarah Day,*** *SARDI*	**Latest strategies in canola disease control** - P31 ***Steve Marcroft,*** *Marcroft Grains Pathology*	**New changes and future opportunities within NVT** - P125 ***Rob Wheeler,*** *GRDC*

3.55 pm **AFTERNOON TEA**

4.25 pm **Hyperspectral sensing for the prediction of nitrogen, water and salt content in wheat** - P135 — ***Brooke Bruning***

4.35 pm **Herbicide resistant common sowthistle and prickly lettuce: dispersal, seed biology and management considerations in lentils** - P141 — ***Alicia Merriam***

4.45 pm **International grain markets - long term trends** - P147 — ***Cheryl Kalisch Gordon,*** *RaboResearch*

5.25 pm **COMPLIMENTARY DRINKS & FINGER FOOD IN TRADE DISPLAY AREA**

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GRDC Grains Research Update ADELAIDE

PROGRAM DAY 2 - FEBRUARY 12th

8.15 am **EARLY RISERS: Assessing the value in soil and plant testing** - P157 ***Sean Mason,*** *Agronomy Solutions*

CONCURRENT SESSIONS (40 minutes including time for room change)

(R = session to be repeated)

	Hall C	Room E1	Room E2	Room E3
9.00 am	**Seeder strategies for non-wetting soils (R)** - P165 ***Jack Desbiolles,*** *University of South Australia*	**New strategies to manipulate flowering date and yield (R)** - P177 ***Kenton Porker,*** *SARDI*	**Cereal disease wrap up (R)** - P185 ***Hugh Wallwork,*** *SARDI*	**Latest research for improving management of snails (R)** - P191 ***Helen Brodie,*** *SARDI*
9.40 am	**Integrating new chemistries in the field** - P199 ***Chris Preston,*** *University of Adelaide,* ***Chris Davey,*** *YP AG and* ***Brian Lynch*** *(Elders)*	**Spotlight on pulses (R)** - P203 ***Penny Roberts,*** *SARDI*	**Rapid post-event frost damage assessment - can it be achieved? (R)** - P213 ***Glenn Fitzgerald*** *and* ***Audrey Delahunty,*** *Agriculture Victoria*	**Septoria - no longer only an issue for the high rainfall zone (R)** - P231 ***Andrew Milgate,*** *NSW DPI*
10.20 am	**MORNING TEA**			
10.50 am	**Soaks are seeping across SA - what can be done about it? (R)** - P237 ***Chris McDonough,*** *Insight Extension for Agriculture*	**Improving the heat tolerance of wheat** - P245 ***Rebecca Thistlethwaite,*** *University of Sydney*	**Septoria - no longer only an issue for the high rainfall zone** - P231 ***Andrew Milgate,*** *NSW DPI*	**Latest research for improving management of snails** - P191 ***Helen Brodie,*** *SARDI*
11.30 am	**Spotlight on pulses** - P203 ***Penny Roberts,*** *SARDI*	**New strategies to manipulate flowering date and yield** - P177 ***Kenton Porker,*** *SARDI*	**Subsurface acidity - how far has the research advanced?** - P251 ***Melissa Fraser,*** *PIRSA*	**Cereal disease wrap up** - P185 ***Hugh Wallwork,*** *SARDI*

CONCURRENT SESSIONS (40 minutes including time for room change) (R = session to be repeated)

	Hall L	Room L1	Room L2	Room L3
12.10 pm	**Soaks are seeping across SA - what can be done about it?** - P237 ***Chris McDonough,*** *Insight Extension for Agriculture*	**Seeder strategies for non-wetting soils** - P165 ***Jack Desbiolles,*** *University of South Australia*	**Eye on active plant pests** - P259 ***Rohan Kimber,*** *SARDI*	**Rapid post-event frost damage assessment - can it be achieved?** - P213 and P223 ***Glenn Fitzgerald*** *and* ***Audrey Delahunty,*** *Agriculture Victoria*

12.50 pm **LUNCH**

1.30 pm **Predicted climate change impacts on southern farming systems & how we should act** - P271 — ***Peter Hayman,*** *SARDI*

2.10 pm **What's the cost of HWSC for you?** - P281 — ***Pete Newman,*** *AHRI*

2.50 pm **CLOSE AND EVALUATION**

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Australia's grains industry in 2030 - a look into the future

***Ross Kingwell*[1].**

[1]*Australian Export Grain Innovation Centre (AEGIC).*

Keywords

- grains industry, strategic analysis, grain markets, competition.

Take home messages

- South Australia's grains industry is well poised to benefit from strategic change in Australia's grains industry.

Background

Dorothea Mackellar's famous poem, My Country, sums up Australia as a land 'of droughts and flooding rains'. Her assessment, written over a century ago, remains apt. Australia's environmental extremes of drought, flood and bushfire continue to seriously disrupt Australian agriculture; affecting livestock and grain production, and lessening exports of agricultural commodities. Also largely unchanged is the familial basis of farm production in Australia. Yes, farms are larger; yes, there is greater mechanisation; yes, there are fewer farm families but, most of the grain, sheep and wool production still comes from farm families who pass their farm business wealth, knowledge and skill in farming down through their generations.

However, many other things are changing to affect greatly or gradually farm production, especially grain production, in Australia. The list of factors includes:

(i) Technological change. Long gone from Dorothea Mackellar's era is the vital role of horses in crop production. Now, powerful machinery with in-built precision and intelligence aid the sowing, spraying and harvesting of crops. Bulk-handling underpins most aspects of crop production. Computer and mobile phones facilitate communication, commercial transactions, information receival, record-keeping and various types of analysis.

(ii) New crops and changing crop mixes. The wheat/sheep belt, the mainstay of Australian agriculture, has switched its land use to favour more crops, with greater crop diversification. Canola, chickpeas, lentils and lupins, once virtually unknown crops, have emerged to be important components of cropping systems in different regions. The swing into greater reliance on crop revenues is evidenced by Australia's sheep population shrinking to current levels as small as it was in 1905, 115 years ago. Yet, by contrast, in 1905 in Australia, 1.5mmt of wheat was produced from 2.5mha compared to 15.9mmt being grown on 10.1mha in 2019.

(iii) Altered soil management. Traditionally paddocks were ploughed repeatedly to form a friable seed bed to combat weeds. However, the advent of conservation agriculture (Kingwell et al. 2019) now sees crops established in single pass operations, with minimal soil disturbance with increased reliance on herbicides and weed seed management at harvest.

Soil amelioration is increasingly commonplace (Davies et al., 2017).

(iv) A changing climate. Grain production in Australia is based on rain-fed farming systems. Hence, temporal and spatial changes in rainfall and temperatures crucially affect national crop production. Investigations of long-term weather records reveal a warming trend underpins Australian grain production. Winter crop regions, especially in Western Australia (WA), are also affected by a downward trend in growing season rainfall. Extreme heat during grain filling poses a further problem in some regions where farmers observe occasional 'heat frosts' with grain yield and grain quality being adversely affected.

(v) An altered role of government. Traditionally, government played a major role in Australia's grain industry. Rail systems were owned and operated by State governments. Statutory grain marketing was ubiquitous. Research and advisory services were funded and supplied principally by State governments, with the Commonwealth government playing an important collaborative role in research funding. Provision of new plant varieties was almost solely the province of State government agencies, universities and the CSIRO. Governments were important employers in many rural towns. Yet now, the march of privatisation, the lesser, relative economic contribution of agriculture and the emergence of other claims on the public purse from environment (natural disaster relief, environment, health and social welfare) have altered the role of government in the farm sector. Increasingly grain growers pay fully or a large part for advice, grain marketing, research services and grain transport.

Privatisation has not only affected government services, grain handling and storage that typically was under cooperative ownership and management by grain growers also has passed into private ownership; Cooperative Bulk Handling in WA being a key exception.

(vi) Emergent low-cost overseas competitors. Over the last few decades, a seismic shift in grain export prowess and rankings has occurred. In previous decades North America, Europe and Australia were the main grain exporters. However, first South America (i.e. Brazil and Argentina) and then the Black Sea region (i.e. Russia, Ukraine and Kazakhstan) greatly have increased their grain production and grain exports. AEGIC have released reports on several of these grain exporters (for example; Kingwell et al. 2016a, 2016b and Kingwell and White 2018). Russia has replaced the USA as the world's main exporter of wheat. Argentina and Brazil are the main export suppliers of feed grains (soybean and corn).

All these changes, in combination, are affecting the current and future potential of grain production in Australia. Drawing on these changes and other key influences, the next section of this paper outlines a possible future for Australia's grains industry at 2030. The ramifications for South Australia (SA)'s grains industry are highlighted.

Australia's grain industry towards 2030

Late last year I released a report (Kingwell 2019) that describes the likely situation and outlook of Australian grain production towards 2030. Similarly, Rabobank examined strategic trends in Australia's grains industry and came to a similar conclusion that, towards 2030, feed grain demand and supply will increase in prominence in Australia, especially in eastern Australia.

Any interested readers can read the full report, but for now, the report's following key findings are highlighted.

Key findings

- Australia's population is projected to increase by between 16 and 19 per cent by 2030. This means between 4.07 and 4.89 million additional people in Australia.
- Little increase in the area sown to winter and summer crops in Australia has occurred since the mid-2000s and further increases are unlikely towards 2030.
- Despite plant breeding, agronomic and technology improvements, the average rate of crop yield improvement has been 0.6 per cent per annum since the late 1980s. There is spatial variation in yield improvement trends and yield volatility has worsened in eastern Australia.
- Climate change and seasonal variation are limiting yield growth in many grain-growing regions.
- The mix of crops grown across Australia is fairly stable with a slight increase in the relative importance of canola over the last decade. In eastern Australia, coarse grains and pulses feature more in the mix of crops.
- The pattern of meat consumption among Australians is changing, with a growing dominance of chicken and pork consumption at the expense of beef and lamb.

- Increasingly, the main meats consumed by Australians are from grain-fed animals.
- By 2030:
  - (i) Feed grain demand in Australia will increase by between 2.24mmt and 2.48mmt.
  - (ii) An additional 0.64mmt to 0.77mmt of grain will be required for flour and malt production.
  - (iii) An additional 5.65mmt of grain will be produced, increasing from current production of 49mmt in 2017/18 to 54.6mmt.
  - (iv) The surplus of grain available for export is expected to be between 2.4mmt and 2.8mmt.
  - (v) Almost all the additional grain production in eastern Australia will need to flow to the east coast domestic market to satisfy its growth in feed and food demand based on grains.
  - (vi) The main sources of additional exportable surpluses of grain will be in WA and SA.
  - (vii) The grain quality profile of Australia's main export crop, wheat, is likely to alter, as WA's and SA's share of national wheat exports increases.

A key implication of these findings is that towards 2030, Australia's domestic requirements for grain will become increasingly important, especially in eastern Australia where most of the population increase and greater demand for feed grains, flour, oil for human consumption and malt will occur. By contrast, most of the exportable surpluses of grain will increasingly come from the less populous states of WA and SA.

The task of finding export markets for the additional 2.4mmt to 2.8mmt of export grain available by 2030 may not be overly challenging, given the projected increase in grain imports envisaged for many of Australia's current grain customers. Nonetheless, it needs to be noted that this task of selling more Australian grain will occur against the backdrop of burgeoning exports from low-cost international competitors previously mentioned.

Assuming crop production in Australia towards 2030 remains seasonally volatile, while the east coast domestic demand for grain increases in relative importance, then farmers and grain users are likely to react by:

(i) Investing in more grain storage; especially while interest rates are low, making the cost of carrying grain affordable.

(ii) Focusing more on domestic market opportunities, especially in eastern Australia.

(iii) Focusing more on feed grain production, especially in eastern Australia and possibly in an adjacent state like SA.

(iv) Opportunistically selling grain from SA and WA to end-users in eastern Australia when low production occurs on the east coast. However, this will adversely affect SA's and WA's reputation as reliable exporters to overseas' consumers.

(v) Looking more closely at grain supply security when investing in export-focussed grain processing/animal protein industries; with access to export parity grain rather than exposure to import parity on the east coast.

Implications for SA grain producers

Although the increased demand for feed grains in eastern Australia may encourage more SA grain producers to alter their crop mix towards more feed grain production, it is unlikely that most farmers will additionally allocate more land to cropping rather than sheep production. Despite the sizeable reduction in the national sheep population, SA farmers have maintained their investment in sheep (Figure 1).

In order to retain sheep numbers, either pasture areas need to be allocated for sheep production or affordable feed grains need to be always readily available. Given the strong upward movement in sheep meat and wool prices over the last several years, on a gross margin basis, farmers are unlikely to switch land and other resources away from sheep production. Moreover, as the domestic and overseas demand for sheep meat and wool continues to expand, then retention of sheep in farming systems is increasingly likely. In addition, retaining sheep provides a means to add value to feed or downgraded grain produced on a farm. Currently, sheep enterprises form a profitable, risk-diversifying role for many SA farm businesses. As a result, SA crop production growth will be based largely on yield increases rather than crop area increases. Accordingly, crop breeding and crop agronomy will play crucial roles in ensuring gains in crop production in SA.

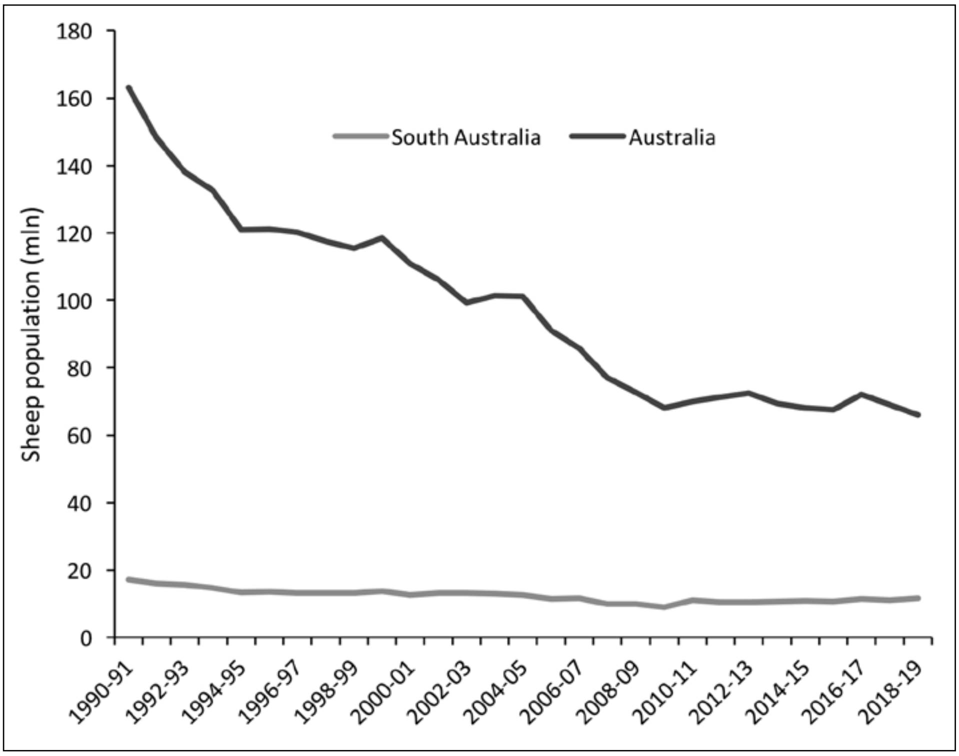

Figure 1. Sheep population in Australia and SA since 1990.

In coming decades, the traditional flow of grain from SA farms down to ports for overseas export could be a less dominant feature of SA crop production, as east coast demand for grain increases in relative importance; especially in years of low production in eastern Australia. Interstate grain flows from SA are likely to feature more frequently. SA's small domestic market and SA's more reliable climate for grain production will facilitate grain flows into NSW and Qld. These grain flows however, will affect the returns from owning infrastructure (trains, port terminals, port storage) required for grain export.

As an illustration of how reduced east coast grain production can affect national grain flows, consider the impact of the 2018 drought in eastern Australia (Figure 2) on grain production, domestic consumption (Figure 3) and grain flows (Figure 4).

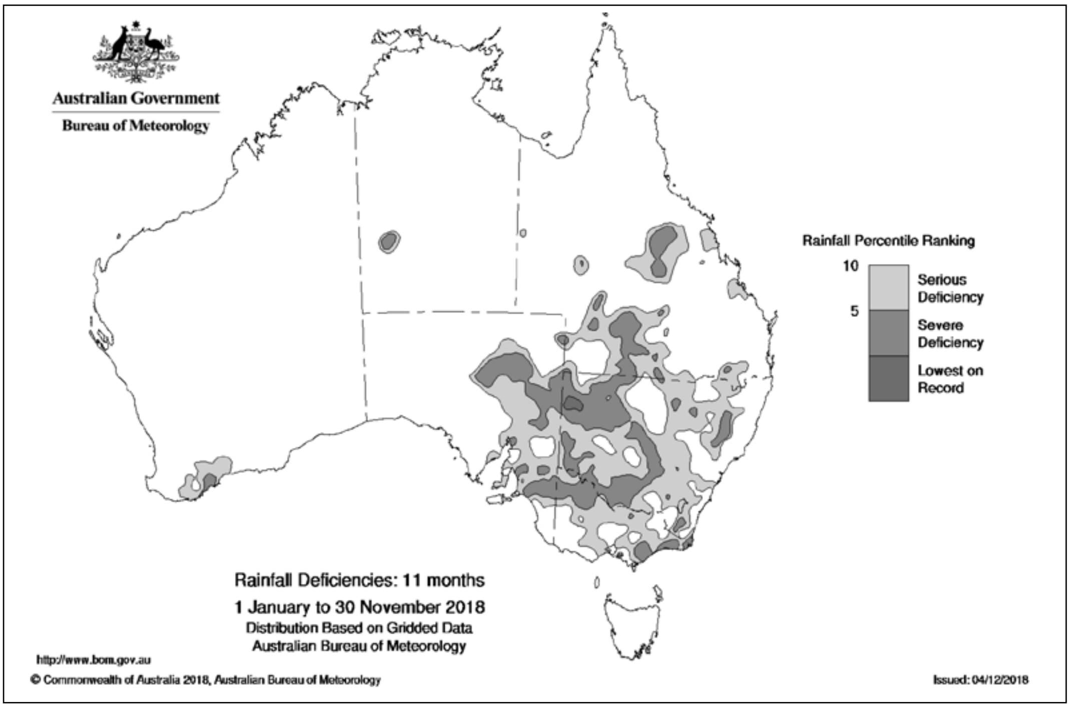

Figure 2. Rainfall deficiencies across Australia in 2018 (up until Nov 30) (Source: Bureau of Meteorology).

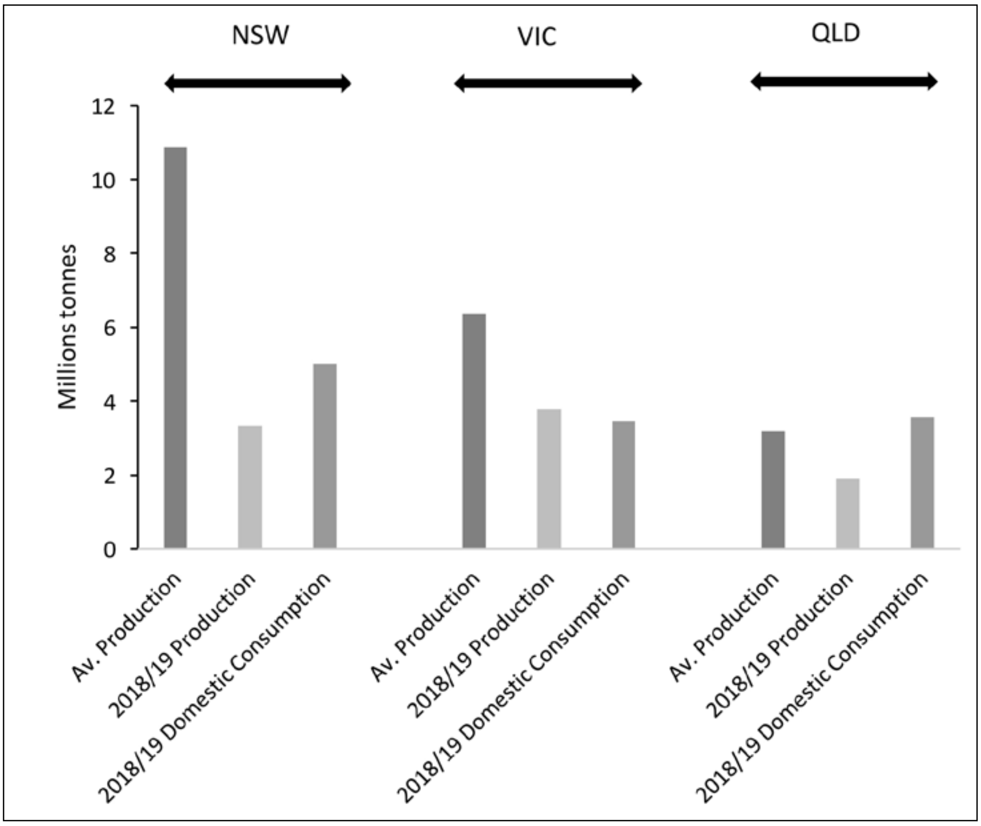

Figure 3. The impact of the 2018/19 drought: New South Wales (NSW), Queensland (Qld) and Victoria (Vic) became grain importers (Source: Based on data in an appendix in ACCC (2019) Bulk grain ports monitoring report 2018–19, Canberra).

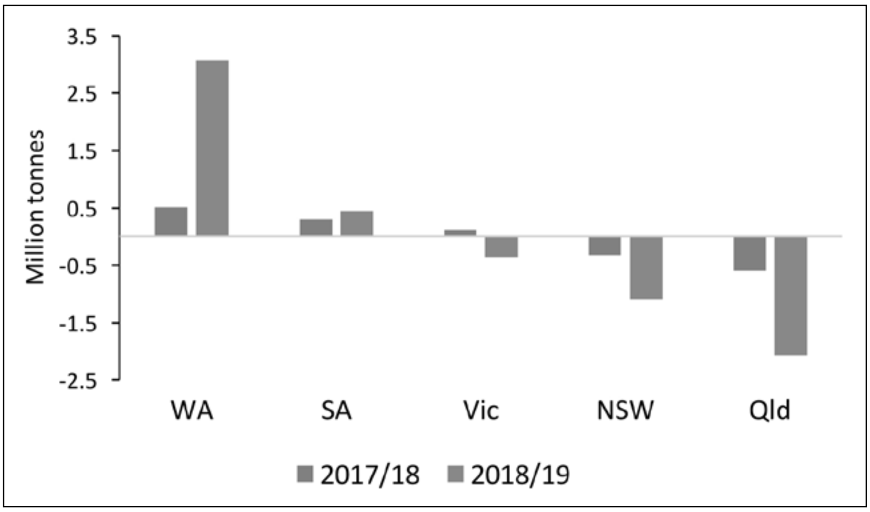

Figure 4. Coastal shipping flows from or into each State in 2017/18 and 2018/19 (Source: Based on data in an appendix in ACCC (2019)).

In 2018/19 some regions in SA were also affected by drought. The SA grain harvest was approximately 5.6mmt, of which the main grain handler and exporter, Glencore, only exported around 2.6mmt, indicating that around 3mmt was either stored, used locally or exported to eastern Australia. Hence, due to SA's small domestic market, even in low production years, SA can capitalise on favourable market opportunities in eastern Australia.

In years when SA escapes drought, yet NSW and Qld are drought-affected, then sizeable interstate grain flows from SA are likely. Freight differentials in coming decades could be further affected by construction of the inland rail in eastern Australia, due for completion in 2025. If the inland rail is sufficiently cost-effective, then interstate grain flows from SA could be much enhanced in some years. In addition, construction of additional grain port infrastructure in SA will facilitate coastal trade. In eastern Australia, south to north flows of grain by rail, road and ship are likely to become increasingly important towards 2030 as a product of climate volatility and continuing growth in the east coast increases the demand for grain.

The constant challenge of a warming, drying climate is likely to limit crop yield growth in SA and will increase the dependence of extensive livestock production (sheep, cattle, dairy) on supplementary grain feeding. Simultaneously, further population growth in SA and more especially greater population growth in the eastern states of Australia will increase the national market demand for grains, especially feed grains. The corollary is that growth in grain production in SA is likely to be modest and the tendency will be for a growing proportion of SA grain to flow to domestic markets. Exports of SA grain are likely to be constrained by the growth in the Australian domestic market and the constraints of climate trends on crop yields.

Nonetheless, on balance, the SA grains industry mostly will remain focused on grain export, as usually over 85 percent of SA grain production flows to export markets. However, depending on seasonal conditions in eastern Australia, interstate flows of grain strategically will become more important and will add to the volatility of SA grain exports.

In coming decades, SA's grain supply chains will be affected by the combination of limited growth in crop production and an increased frequency of interstate grain flows. Farmers and grain users are likely to react by increasing their investment in grain storage; especially while interest rates are low which makes affordable the cost of carrying grain across seasons. Easily stored feed grains like lupins and barley, if high-yielding varieties become available, could feature more in farmers' crop portfolios. Farmers are likely to enlarge their focus on feed grain production and will target, more frequently, domestic market opportunities in eastern Australia and local feed grain value-adding opportunities.

Farmers are likely to have increasing choices over where and when they sell grain, due to the low cost of storing grain (i.e. a low interest rate environment), and the emergence of a range of domestic market opportunities. One other implication is that the case for maintaining the high degree of port access regulation that especially characterises SA's grains industry will weaken through time.

Conclusion

Relatively modest population growth in SA is expected towards 2030. By contrast, Australia's population is projected to increase by between 16 and 19 per cent by 2030. This means between 4.07 and 4.89 million additional people, mostly residing in eastern States. Despite this projected increase in population and the associated demand for feed and human consumption grains, little increase in the area sown to crops in Australia is envisaged.

The corollary is that, especially during periods of drought in the eastern States, SA's grains industry is well poised to benefit from domestic market opportunities in eastern Australia. SA's proximity to these markets, facilitated by further investment in grain supply chains, will fuel the profitability of SA grain production towards 2030.

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New and old herbicides - the best integration to prolong their impact

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GRDC project codes: UWA1803-004SAX, UWA 00171 AHRI 5

Keywords

- herbicide mixtures, herbicide resistance, herbicide technology, herbicide testing, ryegrass.

Take home messages

- The efficacy of the herbicide mix; clethodim and butroxydim is significantly greater than either clethodim or butroxydim when applied stand-alone.
- The efficacy of the herbicide mixture; trifluralin and prosulfocarb is significantly greater than either trifluralin or prosulfocarb when applied stand-alone.
- There is little or negligible resistance to some mixtures of pre-emergent herbicides.
- A comprehensive test of old and new herbicides (stand-alone and mixtures) helps to find solutions for effective control of weeds and mitigation of resistance.

Background

In Australia herbicide resistance has increased in a number of major weed species such as annual ryegrass. Resistance has evolved to many foliar post-emergent herbicides and their efficacy has been largely compromised. Grain growers have responded to resistance by the adoption of soil-applied pre-emergence herbicides. Many grain growers have responded to the escalating herbicide resistance challenge by adopting harvest weed seed control in combination with strategic use of old chemistry. However, new cases of herbicide-resistant weeds continue to be reported, largely due to the over-reliance on herbicides in current farming operations. New pre-emergence herbicides have also been developed and commercialised in Australia, but initial cases of field resistance have recently been reported. Herbicide mixtures have been shown to decrease the risk of resistance evolution but they have been rarely tested on weed seed samples collected from problematic paddocks and targeted or random geographical surveys.

From 2020 there are several new herbicides available to control annual ryegrass. This study aims to report the most up-to-date state of knowledge of herbicide resistance levels in the most damaging weeds infesting Australian grain crops. The study aims to reinforce the benefits of proactively testing for herbicide resistance in major weed species with special emphasis on the adoption of herbicide mixtures to mitigate the impact of herbicide resistance on farm profitability. The observed efficacy of weed control, the frequency of resistance to old and new herbicides and the future of herbicide resistance testing with a focus on herbicide mixtures are reported and discussed.

Methods

Weed seed sample collection

Seed samples of annual ryegrass were collected from cropped paddocks at different locations in Western Australia (WA) in 2018 and 2019. Approximately 140 populations of annual ryegrass were screened and tested for resistance. Within each farm, samples were collected from paddocks chosen according to the grower/consultant resistance perceptions. Weed seed was bulked to obtain one population per sampled paddock at the time of collection. Seeds were stored in dry conditions and prepared for herbicide testing. Herbicides were applied at the correct stage to the soil (PRE, pre-emergence herbicides) or to two-leaf seedlings (POST, post-emergence herbicides) at dosages indicated in Table 1. Plant survival was assessed one month after treatment. Mean values of plant survival and resistance frequency are presented in this paper as percentages (%).

Data analyses

Populations were classified as susceptible with zero to 5% plant survival. Populations with resistant survivors were classified into two groups: those with ≥20% plant survival and those having <20% survival (this includes all plant survival between 6% and 19%). ANOVA was conducted on plant survival data expressed as percentage and means were separated with Tukey's test. Resistance frequencies were analysed by chi-square analysis and means separated with heterogeneity tests.

Results and discussion

Overall, there was 15% plant survival to the POST herbicides tested, which indicates substantial herbicide resistance in a large proportion of samples, whereas the mean survival to PRE herbicides was only 2%, reflecting effective control of the many annual ryegrass field populations tested.

Post-emergence herbicides (POST)

As expected and reported in several random herbicide resistance surveys of annual ryegrass in WA, resistance frequency to diclofop-methyl was high, with >90% of samples tested classified as resistant, with a mean plant survival of >40% observed in the samples tested (Figure 1). Approximately 60% of the tested samples were clethodim-resistant and the overall frequencies of resistance and developing resistance were significantly lower than diclofop-methyl (Table 2). Overall, the mean survival observed across all tested samples was 12% (Figure 1). With butroxydim, there was a similar frequency of developing resistance but significantly lower frequency of resistance samples (Table 2). Similarly, the mean survival observed was 6%, which was statistically lower than the plant survival in response to clethodim

Table 1. Herbicide products, formulations, Herbicide Resistance Action Committee (HRAC) classification, use (PRE, POST or mixtures) and dosages used to assess plant survival (%) in populations of annual ryegrass and wild radish collected in Western Australia in 2018 and 2019 from cropped paddocks.

Herbicide (formulation)	HRAC Group	Use	Dose a.i. (g/ha)	Survival % (Std. Err.)
Annual ryegrass				
Diclofop-methyl (500g/L)	A	POST	375	39 (2)
Butroxydim (250g/kg)	A	POST	45	6 (1)
Clethodim (240g/L)	A	POST	120	12 (1)
Clethodim + Butroxydim	A	POST (mixture)	120 +45	2 (1)
Prosulfocarb (800g/L)	N	PRE	2000 – 2400	5 (0.5)
Pyroxasulfone (850g/kg)	K3	PRE	100	2 (0.3)
Triallate (500g/L)	N	PRE	1500	2 (0.3)
Trifluralin (480g/L)	K1	PRE	480 - 720	12 (2)
Trifluralin + Prosulfocarb	K1 + N	PRE (mixture)	720 + 2400	0.9 (0.2)
Trifluralin + Pyroxasulfone	K1 + K3	PRE (mixture)	720 + 100	0.8 (0.2)
Trifluralin + Triallate	K1 + N	PRE (mixture)	720 + 1500	0.1 (0.0)
Prosulfocarb + Triallate	N + N	PRE (mixture)	2400 + 1500	0.4 (0.1)
Pyroxasulfone + Prosulfocarb	K3 + N	PRE (mixture)	100 + 2400	0.2 (0.1)
Pyroxasulfone + Triallate	K3 + N	PRE (mixture)	100 + 1500	0.0 (0.0)
Cinmethylin	Z	PRE (new)	375	2.6 (0.2)
Cinmethylin + trifluralin	Z + D	PRE (new mixture)	375 + 720	**

***Data not shown in this paper but will be presented orally at the '2020 GRDC Grains Research Updates'.*

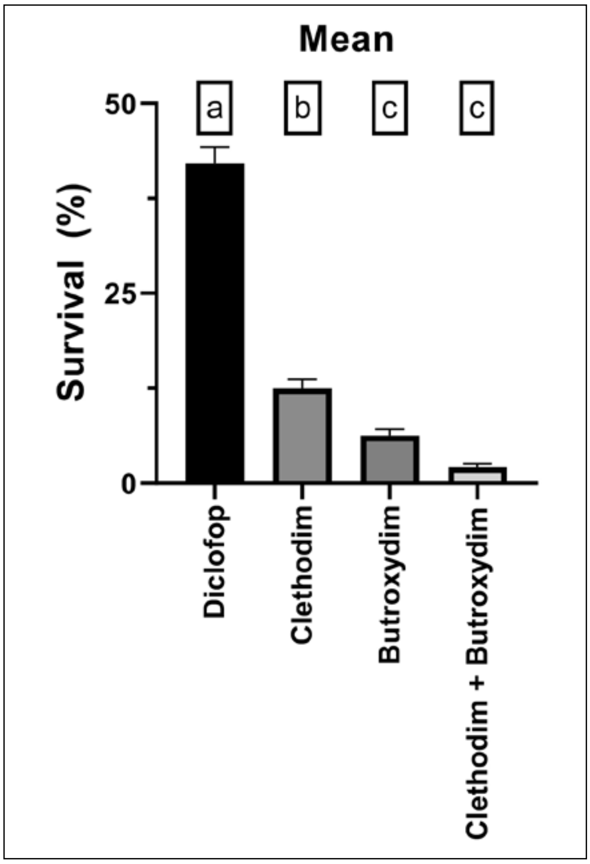

Figure 1. Mean plant survival (%) observed across 140 field populations of annual ryegrass collected in Western Australia in 2018 – 2019 and tested for herbicide resistance at the recommended label dose of three POST ACCase stand-alone herbicides and a binary mixture. Different letters indicate significantly different mean values separated by multiple comparisons by a *post-hoc* Tukey test (P < 0.05).

(Figure 1). The survival to the mixture of clethodim + butroxydim was the lowest (approximately 2%) but not significantly lower than survival to butroxydim. Conversely, the proportions of samples classified as developing resistance or resistant in response to the mixture clethodim + butroxydim were significantly lower than in response to stand-alone application of either herbicide (Table 2).

Pre-emergence herbicides (PRE)

The mean survival to trifluralin was significantly greater than all other PRE herbicide treatments tested and ranged widely from 0% up to approximately 90% in a few samples (Figure 2). Similarly, trifluralin resistance was found in > 50% of the samples (Table 3). Survival to prosulfocarb was significantly lower than trifluralin, but greater than all other PRE treatments except for cinmethylin (Figure 2). There was a similar frequency of developing resistance to prosulfocarb and trifluralin, which was significantly higher than all other tested herbicides (Table 3). The observed mean plant survival to all other herbicide treatments was similarly low, including stand-alone and binary mixtures (Figure 2). There were no highly resistant samples to several PRE herbicides except for 3% to prosulfocarb and 17% to trifluralin (Table 3). The frequency of developing resistance was similar in all other treatments except for the mixtures trifluralin + triallate and pyroxasulfone + triallate (Table 3). There were no samples found to be resistant to these two highly effective mixtures: trifluralin + triallate and pyroxasulfone + triallate (Table 3).

Table 2. Herbicide resistance frequencies of 140 populations of *Lolium rigidum* collected in Western Australia in 2018 - 2019 and tested for herbicide resistance to POST ACCase herbicides and their mixtures. Tested samples were divided into three categories according to the percentage survival observed at the recommended label dose. Herbicide "Resistance" was diagnosed with ≥ 20 % survival, "Developing" resistance with survival ranging between 6% - 19% and "Susceptible" samples with survival ≤5%. Within each column different letters indicate significantly different resistance frequencies (as proportions of samples resistant, developing or susceptible to each respective herbicide). Values were separated by multiple comparisons with a χ^2 heterogeneity test performed using the statistical software R with the command *prop.test*.

Herbicide POST	Resistance ≥20% survival	Developing 6-19% survival	Susceptible ≤5% survival
Diclofop	77.3 a	16.7 a	6.1 a
Clethodim	24.6 b	36.6 b	38.7 b
Butroxydim	9.7 c	29.9 b	60.4 c
Clethodim+Butroxydim	2.9 d	9.5 c	87.6 d

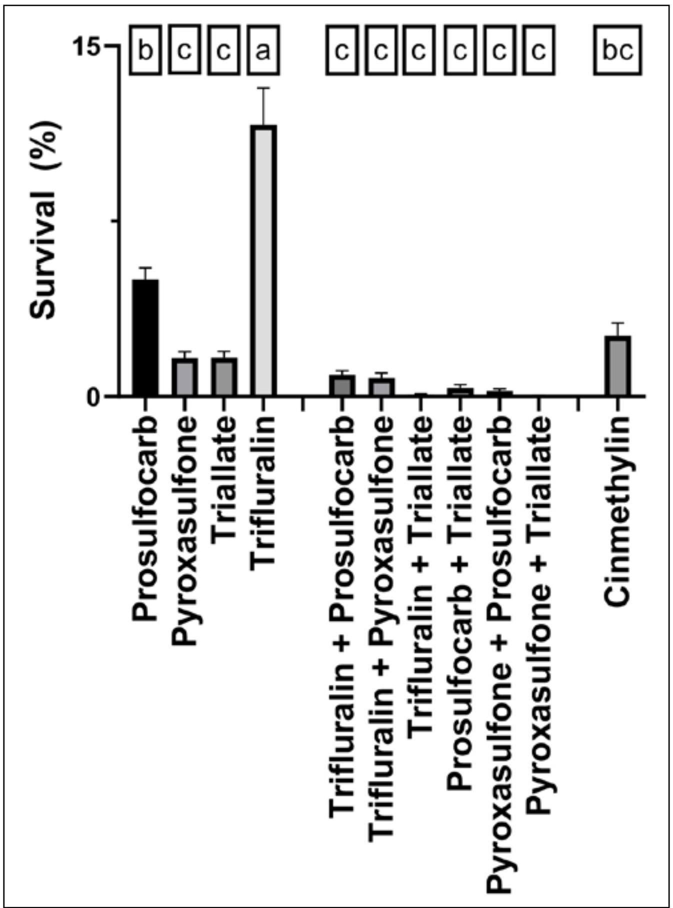

Figure 2. Mean plant survival (%) observed across 140 field populations of annual ryegrass collected in Western Australia in 2018 – 2019 and tested for herbicide resistance at the recommended label dose for four PRE stand-alone herbicides versus six binary mixtures of the same herbicides versus two new herbicides. Different letters indicate significantly different mean values separated by multiple comparisons by a post-hoc Tukey test (P < 0.05).

Conclusion

Annual ryegrass can evolve multiple resistance to D, J and K herbicides. However, consistently, herbicide mixtures of PRE herbicides (Group D, J and K) were highly effective in controlling resistant ryegrass. No resistance was found to some herbicide mixtures of PRE herbicides. Herbicide mixtures should be tested and then adopted to reduce population size and risk of herbicide resistance.

In Australia proactive herbicide resistance testing has been considered by growers and consultants to closely monitor the rate of herbicide resistance evolution. As there are some field populations of annual ryegrass reported to be multiple-resistant to trifluralin, prosulfocarb, triallate and pyroxasulfone (Busi et al. 2012, Busi and Powles, 2013, 2016, Brunton et al. 2018), it is recommended to closely monitor resistance on a proportion of the problematic paddocks on farm.

Some herbicide mixtures remain fully effective and appear immune to resistance, and therefore, effective herbicide mixtures of 'old' and newly commercialised herbicides need to be identified by screening large numbers of field populations of annual ryegrass. Results immediately conveyed to growers and consultants could allow that herbicide mixture to be widely adopted as an effective solution to mitigate weed resistance.

It is finally emphasized that adoption of harvest weed seed control and other measures of integrated weed management should continue, in

Table 3. Herbicide resistance frequencies of 140 populations of *Lolium rigidum* collected in Western Australia in 2018 - 2019 and tested for herbicide resistance to PRE herbicides and their mixtures. Tested samples were divided into three categories according to the percentage survival observed at the recommended label dose. Herbicide "Resistance" was diagnosed with ≥ 20 % survival, "Developing" resistance with survival ranging between 6% - 19% and "Susceptible" samples with survival ≤5%. Within each column different letters indicate significantly different resistance frequencies (as proportions of samples resistant, developing or susceptible to each respective herbicide). Values were separated by multiple comparisons with a χ^2 heterogeneity test performed using the statistical software R with the command *prop.test.*

Herbicide PRE	Resistance ≥20%	Developing 6-19%	Susceptible ≤5%
Prosulfocarb	3 b	33.2 a	63.4 b
Pyroxasulfone	0 b	13.1 b	86.9 c
Triallate	0 b	11.3 b	88.7 c
Trifluralin	17 a	33.8 a	49.0 a
Trifluralin + Prosulfocarb	0 b	8.4 b	91.6 c
Trifluralin + Pyroxasulfone	0 b	5.8 b	94.2 c
Trifluralin + Triallate	0 b	0 c	100 d
Prosulfocarb + Triallate	0 b	2.5 bc	97.5 cd
Prosulfocarb + Pyroxasulfone	0 b	3.3 bc	96.7 cd
Pyroxasulfone + Triallate	0 b	0 c	100 d

***Field samples with survival >6% to cinmethylin re under investigation and data is not reported.*

order to achieve diversity of selection pressures on weeds, keep weed numbers low and complement effective control achieved with knock-down, PRE and POST herbicides.

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Concurrent session Day 1

Blackleg – new seed treatment, stubble management and fungicide resistance

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GRDC project codes: UOM1904-004RTX, UM00051, CSP00187, MGP1905-001SAX

Keywords

- canola, blackleg, stubble management, fungicide resistance, seed treatment

Take home messages

- Blackleg crown canker results from infection during early seedling growth. Prior to sowing, use the BlacklegCM decision support tool to identify high risk paddocks and explore management strategies to reduce yield loss.
- New succinate dehydrogenase inhibitor (SDHI) seed treatment fungicides have higher efficacy, increased longevity and improved seed safety.
- The improved efficacy of SDHI fungicide may result in a reduced need for early foliar application of fungicide (4-10 leaf applications).
- Modern farming systems that enable earlier sowing/germination may result in reduced damage from blackleg crown cankers.
- Blackleg pathogen populations with resistance to the triazole fungicides fluquinconazole, flutriafol and a tebuconazole + prothioconazole mixture have been detected. No resistance has been detected for new SDHI and quinine-outside inhibitor (QoI) chemistries.
- Blackleg upper canopy infection (UCI) is the collective term for flower, peduncle, pod, main stem and branch infection, but does not include crown canker.
- UCI can cause yield losses of up to 30%. Yield loss is reduced by selecting cultivars with effective major gene resistance and using crop management strategies to delay the commencement of flowering to later in the growing season, especially in high disease risk areas.
- Fungicide applications at 30% bloom often controls UCI but does not always result in yield gains. Thirty per cent bloom fungicide application is unlikely to control pod infection.

Blackleg crown canker - seed treatment

Do you need a seed treatment?

Severe crown canker is most likely to develop when plants are infected during the early seedling stage (cotyledon to 4th leaf). The fungus grows from the cotyledons and leaves asymptomatically through the vascular tissues to the crown, where it causes necrosis resulting in a crown canker at the base of the plant. Cankers at harvest are due to infection at the seedling stage. Yield loss results from restricted water and nutrient uptake by the plant.

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. For infection to occur blackleg fruiting bodies on the canola stubble must be ripe and ready to release spores. Fruiting bodies typically become ripe approximately three weeks after the break of the season when the stubble has stayed consistently moist. Spore are then released with each rainfall event. Temperature also has a large influence as it will determine the length of time that the plant remains in the vulnerable seedling stage. Once plants progress to the 4th leaf stage they are significantly less vulnerable. 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.

Plants sown early often have reduced crown canker severity due to rapid growth through the vulnerable seedling stage and the seedlings are likely to avoid blackleg spores as fruiting bodies are less likely to be mature and able to release spores early in the growing season. Consequently, modern farming systems that enable early sowing will reduce crown canker susceptibility. However, early sowing will likely result in earlier flowering times, which increases the risk of UCI (see following sections within this paper).

Seed treatments

Fungicide seed treatments are extremely effective control against blackleg for crown cankers. As previously mentioned, plants are susceptible at the early seedling stage and this is when seed treatments are most effective. However, seed treatments will not provide complete control so they should be used in conjunction with genetic resistance, for instance moderately susceptible (MS) to moderately resistant (MR) cultivars protected with Jockey® (fluquinconazole) when gown under high blackleg severity conditions are likely to get a yield response from a seed treatment. Cultivars with inadequate resistance, for example; MS-S will get a response but may still have significant damage while cultivars rated very highly for resistance such as MR-R to R will generally not respond to a seed treatment. The BlacklegCM app will predict responses from seed treatments based on the crop parameters that you enter.

New SDHI seed treatments

In 2020 new seed treatments from the SDHI fungicide class will be commercially available to growers. These new fungicides will be adopted very quickly and extensively for two reasons; firstly, they do not have the seed safety issues that may be associated with some other seed treatments. Secondly, the SDHI fungicides have a higher efficacy and provide a longer period of protection compared to the demethylation inhibitors (DMI) fungicide. Further research is required, but it is likely that in some situations an early foliar fungicide may no longer be required if cultivars are protected with a SDHI fungicide rather than the current DMI fungicide seed treatment.

A decision support tool, BlacklegCM, is available and should be used to assess the risk for blackleg crown canker prior to cultivar selection and sowing. BlacklegCM is available for iPad or android tablets. BlacklegCM does not work on iPhones. The tool is interactive, allowing growers and advisers to determine the blackleg risk for each paddock and consider the possible economic return of different management strategies. The tool also provides in-season support for the application of foliar fungicides.

Fungicide resistance

With the high use of fungicides comes the risk of fungicide resistance developing. In 2018 and 2019, 300+ *Leptosphaeria maculans* populations have been screened for resistance to all commercially available and soon to be released fungicides (Table 1). The 2019 screens showed similar results to 2018 whereby 25% and 20% of populations have a high frequency of isolates resistant to the DMI fungicides, flutriafol and fluquinconazole, while only 7% of populations have a high frequency of resistance to the tebuconazole + prothioconazole mixture. No resistance was detected to any of the SDHI or QoI fungicides. Screening of populations in 2020 will continue, to monitor changes in the frequency of resistance to both the old DMI chemistries and the new SDHI and QoI chemistries.

Although these screens have detected fungicide resistance within Australian populations, it is currently unknown what proportion of the isolates within a population have resistance. Therefore, it remains unclear whether these resistance isolates are impacting on the efficacy of fungicide use or not. Further work is underway to try and determine the impact of these fungicide resistant isolates to on-farm practices.

The development of fungicide resistance in blackleg pathogen populations in Australia highlights the importance of fungicide-use stewardship. Oversees experience informs us that the new SDHI fungicides are more likely than the current DMI fungicides to develop resistance. To reduce the potential risk of fungicide resistance evolving, it is recommended that a maximum of two chemical applications from a single fungicide class be used within a growing season.

Fungicide resistance screening sample submission

If you would like to screen your blackleg populations for fungicide resistance in 2020, 30 pieces of canola stubble from your 2019 paddock are required. Please email Angela Van de Wouw at angela@grainspathology.com.au for stubbles collection protocol. The fungicide resistance results for the current DMI blackleg fungicides and the new SDHIs will be provided to you. The cost is free to growers/advisers. Costs are covered by an Australian Research Council (ARC)/private industry investment.

Blackleg spore release has changed with modern farming systems

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 spores with each rainfall event. Stubble which was two or three years old produced very few spores that were highly unlikely to add to annual disease severity. Research work undertaken in the mid-1990s led to the recommendations to maintain a 500m buffer between your current canola crop and the previous year's stubble and to not be so concerned with rotation length as was the prior recommendation. 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 and the release is later in the growing season (Figure 1). It is hypothesised that delayed spore release in the growing season may result in increased UCI as the reproductive parts of the plant are directly infected rather than seedlings and leaves.

However, what happened to the standing stubble when it is eventually knocked down in the second year? This is particularly pertinent as it is the second year that is often sown back to a canola crop.

Experiments undertaken in Horsham in 2019 (Table 2) found that stubble which is standing in year 1 and lying in year 2 released fewer spores in the first half of the growing season but increased in proportion of released spores in the second half of the growing season. The data missing from this experiment is the tonnes/ha of stubble that is available to produce blackleg spores. In the 1990s experiments found that few canola stalks survive lying/lying for two years (stalks are either buried or decompose). Therefore, it is now known that standing stubble in year 1 releases few spores but it will release spores in the second year if it is knocked down and becomes lying stubble in year 2. The key driver in this situation is that the stubble has been preserved in the inter-row sowing system and has therefore not been buried or decomposed. The other very intriguing part of this story is that if stubble is maintained standing in the second year it will produce very few spores (Table 2).

Table 1. The percentage of populations with high, moderate and low levels of resistance to all currently used and upcoming fungicides.

Fungicide	Fungicide class	Percentage of populations with high, moderate and low levels of resistance					
		2019 results			2018 results		
		High	Moderate	Low	High	Moderate	Low
Flutriafol®	DMI	**25.1**	22.0	52.9	**28.6**	31.6	39.8
Jockey®	DMI	**20.4**	24.6	55.0	**22.4**	22.4	45.9
Prosaro®	DMI	**7.3**	13.1	79.6	**7.1**	7.1	75.5
Saltro®	SDHI	**0**	0	100.0	**0**	0	100.0
Veritas®	QoI + DMI	**0**	3.1	96.9	**0**	1.0	99.0
Aviator®	SDHI + DMI	**0**	0	100.0	**0**	0	100.0
ILeVo®	SDHI	**0**	0	100.0	**0**	0	100.0
Miravis®	SDHI	**0**	0	100.0	**0**	0	100.0

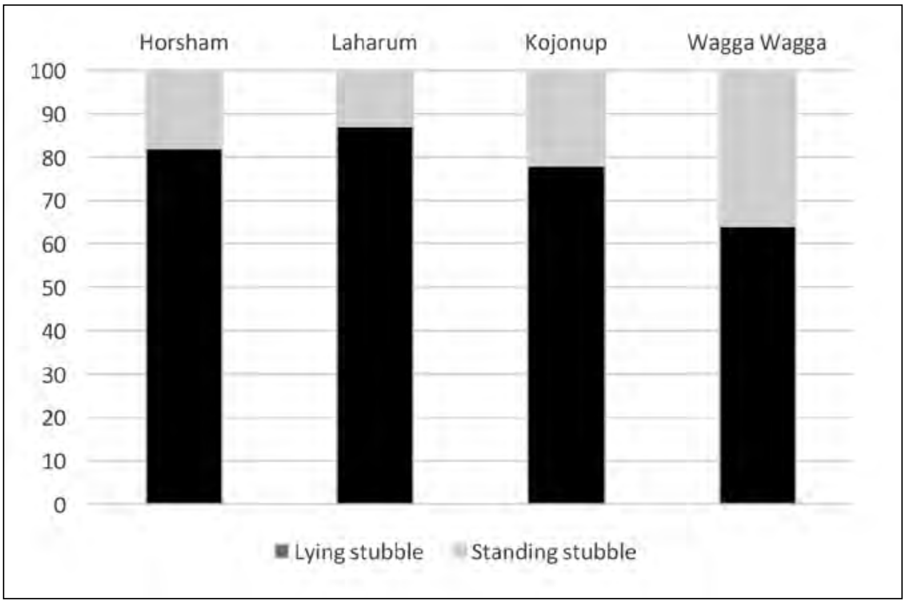

Figure 1. Proportion of total spores from specific stubble types and sections produced over a growing season for four sites in 2018.

Further investigation is required to determine what impact standing stubble has on disease pressure, and therefore, yield losses associated with blackleg.

Blackleg upper canopy infection (UCI)

Blackleg can infect all parts of the canola plant. UCI is a collective term that describes infection of flowers, peduncles, pods, upper main stem and branches (Figure 2). UCI has become increasingly prevalent over recent years and may be associated with earlier flowering crops because of the earlier sowing of cultivars and more rapid phenological development during warmer autumns and winters. There is also evidence of delayed and prolonged release of blackleg spore release in stubble-retained systems and increased intensity of canola production. While crown canker blackleg is well understood, the factors contributing to UCI and possible control strategies are currently under investigation. An outline of findings to date are presented.

Figure 2. Upper canopy infection includes blackleg infection of flowers, peduncles, pods, main stems and branches

Table 2. Percentage of total blackleg spore released from two year old canola stubble that is either lying or standing.

Stubble standing or lying	Month							Season spore release
	May	June	July	August	Sept	Oct	Nov	
Lying yr 1 / lying yr 2	64	70	69	44	40	69	4	58
Standing yr 1 / lying yr 2	31	29	29	55	42	18	38	36
Standing yr 1 / standing yr 2	6	2	2	1	17	12	58	6

Blackleg upper canopy infection research results

In field experiments, UCI has caused up to 30% yield loss. The impact on yield varies depending on the timing of infection and the plant part infected. Flower loss from infection of flowers or peduncles is unlikely to directly reduce yield as the plant can compensate by producing more flowers. However, the fungus can grow into the associated branch which can then affect seed set and grain filling in surrounding pods. Infection of pods or peduncles after pod formation can result in significant yield loss. Infected branches and upper main stems can affect all developing flowers and pods above the point of infection causing a reduction in pod and seed set as well as smaller seed. Severe infection can cause stems and branches to break off, premature ripening leading to shattering or difficulty in ascertaining correct windrow timing due to maturity differences between seed affected or unaffected by blackleg.

New knowledge from 2019

Entry of UCI blackleg into the plant is via the stomatal openings and/or physical damage to the plant by insects, hail or frost. Up until 2018 it was thought that the damage UCI caused was the physical lesion or death of the flower. However, it is now evident that UCI infections are also systemic, causing damage to the plant's vascular tissue similar to traditional blackleg crown infections. The issue for growers is that the external symptoms may appear insignificant, but internal vascular damage may cause significant yield losses. Preliminary results indicate that this may be why fungicide applications on crops with few symptoms can still result in economic yield returns. Interestingly, researchers have noted that symptoms of internal vascular damage result in blackened stems post the windrowing growth stage; post 100% seed colour change (Figure 3).

Figure 3. Blackened branches caused by internal vascular damage; symptoms become visible post 100% seed colour change. These symptoms may not occur in crops that received the Sclerotinia 30% bloom fungicide application.

During 2019 two experiments were managed to develop new techniques for artificially inoculating plants to enable specific experiments to be undertaken. A laboratory/controlled environment glasshouse experiment (Table 3) showed that on average the external lesions from the artificial inoculation were 38mm long but when the plants were individually cut open the blackleg pith inside was 134mm. Polymerase chain reaction (PCR) and microscopy are currently being done to determine if symptomless infection has also occurred. This data shows clearly that blackleg is invading the vascular tissue of the plant, and therefore, a small external lesion may reduce moisture and nutrient supply to the entire branch because of vascular tissue damage.

The other meaningful finding from 2019 is that the plant development stage at infection must also be considered with the seasonal timing of infection. For instance, June inoculation at 30% bloom appears to cause more damage than identical inoculation in August or September. The data from 2019 suggests that the fungus requires sufficient time to colonise the vascular tissue and then cause yield reducing damage. Early sown/flowering plants mature slower under cooler conditions compared to later sown/flowering plants that mature quickly under warmer spring conditions. This is a major finding and is likely to provide knowledge on why yield responses to

Table 3. Artificial infection of canola plants for upper canopy blackleg, effect of internal infection and timing of infection.

Experiment location	Time of sowing	Inoculated at 30% bloom	External lesion length (mm) Average	Internal pith colonisation (mm) Average
Glasshouse lab inoculation	21-Mar	10-Jun	38	134
Glasshouse lab inoculation	3-Jun	21-Aug	12	5
Spore shower from stubble	21-Mar	29-Jun	183	NA
Spore shower from stubble	24-May	6-Sep	43	NA

Table 4. Regional effectiveness of major gene resistance across 34 monitoring sites across Australia. Cultivars representing each of the resistance groups were sown adjacent to 34 canola trials across Australia and monitored for levels of blackleg. These data indicate which resistance groups have high levels of disease compared to the other groups at a particular site.

Key:

Low (L) blackleg severity compared to other groups at that site suggesting major gene resistance still effective - Continue with current management strategy.
Moderate (M) blackleg severity compared to other groups at that site – monitor crops for disease, see the Blackleg Management Guide for management options.
High (H) blackleg severity compared to other groups at that site – suggests major gene is ineffective and therefore disease control relies on quantitative resistance. If growing cultivars from this resistance group, select cultivar with appropriate blackleg rating for your region and consider a fungicide control for upper canopy infection if seasonal conditions are conducive – see the Blackleg Management Guide for management options.
No data (blank)

Site	Resistance Group							
Victoria	A	B	C	ABD	ABDF	BF	BC	H
Charlton	H	M	H	L	L	H	M	
Diggora	H	M	H	L	L	M	M	L
Hamilton	H	H	H	M	L	H	H	L
Kaniva	H	H	M	L	L	H	M	L
Lake Bolac	H	H	H	M	M	H	H	L
Minyip	H	H	H	L	L	H	M	
Wunghnu	H	H	H	L	L	H	M	L
Yarrawonga	H	M	H	L	L	H	M	
Site	Resistance Group							
SA	A	B	C	ABD	ABDF	BF	BC	H
Arthurton	H	H	M	L	L	H	M	
Bordertown	H	H	H	L	L	H	M	L
Cummins	H	M	H	M	L	H	M	L
Riverton	M	M	H	L	L	H	M	
Roseworthy	H	M	H	L	L	M	M	
Spalding	H	M	H	L	L	M	M	
Wangary	H	H	H	H	M	H	H	
Yeelanna	H	H	H	M	M	H	M	M
Site	Resistance Group							
NSW	A	B	C	ABD	ABDF	BF	BC	H
Beckom	Insufficient data due to drought							
Condobolin	Insufficient data due to drought							
Cootamundra	H	H	H	L	L	M	M	L
Cudal	H	H	H	L	L	H	M	L
Gerogery	H	H	H	L	L	H	M	
Grenfell	Insufficient data due to drought							
Lockhart	Insufficient data due to drought							
Parkes	Insufficient data due to drought							
Wagga Wagga	H	H	H	L	L	H	M	L
Wellington	Insufficient data due to drought							
Site	Resistance Group							
WA	A	B	C	ABD	ABDF	BF	BC	H
Bolgart	H	H	H	L	L	H	M	
Gibson	H	H	H	L	L	L	M	L
Katanning	H	H	M	L	L	M	M	L
Kendenup	No data							
Kojonup	H	H	H	L	L	L	M	L
Stirlings South	H	H	H	L	L	M	M	L
Williams	H	H	H	L	L	H	H	L
Yealering	H	M	H	L	L	M	M	

fungicides can vary so much across regions. If a plant is infected earlier in the growing season the vascular damage will be greater than an identical plant infected at the same growth stage but infected later in the season.

The above new knowledge appears to correlate with 2019 field results in Victoria; wet conditions in late August triggered severe leaf and flower infections. In some cases, these infections resulted in yield responses from fungicide applications whereas, in other situations the same blackleg severity in late August did not result in yield gains from fungicide. It may have been that the blackleg had not caused enough damage to the vascular tissue by windrowing.

Blackleg upper canopy infection control strategies

Genetic resistance

Effective major gene resistance prevents infection of all canola plant parts (cotyledons, leaves, stems, branches, flowers, pods). Effective major genes can thereby prevent both crown canker and blackleg UCIs. Unfortunately, most major genes present in current cultivars have been overcome by the blackleg pathogen across many canola producing regions. It is therefore crucial to know if major genes are effective or have been overcome in your growing region. A network of 34 blackleg monitoring sites are established across Australia each year, sown with cultivars representing each resistance group. These sites are used to provide regional information on the effectiveness of resistance genes (Table 4). The Blackleg Management Guide (www.grdc.com.au/resources-and-publications/all-publications/publications/2019/blackleg-management-guide) provides information that is relevant for control of blackleg crown canker.

Commencement of flowering

There is a strong relationship between the earlier onset of flowering and yield loss caused by UCI.

Plants commencing flowering early in the growing season are more likely to be infected as they will flower under cooler and wetter conditions which are conducive for lesion development. However, it is now also known that plants infected earlier in the growing season have more time for the fungus to damage the vascular tissue prior to plant maturity and harvest.

Canola plants are particularly susceptible to stress during the early stages of flowering (Kirkegaard et al. 2018). Evidence from controlled environment and field experiments indicates that plants infected by blackleg on the upper main stems and branches during the early flowering period results in the greatest reduction of grain yield compared to crops that flower later or are infected at later growth stages. Yield loss can be due to a reduction in seed size, seeds/pod and/or pods per m2. Oil content can also be reduced. By delaying the commencement of canola flowering, growers may be able to avoid severe UCI infections.

Fungicides

If UCI occurs, it has been shown that fungicides that are used to control Sclerotinia will also reduce UCI severity and yield losses. Application of Prosaro®/Aviator® Xpro for Sclerotinia control around 30% bloom can also provide protection from blackleg infection during early flowering. The 30% bloom spray may control flower, peduncle, stem and branch infections but is unlikely to provide pod protection. There are currently no control strategies for pod infection. High levels of pod infection tend to occur in seasons with frequent late rainfall events (such as 2016) or where there is physical damage to the pods from hail (such as 2018). In 2019, fungicide applications gave excellent control of UCI but did not control pod lesions. Although UCI was controlled it did not always result in yield returns from fungicides.

Acknowledgements

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Useful resources and references

BlacklegCM App for iPad and android tablets

www.grdc.com.au/resources-and-publications/all-publications/publications/2019/blackleg-management-guide

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

Van de Wouw et al. (2016) Australasian Plant Pathology 45: 415-423

Marcroft Grains Pathology website: www.marcroftgrainspathology.com.au

Kirkegaard et al. (2018) Ten Tactics for Early-Sown Canola (https://grdc.com.au/resources-and-publications/groundcover/groundcover-133-march-april-2018/ten-tactics-for-early-sown-canola)

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Notes

SOUTHERN/WESTERN REGION*

PREDICTA B
DNA Soilborne disease tests

PREDICTA® B
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*CENTRAL NSW, SOUTHERN NSW, VICTORIA, TASMANIA, SOUTH AUSTRALIA, WESTERN AUSTRALIA

Cereal root diseases cost grain growers in excess of $200 million annually in lost production. Much of this loss can be prevented.

Using PREDICTA® B soil tests and advice from your local accredited agronomist, these diseases can be detected and managed before losses occur. PREDICTA® B is a DNA-based soil-testing service to assist growers in identifying soil borne diseases that pose a significant risk, before sowing the crop.

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http://pir.sa.gov.au/research/services/molecular_diagnostics/predicta_b

Potential high-risk paddocks:

- Bare patches, uneven growth, white heads in previous crop
- Paddocks with unexplained poor yield from the previous year
- High frequency of root lesion nematode-susceptible crops, such as chickpeas
- Intolerant cereal varieties grown on stored moisture
- Newly purchased or leased land
- Cereals on cereals
- Cereal following grassy pastures
- Durum crops (crown rot)

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- Crown rot (cereals)
- Rhizoctonia root rot
- Take-all (including oat strain)
- Root lesion nematodes
- Cereal cyst nematode
- Stem nematode
- Blackspot (field peas)
- Yellow leaf spot
- Common root rot
- Pythium clade f
- Charcoal rot
- Ascochyta blight of chickpea
- White grain disorder
- Sclerotinia stem rot

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New pasture opportunities to boost productivity of mixed farms in low/medium rainfall areas

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GRDC project code: 9175959

Keywords

- medic, clover, serradella, biserrula, vetch, nitrogen (N2)-fixation, pasture ley.

Take home messages

- A critical assessment of the regional performance of existing and new pasture legumes over two years has shown that annual medics continue to provide the best pasture option for neutral/alkaline sandy soils in the Mallee. Common vetch is an alternative option where a sown legume ley of one-year duration is preferred.
- PM-250 strand medic will be released in 2021. For the first time, it combines resistance to the foliar fungal pathogen, powdery mildew, and tolerance to sulfonylurea herbicide residues.
- Aim to maximise pasture legume seed set in the establishment year. Legumes with very high hard seed levels (>90%) are best cropped in the year following establishment.
- Differences in legume production and N_2-fixation have been measured and impacts on wheat production will be measured at multiple sites in 2020.
- Alternative pasture establishment methods (for example; summer sowing) are viable in the Mallee, however, are not suitable for all legume species. Further investigation is needed to define the conditions where summer sowing and twin sowing practices are reliable.

Background

A project, informally known as the Dryland Legume Pasture Systems (DLPS) project, is evaluating a diverse range of annual pasture legumes on mixed farms in the low to medium rainfall zone (<450mm). The DLPS project aims to:

- Provide a critical assessment of the regional performance of existing and new pasture lines.
- Determine if pasture legumes can be established more efficiently.
- Quantify the benefits provided by pasture legumes to crops and livestock.

Legumes close to commercial release, including strand medic line, PM-250⦶, existing legumes not widely utilised in south-eastern Australia (for example; serradella, bladder clover and biserrula) as well as undomesticated legumes (for example; Trigonella and Astragalus spp.) are being compared with traditionally grown medics and vetch. Commercial legume species options are shown in Table 1. Legume production, N_2 fixation, nutritive value and ability to regenerate after cropping phases is being measured to understand different legume species adaptation to soil type, so that growers can be confident in their performance and benefits for the crops that follow.

A significant obstacle to the adoption of new pastures legumes is the high cost of pasture seed and difficulty in establishment, particularly in low to medium rainfall areas. A feature of some legumes under investigation is their aerial seeded habit and retention of seed, allowing seed to be grower harvested and re-sown with standard cropping equipment. The project is examining the potential of different pasture legume species to be established more efficiently.

Table 1. Annual pasture legumes. Cultivars (release date and key traits) and indicative adaptation.

Legume and rhizobia	Preferred soil texture	Preferred soil pH_{CaCl}	Cultivars and key traits
Strand medic Group AL inoculant (strain RRI-128)	Sandy loams & loams	>5.8	PM-250ᶲ (2021; PM, HT, BGA, ¥Early, ¥HS70) *Jaguarᶲ (2004; PH, BGA, SAA, Early, HS80) Angel (2000; HT, BGA, SAA, Early, HS80) Herald (1994; BGA, SAA, Early, HS80) Harbinger (1959; Early, HS80)
Disc medic Group AL inoculant (strain RRI-128)	Sands & sandy loams	>5.8	Toreador (2000; BGA, SAA, Early, HS75) Tornafield (1969; Early, HS75)
Barrel medic Group AM inoculant (strain WSM-1115)	Loams & clays	>5.8	*Sultan SU (2015, HT, BGA, Early, HS85) *Cheetahᶲ (2007, PH, BGA, SAA, Early, HS>90) *Jesterᶲ (1998, BGA, SAA, Mid, HS80) *Caliph (1993, BGA, SAA, Early, HS>90)
Spineless burr medic Group AM inoculant (strain WSM-1115)	Loams & clays	>5.2	*Scimitarᶲ (2000; BGA, Mid, HS70) *Cavalierᶲ (2000, Mid, HS80) *Santiago (1988; Early, HS85)
Pink (French) serradella Group S or G inoculant (strain WU425 or WSM471)	Deep sands & sandy loams	4.0 to 7.0	Frano (2021: PH, Mid-late) *Marguritaᶲ (2002, PH, Mid, HS60)
Yellow serradella Group S or G inoculant (strain WU425 or WSM471)	Deep sands & sandy loams	4.0 to 7.0	*Santorini (1995; PH, Mid-late, HS>90)
Biserrula Biserrula 'special' inoculant (strain WSM1497)	Loams	4.5 to 8.0	*Casbah (1997; PH, Early-mid, HS>90)
Sub clover (ssp. subterranean) Group C inoculant (strain WSM1325)	Sandy loams & loams	4.5 to 6.5	Tamminᶲ (2021, Early, HS60)
Rose clover Group C inoculant (strain WSM1325)	Sandy loams & loams	4.5 to 7.0	SARDI Rose (2005; SH, Mid, HS80)
Bladder clover Group C inoculant (strain WSM1325)	Sandy loams & clay loams	5.0 to 8.0	*Bartolo (2007, SH, Mid, HS80)
Vetch Group E or F inoculant (strain SU303 or WSM1455)	Sandy loams & clay loams	5.5 to 8.5	Studenicaᶲ (2021; Early, SH, HS<1) *Volgaᶲ (2013, Early, SH, HS3)

¥ This table provides general information for hard seed levels and maturity time. Environment can significantly affect these traits.
**Seed available through Australian seed marketers. Other cultivars may still be grown and traded between farms.*
Key for traits
PM: resistant to powdery mildew
PH or SH: pod holding or seed able to be collected with cereal harvester
HT: bred to be tolerant of SU herbicide residues; is tolerant of Intervix® residues
BGA: tolerance to blue-green aphids
SAA: tolerance to spotted alfalfa aphids
HS%: approximate level of hard-seed remaining at break of season
Early, mid or late maturity

Results and discussion

A new strand medic

A new strand medic (*Medicago littoralis*) cultivar is scheduled for release in 2021. Currently known as PM-250⏀, it provides a significant advantage over the cultivar Angel, which it will replace. PM-250⏀ combines for the first time, resistance to the foliar fungal pathogen, powdery mildew (Erysiphe trifolii), and tolerance to sulfonylurea (SU) herbicide residues. It is suited to neutral and alkaline sandy loams receiving 275 to 400mm rainfall.

The commercialisation of PM-250⏀ is based on the assessment of its performance at 10 field sites. Across these sites, 34 assessments of dry matter (DM) production and 12 assessments of seed yield were completed. Overall, PM-250⏀ produced 16% more DM than Angel medic and similar high seed yields (Figure 1). Production increases are likely to be greatest, but not limited to, where powdery mildew occurs. Increases of up to 49% and reduced levels of the phytoestrogen, coumestrol have been measured in the presence of powdery mildew. PM-250⏀ is being further assessed in the DLPS project described below.

Casting the net to identify the next opportunity

On 15 June 2018, 30 annual pasture legumes (12 medics, 10 clovers, two serradellas, two lotus, two trigonella, biserrula and astragalus) and two vetches were established at the earliest opportunity after late opening rains in a small plot trial at Lameroo, SA. A similar trial sown at Minnipa SA (27 June 2018) contained an extra vetch, but only seven clovers (Table 2). The Lameroo trial was located on a sandy soil, on the lower-mid dune (pHCa 5.8). The Minnipa trial was located on a uniform area of sandy loam (pH_{Ca} 7.8). Seed was inoculated with the appropriate rhizobia strain and sown at 5, 7.5, 10 or 40kg/ha germinable seed for the small, small-medium, medium and large seeded legumes, respectively. Plots were un-grazed and managed to maximise seed set. In 2019, the legume plots were allowed to regenerate. Plant DM production (2018 and 2019), seed set (2018) and plant regeneration (2019) were measured.

Growing season rainfall was 48% in 2018 and 71% in 2019 of the long-term average at Lameroo (269mm), and 62% in 2018 and 89% in 2019 of the long-term average at Minnipa (242mm).

Performance of commercial legume species

Production in 2018 was limited to less than 1,500kg/ha by seasonal conditions. Even so, differences in the production and seed set of the commercially available legumes were measured (Figure 2). Vetch was most productive (1,098kg DM/ha), followed by barrel medic (820kg DM/ha) and strand medic (688kg DM/ha). Barrel medic was the most productive pasture species at Minnipa, consistent with the recommendation for use on alkaline loam soils. Legumes developed for acidic sands in WA (bladder clover, serradella and biserrula) were less productive.

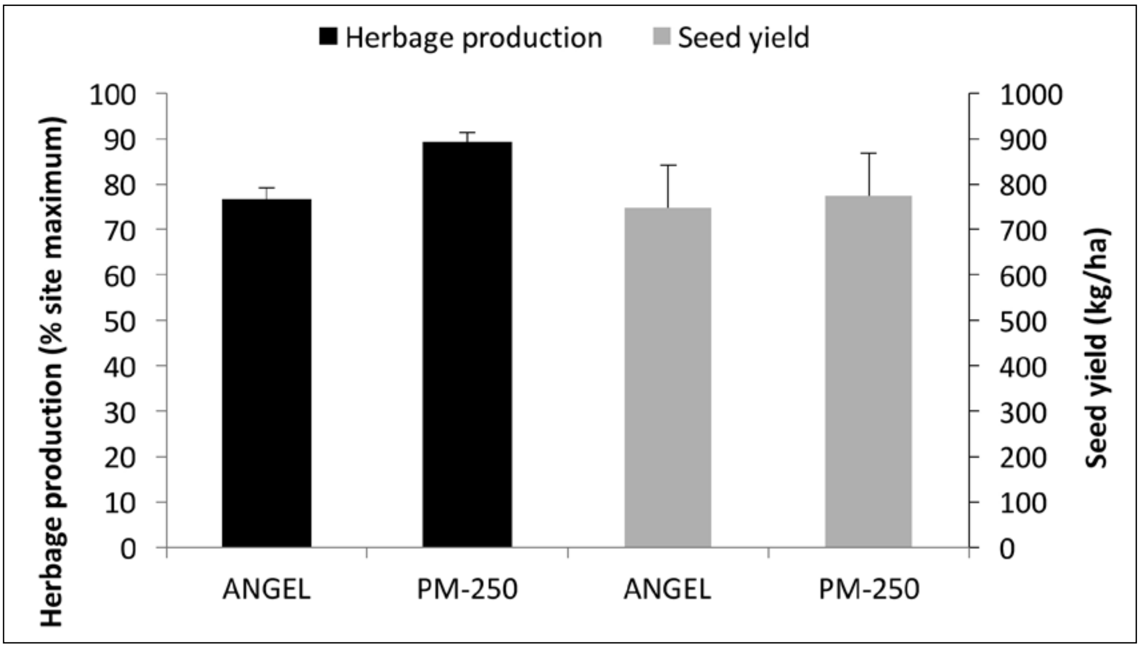

Figure 1. Relative mean herbage production (% site maximum) and seed yield (kg/ha) of PM-250⏀ and Angel strand medics across ten field sites. Includes 34 assessments of dry matter production and 12 seed yield assessments. Bars above columns indicate standard error.

Seed set of the commercial legume species generally exceeded 200kg/ha, with the exception Margurita$^{\phi}$ serradella (129 and 47kg/ha) and vetch at Minnipa (55kg/ha) (Figure 2). The later flowering time of the French serradella likely contributed to its low seed production.

There were large differences in legume regeneration in 2019. Strand and barrel medics regenerated adequately (>200plants/m^2) at both sites, as did rose clover at Lameroo. This provided some flexibility to extend the pasture phase into a second year and consolidate the seed bank (Figure 2). Although biserrula produced a reasonable seed yield in 2018, it regenerated at <20plants/m^2 in 2019. This is due to its high hard seed level (Table 1) and is consistent with the recommendation that this legume be cropped the year following its establishment, to enable some breakdown of hard seed. Vetch, which has been selected to have <5% hard seed to prevent it becoming an in-crop weed, did not regenerate.

DM production of the commercial legumes in 2019 was generally consistent with the results for 2018. The annual medics (developed for alkaline soils) generally produced most winter DM. Rose clover performed better on the sandy loam soil at Lameroo. The WA bred legumes produced less DM, the result of poor regeneration (for example; Casbah) and sub-optimal adaptation to soil type.

Performance of other pasture legume species, cultivars and lines

Ranked performance of all legumes sown at Lameroo and Minnipa is shown in Table 2.

In 2018 when growing season rainfall was less than 200mm, vetches and barrel medics were consistently the most productive species. In the absence of powdery mildew, PM-250$^{\phi}$ strand medic ranked 11th, achieving about 65% of the best legume lines, namely Studenica$^{\phi}$ vetch at Lameroo and Caliph barrel medic at Minnipa. Rose clover and astragalus were the most productive alternative species, even though astragalus is known to have been constrained by poor nodulation.

In 2019, strand medics (Herald, Harbinger, Jaguar$^{\phi}$, PM-250$^{\phi}$ and Pildappa) and the strand

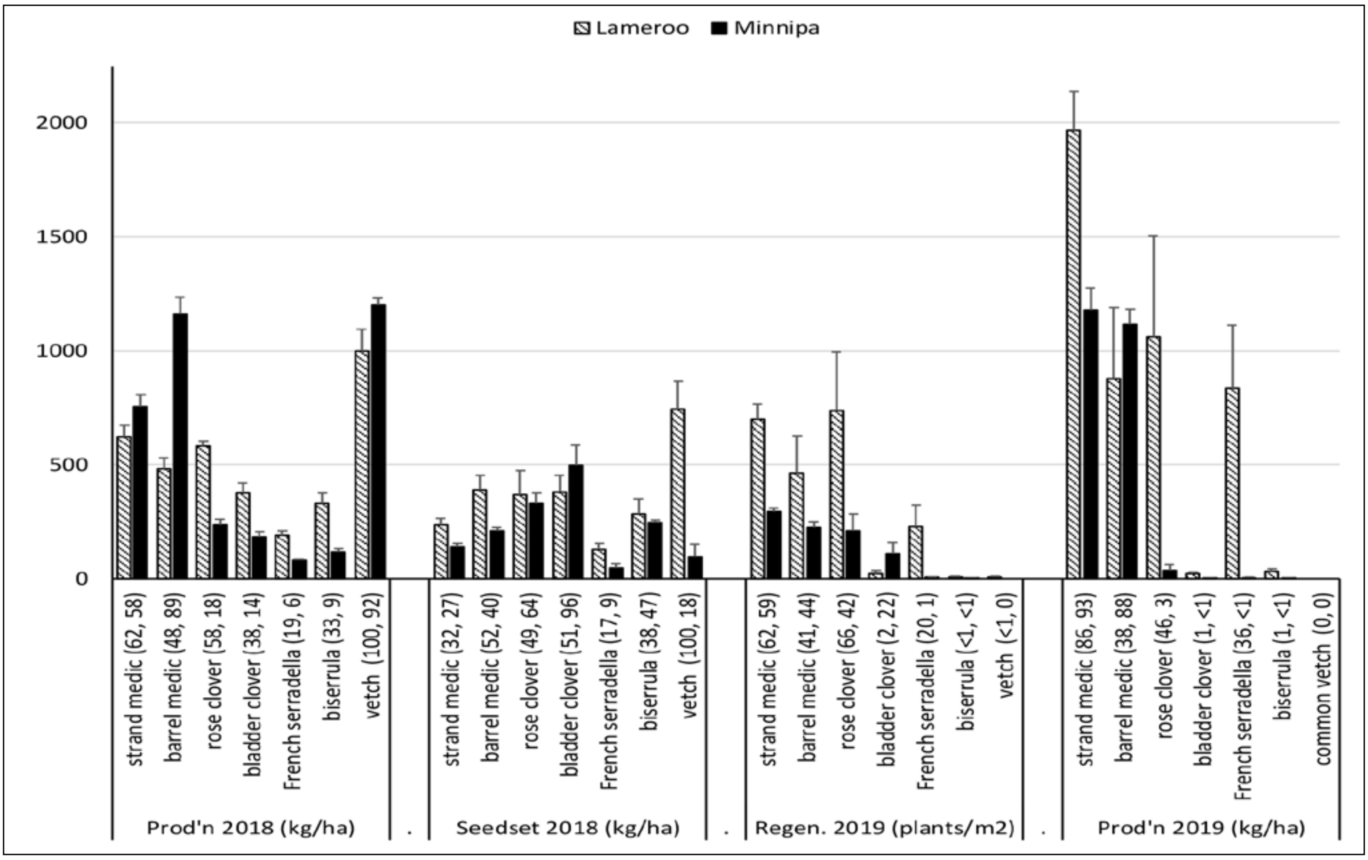

Figure 2. Dry matter production, seed set and regeneration of strand medic (multiple cultivars), barrel medic (multiple cultivars), bladder clover (cv. Bartolo), rose clover (cv. SARDI Rose), French serradella (cv. Margurita$^{\phi}$), biserrula (cv. Casbah) and vetch (cv. Studenicia$^{\phi}$) at Lameroo and Minnipa, SA. Numbers in parentheses accompanying the legume name (e.g. 62, 58) indicate % performance relative to the best legume entry at Lameroo and Minnipa, respectively. Bars above columns indicate standard error.

medic hybrid (Toreador) occupied six of the top ten ranked positions. They established and grew well at both sites, regenerating at >250plants/m^2 and producing more than 1,100kg/ha biomass. Sultan SU was the best barrel medic (rank 9th). Caliph and Cheetah$^{(b}$ (best two pasture legumes in 2018), performed less well in 2019, falling to ranks 17 and 20. The best alternative legumes were the early flowering selection of trigonella, burr medic with putative boron tolerance, rose clover and two lotus species. These legumes performed best on the loam soil at Minnipa. Astragalus fell to rank 27 in 2019, due to high hard seed levels.

Legume performance in other environments

A sub-set of the legumes in Table 2 is being tested in other low rainfall environments.

Table 2. Ranked performance by mean of measures and sites, of 33 legumes in 2018 (establishment year) and 2019 (regenerating year). Parentheses show % performance relative to the best legume at Lameroo and Minnipa respectively.

Legume	2018 performance ranking and (% of site maximum)		2019 performance ranking and (% of site maximum)	
Studenica$^{(b}$ vetch	1	(100, 95)	30	(06, 14)
Capello$^{(b}$ woolly pod vetch	2	(88, 78)	31	(06, 00)
Caliph Barrel medic	3	(65, 100)	17	(26, 80)
Cheetah$^{(b}$ barrel medic	4	(63, 87)	20	(13, 75)
Sultan SU barrel medic	5	(74, 74)	9	(50, 86)
Toreador strand × disc hybrid medic	6	(78, 67)	1	(92, 99)
Scimitar$^{(b}$ burr medic	7	(63, 78)	5	(58,96)
Harbinger strand medic	8	(68, 70)	3	(86, 87)
Astragalus	9	(58, 76)	27	(03, 59)
Pildappa strand medic	10	(74, 60)	7	(61, 83)
PM-250$^{(b}$ strand medic	11	(68, 64)	6	(62, 90)
Volga$^{(b}$ vetch*	12	(---, 65)	33	(---, 00)
Boron tolerant line of burr medic	13	(65, 64)	11	(29, 92)
Herald strand medic	14	(68, 54)	2	(100, 86)
SARDI Rose clover	15	(70, 51)	15	(56, 53)
Frontier balansa clover**	16	(58, ---)	23	(34, ---)
Jaguar$^{(b}$ strand medic	17	(58, 53)	4	(84, 86)
Zulu arrowleaf clover	18	(59, 50)	26	(01, 66)
Bartolo bladder clover	19	(60, 48)	28	(03, 45)
Helmet clover APG2970**	20	(48, ---)	32	(03, ---)
Sand clover APG83821**	21	(47, ---)	21	(39, ---)
Prima gland clover	22	(61, 30)	19	(29, 71)
Early rose clover APG35623	23	(58, 33)	12	(48, 70)
Early trigonella balansae APG37928	24	(42, 46)	10	(24, 100)
Casbah biserrula	25	(56, 32)	29	(02, 39)
Santorini yellow serradella	26	(48, 30)	25	(07, 62)
Trigonella balansae APG5045	27	(33, 43)	18	(20, 85)
Balansa x nigrescens clover	28	(50, 24)	16	(27, 81)
Lotus arenarius APG37667	29	(39, 31)	13	(29, 85)
Minima$^{(b}$ spineless burr medic	30	(38, 31)	8	(43, 95)
Lotus ornithopodioides APG33729	31	(35, 34)	14	(21, 93)
Tammin$^{(b}$ sub-clover	32	(44, 12)	22	(31, 44)
Margurita$^{(b}$ French serradella	33	(39, 15)	24	(30, 40)

*Only at Minnipa**

*Only at Lameroo***

APG = Australian Pasture Gene-bank number

On a neutral (pHC$_{aCl}$ 7.4) sandy soil in Piangil, Victoria, the production of several legumes established in 2019 exceeded 4,000kg/ha, more than double that measured at the SA sites. Even so, relative legume production at Piangil was significantly correlated (n=19, $P<0.01$, $R^2 = 0.57$) with production in the establishment year (2018) at Minnipa (Table 2). Studenicaᶲ vetch (4,880kg/ha) and the barrel medics (Caliph, Sultan SU and Cheetahᶲ) were most productive (≥3 500kg/ha). Margaritaᶲ, Santorini serradellas and biserrula produced less than 1 ,000kg/ha DM at Piangil.

In NSW, legume performance has been different on the acidic red loams at Kikoira (pH$_{CaCl}$ 4.9) and Condobolin (pH$_{CaCl}$ 5.1). In trials established in 2018, biserrula was the outstanding species across both sites. It was the only legume to survive extreme drought conditions at Condobolin. Biserrula produced more than 120kg/ha seed at Kikoira with approximately one-third of that produced prior to the end of October. Other species including Margaritaᶲ, Santorini serradella and arrowleaf clover also produced useful quantities of herbage (around 1,200kg/ha) under severe drought at Kikoira but had not commenced reproductive growth by late October. Whilst they managed some seed set after 53mm rain in November, had this not occurred, these later maturing species may have failed to produce seed. Both Casbah biserrula and Lotus ornithopodioides regenerated well in 2019.

Pastures in rotations

A cropping systems experiment at Lameroo is evaluating the duration of pasture benefits and pasture regeneration after cropping, using a range of legume species grown for two years, (PM-250ᶲ medic, Margaritaᶲ serradella, SARDI rose clover and Trigonella balansae), or one year (PM-250ᶲ medic, and Margaritaᶲ serradella). Crop benefits will be measured in 2020 after the one or two-year pasture phase, when the pasture systems will be compared against three control treatments; vetch-cereal, pea-cereal and continuous cereal. Similar experiments (not reported here) are being undertaken at Piangil in Victoria, and at Harden and Uranquinty in NSW.

Growing season rainfall at Lameroo in 2018 was 140mm. In 2018 pastures were established primarily to set seed for regeneration in 2019. Seed set was adequate for each species and was estimated to range between 190-320kg/ha. PM-250ᶲ medic produced the greatest DM up until late September (1.8t/ha, Table 3), however late rains in October/November (33mm) may have supported some further growth and seed set of the later flowering species, particularly serradella.

After the first season, soil mineral nitrogen was the parameter that varied most. Measured in early 2019 it reflected N fixed by the pasture species in 2018 (Table 3), medic>rose clover>trigonella>serradella>wheat. Some serradella plants were pale yellow and because nodulation in adjacent plots was observed to be less than ideal, we speculate that sub-optimal nodulation was probably limiting in the system experiment. While there were significant differences in nutritive values of metabolisable energy (ME), digestibility and crude protein, they were not large.

In 2019, regenerating pasture treatments had higher plant establishment than plots sown in autumn, namely PM-250ᶲ and Margaritaᶲ. PM-250ᶲ density in the regenerating plots was five times (232 versus 38plants/m^2) and Margaritaᶲ density seven times (373 versus 47plants/m^2) levels in the sown plots. Rose clover and trigonella regenerated at 304 and 151plants/m^2, respectively. These differences affected production (Figure 3).

Table 3. Summary of N_2 fixation and biomass production, metabolisable energy (ME), digestibility and crude protein at peak biomass from 2018 sampling, and soil mineral nitrogen and moisture from 0-100cm from soil cores taken in May 2019 at Lameroo, SA.

Treatment 2018	N_2 fixation (kg/ha)	Dry matter at peak biomass (t/ha)	ME (MJ)	Digestibility (%)	Crude protein (%)	Soil moisture (mm)	Soil mineral N kg/ha (0-100 cm)
Wheat	--	3.2	--	--	--	105	49
Serradella (Margaritaᶲ)	6	1.2	8.8	61	12	96	54
Trigonella balansae (5045)	14	0.8	9.4	65	14	108	55
Rose Clover (SARDI)	20	1.1	9.2	63	13	93	65
Medic (PM250ᶲ)	24	1.8	9.1	63	13	108	70
P-value	<.001	<.001	<.001	<.001	<.001	NS	0.006
LSD (5%)	5	0.57	0.1	0.8	0.6	--	12

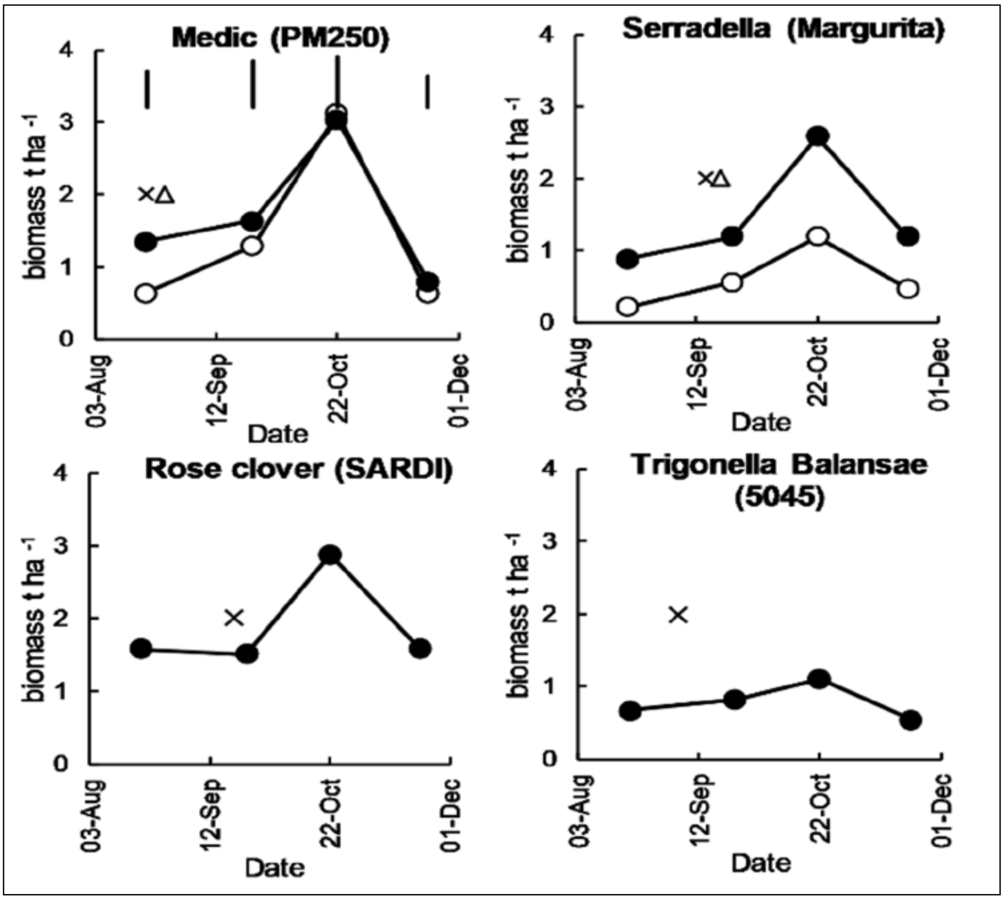

Figure 3. Biomass in Lameroo 2019 for pasture species either sown on 14 May 2019 (O) or regeneration from seed set in 2018 (●). Solid vertical line in the Medic figure is LSD (5%) at each biomass measurement, and markers are the date that first flowers were observed in autumn sown treatments (Δ) and regenerating treatments (×).

Growing season rainfall (April to October) in 2019 at Lameroo was 205mm. All treatments produced most DM in mid-October when all species were podding (Figure 3). There was no significant difference at the mid-October cut between autumn sown medic, regenerating medic, regenerating rose clover and regenerating serradella. The extent to which lower production of trigonella and autumn sown serradella effect crop production, will be measured in 2020.

Pasture establishment in the Mallee

Alternative pasture establishment methods were evaluated at Waikerie, SA, and Piangil, Vic, in 2019 using a range of annual pasture legumes, including some not commonly grown in the Mallee region. Indicative sowing rates are shown in Table 4. Establishment methods evaluated were:

- Twin-sown, where 'hard' pasture seed/pod was sown with wheat seed in 2018 for pasture establishment in 2019.
- Summer-sown (February), where 'hard' seed/pod was sown in summer and softens to establish on the autumn break.
- Autumn-sown (control treatment), where 'soft' germinable seed is sown on the break of the season.

In 2019 at Waikerie, the seasonal break occurred on 9 May with 20mm rainfall. Rainfall prior to 9 May was 22mm. In Piangil, the seasonal break occurred on 2 May with 19mm rainfall, and rainfall prior to 2 May of 17mm. At both sites, all establishment treatments emerged within two weeks of each other. Sowing method had a significant effect on plant density at both sites (Figures 4A and 4B). The targeted population for sown pastures is typically 150-200plants/m^2.

Seedling establishment

At Waikerie, mean plant density across all legumes were; autumn-sown 132plants/m^2, twin-sown 64plants/m^2 and summer-sown 159plants m^2

Table 4. Indicative rates of sown pod or seed (kg/ha) and equivalent amount (kg/ha) of viable hard seed sown in twin- and summer-sown treatments; and rate of germinable seed (kg/ha) in the autumn sown treatment.		
Legume	Twin and summer-sown treatments (kg/ha)	Autumn sown treatment (kg/ha)
PM-250⁽ᵇ⁾ medic	28 as pod; providing 7kg/ha viable hard seed	5
Trigonella balansae	12 as seed; providing 6kg/ha viable hard seed	4
Bladder clover	18 as seed; providing 16kg/ha viable hard seed	7
Rose clover	44 as seed; providing 11kg/ha viable hard seed	6
Biserrula	8 as seed; providing 4kg/ha viable hard seed	5
French serradella	30 as pod; providing 8kg/ha viable hard seed	6
Gland clover	10 as seed, hard seed not measured	5

(Figure 4). In Piangil, mean plant density across all legumes were; autumn-sown 73plants/m^2, twin-sown 42plants/m^2 and summer-sown 60plants/m^2. An observation relevant to the lower establishment in twin-sown plots, is that seed may have been buried too deep as a result of collapse of furrows and sand movement over the 2018/19 summer period.

At both sites, serradella had the highest establishment for all twin- and summer-sown treatments compared to other species but established best when summer-sown. Medic densities were greatest when autumn sown.

Production

Treatment differences in dry matter production were measured at Waikerie, despite production being limited by low rainfall (Figure 5). Production was greatest for summer and autumn-sown PM-250⁽ᵇ⁾ medic. Although serradella and rose clover produced more DM when summer-sown, their overall production was lower, suggesting they are less well adapted to Mallee soils. Dry matter was lowest in the twin-sown treatment, consistent with lower plant numbers.

At Piangil, twin-sown treatments performed better than at Waikerie (Figure 6). Higher plant density did not necessarily result in higher biomass production. For example, there was higher plant density in summer-sown serradella, but twin-sown treatments produced more biomass. Medic produced similar biomass in the autumn- and twin-sown treatments. Production of trigonella and gland clover was generally low, indicating they are less adapted to the soil type.

Results from 2019 indicate that twin and summer-sowing may be a viable establishment method for the Mallee region, however it is not suitable for all legume species. In both environments, Margurita⁽ᵇ⁾ serradella gained the most advantage from the alternative establishment methods. Results for PM-250⁽ᵇ⁾ medic were inconsistent, with twin-sowing inferior at Waikerie and summer-sowing inferior at Piangil. Given that all treatments emerged on similar

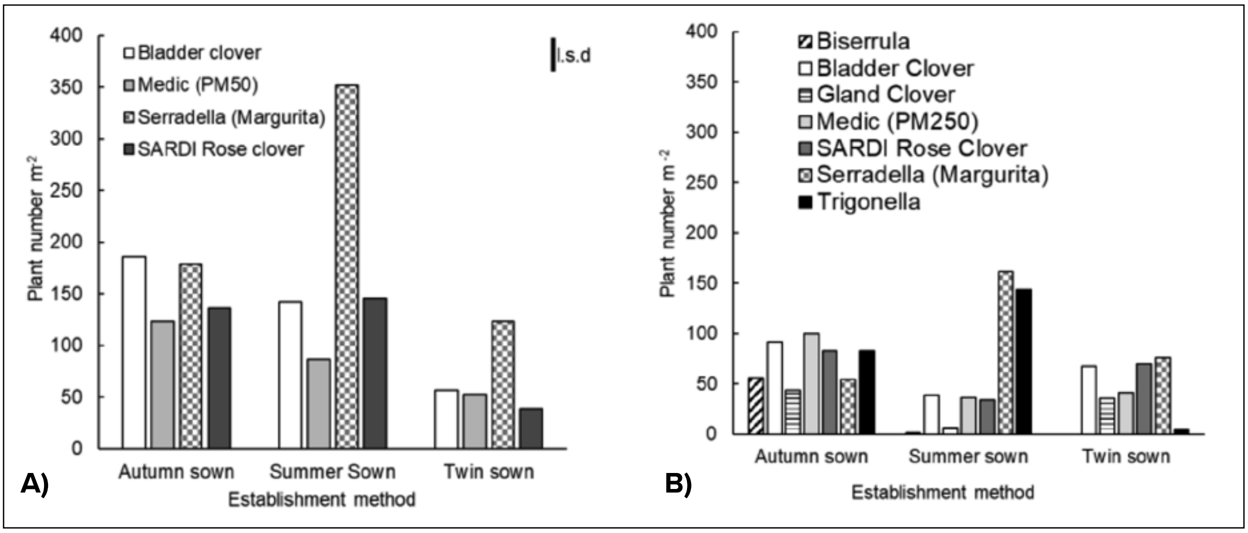

Figure 4. Plant establishment resulting from different establishment methods at A) Waikerie on 25 June 2019 and B) Piangil on 5 June 2019.

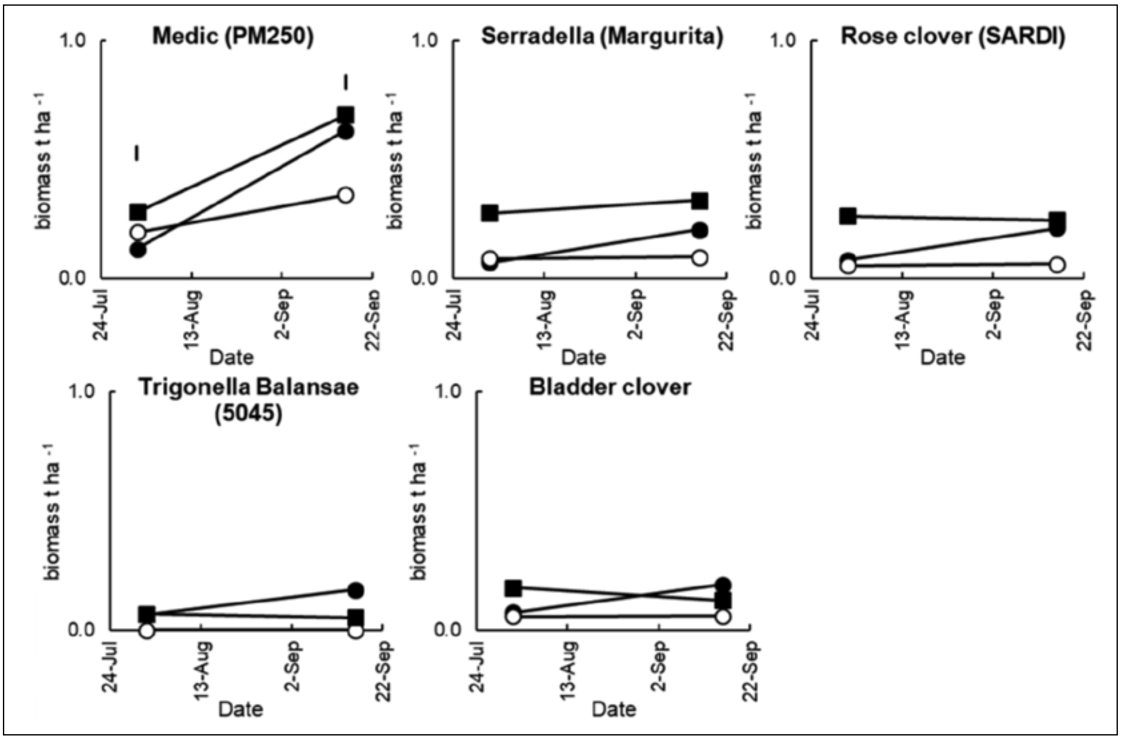

Figure 5. Biomass production in 2019 at Waikerie in the establishment treatments; autumn-sowing (●), twin-sowing (O) and summer-sowing (■).

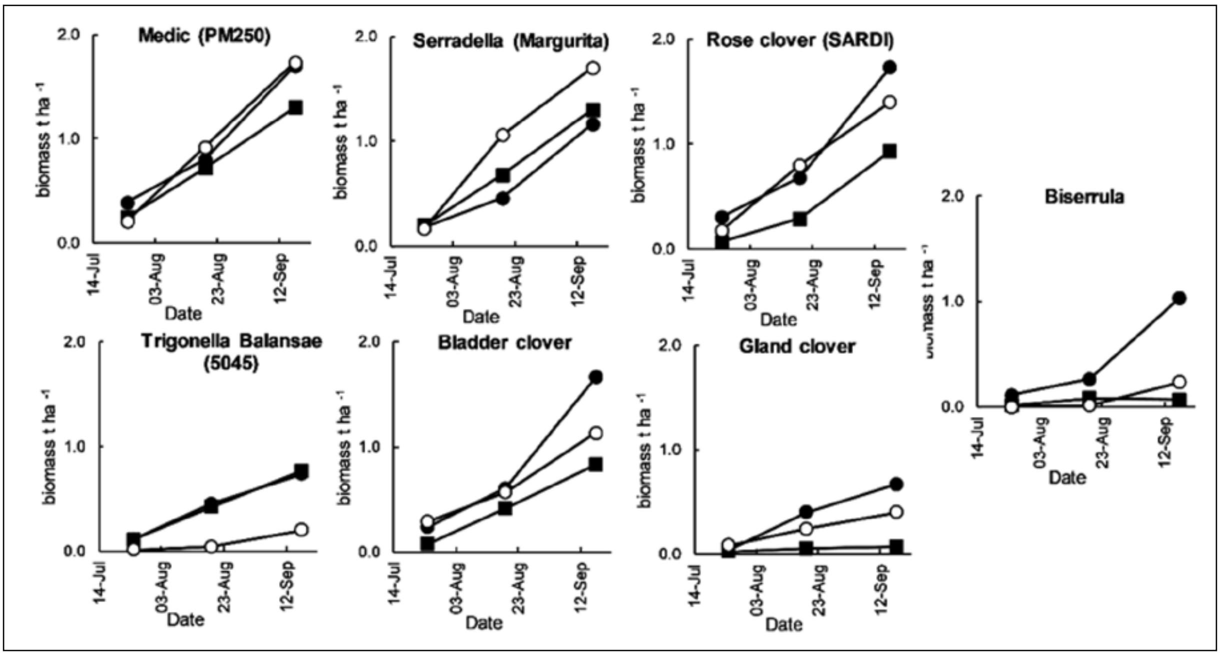

Figure 6. Biomass production in 2019 at Piangil in the establishment treatments; autumn-sowing (●), twin-sowing (O) and summer-sowing (■).

dates, and there was very little summer rainfall in 2019, further exploration of the methods are required under a range of growing seasons such that risks and/or benefits associated with earlier seasonal or false breaks can be evaluated.

Weed management

Weed control is an important consideration with twin and summer-sowing. At Waikerie there were significantly greater numbers of broad leaf weeds in the twin and summer-sown plots, compared to autumn-sown plots. Weed DM for the treatments was; twin-sowing 500kg/ha, summer-sowing 440kg/ha and autumn-sowing 360kg/ha (P<.001). Autumn-sown plots received a knock-down spray at sowing, while twin and summer-sown plots did not. Twin and summer-sowing methods should only be considered for paddocks with low weed levels.

Seasonal analysis

To understand the likely suitability of summer and twin-sowing in other low rainfall environments, historic climate records (1970 to 2018) were analysed to reveal 25th to 75th percentiles of when the seasonal break occurred. Using the APSIM model (version 7.10) and historic weather records, the approach of Unkovich (2010) was used to estimate the mean break of a season, that is, when over a seven-day period, accumulated rainfall exceeds accumulated pan evaporation. An additional rule was added, which was that soil temperature should be below 20°C. Figure 7 shows 'box and whisker' plots for six locations, and the probability of a break occurring on 25 April.

The analysis revealed that Lameroo and Condobolin have the earliest median break, and higher probability of a break occurring before 25 April, while Minnipa and Waikerie typically have the latest seasonal break. In environments with a greater probability of an early seasonal break, summer-sowing will likely be more beneficial — soil conditions are warmer, and a longer growing season can be exploited more often. In environments where the seasonal break is often later, there is greater risk of seed losses or burial, rhizobia death and exposure to pathogens. Establishment following autumn, summer and twin-sowing methods will also be measured in Lameroo in 2020.

Conclusion

Pasture legume production, regeneration and persistence is determined by multiple factors (Nichols et al. 2012), including adaptation to soil type (texture and pH), capacity to set seed (early flowering desirable in low rainfall areas) and hard seed levels that allow regeneration and persistence through the cropping sequence.

On neutral/alkaline soils in the low rainfall regions, annual medics continue to provide the best option where a self-regenerating pasture is preferred. The SA trials reported in this paper, reiterate strand and disc medics as the best pasture legume choice for the lighter sands and barrel medics for the heavier loams in the Mallee. PM-250⦶ strand medic is scheduled for release in 2021 and has demonstrated a production benefit of 16% over the cultivar Angel which it will replace. In addition, larger benefits are expected where powdery mildew and herbicide residues are present. Cohorts of disc, strand and burr medic have been developed and are being assessed by the DLPS project.

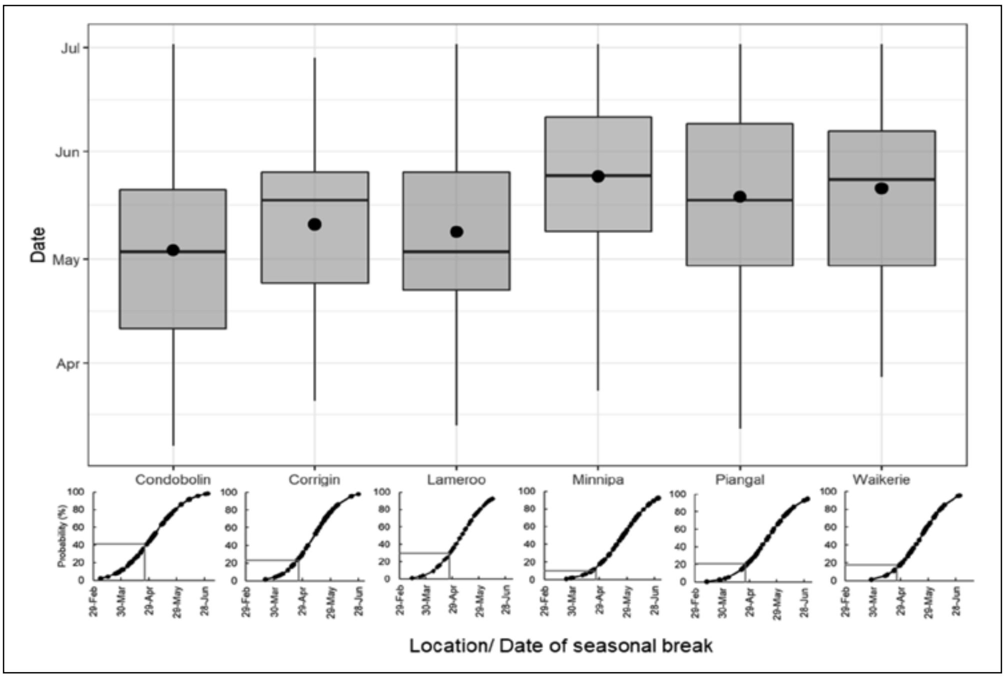

Figure 7. 'Box and whisker' plots showing 25th to 75th percentiles of when the autumn break occurred in historic data set 1970-2018, using Unkovich (2010), and the probability of the seasonal break occurring on 25 April.

Legumes developed for WA soils and farming systems (biserrula, serradella and bladder clover) have so far performed less well on Mallee soils in SA but have performed well on other soil types. Specifically, biserrula has grown and regenerated well on acidic red sands in NSW. Pasture legume species other than medics have on occasion shown promise in the Mallee but have neither been outstanding or consistent. If trialling the 'alternative' species, it suggested that small areas are initially sown. Common vetch may be a better option where a sown legume ley of one year is preferred, because of its ability to provide early production and options for late weed control. A new vetch cultivar (Studenica^(b)), scheduled for release in 2021, has performed well in the DLPS trials.

The aim in the establishment year of legume pastures should be to maximise seed set, and if done well the resultant seed bank (25 times what is sown) will support pasture regeneration for many years. Alternative establishment methods have demonstrated potential in the Mallee but are not suitable for all legume species. Margurita^(b) serradella gained greatest advantage from the alternative establishment methods. Results for PM-250^(b) medic were inconsistent but showed some promise and are worthy of further investigation given their potential to provide growers with greater sowing flexibility and reduce seed costs. Differences in N_2 fixation by the different legumes have been measured. The impact of this and other pasture impacts on wheat production will be measured in 2020.

The studies reported in this paper have focussed on legume monocultures. Legume mixtures such as medic and vetch in the establishment year may be useful to achieving more consistent production through the season and across variable soils.

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We thank the Pocock and Schmidt families for hosting trials at Lameroo and Waikerie, SA.

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Notes

Recommendations for deep ripping sandy soils

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GRDC project code: DAS00169-BA: Improving sustainable productivity and profitability of Mallee farming systems with a focus on soil improvements.

Keywords

- deep ripping, soil compaction, sandy soils, subsoil.

Take home messages

- Deep ripping is most effective in deep sandy-textured soils, when the ripper tines go beyond the compacted layer (+60cm). Grain yield increases usually persist for several years on deep sands.
- Based on 2 years of limited data in SA, ripping with narrow (30cm) or wide (60cm) tine spacing resulted in similar grain yield responses, and therefore, wide ripping should be considered as it requires less machinery horsepower and less operational costs.
- A potential downside associated with deep ripping in low rainfall areas is that it increases the risk of crops 'haying off' when soil water reserves are rapidly exhausted and the finish to the season is harsh and dry.

Background

Sandy soils dominate the landscape across the low rainfall region of south-eastern Australia and soil compaction mainly caused by heavy machinery is a widespread constraint to root growth. Other constraints that may occur simultaneously on these soils include water repellency and acidity. Compaction inhibits root growth and reduces the storage and supply of water and nutrients, especially from the subsoil. It increases soil bulk density and soil strength, decreases porosity, water infiltration and water holding capacity, and can also adversely affect soil biological activity. In the absence of compaction forces some sandy soils have a natural tendency to form hard layers in the subsurface, thought to be caused by physical and/or chemical cementation processes.

Deep ripping is most effective treatment to loosen compacted subsoils and allow roots to access soil moisture and nutrients at depth. Significant benefits to crop growth from deep ripping are frequently measured on compacted sandy-textured soils, however responses on other soils are often smaller and less frequent (Paterson and Sheppard, 2008). For example, Isbister et al. (2018) reported that responses to deep ripping in Western Australia (WA) were greater in sandy soils (20-37% yield increase) than loamy duplex soils greater than 30cm deep (22%) or shallow duplex soils (4%). For sodic clays and prone to dispersion, ripping is often detrimental to crop growth.

Tine spacing, working depth, shallow leading tines or discs, soil moisture content, timing and soil type all need to be considered to maximise productivity gains and make the process off deep ripping cost effective. Research by the Department Primary Industry and Regional Development (DPIRD), supported by investment from the GRDC, estimates that the costs associated with deep ripping can range from $50-60 per hectare for standard ripping at 50cm spacing to a depth of 30-40cm, and up to $70-90/ha for ripping at narrower spacings and/or a depth of 50-70cm, depending on machinery and soil conditions. Therefore, the challenge that growers face is refining how best to ameliorate compacted soils while keeping costs down, but at the same time maximising and prolonging the benefits. It is important to note that if the soil contains other constraints in, or below the ripping depth such as acidity, poor structure from sodicity or subsoil salinity, the benefits of deep ripping may not be fully realised unless these are also addressed.

This paper summarises the results from replicated trials conducted in different low – medium rainfall cropping regions of Australia to gain insight into how deep ripping is impacting crop performance and how to maximise the benefits on different soil types. Collation of data from these trials will assist in developing guidelines for growers which address key questions around if and why they should be considering deep ripping as a soil amelioration strategy. Once the decision is made to proceed with a ripping program, trial results will also help inform growers of how best to undertake the ripping to achieve sustainable and improved crop yields and sound returns for every dollar invested.

Justification for deep ripping

Research conducted in the 1970s and 80s demonstrated that on deep sands and sandy loams in WA, wheat roots can extract water from depths ranging from 1.4 to 2.5 metres (Hamblin et al. 1982; Hamblin et al. 1988). In moisture limited environments the capacity of roots to extract water and nitrogen from such depths is critical on soil types with relatively low water holding capacity, or where the use of deep subsoil moisture is critical for grain filling. In compacted sandy soils where penetration resistance exceeds 1500kPa, crop root growth is restricted and yield potentials cannot be realised. In these situations, deep ripping can break up that compaction, improve root penetration and ultimately crop performance. Resistance values of 1500-2500kPa are considered moderate, 2500-3500kPa severe and >3500kPa extreme.

During the 1980s, peak soil strength in deep sands and sandy earths typically occurred at depths of 30 to 35cm and reached strengths of 2000 – 2500kPa as shown in Figure 1 (right). Since then, as farms have got larger and machinery sizes and axle loads have increased, the severity of the compaction problem has continued to worsen. Recent soil strength measurements indicate that peak soil strength now occurs at depths as shallow as 20cm, with strengths ranging from 3000 to 3500kPa (Figure 1 left and right). Therefore, when considering shattering soil compaction, deeper ripping past the compacted layer is recommended in order to maximise the benefits.

Crop responses to deep ripping

Reviews of deep ripping trials conducted 20-30 years ago have shown substantial benefits with cereal yield increases of 22 to 37% in the first year (Crabtree 1989; Davies et al. 2006; Jarvis 2000).

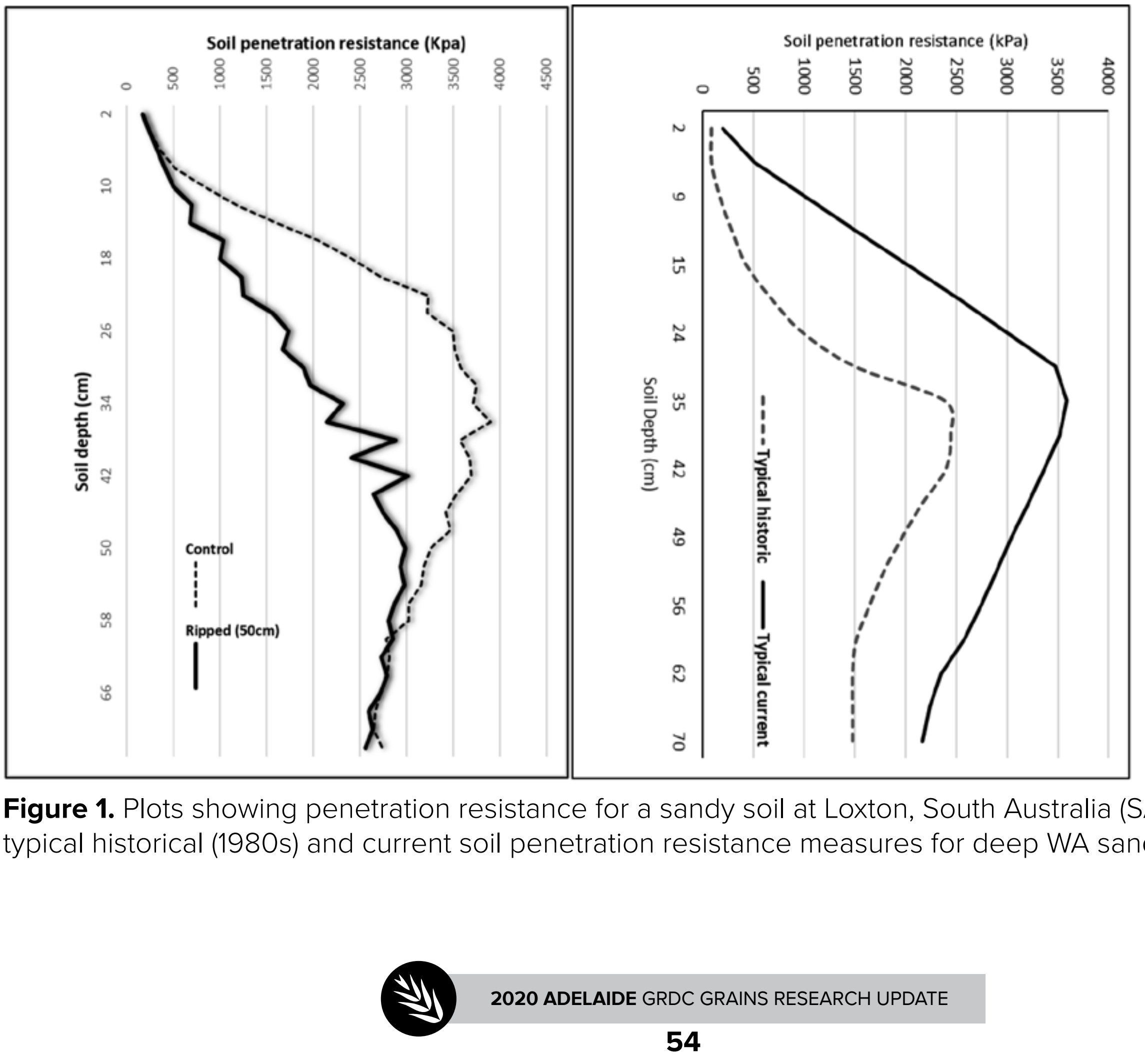

Figure 1. Plots showing penetration resistance for a sandy soil at Loxton, South Australia (SA) (left), and typical historical (1980s) and current soil penetration resistance measures for deep WA sandy soils (right).

Table 1. Crop yield responses to deep ripping at different depths and the impact of topsoil slotting (with inclusion plates). Trials conducted in WA during 2014 to 2016 (Davies et al., 2017).									
Location, crop	Soil type	GSR (mm)	Control yield (t/ha)	Ripped 30-40cm		Ripped 50-70cm		Ripped 50-70cm + topsoil slotting	
				Yield (t/ha)	%	Yield (t/ha)	%	Yield (t/ha)	%
Moora, canola	Loamy sand	177	1.9	2.2	16	2.8	47	2.9	53
Wubin, wheat	Deep sand	228	2.1	2.7	29	3.0	43	-	-
Binnu, wheat	Deep sand	219	0.8	0.8	0	1.4	75	1.8	123
Binnu, wheat	Loamy sand	219	2.1	2.1	0	2.8	33	3.6	71
Beacon, wheat	Sandy duplex	240	3.8	3.9	3	3.5	-11	4.5	15
Broomehill, wheat	Sandy duplex	227	1.8	2.0	11	3.0	67	-	-
Munglinup, wheat	Sandy duplex	280	3.6	3.6	0	3.6	0	4.2	17
Meckering, wheat	Sand over gravel	323	2.7	-	-	3.4	26	-	-
Meckering, wheat	Deep sand	323	2.4	-	-	3.4	46	-	-
Meckering, wheat	Sand over gravel	323	2.2	2.5	15	3.0	38	3	38
Walkaway, lupin	Deep sand	219	1.2	-	-	2.3	92	-	-

In recent experiments conducted in WA (Davies et al., 2017) during 2014 to 2016, ripping increased average wheat yields by 8% for shallow ripping (30 to 40cm), 35% for ripping to depths of 50cm or more, and 53% for deep ripping with topsoil slotting (Table 1). Topsoil slotting is produced when inclusion plates are bolted behind ripping tines with the top of the plate working 100mm below the soil surface, thereby keeping the ripping slot open while allowing topsoil to fall down towards the bottom of the slot.

SA Mallee trials

Similar grain yield improvements with deep ripping (+60cm) were previously reported at Waikerie (McBeath et al., 2018). However, intervention to 60cm did not provide any significant yield benefits over a depth of 30cm at several other South Australian (SA) and Victorian (Vic) sites (Moodie et al., 2018; McBeath et al., 2019).

As part of this study five replicated field trials (Table 2) were conducted during the 2018 and 2019 cropping seasons on sandy soils across the SA northern and southern Mallee, and the upper Eyre Peninsula (UEP). Trial 1 (depth x spacing) was set up at Peebinga (2018 and 2019) and at Buckleboo (2019) to investigate the impact of depth of ripping and tine spacing on crop productivity and the longevity of the amelioration benefits.

Trial 2 was set up at Loxton as a crop rotation experiment with three different crop types (wheat, barley and field peas each year), with the aim of assessing which crop types respond best to deep ripping in the 1st, 2nd and 3rd year after amelioration.

Deep ripping treatments were imposed using a straight tine ripper on 11 May and 21 May 2018 at Loxton and Peebinga, respectively and at Buckleboo on 10 April 2019. Penetration resistance readings were taken on 7 August 2018 at both Mallee sites using a Rimik CP40 (II) cone penetrometer to estimate the magnitude and depth of compaction and the impact of the ripping treatments. The

Table 2. Deep ripping locations and treatment details for 2018 and 2019 cropping seasons.				
Year	Trial #	Location (crop)	Region	Treatments
2018	Trial 1	**Peebinga** (barley)	southern Mallee	Depths (0, 20, 40, 60, 70cm) Tine spacings (Narrow = 30cm and wide = 60cm)
	Trial 2	**Loxton** (wheat, barley, peas)	northern Mallee	Ripped (50cm) vs compacted (control) Tine spacing 50cm
2019	Trial 1	**Peebinga** (wheat)	southern Mallee	Depths (0, 20, 40, 60, 70cm) * Tine spacings (Narrow = 30 cm and wide = 60 cm)
		Buckleboo (barley)	upper EP	
	Trial 2	**Loxton** (wheat, barley, peas)	northern Mallee	Ripped (50cm) vs compacted (control) Tine spacing 50cm

Growing season rainfall: 2018 Loxton (105mm), Peebinga (116mm); 2019 Loxton (93mm), Peebinga (152mm), Buckleboo (143mm).

depth of compaction layer was measured around 18 – 20cm at Peebinga and Loxton in 2018. To get accurate data, penetration resistance measurements are recommended to be done when the soil moisture is at or near field capacity. Due to the nature of the season with inconsistent low rainfall, no measurements were taken in 2019 at all sites. In-season assessments of crop density, dry matter (DM) production, grain yield and quality were undertaken to understand the effect of ameliorating compaction in typical deep sands of the SA Mallee.

With total growing season rainfall (GSR) ranging from only 93 to 152mm, crop growth and productivity were severely limited at all sites. However, visual and positive responses in crop establishment and biomass to ripping were evident throughout the growing season in all trials. No harvestable grain yield was achieved in field peas at the Loxton site for 2018 and 2019 because of severe frost which resulted in pod damage.

Despite the dry conditions and poor yields, the trials demonstrated that ameliorating compacted sandy soils in low rainfall environments can lead to substantially improved crop biomass (data not shown) and grain yield in cereals. Deep ripping increased wheat yields by up to 135% for shallow (20-40cm) ripping, and up to 235% for deeper ripping to depths of 50cm or more. Barley grain yield was increased by up to 93% for shallow (20-40cm) ripping, and up to 193% for deeper ripping to depths of 50cm or more (Table 3). Only shallow ripping did not cause large grain yield gains.

Averaged over all ripping depths, deep ripping with tines spaced at 30cm resulted in a significant increase in early and late shoot DM (data not shown). However, this benefit did not carry through to grain yield (Figure 2). Deep ripping has the potential to promote early biomass growth but in moisture limited environments, one of the greatest potential downsides associated with deep ripping is that it increases the risk of 'haying off' when soil water reserves are low and the finish to the season is dry (Davies et al., 2017). In some situations, faster water use and increased vegetative biomass caused by deep ripping can leave inadequate stored soil water for grain filling resulting in 'haying off' and reduced yields.

There was a consistent trend of increasing grain yield with increasing ripping depth across all sites in the two years of conducting these trials (Figure 3). But the cumulative grain yields over the two seasons showed that the deepest ripping treatment (70cm) achieved the highest yield. This is attributed to increased plant root growth, and increased access to nutrients and water down the soil profile. Similar results of improved grain yields with deeper ripping have generally been reported by several authors (Davies et al., 2017; Isbister et al., 2018; McBeath et al., 2018; McBeath et al., 2019; Moodie et al., 2018). However, it is important to note that the highest yielding treatment does not necessarily translate to the most profitable and most sustainable tillage strategy. In addition, the optimum depth of ripping will depend upon the depth of the compaction. For example, there is no point in ripping to 70cm if the compacted layer is only between 20 and 30cm.

Table 3. Deep ripping trials conducted during 2018 and 2019, showing grain yield responses to ripping at varying depths and tine spacings.

Year	Location	Crop	Tine spacing (cm)	Control	Ripped 20cm		Ripped 40cm		Ripped 50cm		Ripped 60 - 70cm	
				Yield (t/ha)	Yield (t/ha)	% change	Yield (t/ha)	% change	Yield (t/ha)	% change	Yield (t/ha)	% change
2018	Loxton	Wheat	50	0.58	*	*	*	*	0.69	**19**	*	*
	Loxton	Barley	50	0.54	*	*	*	*	1.08	**100**	*	*
	Peebinga	Barley	30	0.27	0.46	**70**	0.52	**93**	*	*	0.79	**193**
	Peebinga		60		0.23	**-15**	0.43	**59**	*	*	0.77	**185**
2019	Loxton	Barley	50	0.13	*	*	*	*	0.18	**38**	*	*
	Loxton	Wheat	50	0.22	*	*	*	*	0.56	**155**	*	*
	Peebinga	Wheat	30	0.2	*	*	0.47	**135**	*	*	0.67	**235**
	Peebinga		60		0.28	**40**	0.29	**45**	*	*	0.62	**210**
	Buckleboo	Barley	30	2.13	2.79	**31**	2.88	**35**	*	*	3.35	**57**
	Buckleboo		60		2.38	**12**	3.46	**62**	*	*	3.33	**56**

*n.b. *no statistically significant response (i.e. no different to the control).*

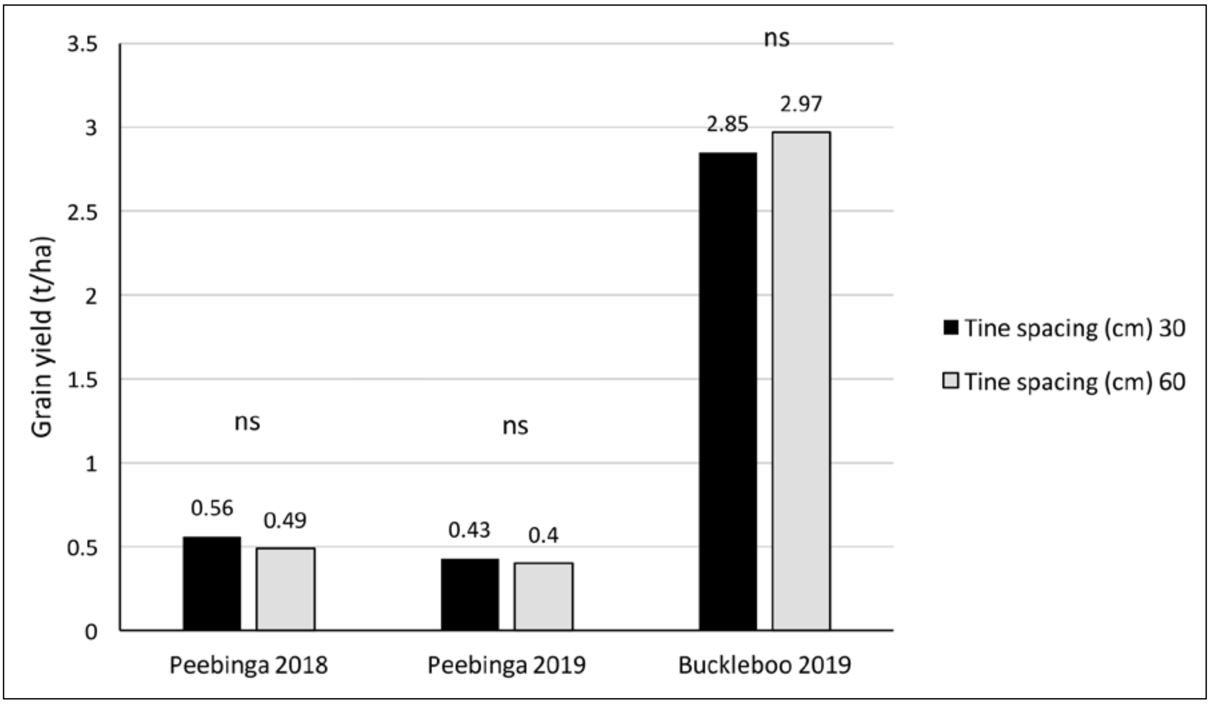

Figure 2. Mean cereal grain yield (t/ha) on 30cm and 60cm tine spacing at Peebinga and Buckleboo.

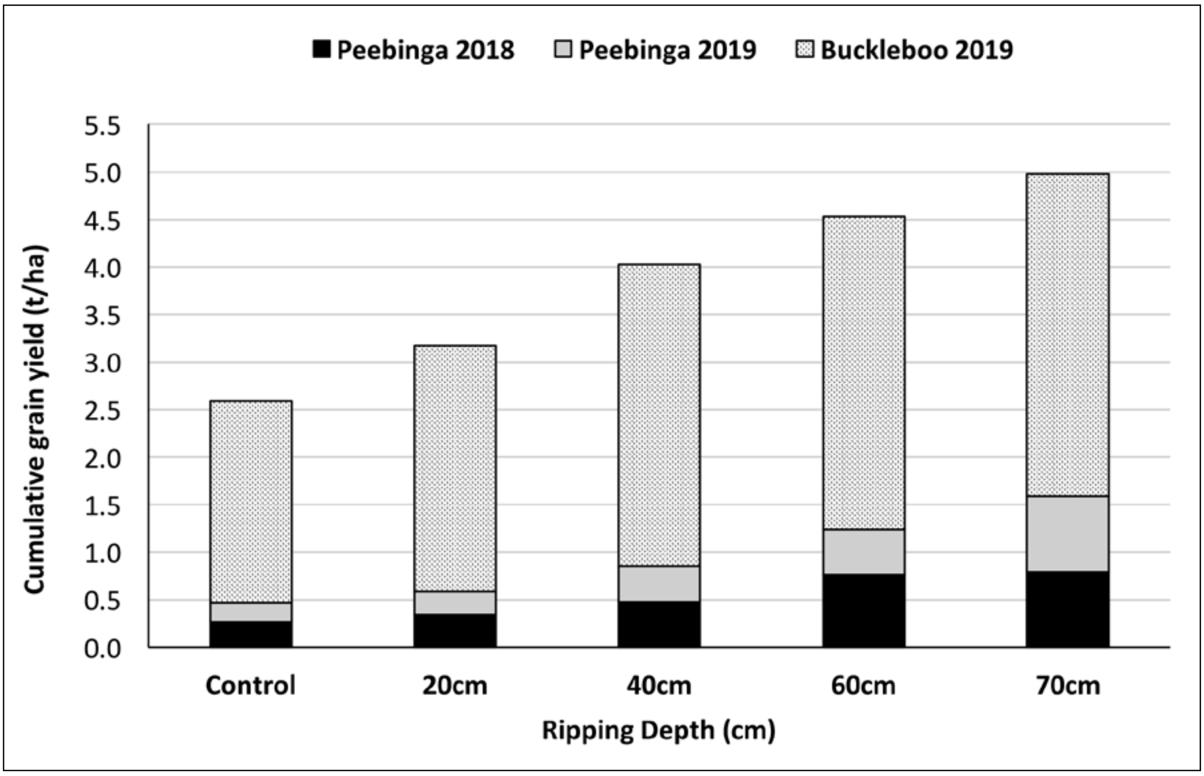

Figure 3. Cumulative cereal grain yield (t/ha) at Peebinga (2018, 2019) and Buckleboo (2019).

Economics of deep ripping

Economics are an important factor when evaluating whether an amelioration strategy should be implemented on-farm or not. Soil amelioration is often costly, so it is necessary to have significant and long-term benefits to achieve a good return on investment. Physical interventions like deep ripping have the potential to improve crop productivity in compacted sandy soils, but there is a risk of low returns in low rainfall seasons. Our results from two years of conducting ripping depth x tine spacing trials are showing that better returns are achieved when deep ripping is achieved below 60cm (Table 4). If a narrow tine spacing is being considered, then going deeper than 60cm may not give the best economical return in the first year because the yield gain and extra income may not outweigh the extra cost of ripping further down the soil profile. However, the two years of data from Peebinga showed that by ripping down to 70cm, the marginal benefits in the second year (2019) improved by more than 100%, compared to shallow ripping. There is no evidence from our data of a drop off in yield in the second year after ripping, which implies that the benefits of deep ripping could extend into the third year and beyond, improving the economic returns even more.

Tackling more than just one constraint

Our experiments have focused only on the physical intervention of deep ripping to ameliorate subsoil compaction, however, other research has acknowledged that tackling more than one constraint is better in the long run to improve and sustain crop yields, particularly on sands in medium to low rainfall environments. Trials in the WA wheatbelt have found deep ripping combined with topsoil slotting with inclusion plates can increase yields from sandy soils by more than deep ripping alone. The aim of this topsoil slotting is to improve root growth into the subsoil by providing a nutrient and organic matter rich pathway through infertile subsoil layers, to overcome aluminium toxicity associated with subsoil acidity and to improve the longevity of the ripping benefit. At Meckering WA in 2016, shallow ripping of pale sand over gravel increased wheat grain yield by 11% (320kg/ha), while the addition of topsoil slotting increased the yield by 26% (560kg/ha) over the control (Davies et al. 2017). It is likely that the organic rich topsoil will help prevent re-compaction, and research is continuing to investigate if topsoil slotting will improve the longevity of the benefits of deep ripping.

Ripped soil can be very soft and susceptible to trafficking issues for field operations. To maximise the benefits of deep ripping and minimise risks of re-compaction, adopting a controlled traffic farming (CTF) system should be considered. CTF is a system built on permanent wheel tracks where the crop zone and traffic lanes for seeding, spraying and harvest are permanently separated. For many deep sandplain soils, deep ripped areas can remain soft for at least four to five years in controlled traffic systems (Davies et al., 2017), and the benefits of deep ripping can be maximised (Wilhelm et al., 2018).

Other research activities are investigating alternative methods to overcome a range of soil constraints including acidity and water repellency to further improve grain yield with cost effective

Table 4. Summary of marginal economic benefits from deep ripping at Peebinga (2018, 2019) and Buckleboo (2019).

		Tine spacing (30cm)				Tine spacing (60cm)			
	Depth (cm)	20	40	60	70	20	40	60	70
	Estimated cost ($/ha)*	40	60	90	100	30	50	70	80
Peebinga 2018	Yield change from control (t/ha)	0.19	0.25	0.56	0.48	-0.04	0.16	0.42	0.57
	Value of extra yield ($/ha)	42	55	123	106	-9	35	92	125
	Marginal benefit ($/ha)	**2**	**-5**	**33**	**6**	**-39**	**-15**	**22**	**45**
Peebinga 2019**	Yield change from control (t/ha)	0	0.27	0.3	0.62	0.08	0.09	0.26	0.57
	Value of extra yield ($/ha)	0	78	87	180	23	26	75	165
	Marginal benefit ($/ha)	**0**	**78**	**87**	**180**	**23**	**26**	**75**	**165**
Buckleboo 2019	Yield change from control (t/ha)	0.58	0.67	1.34	0.94	0.17	1.25	0.82	1.42
	Value of extra yield ($/ha)	145	168	335	235	43	313	205	355
	Marginal benefit ($/ha)	**105**	**108**	**245**	**135**	**13**	**263**	**135**	**275**

**Estimated cost of deep ripping extrapolated from Davies et al., 2017.*

***Cost of deep ripping has only been factored in once in 2018, and therefore, the value of extra yield in 2019 is the same as the marginal benefit in 2019 because there is no cost associated with ripping.*

Assumptions. Price of wheat @ $250/t (2018), $290/t (2019), and barley @ $220/t (2018), $250/t (2019)

(Source: http://image.info.cargill.com/lib/fe911574736c0c7e75/m/1/Wheat_SA_Mallee_UpperSE.pdf http://image.info.cargill.com/lib/fe911574736c0c7e75/m/1/Barley_Feed_SA.pdf)

soil modification and ameliorants (Masters and Davenport 2015, McBeath et al. 2018). Common modifications and ameliorants being investigated include delving and spading, and incorporating gypsum, lime, clay, fertilisers or organic matter. However, with all of these soil amelioration strategies it is important to take into consider practices to minimise the risk of wind erosion, especially on sandy soils with low amounts of stubble cover.

Conclusions

Slow and restricted crop root growth caused by subsoil compaction can often reduce uptake of water and nutrients and poor growth, yields and profits, while increasing the risk of erosion. Soil amelioration, using strategic deep ripping is costly and time consuming and multiple constraints may occur variably within a paddock, so careful diagnosis of compaction is critical to targeting the right practice in the right location.

Our trials in the dry 2018 and 2019 seasons have shown that ameliorating compacted sandy soils in low rainfall environments of SA often improves crop biomass and grain yield significantly. Ripping with narrow tine spacing (30cm) or wide tine spacing (60cm) gave similar outcomes in terms of grain yield responses, therefore wider tine spacings of 50-60cm which require less fuel and machinery horsepower should be considered.

Ongoing research is showing that deep ripping alone may not be the ultimate strategy to improving soil productivity and crop performance. Where water repellency, acidity, other constraints occur in conjunction with compaction, other practices could improve the longevity of benefits and overall returns on investment.

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The research undertaken as part of this project is made possible by the significant contributions of growers (Gum-Peebinga, Schaefer-Loxton, Baldock-Buckleboo) through both trial cooperation and the support of the GRDC, the author would like to thank them for their continued support. SAGI for statistical analysis and support.

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Future farm - towards an improved sensor-based approach to nitrogen management

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GRDC project code: CSP1803-020RMX

Keywords

- site specific management, proximal canopy sensing, soil sensing, spatially distributed on-farm experimentation.

Take home messages

- Future Farm is a large multi-institutional project which seeks to improve nitrogen (N) fertiliser decision making through the automated use of crop and soil sensors and other on- and off-farm data sources.
- Early results from the field-based component of the research confirms the idea that an N fertiliser decision is a multivariate decision in which many factors contribute to the decision. That is, reliance on crop canopy sensing alone is unlikely to be effective.
- Further work is aimed at developing appropriate multivariate models to support improved, site-specific N fertiliser decision making.

Background

Optimising the efficient use of nitrogen (N) fertiliser is an important driver of both profitability and productivity on cereal enterprises across Australia, typically representing approximately 30-40% of total input costs for a given season, with farmer risk shown to be closely related to the magnitude and effectiveness of expenditure on N fertiliser (Monjardino et al., 2013, 2015). On an industry-wide basis, the Australian grains sector applies approximately 1Mt N fertiliser annually (Angus and Grace, 2017), yet crop recovery of fertiliser N in the year of application is only around 45% (Angus et al., 2019). One way to optimise N use is to use the tools of Precision Agriculture (PA) to deliver on the '4 Rs' – putting the **right** amount of the **right** product in the **right** place at the **right** time. However, in the absence of well defined, site-specific norms to underpin the '4 Rs', implementing such strategies can require a substantial investment in time spent acquiring, processing and analysing data and may involve several steps that are not well integrated. Given the results of a recent survey (Bramley and Ouzman, 2018) which showed that farmer adoption of soil and crop sensors is low, and that confidence in the various decision aids which support N management is equivocal, there is an opportunity to re-examine and improve the way in which soil and crop sensors are used to inform decisions on N management.

The Future Farm project is supported by a joint investment by GRDC, CSIRO, the Universities of Sydney and Southern Queensland, Queensland University of Technology and Agriculture Victoria and is supported by a growing list of collaborating farmers. It aims to re-examine and improve the way in which soil and crop sensors are used to inform decisions on input management and to provide a way of automating the process from data acquisition, through analysis, to the formulation and implementation of decision options. Whilst the initial focus is on improving the efficiency and profitability of applied N, Future Farm is not a nutrition project per se. Rather, the main research focus is on the adaptive generation of site-specific management models through increased and improved use of in-season field monitored data (soil, crop, climatic), historic on-farm data, external public and private data and automation of decision rules in software that may potentially be linked to real-time application equipment. Further to a number of preliminary review projects (Bramley and Ouzman, 2018; Chlingaryan et al., 2018; Colaço and Bramley, 2018; Lawes et al., 2019), the development of such a decision aid is being based on the following identified operational targets:

- N fertiliser application decisions should be supported by measures of plant N status (which in turn requires estimation of biomass), soil N status and soil water status/availability (i.e. a multi-sensor approach is required), together with assessment of the relative importance of measures of these attributes.
- The decision support aid will use sensor data as a key input and employ machine learning methods of data integration for development of location-specific decision options.
- Both remote and proximal sensing of the crop canopy will make an important contribution to N fertiliser decision-making, but need to be supported by some form of on-farm experimentation, with a zero N treatment (plot or strip); a critical enabler for interpretation.
- Publicly available on- and off-farm data (soil survey data, weather and climate data sourced from the Bureau of Meteorology) along with historic yield monitor data and remotely sensed imagery (both on-farm and from adjacent areas) may provide valuable input to the decision tool.
- The decision tool will be deployable in a way that will be complementary to the inclusion of other inputs/assessments that farmers and their advisers may also apply in decision making.

Key to the project is the recognition that in contrast to the univariate, plot-based, mechanistic approach used in much of the sensor-based N research (Colaço and Bramley, 2019), an N fertiliser decision is a multivariate decision in which the farmer and/or his/her adviser combines information from multiple sources; knowledge of historical paddock performance, crop and soil sensors, historical spatial data, publicly available datasets (for example; satellite imagery and weather data) and crop models, to predict the optimum N decision or variables that can be used for an N decision. Recognising the site-specific nature of the decision, it may be further informed by on-farm trials which are paddock-scale and spatially distributed (Bramley et al., 2013) and implemented and monitored using precision/digital agriculture tools (for example; variable rate applicators and yield monitors). In the present paper, we focus solely on the South Australian-based components of the Future Farm research, involving the use of proximal crop and soil sensing coupled with on-farm experimentation. We note however, that Future Farm is a national project with similar complementary field research to that described here being undertaken in each of the GRDC grain growing regions. Further information on the other components of the project are available in the proceedings of GRDC Updates (2020) held in other locations and, in the case of the use of off-farm data for on-farm decision support, in Fajardo (2019) and Fajardo et al., (2019).

Method

The four-year field program initiated in 2018 comprises two types of on-farm experiments; referred to here as 'core' and 'satellite' sites. Both employ spatially distributed, strip-based designs and 'target' calibration points where plant and soil samples are collected. Experiments at 'core' sites were designed with three specific objectives:

- To provide on-farm estimates of the optimum N rate (ONR) against which a multivariate sensor-based model can be calibrated;
- to enable investigation of the value of 'N-rich' and 'N-minus' strips as a 'business as usual' approach to in-season prediction of ONR and thus, fertiliser decision making; and
- to provide a range of crop and soil conditions from where sensor calibration data can be taken.

On-farm experimentation

'Core' sites

Figure 1 shows the experiment implemented in 2018 at the 'core site' near Tarlee, South Australia (SA). In a 64ha paddock, N-rich and N-minus strips were established using a liquid fertiliser sprayer of 39m width, split into three sections such that the N-rich strip was 26m wide, whilst the N-minus strip was 13m wide. After crop emergence (early June), the N-rich strip received 85kg N/ha. Additional N was applied to the paddock on three further occasions until flag leaf emergence; in early (28kg N/ha) and mid-July (38kg N/ha), and late August (34.5kg N/ha), the first two of these excluding the N-minus area and the last one across the

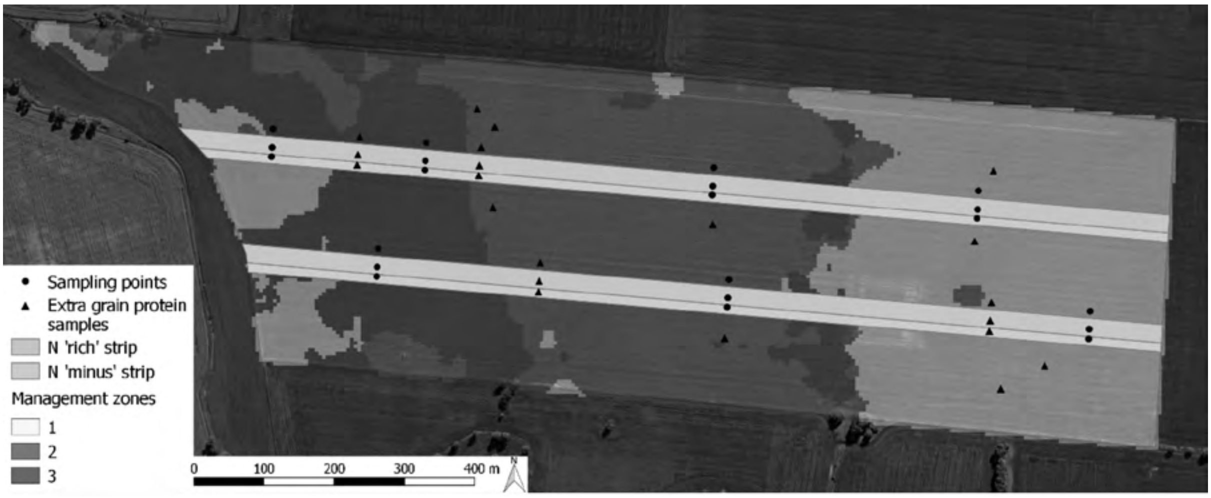

Figure 1. Trial layout at the 64ha South Australian 'core' site near Tarlee, in 2018.

entire paddock area. Given that mono-ammonium phosphate (MAP) applied at sowing resulted in an initial application to the whole paddock of 10kg N/ha, the final N rates applied were 195, 110 and 45kg N/ha for the 'rich', 'paddock' and 'minus' area, respectively. The strips were located such that they crossed the different management zones in the paddock, which were previously defined based on a cluster analysis of historical yield and soil electrical conductivity maps. For crop sensor calibration, 21 target locations spread across zones and strips were defined for soil and plant sampling. Three soil moisture probes (sensing to 1m depth) were installed, one for each management zone of the paddock; these were in addition to one already installed in the paddock. More details on the data collected is available in Table 1.

'Satellite' sites

The 'core' experimental sites were supplemented from 2019 by numerous 'satellite' sites based on a simpler experimental design and less intense monitoring; these are farmer-initiated N strip trials used to guide their mid-season N decision. The

Table 1. The range of data collected at the South Australian 'core' site.

Variable	Source	Sampling intensity	Crop stage
Vegetation indices	Proximal on-the-go (CropCircle™) and remote sensing (Sentinel imagery)	Whole paddock	GS22-23, GS31 and GS33-34
Visible and near-infrared crop reflectance	Proximal hyperspectral sensing (hand-held ~300-1800nm in ~1.5nm increments)	Multiple target points	GS31
Grain yield and protein	Yield and protein monitors at harvest on-the-go	Whole paddock	Harvest
Crop height and biomass	Light detection and ranging (LiDAR) on-the-go	Whole paddock	GS31
Biomass, plant N concentration, and other plant nutrition status	Plant sampling	Multiple target points	GS31 and at harvest
Soil N, other fertility status and texture	Soil sampling	Multiple target points	Pre-sowing, GS31 and harvest
Soil moisture	Soil moisture probe (insert type)	One target point in each zone	Daily across season
Soil drained lower and upper limits, bulk density	Soil profile characterisation	One target point in each zone	-
Soil electrical conductivity, soil gamma radiation, historical yield, etc.	Historical data base from farm records and previous research projects	Whole paddock	-

purpose of these trials to Future Farm is to broaden the range of biophysical conditions (soils and climate, especially rainfall) over which we collect data for calibrating the crop sensors for prediction of variables that can be used in N decision models; for example, mid-season crop biomass, plant N uptake and yield potential. In the southern region one 'core' site and seven 'satellite' sites were implemented in 2019.

Figure 2 shows the experimental design implemented in a 'satellite' trial located near Loxton, SA. At seeding, the farmer applied a 12m width strip with 46kg N/ha alongside a zero N strip, to guide his mid-season N decision. The paddock was divided into productivity zones based on historical yield maps. Twelve target points across the strips/zones were selected for crop scanning and plant sampling.

Data analysis

Interpolation of yield maps, establishment of management zones and other basic analysis of PA data followed accepted methods predominantly based on those outlined in Taylor et al., 2007 and implemented using PAT (Ratcliff et al., 2019). Here, the focus is on the analysis of the experimental data.

Two main approaches were followed for analysis of experimental data:

- Prediction of ONR (i.e. building an N decision model); and
- prediction of relevant variables for N management (mid-season crop biomass, plant N uptake, yield potential and grain N uptake) which can be used for a given N decision model.

Both approaches draw on our multivariate dataset.

The dataset from the 2018 core site in SA and the calibration dataset from SA in 2019 ('core' and 'satellite' sites) are used here to illustrate some of the analysis being explored in this project.

With the 2018 'core' dataset, the difference in grain N removal between the N-minus and N-rich strips was calculated along the length of the strips in increments of 10m using the point data from the yield and protein monitors. These paired comparisons were also analysed using the moving window t-test of Lawes and Bramley (2012). The difference between the N-minus and N-rich strips was also used to calculate an N recommendation (in this case, the N rate which will maximise grain N removal) along the length of the paddock based on a given fertilisation efficiency factor (N rate = N removal difference between strips / fertiliser efficiency factor). Other options for N rate calculations will include an N budget approach based on soil data collected around each of the target points and crop modelling. In time, grain and fertiliser prices may also be added for the estimation of economically optimum N rates.

The normalized difference vegetation index (NDVI) and the normalized difference red-edge index (NDRE), measured at GS31 and obtained from both the CropCircle™ proximal canopy sensor and Sentinel satellite imagery, were used to calculate response indices (ratios between N-rich and N-minus strips; Raun et al., 2005) and examined as predictors of the final crop response to N and N requirement.

For demonstration of the second analytical approach, sensor calibrations for mid-season crop biomass, plant N uptake, grain yield, grain protein concentration and grain N uptake were generated based on the 2019 dataset using the target sampling locations.

For this paper, the results of simple linear regressions for both approaches are presented. It is the intention that these analyses will be

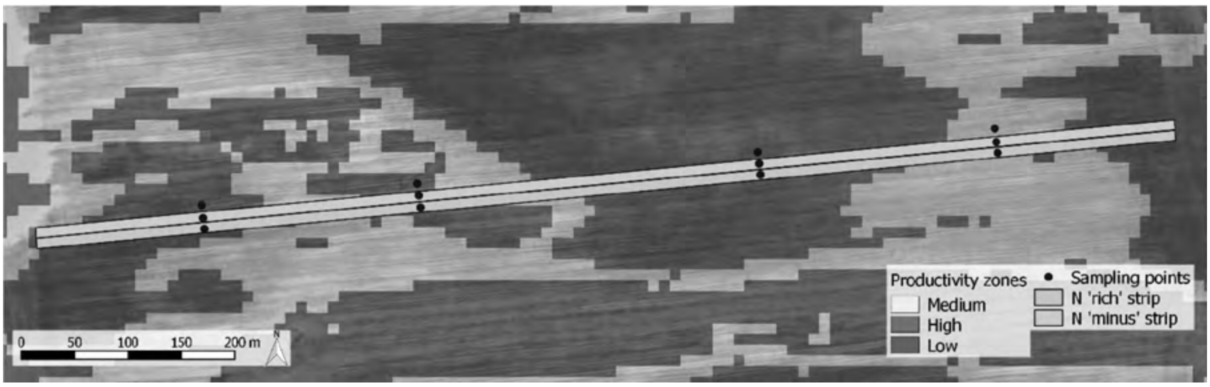

Figure 2. Trial layout at a South Australian 'satellite' site near Loxton, in 2019.

enhanced using machine learning techniques to implement multivariate prediction algorithms. For the development of an N decision algorithm, such analyses will allow the assessment of which combination of variables can best predict ONR and where they should be measured (within reference areas (for example; N-rich, N-minus), under normal field conditions or both). The focus here on simple linear regression is to emphasise the need for a more multivariate approach.

Results and discussion

Figure 3 illustrates the results obtained from the strip analysis for the 'core' 2018 trial. Based on the difference observed between the N strips, it is seen that the crop responded to N mostly in terms of grain protein concentration and less so in terms of grain yield. As expected, grain N removal was greater in the N-rich compared to the N-minus strip, although to a varying extent along the strip. Consequently, the recommended N rate was also variable along the examined area. The relationships between vegetation indices and crop parameters were generally weak, especially for the Crop Circle data (Table 2), although the general trends of significant yield differences between strips (mainly between the 900 and 1250m marks, Figure 3) were identified by the sensors mid-season. Simple ratios between vegetation indices measured in the N-rich and N-minus strips were also poor predictors of crop response to N and of N requirement (Table 2), which might be partially due to the difficulty of predicting grain protein concentration by the sensors. However, and as expected, given the previous work of Colaço and Bramley (2019), mid-season predictions of harvest parameters (grain yield, grain protein and grain N uptake) and N demand based solely on vegetation indices were not successful. That is, a univariate approach based on sensor data alone, is not a sound basis for N fertiliser decision making. Further analysis will investigate the benefit of combining more prediction variables for multivariate models.

Figures 4 and 5 show the relationships between Crop Circle indices and crop parameters at mid-season (N concentration, dry weight and N uptake) and at harvest (grain yield, grain protein and grain N uptake) for the 2019 SA trials. Overall, sensor calibrations for individual sites were poor. Whilst the sensor indices are sensible to variations in some crop parameters (particularly to crop biomass), relationships between sensor and crop variables can be site-specific. Nonetheless, global calibrations were produced reaching R2s of up to 0.65 (for NDRE vs mid-season N uptake). As expected, predictions of harvest parameters were more difficult than prediction of mid-season crop measures. Again, further analysis will explore the use of multivariate models to improve predictions of such parameters.

The strip analysis shown for the 2018 'core' site (Figure 3) demonstrates the approach's ability to generate data (observations of crop parameters and crop response to N) that covers a range of biophysical conditions within a single paddock for the calibration of sensor-based decision models. The study was able to capture an even greater range of variability for the sensor calibrations through the farmer-led 'satellite' trials; both 'core' and 'satellite' trials highlighting the value of on-farm experimentation in developing a basis for site-specific decision making. Thus, just as the technologies of precision and digital agriculture (PA/DA) promote an ability for these new spatially distributed approaches to field experimentation, the successful adoption of PA/DA (for N management in this case) is likely reliant on such experimentation for the development of management norms appropriate to the farming system at any given location. The approach being used in Future Farm is reflective

Table 2. Correlation (*r*) between vegetation indices and harvest parameters. 'Response' was calculated as the ratio between N-rich and N-minus values.

	Grain yield	Grain protein	Grain N uptake	Grain yield response	Grain protein response	Grain N uptake response	Recommended N rate
Crop Circle NDVI	0.34	0.18	0.46	-	-	-	-
Crop Circle NDRE	0.33	0.27	0.51	-	-	-	-
Sentinel NDVI	0.56	-0.10	0.50	-	-	-	-
Sentinel NDRE	0.44	0.23	0.59	-	-	-	-
Crop Circle NDVI response	-	-	-	0.31	-0.13	0.18	0.14
Crop Circle NDRE response	-	-	-	0.32	-0.10	0.18	0.15
Sentinel NDVI response	-	-	-	0.59	-0.25	0.40	0.37
Sentinel NDRE response	-	-	-	0.38	-0.04	0.25	0.20

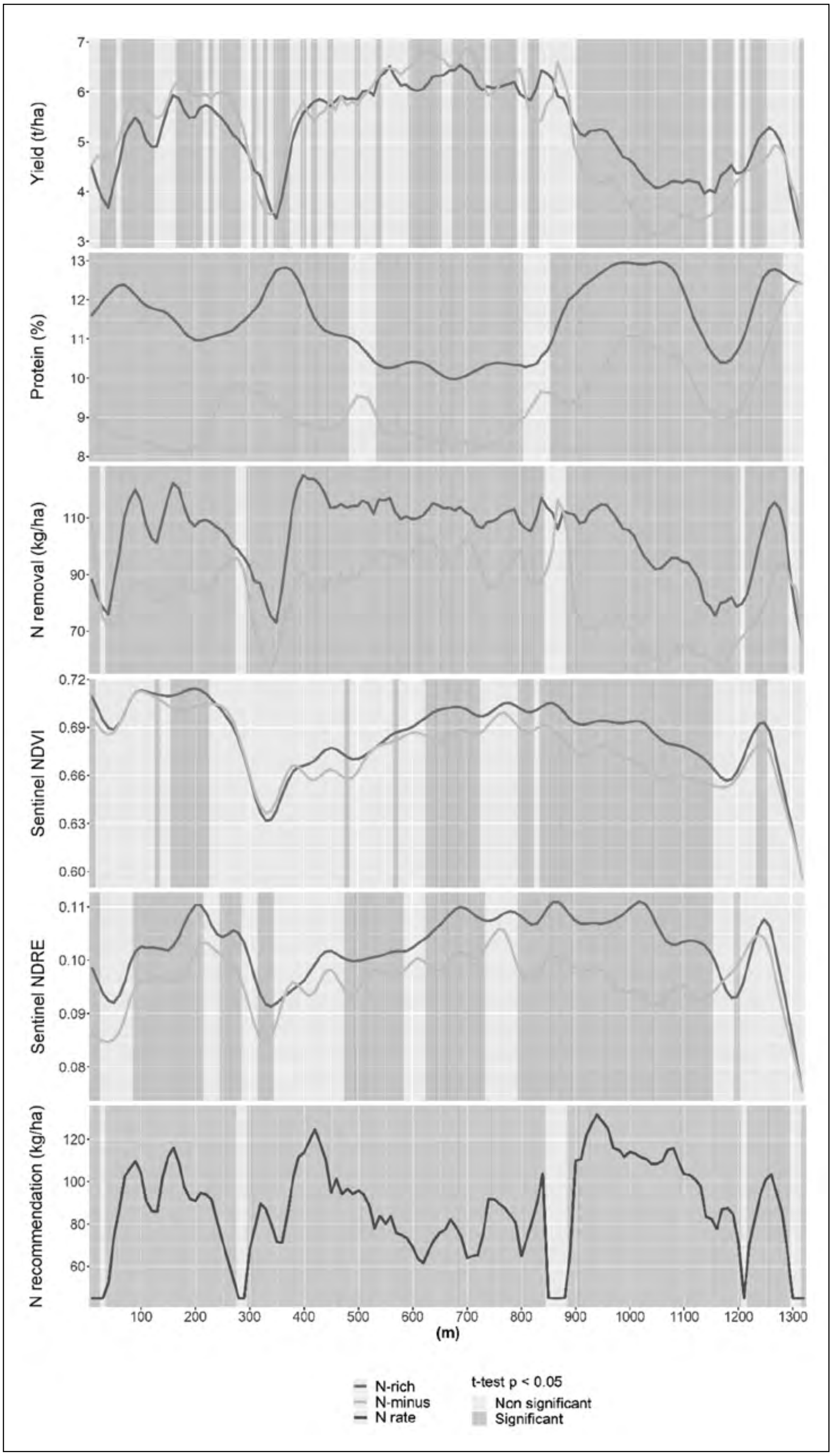

Figure 3. Grain yield, grain protein, grain N removal and mid-season crop normalized difference vegetation index (NDVI) and the normalized difference red-edge index (NDRE from the Sentinel satellite across the length of N-rich and N-minus strips (top five graphs)) (results of strip comparison based on moving window t-test shown in different background colours) and N rate recommendation (bottom graph) along the length of the strips.

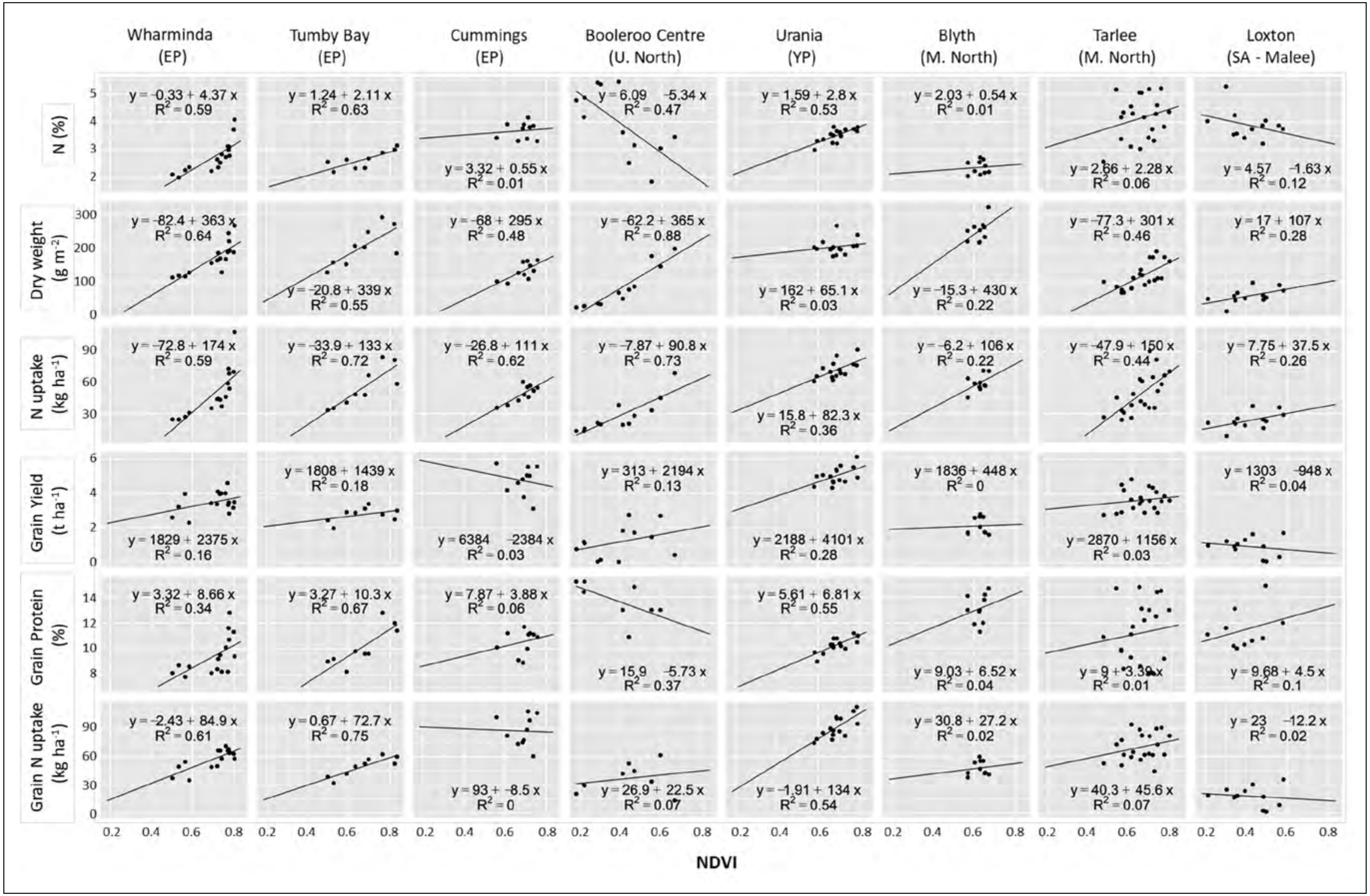

Figure 4. Crop Circle calibration data for each of the 2019 experimental sites in South Australia (top three rows refers to crop parameters around GS31-33).

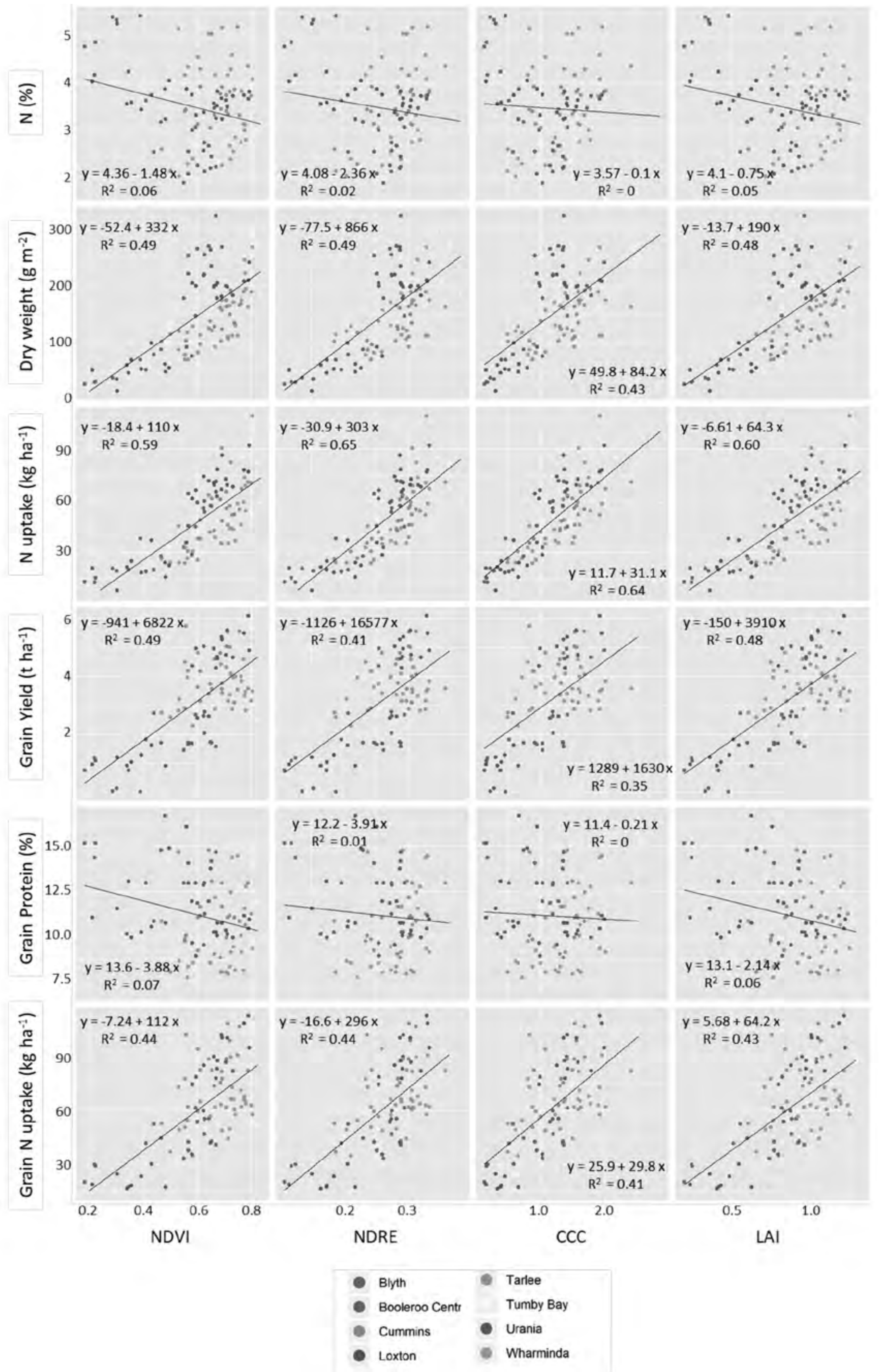

Figure 5. Crop Circle sensor calibrations using pooled data for all South Australian sites in 2019.

of this, in that our focus is on the development of an appropriate process for the acquisition and analysis of multivariate data to inform site-specific management. Thus, we are using the techniques of PA/DA to move away from the idea that norms for fertiliser management are ubiquitously applicable. It is hoped that the merits of this approach will be demonstrated in future updates to industry.

Conclusion

N fertiliser decisions are a multivariate issue which therefore require multivariate input. Future Farm is seeking to develop an automated, sensor-based approach to the delivery of site-specific decision support. Results to date confirm that a univariate approach based solely on either satellite imagery or proximal crop canopy sensor data alone is unlikely to deliver value to farmers. Moving forward, the focus will be on adding value to such sensor data through the development of multivariate N decision models.

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Useful resources

A video describing much of the above work at our SA 'core' site is available at https://www.youtube.com/watch?v=mGtYdi0Re0g&feature=youtu.be

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The 10 key lessons from the Optimised Canola Profitability project

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GRDC project code: CSP00187

Keywords

- canola, variety, sowing time, phenology, risk management, nitrogen.

Take home messages

- Lesson 1: Crop planning and preparation.
- Lesson 2: Variety selection.
- Lesson 3: Matching varietal phenology with sowing time.
- Lesson 4: Sow slow spring canola late March to mid-April.
- Lesson 5: Sow mid spring canola mid-April to early May.
- Lesson 6: Sow fast spring canola late April to mid-May.
- Lesson 7: Apply post-sowing nutrition as required.
- Lesson 8: Understand the critical growth period.
- Lesson 9: Harvest management.
- Lesson 10: Evaluate financial performance.

Background

Between 2014 and 2019 research to better understand the yield drivers of canola was conducted in southern and eastern Australia through the Optimised Canola Profitability (OCP) project, which is a project supported by a joint investment from CSIRO, NSW DPI and GRDC.

The aim of the project was to improve canola profitability through a better understanding of how phenology and physiology can guide tactical agronomy to improve canola yield and profit in different environments. This research is targeted at low to medium rainfall zones and is a collaboration between CSIRO, NSW DPI and GRDC, in partnership with SARDI, CSU, MSF and BCG (CSP00187). The project links closely with similar GRDC supported projects in Western Australia and in high rainfall zones (HRZ). From southern Queensland, through New South Wales (NSW), and into Victoria (Vic) and across to South Australia (SA) the OCP Project has conducted a range of field experiments and modelling simulations to improve canola profitability in the region.

This article will summarise ten of the key findings in the project, with further information available in the '20 tips for profitable canola' guide found online here: https://grdc.com.au/resources-and-publications/all-publications/publications/2019/20-tips-for-profitable-canola-south-australia

Lesson 1: Crop planning and preparation

The two most important factors to consider when selecting paddocks for canola are nitrogen (N) and stored soil water. Growing canola after a pulse crop or long fallow will ensure relatively high N and plant available water (PAW) levels. In the low rainfall zones of SA (Upper Eyre Peninsula, Upper North and Mallee) it is risky to sow canola when either water or N levels are low, and especially when both are low. In South Australian areas with reliable winter and spring rainfall, selecting paddocks with high starting N will increase crop yield potential, especially for hybrid canola varieties.

Lesson 2: Variety selection

There are three key decision areas with variety selection:

1. Varietal phenology.

Each canola variety has a set of triggers that drive its development and control flowering time; thermal time (day degrees), vernalisation (cold) and photoperiod (day length). Each of the development triggers could play a different role in each variety.

2. Breeding type (hybrid or open-pollinated).

Whilst open pollinated (OP) canola varieties dominate much of the area planted in SA (due to reduced seed costs from retaining seed), hybrids are increasing in area as they currently offer a wider range of phenology, herbicide tolerance options, and disease resistance levels, as well as producing higher yields as varieties improve.

3. Herbicide tolerance

It is important to consider the spectrum of weeds (and resistance status) that may need controlling when selecting a canola variety so that the appropriate varietal herbicide tolerance is selected. Canola's critical role as a break crop for weeds needs to be achieved to maximise benefits of their use.

Table 1. Phenology, maturity, herbicide tolerance and breeding type rating of most of the modern canola varieties.

Variety	Phenology[#]	Maturity	Herbicide tolerance	Breeding type (hybrid or OP)
Nuseed Diamond	Fast	Early	Conventional	Hybrid
ATR Stingray	Fast	Early	Triazine	OP
Hyola®350TT	Fast	Early	Triazine	Hybrid
SF Spark TT	Fast*	Early	Triazine	Hybrid
Hyola®506RR	Fast	Mid-early	Roundup Ready	Hybrid
Hyola®580CT	Fast	Mid-early	Imi/Triazine	Hybrid
HyTTec® Trident	Mid-fast	Early	Triazine	Hybrid
Hyola®550TT	Mid-fast*	Mid	Triazine	Hybrid
InVigor®T3510	Mid-fast*	Early to early-mid	Triazine	Hybrid
Banker CL	Mid-fast	Mid	Imidazolinone	Hybrid
InVigor®T4510	Mid-fast	Early-mid	Triazine	Hybrid
Saintly CL®	Mid-fast	Early-mid	Imidazolinone	Hybrid
Pioneer®44T02 (TT)	Mid-fast	Early-mid	Triazine	Hybrid
Hyola®530XT	Mid-fast*	Mid	Truflex/Triazine	Hybrid
Xseed™Raptor	Mid-fast*	Mid-early	Truflex	Hybrid
Hyola®410XX	Mid-fast*	Mid-early	Truflex	Hybrid
ATR Flathead	Mid-fast*	Early	Triazine	OP
ATR Bonito	Mid-fast	Early to early-mid	Triazine	OP
InVigor® R4022P	Mid-fast*	Mid-early	Truflex	Hybrid
Pioneer®43Y92 (CL)	Mid-fast	Early	Imidazolinone	Hybrid
Pioneer®43Y29 (RR)	Mid-fast*	Early	Roundup Ready	Hybrid
Pioneer®44Y27 (RR)	Mid-fast	Early-mid	Roundup Ready	Hybrid
Pioneer 44Y90 (CL)	Mid-fast	Early-mid	Imidazolinone	Hybrid
ATR Mako	Mid-fast	Mid-early	Triazine	OP
Nuseed Quartz	Mid	Mid to mid-early	Conventional	Hybrid
HyTTec®Trophy	Mid	Early to early-mid	Triazine	Hybrid
Pioneer®45T03 (TT)	Mid	Mid	Triazine	Hybrid
ATR Gem	Mid	Mid-early	Triazine	OP
DG 670TT	Mid	Mid	Triazine	Hybrid
GT-53	Mid	Mid	Roundup Ready	Hybrid
Victory V75-03CL	Mid-slow*	Mid	Imidazolinone	Hybrid
Pioneer®45Y93 (CL)	Mid-slow*	Mid	Imidazolinone	Hybrid
Pioneer®45Y91 (CL)	Mid-slow	Mid	Imidazolinone	Hybrid
InVigor®R5520P	Mid-slow	Mid to mid-late	Roundup Ready	Hybrid
SF Ignite TT	Mid-slow	Mid to mid-late	Triazine	Hybrid
ATR Wahoo	Mid-slow	Mid-late	Triazine	OP
Pioneer®45Y25 (RR)	Mid-slow	Mid	Roundup Ready	Hybrid
Archer	Slow	Mid-late	Imidazolinone	Hybrid
Victory 7001 (CL)	Slow	Mid-late	Imidazolinone	Hybrid
Phoenix CL	Winter	Winter	Imidazolinone	Hybrid
Edimax CL	Winter	Winter	Imidazolinone	Hybrid
Hyola®970CL	Winter	Winter	Imidazolinone	Hybrid

 # Phenology response to early sowing. Rankings may vary for later sowing dates. Varieties are ranked from fastest to slowest within phenology groups

** One-year (2019) experiment data only*

Lesson 3: Matching varietal phenology with sowing time

Optimal start of flowering in canola

The optimal start of flowering (OSF) for canola has been identified for locations across Australia a subset of which is displayed in Table 2.

The duration and timing of the OSF varies with site and season but not with variety. Sowing date by variety combinations that achieve OSF and maximise yield have been identified.

- Flowering in the OSF period maximises average yield.
- Flower too early: the risk of frost stress during early grain fill is high.
- Flower too late: the risk of heat stress during flowering is high.
- Flowering too late increases the risk of water stress.
- Locations differ in the relative importance of frost, heat and water stress.

Lesson 4: Sow slow spring canola late March to mid-April

Slow developing spring canola can be sown from late March to mid-April. Slow spring varieties respond to vernalisation, so they require more thermal time to flower when conditions are warm (for example, from early sowing) than when it is cold (later sowing). Slow spring varieties sown in this window will still flower at the optimum time in SA. There are currently both hybrid and OP varieties available to sow in this window (Table 2). Attention to detail in the fallow period will also increase the likelihood of canola establishing well from a March/ early April sowing. Consider the likelihood of having enough moisture for canola to germinate in this period before selecting a slow developing variety. Early sowing of slow spring canola is a useful strategy after a wet summer, where the longer vegetative phase (compared with sowing faster varieties later) gives more time for roots to access subsoil water, resulting in higher biomass and higher grain yield. Sowing a slow spring variety is a useful strategy to avoid frost as they have a very stable flowering window, meaning that they will flower in a relatively tight window in late winter/early spring regardless of sowing date and they also provide grazing options on mixed farms.

Lesson 5: Sow mid-spring canola mid-April to early May

Mid-spring canola has universal adaptability in SA. It can be sown from the second week of April if rainfall allows, and will also perform well when sown later, from the last week of April to early May. These mid-spring varieties often have a subtle vernalisation response (less than slow spring canola). This means that they are slower in warm autumn conditions than fast spring varieties. When sown later (late April to early May), this small vernalisation requirement is quickly met, so mid spring varieties may not be significantly slower than fast spring varieties from

Table 2. Optimal start of flowering date for canola growing localities in South Australia.

Location	Optimal start of flowering date	Acceptable range (days)*	Soil type	PAWC ** (mm)
Bute	18 July	42	Red sandy clay loam	139
Kadina	18 July	36	Calcic loam	102
Lameroo	19 July	32	Loamy sand	90
Yeelanna	19 July	53	Duplex	152
Minlaton	21 July	43	Red sodosol	88
Loxton	21 July	25	Sand	118
Wudinna	22 July	20	Red sandy clay loam	139
Karoonda	22 July	33	Sandy loam	136
Hart	25 July	37	Clay calcarosol	183
Booleroo	26 July	31	Clay loam	128
Naracoorte	28 July	29	Dark grey clay	80
Spalding	29 July	38	Red chromosol	143
Tarlee	4 August	47	Duplex	225
Bordertown	11 August	34	Grey vertosol	128

** Maximise yield by flowering in the period around the optimum flowering date. For example, at Hart canola should start flowering between 6 July and 12 August (from 19 days before 25 July to 19 days afterwards).*

***PAWC = plant available water content (mm) of predominant soil type.*

(Source: Lilley et al., 2019; further information at http://www.canolaflowering.com).

later sowing. In an ‘average’ season, mid-spring canola varieties have similar yield across sowing dates (not necessarily the highest at any one date), whereas slow spring varieties are higher yielding from early sowing and fast spring varieties higher yielding from later sowing.

Lesson 6: Sow fast spring canola late April to mid-May

Fast developing spring canola varieties have little to no vernalisation response. These varieties are suitable for sowing in late April to mid-May. When sown earlier, fast spring varieties develop rapidly and can be exposed to frost damage (dry frosty years) and disease (wet years) or produce low biomass. Sowing fast spring varieties early resulted in significant grain yield penalties from disease (2016) and frost (2014 and 2018) across OCP experiments in SA. In contrast, at very high yielding sites (> 4t/ha) fast spring canola sown late often had the highest yield.

Unlike mid-spring canola, there is little flexibility in the sowing window of fast spring canola. Fast spring canola is best suited to systems where sowing is likely to be later in the window, and in low rainfall environments. In seasons where there is a wet summer followed by dry winter, fast spring canola can be penalised as there is not enough time to access water stored deep in the subsoil.

Lesson 7: Apply post-sowing nutrition as required

Once the crop has established well and growers and agronomists have a better gauge of the season, further N decisions need to be made.

The average seed protein content across all OCP experiments was 22.6%. On average N removal in grain was 36kg N/t. Assuming 50% efficiency, 72kg N/ha was required for each t/ha expected yield.

Protein ranged from 17% (low N, high rainfall sites) to 32% (low rainfall, high N sites), meaning that N removal ranged from 27 to 51kg N per tonne of grain. Seed protein concentration was always negatively correlated with oil concentration, so as protein increased, oil declined. On average, oil and protein comprised 64% of the canola seed. Nitrogen use efficiency was highly variable across trials, but a rule of thumb is to use a figure of 50%, meaning that 50% of the N available to the crop (mineral N at sowing + mineralisation in-crop + fertiliser inputs) will be converted into grain (in an average season). Therefore, growers should budget on 72kg/ha N (through a combination of mineral N at sowing + mineralisation in-crop + fertiliser inputs) per tonne of targeted grain yield.

Despite being one of the most widely researched aspects of grain production, there have been few major advances in N nutrition management over the

Table 3. Recommended sowing dates for key South Australian locations for three phenology types. Following these sowing guidelines will ensure varieties flower within their ideal OSF window.

		March				April				May			
		1	2	3	4	1	2	3	4	1	2	3	4
Lameroo	Slow												
	Mid												
	Fast												
Hart	Slow												
	Mid												
	Fast												
Yeelanna	Slow												
	Mid												
	Fast												

Dark shade = optimum sowing time; all other shading = earlier or later than optimal.

time canola has been widely cultivated. However, it is known that under intensive cropping the levels of soil organic C, and therefore, the ability of the soil to supply N to crops is in decline. This means that in the future more fertiliser N may need to be supplied or more efficient techniques to achieve crop yield need to be found. Applying N by mid-row banding may be a useful option as a method of using available inputs in a different way and there has been some recent research on mid-row banding N in cereals. Further experiments exploring mid-row banding of N fertiliser for canola nitrogen use efficiency are underway.

Lesson 8: Understand the critical growth period

All grain crops have a 'critical period' for yield determination during their growth; when the number of grains, and hence, the yield potential is determined. During the critical period, yield is very sensitive to any kind of stress (for example, water, nutrition, temperature and radiation) and so in any environment it is important to sow and manage crops to minimise the risk of stress and ensure adequate water and nutrients are available to the crop at this time.

The critical period for cereals has been established as the period approximately 20 days before flowering, while for grain legumes it has been identified as the period approximately 20 days after flowering. Surprisingly the critical period for canola had never been identified prior to OCP. Understanding the timing of the critical growth period enables growers to select a sowing date and variety combination which ensures the critical growth period occurs when the growing environment is likely to be the most favourable (balancing risks of water, heat and frost stress). The critical period for canola occurred approximately 350°C days after the start of flowering (Kirkegaard et al., 2018). The crop at this stage has the largest number of very sensitive organs – recently opened flowers, flower buds and small pods. Any significant stress at this time causes the abortion of flowers and pods, and those pods that remain will be smaller and develop fewer and smaller seeds due to the impacts of stress on their developing ovaries during the critical period. Yield was significantly reduced by 40% when stress was applied during this period but was less affected before or after that period (see next section of this paper). Oil% was also reduced by stress during this period.

Managing canola to avoid stress in the critical period

There are two main ways in which growers and consultants can use this information:

1. Careful sowing date and variety selection

Sowing suitable varieties at the correct time to ensure that flowering commences at the optimum time (optimal start of flowering; OSF) will minimise the exposure of the crop to the combined risks of temperature, water and radiation stress.

2. Managing water and N supply

Managing the crop to ensure there is adequate water and N available during the critical period is important. Rainfall may be uncertain, but agronomic strategies can include:

- Good fallow weed and stubble management to conserve summer rain and mineralise N. If there is no fallow rain, it may be better to abandon plans of growing canola in low rainfall environments.
- Sowing canola after grain legumes, hay, pasture or fallow.
- Ensure sufficient N (soil and fertiliser) for yield potential (70–80kg N/t expected seed yield).
- Split N fertiliser application or mid/side row banding to ensure N is available at flowering.

Lesson 9: Harvest management

Windrowing canola is a useful tool to even and hasten the crop ripening process, and to reduce shattering losses at harvest. Industry recommendations in the past state that canola should be windrowed when 40–60% of seeds on the main stem have changed colour from green to red or brown or black. However, more research conducted in northern NSW over four seasons as part of OCP showed that branches contributed up to 80% of grain yield. Seed colour change (SCC) on the branches starts later than the main stem, so relying solely on the main stem for windrowing decisions will underestimate seed colour change across the whole plant. Windrowing early will lead to smaller seed at harvest, lower yield and lower oil concentration.

It is now recommended that windrowing is carried out when 60% of seed sampled from the middle third of main stem and branches across the whole plant has changed colour from green to red, brown or black.

There can also be significant decreases in oil concentration as a result of windrowing at early stages of SCC. At Tamworth, there was a 6.3 percentage point reduction in oil concentration (38.9% versus 45.2%) when windrowing at the start of SCC compared with windrowing at approximately 60% SCC (averaged across the plant). Findings from this study highlight the potential for significant yield and quality penalties due to early windrow timings with yield losses of up to 55% and decreases in oil concentration of up to 7.7% (37.5% versus 45.2%). Seed should be sampled from across the whole plant to accurately assess seed colour change. Furthermore, results demonstrated the potential benefit of delaying windrow timings with yields optimised at the upper end of traditional industry guidelines of 60% or greater SCC.

Lesson 10: Evaluate financial performance

Crop yield and cost of production as well as risk must be considered when determining the profitability of a canola crop. There is a trade-off between gross income and the expense and risk of producing that crop. The profit-risk effect of critical decisions for canola management has been explored including cultivar (hybrid versus OP), time of sowing and sowing conditions (dry sown versus sown on establishment opportunity) and N fertiliser inputs across the project area (examples for SA include Yeelanna, Hart, Mallee, Upper EP and Brinkworth).

Matching variety to the sowing date in order to achieve flowering in the optimal window is critical to maximising canola annual gross margin ($/ha). As an example, at Yeelanna, modelling using data from OCP field trials, showed sowing hybrid canola with adequate N between 16 and 30 April produced an average gross margin of $1,010/ha (ranging from $309 to $1,153/ha). If sowing was delayed to between 1 and 15 May, average gross margin was $942/ha ($-39 to $1,161/ha), with losses in low rainfall years.

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Useful resources

https://grdc.com.au/resources-and-publications/all-publications/publications/2019/20-tips-for-profitable-canola-south-australia

https://grdc.com.au/10TipsEarlySownCanola

http://www.canolaflowering.com

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Notes

Potassium and sulphur - emerging deficiencies in the southern region

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Keywords

- soil test, tissue test, deficiency symptoms, 4R nutrient stewardship.

Take home messages

- Potassium (K) deficiency is likely on acid sands where hay cutting has occurred.
- Soil test critical values for K are likely higher than the current published crop values, and more likely reflect the pasture critical values.
- Sulphur (S) deficiency is likely on lighter low organic matter (OM) soils after a wet summer.
- Deeper soil tests (30 to 50cm) are appropriate to assess S supply.

Background

In some ways it is unusual to discuss K and S together as they are quite opposites in terms of their soil and plant chemistry. Even so, there are some important aspects to consider about the nature of these two essential plant macronutrients that are removed in quite large amounts in grain and hay (Table 1). Unlike in Western Australia (WA), deficiencies of K and S are not currently common within the southern region, and relatively little research has been conducted in this part of the country. But it is important to have these nutrients on your agronomic checklist as deficiencies can occur in particular situations and these appear to be increasing.

Table 1. Approximate removal rates for nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) (Source: International Plant Nutrition Institute (IPNI)).

Crop	Yield target (t/ha)	Removal in product (kg/ha)			
		N	P	K	S
Wheat	3.5	75	12.	14	5
Field pea	2.5	93	10	21	5
Canola	2.5	100	16	23	12
Wheat (hay)	4.0	80	8	48	6
Canola (hay)	4.0	120	12	100	32
Lucerne (hay)	5.0	173	14	100	16

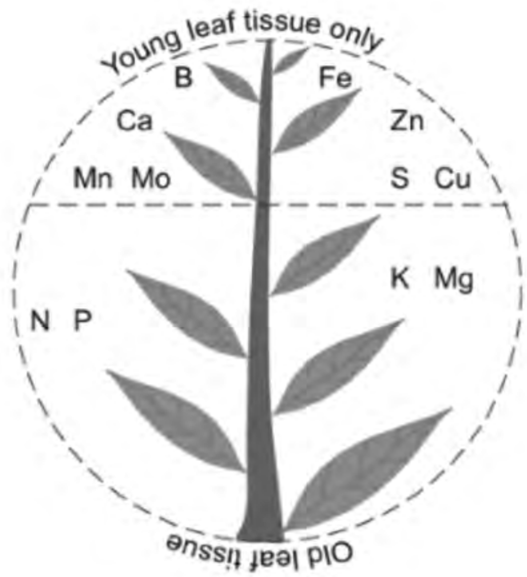

Figure 1. Typical location of mineral deficiency symptoms.

Potassium (K)

K in plants

K is highly mobile in plants and is involved in many essential functions. It serves to regulate water pressure in plant cells, affecting cell extension, gas exchange, and movement of leaves in response to light. K can activate enzymes, assist with protein synthesis, pH regulation, improved carbon dioxide fixation during photosynthesis. It also assists with transport around the plant.

Plants that are supplied with adequate K are also better equipped to withstand stress caused by pests, diseases, and some abiotic stresses compared with plants with a low supply of K.

The amount of K removed from the soil varies greatly among crop species. Table 1 shows the amount of K that it taken up by different crop species and how much is removed from the paddock when the crop is harvested. It shows the difference in K uptake between crops with high demand, such as lucerne, and crops that require less K, such as wheat. It also illustrates that removing crops like lucerne hay or corn silage leaves very little K to be recycled back into the soil, compared to crops where only the grain is removed.

K in soils

Soils are often high in total K, but most of it is unavailable for plant uptake. There are four K pools in any given soil from which the plant can access K. The four pools of K are:

- Structural K is immobile and tightly fixed. Small amounts of K are gradually released as minerals (micas and feldspar) weather over long periods of time.
- Fixed K slowly becomes available (or fixed) over a growing season. K is fixed between layers in clay minerals like illite, vermiculite and smectite, and can be released if the conditions are favourable.
- Exchangeable K is held on the surface of clay minerals and OM by its negative charge and is readily available to the soil solution and plants.
- Solution K is dissolved in the soil solution and available for plant uptake. This is the smallest pool and continually needs to be replenished by the other three pools.

As a cation with positive charge, K is relatively immobile in soil and does not move unless a root comes in direct contact, or it is mobilised into the soil solution. There are three methods by which K comes in contact with the root in order to be absorbed; root interception, mass flow as water moves in the soil and diffusion. Of these, diffusion is the mechanism that moves most of the K in the soil solution. When the root takes up the K in solution in its vicinity, it creates a diffusion gradient that draws other K particles towards the root.

K deficiency

Most agricultural soils in Australia contain sufficient K levels, but deficiencies have been reported in all states and are especially prevalent in areas that receive high rainfall in addition to sandy soils.

Because K is highly mobile within plant tissue deficiency symptoms are generally visible on the older leaves first. Deficiency symptoms include scorching or burning along the leaf margins, and generally poor growth resulting in smaller root systems, small leaves, weak stems (inducing lodging in mature plants) and small and shrivelled grain.

Deficiency may be seen as poor crop growth between windrows or header tracks the previous year. K from the residue of the previous crop is concentrated in rows, resulting in better crop growth in those areas. K is often taken up from deeper in the soil profile as the crop grows, can be leached from the tissue and deposited on the soil surface when the crop is cut and left to dry. This process increases K in the soil surface and the difference between and within windrows is a good ‘diagnostic’ for low soil K.

If a K deficiency is suspected, soil testing is a useful tool to identify the need to apply additional K to the paddock. A soil test that measures 10-30cm as well as the top 10cm may be useful, as a surface test may not reflect K concentrations at depth. The top 10cm may indicate a concentrated supply of K in the soil, but at depth it may be deficient and additional management options may be required to avoid K deficiency. In addition the K concentrated in the surface soil may be less available to the plant as the soil dries.

Soil tests such as Colwell K and ammonium acetate extractions can accurately predict plant available and exchangeable K in low fixing soils. Other tests, such as a nitric acid or sodium tetra-phenyl-borate extraction, are more accurate when it comes to soils with a higher content of multilayer clay minerals. These tests also measure the rate at which K will be released from the fixed pool. Testing for the amount of total or structural K is of little use due to its slow release rate.

The current recommendations on critical soil test (Colwell) K values were largely derived from data generated in WA where deficiency is more common, and are around 40mg/kg for wheat on Tenosols and Chromosols. The most recent work with high yielding crops in southern Victoria suggests that the critical values are more like the pasture critical values of around 120mg/kg.

Fertilising soils with K

Potassium minerals are extracted from geologic sources located throughout the world. Impurities are removed from the ore and the remaining K is transformed into a variety of modern fertilisers.

- Right source - the most commonly used K fertiliser source is potassium chloride (KCl), also referred to as muriate of potash (Table 2). Chloride-free sources of K fertiliser are sometimes preferred for applications to chloride-sensitive horticultural crops, but this is not an issue for broad-acre crops. Compound K fertilisers containing chloride, S and/or magnesium may be warranted when soil supplies of these other nutrients are limiting.
- Right rate - recommended rates of K application are based on both soil testing and crop removal. 'Maintenance rates' are those equal to the quantities of K removed and are used to maintain soil fertility. Cereal crops require less K than pastures or hay crops.
- Right time - in cropping systems, K fertiliser is usually applied at or before seeding. On soils that are sandy and/or have a low capacity to retain K and in high rainfall situations, two or three applications of K fertiliser may be beneficial.
- Right place - K sources vary widely in their effect on the soil solution (salt index) and toxicity may occur if Muriate of Potash is drilled with the seed. K fertiliser sources with a lower salt index may be necessary at higher rates when placed near or in direct contact with seed. Subsurface bands of K can provide benefits over broadcast applications when subsoil fertility is low and where topsoils dry out during the growing season. Topdressing K is also effective on sandy soils in medium to high rainfall environments.

Crop responses to K

The greatest crop responses to K application in Australia have been seen in sandy soils. Maize is the most responsive crop followed by canola, pulses, wheat and then lupins are least responsive. Figure 2 gives some results for wheat responses to K rate, timing and placement in South Australia.

Sulphur (S)

S in plants

Soluble sulphate (SO_4^{2-}) is the primary source of S taken up by plants from the soil. S can sometimes be absorbed through the leaves from the air as sulphur dioxide (SO_2), but this source does not play a significant role in Australian agriculture. Within the plant, S performs many functions, the most important being energy and protein production. S is a constituent of three of the 21 essential amino acids that form proteins. This function is particularly important for cereals as low grain protein correlates to low grain quality. S is also essential for nitrogen (N) fixation by legumes.

Since both S and N are needed for protein formation, these two nutrients are closely linked. Crops have varied requirements for S compared with N and have a wide N:S ratio in the harvested product (Table 1). For example, wheat and chickpea have relatively low S removal, with an N:S ratio in

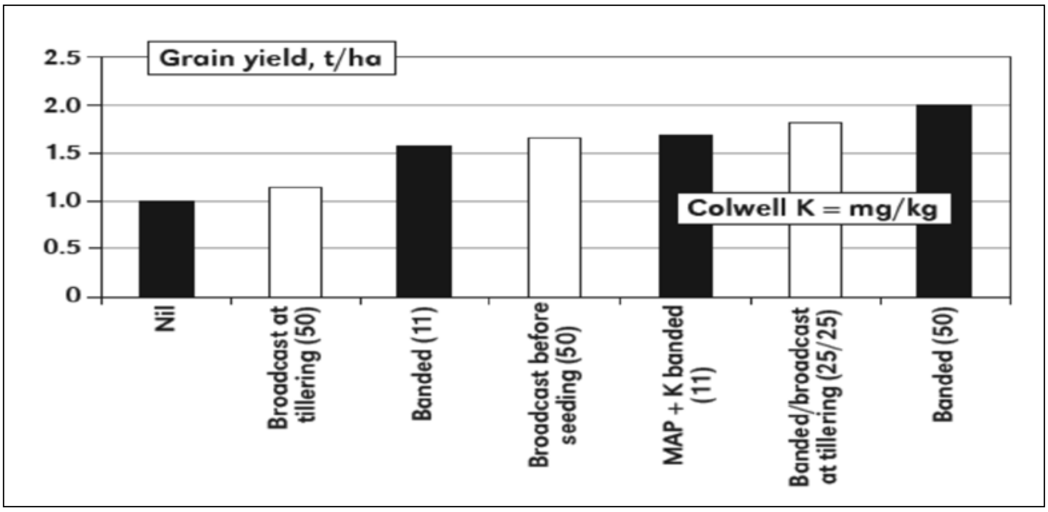

Figure 2. Response of wheat to K applied at different rates (in brackets, K kg/ha), timing and placement (Wilhelm and White, 2004).

grain of 17:1 and 12:1 respectively. Canola however, has a much higher S removal, with a N:S ratio of 8:1 in the seed. While removal ratios do not necessarily determine the nutrient demand, canola and high-yielding forages generally have a higher demand for S than cereal crops.

S in soils

Like N, the majority of S in soil is found in OM and crop residues, and is not immediately available for plant uptake. Before S can be absorbed it needs to be converted to sulphate, which occurs as OM mineralises. Elemental sulphur (S_0, either native or fertiliser) is oxidised to sulphate by common soil bacteria (e.g. Thiobaccilus species) and this process can take from weeks to months, or longer. The rate of oxidation depends on environmental conditions including soil moisture, temperature, aeration, pH, and the size of the S_0 particles being broken down. Sulphate derived from OM mineralisation or S_0 oxidation is soluble and readily moves with soil water to roots — or can be subject to leaching below the root zone in areas with high rainfall or with excessive irrigation.

S deficiency

Sulphur deficiency symptoms include pale green leaves and the chlorosis of young tissue. Tissue samples for youngest expanded blade/leaf provide the best diagnostic guide because S is relatively immobile in the plant. Once S has been taken up by the plant and assimilated into organic compounds, it does not move again. In canola, plants may also suffer from thin stems and leaves may develop a reddish colour, first apparent on the underside of the leaves. In canola, the flowers may also be visibly affected, and can appear pale in colour and in severe cases, almost grey.

Fertilising soils with S

There are numerous sources of S fertiliser available for use, and some containing soluble sulphate that provides immediate plant-available S. Others contain insoluble elemental S, that requires oxidation to sulphate, before the plant can access the additional nutrients. A blend of both elemental and sulphate-S can provide a balance of S supply over time, especially where leaching can be a problem. Many growers also use gypsum (calcium sulphate dehydrate) as a soil amendment, which also provides large amounts of sulphate-S for crop nutrition.

In Australia, soil tests such as the KCl-40 or MCP extraction provide guidance. However, because S is mobile, samples to 30cm depth are often a better indicator of the response to S fertiliser than 0-10cm samples. However, soil testing should not be considered alone. Decisions should be made in conjunction with visual crop assessments and plant tissue tests, and take into consideration other factors such as soil organic matter, soil texture, rainfall, and rooting pattern of the crop.

Crop response to S

Crops frequently respond rapidly to fertilisation with topdressed sulphate, especially under conditions of low S availability and low OM. Responses are generally greater in sandy soils, especially in crops with a high requirement for S, such as canola. The study reported in Table 2 shows significant increases in seed oil content in response to added S. Attention to S fertilisation is becoming more important, given reduced S emissions from industry, increased conservation tillage and higher-yielding crops taking up and removing more S from the soil, as harvested products.

Table 2. Effect of timing and rate of sulphate-S application on the yield of canola in central NSW (Hocking et al. 1996). Yield with nil S application = 1.03t/ha, and N at 80kg/ha supplied. The LSD = 0.43 (p = 0.05).

S applied t/ha	Yield t/ha			
	Sowing	5-6 Leaf	Buds visible	Stem elongation
10	1.73	1.62	1.56	1.41
40	2.15	2.26	2.11	2.19

Summary

K in soils is derived largely from the mineral fraction and is present as the cation K^+ , mainly adsorbed onto the exchange complex. It does not readily leach unless the exchange sites are dominated by H^+ (i.e. in acid conditions), and is often stratified in the topsoil. In the plant it does not form organic molecules and exists entirely in the ionic form. It rapidly leaches out of crop residues into the topsoil.

S in soils is most often tied up in OM and when mineralised is released as the sulphate anion (SO_4^{2-}) which is mobile, and liable to leaching deeper into the soil. In the plant S is taken up as sulphate and is incorporated into a range of organic molecules such as proteins. S is largely immobile in plants, so deficiency symptoms appear in the younger leaves.

Acknowledgement

These notes were taken from the Australian and New Zealand versions of IPNI *Nutrient Source Specifics*, number 3 (K) and number 4 (S) written by the author. Copies of this and other IPNI materials can be obtained at: https://www.fertilizer.org.au/Fertcare/Nutrients-And-Fertilizer-Information/International-Plant-Nutrition-Institute-Resources.

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Integration of time of sowing, crop seed rate and herbicides for the control of annual ryegrass and brome grass

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Keywords

- time of sowing, seed rate, ryegrass, brome grass, weed management.

Take home messages

- The response of weed density to delayed sowing is influenced not just by the weather conditions, but also by the seed dormancy attributes of the weed populations. Less dormant weed populations tend to emerge quickly after the opening rains, and they can be managed well by moderate delays in sowing. However, much longer delays in sowing would be needed to reduce infestations of highly dormant weed populations.
- At Washpool in 2019, a three-week delay in sowing had no impact on in-crop ryegrass density. In contrast, delayed sowing at Minnipa in 2018 caused a significant reduction in ryegrass density in wheat. Similarly, in-crop density of brome grass was also significantly reduced by the delayed sowing at Marrabel in 2018.
- A lower weed density after delayed sowing does not always reduce weed seed set. For example, late sown wheat at Washpool had more than double the ryegrass head number than in the early sown crop. Colder soil temperatures in later sown crops can reduce crop vigour, which allows weeds to thrive.
- Delayed sowing in June resulted in a significant yield penalty across all these trials. A decision to delay sowing to manage weeds needs to be considered very carefully.
- Higher crop seeding rates appear to consistently improve weed suppression especially in the later sown crops.

Background

Constantly evolving weed infestations in Australia are responsible for significant annual expenditures ($2.5billion) and yield revenue losses ($745million) for grain growers (Llewellyn et al. 2016). Herbicide resistance is a major concern in the southern and western grain growing regions of Australia where 36 weed species have been confirmed resistant to one or more herbicide modes of action. Annual ryegrass has maintained its number one ranking as a weed of Australian cropping systems for many years. However, brome grass has increased in importance and has climbed to be the fourth worst weed in terms of the area infested, as well as yield and revenue loss in grain crops in Australia (Llewellyn et al. 2016).

After the loss of post-emergence (POST) herbicides used in cereals due to widespread resistance, growers now largely rely on pre-emergence (PRE) herbicides for ryegrass control. PRE herbicides, such as Sakura® and Boxer Gold®, are usually not as effective for ryegrass control as the previously used POST herbicides. Furthermore, the efficacy of the PRE herbicides tends to be strongly influenced by the soil moisture conditions at sowing and in the early weed emergence period after sowing. As the autumn-winter rainfall in southern Australia and Western Australia (WA) has become more erratic in the last few years, the performance of the PRE herbicides has also become quite variable. Therefore, many cereal crops sprayed with PRE herbicides in dry starts to the season can be quite weedy, which means greater crop yield loss and weed seed set for future infestations.

Previous research has shown the benefits of higher wheat seed rates for the suppression of ryegrass (for example Lemerle et al. 2004), which can be easily integrated with herbicide tactics. Delay in crop sowing can be used to manage dense weed infestations by exposing a greater proportion of the weed seedbank to pre-sowing weed control tactics. However, delayed sowing is often associated with lower crop yields, especially in the low to medium rainfall environments. Gill and Kleemann (2013) have also shown that brome grass populations from cropping fields in the Mid North of South Australia (SA) and Victorian Mallee regions can have significantly longer dormancy than those from non-cropped habitats. Similar patterns of selection for increased seed dormancy have also been observed in ryegrass populations from WA under high cropping intensity (Owen et al. 2015). This adaptation mechanism facilitates avoidance of pre-sowing weed control practices.

In this GRDC investment, research is being undertaken to investigate the effects of integrating crop sowing time, seed rate and herbicide tactics on ryegrass and brome grass management. Three case studies are presented here to highlight the impact of these management tactics on weed control.

Results and discussion

Case study 1: ryegrass management Washpool 2019

There was no evidence at this site of any reduction in ryegrass infestation in wheat by delaying sowing by three weeks between TOS 1 (77plants/m^2) and TOS 2 (74plants/m^2). In 2019, the trial site only received 22.6mm rain during the three weeks between TOS 1 and 2. Dry surface soil conditions during the delay in sowing time period may have been responsible for the lack of response in ryegrass plant density observed at this site. Weed populations are also known to differ greatly in seed dormancy. It's quite likely that the Washpool population has a high level of seed dormancy, which reduces the rate of ryegrass germination after the season's opening rainfall events.

Wheat was much more competitive against ryegrass when sown early (TOS 1; Figure 1a). Even in the Control trial (knockdown only), ryegrass head number was significantly lower in TOS 1 than in TOS 2. This trend of superior crop competitive ability against ryegrass was also evident in Boxer Gold and Sakura + Avadex Xtra treatments. In-crop ryegrass density was quite similar between TOS 1 and 2 — it can be argued that on a per plant basis, ryegrass was much more competitive against wheat sown under cold conditions of TOS 2 than warmer conditions conducive for the early crop vigour in TOS 1.

Wheat grain yield at this site was significantly influenced by the time of sowing (P=0.001), seed rate (P=0.001), herbicide treatments (P=0.001), and the interaction between the time of sowing and herbicides (P=0.011; Figure 1b). Wheat was much more tolerant to ryegrass competition when sown early (TOS 1) — there was a small increase in grain

Table 1. Management information on weed control trials.

Detail	Washpool 2019	Minnipa 2018	Marrabel 2018
Weed species	Ryegrass	Ryegrass	Brome grass
Crop (variety)	Wheat (Scepter⁽ᴰ⁾)	Wheat (Scepter⁽ᴰ⁾)	Barley (Spartacus CL⁽ᴰ⁾)
Sowing date	TOS 1: 15 May 2019 TOS 2: 5 June 2019	TOS 1: 11 May 2018 TOS 2: 25 June 2018	TOS 1: 24 May 2018 TOS 2: 19 June 2018
Crop seed rate	100, 150 or 200 seeds/m^2	100, 150 or 200 seeds/m^2	100, 150 or 200 seeds/m^2
Herbicides	1. Control (knockdown only) 2. Boxer Gold 2.5L/ha IBS 3. Sakura 118g/ha + AvadexXtra 1.6L/ha IBS	1. Control (knockdown only) 2. Boxer Gold 2.5L/ha IBS 3. Sakura 118g/ha+ Avadex Xtra 1.6L/ha IBS	1. Control (knockdown only) 2. Treflan 2L/ha + Avadex Xtra 2L/ha IBS 3. Treflan 2L/ha + Avadex Xtra 2L/ha IBS followed by Intervix 750mL/ha at GS14
Growing season rainfall (mm)	229	186	195

Active ingredients: Boxer Gold® = 800 g/L prosulfocarb + 120 g/L s-metolachlor; Sakura® = 850 g/kg pyroxasulfone; Avadex® Xtra = 500 g/L triallate; Treflan® = 480 g/L trifluralin; Intervix® = 33 g/L imazamox plus 15 g/L imazapyr; time of sowing (TOS); incorporated by sowing (IBS); growth stage (GS)

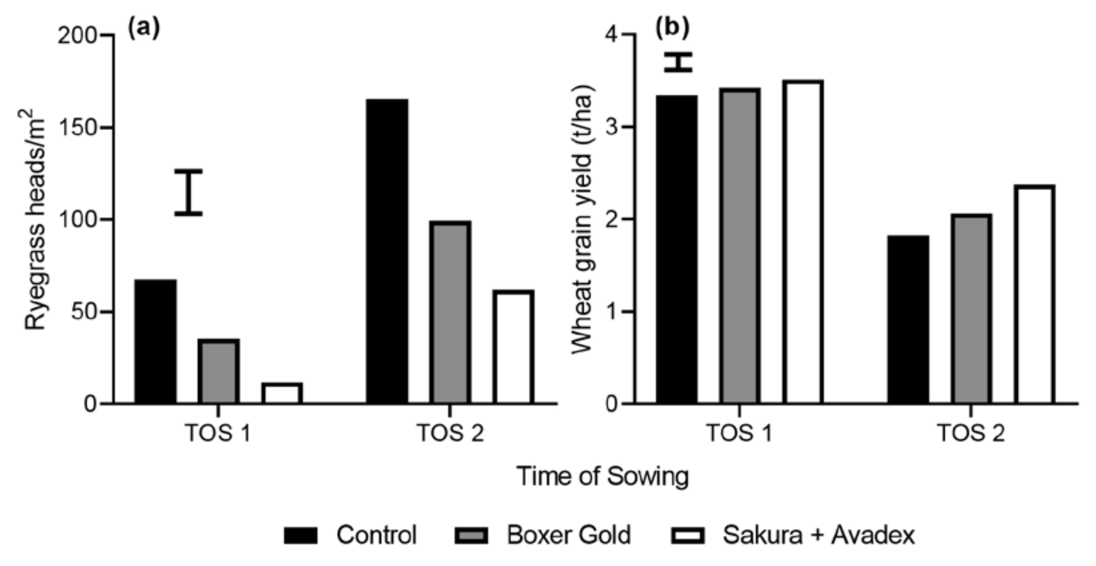

Figure 1. The effect of time of sowing (TOS) and herbicide treatments on ryegrass head density (a), and wheat grain yield (b), at Washpool in 2019. The error bars represent LSD (P=0.05).

yield in herbicide treated plots, but the differences were non-significant. In contrast, there was a significant increase in wheat grain yield in herbicide treatments in TOS 2. The yield gap between TOS 1 and TOS 2 in herbicide treatments ranged from 45% in the Control to 40% in Boxer Gold and 32% in Sakura + Avadex Xtra. The yield gap between the two sowing dates ranged from 1.14 to 1.52t/ha. The results of this study clearly show that delayed sowing of wheat allows for greater seed set by ryegrass and is also associated with a large yield penalty.

Case study 2: ryegrass management Minnipa 2018

A six-week delay in sowing reduced establishment of ryegrass in wheat at this site (Figure 2a). This was particularly evident in the untreated control trial, as weed density decreased from 262plants/m^2 (TOS 1) to 139plants/m^2 (TOS 2). The ryegrass population at Minnipa appears to have low seed dormancy, which allowed it to germinate and establish in response to many small rainfall events in June. Delayed sowing also created a synergistic interaction between the more favourable soil moisture conditions and the reduction in ryegrass density by the knockdown treatment, which collectively improved the efficacy of herbicide treatments in TOS 2.

Ryegrass seed production was significantly affected by the time of sowing (P=0.047), herbicide treatments (P=0.001) and the interaction between the TOS and the herbicide treatments (P=0.023). PRE herbicides performed much better in TOS 2. (Figure 2b). Sakura + Avadex Xtra was the most effective herbicide treatment across both times of sowing; however, coupling this treatment with delayed sowing provided a 94% reduction

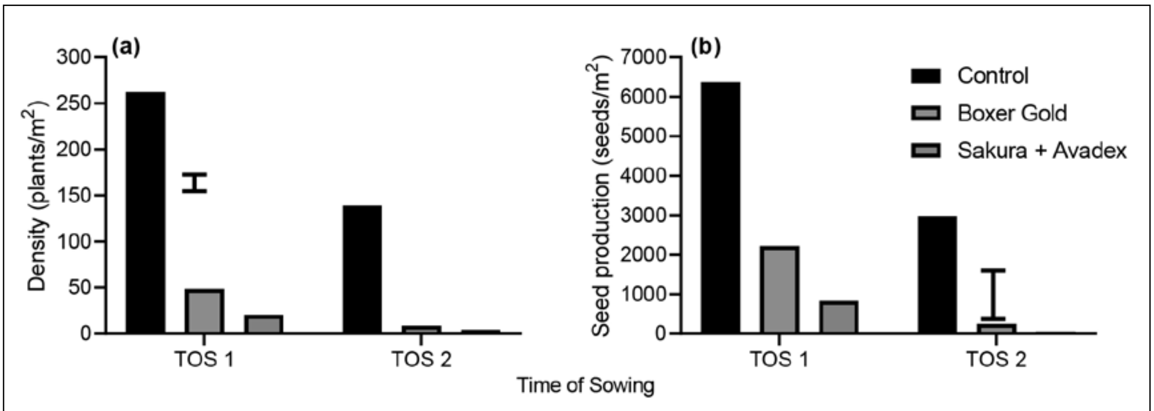

Figure 2. The effect of time of sowing (TOS) wheat and herbicide treatments on in-crop ryegrass plant density (a), and its seed production (b), at Minnipa in 2018. The error bars represent LSD (P=0.05).

in ryegrass seed set in TOS 2 (53seeds/m^2). In contrast, seed production exceeded 800seeds/m^2 for all herbicide treatments in TOS 1. This highlights the value of the knockdown treatment alone, as there was a 53% reduction in seed production with delayed sowing. Boxer Gold efficacy also exhibited greater response to delayed sowing than Sakura + Avadex Xtra, with seed production ranging from 35% (TOS1) to 9% (TOS 2) of the control. Sakura + Avadex Xtra offered greater stability in preventing ryegrass seed production in TOS 1 (13%) and TOS 2 (2%) relative to the control.

Wheat grain yield at Minnipa was significantly influenced by the time of sowing (P=0.002), seed rate (P<0.001), herbicide treatment (P<0.001), and the interaction between the time of sowing and herbicide treatments (P<0.001). Averaged across the seed rates and herbicide treatments, wheat produced grain yield of 1.67t/ha in TOS 1, as compared to 1.06t/ha in TOS 2. Even though the amount of rainfall received in May and June was well below the long-term average, a six-week delay in sowing reduced wheat yield by 36%. Wheat yield increased as seed rate increased from low (1.25t/ha), to medium (1.41t/ha) and high (1.44t/ha). Even though the increase in wheat yield in response to seed rate was only 13%, it was statistically significant. There was no negative effect of crop seed rate on grain screening content, which ranged from 4% in low seed rate to 3% in the medium and high seed rate treatments.

There were large benefits of delayed sowing on weed control by herbicides in terms of ryegrass plant density, head density and seed production. However, these benefits came at a significant cost in wheat grain yield (Figure 3). Wheat grain yield was reduced in all the herbicide treatments due to delayed sowing. Wheat benefited much more from herbicide treatments in TOS 1, where ryegrass density was much greater than in TOS 2. Therefore, it would not be advisable to delay sowing wheat to manage ryegrass unless weed seedbanks are excessively large. It would be preferable to target the optimum sowing date for wheat in the region and use the most effective herbicide options available to control ryegrass. Based on grain yields achieved and Australian Premium White (APW) prices in 2018, TOS 1 treated with Boxer Gold provided $291/ha greater gross margin than TOS 2 treated with the same herbicide. The superior levels of ryegrass control achieved by the Sakura + Avadex Xtra treatment with delayed sowing translated to a $9/ha advantage in gross margin over applying Boxer Gold.

Case study 3: brome grass management Marrabel 2018

Brome grass plant density was significantly affected by the time of sowing (P=0.018) and the herbicide treatments (P<0.001). The four-week interval between TOS 1 and TOS 2 extended the opportunity for brome grass seedlings to emerge before sowing. Consequently, barley sown at TOS 2 had 48% lower brome grass infestation (108plants/m^2) than in TOS 1 (207plants/m^2). As expected, herbicide treatments had a significant (P<0.001) effect on brome grass plant density.

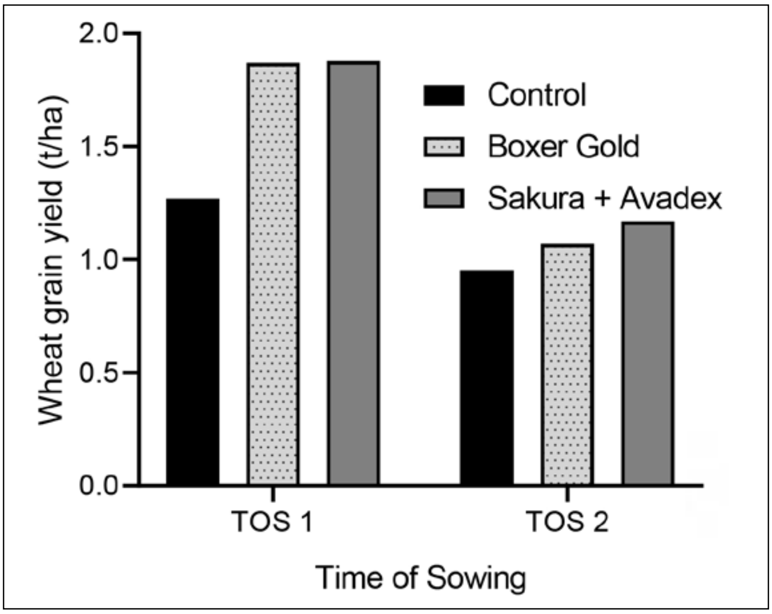

Figure 3. The effect of time of sowing (TOS) wheat and herbicide treatments on wheat grain yield at Minnipa in 2018.

When averaged across the sowing time and seed rates, the treatment of Treflan + Avadex Xtra was moderately effective and reduced brome grass density by only 36% (173plants/m^2) relative to the untreated control (271plants/m^2). In contrast, the same PRE treatment (Treflan + Avadex Xtra) followed by Intervix reduced brome grass density by 90% (28plants/m^2).

There was a significant interaction between the time of sowing and herbicide treatments (P=0.026). This interaction appears to be mainly associated with improved activity of Treflan + Avadex Xtra in TOS 2 compared to TOS 1 (Figure 4a). In TOS 2, there was 32.4mm rainfall during the week before crop sowing, which would have created a moist seedbed and suitable conditions for the activity of trifluralin and triallate. In contrast, the total rainfall for the week before and week after sowing for TOS 1 was only 8.8mm.

Brome grass seed production was significantly affected by the herbicide treatment (P<0.001) and the interaction between sowing time and herbicide treatment (P=0.007). The interaction between these two management factors was almost entirely due to significantly lower brome grass seed production in the untreated control in TOS 1 than in TOS 2 (Figure 4b). This result appears to be associated with the lower panicle density in the control plots in TOS 1 than TOS 2. Delayed sowing reduced the competitiveness of barley with brome grass because the crop emerged under cool conditions in mid-June. The imidazolinone herbicide, Intervix was extremely effective and completely prevented brome grass seed production in this trial. The cheaper herbicide option of Treflan + Avadex Xtra was weak against brome grass, which was reflected by much higher seed production in TOS 1 (6258seeds/m^2) than in TOS 2 (5667seeds/m^2).

The time of sowing of barley had a significant effect on its grain yield (P=0.011); TOS 1 produced 940kg/ha greater barley grain yield than TOS 2. Barley sown in May (TOS 1) was growing in a warmer soil, whereas TOS 2 experienced lower establishment and cooler conditions during early growth. Therefore, barley showed a small response to increased seed rate in TOS 1, but there was a significant increase in yield with seed rate in TOS 2. Herbicide treatment had a large effect on crop yield (Figure 5), which was reflected in a significant increase in grain yield by the herbicide treatments compared to the untreated control. The POST application of Intervix to the crop treated with Treflan + Avadex Xtra further increased barley grain yield by 872kg/ha. Even though there were more brome plants present in all the treatments in TOS 1, barley was able to compete with them effectively and produced consistently higher yields in the early sown crop. Furthermore, when no PRE herbicides

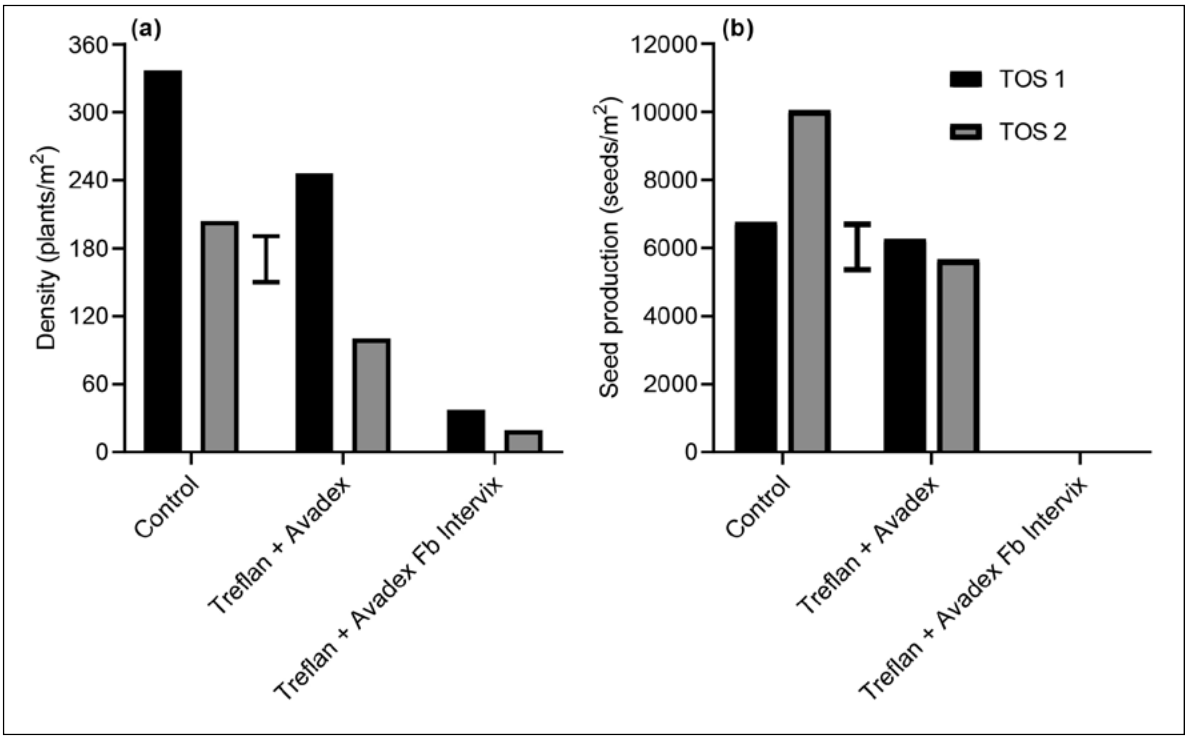

Figure 4. The effect of sowing time and herbicide treatments on brome grass plant density (a), and brome grass seed production (b), at Marrabel in 2018. The error bars represent LSD (P=0.05).

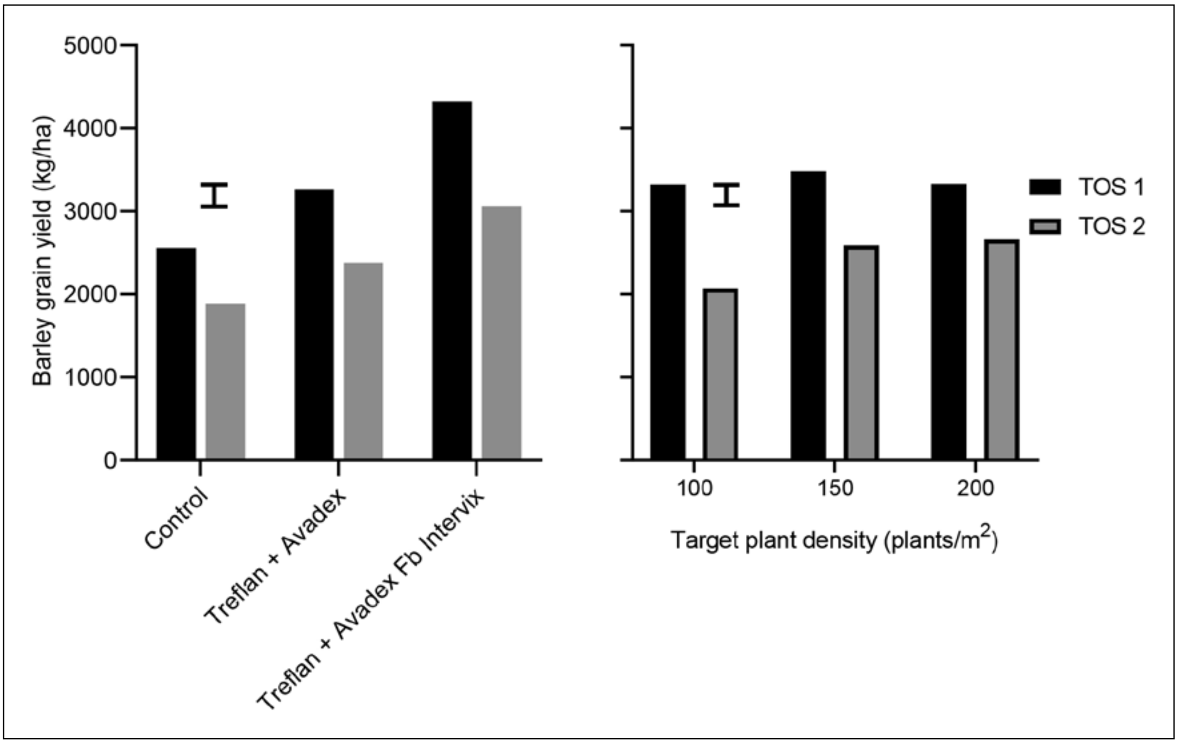

Figure 5. The effect of sowing time and herbicide treatments on barley grain yield (a), and sowing time x seed rates on barley grain yield (b), at Marrabel in 2018. The error bars represent LSD (P=0.05).

were used (control), brome grass produced significantly greater number of seeds in TOS 2 (10048 seeds/m^2) than in TOS 1 (6754seeds/m^2). This result highlights the superior crop competitiveness of early sown barley.

Conclusion

Field trial results from Washpool in 2019 showed no reduction in ryegrass in-crop density from the three-week delay in sowing wheat. Furthermore, delayed sowing reduced the competitive ability of wheat, which was reflected in greater ryegrass head numbers in TOS 2 than in TOS 1. Greater head density in weeds is invariably associated with increased seed production. Ryegrass also caused a greater yield loss in wheat in TOS 2 than in TOS 1, which can be seen by the difference between the Control and herbicide treatments. Even more importantly, there was a large yield penalty from delayed sowing of 1t/ha due to reduced utilisation of resources, such as water, light and nutrients.

At Minnipa in 2018, delay in sowing of wheat was able to reduce in-crop ryegrass density and its seed production, but it was again associated with a significant yield penalty (25-43%). In the brome grass management trial at Marrabel in 2018, delayed sowing caused a large reduction in brome grass plant density in barley — however, surviving brome plants were more vigorous in TOS 2 and compensated for reduced plant density. The application of POST Intervix after the PRE herbicide treatment completely prevented weed seed set in TOS 1 and TOS 2. Consistent with the other two trials, delay in barley seeding to improve weed control reduced barley grain yield by 26-29%.

Increasing the density of wheat and barley improved the tolerance of these crops to competition from brome grass and ryegrass without negatively impacting on grain quality at all sites. Growers should carefully consider the emergence patterns of field populations of brome grass and ryegrass, as this will have overarching implications to the both the efficacy of the PRE herbicides, and the water limited yield potential from delayed sowing.

Acknowledgements

The research undertaken in this project was 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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The health report - do you need to spray for pulse Botrytis diseases? Ask the new data logger

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GRDC project code: DAS1905-010BLX Managing Botrytis diseases in intensive pulse cropping systems

Keywords

- faba bean, lentil, chocolate spot, grey mould, fungicide, trigger warning alert, environmental data.

Take home messages

- New-age data loggers with telemetry transmitted in-canopy environmental data to a server.
- Disease risk alerts based on the environmental data were emailed in near real-time from the server to researchers and agronomists.
- This risk alert system may ultimately remove the uncertainty around timing of and need for fungicide sprays to control foliar disease.
- It is anticipated this system may reduce the number of sprays and hence reduce costs to growers without increasing the risk of disease.

Background

Chocolate spot disease of faba beans and grey mould of lentils, caused by *Botrytis fabae* and *B. cinerea*, respectively, can be difficult to control and growers often use multiple prophylactic fungicide sprays in crops. The area sown to pulse crops is expanding into new districts, both higher and lower rainfall than the traditional growing areas. Appropriate disease management strategies need to be identified for these regions to ensure the successful uptake of these crops.

Current disease management strategies based on prophylactic sprays have been devised in medium to high rainfall zones with a relatively high intensity of individual pulse crop types i.e. with the assumption of high risk of disease. The new higher rainfall zones generally have longer and colder growing seasons than traditional regions, which impacts on disease severity and the number of foliar sprays required to control disease. Following the standard practices has led to a high input cost, with multiple sprays applied during the longer growing season. Conversely, lower rainfall areas may have a lower disease risk, thereby requiring fewer sprays, and lower yields which demand fewer costly inputs. This potentially renders the current strategy of applying fungicides at early flowering ineffective and may be an unnecessary expense.

Botrytis spp. need very humid conditions with temperature above 15°C continuously for several hours within the canopy to infect the faba bean or lentil plants (Davidson and Krysinska-Kaczmarek, 2007; Davidson, 2011). Hence, it seems possible to optimise fungicide application using field observations of the in-canopy environmental conditions via near real-time monitoring.

Method

Recent advances in Internet of Things (IoT) connectivity, referred to as Low Power Wide Area Networks (LPWANs), present opportunities to affordably acquire real-time field data. This can be used to help mitigate the risks associated with agricultural pests and pathogens. These networks are based on wireless technology that connects devices/sensors deployed in the field. The LPWAN technology utilised by this project is Narrow Band IoT (NB-IoT) and is currently operated in Australia by Telstra and Vodafone.

Compared to traditional mobile networks (3G/4G), NB-IoT operates at a lower cost, has greater power efficiency (devices with years of battery life), transfer small packets of data (for example, temperature, relative humidity (RH) and soil moisture for this project), and support more devices over a greater area ($10km^2$).

We deployed data loggers (Figure 1) and passive spore traps at seven sites across the south east (SE), Yorke Peninsula (YP) and Mid-North (MN) of South Australia (SA). Slides from passive spore traps were collected fortnightly. These samples were quantified for conidia of pulse *Botrytis* spp. by DNA assays at the end of the growing season, to compare spore release with environmental data. Field cameras were installed at several of these locations to monitor symptom development in the crops. A foliar fungicide trial in faba beans was sown at one of the monitoring sites, Frances, in SA to investigate whether an alert triggered by the in-crop environmental data can determine the need for foliar fungicides.

The treatments were:

a) Nil

b) Tebuconazole at 145mL/ha (Orius® 430 SC, 430g/L active ingredient (a.i.)) at grass spray, carbendazim 500mL/ha (Nufarm Spin Flo® Systemic Fungicide, 500g/L a.i.) at canopy closure and carbendazim 500mL/ha at early podding spray if required

c) Tebuconazole at 145mL/ha at grass spray, carbendazim 500mL/ha at early flower and carbendazim 500mL/ha at early podding spray if required

d) Tebuconazole at 145mL/ha at grass spray, carbendazim 500mL/ha according to in-canopy conditions (RH and temperature)

e) Carbendazim 500mL/ha according to in-canopy conditions (RH and temperature).

**note: Tebuconazole can be used on faba beans for Cercospora Leaf Spot and Faba Bean Rust control under APVMA Permit 13752*

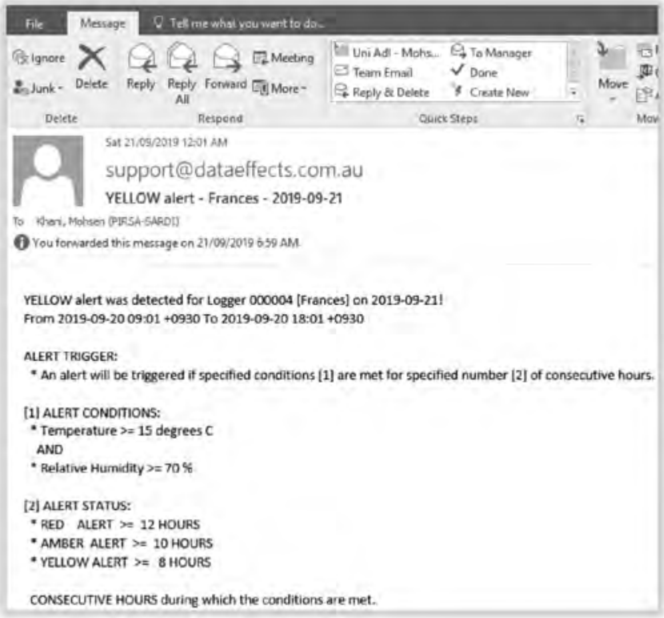
Results and discussion

Although some remote monitoring sites in this study had none or a very poor mobile (3G/4G) signal reception, our deployed data loggers on NB-IoT successfully transmitted every six hours to the server. Data consists of hourly recordings of temperature and RH and six-hourly records of soil moisture. Hourly photographs were captured from cameras in the paddocks and transmitted to the server. The RH and temperature data transmitted by the loggers were used to set three levels of trigger warning alerts that were emailed by the server if in-canopy conditions were conducive for Botrytis infection. Yellow, amber or red alerts were emailed if RH was at or above 70%, and temperature was at or above 15°C for more than eight, 10 and 12 hours, respectively.

By the end of 2019 cropping season, nine yellow alerts and one amber alert were received, which finally progressed to a red alert from two data loggers in SE. Interestingly, although five yellow alerts for the fungicide trial site were received, those alerts never progressed to red. As a result, no foliar fungicides were sprayed in treatments (d) and (e) at Frances, according to in-canopy conditions. Only one yellow alert was received for 2019 season from data loggers deployed in YP and MN sites.

The trial site and commercial crops at monitoring sites were observed for disease development with minimal, or no symptoms of chocolate spot or botrytis grey mould seen in crops to the end of season. This suggests that in 2019 in SA, for all seven regions that data loggers were deployed, there was only one instance when fungicides may have been required to control chocolate spot in faba beans, or grey mould in lentils. This system could potentially save growers substantial amounts of money and time and fewer sprays reduce the risk of fungicide resistance developing in pulse crops.

Figure 1. An environmental data logger with telemetry deployed in a faba bean crop.



Sat 21/09/2019 12:01 AM

support@dataeffects.com.au

YELLOW alert - Frances - 2019-09-21

To Khani, Mohsen (PIRSA-SARDI)

You forwarded this message on 21/09/2019 6:59 AM.

YELLOW alert was detected for Logger 000004 [Frances] on 2019-09-21!
From 2019-09-20 09:01 +0930 To 2019-09-20 18:01 +0930

ALERT TRIGGER:
* An alert will be triggered if specified conditions [1] are met for specified number [2] of consecutive hours.

[1] ALERT CONDITIONS:
* Temperature >= 15 degrees C
AND
* Relative Humidity >= 70 %

[2] ALERT STATUS:
* RED ALERT >= 12 HOURS
* AMBER ALERT >= 10 HOURS
* YELLOW ALERT >= 8 HOURS

CONSECUTIVE HOURS during which the conditions are met.

Figure 2. A yellow trigger warning alert received via email from the server, based on in-crop, real-time environmental data.

Conclusion

By using NB-IoT data transmission faba bean and lentil canopies were remotely monitored at several sites in SA. Ultimately, this monitoring will provide a better understanding of microclimate elements, and their effects on Botrytis disease initiation and progression during the season. Based on trigger warning alerts received from telemetry data loggers compared to multiple prophylactic fungicide applications, this technology could avoid unnecessary fungicide application.

Using NB-IoT data telemetry to transmit near real-time environmental data, incorporated with our knowledge of Botrytis biology, can lead to precise timing of fungicide application for better control of Botrytis diseases in pulse crops. In the 2019 season, the trigger warning system for foliar fungicide spray did not send any red alerts for the fungicide trial site at Frances, SA. At this site, the level of the Botrytis disease was none or negligible in those treatments without any foliar fungicide spray during the season.

Despite the 2019 cropping season in many regions in SA being relatively drier than an average year, anecdotal data shows that growers sprayed their paddocks a few times for faba bean chocolate spot or lentil grey mould regardless of the weather conditions in 2019 season. This highlights that the trigger warning system can be a powerful tool to use even in a dry year for growers. Understandably this technology needs to be examined during a number of average, or wet growing seasons to validate its applicability; especially after being examined in a moderately dry year. The results will optimistically help growers to reduce the number of fungicide sprays and make these crops more profitable. This technology has the potential to be used for real-time monitoring of in-crop environmental data in many crops and areas and to be utilised for management of several diseases.

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.

Thanks to Jamus Stonor, Marzena Krysinska-Kaczmarek and Michelle Russ (SARDI) for their invaluable technical help. We thank Andrew Baker and his team from DATA EFFECTS for providing data loggers and technical support during the 2019 cropping season.

Useful resources

http://communities.grdc.com.au/field-crop-diseases/spot-the-difference-identifying-faba-bean-diseases/

http://pulseaus.com.au/growing-pulses/crop-protection-products#faba-bean

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The pulse health report - 2019 pulse disease seasonal update and National Variety Trial (NVT) disease ratings

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GRDC project codes: CUR00023, DAV00150, UA00163, DAS1905-013SAX

Keywords

- lentil, faba bean, chickpea, field pea, disease, fungicides, resistance changes, National Variety Trials, NVT.

Take home messages

- SARDI testing in 2019 found some *Ascochyta fabae* isolates aggressive on PBA Samira⊕ faba bean; potentially this is a third pathotype. However, the majority of reports of high levels of Ascochyta blight (AB) in PBA Samira⊕ were due to on-farm retained seed which has outcrossed in previous seasons. At this stage resistance ratings to AB for faba bean cultivars have not changed, but reactions on PBA Samira⊕ require ongoing monitoring.
- The new faba bean cultivar PBA Amberley⊕ has a high level of resistance to AB and has a provisional rating of moderately resistant (MR) to chocolate spot.
- Severe lentil AB infections were seen in PBA Hurricane XT⊕ crops and volunteer plants early in the 2019 season on Yorke Peninsula and in the Mid North region indicating that the moderately resistant -moderately susceptible (MRMS) rating in this cultivar may need to be downgraded in future seasons. The source of resistance in both PBA Hurricane XT⊕ and PBA Hallmark XTv is now compromised, so monitor closely for infection and manage as if there is a potentially higher risk of AB.
- The new lentil cultivar PBA Highland XT⊕ has a high level of resistance to AB and is rated MRMS to botrytis grey mould (BGM).
- AB was common in chickpea crops despite the drier than average season. This confirms all chickpea crops must be protected against the disease early in the season using a thiram-based seed dressing and foliar fungicide sprays timed ahead of rain.
- The new chickpea cultivar PBA Royal⊕ has a provisional rating of moderately susceptible (MS) to AB.
- Cercospora leaf spot (CLS) was widespread across South Australia (SA) in faba bean crops early in the 2019 growing season. A trial at Bool Lagoon confirmed that a tebuconazole foliar spray timed with the grass spray is most effective at controlling CLS, even after the disease has established.
- Bacterial blight (BB) affected some field pea crops following severe frost in spring. There are no chemical treatments to control this disease. Avoid sowing field peas in frost prone paddocks, or, in these paddocks, sow PBA Oura⊕, PBA Percy⊕ or PBA Butler⊕ which are less susceptible to BB. Consider removing stubble before sowing to reduce the frost risk.

2019 pulse disease seasonal update

The dry conditions in 2019 resulted in reduced disease levels in pulse crops although early observations of severe AB were seen on lentil and chickpea crops and volunteers. In addition, CLS was widespread in seedling faba bean crops across SA.

Chickpea

Ascochyta blight (AB)

In 2019, early reports of AB infection in Genesis090 chickpea crops, as well as volunteer plants, were received from the upper Yorke Peninsula and Lower North regions of SA. Despite the dry season, there were still reports of heavy infection occurring in some commercial crops and field trials in those regions following rain events, especially where planned fungicide sprays had been mistimed. This confirms the importance of monitoring crops for signs of infection and applying fungicides ahead of rainfall. A thiram-based seed dressing is also essential to prevent seed transmission of AB onto the emerging seedlings in 2020. All current commercial cultivars of chickpea are rated MS or susceptible (S), including PBA Royal$^{\phi}$ which was released in 2019 with a provisional rating of MS to AB.

Lentil

Ascochyta blight (AB)

Early and severe reports of *Ascochyta lentis* infection in PBA Hurricane XT$^{\phi}$ crops and volunteer plants were reported this season on the Yorke Peninsula and in the Mid North region indicating that its MRMS rating in SA is under threat.

SARDI's annual testing has confirmed two pathotypes of *A. lentis* are present in SA; a Nipper-virulent type, and a Hurricane-virulent type. Forty isolates of *A. lentis* collected in 2018 from lentil field trials and commercial crops (35 from SA, 5 from Victoria (Vic)) were tested in controlled environment conditions in 2019 on a differential host set that included NipperA$^{\phi}$ and PBA Hurricane XT$^{\phi}$ (Table 1). Of the isolates tested, 27 of 40 (67.5%) were capable of infecting PBA Hurricane XT$^{\phi}$, an increase from 50% in 2018 and 28% in 2016 (Blake et al 2019a, Blake et al 2019b, Blake et al 2017). Indianhead is a source of resistance for the breeding program and the presumed source of resistance in PBA Hurricane XT$^{\phi}$, however it was infected by 25 of the 40 isolates (62.5%), an increase from 33% in 2018 and 5% in 2016 (Blake et al 2019a, Blake et al 2019b, Blake et al 2017). Hence this source of resistance is now compromised across SA lentil growing regions. The A. lentis pathogen population is naturally variable and these aggressive forms have been selected, over time, in intensive cropping systems.

In light of the observed reactions on PBA Hurricane XT$^{\phi}$, growers should regularly inspect both PBA Hurricane XT$^{\phi}$ and PBA Hallmark XT$^{\phi}$ lentil crops to determine if AB infection is severe enough to directly affect yield. PBA Hallmark XT$^{\phi}$ is presumed to have the same source of resistance to AB as PBA Hurricane XT$^{\phi}$ and tests at SARDI (as CIPAL1422) have found that the former is able to be infected by recently collected Hurricane-virulent isolates at a moderate level.

The newly released lentil cultivar, PBA Highland XT$^{\phi}$, has a provisional rating of MR to foliar AB in SA with resistance to both the Nipper-virulent and Hurricane-virulent AB pathotypes. However this rating may be subject to change when more data becomes available. Growers should monitor for AB and if infection is present, plan to spray ahead of rain fronts at podding to protect the developing seed. The cultivar also has a provisional BGM rating of MRMS, similar to PBA Hurricane XT$^{\phi}$, PBA AceA$^{\phi}$ and PBA Flash$^{\phi}$.

Faba bean

Ascochyta blight (AB)

There were numerous reports of mild AB leaf infection in faba bean crops in 2019 that did not

Table 1. Forty *Ascochyta lentis* isolates collected in 2018 were inoculated onto a lentil host differential set in controlled environment conditions in 2019. Entries in the table are the number of isolates per category.

Test reaction	Cumra (susceptible check)	Nipper$^{\phi}$	PBA Hurricane XT$^{\phi}$	Indianhead (resistant line)	ILL7537 (resistant line)
R	2	22	13	15	40
MR	3	10	8	14	0
MRMS	11	8	15	10	0
MS	10	0	4	0	0
S	14	0	0	1	0

Note: R = resistant, MR=moderately resistant, MRMS = moderately resistant-moderately susceptible, MS = moderately susceptible; S = susceptible cause major problems, as the cool (5-15°C) and wet conditions did not persist in most growing regions. There are no changes to disease ratings for faba bean cultivars for 2020. However, the two pathotypes of *A. fabae* are found in all the faba bean growing regions in SA and the more aggressive pathotype 2 is now widespread in the South East and on the Eyre Peninsula. Farah⁽ᵇ⁾ is rated S to pathotype 2, while PBA Rana⁽ᵇ⁾, PBA Zahra⁽ᵇ⁾ and PBA Marne⁽ᵇ⁾ are MRMS to this pathotype. PBA Samira⁽ᵇ⁾, Nura⁽ᵇ⁾, the Group B herbicide tolerant PBA Bendoc⁽ᵇ⁾, and the new release PBA Amberley⁽ᵇ⁾ (tested as AF11023) are all resistant-moderately resistant (RMR) to both pathotypes.

During the 2019 season, reports were received of higher than expected levels of AB on PBA Samira⁽ᵇ⁾ in commercial crops. However in all of these reports, crops had been sown with on-farm retained seed and in many of these cases, the seed crop had been grown next to a faba bean cultivar that is susceptible to pathotype 2 of *A. fabae*, such as PBA Rana⁽ᵇ⁾ or Farah⁽ᵇ⁾. Faba beans are open pollinated and this can lead to mixing of genetic material from grower retained seed. These genetic mixtures can lead to perceived changes in the resistance of a cultivar. To minimise the risk of cross-pollination, growers should ensure seed kept for future plantings are isolated from other cultivars by a minimum of 200m.

In 2019, forty isolates of *A. fabae* collected in 2018 from faba bean field trials and commercial crops (23 from SA, 17 from Vic) were tested in controlled environment conditions on a differential faba bean host set. This host set includes the commercial cultivars PBA Rana⁽ᵇ⁾ and PBA Zahra⁽ᵇ⁾ as well as three Ascochyta resistant (AR) selections *viz*. Farah AR, Samira AR and Nura AR, which were fixed for AB resistance within the breeding program and known not to be outcrossed. For the first time, results suggest the presence of a possible third pathotype emerging in the *A. fabae* population that is aggressive on PBA Samira⁽ᵇ⁾. This is demonstrated by 4 of 40 (10%) isolates that caused a MRMS reaction on Samira AR (Table 2). Continued monitoring will be critical to confirm this shift in the pathogen population.

Chocolate spot (CS)

PBA Amberley⁽ᵇ⁾ was released in late 2019 with a provisional MR rating to CS making it more resistant than all other current commercial varieties, which are rated MS or S to CS. There were only a few reports of CS in faba and broad bean crops in SA during 2019 mostly in the South East region, late in the season. This included a disease management trial at Bool Lagoon that became infected in late November. This replicated plot trial was sown with the faba bean cultivars, PBA Amberley⁽ᵇ⁾ (tested as AF11023) and PBA Bendoc⁽ᵇ⁾, and the broad bean cultivar PBA Kareema⁽ᵇ⁾. Plots received one of four fungicide regimes: (1) 'nil', (2) tebuconazole at 145ml/ha (430g/L a.i., Genfarm Blast® 430 Fungicide) with grass spray then carbendazim at 500mL/ha (500g/L a.i., Adama Howzat® SC) at canopy closure and early podding ('standard'), (3) tebuconazole with grass spray ('minimum'), or (4) tebuconazole at grass spray and at canopy closure ('low cost'). PBA Amberley⁽ᵇ⁾ had significantly less disease on pods and leaves compared to PBA Bendoc⁽ᵇ⁾ and PBA Kareema⁽ᵇ⁾ (Table 3a). This infection occurred eight weeks after the last foliar fungicide spray and so the treatments were ineffective except for slightly less disease on pods in the standard treatment compared to untreated plots (Table 3b). It is unlikely that there will be any effect on yield as the infection occurred late in the season.

(n.b. Use of tebuconazole on faba bean crops is covered by permit PER13752)

CS is favoured by mild temperatures (15-25°C) and high humidity (>70%) extending over 4-5 days during flowering and after canopy closure. Areas that receive good rain through August and early spring are at higher risk of CS developing and spreading.

Table 2. Forty *Ascochyta fabae* isolates collected in 2018 were inoculated onto a faba bean host differential set in controlled environment conditions in 2019. Entries in the table are the number of isolates per category. AR lines are Ascochyta resistant selections fixed within the breeding program.

Test reaction	Icarus (susceptible check)	Farah AR	PBA Zahra⁽ᵇ⁾	PBA Rana⁽ᵇ⁾	Samira AR	Nura AR
R	0	2	2	2	32	36
MR	1	1	11	7	4	4
MRMS	0	7	12	16	4	0
MS	9	15	13	13	0	0
S	30	15	2	2	0	0

Note: R = resistant, MR=moderately resistant, MRMS = moderately resistant-moderately susceptible, MS = moderately susceptible; S = susceptible

Table 3a. Chocolate spot assessed as per cent area diseased per plot on pods and leaves in each cultivar of faba and broad bean at Bool Lagoon in 2019. Different letters represent significant difference between varieties.				
% area diseased	Variety			
	PBA Amberley(b)*	PBA Bendoc(b)	PBA Kareema(b)	L.s.d. (p<0.001)
Pods	1.5 a	5.7 b	4.7 b	0.9
Leaves	10.8 A	22.1 B	23.8 B	4.7

*tested as AF11023; L.s.d. = least significant difference.

Table 3b. Percentage of chocolate spot disease symptoms (per cent area diseased per treatment) on pods of faba and broad bean in disease management trial at Bool Lagoon in 2019. Different letters represent significant difference between treatments.					
% area diseased	Fungicide Treatment				
	Nil	Minimum	Low Cost	Standard	L.s.d. (p<0.001)
Pods	4.7b	3.7 ab	4.2 ab	3.2 a	1.1

Nil = no spray; **Minimum** = tebuconazole at grass spray; **Low cost** = tebuconazole at grass spray and at canopy closure (27 August); **Standard** = tebuconazole at grass spray, carbendazim at canopy closure (27 August) and 20 September; **L.s.d.** = least significant difference.

This includes the South East of SA and Lower Eyre Peninsula regions. Growers are encouraged to be proactive in controlling CS by applying pre-emptive fungicide sprays at early-mid flowering before symptoms appear. Follow up sprays may be required in high rainfall regions and high biomass crops (especially where there was high seeding and/or early sowing) as humidity is retained in the canopy which is an ideal environment for CS to proliferate. Areas around trees and under power lines can become hot spots for the disease if spray planes are unable to reach those areas of the crop. Thick canopies from early sowing or high seeding rates can produce warm humid conditions under the canopy which is ideal for disease development and spread. CS can be easily distinguished from other faba bean leaf diseases as it also infects flowers unlike the other faba bean diseases.

Cercospora leaf spot (CLS)

All current commercial cultivars of faba beans are susceptible to CLS and there were early reports of widespread disease across the state in 2019.

In 2019, a replicated plot trial at Bool Lagoon was conducted to assess the effectiveness of including two different pre-sowing fungicide treatments (a seed treatment and an in-furrow treatment, both currently unregistered for use in faba bean) applied at sowing to control CLS however neither treatment gave effective control of the disease.

CLS appears early in the season on the bottom leaves as the pathogen survives on faba bean debris and in soil. The spores are spread through wind and rain splash to plants and the disease moves further up the plant through the season, which can cause extensive defoliation if not well controlled. Short rotation intervals between faba bean crops leads to increased disease carryover and higher infection levels. Paddocks regularly cropped to faba beans benefit from an early fungicide spray (for example; tebuconazole) to prevent infection and spread of CLS. Where CLS has already infected crops, later sprays of carbendazim for CS will also restrict further spread of CLS.

A helpful guide for growers and agronomists to identify common faba bean diseases can be found at: http://communities.grdc.com.au/field-crop-diseases/spot-the-difference-identifying-faba-bean-diseases/. Correct identification is important as different fungicides are used to manage different fungal disease.

Field pea

Bacterial blight (BB)

Severe BB was reported across SA in late August and early September. BB is typically reported after frost events as occurred in 2018 and 2019; frosted cells provide an entry point for the *Pseudomonas* bacteria to infect. However, there is no treatment for the disease, so the only management strategy is to avoid entering the paddock to prevent further spread via wheels or boots. The preferred field pea varieties to grow in frost prone areas are PBA Percy(b), PBA Butler(b) or PBA Ourav as these are less susceptible to BB than other varieties.

This foliar disease begins as fan shaped lesions at the base of the leaf where it is attached to the stem and it spreads up and down the stem. Infection can start in one spot in a paddock then spread over a wide area; including being transported through or between paddocks on shoes or tyres. At harvest, prevent crop residue from infecting grain of clean crops by harvesting infected crops last in the pulse harvesting program. Do not retain grain from infected crops as there is a high chance of seed infection. If only a small area of crop has been infected, then it is possible to harvest a clean area for seed. There is no risk to stock of infected crops being baled for hay but do not spread the hay onto paddocks intended for field pea for the 2020 season. Feed lotting the hay would be the preferred option or it could be used on a property that doesn't grow field pea. During transportation it would be best if the hay was tarped to prevent spread into roadside paddocks.

It is important to identify which strain of *Pseudomonas* bacteria (pv. *syringae* or pv. *pisi*) is causing the outbreaks so the correct isolates are used in resistance screening. Please forward infected samples for research purposes to Dr Pragya Kant, AgVictoria CropSafe Isolate Collection, Reply Paid 69952, Horsham, Vic 3400.

Pulse disease National Variety Trial (NVT) program

Through an expansion of GRDC's NVT program, independent disease ratings of pulses will now be available. This new project provides robust disease ratings using processes adapted from those that were established for wheat and barley. The crops and diseases included are shown in Table 4.

As part of this new project, the definitions for each disease rating category were updated (Table 5). Due to this update, there will be some changes to the current pulse disease ratings with better alignment between crops and diseases.

Table 4. The crops and diseases included in the new National Variety Trial screening that commenced during 2019, and the states where they will be screened.

Crop	Disease	Screening State
Chickpea	Ascochyta blight	SA, Vic, NSW
	Botrytis grey mould	NSW
	Pratylenchus neglectus - Tolerance	Qld
	Pratylenchus neglectus - Resistance	Vic, Qld
	Pratylenchus thornei - Resistance	Vic, NSW, Qld
	Pratylenchus thornei - Tolerance	Qld
Faba bean	Ascochyta blight	SA, Vic
	Cercospora leaf spot	SA
	Chocolate spot	SA
	Pratylenchus neglectus	Vic, Qld
	Pratylenchus thornei	Vic, NSW, Qld
Field Pea	Ascochyta blight (synonym: blackspot)	WA, SA, Vic
	Bacterial blight	NSW
	Downy mildew	SA
	Powdery mildew	SA
	Pratylenchus neglectus	Vic, Qld
	Pratylenchus thornei	Vic, Qld
Lentil	Ascochyta blight	SA, Vic
	Botrytis grey mould	SA, NSW
	Pratylenchus neglectus	Vic
	Pratylenchus thornei	Vic
Lupin	Anthracnose	WA
	Brown spot	WA
	Cucumber mosaic virus	WA
	Phomopsis	WA
	Pleiochaeta root rot	WA
	Sclerotinia	WA

Within this new project there are a total of 49 disease screens conducted annually, drawing on the plant pathology expertise across Australia. The disease screens are conducted in either field and/or glasshouse conditions designed to maximise disease development.

At the end of the season, data collected n ationally are collated and disease ratings assigned by experts for each disease. The disease ratings are updated annually and made available in state-based disease guides and on the NVT web site (https://www.nvtonline.com.au/).

Disease samples of ascochyta blight and sclerotinia sought

Diseased samples of pulses with ascochyta blight or sclerotinia are sought by SARDI for GRDC-investment projects monitoring pathogen populations and changes in cultivar resistance. If you can help, please contact Sara Blake (email: sara.blake@sa.gov.au) for a collection kit that includes sample envelopes and a return Express Post envelope.

Diagnostic pulse plant samples can be sent by Express Post to Jenny Davidson SARDI, Locked Bag 100, Glen Osmond, 5064. Dig up whole symptomatic and asymptomatic plants and send with roots wrapped in damp (not wet) paper towel. Send at the beginning of the week, so the parcel does not get held up in the post. Send an email to jenny.davidison@sa.gov.au to notify that the plants are coming.

Crop protection products

There are often changes to permits for the use of fungicides in pulse crops. See Pulse Australia's website (www.pulseaus.com.au) or the APVMA website (www.apvma.gov.au).for current information on crop protection products including Minor Use Permits.

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This work is supported by investment from GRDC through GRDC Projects DAS1807-006BLX (Improved disease management in South Australian field crops through surveillance, diagnostics and epidemiology knowledge), DAV00150 (Southern Pulse Agronomy), UA00163 (Pulse Breeding: Faba bean breeding), and CUR00023 (Ascochyta blight of pulses). Pulse disease screening for the National Variety Trials in South Australia are supported by investment from GRDC through GRDC Project DAS1905-013SAX. The authors also acknowledge Dr Jeffrey Paull,

Table 5. The updated pulse disease ratings used in the National Variety Trials which will be implemented in pulse ratings released during 2020 and onwards.

Rating	Category	Definition
R	Resistant	No symptoms visible. No fungicides are required.
RMR	Resistant to Moderately Resistant	The disease may be visible but will not cause significant plant damage or loss. However, under extreme disease pressure or highly favourable environments conditions fungicide applications may be required e.g. to prevent seed staining.
MR	Moderately Resistant	The disease may be visible but will not cause significant plant damage or loss. However, under high disease pressure or highly favourable environments conditions fungicide applications may be required e.g. to prevent seed staining.
MRMS	Moderately Resistant to Moderately Susceptible	The disease symptoms are moderate and may cause some yield and/or seed quality losses in conducive conditions. Fungicide applications, if applicable, may be required to prevent yield loss and seed staining.
MS	Moderately Susceptible	Disease symptoms are moderate to severe and will cause significant yield and seed quality loss in the absence of fungicides in conducive seasons, but not complete crop loss.
S	Susceptible	The disease is severe and will cause significant yield and seed quality loss, including complete crop loss in the absence of fungicides, in conducive conditions.
VS	Very Susceptible	Growing this variety in areas where a disease is likely to be present is very high risk. Significant yield and seed quality losses, including complete crop loss can be expected without control and the increase in inoculum may create problems for other growers.

University of Adelaide, faba bean breeder, for his review of this paper.

Useful resources

Subscribe to CropWatch e-newsletter: http://pir.sa.gov.au/research/services/reports_and_newsletters/crop_watch

ExtensionAus website: https://communities.grdc.com.au/field-crop-diseases/

https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/08/disease-management-of-pulses-grown-in-low-to-medium-rainfall-zones

2020 SA sowing guide: https://grdc.com.au/resources-and-publications/all-publications/publications/2020/2020-south-australian-crop-sowing-guide

New pulse variety releases:

PBA Royal⁽ᵇ⁾ chickpea: https://www.seednet.com.au/product/pba-royal

PBA Highland XT⁽ᵇ⁾ lentil: https://www.pbseeds.com.au/docs/PBAHIGHLANDXT.pdf

PBA Amberley⁽ᵇ⁾ faba bean: https://www.seednet.com.au/product/pba-amberley

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Notes

The health report - emerging pulse root diseases

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South Australian Research and Development Institute.

GRDC project code: DJP1907-002RMX

Keywords

- pulse root disease, Phytophthora root rot, Aphanomyces root rot, Fusarium root rot, PREDICTA®B, next generation sequencing.

Take home messages

- Pulse and canola crops can suffer from root diseases.
- Next generation sequencing technology and PREDICTA®B tests are revealing multiple potentially important soilborne pathogens of pulse and oilseed crops in Australia; further work is being undertaken to determine which are the most important.
- In 2020, if you suspect soilborne disease issues in your pulse/canola crops, send samples to SARDI.

Background

International experience indicates that soilborne pathogens can be important constraints to production in pulse crops when cropping frequency increases (Gossen et al. 2016). In 2017, the loss of three chickpea crops to suspected Phytophthora root rot and a faba bean crop to Aphanomyces root rot, prompted the South Australian Grains Industry Trust (SAGIT) to fund a root disease survey of pulse and oilseed crops in South Australia (S218).

Phytophthora root rot, caused by *Phytophthora medicaginis*, is an important root disease of chickpeas in northern NSW. However, *P. medicaginis* was eliminated as the cause of loss of the three chickpea crops in South Australia (SA), using an existing PREDICTA®B (Northern Region) test.

New diagnostic research technology being developed by the GRDC-SARDI bilateral investments; DAS1907-001BLX and DAS1802-011BLX was used to test DNA extracted from the diseased chickpea roots and identified *Phytophthora megasperma* as the likely cause. A PREDICTA®B test was developed to support the survey.

In 2019, GRDC extended the survey nationally as part of DJP1907-002RMX. A panel of 23 tests was assembled to survey the pulse and oilseed root systems collected from across Australia (Table 1 and Table 2). DNA extracted from these samples was also tested using next generation sequencing (NGS), to detect pathogens for which no PREDICTA®B-style test had been developed. The NGS data is still being examined.

Methods

Pulse root samples were sent to SARDI by growers and agronomists across SA. Excess soil was washed from the roots and any plant material above the basal stem was removed. Roots were processed through the PREDICTA®B laboratory and DNA was extracted. The Pulse Research test panel was run on the extracted DNA to quantify targeted pulse pathogens in the samples.

DNA samples were also assessed using NGS to identify potentially important pathogens not detected by the Pulse Research test panel. Three Illumina® MiSeq® libraries were prepared using primer pairs that target the ITS1, ITS2 and elongation factor gene regions to aid identification of oomycetes (for example, *Phytophthora*) and fungal species (for example, *Phoma* and *Fusarium* species).

Where root samples showed distinctive/diagnostic symptoms, or where DNA tests indicated the presence of a potential pathogen, samples were plated on a variety of selective agar media in an attempt to culture the suspected pathogen(s).

Isolates are currently being tested for pathogenicity using the original host crop in a replicated controlled growth room bioassay (pot test). In short, 50ml tubes of sterile sand were planted with a seed of the host crop and inoculated with two millet seeds colonised by the cultured fungus. Plant roots were washed out approximately three weeks after sowing and disease was scored visually in comparison with an uninfected control. For isolates that appear pathogenic, a more representative bioassay will be performed, including other pulse species of interest. This will enable the pathogen's host range to be determined.

Results and discussion

To date 400 samples have been processed from across all cropping regions in Australia, including 97 collected in 2018 from SA and western Victoria (Vic). Crops tested include chickpea, lentil, faba bean, field pea, lupin, canola, vetch, clover and lucerne.

Fifty-six isolates have been retained and sequenced using Sanger sequencing to identify isolates to species level. Of this collection, 20 Fusarium spp. isolates have undergone initial pathogenicity testing.

Pulse Research test panel

The results for the Pulse Research test panel are summarised in Table 1 and Table 2. *Pratylenchus neglectus, Pythium* clade F and *Phoma pinodella* (this test also detects *Didymella pinodes*) were all common.

P. neglectus (root lesion nematode) was detected at substantial levels in many crops including some that were considered to be poor hosts (for example, faba bean and field peas); presumably it does not multiply well in these crops even though it can invade the roots. Its effect on yield of pulses is not known.

P. pinodella has a broad host range amongst pulse crops and pasture legumes. It commonly causes foot rot in field pea and sub clover; it is also part of the pathogen complex causing black spot of field pea. Its effect as a pulse root pathogen is unknown.

Aphanomyces euteiches was found in 18% of samples in 2018 and 1% in 2019, all were from faba bean crops exhibiting moderate to severe root disease. In 2019, a test for *Aphanomyces trifolii* was added to the panel, with six samples (faba bean, lentil, vetch) found to be infected. The pathogen was particularly prevalent in vetch (27% of vetch samples infected). This pathogen is typically associated with sub-clover (O'Rourke et al. 2010). The effect of *A. trifolii* on lentil and vetch has not been described, while the effect on faba bean has only been briefly described (O'Rourke et al. 2010).

Rhizoctonia solani AG8 and AG2.1, *Pythium* clade I and *Macrophomina phaseolina* (charcoal rot) were also present at substantial levels. R. solani AG4, which can be a serious pathogen of pulses and other crops (Hwang et al. 2003), was detected in one sample in each year (chickpea and faba bean).

P. medicaginis was not detected in either year, probably due to drought in north Australia. Conditions were conducive for Phytophthora in the GRDC Southern and Western Regions of Australia

Table 1. Percentage of samples in which the stated pathogen was detected by a quantitative polymerase chain reaction (qPCR) in a survey of pulse roots in the South East region of SA and the Wimmera region of Victoria in 2018.

	% Crop samples infected (no. of samples tested)						
	Chickpea (34)	Faba bean (22)	Lentil (26)	Lupin (4)	Field Pea (2)	Lucerne(4)	Other* (5)
Pratylenchus neglectus	88%	63%	100%	100%	100%	50%	100%
Pratylenchus thornei	41%	32%	31%	0%	0%	25%	0%
Rhizoctonia solani AG8	32%	32%	50%	100%	0%	25%	0%
Rhizoctonia solani AG2.1	18%	27%	54%	0%	0%	0%	0%
Rhizoctonia solani AG2.2	0%	0%	0%	0%	0%	0%	0%
Rhizoctonia solani AG4	3%	0%	0%	0%	0%	0%	0%
Pythium clade F	85%	96%	77%	75%	100%	100%	80%
Pythium clade I	44%	68%	73%	25%	50%	25%	80%
Aphanomyces euteiches	0%	18%	0%	0%	0%	0%	0%
Phytophthora medicaginis	0%	0%	0%	0%	0%	0%	0%
Phoma pinodella	88%	86%	100%	0%	100%	50%	40%
Macrophomina phaseolina	41%	0%	69%	N/A	N/A	N/A	N/A

*Other crop types include vetch, canola and clover.

Table 2. Percentage of samples in which the stated pathogen was detected by a quantitative polymerase chain reaction (qPCR) in a survey of pulse roots from Australia in 2019.

Pathogen	% Crop samples infected (no. of samples tested)						
	Chickpea (41)	Faba Bean (59)	Lentil (91)	Lupin (57)	Field Pea (17)	Vetch (11)	Canola (27)
Pratylenchus neglectus	59%	59%	67%	37%	59%	55%	44%
Pratylenchus thornei	22%	24%	2%	4%	12%	9%	0%
Pratylenchus penetrans	0%	0%	0%	2%	0%	0%	4%
Pratylenchus quasitereoides	0%	2%	0%	5%	0%	0%	7%
Rhizoctonia solani AG8	20%	37%	33%	46%	41%	9%	33%
Rhizoctonia solani AG2.1	17%	25%	11%	12%	18%	9%	26%
Rhizoctonia solani AG2.2	0%	0%	0%	2%	0%	0%	0%
Rhizoctonia solani AG4	0%	2%	0%	0%	0%	0%	0%
Pythium clade F	46%	88%	55%	72%	100%	64%	48%
Pythium clade I	2%	10%	11%	0%	0%	0%	4%
Aphanomyces euteiches	0%	3%	0%	0%	0%	0%	0%
Aphanomyces trifolii	0%	2%	1%	0%	0%	27%	0%
Phytophthora medicaginis	0%	0%	0%	0%	0%	0%	0%
Phytophthora megasperma	0%	0%	2%	2%	0%	0%	0%
Phytophthora clandestina	0%	0%	0%	2%	0%	0%	4%
Phoma pinodella	83%	86%	67%	65%	94%	36%	33%
Phoma rabei	29%	0%	0%	0%	0%	0%	0%
Macrophomina phaseolina	24%	29%	7%	40%	0%	9%	41%
Thielaviopsis basicola	0%	0%	0%	2%	0%	0%	0%
Leptosphaeria maculans	0%	8%	3%	2%	0%	0%	52%
Plasmodiophora brassicae	0%	0%	0%	0%	0%	0%	7%
Ditylenchus dipsaci	0%	2%	0%	0%	0%	0%	0%
Sclerotinia sclerotiorum	7%	8%	0%	19%	0%	9%	4%
Rhizoctonia sp. (Eradu)	10%	19%	3%	39%	18%	9%	15%

and *P. megasperma* and *P. clandestina* were detected in SA and Western Australia (WA) (lentil and lupin). Both species are known to have a wide host range, however their importance in southern Australian pulse crops is yet to be quantified.

Next Generation Sequencing (NGS)

DNA from each root sample was analysed with NGS and a broad range of fungal organisms were detected; some of which have been reported to cause root disease of pulses. Organisms were identified as pathogens of interest based on international research and observed symptoms in plant samples. Pathogens of interest identified in this survey are summarised as follows:

Phytophthora spp.

Sequence data identified several *Phytophthora* species present including *P. megasperma/ crassamurra, P. trifolii* and *P. clandestina*. All three species were detected in chickpea roots with symptoms of Phytophthora root rot in 2018 (i.e. year prior to sampling). *P. megasperma/crassamurra* was also found on faba bean and lucerne roots. These *Phytophthora* species could have been the pathogens responsible for crop failures in the chickpea paddocks from 2017 and crop and root symptoms in 2018. These samples were negative for *P. medicaginis* using the PREDICTA®B test. The potential of *P. megasperma/crassamurra* to also infect faba bean roots could have implications for the South East region and requires further investigation to confirm and quantify its extent and severity.

Australian research in the GRDC Northern Region on Phytophthora root rot (*P. medicaginis*) is currently the best reference point for the impacts of this disease in chickpea as the impacts in the GRDC Southern Region are currently unknown. Further research in the GRDC Southern Region is required to determine the severity of impact of *P. megasperma/crassumurra* and how it compares to Phytophthora root rot in the Northern Region where it was estimated to cost chickpea growers up to $8.2 million annually (Murray and Brennan, 2012).

The only chemical option available for Phytophthora root rot in the GRDC Northern Region is metalaxyl-based seed dressings, which can provide six to eight weeks protection post seeding (Moore et al. 2011). Currently, the best non-chemical options for growers to manage Phytophthora root rot are to use wide rotations and grow varieties that are moderately resistant (Amalraj et al. 2018).

Thielaviopsis basicola

Thielaviopsis basicola sequences were detected on diseased chickpea roots grown in soil from near Naracoorte and from a diseased lupin root system from Coomandook in 2019. *T. basicola* causes black root rot and has a very broad host range including pulses, vegetables and cotton. Internationally, chickpea and lentil have been identified as susceptible to *T. basicola*, and disease has been found in numerous cropping regions (Bowden et al. 1985, Abbas et al. 2007, Bhatti et al. 1992). A test for *T. basicola* has now been added to the PREDICTA®B Pulse Research test panel, with one lupin sample from WA returning a positive detection in 2019.

Fusarium spp.

Globally, *Fusarium* spp. feature frequently in research on pulse root diseases (for example, Gossen et al. 2016, Li et al. 2017, Wong et al. 1985, Banniza et al. 2015). Species reported in the literature and tentatively identified as detected by the survey, include *F. solani, F. redolens, F. oxysporum, F. equiseti, F. avenaceum* and *F. acuminatum*. Internationally, research groups are currently investigating the role of these species as potentially important components of disease complexes with *A. eutiches* and *Phytophthora* spp. (Banniza, 2016).

In North America and Canada, *F. redolens* is considered to be an important component of pulse root disease complexes. Following confirmation of the presence of *F. redolens* in Australia, SARDI developed a PREDICTA®B style test for this species to assist with the survey. Tests for other Fusarium spp. may follow, depending on results of pathogenicity experiments.

Table 3. Disease scores and recovery of pathogen from inoculated plant material from 20 fungal isolates from pulse roots surveyed in South Australia in 2018-19.

Isolate	Suspected identity	Crop	Ave. tap root rot score (0-5)	Ave. lateral root rot score (0-5)	Isolate recovered from bioassay
Control		Chickpea	0.0	0.0	N
Control		Lentil	0.0	0.0	N
Control		Field pea	0.0	0.0	N
Control		Faba bean	0.0	0.0	N
BLBG1	*Phoma pinodella*	Chickpea	3.7	3.3	Y
BC10287a	*Fusarium redolens*	Field pea	4.0	3.7	Y
BC10225(1)	*Cylindrocarpon sp.*	Faba bean	0.0	0.7	N
BC10294(2)	*Cylindrocarpon sp.*	Chickpea	2.0	2.7	N
BC10225(5)	*F. neocosmoporiellum*	Faba bean	0.3	0.0	N/A
BC10287d	*F. oxysporum*	Field pea	0.3	1.0	N/A
BC10287c	*F. redolens*	Field pea	0.0	1.0	N/A
BC10288a	*F. chlamydosporum*	Faba bean	0.7	0.7	N/A
BC10288b	*F. chlamydosporum*	Faba bean	0.3	0.7	N/A
BC10225(3)	*F. avanaceum*	Faba bean	5.0	5.0	Y
BC10225(4)	*F. oxysporum*	Faba bean	2.7	3.0	Y
BC10225(7)	*F. oxysporum*	Faba bean	2.3	2.3	Y
BC10286(2)	*F. oxysporum*	Chickpea	3.0	4.0	Y
BC10286(7)	*F. tricinctum*	Chickpea	0.0	0.3	N/A
BC10300(2)	*F. oxysporum*	Lentil	4.3	5.0	Y
BC10300(4)	*F. oxysporum*	Lentil	4.0	3.7	Y
BC10286(8)	*F. oxysporum*	Chickpea	2.0	2.7	Y
BC10286(9)	*F. oxysporum*	Chickpea	1.7	3.0	Y
BC10300(6)	*F. oxysporum*	Lentil	1.0	2.3	N
Lentil	*F. oxysporum*	Lentil	2.7	2.3	N

There are constraints on the resolution of the NGS. The Illumina® MiSeq® sequences cannot differentiate *Fusarium* species to *forma specialis*. This limits our current ability to identify some of the most important root pathogens of chickpea (*F. oxysporum f. sp. ciceris*) and lentil (f. *sp. lentis*). Both however, are not currently known to occur in Australia (Cunnington et al. 2016, Pouralibaba et al. 2016).

Further investigation is needed to determine which, if any, of the above species play an important role in causing pulse root disease in Australia.

Pathogenicity testing

Screening of isolates of potential pathogens extracted from root samples was undertaken using a bioassay in a controlled growth room. Preliminary results are presented in Table 3. The results indicate that isolates BC10287a, BC10294(2), 10225(3), 10225(4), 10286(2) and 10286(9) are pathogenic and can cause considerable root damage. These isolates have been tentatively identified as belonging to a range of *Fusarium* (and *Cylindrocarpon/Dactylonectria*) species. Other isolates tested in this screening that were identified as the same species, were not pathogenic, or only weakly pathogenic. This confirms that there is likely to be considerable variation in pathogenicity; both between and within species of Fusarium and related genera.

A single isolate of *Phoma pinodella* (BLBG1) included in this test was moderately pathogenic. Isolates that rated moderately to strongly pathogenic in the initial screen will be included in a more extensive bioassay, while new isolates of many other genera including *Phoma, Pythium, Phytophthora* will also be tested in bioassays.

Conclusion

While this research is in the 'problem definition' phase, some patterns are beginning to emerge. *Phytophthora* and *Aphanomyces* have been associated with crop failures in the high rainfall zones, but their occurrence seems to be sporadic. Other potential root pathogens such as *Fusarium, Pythium* and *Phoma* are much more common, within and across regions. Their effect on yield needs to be further investigated however many species of these genera are known to be pathogenic. These potential pathogens being widespread suggests they have greater potential for impact across the industry.

It is likely that pulse root diseases are contributing to poor water use efficiency and unexpected yield losses, and the risk is likely to increase with increased frequency of pulses in cropping sequences. Legume pastures may also be a significant source of infection.

Research to evaluate the impact of pulse root diseases and management options are expected to commence in 2020. In the meantime, SARDI will continue to survey pulse crops in SA under the SAGIT project S218 in 2020, and nationally under the GRDC project DJP1907-002RMX. Consultants and growers are encouraged to monitor their pulse crops and submit plant samples from poor performing areas that previously may have been attributed to waterlogging or other environmental stressors.

If you are interested in assisting with the survey, please contact Blake Gontar for sample kits.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of consultants and growers through sample contribution and the support of GRDC and SAGIT (project S218); the authors would like to thank them for their continued support. From 2019 onward, this survey is being conducted in collaboration with researchers from WA, Queensland, New South Wales and Vic.

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Chemical residues and maximum residue limits (MRLs) – impact, understanding and potential trade issues

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GRDC project code: MCM00003 – Strategic oversight and coordination of grain protection chemicals

Keywords

- chemicals, maximum residue limits, MRLs, market access, domestic marketing, export marketing.

Take home messages

- It is a legal requirement to follow all label directions when applying any chemical.
- There are different perceptions and legal/contractual requirements of key domestic and export markets for chemical residues.
- There are market access implications when using chemicals; applying a chemical according to label directions does **not** necessarily mean that grain will meet market requirements.
- There is a need for advisers and growers to understand market requirements and seek advice on the MRLs that apply. Talk to your marketer if possible, before you intend to apply chemicals to a crop.

What is a maximum residue limit (MRL)?

A range of different types of chemicals are applied to crops for varying reasons. Chemicals may be used prior to planting, during the crop growth stage or following harvest. Only those chemicals registered in Australia for use on a particular crop may be applied. All chemicals registered in Australia must be used according to label directions (for example; crop type, application rates, withholding periods, etc.). This is a legal requirement in Australia.

When using these chemicals, residues may arise in the harvested grain. Residues may also arise when moving that grain using equipment such as augers and trucks that have previously held grain containing chemical residues.

The nature of residues arising are considered by the Australian Pesticides and Veterinary Medicines Authority (APVMA) and if necessary, an MRL is set for that chemical and crop commodity combination.

An MRL is the maximum concentration of a residue resulting from the registered use of an agricultural chemical which is legally permitted or recognised as acceptable to be present in or on a food, agricultural commodity or animal feed.

What are market requirements?

Chemical residues on imported food and food safety in general are arguably the key focus for markets at present.

When marketing grain in Australia or in an overseas country, residue levels must meet the regulated MRL and customer contract specifications of the destination country. These may differ to the Australian MRL.

Each market, whether it be in Australia or overseas, is responsible for ensuring the food that is imported and subsequently consumed is safe to eat in terms of chemical residues. Each market has their own chemical legislation based on their own particular chemical usage and consumption patterns. Hence different MRLs for the same chemical and commodity may apply in different markets.

There is a trend towards markets developing their own chemical regulations and not relying as previously implied on international standards, such as Codex Alimentarius. There is a trend towards requiring lower (or nil) residues on grain supplied. Markets are also increasing their level of monitoring of imported grain via sampling and testing to check compliance with their needs.

The increase in grain traded internationally may cause a market access issue for Australian grain where:

- The market has no MRL (missing MRL).
- The market doesn't apply a Codex MRL (divergent MRL).
- There is no Codex MRL for those markets that follow or default to Codex.
- The market does not have a default policy and hence a zero limit applies.
- The market applies a low level of detection (LOD).
- In some instances, contracts do not state the MRLs that apply. It is the responsibility of the supplier or the marketer of the grain to ensure that they know the regulations and that the grain supplied meets those requirements.

Implications for advisers and growers

Even though a grower may apply a chemical correctly and in accordance with label directions, the resulting grain residues may not meet market requirements.

In addition, there is the concern that in many situations the adviser/grower does not know the market requirement before they use the chemical?

All grain trading standards have wording in relation to chemical use that growers must comply with.

An example for the Grain Trade Australia Wheat Trading Standards is outlined as follows:

Chemicals not approved for Wheat – a nil tolerance applies, and this refers to the following:

- *Chemicals used on the growing crop in the State or Territory where the wheat was grown in contravention of the label*
- *Chemicals used on stored wheat in contravention of the label*
- *Chemicals not registered for use on wheat*
- *Wheat containing any artificial colouring, pickling compound or marker dye commonly used during crop spraying operations that has stained the wheat*
- *Wheat treated with or contaminated by Carbaryl, Organochloride chemicals, or diatomaceous earth*
- *Chemical residues in excess of Australian Commonwealth, State or Territory legal limits*

Residue testing is done either by the marketer or by the National Residue Survey on domestic grain and export grain shipments, the latter funded via a grower levy. If residues arise that exceed the market MRL, price penalties may occur, or the shipment may be rejected and returned to Australia. Costs may be passed from the marketer to the supplier of that grain where there is evidence of chemical misuse or false chemical use declarations. Sampling and testing of future grower loads and shipments

Table 1. Some key Australian markets and their chemical MRL regulations.

Market	Codex	Australia	China	EU	Indonesia	Japan	South Korea	Taiwan	Thailand	Vietnam
Regulation applied	Not adopted by all markets	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard	Own MRL Standard
Default MRL	No default	No default	No default	Default system	No Default	Default system	Default system	No default	Default system is complex	No default
If no MRL	ZERO	ZERO	ZERO	0.01	CRA / ZERO	0.01	0.01	ZERO	0.01	ZERO
MRL Updates	Yearly	Monthly – 6 weeks	Bi-annually	Often	Rarely	Often	Often	Approx. twice/year	Rarely	Rarely

Note: Above is as at 6 January 2020, variations exist for specific chemicals. MRLs quoted in mg/kg. CRA refers to a Country Recognition Agreement where Indonesia may accept Australian MRLs for some commodities may increase or additional segregations may need to be created, which all create extra costs. These increased costs may be passed onto the grower through the purchase price offered for the grain.

The post-farm gate sector expects that growers apply chemicals follow legal requirements. Sampling and testing of all deliveries for all possible chemicals used on-farm is not conducted due to the expense. Rather, targeted sampling and testing is conducted based on market risk. Thus, growers must provide accurate information on chemicals used on that crop. Growers are encouraged to complete Commodity Vendor Declarations correctly when details of chemicals used are sought by the trade. Failure to do so risks the supply of grain that fails to meet market requirements, a loss in reputation of Australian grain and increased costs for all along the supply chain.

Tools to assist with meeting market requirements

On behalf of industry, the NWPGP is the body responsible for providing management and leadership to industry in the areas of chemical use, post-harvest storage, market requirements and monitoring changing chemical regulations and their impact on market access.

The NWPGP is the linkage between Government and the industry providing:

- Feedback on issues of concern with chemicals.
- Advice on whether government to government submissions are required.
- Strategies for dealing with changing market requirements and actions by all in industry to address these.

An annual 2-day conference is held providing participants with the latest research and developments in the area of chemical usage, post-harvest storage and hygiene and outturn tolerances, international and domestic market requirements, and regulations. The outcomes are provided to industry to assist with market access compliance.

A greater focus has been placed in the last two years on providing industry with knowledge of market requirements. This has involved significant communication and liaison with the pre- and post-farm gate sector. The gap between knowledge of the market requirements and what happens on-farm was recognised and communication to the pre-farm gate sector has increased through development of Fact Sheets and presentations to a range of stakeholders throughout Australia. This has occurred via NWPGP, GRDC and various government departments. Further communication with the grower and the adviser sector will continue to benefit all in the industry.

Conclusion

Given the changing nature of market regulations, all stakeholders along the supply chain need to be aware of market requirements in relation to MRLs. Given the implications of incorrect chemical use, there is a need for greater transparency and understanding by growers and advisers of the impact of chemical use on market access.

Going forward there will be a focus on ensuring all supply chain participants understand the risks of non-compliance with label directions and removing the gaps in networking; including chemical registrants, re-sellers, agronomists, growers and their advisers.

Growers need to talk to their adviser/agronomist and storage agent/marketer and where needed other experts, when seeking advice on market requirements.

Acknowledgement

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Useful resources

On-farm Stewardship Guide 'Growing Australian Grain' http://grainsguide.grainproducers.com.au

National Working Party on Grain Protection www.graintrade.org.au/nwpgp

National Residue Survey https://www.agriculture.gov.au/ag-farm-food/food/nrs

APVMA https://apvma.gov.au

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New changes and future opportunities within NVT

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Break crop selection in low rainfall environments – one size does not fit all

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GRDC project code: DAS00162A

Keywords

- farming system, break crop, rotation, low rainfall, pulse, canola.

Take home messages

- Break crop performance is highly variable across the southern low rainfall zone, and therefore a 'one size fits all' approach does not work.
- Nuseed® Diamond canola, PBA Samira⁽ᴰ⁾ faba bean, Volga⁽ᴰ⁾ vetch and PBA Bateman⁽ᴰ⁾ lupin have shown improved crop performance compared to other varieties of their respective crop species.
- Genesis™ 090 chickpea, PBA Striker⁽ᴰ⁾ chickpea, PBA Bolt⁽ᴰ⁾ lentil, PBA Hallmark XT⁽ᴰ⁾ lentil, PBA Butler⁽ᴰ⁾ field pea, and PBA Wharton⁽ᴰ⁾ field pea were the top performing varieties of their respective crop species, depending on the environment.
- @RISK model analysis outcomes indicate that field peas are profitable in 40.7% of years while lentils can be profitable in 51.6% of years.

Background

Current farming systems in the low rainfall zone (<325mm) of southern Australia are dominated by cereal production. There is increasing concern about grass weed and soil-borne disease pressure, as well as diminishing soil fertility (particularly nitrogen (N)), and poor water use efficiency (WUE) as a result of continuously cropping cereals (Seymour et al. 2012; Angus et al. 2015; McBeath et al. 2015). Break crops have a key role to play in addressing these issues, as well as diversifying crop production and economic risk, and maintaining long-term sustainability of the system. The success of a break crop is critical for gaining the most benefit out of the break phase for the subsequent crops.

The use of a break crop in a cereal dominant cropping system consistently results in at least 1t/ha of additional yield in the subsequent crop, in low rainfall environments (McBeath et al. 2015) and can improve profitability of the farming system by up to $100/ha per year (Moodie and Wilhelm 2016). However, there remains a lack of information available to growers about choosing the break crop best suited to their situation, as break crop development to date has largely occurred in medium and high rainfall zones. The aim of this research is to identify the best break crop species and varieties for different climate, soil type and biotic stress situations — within major cropping regions of the southern low rainfall zone.

Method

Break crop species-by-variety trials were undertaken in 2017 at four key locations across the southern low rainfall zone — and were expanded to new locations in 2018 and 2019. A total of 14 trials were undertaken across five locations over three seasons. The trials include three to six varieties of canola, chickpea, faba bean, field pea, lupin, lentil, and vetch (Table 1) — representing potential options for the low rainfall zone. Varieties were selected following consultation with breeders, researchers, and advisors. Varietal options include herbicide-tolerant varieties and those with a potential alternative end-use to grain, such as grazing or hay.

Trial measurements include site soil characteristics, soil moisture, seasonal temperature and rainfall, grain yield, biomass yield, and gross margin (GM). Trials were sown using an experimental plot seeder. Biomass yield was measured at late flowering to early pod development growth stage to identify potential use as a hay, forage or manure crop. Trials were harvested at crop maturity using an experimental plot harvester. GM was calculated using the PIRSA Rural Solutions 'Farm gross margin and enterprise planning guide' and a five-year average grain price for each season.

The plot arrangement was a split plot design with three replicates, and random assignment of break crop species to the whole plot and variety to the sub plot. The use of this design ensures each break crop species receives appropriate agronomic management. A multi-environment trial (MET) analysis using a factor analytic model (Smith et al. 2001), with adjustment for design factors and spatial variation, was conducted for biomass and grain yields. Models were fitted in ASReml-R (Butler et al. 2009) in the statistical software platform R.

A model developed by Rural Directions Pty Ltd using @RISK, (an add-on to Microsoft Excel), to assess risk and net profit associated with different break crop options in a three-year break-wheat-wheat rotation. The model included percentile 10, 50 and 90 yields and prices (Table 2), together with low-input variable costs for each crop — analysing 5 000 seasonal outcomes. Grain yield percentiles were calculated from actual grain yield results from break crop species by variety trials, 2017 to 2019. Grain price percentiles were calculated from long-term commodity price records, based on farm gate prices. Estimated yield benefits and penalties associated with the following crop, and estimated fixed costs (depreciation, finance cost and overhead costs) were also accounted for in the model.

Table 2. Grain price and yield percentiles used in the @RISK model analysis.

	Price ($/t) percentiles			Yield (t/ha) percentiles		
	P10	P50	P90	P10	P50	P90
Wheat	180	230	280	0.4	1.28	2.8
Canola	450	490	530	0.2	0.53	1.2
Lentil	415	660	1 000	0.2	0.59	1.3
Chickpea	620	1 000	1 400	0.2	0.59	1.3
Field pea	200	320	485	0.2	0.79	1.7
Faba bean	240	323	461	0.2	0.57	1.3
Lupin	180	320	500	0.2	0.74	1.6
Vetch hay	180	240	300	0.7	2.4	5.3

Results and discussion

Break crop and variety selection

The MET analysis identified strong correlations for grain yield, biomass yield, and GM between some environments, as well as negative and weak correlations — demonstrating the high variance across the low rainfall environments. Break crop species production was variable, with some species showing improved stability in some environments. In most environments, in particular at Minnipa on the upper Eyre Peninsula (EP), field pea expressed their reliability and stability in low rainfall environments, providing that they are not sown in a frost prone area. Alongside field pea, at Willowie in the upper Mid-North, lentil and vetch have shown stability and reliability. In the northern Victorian Mallee, west of Mildura, canola and chickpea have shown stability across two highly variable seasons.

Table 1. List of break crop species and varieties included in the trials.

Break crop species	Varieties
Canola	ATR Bonito$^{\phi}$, ATR Stingray$^{\phi}$, Hyola® 559TT, Nuseed® Diamond, Pioneer® 44Y90 (CL), Pioneer® 43Y92 (CL)
Chickpea	Genesis™ 090, PBA Monarch$^{\phi}$, PBA Striker$^{\phi}$
Faba Bean	PBA Marne$^{\phi}$, PBA Samira$^{\phi}$, PBA Bendoc$^{\phi}$
Field Pea	Kaspa$^{\phi}$, PBA Butler$^{\phi}$, PBA Coogee$^{\phi}$, PBA Percy$^{\phi}$, PBA Gunyah$^{\phi}$, PBA Twilight$^{\phi}$, PBA Wharton$^{\phi}$
Lentil	PBA Flash$^{\phi}$, PBA Hallmark XT$^{\phi}$, PBA Hurricane XT$^{\phi}$, PBA Blitz$^{\phi}$, PBA Bolt$^{\phi}$, PBA Jumbo2$^{\phi}$
Lupin	PBA Bateman$^{\phi}$, PBA Jurien$^{\phi}$, Mandelup$^{\phi}$
Vetch	Rasina$^{\phi}$, Timok$^{\phi}$, Volga$^{\phi}$

The MET analysis also identified varieties in each break crop species that were consistent performers for their relative crop species. Nuseed Diamond canola is a fast growing and early maturing hybrid variety, and with these characteristics has been the top performing canola variety for both grain and biomass yield across all environments. Hybrid Clearfield® canola varieties Pioneer 44Y90 and Pioneer 43Y92 have proven to be the next best performers compared to Nuseed Diamond— and would be suitable options where weeds or herbicide residues are an issue.

Open-pollinated canola varieties did not perform as well as hybrid varieties in the low rainfall environments of this study. PBA Samira⏀ faba bean performed well for both biomass and grain production across all environments, and generally similar to, or slightly better than, PBA Marne⏀ (a low rainfall or short season adapted variety). However, if herbicide residues and or particular broadleaf weeds are an issue, PBA Bendoc⏀ with improved tolerance to Group B herbicides residues is a suitable option.

Sowing time may also dictate faba bean variety selection, as PBA Samira⏀ would be better suited to early sowing than PBA Marne⏀. Early maturing vetch variety, Volga⏀, has high grain and hay yield potential, and has proved to be a top performing vetch variety across the low rainfall environments. PBA Bateman⏀, a recent high yielding lupin variety release with early flowering, has been a consistent performing variety for lupin. Desi chickpea, PBA Striker⏀, and kabuli chickpea, Genesis™ 090, showed improved biomass and grain yield performance, as well as improved early vigour and ground cover compared to large-seeded kabuli chickpea, PBA Monarch⏀.

For field pea, PBA Butler⏀ and PBA Wharton⏀ were high yielding varieties compared to other field pea varieties included in the study. Despite yield being similar for these two varieties, the more recently released variety PBA Butler⏀ showed improved early vigour and canopy structure over PBA Wharton⏀ in some environments. Performance of both semi-leafless (SL) and conventional (C) field pea types were studied across the low rainfall environments to look at alternative end-use options to grain production. However, C type field pea did not offer improved biomass production over SL types (Figure 1). Additionally, C type field pea has poor lodging resistance, and therefore SL varieties may be a more suitable option, regardless of end-use.

PBA Bolt⏀ and PBA Hallmark XT⏀ lentil varieties performed well across all environments for both biomass and grain production. PBA Bolt⏀ offers early to mid-flowering and maturity, lodging resistance, improved tolerance to boron and salt, and high grain

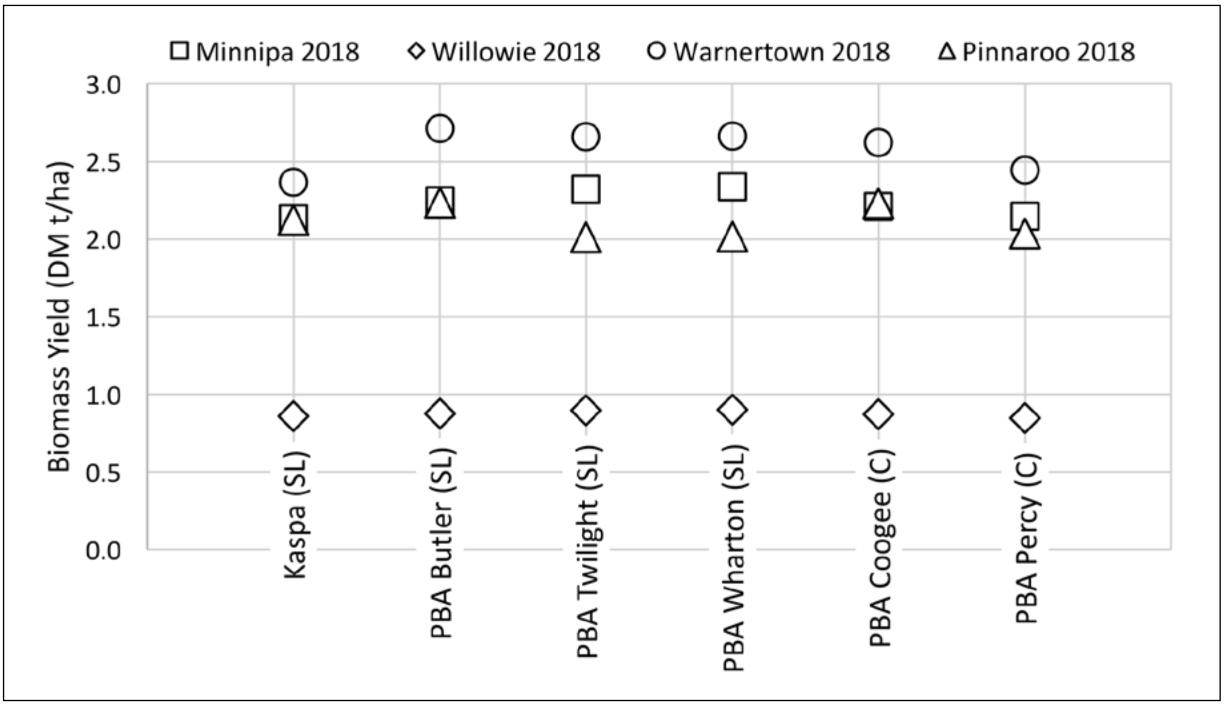

Figure 1. Growing conventional field pea varieties PBA Coogee⏀ and PBA Percy⏀ does not offer improved biomass production over semi-leafless (SL) varieties in the low rainfall zone of South Australia (SA). In 2018, Minnipa, Willowie, Warnertown and Pinnaroo environments are positively correlated for biomass production (0.43-0.9).

Table 3. @RISK analysis of break crop options in a three-year rotation with wheat. The rotation sequence is ranked from lowest risk and most profitable, to highest risk and least profitable.

Rotation sequence	Average gross margin $/ha	Average net profit $/ha	% of years break crop is profitable	Rank
Chickpea-wheat-wheat	281.86	181.86	55.5	1
Vetch hay-wheat-wheat	178.03	78.03	56.6	2
Lentil-wheat-wheat	172.71	72.71	51.6	3
Lupin-wheat-wheat	124.28	24.28	44.3	4
Field pea-wheat-wheat	104.40	4.40	40.7	5
Faba bean-wheat-wheat	89.68	-10.32	38.7	6
Canola-wheat-wheat	55.81	-44.19	34.3	7

Net profit = gross margin minus estimated fixed costs ($100/ha)

yield potential in drought conditions and low rainfall environments. PBA Hallmark XT⁽ᵈ⁾ has improved herbicide tolerance compared to conventional lentil varieties — and would be well suited to areas or seasons where Group B herbicide residues are an issue.

@RISK analysis

The @RISK analysis of 5000 seasonal outcomes provided a percentage of years that each break crop would be profitable, and the net profit for each rotation sequence (Table 3). Average net profit per hectare, per year, over a three-year rotation for chickpea and lentil were $181.86 and $72.71, respectively, compared to $4.40 for field pea. On average over all seasons, rotations with faba bean and canola produced losses of $10.32 and $44.19.

Rotation sequences including field pea were profitable 40.7% of years and those including lentil were profitable in 51.6% of years. Sequences that included chickpea were profitable in 55.5% of years. It is important to keep in mind that this analysis was based on a low input system with the application of only one fungicide spray, and chickpea would not be as profitable in a season with high disease risk or infection of ascochyta blight. The analysis indicated that canola and faba bean were the least profitable, and were relative high risk break crop options — and were only profitable in 34.3% and 38.7% of years, respectively.

Conclusion

The decision to grow a break crop is generally done with a whole systems approach, as break crops can be utilised to address the issues and constraints that arise from continuously cropping cereals. The choice of break crop is made depending on the reason for growing a break crop, crop end-use, financial risk, paddock selection, and soil type.

Field pea production is more stable than other break crop species across the low rainfall environment. However, field pea is a risky option for grain production where spring frost events occur frequently. Field pea have multiple end-uses to grain, and with high biomass potential can be utilised as a hay, forage, silage, or manure crop when frost or drought affected, to salvage a financial return.

Vetch is also a versatile crop, having multiple potential end-uses, and is a good fit in a mixed farming system. Lupin is suited to sandy or acidic soils and has potential to be utilised as a green-brown manure crop.

Canola, lentil, and faba bean can provide herbicide tolerant crop options where in-crop weeds or herbicide residues are an issue. Canola also has a good fit where cereal root diseases are limiting production (Kirkegaard et al. 2008). However, canola requires adequate soil moisture at sowing for successful germination, particularly on heavier soil types and may be an opportunistic crop in some environments. Lentil is more sensitive to soil constraints than other break crop species and plant height is often low, leading to poor harvestability. Faba bean may be suitable where a break crop is needed in a frost prone area, as faba bean tolerate reproductive frost events better than other pulse crop species, providing that there is an early break to the season.

Chickpea have shown stability in the upper Victorian Mallee. However, it is important to consider the ability to manage disease.

Each break crop species has its own unique fit in the farming system, and all available agronomic, local, and paddock information needs to be taken into consideration when selecting a break crop to fit into each individual farming system. Each break crop species has several suitable varieties, with a range of agronomic characteristics to select from, that are suitable to production in the low rainfall environment. Although top performing varieties have been identified for some break crop species, the final selection will depend on the individual farming system — particularly where soil type, herbicide residues, and or broadleaf weeds are a constraint to production.

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Useful resources

http://www.agronomyaustraliaproceedings.org/images/sampledata/2019/2019ASA_Day_Sarah_81.pdf

http://eparf.com.au/wp-content/uploads/2019/04/16.-Break-crop-production-in-southern-low-rainfall-environments-DAY.pdf

https://msfp.org.au/break-crop-production-in-southern-low-rainfall-environments/

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GRDC
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Final session
Day 1

Hyperspectral sensing for the prediction of nitrogen, water and salt content in wheat

Brooke Bruning[1], Bettina Berger[1], Megan Lewis[2], Huajian Liu[1] and Trevor Garnet[3].

[1]Australian Plant Phenomics Facility, The Plant Accelerator, School of Agriculture, Food & Wine, University of Adelaide, Urrbrae, SA, Australia; 2Ecology and Evolutionary Biology, School of Biological Sciences, University of Adelaide, Adelaide, SA, Australia; 3Grains Research and Development Corporation.

GRDC project code: UOA1801-001RSX

Keywords

- hyperspectral, wheat, nitrogen, salinity, reflectance.

Take home messages

- Hyperspectral methods can be used as alternatives to traditional laboratory methods to quantify biochemical plant properties.
- Hyperspectral methods were used to predict and visualise nitrogen (N) and water levels in wheat as well as to distinguish between salt-treated and control plants.
- These non-destructive methods can be used to quantify biochemical parameters of crops throughout the season in a timely and spatially explicit manner.

Background

Quantifying biochemical and physiological parameters of crops can be key to achieving optimal yield. However, traditional laboratory methods are destructive, costly and time-consuming. Hyperspectral methods have the potential to be used as a rapid, precise and non-destructive alternative for monitoring plant traits.

Hyperspectral instruments acquire spectral reflectance information in many narrow, spectrally contiguous bands throughout the visible (VIS), near-infrared (NIR) and shortwave infrared (SWIR) regions of the electromagnetic spectrum (350-2500nm). In the case of vegetation, the properties of this reflectance data are mainly determined by biochemical compounds of leaf tissue and the morphology and structure of the leaf surface. Therefore, hyperspectral reflectance data can provide information on a number of biochemical or physiological plant properties. Compared to other optical techniques, hyperspectral methods have the vast and superior advantage in that they can provide layered trait information within the same spectral region.

This research utilised hyperspectral methods, both imaging and non-imaging techniques, to quantify the N content, water content and salt status of wheat plants in a high-throughput manner.

Method

Greenhouse experiments were carried out in an automated phenotyping platform at The Plant Accelerator (Australian Plant Phenomics Facility, University of Adelaide, Adelaide). The platform houses a hyperspectral imaging chamber which contains two individual cameras, a Specim FX10 (Specim, Oulu, Finland) operating in the visible and near infrared (VNIR: 400-1000nm) range and Specim SWIR operating at the longer shortwave infrared (SWIR: 1300-2500nm) wavelengths. Wheat plants were subjected to various levels of soil N (25 or 100mg/kg), watering conditions (10 or 20% g/g gravimetric water content), and salt treatment (100mM NaCl, control). Two hyperspectral images of each plant were collected using the two cameras operating in different wavelength ranges. The spectral data was extracted from each image and combined to give reflectance throughout the 400-2500nm range.

In addition to the hyperspectral cameras, non-imaging reflectance data (350-2500nm) was also collected for the plants in the salt experiment using a handheld non-imaging spectrometer equipped with a plant probe fore-optic and a leaf clip holder (ASD FieldSpec 3, Analytic Spectral Devices, Boulder, USA).

Due to the large amount of data provided by the hyperspectral instruments, spectral pre-processing was required to achieve accurate predictions of N, water and salt content. Pre-processing of the data involved smoothing, wavelength selection and derivatives to reduce noise and improve subsequent calibration models. Partial Least Squares Regression (PLSR) was used to develop the prediction models alongside reference measurements of N, water and salt obtained using traditional laboratory techniques.

Results and discussion

Nitrogen and water content

Both plant water content and N level could be predicted with 'acceptable' accuracy using hyperspectral images and PLSR modelling (Figure 1). The average N content of the plant was predicted with a slightly higher accuracy than water level (validation R^2 = 0.59 and R^2 = 0.56, respectively). The resultant model parameters were used to develop distribution maps, which enabled changes in the content and spatial distribution of N and water content to be visualised at the pixel level of wheat plants.

The resulting prediction maps revealed the spatial variation in biochemical properties, particularly water content, and allowed for a visual comparison between and within the plants that is otherwise impossible with the raw hyperspectral data (Figure 2). There were noticeable differences between the maps of the watered (Figure 2a) and drought plants (Figure 2c). In general, water content appeared higher at the base of the leaves and decreased towards the tips. Higher levels of water were also apparent around the midrib region as opposed to the outsides of the leaves. The N distribution maps (Figures 2b and 2d) do not appear to follow a plausible spatial pattern; each pixel is a different colour with no clear gradation to the neighbouring pixels. This 'noise' in the image is likely the result of model overfitting.

Salt content

An absolute value for salt ion content could not be accurately predicted using hyperspectral methods. Prediction likely failed due to the small range of values obtained for potassium $(K)^+$ and sodium $(Na)^+$

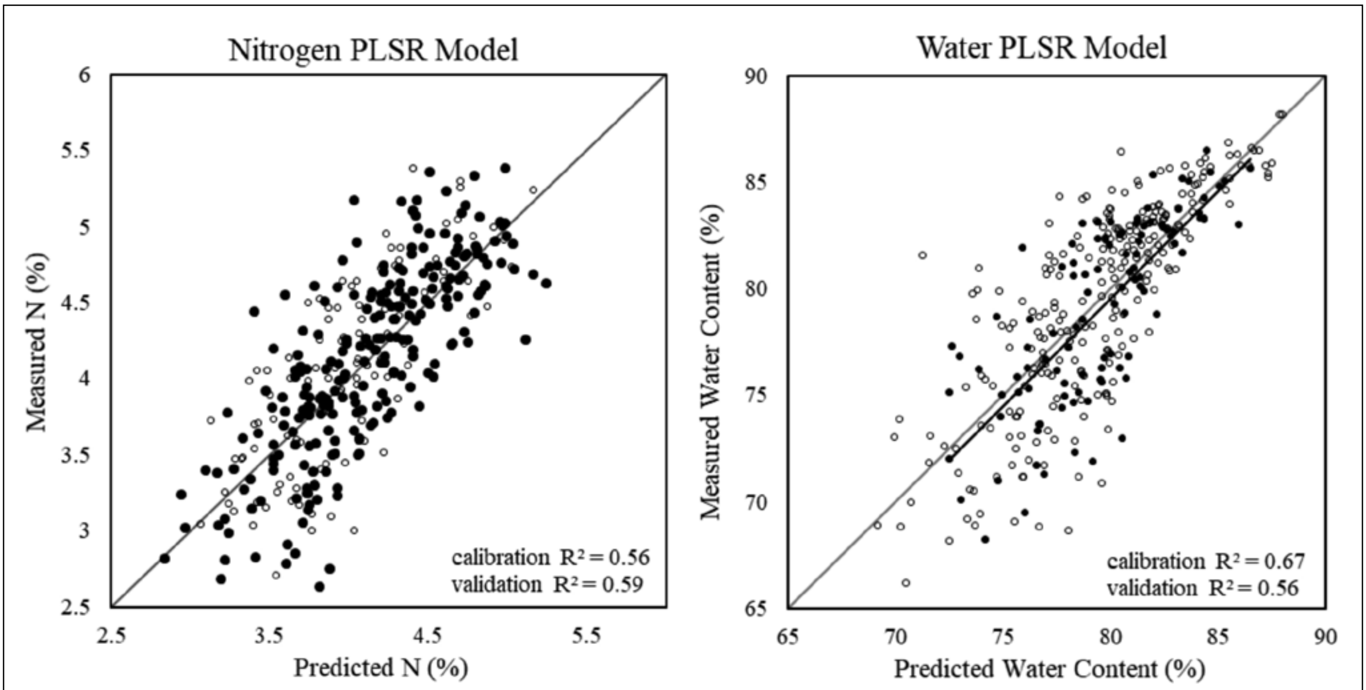

Figure 1. Measured versus predicted N content (%) (left) and water content (%) (right) using hyperspectral imagery and PLSR modelling.

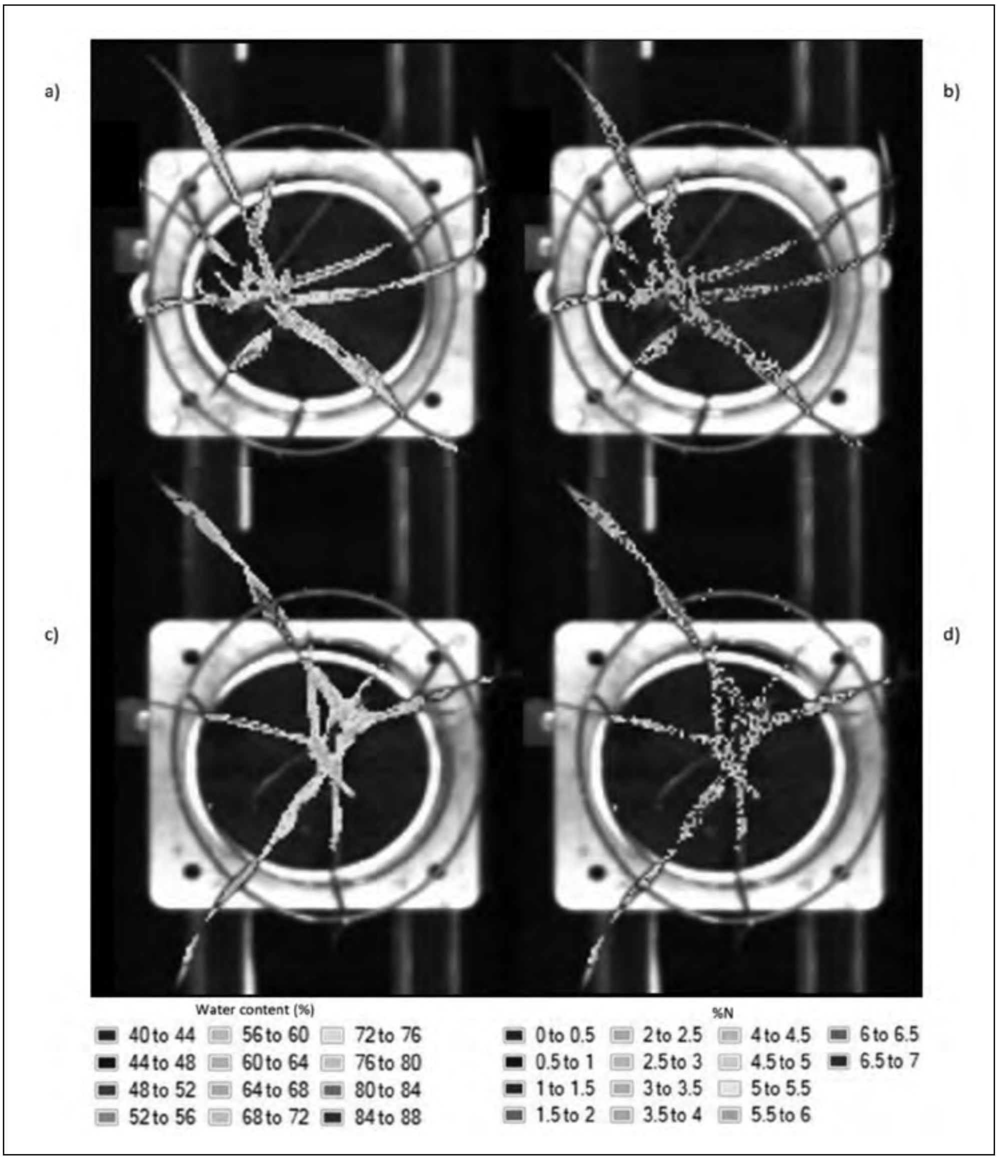

Figure 2. Distribution maps showing the prediction of water content in a watered (a) and drought (c) plant and N levels in a low (b) and high (d) N soil plant. Coloured version available from first author upon request.

in the leaves caused by the experimental treatment applied (only one level of 100mM NaCl added to half of the pots). A larger range in applied salt treatments and resulting salt concentrations in the leaf tissue, would improve the strength of the prediction model.

However, hyperspectral methods were successful in distinguishing salt-treated and control plants based on their spectral signatures. A support vector machine (SVM) algorithm was able to classify salt-treated and control plants with 97.5% accuracy using point spectra from single leaves and 100% accuracy using average plant spectra obtained from the hyperspectral images. An artificial neural network (ANN) algorithm was also able to distinguish between the image spectra of salt-treated and control plants with 100% accuracy. Spectra derived from the whole-plant images consistently gave better results than leaf-level spectra suggesting that whole-plant analysis is more indicative of salt status than single leaf measurements.

Conclusion

Quantifying biochemical and physiological parameters of crops is crucial for achieving optimal yield. Traditional analysis methods are destructive, costly and time-consuming. Hyperspectral methods are emerging as rapid, accurate and non-destructive alternatives. This work utilised hyperspectral data collected in a high-throughput manner to quantify N level, water content and salt status in wheat. Both non-imaging and imaging instruments were used to acquire spectral information at different plant scales under greenhouse environments. Water and N content could be predicted and visualised using hyperspectral methods while salt-treated plants could successfully be distinguished from

Table 1. Classification accuracies of different methods for their ability to classify plants as either control or salt-treated based on their spectral signatures (n= number of samples in validation set).

Field spectrometer, single leaves		
SVM	Predicted Control	Predicted Salt
Reference Control	40	1
Reference Salt	1	38
n=80, Accuracy=97.5%		
DT	Predicted Control	Predicted Salt
Reference Control	19	22
Reference Salt	5	34
n=80, Accuracy=66.3%		
Naïve Bayes	Predicted Control	Predicted Salt
Reference Control	26	15
Reference Salt	6	33
n=80, Accuracy=73.8%		
ANN	Predicted Control	Predicted Salt
Reference Control	24	8
Reference Salt	17	31
n=80, Accuracy=68.8%		

Camera images, whole plant		
SVM	Predicted Control	Predicted Salt
Reference Control	28	0
Reference Salt	0	39
n=67, Accuracy=100%		
DT	Predicted Control	Predicted Salt
Reference Control	24	4
Reference Salt	3	36
n=67, Accuracy=89.6%		
Naïve Bayes	Predicted Control	Predicted Salt
Reference Control	24	4
Reference Salt	6	33
n=67, Accuracy=85.1%		
ANN	Predicted Control	Predicted Salt
Reference Control	28	0
Reference Salt	0	39
n=67, Accuracy=100%		

control plants. Results suggest that with appropriate data collection, pre-processing and analysis, hyperspectral techniques have significant potential for quantifying and monitoring wheat biochemical attributes which are otherwise impossible or unfeasible with traditional methods.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contribution of growers through the support of the GRDC, the author would like to thank them for their continued support. The author would also like to thank all staff at The Plant Accelerator® for their research support. Stuart Roy and Jodie Kretschmer are thanked for their assistance with the salt experiment and flame photometry measurements. The financial support provided by the Grains Development and Research Corporation, Tim Healey Memorial Scholarship (Primary Industries and Regions South Australia) and The Plant Accelerator (Australian Plant Phenomics Facility) is gratefully acknowledged.

Useful resources

www.plantphenomics.org.au/

www.plantphenomics.org.au/wp-content/uploads/HYPERSPEC-200-x-287mm-fact-sheet-web-1.pdf

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Common sowthistle (*Sonchus oleraceus*) and prickly lettuce (*Lactuca serriola*) in lentil crops of southern Australia: managing herbicide resistance and highly mobile resistance genes

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GRDC project code: 9175890

Keywords

- herbicide resistance management, crop rotation, cereals, pulses, wind-dispersed seed.

Take home messages

- Group B resistance in sowthistle and prickly lettuce in the southern region is common.
- Resistance to the imidazolinone herbicides (IMI) in these weeds is increasing and is a major issue for management in IMI-tolerant lentils.
- Resistance status of target weeds can affect control in the current and following season.
- Management of these highly mobile and prolific seed producers requires effective control and seed-set reduction both within the paddock and in surrounding areas.

Background

Common sowthistle (*Sonchus oleraceus*) and prickly lettuce (*Lactuca serriola*) have become common weeds of annual cropping in southern Australia following the adoption of reduced tillage, and are problematic in lentil crops due to poor crop competition and a lack of herbicide options (Preston et al., 2017; Wu et al., 2019). There are very few post-emergent herbicides available for the control of broadleaf weeds in lentil crops, so best practice encourages control of weeds prior to sowing or crop emergence (GRDC GrowNotes™, 2018). Further reduction of broadleaf weeds can be achieved by taking advantage of a cereal phase of rotation prior to a pulse crop, through more diverse herbicide options and increased crop competition. Seed production of both sowthistle and prickly lettuce is highly sensitive to competition, with production estimated in the tens of thousands of seeds per plant in the absence of competition (Amor, 1986; Hutchinson et al., 1984). The relatively short seed bank persistence of both species (Hutchinson et al., 1984; Weaver and Downs, 2003), particularly in reduced tillage systems where seed remains on the soil surface (Alcocer-Ruthling et al., 1992; Chauhan et al., 2006), increases the potential effectiveness of this rotation tactic.

The introduction of IMI-tolerant lentil varieties improved management options for growers by removing barriers to planting lentils where group-B herbicide residues would have otherwise caused crop damage. Recently, permits have been issued allowing limited in-crop use of IMIs in lentils for the control of annual broadleaf weeds. However, the popularisation of IMI-tolerant crop technology has increased selection pressure on weeds. Group B herbicides have a high propensity for resistance evolution and cross-resistance (Tranel and Wright, 2002) so reliance on them is risky and diverse management tactics need to be used in lentils.

Both sowthistle and prickly lettuce have evolved widespread resistance to group B sulfonylurea (SU) herbicides (Lu et al., 2007; Merriam et al., 2018). Surveys of prickly lettuce in the Mid North and Yorke Peninsula of South Australia conducted in 1999, 2004 (Lu et al., 2007) and 2019 (Merriam, unpublished data) have reported the percentage of SU-resistant populations at 66% (n=58), 82% (n=11) and 100% (n=27), respectively. Additionally, all prickly lettuce populations from the 2019 survey screened with IMIs (n=23) were resistant (Merriam, unpublished data). Resistance levels of sowthistle from across the southern region are estimated at 78% (n=355) to the SUs and 68% (n=84) to the IMIs (Merriam et al., 2018). Furthermore, 2,4-D resistance in sowthistle has been detected in the southern region (Preston et al., 2017) and glyphosate-resistant sowthistle is beginning to cause concern in the northern cropping region of Australia (MacIntosh, 2018).

Growing a cereal prior to lentils can help reduce broadleaf weed burden in a paddock however, the effectiveness of control of these species from one year to another is hampered by their ability to readily colonise from outside of the paddock. The seed of both species is highly adapted to wind dispersal (Cummins et al., 2018) and has the potential to travel long distances (Hutchinson et al., 1984; Lu et al., 2007). The prevalence of these weeds on roadsides and other uncropped areas further exacerbates the problem. The aim of this research was to determine if different herbicide management strategies and levels of crop competition within a cereal phase had a measurable carryover effect on density of these weeds in the following growing season.

Method

Two field trials were established in South Australia in 2018 at Kulpara (KYP) on the Yorke Peninsula and Roseworthy (RS2) in the Mid North. Both sites were in lentils the year preceding the trial and were sown to wheat in 2018. Treatments were applied to the 2018 crop in a split-plot design with four replicates and incorporated two levels of crop competition (achieved with seeding rates of 60kg/ha and 90kg/ha) and three post-emergent herbicide treatments (Table 1) in crossed factorial arrangement. Prior to seeding in 2018, glyphosate at 648g ai/ha and pyroxasulfone at 100g ai/ha (Sakura®, Bayer Pty Ltd, Australia) were applied across the whole trial area to control existing weeds. Plots were sown using the grower's knife-point press-wheel seeder on 25cm row spacings on 12 May at KYP and 18 May at RS2 with a plot area of 160m^2.

Herbicides were applied on 12 July at KYP and 1 August at RS2 using a quad bike boom sprayer equipped with TeeJet® 110015 flat fan nozzles spaced 50cm apart and operating at 10km/h and 200kPa for an output of 58L/ha. Detailed measurements and global positioning system (GPS) coordinates were recorded at each site prior to harvest to facilitate re-establishment of the site in 2019 over the same area. This was verified using satellite imagery where available. In 2019 uniform management (common grower practice) was applied across the trial area at each site. Densities of sowthistle and prickly lettuce were assessed at key points during the 2018 season to gauge the effectiveness of treatments, and early in the 2019 growing season (prior to post-emergent herbicide application) to measure carryover effect.

Seed samples of sowthistle and prickly lettuce were collected at both trial sites for herbicide resistance screening. Methods and rates are outlined in detail in Merriam et al. (2018). Rates were based on doses determined to discriminate between resistant and susceptible biotypes and are similar to the field rate. In resistance monitoring surveys in the southern region, populations are considered resistant if percent survival is greater than 20% (Boutsalis et al., 2012).

Results and discussion

Populations of both species at both sites were identified as resistant to Group B herbicides, which is in line with regional data collected during resistance surveys (Table 2). They were also screened with glyphosate and 2,4-D, but no survivors were detected (data not shown). While resistance to both the SUs and the IMIs is very common, the incidence of SU resistance in sowthistle tends to be slightly higher within a region.

Table 1. Active ingredient rates, trade names and manufacturers of post-emergent herbicide treatments.

Treatment	Active and rate	Trade name	Manufacturer
'Conventional'	3g ai/ha metsulfuron-methyl + 675g ai/ha MCPA	Ally®	FMC Pty Ltd, Australia
		MCPA 750®	Nufarm Pty Ltd, Australia
'Proactive'	151g ai/ha bromoxynil + 25g ai/ha picolinafen + 252g ai/ha MCPA	Flight EC®	Nufarm Pty Ltd, Australia
Untreated	Nil		

In the Mid North, 90% (n=70) of sowthistle samples screened have been classified as resistant to SUs, versus 84% (n=37) classified as resistant to IMIs. On the Yorke Peninsula, 88% (n=56) of populations were classified as resistant to SUs, whereas only 67% (n=33) were classified as resistant to IMIs. A recent survey of prickly lettuce in each region found 100% of populations resistant to both herbicides, although sample sizes were small.

The seeding rate treatments resulted in significantly different crop establishment in 2018 at both sites, however there was no significant effect of crop establishment on weed density in 2018 or 2019 (data not shown). Initial weed densities were assessed prior to herbicide application at both sites in 2018 and showed that levels of both weeds were significantly higher at KYP compared to RS2, and that common sowthistle was more prevalent than prickly lettuce at both sites (Table 3). Results were significantly different between the two sites, so data were analysed separately for each site.

Weed densities were assessed six weeks after herbicide treatment application in 2018. At RS2, there was no significant effect of herbicide treatment on sowthistle density (Table 4). This could be due to variability across the plots and the low initial density of sowthistle at the site (Table 3), meaning less opportunity for the herbicide treatment to make a difference. Prickly lettuce was not detected in the RS2 trial following herbicide application (Table 4), likely due to the very low initial density of prickly lettuce at this site (Table 3). Neither weed species showed a carryover effect on density at the beginning of the 2019 growing season, evidenced by the lack of significance between treatments. This would be expected given the lack of significant treatment effect in 2018.

At the KYP site, sowthistle density was significantly correlated with herbicide treatment in 2018, with the lowest density observed under the proactive treatment and the highest density observed in untreated plots (Table 4). However, at the beginning of the 2019 season, there was no significant difference between the untreated and conventional treatment plots, while proactive treatment plots maintained a significantly lower density. The reason for the loss of significance between untreated and conventional plots from 2018 to 2019 may be due to sowthistle resistance to the residual component of the conventional treatment. The conventional treatment relies on a SU, metsulfuron-methyl, for residual control, and the sowthistle population at the site had 100% survival to SU application during screening (Table 2). Prickly lettuce density in 2018 was significantly higher in the untreated plots, but there was no significant difference between the conventional and proactive treatments. By the beginning of the 2019 season, there was no statistically significant difference between any of the treatments.

Table 2. Comparison of sowthistle and prickly lettuce populations from trial sites to regional averages of percent survival of Group B herbicides.

		Common sowthistle		Prickly lettuce	
		Sulfonylurea	Imidazolinone	Sulfonylurea	Imidazolinone
		----percent survival----			
Yorke Peninsula	KYP	100	75	90	100
	Regional	78	51	94	100
Mid north	RS2	100	33	100	60
	Regional	81	64	88	91

Table 3. Initial densities of common sowthistle and prickly lettuce at KYP and RS2 in 2018 post crop emergence but prior to herbicide treatment.

	Common sowthistle	Prickly lettuce
	----plants/ha----	
KYP	2935 ± 295	326 ± 69
RS2	138 ± 21	23 ± 16

Table 4. Treatment means of weed density post-treatment in 2018 and at the beginning of the 2019 season at both trial sites.

	RS2				KYP			
	Common Sowthistle		Prickly Lettuce		Common Sowthistle		Prickly Lettuce	
	2018	2019	2018	2019	2018	2019	2018	2019
	----------plants/ha----------							
Untreated	140 a	79 821 a	0	17 143 a	7914 c	55 833 b	192 b	10 833 a
'Conventional'	124 a	85 000 a	0	11 026 a	4287 b	68 333 b	31 a	9167 a
'Proactive'	41 a	80 714 a	0	10 714 a	1480 a	20 833 a	23 a	9167 a

**Treatment means within a column followed by the same letter were not significantly different at P=0.05.*

These results suggest that carryover effects of herbicide treatment may only be significant in the following season when initial weed densities in the first year are high. Significant differences were only observed in the second year for sowthistle at the KYP site, which had the highest initial density (Table 3), nearly three times higher than the second highest density (prickly lettuce at KYP) and more than 10 times the lowest density (prickly lettuce at RS2). The data also show the potential for a relatively low weed density post-treatment to result in a high density in the following season due to prolific seed production of survivors, colonisation from outside the study area, or contributions from the soil seedbank. Although both sowthistle and prickly lettuce have relatively short seedbank persistence, in the absence of suitable growing conditions they can persist beyond a season (Hutchinson et al., 1984; Weaver and Downs, 2003), so seedbank carryover from 2018 could have made some contribution the following year. Plants growing in uncropped areas may face less intense competition and thus have potential for prolific seed production (Amor, 1986; Hutchinson et al., 1984) and significant contributions to the population in an adjacent paddock. Prickly lettuce was not detected at RS2 following herbicide treatment in 2018 but the site averaged over 10 000 plants/ha at the beginning of the following season (Table 4), suggesting that seedbank recruitment and colonisation from outside the paddock can be an important weed source.

Prices of herbicide treatments used in this study differed at around $10/ha for the conventional and $50/ha for the proactive (Brooke and McMaster, 2019). Therefore, it is important to take the initial weed densities and the resistance status of the population into account when deciding what herbicide option to utilise. High densities may justify the extra expense, especially if Group B resistance is present. Alternatively, less expensive substitutes for the proactive treatment in this study could be explored. Triathlon® (Adama Pty Ltd, Australia) also contains groups C, F, and I and would cost approximately $17/ha at the full field rate.

Conclusion

The results of this study highlight the importance of effectively controlling wind-dispersed weeds both in crop and in adjacent uncropped areas. If initial weed densities are high, as with sowthistle at KYP, the choice of herbicide in a cereal phase can have a significant carryover effect in the following season. However, even if weeds are completely controlled in-crop, they can still be present at significant densities the following year due to colonisation from adjacent areas. Since both sowthistle and prickly lettuce are prolific seed producers in the absence of competition, reducing seed set in plants growing under reduced competition should be a priority. This research also highlights the importance of understanding the resistance status of target populations to all components of the herbicide regime, as resistance to a residual component could be masked by efficacy of a non-residual component in year of application but cause problems in the following year.

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 project is also supported by an Australian Government Research Training Program Scholarship. The author also thanks project supervisors (Dr Christopher Preston, Dr Gurjeet Gill and Dr Jenna Malone) and University of Adelaide Weed Science Research Group colleagues Ben Fleet, Jerome Martin and David Brunton for technical assistance.

Useful resources

Merriam et al (2018):

https://sciences.adelaide.edu.au/agriculture-food-wine/system/files/docs/21st-awc-merriam.pdf

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International grain market trends – maintaining global competitiveness

Cheryl Kalisch Gordon.

RaboResearch.

Keywords

- grain markets, grains, oilseed, international, global, grain marketing.

Introduction

Seven key trends are going to shape the international grain market of the future. Enduring cost pressures, a changed global trade order, 'super' consumers, resource constraints, soaring data possibilities, complex protein demands and a world looking beyond glyphosate will frame the operating environment of the coming decade. These trends all require the Australian industry to up the ante on harnessing its smarts for it to be a competitive global player into the future.

Enduring cost pressures

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A changed global trade order

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‘Super’ consumers

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Resource constraints

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Soaring data possibilities

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Complex protein demands

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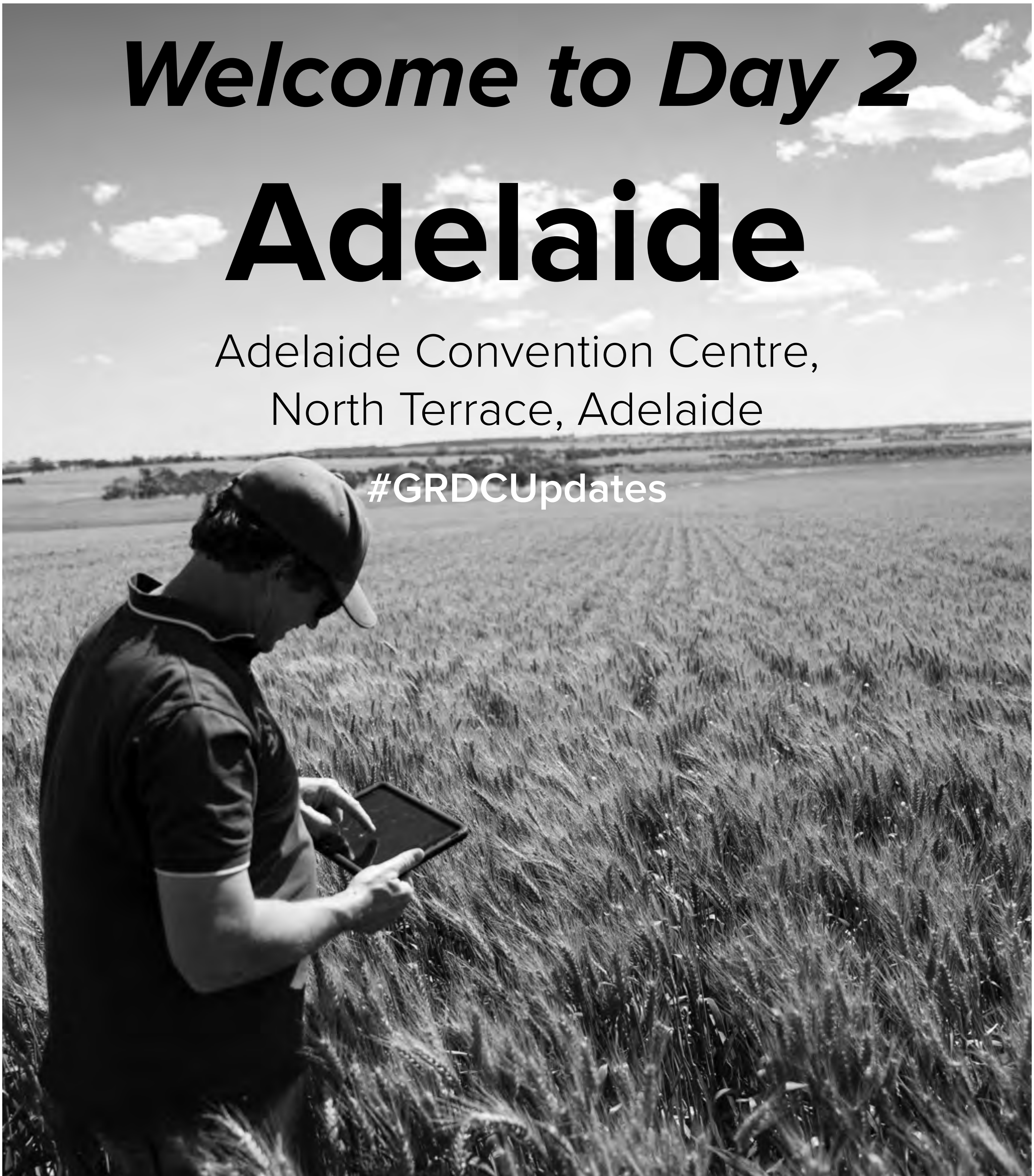
GRAINS RESEARCH UPDATE

Welcome to Day 2

Adelaide

Adelaide Convention Centre,
North Terrace, Adelaide

#GRDCUpdates



Dealing with the Dry

As grain growers across Queensland and New South Wales and parts of Victoria and South Australia continue to be challenged by drought conditions, the GRDC is committed to providing access to practical agronomic advice and support to assist with on-farm decision making during tough times.

Visit our 'Dealing with the Dry' resource page for useful information on agronomy in dry times and tips for planning and being prepared when it does rain.

www.grdc.com.au/dealingwiththedry

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FINAL SESSION

FURTHER INFORMATION

EVALUATION *294*

GRDC Grains Research Update ADELAIDE

PROGRAM DAY 2 - FEBRUARY 12th

8.15 am **EARLY RISERS: Assessing the value in soil and plant testing** - P157 ***Sean Mason,*** *Agronomy Solutions*

CONCURRENT SESSIONS (40 minutes including time for room change)

(R = session to be repeated)

	Hall C	Room E1	Room E2	Room E3
9.00 am	**Seeder strategies for non-wetting soils (R)** - P165 ***Jack Desbiolles,*** *University of South Australia*	**New strategies to manipulate flowering date and yield (R)** - P177 ***Kenton Porker,*** *SARDI*	**Cereal disease wrap up (R)** - P185 ***Hugh Wallwork,*** *SARDI*	**Latest research for improving management of snails (R)** - P191 ***Helen Brodie,*** *SARDI*
9.40 am	**Integrating new chemistries in the field** - P199 ***Chris Preston,*** *University of Adelaide,* ***Chris Davey,*** *YP AG and* ***Brian Lynch*** *(Elders)*	**Spotlight on pulses (R)** - P203 ***Penny Roberts,*** *SARDI*	**Rapid post-event frost damage assessment - can it be achieved? (R)** - P213 ***Glenn Fitzgerald*** *and* ***Audrey Delahunty,*** *Agriculture Victoria*	**Septoria - no longer only an issue for the high rainfall zone (R)** - P231 ***Andrew Milgate,*** *NSW DPI*
10.20 am	**MORNING TEA**			
10.50 am	**Soaks are seeping across SA - what can be done about it? (R)** - P237 ***Chris McDonough,*** *Insight Extension for Agriculture*	**Improving the heat tolerance of wheat** - P245 ***Rebecca Thistlethwaite,*** *University of Sydney*	**Septoria - no longer only an issue for the high rainfall zone** - P231 ***Andrew Milgate,*** *NSW DPI*	**Latest research for improving management of snails** - P191 ***Helen Brodie,*** *SARDI*
11.30 am	**Spotlight on pulses** - P203 ***Penny Roberts,*** *SARDI*	**New strategies to manipulate flowering date and yield** - P177 ***Kenton Porker,*** *SARDI*	**Subsurface acidity - how far has the research advanced?** - P251 ***Melissa Fraser,*** *PIRSA*	**Cereal disease wrap up** - P185 ***Hugh Wallwork,*** *SARDI*

CONCURRENT SESSIONS (40 minutes including time for room change) (R = session to be repeated)

	Hall L	Room L1	Room L2	Room L3
12.10 pm	**Soaks are seeping across SA - what can be done about it?** - P237 ***Chris McDonough,*** *Insight Extension for Agriculture*	**Seeder strategies for non-wetting soils** - P165 ***Jack Desbiolles,*** *University of South Australia*	**Eye on active plant pests** - P259 ***Rohan Kimber,*** *SARDI*	**Rapid post-event frost damage assessment - can it be achieved?** - P213 and P223 ***Glenn Fitzgerald*** *and* ***Audrey Delahunty,*** *Agriculture Victoria*

12.50 pm **LUNCH**

1.30 pm **Predicted climate change impacts on southern farming systems & how we should act** - P271 — ***Peter Hayman,*** *SARDI*

2.10 pm **What's the cost of HWSC for you?** - P281 — ***Pete Newman,*** *AHRI*

2.50 pm **CLOSE AND EVALUATION**

On Twitter? Follow **@GRDCSouth** and use the hashtag **#GRDCUpdates** to share key messages

Soil and plant testing for profitable fertiliser use

Harm van Rees[1], Sean Mason[2], Dan Bell[3], Therese McBeath[4], Jackie Ouzman[4], Rick Llewellyn[4] and Craig Muir[5].

[1]Cropfacts, [2]Agronomy Solutions; [3]Landmark, [4]CSIRO, [5]Agrivision

GRDC project code: 9176604

Keywords

- Soil P, available soil N, nutrient variability, fertiliser response, precision agriculture.

Take home messages

- Based on more than 300 paddocks surveyed in the southern region, soil phosphorus (P) and soil nitrogen (N) status are highly variable across and within paddocks. In many cases, soil sampling intensity should be increased to sample multiple zones in a paddock.
- Low production zones tended to have lower soil P and higher soil N levels, and therefore, adjusting nutrient inputs according to zone could improve profitability.
- An initial paddock analysis of strips trials indicates that intensive soil sampling of production zones provided significant benefits in terms of P application. The yield response was highly variable across the paddock and was closely correlated with soil P status.
- Results from N rate application strips are currently being analysed.

Background

Precision application of variable rate fertiliser demands a knowledge of the soil available nutrient variation across a paddock and an understanding of the likely responses to applied nutrients. In addition, soil testing is shifting from surface sampling (0-10cm) to deep sampling to understand nutrient levels and constraints in the subsurface layers (GRDC farm survey, 2016). However, growers and advisers appear to be unsure of how to interpret soil test results to optimise fertiliser returns, especially with variable rate application of fertiliser. In 2016, it was estimated 15% of paddocks were regularly tested (0-10 cm) as opposed to 23% in 2014 (GRDC farm survey, 2016.).

Method

Landmark, independent consultants and farming systems groups are partnering in this project to raise awareness of the benefits of using soil and plant testing crop to inform fertiliser decisions and responses to N and P fertiliser applications. This includes the role of soil sampling within identified production zones in a paddock to understand soil and crop variability and enable variable rate fertiliser applications. APAL laboratories are undertaking the soil and plant analysis. CSIRO are analysing yield maps, performing the statistical analysis of yields achieved on P and N rate strips, and reviewing the economic implications of implementing 'informed' P rate applications based on soil testing results.

Paddock trials in 2019

Over 300 paddock-based trials were established in 2019 in South Australia (SA) and Victoria (Vic) from close to 700 sampling zones. Production zones in paddocks were defined either by using historical yield maps or the grower's long-term knowledge of the paddock. For two production zones in each paddock, a one-hectare soil sampling area was selected; the two zones were located in-line with the sowing direction. Sampling intensity for each 1ha soil sampling area was 36 topsoil samples (0-10cm) measured for available P: Colwell, Diffusive Gradient in Thin-films (DGT), phosphorus buffering index (PBI. Six deep cores (0-10, 10-30, 30-60, 60-90cm) were also collected and measured for available nitrogen

(NO_3 and NH_4) with the samples combined for each depth to generate one soil test value. Chloride was included in the analysis to determine whether sub-soil salinity was a yield constraint.

In 150 of the 333 paddocks sampled, growers applied P rate strips across the paddock at sowing, ensuring the strips crossed the 1ha soil sampling grids. Available soil P status and likely fertiliser P response rates were calculated from Colwell and DGT tests in association with PBI. The rates of P applied were informed by the soil test result. Most strips trials included a 'zero control', the grower's 'standard rate' of applied P, and double the 'standard rate' in situations predicted to be P responsive. For cases where soil P levels were high and P responses were unlikely, half the 'standard rate' was applied. The P rate strips received the same N as applied by the grower for the rest of the paddock. Tissue samples were collected from each fertiliser strip between growth stage (GS) 16 and 32 to check on tissue P status and possible nutrient deficiencies along with dry matter estimates.

In 2019 a number of paddocks included top-dressed N strips to generate in-crop N rate trials in paddocks where soil N variability was high. These were applied at the same time as the grower's in-crop urea in the rest of the paddock. As with the P scenario, N trials had rates of N applied as informed by the starting soil N profile and crop yield potential, and often included a 'zero control', a 'standard rate' and double the 'standard rate' in responsive situations, and in non-responsive situations a half 'standard rate'.

Harvest and statistical analysis

Yield monitor data was used to calculate the yield for each P and N fertiliser treatment. The yield from each strip within each 1ha soil sampling area was used to correlate crop yield to soil P and N status. Harvest data within each of the two soil sampling zones was analysed for statistical difference using a moving average t-test (Lawes and Bramley 2012) enabling the evaluation of nutrient treatment responses between zones and within zones. A partial gross margin analysis will be undertaken to calculate the change in income achieved from the different fertiliser rate strips.

Results and discussion

Soil nitrogen and phosphorus status 2019

A brief snapshot of the nutrient status across all project paddocks revealed high variability of both N and P between the production zones in each sampled paddock. There were many opportunities identified within each agroecological zone for the establishment of both N and P trials. Overall, the N status was generally good with about 80kg N/ha in the high production areas (Figure 1). Using the rule of thumb of 40kg N/ha required for 1t/ha grain, it was predicted this would support at least the production of a 2t/ha wheat crop without factoring in immobilisation nor mineralisation. In general, the N status was higher in the low production areas (about 100 kg N/ha) than the high production areas which suggests a N build up due to lower yields and N removal in seasons prior, possibly caused by a soil constraint.

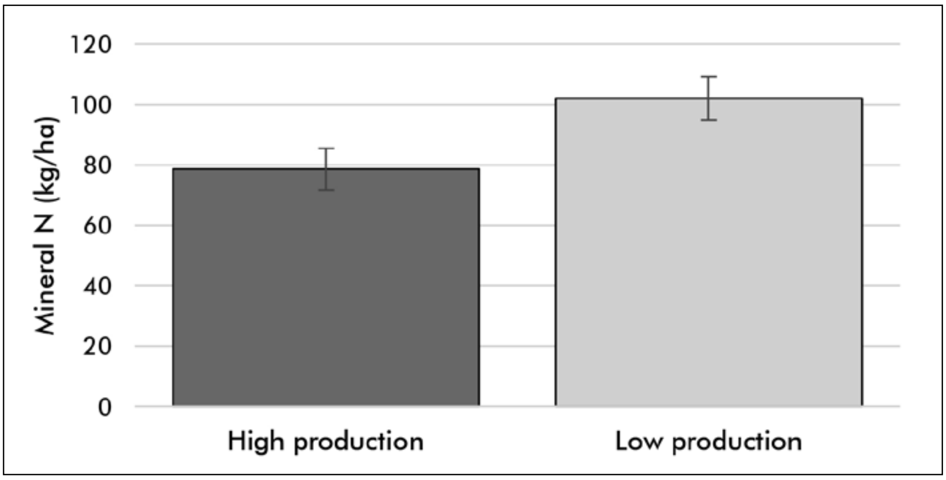

Figure 1. Overall soil mineral N status across the project area (GRDC Southern region) for allocated 'high production' and 'low production' zones within paddocks before the 2019 sowing season. Error bars represent standard error across all sampling sites in each zone.

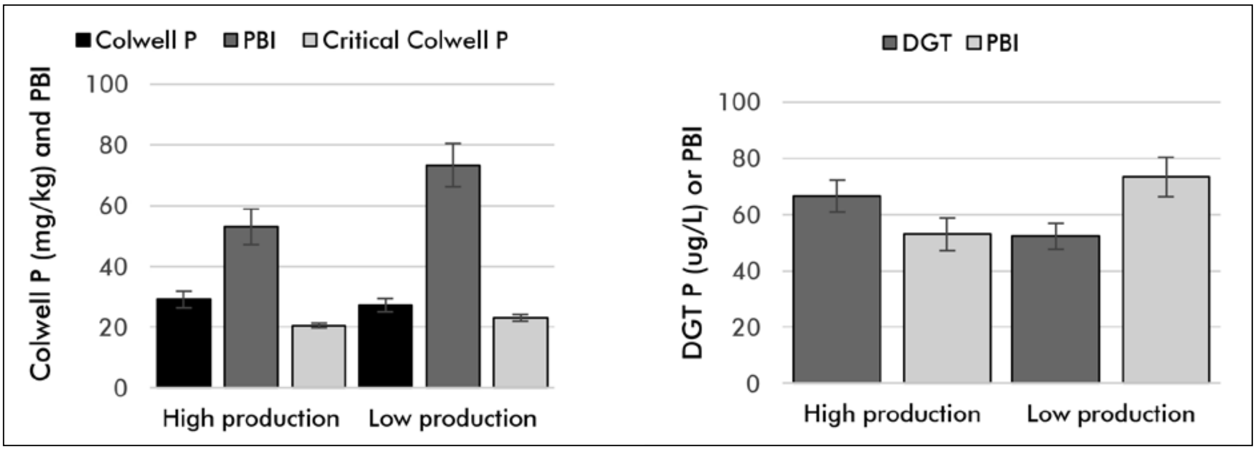

Figure 2. Overall soil P status across the project area for allocated 'high' and 'low' production zones within each paddock as assessed by Colwell P (left) and DGT (right) together with PBI for each zone. Error bars represent standard error across all sampling sites in each zone.

At a paddock level, P deficiency is driven by the ability of different soils to fix or absorb P sources as estimated from the PBI. Critical Colwell P was determined by the relationship generated in Moody (2007). Critical DGT value for wheat is 64µg/L (95% confidence interval (CI) = 53-78µg/L). Quite often low production zones were associated with low extractable P, high PBI and relatively high soil N due to less utilisation of N sources and its subsequent removal (Figure 2).

In these areas, simple 'paddock replacement fertiliser' strategies are often unbalanced for N and P and are creating a wider gap between yield production zones and possibly declining yields. Improved gross margins from more profitable fertiliser applications are expected if different production zones are assessed for the ability of the soil to provide the crop with adequate nutrients.

Victoria Mallee Trial

An example of the experimentation is presented below for a paddock sown to wheat in the Victorian Mallee where Scepter$^{\phi}$ wheat was sown on 15 May 2019. The soil characteristics for both sampling areas in this paddock was slightly alkaline, clay loam to depth with starting profile N between 88-135 kg/ha allowing enough N to support the yield obtained with the additional N applied in season.

Soil P results

Soil P results for Colwell, DGT P and PBI are detailed in Table 1. In Zone 1 both soil tests predicted marginal P, while in Zone 2 the DGT P soil test predicted deficient soil P. PBI was relatively high in Zone 2.

Table 1. Mallee paddock: P test result pre-sowing 2019 (Colwell, DGT and PBI) for Zone 1 and 2.

P Test	Zone 1	Zone 2
Colwell P (mg/kg)	22	30
DGT P (µg/L)	42	12
PBI	64	135

P rate trial

Four rates of P (0, 4.4. 8.8 and 17.6kg P/ha) were applied as MicroEssentials®SZ™ (MESZ) at sowing with double seeder width strips across the paddock through each zone and all strips had urea at 20.7kg N/ha applied at sowing). Urea was top-dressed at 75kg/ha (34.5kg N/ha) on the whole trial area on 28 June 2019.

Harvest yield map data were used to analyse the yield differences between P treatments in each of the two soil sampling areas (1ha areas located in two distinct production zones in line of sowing). Statistical analysis was based on the t-test for comparing two strips (Figure 3).

A significant difference in yield gain was confirmed only in Zone 2 for the high rate of P applied (17.6kg P/ha) (Table 2). This coincided with the lower DGT value and higher PBI area but higher Colwell P. This illustrates the importance of combining PBI with Colwell P interpretation as the critical Colwell P value from this PBI level is slightly higher (32 mg/kg) than measured. Recent GRDC work (UQ00082) has shown for this PBI level that critical Colwell P levels are near 40 mg/kg.

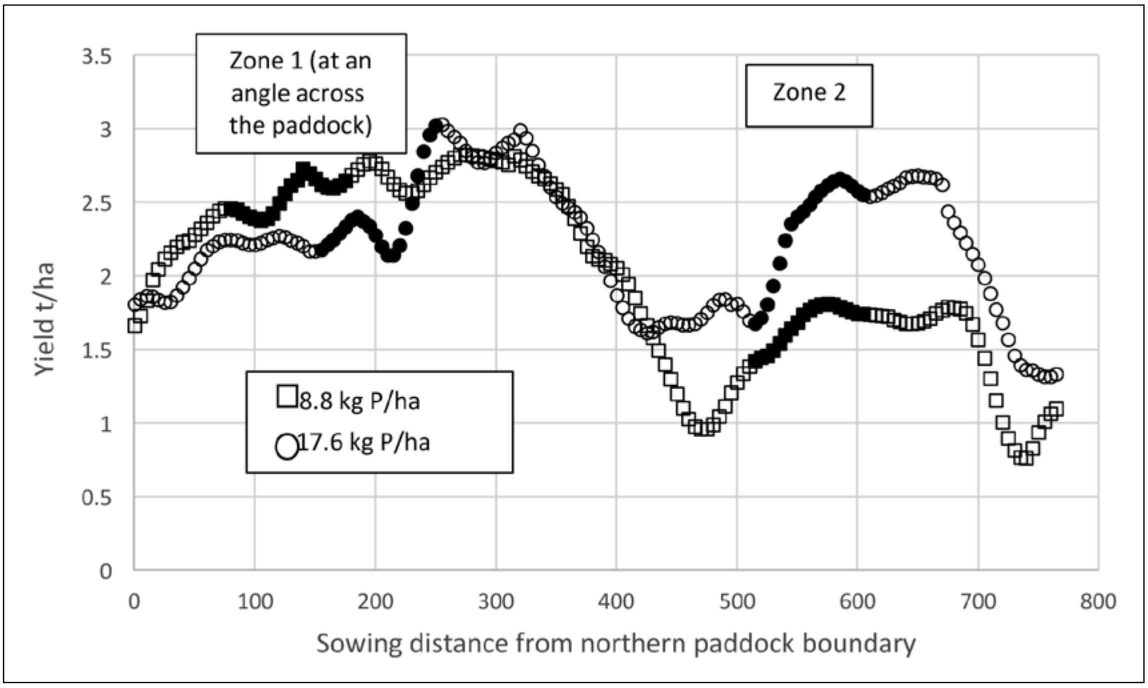

Figure 3. Strip yield (t/ha) for two rates of fertiliser P applied across two soil sampling areas. Solid black circles and squares indicate the yield achieved within the soil sampling areas for Zone 1 and 2.

Table 2. Yield response to four rates of fertiliser P applied at sowing in two zones.

Rate (P kg/ha)	Average yield (t/ha) within production zone		Ave yield (t/ha) entire strip
	Zone 1	Zone 2	
0	2.51	1.76a	2.16
4.4	2.60	1.76a	2.24
8.8	2.59	1.67a	2.01
17.6	2.32	**2.34b**	2.22
Significance	NS	**P<0.05**	

Conclusion

Soil nutrient status is highly variable across paddocks and these initial results indicate the benefits of sampling more than one soil type or production zone within a paddock. Preliminary results indicate that intensive soil sampling of production zones can provide significant benefit in terms of P application while results from the N rate application strips had not been analysed at the time of writing.

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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 thank the GRDC for their continued support. We also acknowledge the farmers who are in this project for sowing the strip trials, applying variable rate P and N, and supplying yield monitor data at harvest.

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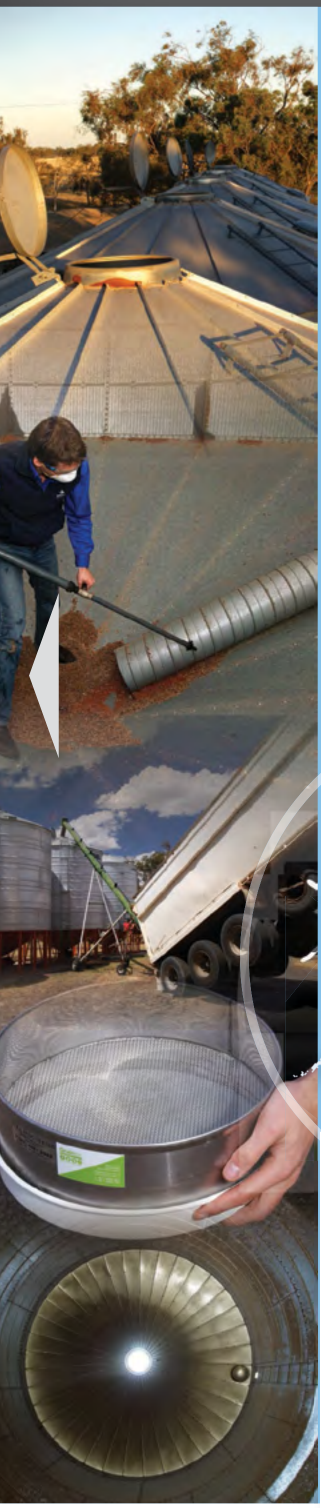

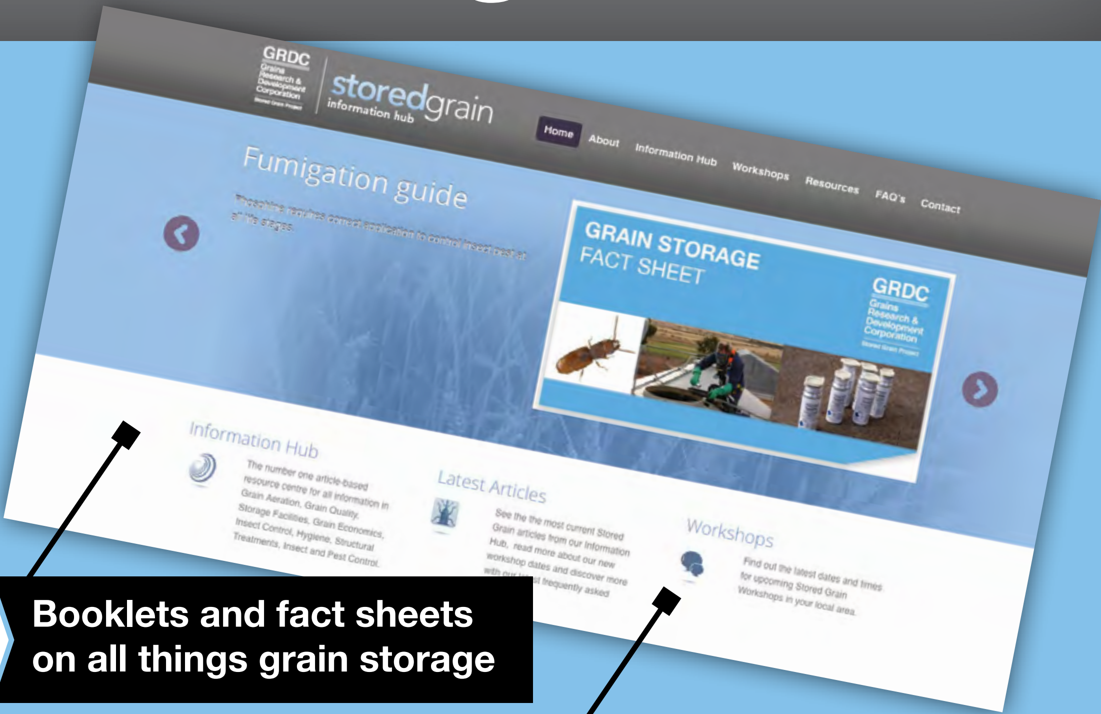

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Seeder-based approaches to reduce the impact of water repellence on crop productivity

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GRDC project code: CSP00203

Keywords

- hydrophobic sands, soil wetter, on-row sowing, moisture delving, deep furrow till.

Take home messages

- Low-cost, low risk seeder-based strategies produced valuable benefits to wheat/barley establishment and grain yield in a severely water repellent sand in two below-average rainfall seasons.
- Several products and application strategies provided consistent and large crop establishment benefits over two years at the same site, while also producing up to 0.22t/ha (Year 1, wheat) and 1.07t/ha (Year 2, barley) extra grain yield.
- Edge-row/on-row sowing achieved the greatest benefits by exploiting existing in-furrow moisture via guided sowing, while 230mm deep furrow tillage produced similar benefits from the opener lifting moist soil deeper in the profile.
- A soil wetter provided grain yield benefits with both edge-row and inter-row seeding over the respective control, while combining the soil wetter with paired-row seeding on the row maximised the grain yield response in the trial (for example; +1.82 t/ha gain over a 0.6 t/ha control).
- Challenges remain in selecting the most effective wetting agents for a particular sand environment due to performance variability.

Introduction

An estimated 12.5 million hectares of sandy soils in southern and Western Australia are deemed at moderate and high risks of water repellence (Roper et al. 2015). These 'non-wetting' sands have low fertility and suffer from delayed and uneven wetting, which leads to erratic crop establishment, staggered weed germination and generally poor crop productivity due to low plant densities, low nutrient access, poor weed control and crop damage in areas prone to wind erosion.

A research project supported by GRDC investment (CSP00203) and led by CSIRO is investigating techniques of amelioration and mitigation of sandy soil constraints. A range of field trials are investigating management options available at seeding time to mitigate the impacts of water repellence. During 2018 and 2019, two trials were conducted in a 270mm growing season rainfall (GSR) zone at Murlong on the Eyre Peninsula (EP), namely a soil wetter evaluation trial and a seeder strategy evaluation trial, aiming to compare a number of seeding strategies.

The soil at the site (-33.691295S, +135.944050E) was classified as severely repellent (molarity of ethanol test results were 2.8 at 0-5cm and 3.0 at 5-10cm). In Year 1, a water repellency profile was estimated at seeding using a Water Drop Penetration Test with de-ionised water (Leelamanie et al. 2008), as follows: severe to extreme water repellency (0-10cm), 'strong' (10-15cm), 'slight' (15-20cm), and non-repellent below 20cm depth.

Soil wetter evaluation trial (2018-19)

Background

Soil wetter chemistries are varied and complex, and little is known of their individual suitability to local water repellence which appears to vary in nature depending up on the soil. Modern soil wetters typically have both surfactant and humectant properties. Surfactants lower the surface tension between water and the soil particles, which allows rainfall to more readily infiltrate into the water-repellent soil. These are penetrant-type products, promoting entry and drainage through the topsoil. Humectants are designed to counter excessive leaching in a low 'surface area' sands and aid moisture retention. Humectant co-polymers promote a horizontal spread of water within the sandy soil and increase moisture retained within the furrow seed zone. The benefits of applying soil wetters at seeding time have been evaluated in Western Australia (WA) over the past 10 years (Davies et al. 2019), and this work recently concluded that:

- Banded wetters are most beneficial for dry sown cereals on repellent forest gravels of the south-west with less reliable benefits for break-crops.
- Benefits of banded wetters are minimal, or at best sporadic, for dry sown crops on deep sands and there is no benefit with sowing into moist soil for any crop or soil type.
- Benefits are larger in seasons with low and sporadic germinating rains in autumn.

South Australian (SA) research at Wharminda on EP conducted from 2015 to 2017 found that the two soil wetting agents evaluated could significantly improve wheat, barley and lupin establishment and also have a positive impact on grain yield, in two years out of three (Ward et al. 2019).

Building on these results, the soil wetter trial instigated at Murlong aimed to broaden the range of soil wetter types and combinations evaluated under contrasting furrow placement scenarios.

Experimental design

The impacts of 13 different wetting agents (both surfactants and humectants), in single and dual placement configurations (furrow surface and/or seed zone) were tested over two years (2018 and 2019 seasons). The treatment costs ranged between $12 and $41 per ha (Table 1).

The range of commercial soil wetters evaluated included pure surfactants, surfactant/humectant (S/H) blends, and S/H blends enriched with organics/nutrients. Six treatments consisted of split applications and included single products split-applied at 50:50 rate or combined products applied at full rate in their recommended furrow delivery locations. All suppliers were consulted to ascertain the recommended application rates and locations of each product.

Table 1. Soil wetter treatments evaluated at the Eyre Peninsula, Murlong site over 2018 and 2019.

Product names (commercial supplier)	Treatment key	Rate (L/ha)	Placement zone*	$/ha (2018)
SE14® (SACOA)	T1	3	SZ	21
RainDrover (SACOA)	T4	2	SZ	12
Aquaforce (SST Australia)	T2	2.5	FS	20
H2Flo™ (ICL Specialty Fertilizers)	T5	2	FS	16
SeedWet (SST Australia)	T7	2	FS	17
H2Pro® TriSmart (ICL Specialty Fertilisers)	T8	2	FS	15
Soak-n-Wet (Victorian Chemicals)	T9	4	FS	14
Bi-Agra Band (SST Australia)	T10	1.5+1.5	FS+SZ	22
Divine® Integrate/Agri mix (BASF)	T11	1+1	FS+SZ	20
Aquaboost AG30 FB + AG30NWS (BioCentral Lab)	T12	2+2	FS+SZ	24
Precision Wetter + Nutri-Wet (Chemsol GLE)	T13	2+2	FS+SZ	21
Aquaforce (SST Australia) + SE14® (SACOA)	T3	2+3	FS+SZ	41
H2Flo™ (ICL Specialty Fertilizers) + RainDrover (SACOA)	T6	2+2	FS+SZ	28

**Key: SZ=Seed Zone; FS=Furrow Surface*

Wetting agents have variable effects in different soil types depending on the site-specific nature of repellence. Treatments were initially pre-tested on the Murlong soil under laboratory conditions showing a de-ionised water control penetration time of more than 120 minutes, whereby the soil wetters at recommended rates resulted in penetration times ranging from 2-3 seconds to 82 minutes.

Plots were 25m long by six crop rows at 0.28m spacings, and were sown at 6km/h using a deep banding knife point operating at 110mm depth, followed by twin seeding discs and a furrow stabilising V press wheel, 140mm wide. A stable consolidated furrow surface is often critical to the efficacy of surface applied soil wetters, working best on a firm settled soil, rather than mixed into loose backfill. Soil wetter treatments were applied in 100L/ha volume of rainwater with foam suppressant at 0.05% v/v, using a Teejet® TPU1501 low angle flat fan nozzle behind press-wheels to produce a 25-30mm wide band on the furrow surface (FS). In contrast, seed zone (SZ) applications were delivered with a *Keeton* in-furrow seed firmer to achieve accurate co-location with the seeds.

The trial had four replications organised into a randomised complete block design. In Year 1, the plots were sown with wheat into a grazed barley stubble, while in Year 2, all plots were inter-row sown with barley into the standing wheat stubble. The 2018 treatments were re-applied to the same plots in 2019.

Some aspects of seeding agronomy are summarised in Table 2. Uniform® fungicide at 400mL/ha and Intake® Hi-Load Gold fungicide at 250mL/ha were also applied in furrow in 80L/ha volume to address medium/high risks of rhizoctonia or yellow leaf spot and take-all, respectively.

Seeding depth in both years was targeted in the range of 3-5cm as a preferred strategy for non-wetting sands.

Crop establishment results (2018-19)

Wheat and barley crop establishment rates at five weeks after sowing are shown in Figure 1. The inter-row control established at 24% and 12% of seeds sown (48 and 27 plants/m^2, respectively), indicating very unfavourable conditions for crop establishment in this severely water repellent sand.

In 2018, the soil wetter treatments increased wheat crop establishment by 25 plants/m^2 on average, with a range of 0 to 58 plants/m^2. In 2019, the same treatments increased barley crop establishment by 17 plants/m^2 on average, with a similar range of 0-56 plants/m^2. The impact of soil wetter treatments on crop establishment was similar in both years, as confirmed by a strongly positive correlation between results in each year ($r = +0.849$, $P<0.001$, Figure 2). No correlation was found between product performance and $/ha cost, indicating that cost is not a useful indicator of performance.

Interestingly, all furrow surface applied wetters performed poorly at Murlong, while the two seed zone applied (humectant) products performed better. Combining a surfactant on the furrow surface (FS) with a humectant in the seed zone (SZ) provided a synergistic response in 2019 for one combination, greater than the cumulative benefits of each single product (i.e. T1+T2 < T3), but not for another (i.e. T4+T5 ≥ T6), which did not improve benefits beyond the seed zone wetter response, in both years. Overall, five out of the six seed zone+furrow surface wetter combinations provided a benefit.

Table 2. Soil wetter trial seeding agronomy and season overview.

Year	Seeding date and crop seed rate	Nutrition (kg/ha)	Rainfall pattern
2018	21-23 June 2018 Razor CL Plus WHEAT at 63kg/ha (32.3g/1000 grains, 99% germination), Rancona® C + Imidacloprid 600 treated	26N+11P+6S+0.5Zn in-furrow (of which 20N+4S deep banded at furrow depth), foliar application of ZnCuMn trace elements at late tillering	16mm opening (early-mid June), 26mm post-sowing over 5 weeks, 193mm GSR, (296mm annual)
2019	15-17 May 2019 Scope CL BARLEY at 68kg/ha (30.5 g/1000 grains, 96% germination), Vibrance® + Cruiser®350 treated	28N+12P+6S+1.5Zn deep banded at furrow depth, foliar application of ZnCuMn trace elements at tillering	20mm opening (early May), 35mm post-sowing over 5 weeks, 174mm GSR, (185mm annual)

(Key: N=nitrogen; P=phosphorus; S=sulphur; Zn=zinc; Cu=copper; Mn=manganese)

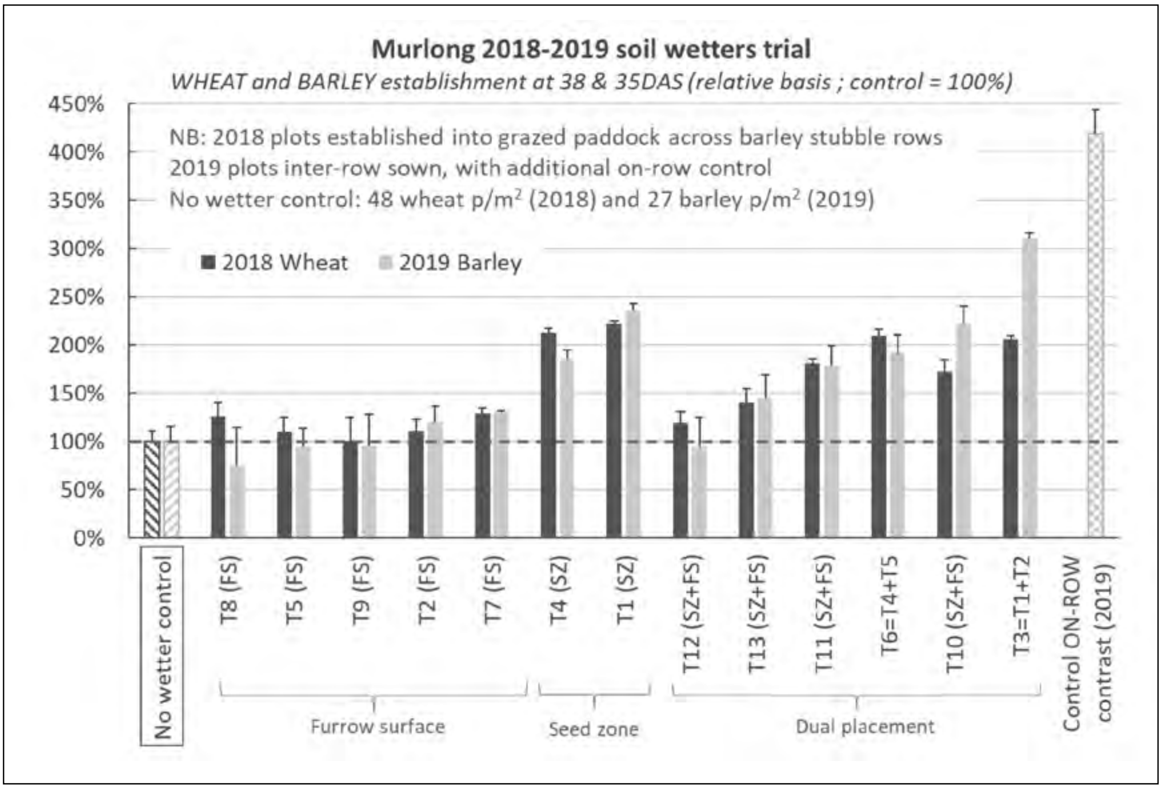

Figure 1. Effect of 13 soil wetter treatments on inter-row sown wheat in 2018 (left bar within treatment) and barley in 2019 (right bar within treatment) crop establishment at five weeks after sowing, relative to a no-wetter control (NB: error bar = 1 standard error of the mean)

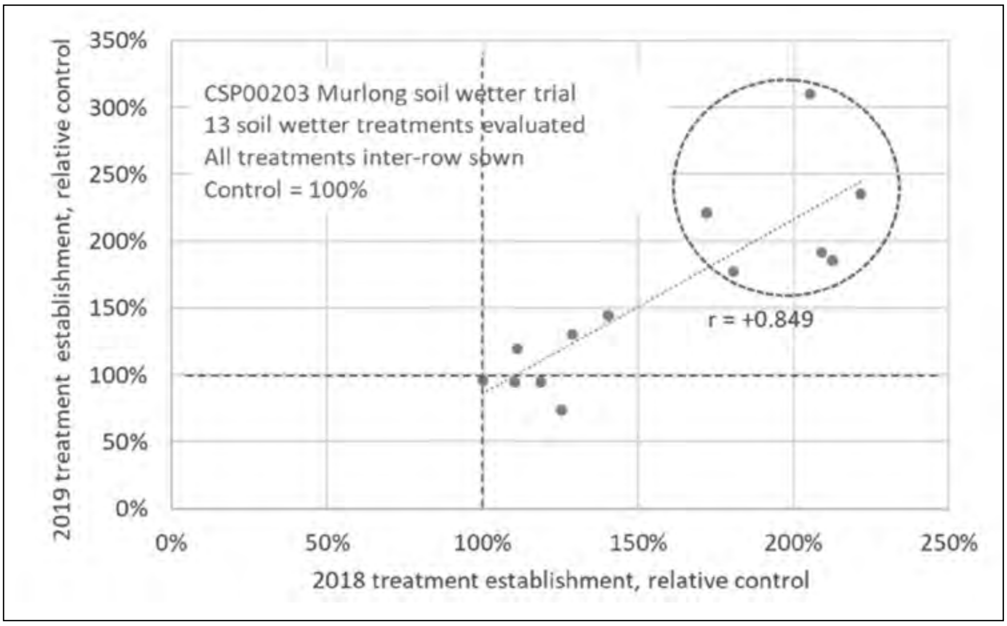

Figure 2. Correlation between 2018 and 2019 soil wetter treatment effect on crop establishment benefits relative to a 100% control (The data suggest a cluster of six products or mixes which consistently performed well at the Murlong site - details in Table 3 within this paper).

Table 3. Synopsis of top six soil wetter treatment* performances: (Snapshot crop establishment ranking at five weeks and grain yield ranking at harvest).				
Ranking**	2018		2019	
	Establishment 36DAS	Grain yield	Establishment 35DAS	Grain yield
1st	T1(SZ)	T3=T1(SZ)+T2(FS)	T3=T1(SZ)+T2(FS)	T3=T1(SZ)+T2(FS)
2nd	T4(SZ)	T10(SZ+FS)	T1(SZ)	T1(SZ)
3rd	T6=T4(SZ)+T5(FS)	T4(SZ)	T10(SZ+FS)	T10(SZ+FS)
4th	T3=T1(SZ)+T2(FS)	T1(SZ)	T6=T4(SZ)+T5(FS)	T11(SZ+FS)
5th	T11(SZ+FS)	T11(SZ+FS)	T4(SZ)	T4(SZ)
6th	T10(SZ+FS)	T13(SZ+FS)	T11(SZ+FS)	T6=T4(SZ)+T5(FS)
Range relative control:	172-222%	109-121%	178-310%	145-197%
(control reference)	(48 p/m^2)	(1.02 t/ha)	(27 p/m^2)	(1.10 t/ha)

**Product details shown in Table 1*

SZ: Seed Zone ; FS: Furrow Surface (30mm wide band spray)

***Some treatments may not be significantly different from others in the ranking*

In 2019, the additional on-row sowing control resulted in crop establishment well above the best soil wetter treatment (+85 plants/m^2), which indicates that access to soil moisture under the stubble row is critical in achieving uniform and fast germination in this non-wetting sand. This trial did not combine on-row sowing + soil wetter, but this was done in a second trial at the same site (see the seeder strategy trial).

Table 3 ranks the top six soil wetter treatments used at Murlong, which were consistent across both years. This indicates these products may prove reliable over many seasons on this particular soil type. Anecdotal evidence suggests that some of the other wetting agents not in the top six at this site have performed well in other areas of the state, so a broad evaluation across other types of water repellent sands is advisable.

Grain yield results (2018-19)

Figure 3 shows the grain yield results for both years. In 2018 (decile 2 GSR), the untreated control had an average wheat grain yield of 1.02t/ha. In the first year, grain yield responses to soil wetter treatments ranged from 0 to 21%, with a maximum response of 0.22t/ha. There was a significant positive correlation ($r = +0.76$, $P<0.01$) between grain yield and plant density at 38 days after sowing (DAS).

The earlier break of the season and slightly drier season in 2019 saw larger barley crop responses to soil wetters, with the grain yield of the inter-row sown control averaging 1.10t/ha. Yield responses to the wetter treatments ranged from +23 to +97%, with a maximum increase of 1.07t/ha. In comparison, the on-row control introduced in 2019 yielded the highest (2.15 times more than the inter-row control), providing a 1.26t/ha grain yield benefit. A strong positive correlation ($r = +0.883$, $P<0.01$) was obtained between grain yield and plant density at 36DAS. The greater yield responses to soil wetters in 2019 may have been influenced by the stability of the water harvesting furrows produced by the seeding system (Figure 4), compared to 2018 when the challenging post-seeding period resulted in early backfilling of the furrows.

Overall, the grain yield responses across all treatments were similar for both years, with a strong positive correlation ($r = +0.815$, $P<0.01$) between the two data sets (Figure 5). This is encouraging and suggests the better treatments may be recommended to growers in this environment.

Table 3 provides a synopsis identifying the top six performers overall for both crop establishment and grain yield for this site. This evaluation was conducted using a precise split seeding system (knife point + independent dual seeding discs) where co-location of the wetter and seed was assured, and a stable wide furrow was created for the surface wetters applied in a 30mm wide band (Figure 4). The lower performance of a less accurate seeding system used in Trial 2 (see seeder strategy trial) suggests seeding system accuracy had a likely impact on securing these results.

Seeder strategy evaluation trial (2019)

Background

In 2019 a dry 11-12cm thick repellent top layer was present in the inter-row zone at seeding, but with consistent moisture below 16-17cm, which was separated by a patchy transition zone. This situation was similar to conditions seen at sowing in 2018.

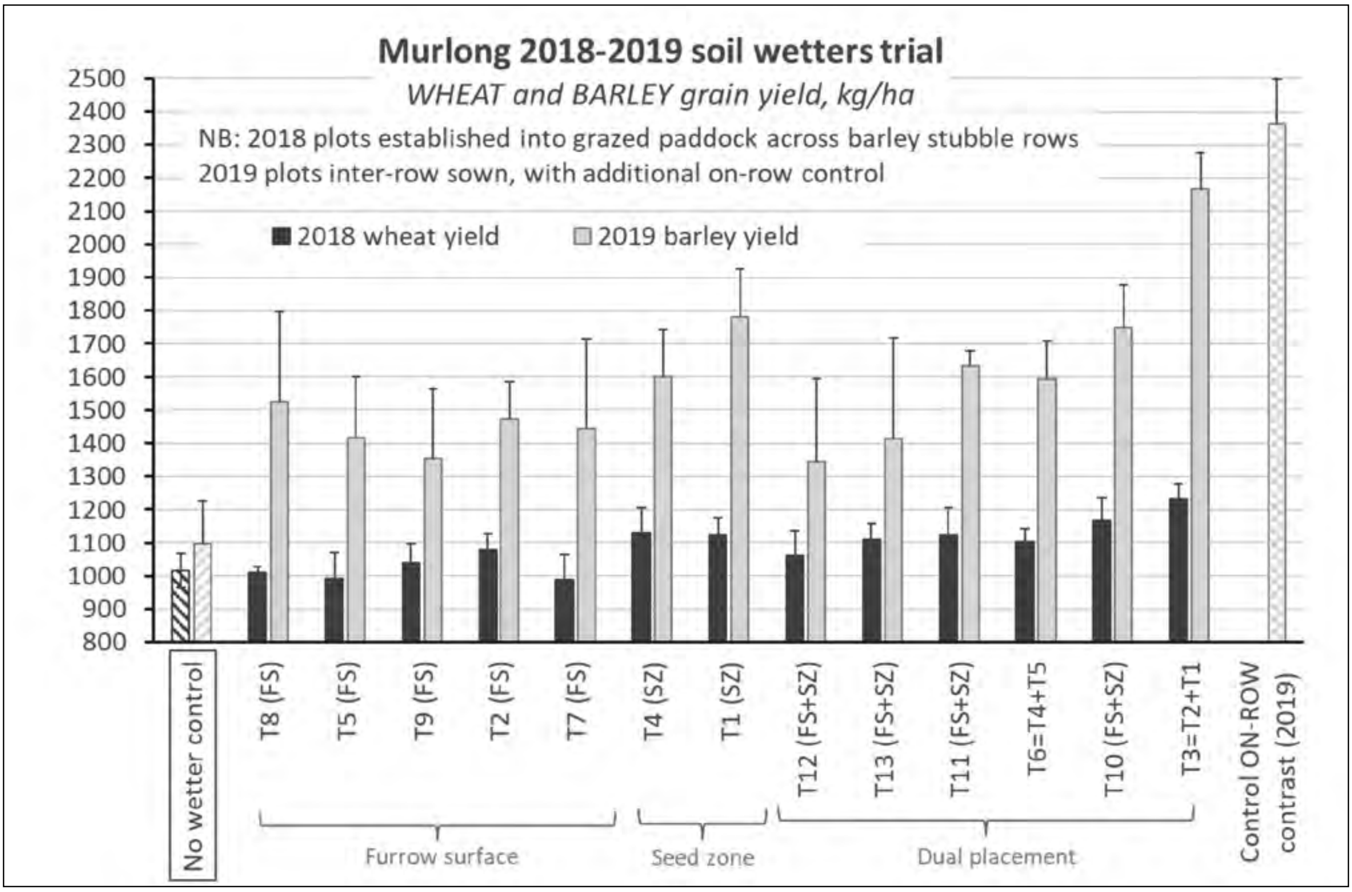

Figure 3. Effect of thirteen soil wetter treatments on grain yield (kg/ha), relative to a no-wetter control (NB: error bar = 1 standard error of the mean).

Figure 4. Left: Precision tine-disc seeding system used in the soil wetter evaluation trial; Right: Stable water-harvesting furrows still apparent at 54 days after sowing during 2019.

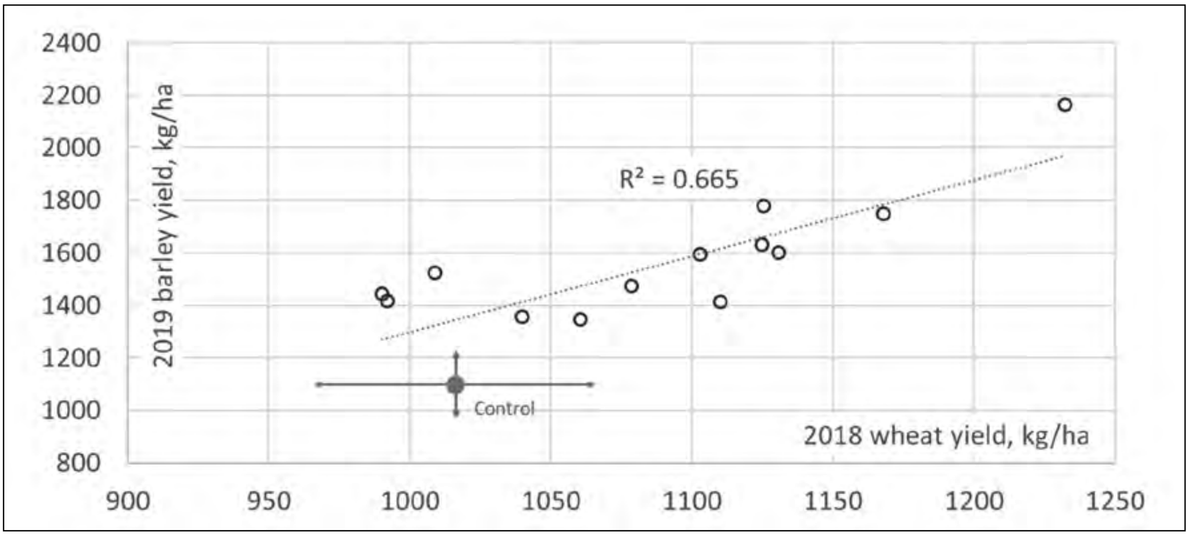

Figure 5. Soil wetter treatment grain yield correlation, relative to control during 2018 and 2019 (NB: arrows indicate ±1 std error of the mean control for both years).

However, there was good moisture 4-5cm below the existing stubble rows in 2019. Measurements quantified 9mm more water stored in the 0-40cm layer in the stubble row zone compared to the inter-row zone, with the majority in the top 25cm layer. This additional soil moisture under the stubble row at sowing was consistent with observations made in a water repellent sand at Lameroo, where 7-9mm of extra water was measured in the 0-40cm layer under the row in 2018 and 2019.

Experimental design

This trial was sown to barley in 2019 into wheat stubble plots established in 2018. Real-Time Kinetic (RTK) AB-line technology ensured high accuracy when sowing row-guided treatments (Table 2). Plot dimensions, sowing and wetter application techniques were the same as the soil wetter evaluation trial, but this trial was sown five days l ater (20 to 22 May 2019). Eleven experimental treatments with four replications were organised in a randomised complete block design, and consisted of:

- Six treatments assessing the impact of a selected seed-zone soil wetter (SACOA SE14® at 3L/ha) under inter-row, edge-row and on-row sowing configurations, at a common 110mm depth of furrow. Different seeding systems were used to achieve edge-row, inter-row and on-row sowing, as shown in Figure 6.
- Two soil wetter treatments assessing the additional impact of a 230mm deep furrow till under inter-row and edge-row sowing.
- Two soil wetter treatments contrasting the impact of an inverted T opener (95mm wide) and of paired-row sowing (75mm spread) at the common 110mm depth of furrow and under on-row sowing configuration.
- One additional contrast to the no-wetter control under inter-row sowing, assessing the impact of a proportion of in-furrow fertiliser; nitrogen (N) and phosphorus (P) (6N+12P) applied with the seeds.

Barley crop establishment

On-row sowing alone increased barley plant density by 39 plants/m^2 over edge-row sowing and by 95 plants/m^2 over inter-row sowing (Figure 7). Edge-row sowing was much more variable than on-row, indicating the sensitivity of this strategy to optimum position which may be a barrier to adoption. Crop establishment with inter-row sowing was 21 plants/m^2 less than the inter-row control in the 2019 soil wetter evaluation trial, which had used a more accurate seeding system (Figure 5 left). The placement of 6N+12P fertiliser with the seed created a small additional loss to an already poor crop establishment in the control (NB: 0.28m row spacing, approximately 10% seedbed utilisation).

The addition of soil wetter increased plant density by 22 and 29 plants/m^2 in the inter-row and edge-row sowing treatments, respectively. In contrast, soil wetters provided no benefits with on-row sowing, where the stubble row soil was already sufficiently moist to achieve good germination. This stands in contrast with a single plot unreplicated

Figure 6. Seeder strategies evaluation trial: Left: Baseline double shoot seeding system used for inter-row and on-row sowing; Right: Side banding double shoot seeding system used for edge-row sowing.

test conducted in the soil wetter evaluation trial combining treatment (T10) with on-row sowing, which produced a total 119 plants/m^2 more than the control, also resulting in the most vigorous and uniform crop growth during the season.

In this case the benefit of the soil wetter (SACOA SE14®) with inter-row sowing was slightly less than that measured in the soil wetter evaluation trial (22 plants/m^2 compared with 36 plants/m^2), which may be due to better seed placement and water harvesting by the better furrows obtained in the soil wetter evaluation trial. This perhaps emphasises the importance of considering a range of furrow management issues when looking at the suitability of soil wetters as a mitigation approach.

Deep furrow till to 230mm had a major positive impact (extra +74 plants/m^2) under inter-row sowing with a soil wetter, whereby the associated deep moisture delving strongly benefited an otherwise dry seed zone. No corresponding benefit occurred with edge-row sowing, where a 26 plants/m^2 decrease was recorded. This may be due to the differences with the side-banding seeding system using a long steep knife point to reach 230mm depth which was probably less effective at lifting moisture up and the extra disturbance may have also reduced the uniformity of seed placement.

Deep furrow till was not evaluated with on-row sowing. However, a positive response to the inverted T opener (+20 plants/m^2) was measured, indicating that the extra quantity of moist furrow from soil lifting and mixing benefited seed germination.

Under on-row sowing with the soil wetter, the paired row system (T25) did not improve crop establishment over the single row equivalent (T27), both using a knife point opener.

Barley grain yield (2019)

Barley grain yields ranged from 0.5t/ha to 2.42t/ha, with inter-row, edge-row and on-row sowing controls yielded 0.59, 1.45 and 2.0t/ha, respectively (Figure 8). All on-row treatments yielded 2t/ha or more, with paired row sowing (T25) yielding 2.42t/ha. The edge-row sowing treatment benefited from the soil wetter (+0.22t/ha) and the 230mm deep-furrow till (+0.24t/ha). Inter-row sowing also benefited from the soil wetter (+0.37t/ha), and considerably more from the 230mm deep furrow till (+1.16 t/ha). The soil wetter had no effect on grain yield when applied on-row where furrow moisture was sufficient to achieve good germination, while a minor grain yield benefit from the inverted T opener was measured (+0.1t/ha).

Overall, grain yield responses to treatments were very highly correlated (r = +0.950; P<0.01) with plant densities established early in the season, indicating higher plant populations was a key factor driving barley grain yield under the trial conditions. The inter-row control in the soil wetter evaluation trial yielded significantly more (+0.5t/ha) than in this trial, which may be explained by the combined benefits of five days earlier sowing, greater water harvesting and stable furrows, more precise seed placement and soil wetter co-location achieved by the tine-disc seeding system.

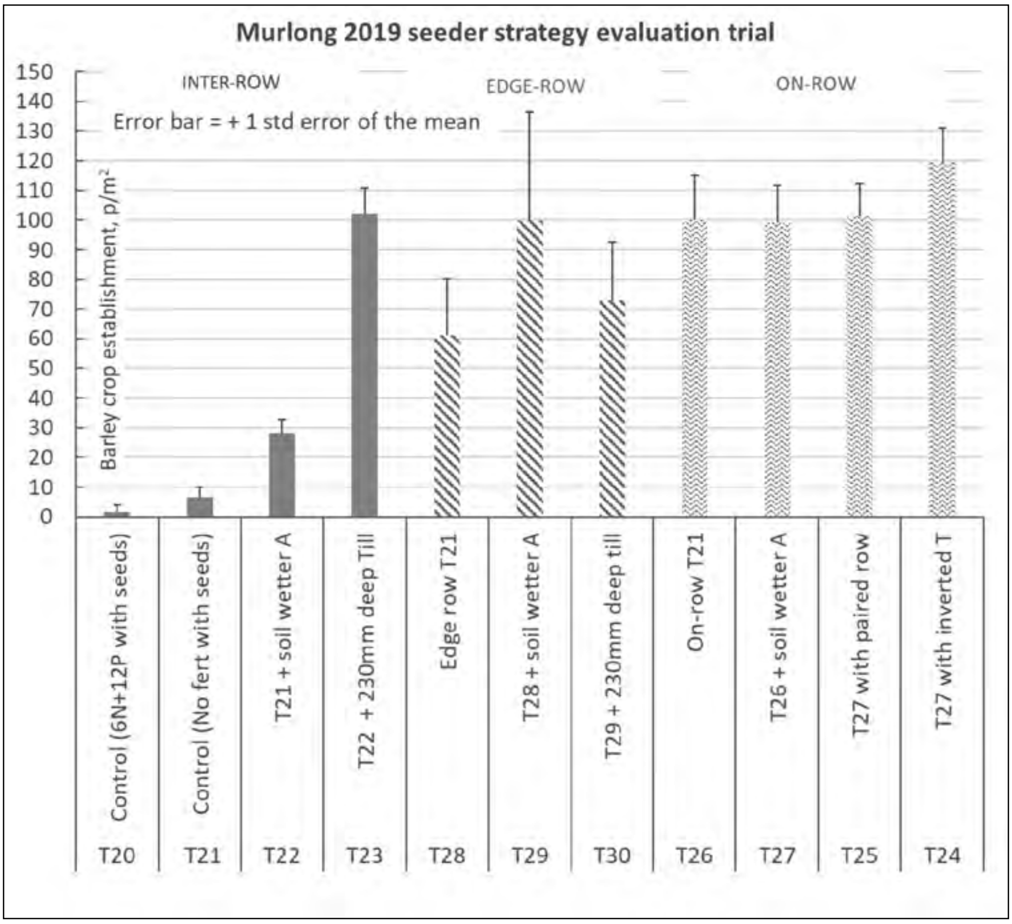

Figure 7. Impacts of various inter-row, edge-row and on-row sowing strategies on crop establishment at five weeks after sowing in barley at Murlong in 2019.

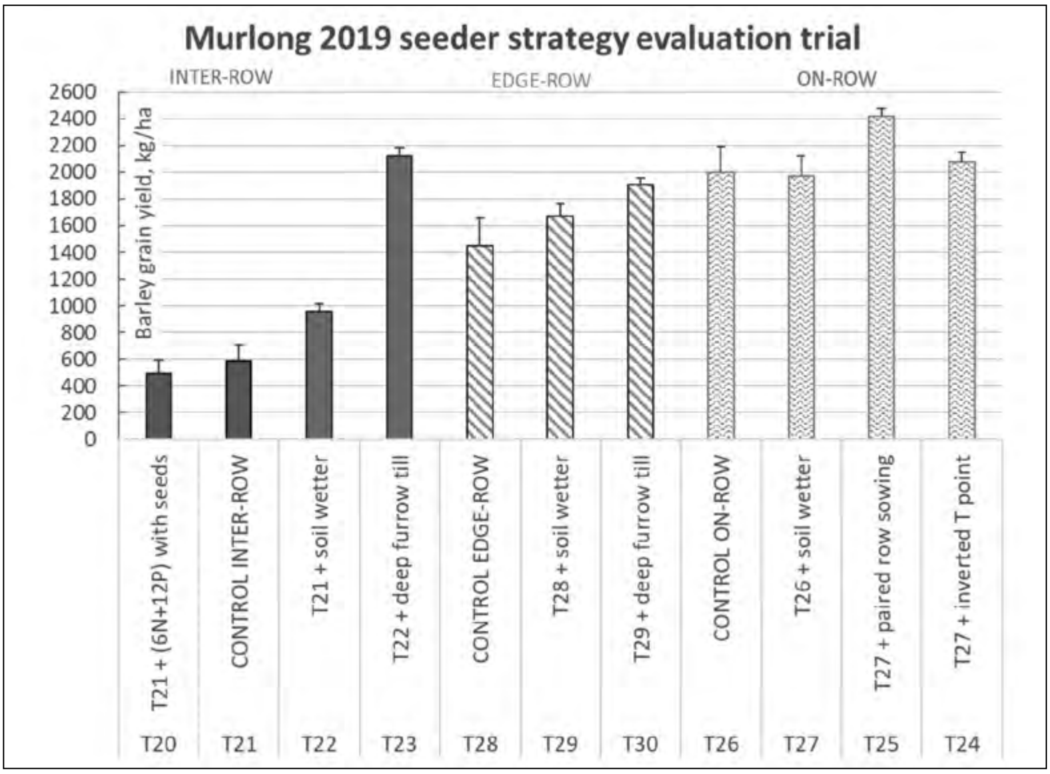

Figure 8. Impacts of various inter-row, edge-row and on-row sowing strategies on barley grain yield at Murlong in 2019.

It is worth noting that, in another project trial conducted in a non-wetting deep sand at Lameroo during 2017-2019, significant benefits of edge-row and on-row sowing on wheat and barley crop establishment and grain yield were also obtained, and significant biomass and grain yield responses to 230mm deep furrow till were also measured (Desbiolles et al., 2019). These reinforce the findings of the trials at Murlong.

Conclusions

Two trials conducted over 2018 and 2019 in a highly water repellent sand and under well below-average rainfall conditions at Murlong SA demonstrated:

- Seeder-based strategies for reducing the impact of water repellence can deliver large benefits on crop establishment and grain yield. The strategies evaluated focussed on accessing stored moisture under existing stubble rows, the deeper moisture found below a dry non-wetting topsoil and maximising in-season rainfall infiltration and use.
- Specific technologies were required to implement these strategies, such as: precision guidance (on-row, edge-row sowing), liquid dispensing (soil wetters), seeding system attributes (adjustable depth of furrow till, stable water-harvesting furrows, precision placement of seed and liquids (in-furrow, paired-row seeding, seed-fertiliser separation).
- Combining technologies can deliver additive benefits to crop establishment and grain yield, thus have the potential to form the basis of best practice. However, adoption of some strategies is likely to be limited if major investments are required by the grain grower. Other complications include the fact that water repellent sands usually occupy a part of large paddocks, and variable tracking accuracy with commercial scale machinery.
- Some of the benefits summarised could be achieved with low-technology options such as upgrading seeders with capability for deep moisture delving and seeding at a small angle to existing stubble rows (without RTK guidance) to maximise the benefits of furrow moisture.
- Additional factors that may influence the cost-effectiveness of a soil wetter include optimising-its furrow location, application rate and water volume per ha. These factors may require further experimentation on a product by product basis.
- Project validation activities in 2020 will work with growers to evaluate which seeder-based strategies can be effectively implemented at farmer scale in different sand environments.

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The research undertaken as part of this project has been 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 technical assistance from Dean Thiele (UniSA) and Ian Richter (SARDI) for trial implementation data sampling and site management, and also support from the soil wetter suppliers listed in Table 1; Syngenta Australia, Nufarm/CropCare, Incitec Pivot Fertilisers and Wengfu Fertilisers. The broader CSP00203 project team input is also gratefully acknowledged.

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Notes

Management of flowering time and early sown slow developing wheats

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Keywords

- winter wheat, crop development, frost, dual purpose, vernalisation.

Take home messages

- Different winter varieties are required to target different optimum flowering windows.
- Best yields of winter wheats sown early are similar to Scepter⁽ᴰ⁾ sown in optimal window.
- If sowing early use the right winter cultivar for the right yield and flowering environment.
- Highest yields for winter wheats come from early – late April establishment.
- Mid - slow developing spring varieties are less suited to pre-April 20 sowing.

Background

Timely operations are key to maximising farm profit, and sowing is one of the most time-critical operations. This is because there is only a short period (approximately 10 days) in spring during which crops can flower and yields be maximised. This period is referred to as the **optimal flowering period** and its timing and length varies with location and climate. During the optimal flowering period, it's important that the combined yield loss from drought, heat, frost and insufficient radiation is minimised, and yield maximised. Increasing farm sizes and cropped area and declining autumn rainfall have made it increasingly difficult to get crops flowering during the optimal period.

Sowing early with appropriate cultivars is one management strategy to increase the amount of farm area that flowers during the optimal period and thus farm yield can be maximised. Sowing early requires cultivars that are slower developing to take advantage of early establishment opportunities. They are ideally sown into a moist seed bed following breaking rain or preceding a convincing forecast of enough rain to allow germination. This should not be confused with dry sowing which will typically use fast developing cultivars sown into dry seed beds that will establish when breaking rains fall.

Winter wheats for early sowing

For sowing prior to April 20, winter cultivars are required, particularly in regions of high frost risk. Winter wheats will not progress to flower until their vernalisation requirement is met (cold accumulation) whereas spring cultivars will flower too early when sown early. The longer vegetative period of winter varieties also opens opportunities for grazing. Winter wheat cultivars allow wheat growers in the southern region to sow much earlier than currently practiced, meaning a greater proportion of farm can be sown on time.

Management of Early Sown Wheat experiments

The aim of this series of the GRDC Management of Early Sown Wheat (MESW) experiments is to determine which of the new generation of winter cultivars have the best yield and adaptation in different environments and what is their optimal sowing window. Prior to the start of the project in 2017 the low to medium rainfall environments had little exposure to the new winter cultivars, particularly at really early sowing dates (mid-March). Three different experiments have been conducted in the southern region in the low to medium rainfall environments during 2017 and 2019, including collaboration in NSW for additional datasets presented in this paper.

Experiment 1 - Which wheat cultivar performs best in which environment and when they should be sown

- Target sowing dates: 15 March, 1 April, 15 April and 1 May (10mm supplementary irrigation to ensure establishment).
- Locations: South Australia (SA) - Minnipa, Booleroo Centre, Loxton, Hart. Victoria (Vic) - Mildura, Horsham, Birchip and Yarrawonga. New South Wales (NSW) – Condobolin, Wongarbon, Wallendbeen.
- Up to ten wheat cultivars - The new winter wheats differ in quality classification, development speed and disease rankings (Table 1).

Different winter cultivars are required to target different optimum flowering windows

Flowering time is a key determinant of wheat yield. Winter cultivars are very stable in flowering date across a broad range of sowing dates which has implications for variety choice as flowering time cannot be manipulated with sowing date in winter wheats like spring wheat. This means that different winter varieties are required to target different optimum flowering windows. The flowering time difference between winter cultivars are characterised based on their relative development speed into three broad groups; fast, mid and slow for medium to low rainfall environments (Table 1 and Figure 1).

For example at Birchip each winter variety flowered within a period of seven to ten days across all sowing dates, whereas spring cultivars were unstable and ranged in flowering dates over one month apart (Figure 1). In this Birchip example, the fast to mid developing winter wheats with development speeds similar to Longsword⚆ and Illabo⚆ are best suited to achieve the optimum flowering period 10 September to 20 September for Birchip. In other lower yielding environments such as Loxton, Minnipa, and Mildura the faster developing winter cultivars; ADV15.9001 and Longsword⚆ were better suited to achieve the flowering times required for the first 10 days in September. Whereas, Illabo⚆ and Kittyhawk⚆ were more suited to the Mid North of SA at Hart and Tarlee (Figure 1).

Table 1. Summary of winter cultivars, including Wheat Australia quality classification and disease rankings based on the 2020 SA Crop Sowing Guide.

Cultivar	Release Year	Company	Development	Quality	Disease Rankings#			
					Stripe Rust	Leaf Rust	Stem Rust	YLS
Kittyhawk⚆	2016	LRPB	Mid-winter	AH	RMR	MS	MRMS-S	MRMS
Longsword⚆	2017	AGT	Fast winter	Feed	RMR	MSS	MR	MRMS
Illabo⚆	2018	AGT	Mid-winter	AH/APH*	RMR	S	MS	MS
DS Bennett⚆	2018	Dow	Slow winter	ASW	RMR	S	MRMS	MRMS
ADV15.9001	?	S&W Seed Company	Fast winter	?	-	-	-	-
Nighthawk⚆	2019	LRPB	Very slow spring	?	RMR	MSS	RMR	MS
Cutlass⚆	2015	AGT	Mid spring	APW/AH*	MS	RMR	R	MSS
Trojan⚆	2013	LRPB	Mid-fast spring	APW	MR	MRMS	MRMS	MSS
Scepter⚆	2015	AGT	Fast spring	AH	MSS	MSS	MR	MRMS

**Southern NSW only; YLS = yellow leaf spot; Australian Hard (AH), Australian Prime Hard (APH), Australian Standard White (ASW), Australian Premium White (APW); Resistant (R), Moderately Resistant (MR), Moderately Susceptible (MS), Susceptible (S)*

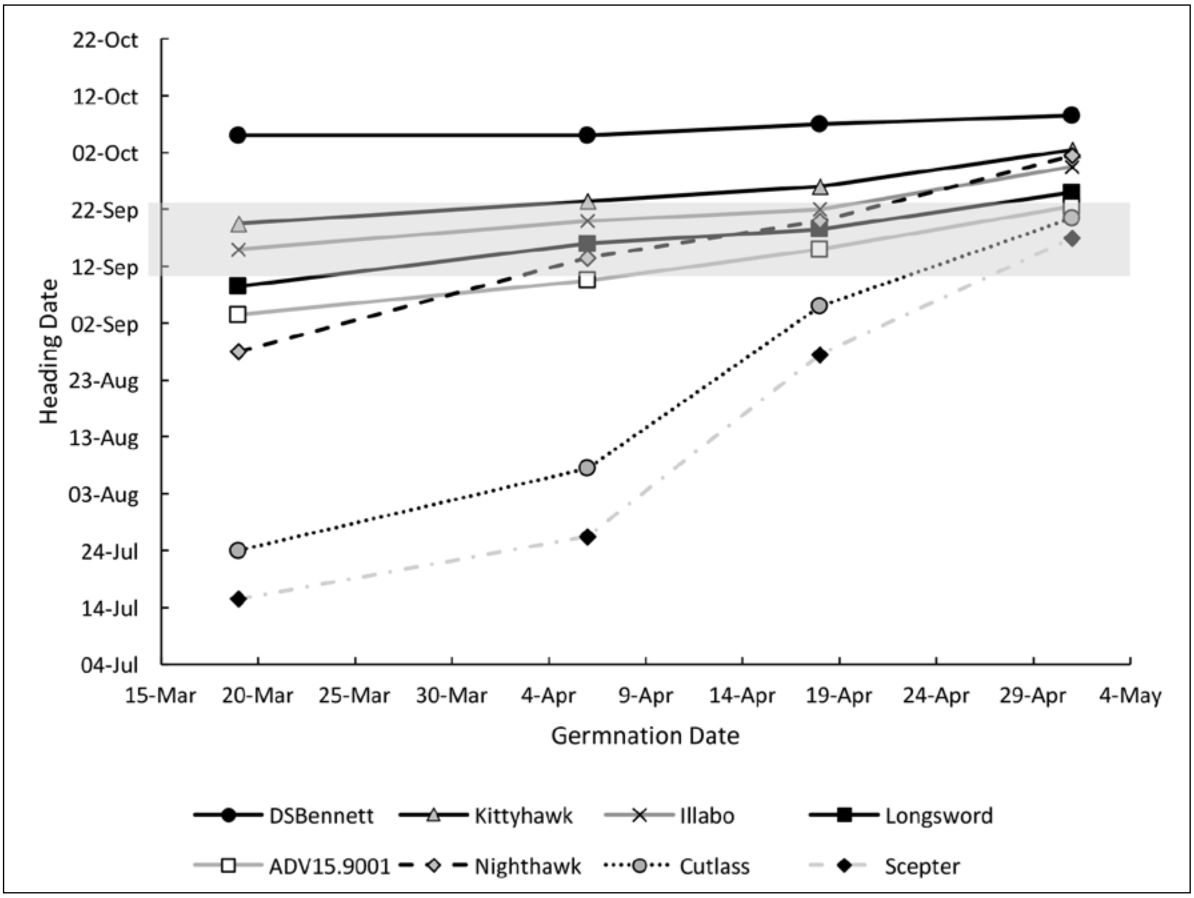

Figure 1. Mean heading date responses from winter and spring cultivars at Birchip in 2018 and 2019 across all sowing times, grey box indicates the optimal period for heading at Birchip.

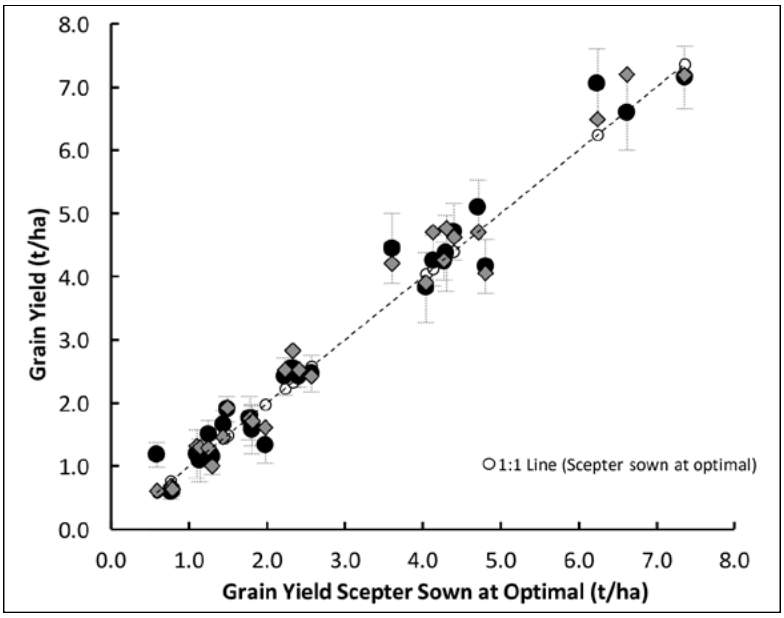

Figure 2. Grain yield performance of Scepter$^{\phi}$ wheat sown at its optimal time (late April-early May) in 28 environments (2017 – 2019) compared to the performance of the best performing winter wheat and slower spring wheat. Error bars indicate LSD (P<0.05).

Best yields of winter wheats sown early are similar to Scepter$^{(D)}$ sown in its optimal window

- Across all experiments the best performing winter wheat yielded the same as the fast developing spring variety Scepter$^{(D)}$ sown at its optimal time (last few days of April or first few days of May, used as a best practice control) in 23 out of 31 sites, greater than in six sites and less than in two sites (Figure 2).
- The best performing winter wheat yielded similar to the best performing slow developing spring variety (alternative development pattern) at 26 sites, greater than at three sites and less than at two sites.

Table 2. Summary of grain yield performance of the best performing winter and alternate spring cultivar in comparison to Scepter$^{(D)}$ sown at the optimum time (late April-early May). Different letters within a site indicate significant differences in grain yield.

Site	Year	Grain yield of	Highest yielding winter cultivar			Highest yielding slower spring cultivar		
		Scepter sown ~1 May (t/ha)	Grain Yield (t/ha)	Cultivar#	Germ Date	Grain Yield (t/ha)	Cultivar#	Germ Date
Yarrawonga*	2018	0.6 a	1.2 b	DS Bennett$^{(D)}$	16-Apr	0.6 a	Cutlass$^{(D)}$	16-Apr
Booleroo	2018	0.8 a	0.6 a	Longsword$^{(D)}$	04-Apr	0.7 a	Trojan$^{(D)}$	02-May
Booleroo	2019	0.8 a	0.6 a	ADV15.9001	05-Apr	0.6 a	Cutlass$^{(D)}$	01-May
Loxton	2018	1.1 a	1.2 a	Longsword$^{(D)}$	19-Mar	1.3 a	Cutlass$^{(D)}$	03-May
Loxton*	2019	1.1 a	1.1 a	ADV15.9001	15-Mar	1.3 a	Cutlass$^{(D)}$	01-May
Minnipa	2018	1.3 a	1.5 b	Longsword$^{(D)}$	03-May	1.3 a	Trojan$^{(D)}$	03-May
Mildura	2019	1.3 a	1.2 a	ADV15.9001	29-Apr	1.0 a	IGW6566	15-Apr
Mildura*	2018	1.4 a	1.7 b	DS Bennett$^{(D)}$	01-May	1.5 a	Nighthawk$^{(D)}$	01-May
Mildura	2017	1.5 a	1.9 b	Longsword$^{(D)}$	13-Apr	1.9 b	Cutlass$^{(D)}$	28-Apr
Minnipa	2019	1.8 a	1.8 a	ADV15.9001	05-Apr	1.7 a	Cutlass$^{(D)}$	05-Apr
Horsham*	2018	1.8 a	1.6 a	DS Bennett$^{(D)}$	06-Apr	1.7 a	Trojan$^{(D)}$	02-May
Hart	2019	1.8 a	1.6 a	Illabo$^{(D)}$	05-Apr	1.7 a	Nighthawk$^{(D)}$	18-Apr
Booleroo	2017	2.0 a	1.3 b	DS Bennett$^{(D)}$	04-May	1.6 b	Cutlass$^{(D)}$	04-May
Minnipa	2017	2.2 a	2.4 a	Longsword$^{(D)}$	18-Apr	2.5 a	Cutlass$^{(D)}$	05-May
Loxton	2017	2.3 a	2.6 a	Longsword$^{(D)}$	03-Apr	2.8 b	Nighthawk$^{(D)}$	03-Apr
Hart	2018	2.4 a	2.4 a	Illabo$^{(D)}$	17-Apr	2.5 a	Nighthawk$^{(D)}$	17-Apr
Condobolin	2018	2.6 a	2.5 a	DS Bennett$^{(D)}$	19-Apr	2.4 a	Trojan$^{(D)}$	07-May
Yarrawonga	2019	3.6 b	4.5 a	ADV15.9001	15-Mar	4.2 a	Nighthawk$^{(D)}$	05-Apr
Birchip	2018	4.0 a	3.8 a	Longsword$^{(D)}$	30-Apr	3.9 a	Trojan$^{(D)}$	30-Apr
Hart	2017	4.1 a	4.3 a	Illabo$^{(D)}$	18-Apr	4.7 b	Nighthawk$^{(D)}$	18-Apr
Yarrawonga	2017	4.3 a	4.2 a	DS Bennett$^{(D)}$	03-Apr	4.3 a	Cutlass$^{(D)}$	26-Apr
Wongarbon	2017	4.3 a	4.4 a	DS Bennett$^{(D)}$	28-Apr	4.8 a	Trojan$^{(D)}$	13-Apr
Tarlee	2018	4.4 a	4.7 a	Illabo$^{(D)}$	17-Apr	4.6 a	Nighthawk$^{(D)}$	17-Apr
Birchip	2019	4.7 a	5.1 a	DS Bennett$^{(D)}$	01-May	4.7 a	Nighthawk$^{(D)}$	01-May
Horsham	2019	4.8 a	4.2 b	Longsword$^{(D)}$	05-Apr	4.1 b	Nighthawk$^{(D)}$	05-Apr
Wallendbeen	2018	NA	4.2 a	DS Bennett$^{(D)}$	28-Mar	4.2 a	Nighthawk$^{(D)}$	28-Mar
Wallendbeen	2019	5.0 a	5.8 b	DS Bennett$^{(D)}$	10-Apr	5.5 ab	Nighthawk$^{(D)}$	27-Mar
Tarlee	2019	5.1 a	5.3 a	Illabo$^{(D)}$	16-Apr	4.5 b	Nighthawk$^{(D)}$	16-Apr
Wallendbeen	2017	6.2 a	7.1 b	DS Bennett$^{(D)}$	28-Mar	6.5 a	Cutlass$^{(D)}$	01-May
Birchip	2017	6.6 a	6.6 a	DS Bennett$^{(D)}$	15-Apr	7.2 a	Trojan$^{(D)}$	15-Apr
Horsham	2017	7.4 a	7.2 a	DS Bennett$^{(D)}$	16-Mar	7.2 a	Trojan$^{(D)}$	28-Apr

**stem and/or reproductive frost substantially affected yield; #Cultivars ADV15.9001, TrojanA and IGW6566 were not included at all sites*

The best performing winter cultivar depends on yield environment and development speed

The best performing winter wheat cultivars depended on yield environment, development speed and the severity and timing of frost (Table 1). The rules generally held up that winter cultivars that are well-adjusted to a region yielded similar to Scepter⁽ᵇ sown in its optimal window. These results demonstrate that different winter wheats are required for different environments and there is genetic by yield environment interaction:

- In environments less than 2.5t/ha the faster developing winter cultivars Longsword⁽ᵇ and ADV15.9001 were favoured (Table 2, Figure 3).
- In environments greater than 2.5t/ha the mid to slow developing cultivars were favoured; Illabo⁽ᵇ in the Mid North of SA, and DS Bennett⁽ᵇ at the Vic and NSW sites (Figure 4).

The poor relative performance of Longsword⁽ᵇ in the higher yielding environments was explained by a combination of flowering too early and having inherently greater floret sterility than other cultivars irrespective of flowering date.

Sites defined by severe September frost and October rain included Yarrawonga, Mildura and Horsham in 2018. In this scenario the slow developing cultivar DS Bennett⁽ᵇ was the highest yielding winter wheat and had the least amount of frost induced sterility. The late rains also favoured this cultivar in 2018 and mitigated some of the typical yield loss from terminal drought (for example, Birchip 2019). Nonetheless, the ability to yield well outside the optimal flowering period maybe a useful strategy for extremely high frost prone areas for growers wanting to sow early.

Highest yields for winter wheats come from early to late April establishment

- Across all environments the highest yields for winter wheats generally came from early to late April establishment and results suggested that the yields may decline from sowing dates earlier than April and these dates may be too early to maximise winter wheat performance (Table 2, Figure 3 and Figure 4). The cultivar DS Bennett⁽ᵇ maintained yield better than other cultivars from March establishment.

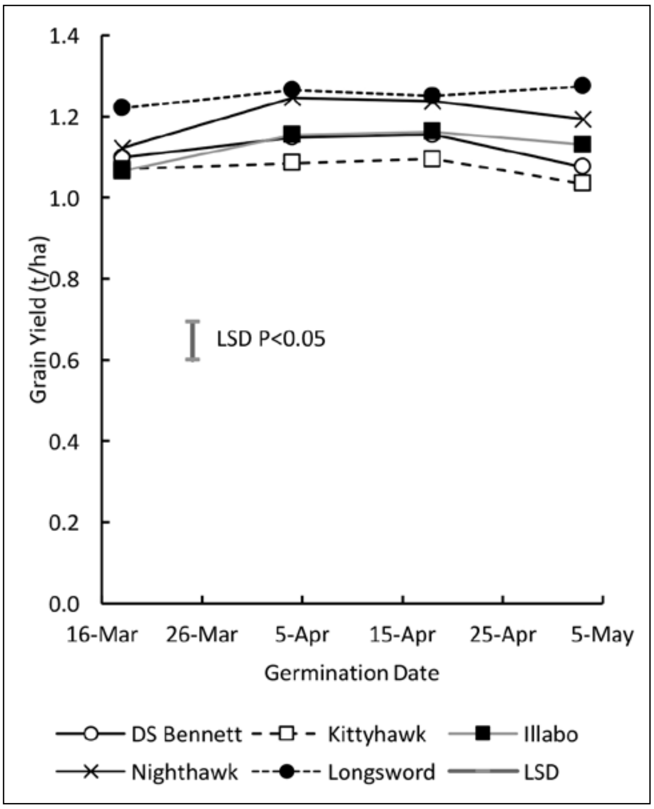

Figure 3. Mean yield performance of winter wheat in yield environments less than 2.5t/ha (n=16 sites in SA/Vic).

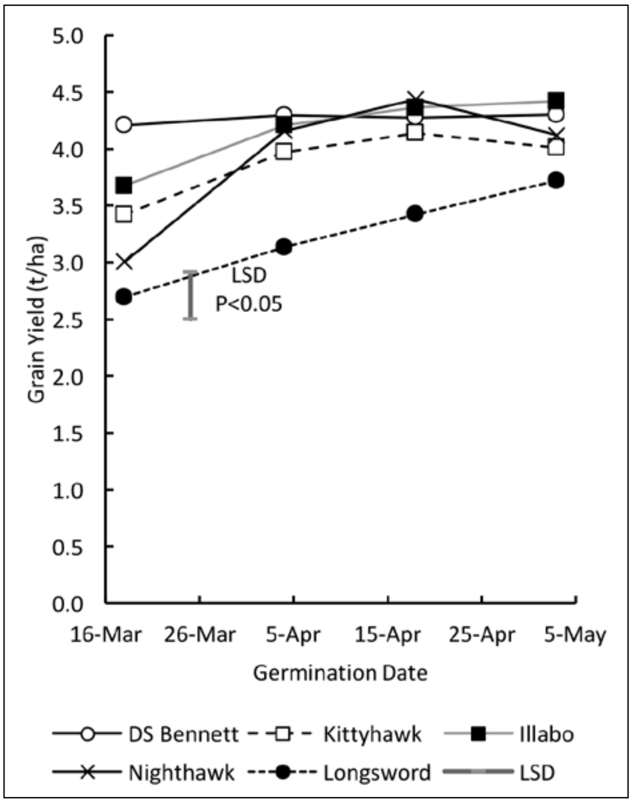

Figure 4. Mean yield performance of winter wheat in yield environments greater than 2.5t/ha (5 sites in SA/Vic).

- Mid to-slower developing spring wheats (for example, Cutlass$^{(\phi)}$) performed best from sowing dates after April 20 and yielded less than the best performing winter cultivars when sown prior to April 20. This reiterates slow developing spring varieties are not suited to pre-April 20 sowing in low to medium frost prone environments.

- The very slow developing spring wheat; Nighthawk$^{(\phi)}$ yielded similar to the best performing winter cultivar in both yield environments from mid-April establishment dates.

More details on experiment one can be found here: http://agronomyaustraliaproceedings.org/images/sampledata/2019/2019ASA_Hunt_James_173.pdf

Conclusion

Growers in the low to medium rainfall zones of the southern region now have winter wheat cultivars that can be sown over the entire month of April and can achieve similar yields to Scepter$^{(\phi)}$ sown at its optimum time. However, grain quality of the best performing cultivars is modest (Longsword$^{(\phi)}$=feed, DS Bennett$^{(\phi)}$=ASW). Sowing some wheat areas early allows a greater proportion of farm area to be sown on time. Growers will need to select winter wheats suited to their flowering environment (fast winter in low rainfall, mid and mid-slow winter in medium rainfall) and maximum yields are likely to come from early to mid-April planting dates.

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 project is led by La Trobe University in partnership with the South Australian Research and Development Institute (SARDI), Hart Field Site Group, Moodie Agronomy, Birchip Cropping Group, Agriculture Victoria, FAR Australia, Mallee Sustainable Farming. Collaboration with New South Wales DPI and Central West Farming systems.

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Cereal diseases update for 2020 in South Australia

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South Australian Research and Development Institute (SARDI).

GRDC project codes: DAS00139, DAQ00187, DJP1907-002RMX

Keywords

- net form net blotch, Rhizoctonia, wheat powdery mildew, crown rot, eyespot, rusts fungicide resistance.

Take home messages

- With a very large area being sown to Spartacus⁽ᴾ⁾ and Compass⁽ᴾ⁾ we are seeing a heavy selection for increased virulence of net form net blotch (NFNB) on these varieties.
- The repeated use of fungicides on susceptible wheat and barley varieties has seen a loss of efficacy to NFNB in some demethylation inhibitors (DMIs) and Systiva®, and to wheat powdery mildew in strobilurins.
- It is important to try and keep a step ahead of pathogens by rotating varieties and fungicides to disrupt selection in the populations.
- Rhizoctonia may have built up under the dry conditions of 2018 and 2019 and so could present significant problems in 2020.

Season summary

2019 saw another year with generally low levels of foliar diseases owing to low carryover of inoculum from 2018, relatively dry growing conditions in most areas and many growers using fungicides as protectants. Large areas of the state are now being sown to a very narrow range of wheat and barley varieties, such that the predominant varieties are determining which diseases are most prevalent.

Rusts were almost absent from 2019 South Australian (SA) crops. Just a smattering of barley leaf rust was observed in the most susceptible varieties in untreated National Variety Trials (NVT) plots on the Yorke Peninsula (YP) and in the South-East (SE). Stripe rust, although absent from SA this season, has changed in virulence once again with the new strain observed in Victoria and southern NSW. This new strain's most notable feature is increased virulence on almost all durum varieties. It also has significantly increased virulence on DS Bennett⁽ᴾ⁾, Emu Rock⁽ᴾ⁾ and Trojan⁽ᴾ⁾.

In most parts of SA, Rhizoctonia has built up substantially over the last two seasons. This pathogen is favoured by the dry winter and spring conditions experienced in both 2018 and 2019, while a dry summer (such as the 2018/19) also ensures the soilborne inoculum carries through to the next season. Rhizoctonia is hosted by a broad range of plants, however cereals and grassy weeds are preferred hosts and will increase inoculum greatly. The run of bad seasons may put pressure on growers to plant repeated cereals, and sometimes also limit effective grassy weed control in pastures and break-crops, which is likely to favour Rhizoctonia.

There are two key messages for Rhizoctonia in 2020. While growers who have had Rhizoctonia problems are likely to recognise the 'classic bare-patch' symptoms, many crops which are badly affected do not express this symptom. This is usually due to an early sowing opportunity, as was the case in many parts of SA in 2019, and good agronomy. Crops establish well under these conditions, before

Rhizoctonia becomes active. However, during the dry, cold winter, Rhizoctonia will build up and infect crop roots, often without obvious symptoms. Crop effects and even yield loss may have gone un-noticed or simply been attributed to the poor finish and/or frost. If you are unsure of whether Rhizoctonia has built up in your paddocks, request a PREDICTA®B test from your agronomist.

The second message for 2020 is around management. Although not predicted at the time of writing, significant (>20mm), repeated summer rain (more than two to three events), can reduce soilborne inoculum carryover **only if** summer weeds are quickly controlled. If summer weeds are valued as stock feed, prioritise removing weeds from paddocks which will be sown to cereals, particularly barley, in 2020. Where possible, plant a break crop such as canola or a pulse; although still slightly affected by Rhizoctonia, these have all been shown to reduce inoculum overall. If a cereal must be sown into a high inoculum situation, wheat is likely to suffer less yield loss than barley; although both are susceptible and likely to increase inoculum for the following season. The single most important action to limit yield loss where a cereal is planted into high inoculum, is to prioritise planting these paddocks as early as possible while the soil is warm. Liquid streaming fungicides, particularly as split applications on and in-furrow, can also be effective, but generally only under higher yield potential situations.

Crops that establish well can still be affected by Rhizoctonia in mid-winter when root growth is slowed due to low soil temperatures (<10°C). In this situation, Rhizoctonia will infect the crown roots, causing reduced tiller number and height. Infection can then spread down the soil profile in spring resulting in reduced root mass to fill grain.

To reduce root infection, growers should consider using seed treatments or liquid streaming fungicide below the seed to help protect the seminal roots and consider liquid-streaming fungicide above the seed to reduce crown root infection. Roots are only protected inside the fungicide diffusion zone. Increased seeding rate can help compensate for loss of tillers.

The risk will be reduced if multiple rain events, each >20mm, fall during summer and early autumn, and weeds are controlled.

Crown rot was a big problem for cereal crops which had acceptable rainfall early in 2019 but had little rainfall during grain filling. Low rainfall at the start of the season in many areas meant that infection with crown rot has been lower than expected in those crops, and expression of crown rot has been limited. The low rainfall in 2019 also meant that breakdown of infested cereal residues will have been very slow, with inoculum levels after non-cereals higher than expected in 2019. It will be particularly important to know the crown rot risk (using the PREDICTA®B service) prior to making the decision to sow very-susceptible cereal crops, such as durum wheat, in 2020.

Eyespot was less of a problem in most crops in 2019 due to low rainfall. There were some exceptions to this, where eyespot expression was much higher than expected given the low rainfall. Crops affected in this way seem to have had higher loads of infested stubble from previous crops. This suggests that the infested stubble has been wetted up by small rainfall events, producing a very humid environment at the base of the new crop, allowing higher than expected levels of spore production and infection.

Net form net blotch

The major concern coming out of 2019 is the rapid spread of resistance to fungicides observed in NFNB and wheat powdery mildew.

The large area sown to Spartacus⫚ and Compass⫚ in SA has seen virulence on these varieties increase in the past three years. This is particularly the case with Spartacus⫚. Testing of specific samples collected from the YP by SARDI in 2019 has shown that a proportion of the pathogen population is now highly virulent on this variety. This is reflected in the lower rating provided in the 2020 Cereal variety disease guide.

The growing of barley in infected barley stubbles from the same variety, will have greatly sped up this natural evolutionary process. The use of fungicides may have helped protect barley crops up to this point. However, it is now apparent that the same evolutionary processes have led to the development of resistance to succinate dehydrogenase inhibitor (SDHI) products, including Systiva, and some DMI products including tebuconazole, which was the marker active ingredient (a.i.) in the tests. A limited survey conducted by Fran Lopez and SARDI across the YP suggests that the SDHI resistance is currently focussed on the mid to lower YP whilst the DMI resistance is likely to be much more widespread across SA.

There has been a suggestion in the literature that resistance to strobilurins is unlikely to develop in future in the net blotches and rusts, owing to the resistance mutation site being linked to a lethal

Table 1. Results of adult plant tests with NFNB isolates collected in 2018.

Isolate	49/18	50/18	51/18	52/18	21/18	47/18	25/18a	69/18	70/18	71/18	75/18	73/18a	76/18	72/18a
Host	Keel	RGT Planet[PBR]	Topstart	RGT Planet[PBR]	RGT Planet[PBR]	RGT Planet[PBR]	Keel	Gairdner	La Trobe[PBR]	Compass[PBR]	Rosalind[PBR]	Westminster[PBR]	Oxford	Fatima
	Elliston	Elliston	Wanilla	Wanilla	Yeelanna	Yallunda Flat	Brentwood	Conmurra	Conmurra	Conmurra	Rendels FAR	Rendels FAR	Rendels FAR	Rendels BP
Clipper	3	4	3	2	4	3	2	3	4	4	3	2	2a	2
Schooner	4	3	2	3	4	2	2	3	2	4	2	2	3	2
Scope[PBR]	2	2	2	2	2	2	2	2	2	3	2	2	2	2
SloopSA	2	2	2	2	5	2	2	2	2	2	3	2	2	2
Alestar[PBR]	3	5	8	3	7	5	4	3	3	3	7	8	8	7
Banks[PBR]	2	1	2	1	2	1	2	6	1	2	2	2	2	2
Commander[PBR]	7	6	5	6	8	4	9	6	5	7	4	3	9	6
Compass[PBR]	6	7	7	7	7	3	7	4	5	6	5	4	7	6
Fathom[PBR]	6	7	7	8	7	4	8	7	3	7	7	5	8	5
Fleet[PBR]	1	1	1	1	1	2	3	3	2	2	2	4	2	2
RGT Planet[PBR]	3	4	7	3	9	5	4	3	3	6	7	7	8	8
Maritime[PBR]	2	2	2	2	2	2	3	2	2	2	3	2	2	2
Navigator	7	7	8	7	7	5	6	7	5	8	8	7	8	8
Oxford	3	3	8	4	9	5	3	4	4	6	7	8	9	9
Rosalind[PBR]	2	2	3	2	4	2	2	2	2	2	3	2	4	3
Spartacus[PBR]	6	6	7	5	3	4	8	3	3	6	3	3	7	7
Traveller	2	3	7	3	5	6	2	1	2	4	7	7	6	8
Westminster[PBR]	3	2	5	2	6	4	2	4	2	3	7	5	5	7
IGB1705T[PBR]	5	4	7	4	3	3	4	2	2	3+	3	5	4	4
WI4952[PBR]	4	4	5	5	4	2	5	2	2	3	2	4	3	6
Leabrook[PBR]	7	7	5	7	7	5	8	5	5	7	4	5	4	7
Biere[PBR]	5	4	9	4	7	7	6	4	4	8	5	7	9	7
Charles	8	8	8	7	7	5	7	3	3	4	8	8	7	8
Sunshine	7	6	7	5	8	6	5	4	5	7	7	8	6	8

n.b. 1= resistant (R), 3 = moderately resistant (MR), 5 = moderately susceptible (MS), 7 = susceptible (S), 9 = very susceptible (VS) gene. However, it is now apparent that this could be wishful thinking and that, given sufficiently high selection pressure, resistance to strobilurins could indeed occur, albeit at a slower rate.

Measures to reduce the new increased risks from NFNB must involve reducing inoculum levels by avoiding the sowing of susceptible barleys in high risk situations, disrupting pathogen selection processes by mixing up variety resistances in the landscape and rotating and mixing fungicides within crops.

The results of adult plant testing of NFNB isolates collected in SA in 2018 and 2019 respectively are shown in Tables 1 and 2. The results show how diverse the NFNB population is and, when compared across a number of years, how the pathogen shifts in response to the varieties being grown. For example, most isolates collected in the past two years have shown low virulence on Fleet⁽ᵈ⁾ and Maritime⁽ᵈ⁾; varieties that had previously been very susceptible. Instead we have seen a gradual increase in virulence on Compass⁽ᵈ⁾ and Spartacus⁽ᵈ⁾. RGT Planet⁽ᵈ⁾ is shown to be very susceptible in the SE and the Lower Eyre Peninsula (EP), but still moderately resistant in the mid and lower rainfall regions of the state. These results, along with others from previous years, have provided advanced warning of the potential susceptibility of new varieties and advanced breeding lines. The results also show how the older varieties; Clipper, Schooner, Sloop SA and Scope⁽ᵈ⁾, have remained stable over a long period of time, indicating the durability of their resistance. The new variety Banks⁽ᵈ⁾ is seen to be mostly resistant but could become susceptible if grown widely as revealed by an isolate from Conmurra in 2018. Rosalind⁽ᵈ⁾ on the other hand shows promise as a potentially durable, resistant variety.

The isolates in Table 2 were all collected on the Lower YP. The first five were collected from paddocks where Spartacus⁽ᵈ⁾ was grown into Spartacus⁽ᵈ⁾ stubbles and where Systiva and foliar fungicides had been used. It is notable that these YP isolates are all highly virulent on Spartacus⁽ᵈ⁾, and with the exception of the isolates from Urania and Pine Point, were generally less virulent on other varieties with the exception of Commander⁽ᵈ⁾.

Table 2. Results of adult plant tests with NFNB isolates collected in 2019 on the Yorke Peninsula.

Isolates	5/19	9/19a	9/19b	16/19	17/19	7/19
Host	Spartacus⁽ᵈ⁾	Spartacus⁽ᵈ⁾	Spartacus⁽ᵈ⁾	Spartacus⁽ᵈ⁾	Spartacus⁽ᵈ⁾	Fairview⁽ᵈ⁾
Location	Minlaton	Minlaton	Minlaton	Urania	Pine Point	Minlaton NVT
Clipper	2	2	2	4	4	2
Schooner	2	2	3	2	2	2
Scope⁽ᵈ⁾	2	2	2	3	2	1
SloopSA	3	2	2	2	3	2
Alestar⁽ᵈ⁾	3	2	3	5	4	2
Banks⁽ᵈ⁾	2	2	1	2	2	2
Commander⁽ᵈ⁾	7	8	4	9	8	5
Compass⁽ᵈ⁾	4	3	6	8	5	3
Fathom⁽ᵈ⁾	6	6	5	9	9	4
Fleet⁽ᵈ⁾	2	1	2	2	3	1
RGT Planet⁽ᵈ⁾	2	2	2	3	2	1
Maritime⁽ᵈ⁾	2	2	1	3	3	1
Rosalind⁽ᵈ⁾	2	1	2	3	3	1
Spartacus⁽ᵈ⁾	9	7	7	9	8	4
Westminster⁽ᵈ⁾	3	2	2	3	4	1
Leabrook⁽ᵈ⁾	6	4	4	8	5	3
Bottler⁽ᵈ⁾	2	2	2	2	2	1
Kiwi⁽ᵈ⁾	2	2	2	3	2	1
Traveller	2	1	2	2	2	1
IGB1705T⁽ᵈ⁾	5	2	5	5	6	3
WI4933	3	2	3	8	5	3
WI4952⁽ᵈ⁾	4	2	3	6	5	2

n.b. 1= resistant (R), 3 = moderately resistant (MR), 5 = moderately susceptible (MS), 7 = susceptible (S), 9 = very susceptible (VS)

Powdery mildew in wheat

Powdery mildew disease has become a regular problem in the northern part of the YP, particularly around Bute. Close rotations with the very susceptible varieties, Scepter⁽ᴰ and Chief CL Plus⁽ᴰ, are largely responsible for this situation. Frequent use of fungicides to manage this disease as well as preventative sprays for rusts and Septoria have now resulted in the mildew population developing resistance to strobilurins and some DMI products. A limited survey conducted in the area by Fran Lopez from Curtin University revealed a high level of resistance to both strobilurins and tebuconazole in several paddocks.

This situation can only be managed by reducing the area sown to these, and related, susceptible varieties, avoiding sowing into stubbles infested with the mildew fruiting bodies and by using fungicides in a more strategic manner. Because the fungicides are also being used to manage other diseases, care will need to be taken in selecting varieties that are also not too susceptible to them. Or, if the varieties are susceptible, then only grow them over a limited area and select another, different variety to provide diversity across the landscape. It is landscape and temporal diversity in varieties and treatments that will provide the most sustainable way forward.

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 therefore like to thank them for their continued support.

Useful resources

Cereal seed treatments 2020, SARDI factsheet; www.pir.sa.gov.au/__data/assets/pdf_file/0005/237920/Cereal_seed_treatments_2020.pdf

Cereal variety disease guide 2020 - to be released just prior to the Adelaide GRDC update.

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Snail management - learnings from recent studies

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GRDC project codes: DAS00134, DAS00160, CSE00061, DAS300, DAS00174, YPA0002

Keywords

- snails, molluscicide baits, integrated control.

Take home messages

- Baiting efficacy requires adequate pellet densities (30-60m^2).
- To minimise bait degradation, avoid baiting in significant rainfall or high temperatures and consider bait storage temperatures.
- Sound, evidence-based science is reinforcing the best practice management: baiting efficacy is higher earlier in the season than in spring.
- A better predictive ability around the optimal conditions for baiting in 2020 is expected to be gained when extensive analysis of snail video footage and microclimate data is completed.
- Baiting is a crucial snail management tool but often does not achieve high order control. Consequently, implementation and development of other integrated strategies remains important.

Background

Four introduced snail species of European-Mediterranean origin remain a significant challenge for grain growers; the vineyard or common white snail, *Cernuella virgata*, the conical snail, *Cochlicella acuta*, the small pointed snail *Cochlicella barbara*, and the white Italian snail, *Theba pisana*. These species are advantaged by modern low-disturbance farming systems and pose an increasing market access threat. Over the past six years, GRDC investments (DAS00134 and DAS00160; led by SARDI) have aimed to improve snail management with a focus on molluscicidal baiting (products, rates, timing), evaluation of novel molluscicides and improving the parasitism success of the introduced parasitoid fly, *Sarcophaga villineaveana*, against the conical snail (CSE00061, CSIRO/SARDI). This work has provided guidelines to improve snail control using baits. However, further development of integrated controls is still required and is becoming more feasible with new technologies. Provided in this paper, is a brief overview of key learnings on snail management from recent projects and new directions for snail research and development.

Baits - products and rates

Australian grain growers are heavily reliant on a single molluscicidal active ingredient, metaldehyde, for snail control. This molluscicidal is marketed under various product formulations with different pellet characteristics (for example bran or flour-based pellets) and concentrations of active ingredient (ranging from 1.5 to 5% a.i. metaldehyde). Iron chelate (iron EDTA complex) has an alternative mode of action and is less common in baiting programs which is possibly due to its higher cost.

Baits are not considered attractive to snails, and therefore, efficacy relies on snail movement activity and sufficient pellet densities to ensure active snails encounter pellets and consume a lethal dose. During 2014 and 2015, SARDI conducted field arena trials investigating bait efficacy for two metaldehyde products (Metarex® and Meta®) and one iron-chelate product (Eradicate®) for different snail species at a range of snail densities. Snails were placed in the field within 0.2m^2 bare earth arenas at one of five densities (40, 80, 160, 320, 640 snails/m^2) and exposed to one of five treatments (nil and 4 different pellet densities).

These trials found:

- At least 30 pellets per m^2 were required for optimal baiting efficacy. In areas of higher snail densities, up to 60 pellets per m^2 may be required to avoid complete consumption of pellets and maintain adequate rates of encounter.
- Across all trials, using more than 0.5 pellets per live snail per unit area did not greatly increase efficacy (Figure1); however, snail mortality often varied substantially between individual trials.
- Registered rates of some products gave fewer than 30 pellets per m^2 (Table 1), suggesting that repeat applications may be necessary in some instances.
- Trials conducted by SARDI and the Yorke Peninsula Alklaline Soils Group (YPASG) showed that bait spread was often uneven. It is important for bait spreaders to be calibrated for the selected bait product, then checked to ensure spread is occurring as expected (check for underdosed strips and bait shattering).
- The SARDI snail and slug baiting guidelines assist growers with baiting decisions (see 'Useful Resources' section of this paper).
- Baits often do not achieve high order control; other integrated control methods are required.

Baits - timing

Pellets are considered a superior bait form compared with sprays for molluscs; they have the advantage of persisting in the field during periods of inactivity. One drawback is that successful baiting requires an element of prediction; baits must be applied **just before** prolonged periods of snail activity (driven by weather conditions) to ensure pellet encounter. Additionally, baiting aims to control populations by knocking out mature snails **before** significant reproduction has occurred.

Since 2017, a GRDC project (DAS00160) led by SARDI together with DPIRD, has investigated the seasonal activity patterns of snails with respect to weather, in order to improve prediction of optimal bait timing. Eight field sites were established across Western Australia (WA) and South Australia (SA). Approximately 45 snails were collected at monthly intervals and dissected to determine their reproductive status. Time lapse video was used to monitor snail movement continuously together with logging of climate variables.

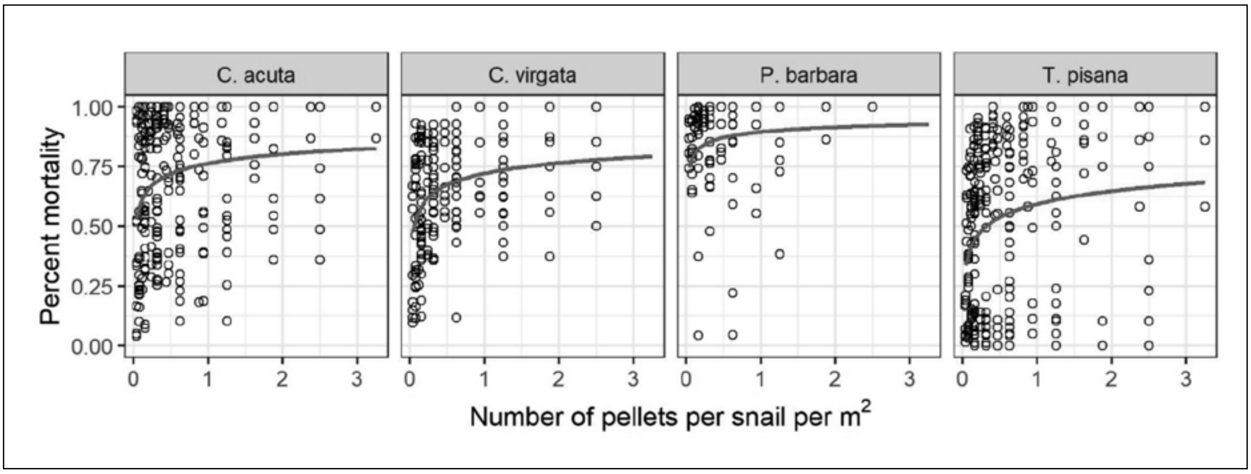

Figure 1. Mortality response versus density of pellets per snail per m^2 for four snail species (*Cochlicella acuta, Cernuella virgata, Prietocella barbara* and *Theba pisana*). Plots show pooled data for nine field cage trials with three different bait products. Circles represent mean mortality per cage; lines represent a crude model fit as an indicative guide.

Table 1. Pellet densities for registered rates of different bait products in Australian broad-acre grain production.

Product	Registered rate (kg/ha)	Pellets per m^2
Meta (15g/kg metaldehyde)	7.5	25
Metarex (50g/kg metaldehyde)	5	35
Eradicate (60g/kg Iron EDTA complex)	10	25

The work has found:

- Snails show a highly seasonal reproductive cycle. Enlarged 'albumen' glands indicate that snails are (or are about to become) reproductively active.
- For common white snails in SA, reproduction generally occurred from April to mid-spring (Figure 2). Increasing proportions of snails 'shut down' breeding between August to October depending on the finish to the season.
- The timing of the onset of reproduction can vary greatly from year to year, driven largely by rainfall (for example; common white snails at Gairdner WA, Figure 3).
- Currently, climatic triggers for reproduction and snail movement are being investigated through statistical analysis (March 2020 completion).
- Interestingly, laboratory trials at SARDI show that baiting efficacy also follows a seasonal cycle. Snails collected from Urania (1.5 years collection period) and Palmer (3.5 years collection period) and exposed to Metarex® in bioassays were killed more efficiently during periods coinciding with snail reproduction (approximately April to August; see Figure 4) compared with other times (for example; spring).
- Together, the results reinforce the need to concentrate baiting efforts in autumn prior to reproduction and when the baits kill the snails most efficiently.

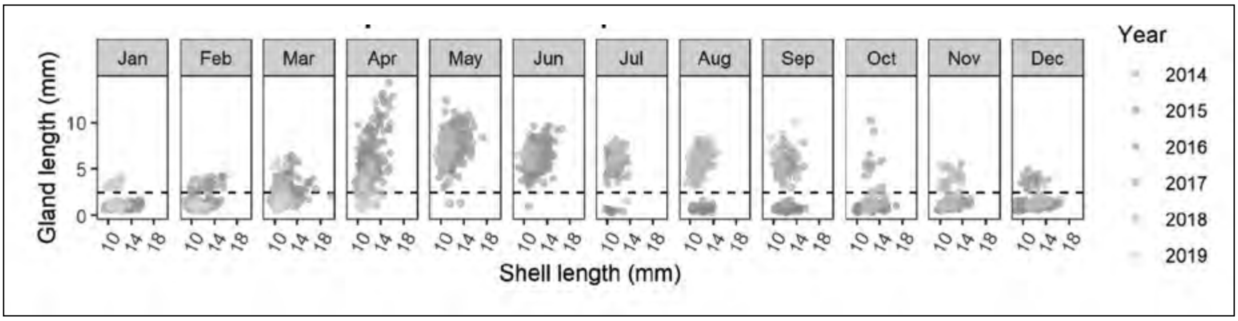

Figure 2. The seasonal reproductive cycle of common white snails at Palmer SA, shown by changes in the size of albumen glands over time. Each point represents one snail.

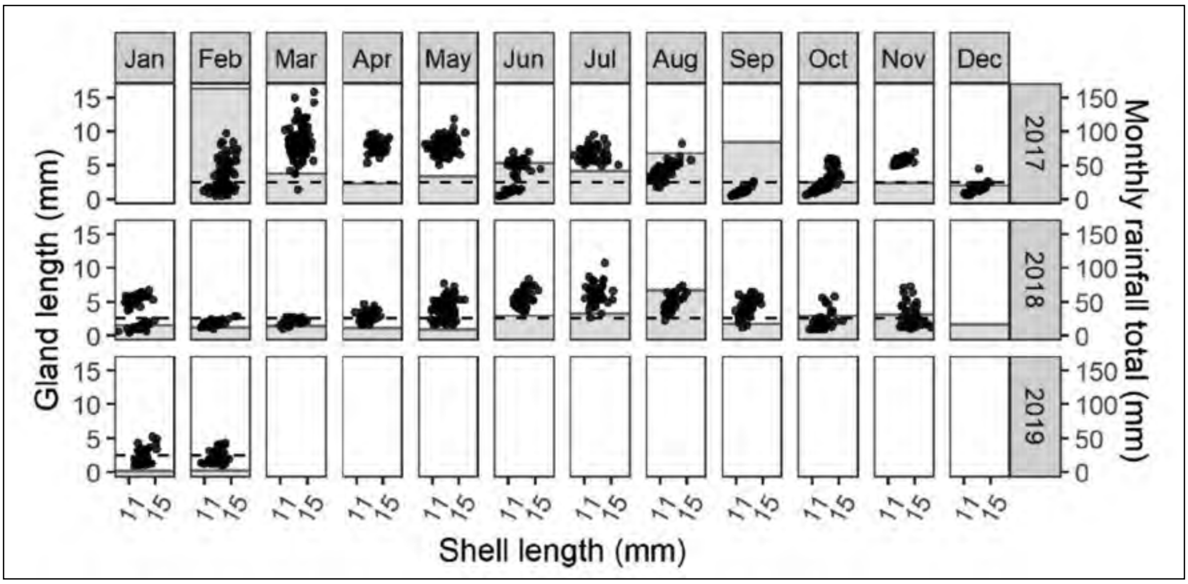

Figure 3. The seasonal reproductive cycle of common white snails at Gairdner WA together with total monthly rainfall (shading). Note that gland enlargement commenced in February of 2017 coinciding with high summer rainfall, compared to May of 2018 coinciding with a dry start.

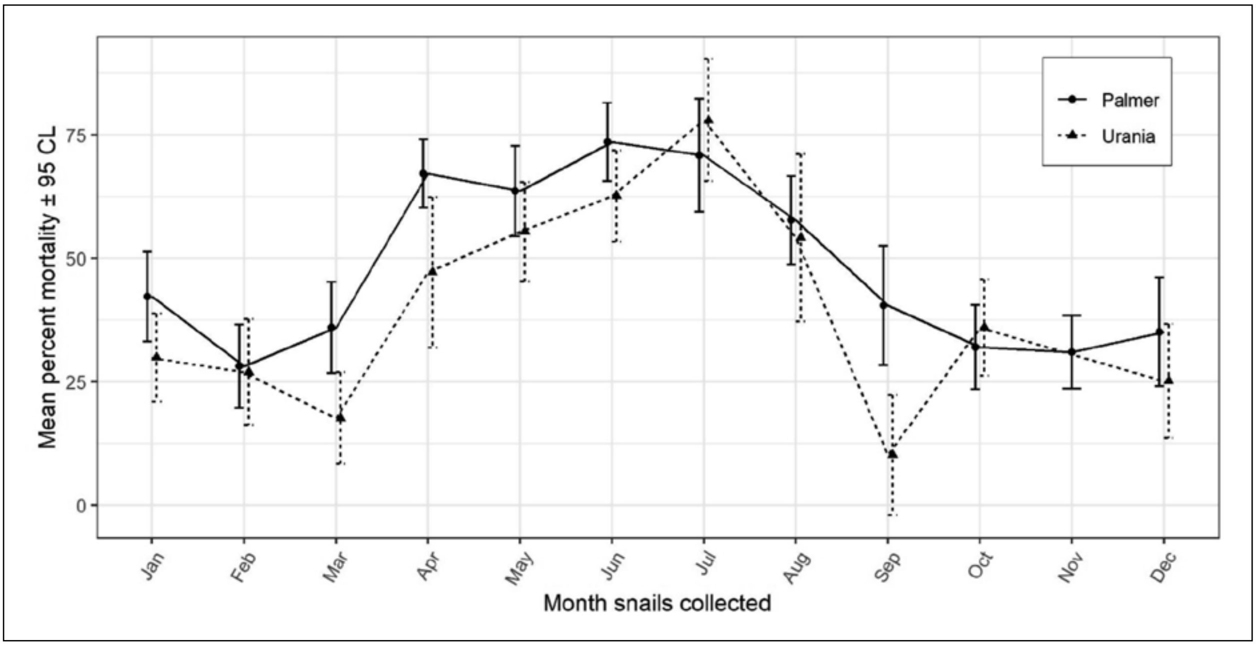

Figure 4. Mortality of common white snails exposed to Metarex baits in laboratory trials, for snails collected in each month of the year. Results from samples taken at Palmer include combined data for 2016-2019; Urania includes combined data for 2018-2019.

Baits - degradation

In recent years there has been more interest in baiting opportunistically during late summer following rain events. To investigate the possible effects 'baiting opportunistically' has on bait persistence, laboratory assays were conducted to test efficacy of baits exposed to ultra violet light (UV), high temperatures and rainfall. In each trial, eight pre-exposed baits were placed into arenas with five white Italian snails for three days and snail mortality recorded after eight days.

These trials found:

- There was no evidence that UV exposure degrades baits.
- High rainfall (35mm) on iron chelate products reduced bait efficacy.
- Meta and Metarex baits stored at high temperatures for seven days had reduced snail mortality following use.
- Third party laboratory analysis of the heat-treated Meta and Metarex pellets revealed a significant reduction in active ingredient following the heat treatments (20°C (stored) to 60°C). The concentration of metaldehyde in Meta baits declined at an approximately linear rate of 1g/kg lost for every 10°C above 20°C during the seven days of storage. Metaldehyde in Metarex baits degraded at a faster rate of approximately 4g/kg lost for every 10°C above 20°C during the seven days of storage.
- Baits should be stored in cool conditions and consideration given to the forecast weather for the period following bait application.

Novel molluscicides

Between 2015 and 2016, numerous potential molluscicides have been evaluated on snails in the field and laboratory. Tested products have included: Copper oxychloride, Copper oxide (Cu_2O), Copper sulphate ($CuSO_4$), iron sulphate ($FeSO_4$), paraquat, diquat, omethoate, thiodicarb, caffeine, UAN, Perlka®, methomyl, carbendazim and *Bacillus subtilus*. Unfortunately, these products all gave nil or low or highly variable (carbendazim) effects on snail mortality. Usage of the fungicide carbendazim, against snails has increased in recent years, but growers must strictly adhere to registered crop situations to avoid chemical residue violations and market access risks. The above-mentioned products are only to be used in accordance with the label Directions For Use including the crop, rate and all WHPs being followed.

In the hope of discovering a new control tool, any suggestions or observations regarding other novel molluscides are welcome.

Biological control of the conical snail

A parasitoid fly, *Sarcophaga villeneuveana*, was imported from Europe, reared at SARDI and released in SA during 2001-2004 at 21 sites (19 on Yorke Peninsula and two sites on the Limestone

Coast) to control the conical snail , *C. acuta* (Leyson et al. 2003; Hopkins 2005; Coupland & Baker 2007). The fly has established on Yorke Peninsula, but has only dispersed approximately 20km from its original release sites on the southern 'foot', and it displays low parasitism rates (0-25%) (Muirhead, Brodie, Baker and Perry, unpublished). Under a current GRDC investment (CSE00061, CSIRO, SARDI), a geographic strain of the fly that is better matched genetically and climatically to C. acuta in Australia, was imported in early 2020 for host specificity testing which will be followed by a rear-and-release program in snail-affected regions.

Synthesis and directions

Baiting programs can be optimised by achieving adequate pellet densities (30 to 60m^2), monitoring the effectiveness of spreader settings and taking care to minimise bait degradation before snails encounter them by avoiding high temperatures or significant rainfall. The science is providing a sound, evidence base which is reinforcing best practice management (for example; baiting causes higher mortality earlier in the season, and therefore, avoid spring baiting). It is expected that a better predictive ability around the optimal conditions for baiting will be gained on the completion of DAS00160 (March 2020). Baiting is a crucial management tool, but it often does not achieve high order control Therefore, continuing to implement and develop other integrated strategies remains important.

Future risks for the industry include the tightening of delivery standards for snail/grain contamination for export markets and the heavy reliance on a single molluscicide active ingredient (regulatory risks and potential for resistance to evolve). Behind the scenes, researchers, growers and funding bodies around Australia are working together to identify and integrate new technologies that can provide transformational change for snail control in modern farming systems (Perry 2018, Perry et al. 2019). In the foreseeable future, new system's approaches involving biological, sensing and mechanical solutions are likely to be required to meet the challenges posed by snails.

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.

Much of the project work under DAS00134 and DAS00160 was undertaken with the leadership of Dr Michael Nash (formerly SARDI). We thank him for the establishment of these projects.

We also acknowledge the contribution of Michael Richards (formerly NYNRM) who initiated the use of time-lapse cameras to spy on snails and assisted with the establishment our own monitoring sites.

Useful resources

SARDI snail and slug baiting guidelines http://www.pir.sa.gov.au/__data/assets/pdf_file/0004/286735/Snail_and_slug_baiting_guidelines.pdf

https://grdc.com.au/__data/assets/pdf_file/0024/117249/grdc-fs-snailbait-south_lr-pdf.pdf.pdf

https://grdc.com.au/__data/assets/pdf_file/0016/109060/snail-management-fact-sheet.pdf.pdf

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Sustaining our herbicide options into the future

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GRDC project codes: UCS00024, UA00158

Keywords

- pre-emergent herbicide, annual ryegrass, broadleaf weeds.

Take home messages

- Resistance to pre-emergent herbicides is increasing across southern Australia.
- New pre-emergent herbicides are becoming available; however, it is vital that these are used appropriately to get the best results.
- Rotating pre-emergent herbicide modes of action and using other weed management practices will be essential to managing resistance to these new herbicides.

Resistance to pre-emergent herbicides in south-eastern Australia

Pre-emergent herbicides have become more important for the control of grass weeds, particularly annual ryegrass, in the past decade as resistance to post-emergent herbicides has increased. However, resistance to trifluralin is now common across many cropping regions of South Australia (SA) and Victoria (Vic) (Table 1). Worryingly, resistance to the Group J and K pre-emergent herbicides has also been detected in random weed surveys. In some parts of SA, resistance to triallate is also becoming common. This means that it will become more difficult to control annual ryegrass with the current suite of herbicides available.

New pre-emergent herbicides

There are several new pre-emergent herbicides coming to market in the next few years. As with previous recent introductions of pre-emergent herbicides, it is important to understand their best use in different environments and farming systems. Some of these products will be new modes of action, which will provide an opportunity to manage weeds with resistance to existing herbicides. However, it will be important to rotate these new herbicide modes of action to delay resistance.

Table 1. Resistance to pre-emergent herbicides in annual ryegrass populations from random surveys in South Australia and Victoria. Samples were considered resistant to a herbicide if more than 20% of individuals survived the herbicide application.

Herbicide	Trade name	South Australia				Victoria		
		Mid North	Mallee	Eyre Peninsula	South East	Wimmera/ Mallee	North East	Southern
		Samples resistant (%)						
Trifluralin	TriflurX®	62	39	34	41	31	0	2
Triallate	Avadex® Xtra	26	2	2	23	3	2	10
Prosulfocarb + S-metolachlor	Boxer Gold®	2	0	1	5	0	0	0
Prosulfocarb	Arcade®	2	0	1	5	-	1	0
Pyroxasulfone	Sakura®	0	1	0	5	0	0	0
Propyzamide	Edge®	0	0	0	0	0	0	0

Grass herbicides

Luximax

Luximax® from BASF is a new mode of action herbicide (currently Group Z), containing cinmethylin that is available from 2020. Luximax will be a pre-emergent herbicide for annual ryegrass control in wheat, but not durum. It will provide some suppression of brome grass and wild oats. In our trials, control of ryegrass is as good as Sakura®.

Cinmethylin has high water solubility and moderate binding to organic matter in soils. Cinmethylin will move readily into the soil with rainfall events but will be held up in soils with high organic matter. Less rainfall will be required to activate the herbicide similar to Boxer Gold® (prosulfocarb + S-metolachlor). Persistence of Luximax is generally good, but it degrades sufficiently quickly so that plant backs in subsequent years are not likely to be a problem.

Wheat is not inherently tolerant of cinmethylin, so positional selectivity (keeping the herbicide and the crop seed separate) is important. Knife-points and press-wheels are the only safe seeding system and the crop seed needs to be sown 3cm or deeper. Obtaining crop safety with Luximax will be challenging on light soils with low organic matter. Heavy rainfall after application can also see the herbicide move into the crop row and cause crop damage. Due to its behaviour, Luximax is not generally suitable for dry seeding conditions. Mixtures with trifluralin, triallate and prosulfocarb are good and can provide some additional ryegrass control; however, mixtures with Sakura, Boxer Gold or Dual Gold® are likely to cause crop damage and need to be avoided.

Overwatch™

Overwatch, active ingredient bixlozone, from FMC is a Group Q herbicide that will be available for 2021. Overwatch controls annual ryegrass and some broadleaf weeds and will be registered in wheat, barley and canola. Suppression of barley grass, brome grass and wild oats can occur.

Wheat is most tolerant to bixlozone, followed by barley and then canola. The safest use pattern will be incorporated by sowing (IBS) with knife-points and press wheels to maximise positional selectivity, particularly with canola. Some bleaching of the emerging crop occurs often, but in our trials, this has never resulted in yield loss. In situations where the crop grows poorly, for example, water logging, high root disease, etc., the crop may have more difficulty growing away from the initial bleaching effect.

The behaviour of Overwatch in the soil appears to be similar to Sakura. It needs moisture to activate and has low to moderate water solubility. The level of ryegrass control in our trials has been just behind Sakura. Mixtures with other herbicides can increase control levels and in our trials in the high rainfall zones, the mixture of Overwatch plus Sakura has been very good.

Ultro

Ultro, active ingredient carbetamide, from Adama is a Group E herbicide that will be available from 2021. Ultro will be registered for the control of annual ryegrass, barley grass and brome grass in all pulse crops.

Pulses are all tolerant of Ultro, so crop damage should be rare. Ultro provides the best control of annual ryegrass when used pre-emergent. Ultro has relatively high-water solubility, so is more effective on weeds like brome grass that tend to bury themselves in the soil. Persistence of Ultro is shorter than Sakura.

Persistence in the soil is medium; however, extended use of carbetamide in the pasture seed industry in the 1990s led to enhanced soil breakdown. This is unlikely to be a problem in grain production, as pulse crops are not grown every year. However, these soils also developed enhanced breakdown of propyzamide.

Devrinol-C

Devrinol-C, active ingredient napropamide, is a Group K herbicide from UPL registered in 2019. Devrinol-C is registered for annual grass weed control in canola.

Napropamide is not as water soluble as metazachlor (Butisan®) and has less movement through the soil. Canola has much greater tolerance to napropamide compared to metazachlor making its use much safer under adverse conditions. Devrinol-C offers an alternative pre-emergent herbicide to propyzamide or trifluralin for canola.

BAY167

BAY167 is an experimental product from Bayer. It will be a new mode of action, pre-emergent and early post-emergent herbicide for the control of grass and some broadleaf weeds in wheat and barley. Registration is expected in 2023.

The behaviour of this herbicide in the soil will be more similar to Sakura, compared to Boxer Gold. It will require more rainfall to activate and will have similar persistence to Sakura. It will most likely work best as a pre-emergent IBS herbicide. The timing of the early post-emergent application will be similar to Boxer Gold, at the 1 to 2-leaf stage of annual ryegrass. It will require more rainfall after application than Boxer Gold does, so the post-emergent application will be more suited to higher rainfall regions.

Broadleaf herbicides

Callisto®

Callisto, active ingredient, mesotrione is a pre-emergent Group H herbicide from Syngenta with expected registration in 2020. It will be registered as for IBS, knife-point press wheel use in wheat and barley. It will control a range of broadleaf herbicides including brassicas, legumes, capeweed and thistles.

Wheat is more tolerant than barley, **and in both cases**, positional selectivity is important for crop safety. Mesotrione has high water solubility and medium mobility in soils. High rainfall resulting in furrow wall collapse could result in crop damage. Callisto has moderate persistence with plant backs of only nine months, provided 250mm of rainfall has occurred. Callisto offers an alternative to post-emergent Group H herbicide mixtures, where early weed control is important.

Reflex®

Reflex, active ingredient fomesafen, is a Group G herbicide from Syngenta with expected registration in 2021. It will be registered pre-emergent and post-sowing pre-emergent (PSPE) in pulse crops for control of broadleaf weeds; IBS only in lentils. It will have similar weed spectrum to Terrain®, but will likely provide better control of brassicas, sowthistle and prickly lettuce.

Fomesafen has more water solubility than flumioxazin (Terrain), so will be more mobile in the soil. It does not bind tightly to organic matter. Pulse crop safety is good, except for lentils, which are most sensitive. Care will be needed in lentils on light soils with low organic matter. Fomesafen persistence is good; however, plant backs are expected to be nine months provided 250mm rainfall has occurred.

Voraxor

Voraxor, from BASF, contains the active ingredients trifludimoxazin and saflufenacil, which are both Group G herbicides. Voraxor will provide broadleaf weed control and some annual ryegrass control as a pre-emergent herbicide in cereals. It is expected to be registered in 2021.

Voraxor is a little more mobile in the soil compared to Reflex® and considerably more than Terrain. Voraxor will offer a broader spectrum of broadleaf weed control compared to Terrain and more annual ryegrass control. However, annual ryegrass control will not be as good as with current annual ryegrass pre-emergent standards. This means that it will be best used where broadleaf weeds are the main problem and annual ryegrass populations are very low. Grass pre-emergent herbicides cannot be tank mixed with Voraxor and will have to go out as a separate application.

Managing resistance to the new pre-emergent herbicides

The availability of new modes of action, particularly for annual ryegrass control, is a valuable aid to maintaining no-till in grain production. However, overreliance on any herbicide mode of action can lead to resistance. Some of the annual ryegrass populations with widespread resistance to other herbicides already have low level resistance to napropamide and bixlozone. In addition, there are an increasing number of Group H and Group G herbicides becoming available. Care needs to be taken to rotate herbicide modes of action through the cropping rotation to delay the onset of resistance. Other weed management practices such as crop competition, crop topping and harvest weed seed control should be employed where appropriate.

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.

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Spotlight on pulses

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Keywords

- lentil, faba bean, field pea, chickpea, agronomy, weed management, pre-breeding.

Take home messages

- Group B tolerance traits are now commercially available in lentil and faba bean.
- There are several emerging technology and genetic traits being developed, including target site tolerance traits to different modes of action (Group C and Group I).
- Integrated weed management strategies are critical to sustainable farming systems and several alternative methods are being explored including wick wiping and clipping.
- Deep ripping in the right situation can overcome subsoil constraints and result in improved lentil yield in the first year of ripping.
- Pulse-oilseed intercropping has the potential to increase productivity in the low rainfall environment.

Background – the pulse journey in South Australia (SA)

The adoption of pulse crops in SA has increased over the past 20 years, with pulses making up an important part of the farming system in all rainfall zones of SA. The total area planted to pulses has increased from 300 000 ha in the early 2000s to over 400 000 ha by 2019, with a corresponding increase in total pulse grain production (ABARES, 2019). There have also been shifts in the areas planted to specific pulse crop types over this timeframe. Since the mid-2000s the area planted to field pea and lupin has steadily declined (ABARES, 2019). In contrast, we have seen a rapid increase in the areas of lentil planted, which is now the predominant pulse grown in SA. Strong commodity prices for lentil and faba bean have influenced the expansion in area planted to both crops since 2014/2015. While the release of herbicide tolerance cultivars such as PBA Hurricane XT$^{\Phi}$ in 2014, has seen expansion of lentil into new areas. With significant improvements in disease management strategies for faba bean, and the recent release of an herbicide tolerant faba bean, we expect to see planting areas increase. In the meantime, chickpea production area has seen a consistent and steady increase despite the increased challenge of managing ascochyta blight (AB).

Recent reviews into pulse production trends into the future indicate 'the commodity supply and demand scenario for pulse crops to 2030 looks healthy, albeit with some volatility' (Pulse Australia, 2019). This outlook is driven by the expectation of existing and expanding markets through the sub-continent, China and Africa, as well as the evolving demand for plant-based protein in the food sector (Pulse Australia, 2019). One of the big future challenges for the pulse industry is to achieve greater yield stability in pulse crops across a range of environments. Experience has shown that this will come from the combination of genetic and agronomic solutions.

This paper describes and highlights some of the current and future research directions that will enable continued growth of the SA pulse industry. The research highlights the focus on efforts to improve pulse production on constrained soils, novel agronomic opportunities to increase productivity in the low rainfall zones through mixed species cropping, future genetic solutions in the development of herbicide tolerance traits, and alternative strategies for weed control in pulses.

Results and discussion

Agronomy – priority constraints to pulse production

With the rapid expansion and intensification of pulse crop production over the last two decades, there are a range of new constraints to production. In addition, the potential for each specific crop within the different growing regions is not well understood. Emerging research into soil constraints, as well as alternative production strategies such as intercropping, could provide growers with different strategies to maximise pulse potential, particularly in marginal growing areas.

Constrained soils

The aim of this research is to understand the impact of a range of management and agronomic treatments on soil types identified as constrained by local farmers or agronomists, within key pulse growing regions.

One management strategy in focus is the use of mechanical ripping prior to seeding a pulse crop in year one, with the aim of improving root growth and yields of pulses on sandy loam to loam soils. Trial sites were established at Bute (lentil) and Kimba (faba bean, field pea, and lentil) in 2019. Soil sample were taken pre-seeding 2019. The soil type at Bute is sand to sandy loam with pH ($CaCl_2$) of 6.9 in 0-10 cm layer and 5.8 in 10-30 cm. The soil type at Kimba is loam with a pH ($CaCl_2$) of 7.7 in 0-10cm layer and 7.9 in 10-30 cm layer.

Ripping improved the agronomic performance of lentil at Bute, with grain yields 126% higher in the ripped versus un-ripped plots (Figure 1a and 1b). Similarly, biomass was 70% and 116% higher at flowering and maturity respectively in the ripped versus un-ripped plots. In addition, the ripped plots achieved canopy closure while the un-ripped plots did not. The only negative response to ripping at this site was an increase in lodging for both PBA Hallmark⁽ᵖ⁾ and PBA Hurricane⁽ᵖ⁾, as a result of increased biomass production (Figure 1c).

In contrast, there was a negative grain yield and biomass response to the ripping treatment at Kimba for lentil, faba bean and field pea (Figure 2a and 2b). Establishment in lentil was reduced in the ripped treatment, whilst faba bean and field pea were unaffected (Figure 2c). Biomass was reduced in the ripped treatments, as was grain yield. It is important to note; grain yields ranged between 170 kg/ha to

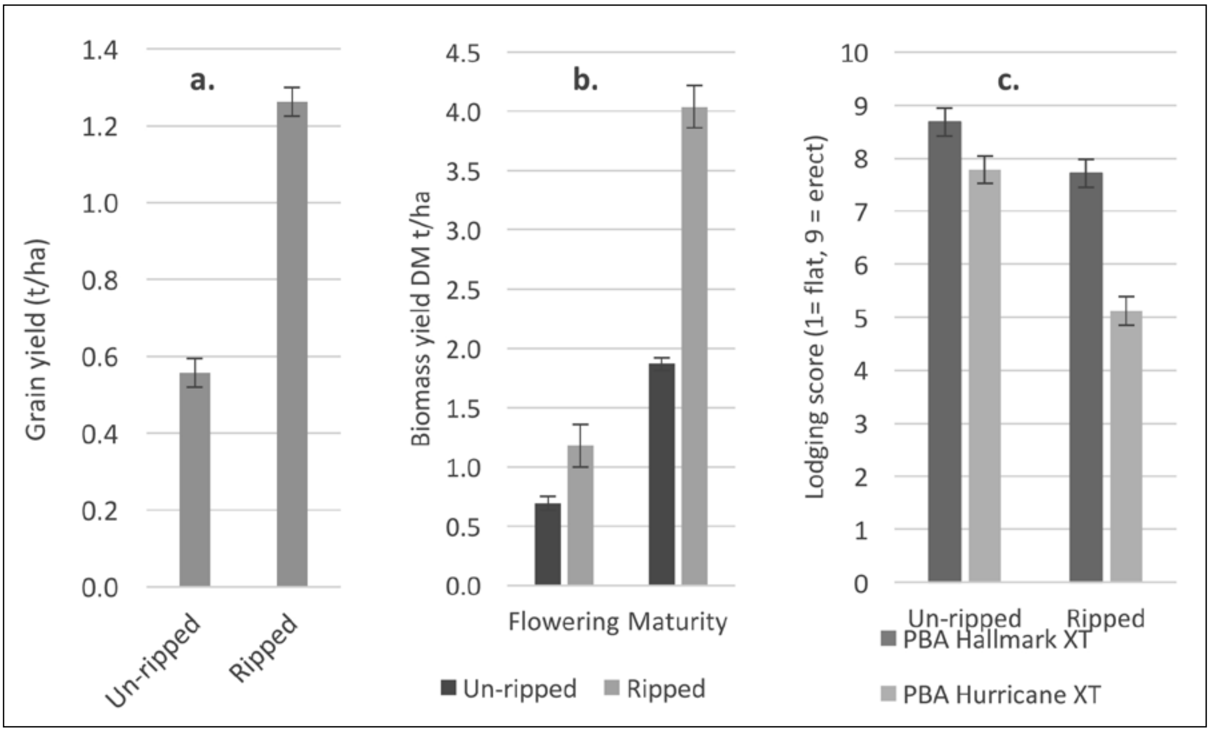

Figure 1. Lentil grain (a.) and biomass (b.) yielded higher in the ripped versus un-ripped treatment, whilst lodging score (c.) was lower at Bute, 2019. Bars represent least significant difference (LSD) at p=0.05.

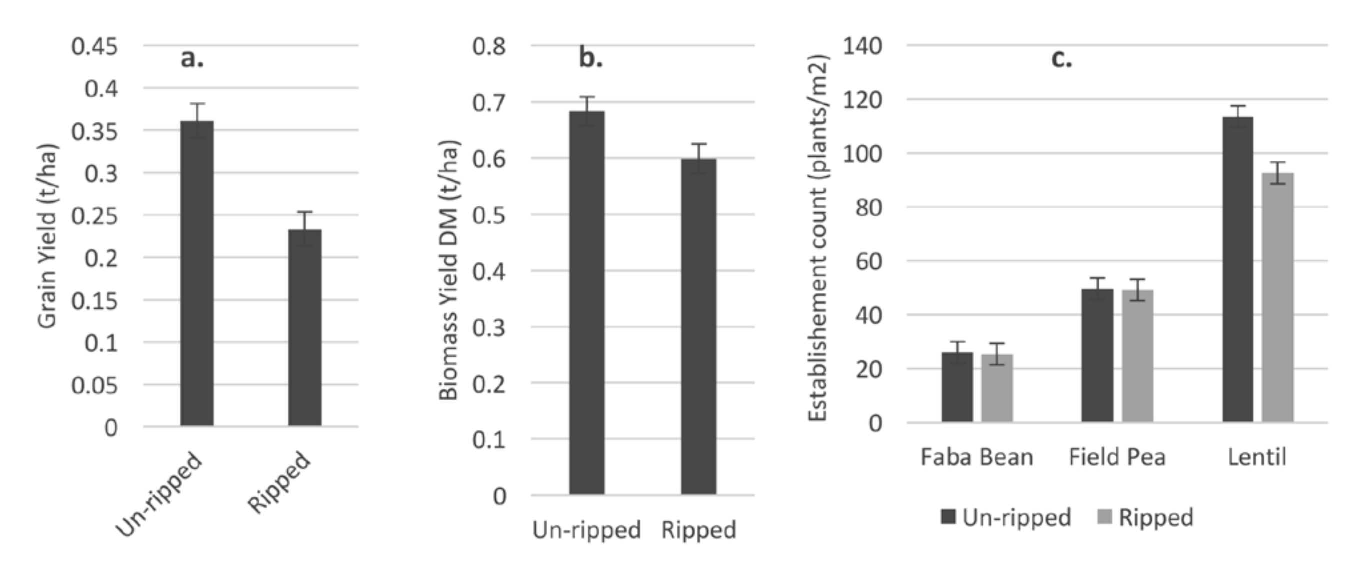

Figure 2. Grain yield (a.) and biomass yield (b.) response to ripping treatment. Lentil emergence counts (c.) were lower in ripped treatment versus un-ripped treatment; faba bean and field pea were unaffected by ripping treatment at Kimba, 2019. Bars represent least significant difference (LSD) at p=0.05.

430 kg/ha due to rainfall less than half of the long-term average. The negative response to ripping at Kimba is likely to be the result of the soil texture being heavier than that of a sand to sandy loam — the response to ripping is expected to be greater in sandy soils and reduces as texture increases (Sadras et al., 2005). Poor seasonal conditions may have also impacted results. Conditions at Kimba were drier than ideal at the time of ripping (January to April rainfall total of 10.4mm), followed by below average growing season rainfall (129mm).

This contrasting first year response between Bute and Kimba highlights the opportunity for improved pulse production on compacted soils, keeping in mind the importance of understanding the individual-site soil characteristics and seasonal outlook prior to imposing any mechanical management techniques to reduce compaction.

Novel agronomy – intercropping in the low rainfall zone

The aim of the research was to demonstrate that intercropping has the potential to increase both productivity and financial return in low rainfall cropping regions. In addition, the adoption of this practice could lead to ancillary benefits, such as increasing groundcover on erosion-prone soils. Sites were established at Warnertown and Wudinna in 2019 based on previous work undertaken at Waikerie in 2016 and 2017 (Roberts et al., 2019), data included. Treatments included the intercrop combination of chickpea-canola, field pea-canola, lentil-canola, vetch-canola and monoculture treatments of each crop type.

To determine the relative benefit of intercropping, compared to growing crops as monocultures, land equivalent ratio (LER) values were calculated. The LER is expressed as:

$$LER = LA + LB = YA/SA + YB/SB$$

LA and LB are the LER for the individual crop yield components, where YA and YB are the individual crop yields in the intercrop combinations, and SA and SB are the yields of the monocultures (adapted from Mead and Willey, 1980). An LER value of 1.0 means the productivity of the intercrop components was equivalent to the monocultures. An LER value of <1.0 means the productivity of the intercrop components are lower than the monocultures, while an LER value >1.0 means the intercrop components are more productive than the monocultures, which is referred to as ‘over-yielding’. Confidence limits (CL) were used to determine over-yielding effects for LER values. We concluded that over-yielding occurred when the 95% lower CL was >1.

The results from Waikerie, Warnertown and Wudinna support the hypothesis that intercropping pulses and oilseeds in the low rainfall zones of SA has the potential to increase productivity (Figure 3). Over-yielding, as measured by LER, occurred in both years at Waikerie for the intercropping combination of vetch-canola. Additionally, lentil-canola intercrops over-yielded at Waikerie and Wudinna. Further crop combinations warrant exploring in low rainfall environments, as do the potential ancillary benefits,

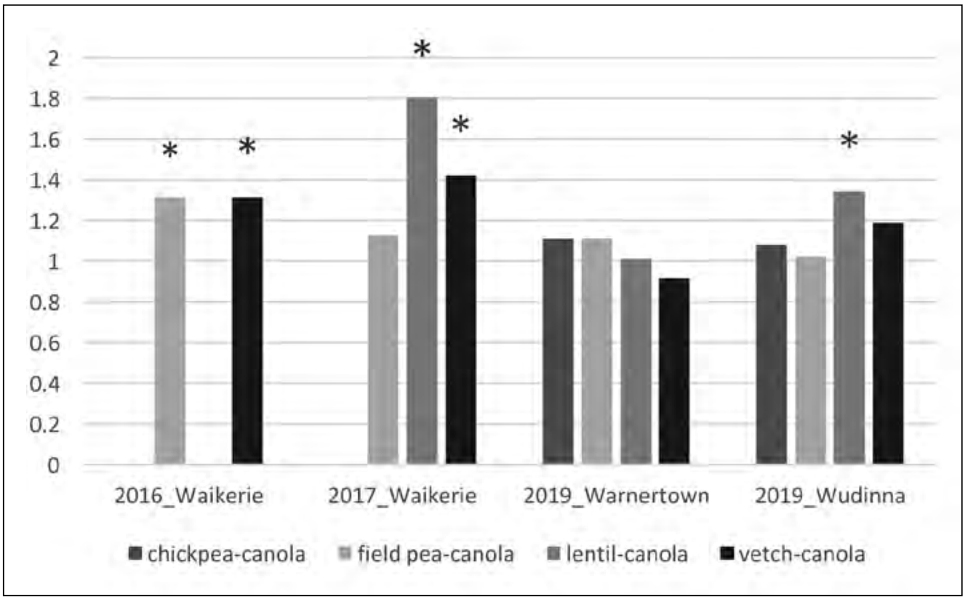

Figure 3. Intercropping demonstrates grain yield benefits for some intercrop combinations with land equivalent ratio (LER) values of greater than one, treatments marked with * were determined over-yielding (95% confidence limit greater >1).

such as increasing groundcover on erosion-prone soils, nitrogen fixation, and fodder production as a secondary end use benefit.

Weed management and novel traits

A major constraint to pulse production is weed management. The recent Group B herbicide tolerance traits in lentil and faba bean have been extremely popular, and the uptake of this technology across crops is creating a shift in herbicide usage patterns across the whole cropping system. Various strategies are being explored to address both current and emerging issues from this continuously changing dynamic, including the development of herbicide tolerance traits across multiple modes of action, and alternative weed management strategies such as wick wiping and clipping.

Emerging technology and potential for new traits

Modern day farming practices have increased the reliance on herbicides for weed control. However, with limited safe or suitable control options currently registered in pulse crops and few, if any, new herbicides being introduced to the market, there is an increasing need to maximize the use of available products.

GRDC-supported research at SARDI has been focusing on developing herbicide tolerance traits across multiple modes of action to provide robust, broad-spectrum weed control as well as to ensure the longevity of these technologies and sustainable weed control options into the future. This work has resulted in the delivery of Group B tolerance traits in faba bean, with work underway in chickpea and field pea.

In addition, high levels of target site tolerance have been developed across multiple herbicide groups including Group C in lentil and Group I in lentil, field pea, faba bean and chickpea (Figure 4 and 5). These herbicide groups, and their usage in mixtures, could provide growers with control options for a range of key problematic weeds in pulse production.

With the successful development of tolerance traits to multiple herbicide groups in each crop, one of the on-going aims of the SARDI research is to evaluate and maximise the potential of these traits, together with their integration into pulse breeding programs. The research will also focus on maximising the benefit of this technology for each crop, including their potential for use in mixtures and the development of dual tolerant lines. Given the novelty of these traits, particularly the group C and I traits — never reported in any other crop, further work including exploring the genetic control and adaptation of these traits is required to commercialise this technology.

GRDC supported research has also been underway to evaluate the current and future implications of changing herbicide usage patterns on weed management. The research aims to evaluate the potential for best management practices with these new and emerging herbicide tolerant technologies. Research findings on the Group C tolerant lentil germplasm line (M043) has

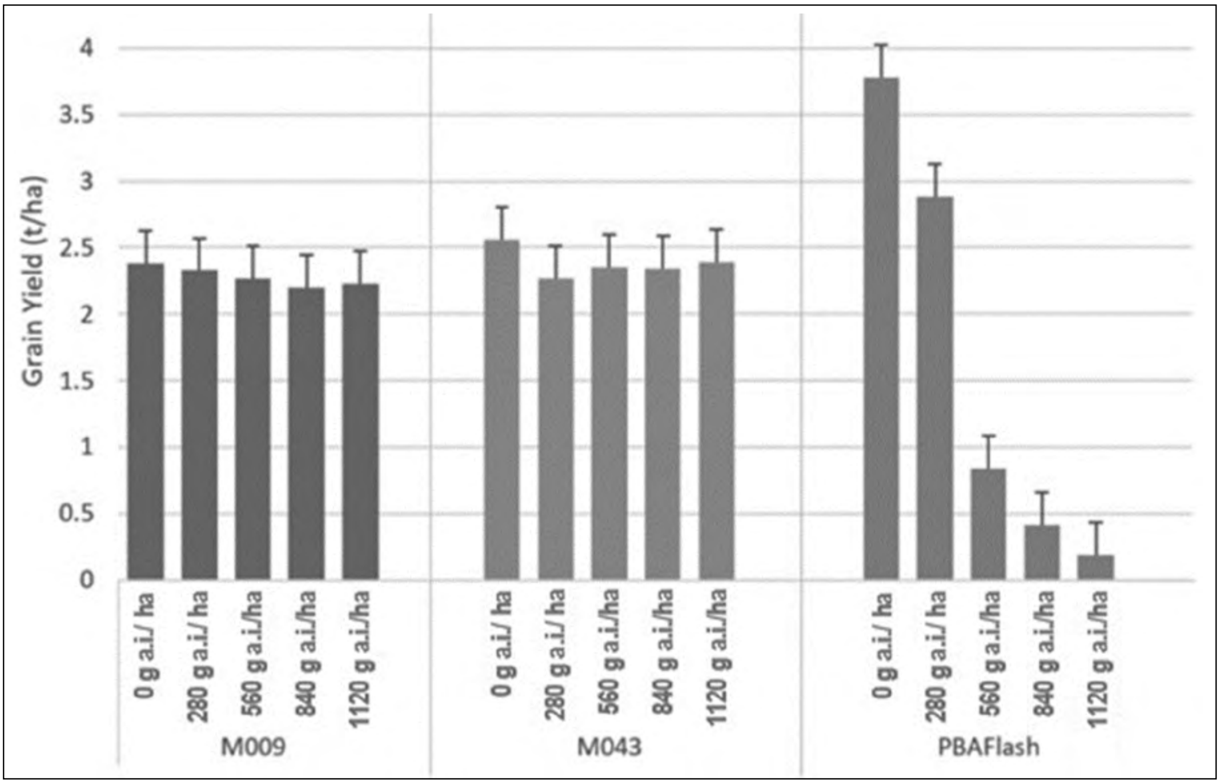

Figure 4. Across site analysis of lentil grain yield from Melton and Pinery 2016 trials comparing two Group C tolerant lines (M009 and M043) with commercial variety PBA Flash⁽ᐩ⁾ at five rates of metribuzin herbicide applied at the five-node growth stage. Error bars represent least significant difference (LSD) at p=0.05. (Data from L McMurray PhD).

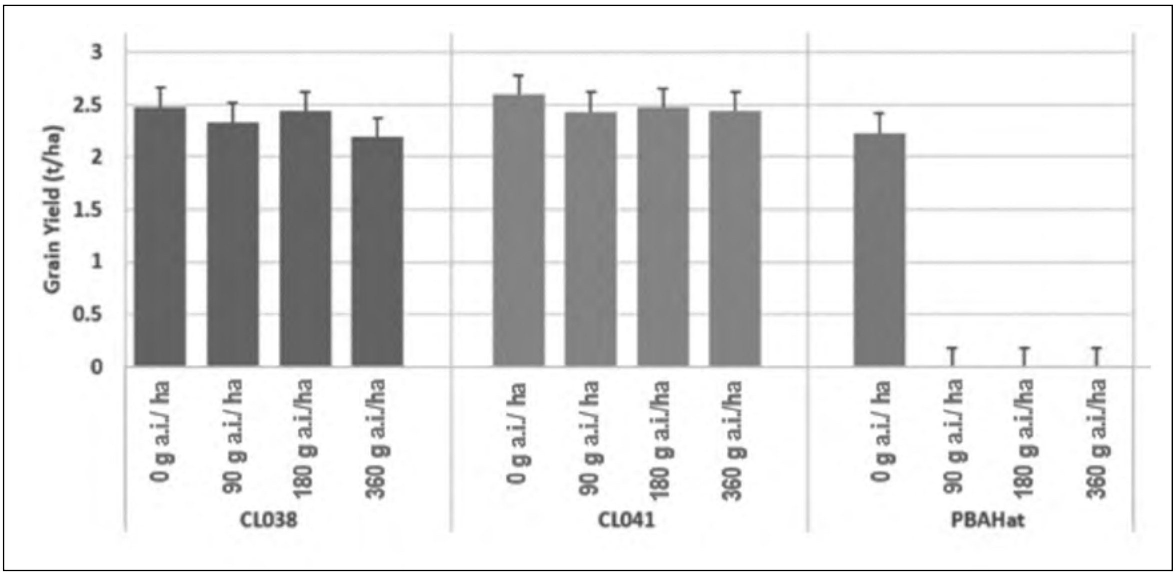

Figure 5. Grain yield response of Group I tolerant chickpea selections CL038 and CL041 compared to PBA HatTrick⁽ᐩ⁾ at four rates of clopyralid applied at the five-node growth stage, Riverton, SA, 2018. Bars represent least significant difference (LSD) at p=0.05.

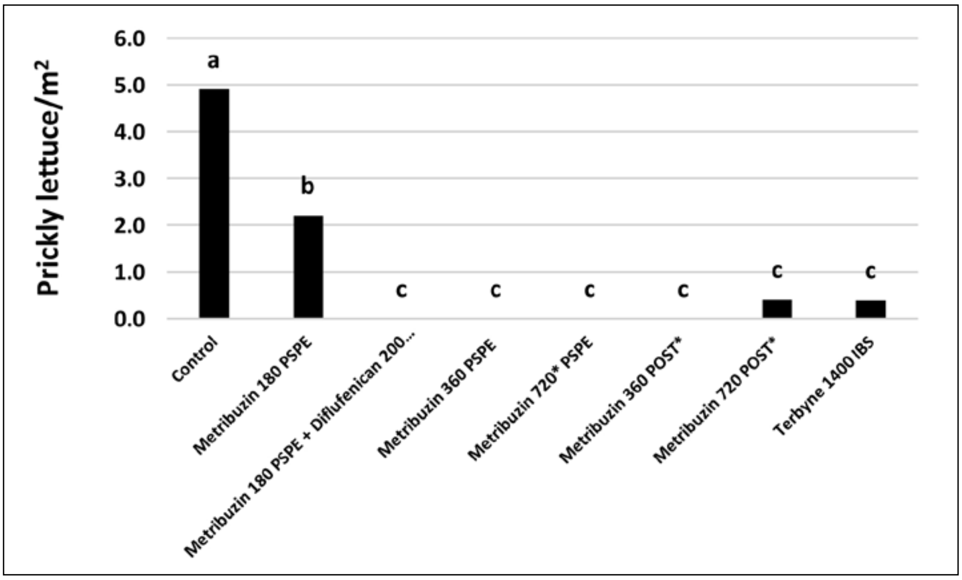

Figure 6. Prickly lettuce populations in Group C lentil germplasm (M043). Bars labelled with the same letter are not significantly different (P≤0.05). *Herbicide usage pattern/dose for experimental purpose only.

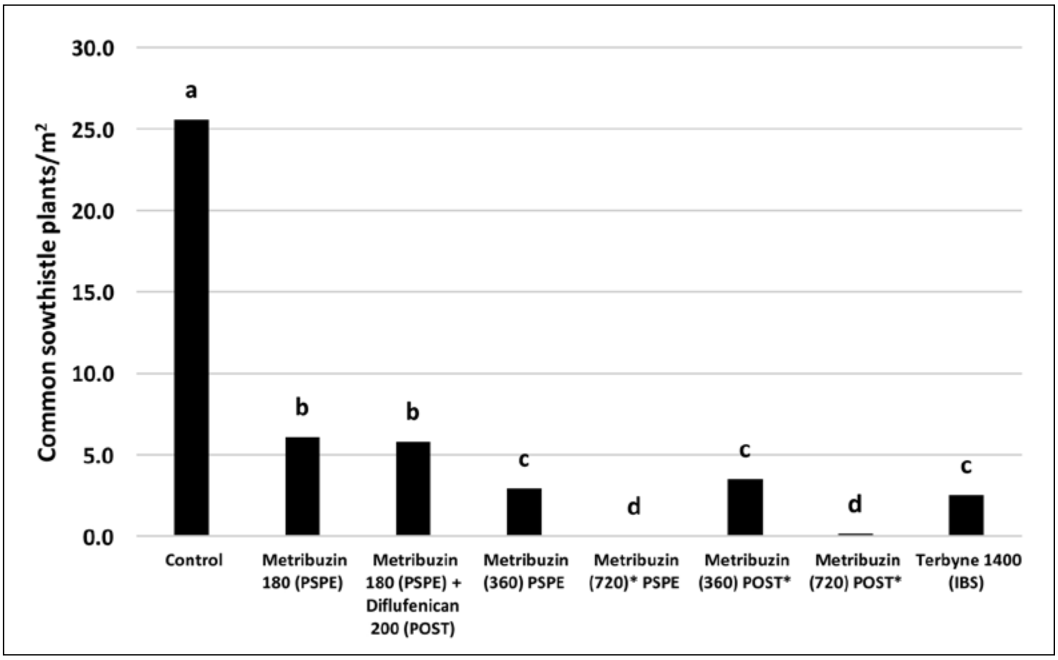

Figure 7. Common sowthistle populations in Group C lentil germplasm (M043). Bars labelled with the same letter are not significantly different (P≤0.05). *Herbicide usage pattern/dose for experimental purpose only.

shown potential to control prickly lettuce (Figure 6) and Group B resistant common sowthistle (Figure 7). Group C herbicides were applied as incorporation by sowing, IBS (Terbyne®750 WG at 1400 g/ha), post-sowing pre-emergence (PSPE) and post-emergence (POST) applications of Metribuzin 750 WG at 360-720 g/ha (at five-node crop stage). Once available, the Group C tolerance traits have the potential to diversify selection pressure from Group B herbicides used in PBA Hurricane XT⁽ᵇ⁾ lentil. This would be achieved by offering alternative herbicide options, particularly for controlling Group B-tolerant broadleaf weeds in pulse crops. A post emergent application of Diflufenican 500 SC at 200 mL/ha caused some bleaching in lentil leaves but the crop recovered two to three weeks post application.

Integrated Weed Management (IWM) – alternative strategies for weed control in pulses

With the increasing frequency of pulse crops in rotation, broadleaf weed control has become challenging due to limited safe herbicide options.

While there is an increasing availability of herbicide tolerance traits in all crop species, alternative strategies are crucial to maintaining sustainable weed control options. Alternative methods have significant importance for pulse crops due to broadleaf weeds, such as wild turnip, common sowthistle and Indian hedge mustard, now reported to have developed resistance against imidazolinone herbicides (Boutsalis et al., 2016, and Aggarwal et al., 2019). The development of new IWM strategies will allow greater in-crop broadleaf control and reduce in-crop weed seed set and build-up of the soil weed seed bank in pulse-based rotations.

The potential benefits from wick wiping and clipping for reducing the seed set of wild turnip in lentil were studied in a research trial established at Turretfield Research Centre in 2019. The trial tested the response of wild turnip to wick wiping with Glyphosate + LVE MCPA + water mixed as 1:1:1 and the application of weed clipping just above the lentil canopy at different growth stages. The wick wiping and clipping treatments were applied at weekly intervals, starting from wild turnip pod initiation stage. A gravity-based wick wiper was used, and clipping was done manually. Observations on wild turnip pod set were recorded just before harvest of the lentil crop.

The timing of clipping treatments was an important factor in reducing pod set of wild turnip, with later clipping treatments (at two and three weeks after wild turnip pod initiation) reducing pod set compared to the earlier treatment (at pod initiation). However, the opposite effect was observed with wick wiping. Earlier wick wiping treatments (up to two weeks after pod initiation) resulted in reduced weed pod set, compared to late wick wiping (three weeks after pod initiation). Both earlier treatments of wick wiping, and later treatments of clipping resulted in lower weed pod set compared to the control. When combining the two treatments of clipping and wick wiping, earlier timing (at pod initiation) reduced weed pod set compared to the later timing (one week after pod initiation). Both combined treatments resulted in reduced weed pod set compared to the control but were not significantly different to the treatments of delayed clipping, or straight wick wiping at pod initiation.

Conclusion

This paper demonstrates the growth of pulse production in SA over the last 20 years, and the opportunity to achieve greater yield stability in pulse crops across a range of environments. Results from pulse agronomy and pre-breeding research demonstrates the continued combination of both genetic and agronomic solutions will allow us to achieve future gains to pulse production in both established and developing production regions.

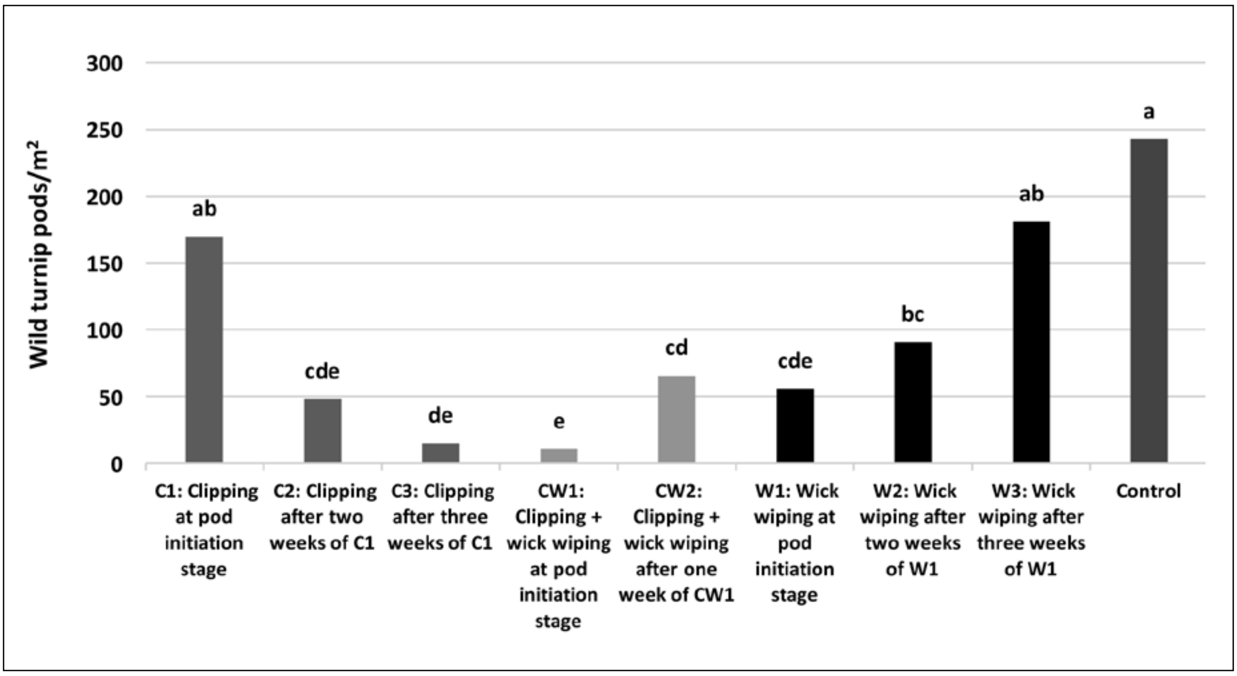

Figure 8. Wild turnip pod set as affected by wick wiping and clipping in lentil. Bars labelled with the same letter are not significantly different (P≤0.05).

Acknowledgements

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Useful resources

https://grdc.com.au/resources-and-publications/all-publications/publications/2019/south-australian-crop-sowing-guide

https://www.nvtonline.com.au/

https://grdc.com.au/__data/assets/pdf_file/0028/91756/grdc_fs_deepripping_lr.pdf.pdf

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Quantification of frost damage in grains using remote sensing

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GRDC project code: CSP00198

Keywords

- frost, wheat, remote sensing, multispectral, hyperspectral, thermal, fluorescence.

Take home messages

- Frost damage can be detected through sensing but cultivar, plant component, canopy structure and time after frost affects the spectra. Consequently, there are some approaches that look promising but there is currently no unique index that can consistently detect frost damage.
- Temperature variation within canopies due to canopy architecture, plant components and cultivar type causes spectra of frost damage to vary, making quantifying frost damage challenging.
- It appears likely that frost damage can be detected before the onset of visual symptoms, but it is unclear whether this is a relative measure or whether frost severity can be quantified.
- Quantifying frost damage requires comparison to a reference or control area of a paddock where little to no frost damage has occurred.
- Mapping frost damage for the purposes of cutting hay may be feasible but these techniques require field validation.

Background

Recent statistics for frost related damage in Australia estimated agricultural losses at $360 million each year (Rebbeck et al. 2007; March et al. 2015). Frosts that occur in wheat during or after ear-emergence can often result in severe stem and head damage, which can reduce grain yields and quality by up to 80%, depending on location, altitude, soil type and the severity of the frost. Wheat is particularly vulnerable to frost in the period between heading and grain-fill. Other than visually assessing a crop five to ten days after a frost event, there are no tools available to determine if frost damage has occurred or to map its extent across paddocks. Farmers would benefit greatly if they could obtain near real time information about the spatial extent of frost damage in paddocks that are likely to have yield losses. This knowledge would then enable decisions on when and how much of the crop to cut for hay. Maps of frost damaged areas of the paddock would also help farmers at harvest time as frosted areas of the paddock could be selectively harvested or left unharvested if necessary.

As part of the GRDC National Frost Initiative, a Rapid Frost Damage Assessment program was developed to investigate the application of a range of different sensors for the rapid detection of frost damage in wheat. Optical and thermal sensing systems are now being widely developed to measure crop response to abiotic and biotic stresses. These systems, coupled with recent advances in satellite and unmanned aerial vehicle (UAV)/drone technology, means that new opportunities exist for developing techniques to quickly map frost-damage in crops. Remote sensing tools for the rapid spatial quantification of frost damage could help Australian growers (and their advisers) to spatially, understand the impact of frost on yield. Before this research, it was not known whether frost damage in crops could be detected using sensors and/or whether it could be mapped.

The major questions asked in this research were:

- Can frost damage be detected and, if so, can impacts to yield be quantified?
- How soon after a frost event can frost damage be detected?
- What is the potential to map frost damage to provide information for cutting hay?

Methods

Frost exclusion – passive and active methods

Before being able to determine whether frost damage can be quantified either with temperature or a spectral response, it was necessary to develop methods to exclude frost so that an experimental control could be established. Without a control there is no definitive way to determine whether crop damage is due to frost or something else and there is no way to compare data from damaged and non-damaged plants. The two methods developed were: 1) exclusion chambers and 2) active heating.

Several exclusion chamber designs were tested with the final version (1m^2 frame made of 40mm PVC pipe with a double skin consisting of 10 layers of 23µm plastic wrap) shown in Figure 1. By erecting the shelter on a clear afternoon about 90 to 120min before sunset, the chamber was able to maintain internal temperatures above 0°C when ambient canopy temperature dropped to -4.0 to -4.5°C during the night. The multiple layers of plastic wrap provided air spaces that insulated the space in the chamber. It was noted that after five to seven days of plants being protected by the chamber there was a chamber-induced effect on plant growth, even when the chambers were removed during the day. Consequently, the use of passive chambers is limited.

Figure 1. Frost exclusion chamber (photo by Mick Faulkner).

The second method used to exclude frost was through active heating at night during frost events to maintain temperatures just above freezing using a generator and a diesel caravan air heater with air piped through a PVC manifold (Figure 2). The automated system that was developed could be deployed at multiple locations within a research or paddock setting to provide a control area so that frosted areas could be compared with control

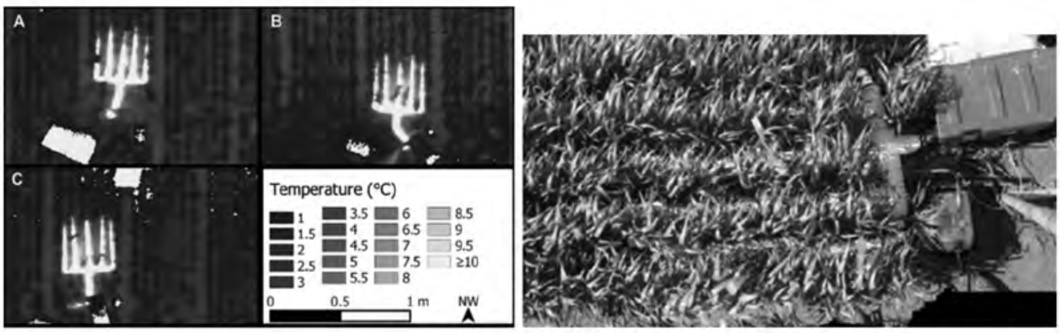

Figure 2. (left) Thermal image of the plot heater effect acquired from a UAV and (right) Close-up picture of diesel plot heater (Stutsel et al., 2019b).

areas and damage accurately assessed. This also alleviated the tedious task of placing chambers at night before an expected frost event.

Frost-imposition chambers were also developed to allow control of the timing and severity of frost for research and this is described in the companion paper in these proceedings (Nuttall et al., 2020).

Quantifying Frost Exposure

Measuring canopy temperatures

Low temperatures from a standard weather station are typically used to assess when a frost event might occur. It has been noted however, that temperatures within a canopy can be colder than those recorded at the 1.2m standard height of a weather station. Temperatures in this study were recorded at canopy height (upper most flag leaf) and these were used to calculate cold sums (Nuttall et al., 2020) to develop relationships to yield. Tiny tags were placed in the different experiments to record temperature at canopy/head height.

Spatial distribution of temperature

A fibre optic Distributed Temperature Sensing (DTS) was used to measure temperatures at the field scale, rather than the traditional point scale to determine the vertical and horizontal temperature distribution in the canopy (Stutsel et al., 2019a; Figure 3). The aim of using this technology was to identify where and when minimum temperatures developed within the crop.

Non-destructive frost detection – temperature

To understand canopy temperature dynamics, sensors were deployed in the field as infrared thermometers (Figure 4) looking at the crop canopy across the experimental plots. This provided information that could be used to validate aerial temperature data and basic crop physiological measurement of damage to transpiration due to frost.

Non-destructive frost detection – spectral reflectance

Multispectral images were acquired from UAVs and proximal hyperspectral sensor measurements (350 - 2500nm, FieldSpec FR, Analytical Spectral Devices, Boulder, CO, USA) were also collected at ground level to assess spectral response to frost. Spectral data included sensor and imagery from the control chambers (removed from the crop) and frost-affected areas of plots or transects within paddock, depending on location, year and experiment. In addition, spectral data were collected in a laboratory experiment using an imaging spectrometer on frosted (Fr) and non-frosted (NFr) wheat heads and leaves (Murphy et al., submitted) and regions of significant differences were determined between 392-889nm.

Handheld spectral measurements were collected using a Polypen™ (Photon Systems Instruments, Drasov Czech Republic, 324-792nm) on leaves, heads and grains to determine its utility for use in frost detection. This is a relatively new tool that could be used by farmers or agronomists for assessment of abiotic stress damage to plant components.

Spectral mixture analysis

One of the main difficulties of using spectral information for detection of frost (and other stresses) is that the spectral signal is 'mixed' with other spectra from the canopy; such as heads, green leaves, senescent leaves, soil background and even shade. Thus a 'spectral mixture analysis' was used to 'unmix' the spectra using spectral libraries composed of other canopy spectra (Fitzgerald et al.,

Figure 3. Distributed Temperature Sensing (DTS) fence. (left) Fence support pole. (right) DTS fence at the trial site (cables).

Figure 4. Infrared thermometers (Arducrop) that were used to measure canopy temperatures.

2019). The technique compares the mixed spectra to the library and estimates the fraction of the target signal (frost, in this case) in the mixed signal. When the frost fraction is compared to yield, a relationship can be developed to estimate severity of frost to yield loss.

Fluorometer

An active fluorometer (Multiplex 3.6, Force A, Orsay Cedex, France) (Figure 5) was used on wheat canopies and individual plant components (heads and leaves) to assess subtle difference in fluorescence emissions that could be related to frost exposure.

Figure 5. Multiplex fluorometer collecting measurements in wheat.

Results and discussion

Determining whether frost can be detected with sensors

Temperature and thermal imagery

Research in this program demonstrated the first application of DTS within an active trial environment, providing a new method to measure and understand temperature dynamics across trial sites. Results showed that even in mild frost events vertical temperature gradients of 0.24°C per 100mm height develop within wheat crops, with the coldest temperatures developing ~100 to 200 mm below the top of the ear. We also showed that there was a varietal influence on cold temperature development that was most likely driven by differences in height, canopy density and closure. Finally, there was greater variation in temperature within a sowing block than between blocks and that trial design and subsequent variety randomisation may impact the development of cold temperature more than topographic or soil differences. This information should lead to more confidence in results from frost trials and reduce instances of falsely identifying plants as being more frost-resistant when they may merely experience less severe cold.

Lightweight thermal cameras on UAVs are not stabilised to a constant temperature, resulting in poor accuracy. Weather data is also needed to normalise and compare across flights, likely making it an impractical method for commercial growers to detect frost in the near future. Infrared sensors (Fig. 5) provide good ground-level data to calibrate aerial imagery in a research context but they may not be practical to deploy in a paddock as many would be required to cover a paddock or farm.

Spectral measurements

Abiotic stresses, such as frost, can be detected with sensors and imagers but using spectral information to detect frost damage in crops had not been an active area of research before this research program. Once a frost event occurs, there are physiological changes to plants, including damage to photosynthetic processes and physical damage to tissues which can potentially manifest as changes in plant colour detected using spectral sensors.

To identify spectral regions that could indicate frost damage in wheat, spectra were collected from positively-identified Fr and Nfr wheat canopies in two seasons; 2006 and 2015. To clarify the differences, a normalisation of the data was performed, which helped identify eight spectral absorption regions (noted as 'dips' in the spectra, Figure 6a, shaded areas (1-8)). Taking the difference between the normalised NFr and Fr spectra from each data set (Figure 6b) determined where there were similarities and differences between the two years within each of the absorption regions identified in Figure 6a. Maximum differences are noted as higher values along the horizontal x-axis; and areas where there are peaks denote where the relationship changes. Maximum values, peaks and where there are similarities between the two years, show potential spectral regions for detecting frost damage (shaded areas, Figure 6b).

In a laboratory experiment where wheat heads and leaves were imaged using a hyperspectral imager (Murphy et al., submitted) it was shown that spectral responses differed between frost damaged heads and leaves, but there were spectral regions in common. From both laboratory and field studies, the regions in common for detection of frost damage across canopy, leaves and heads were 419-494nm and 670-675nm. Areas outside the range of the laboratory analysis include those identified in Figure 6b (shaded region). Those areas where data from multiple years overlap show potential to detect frost across a range of conditions. Wide regions showing similarity between the sites may indicate relatively stable regions in the infrared (for example

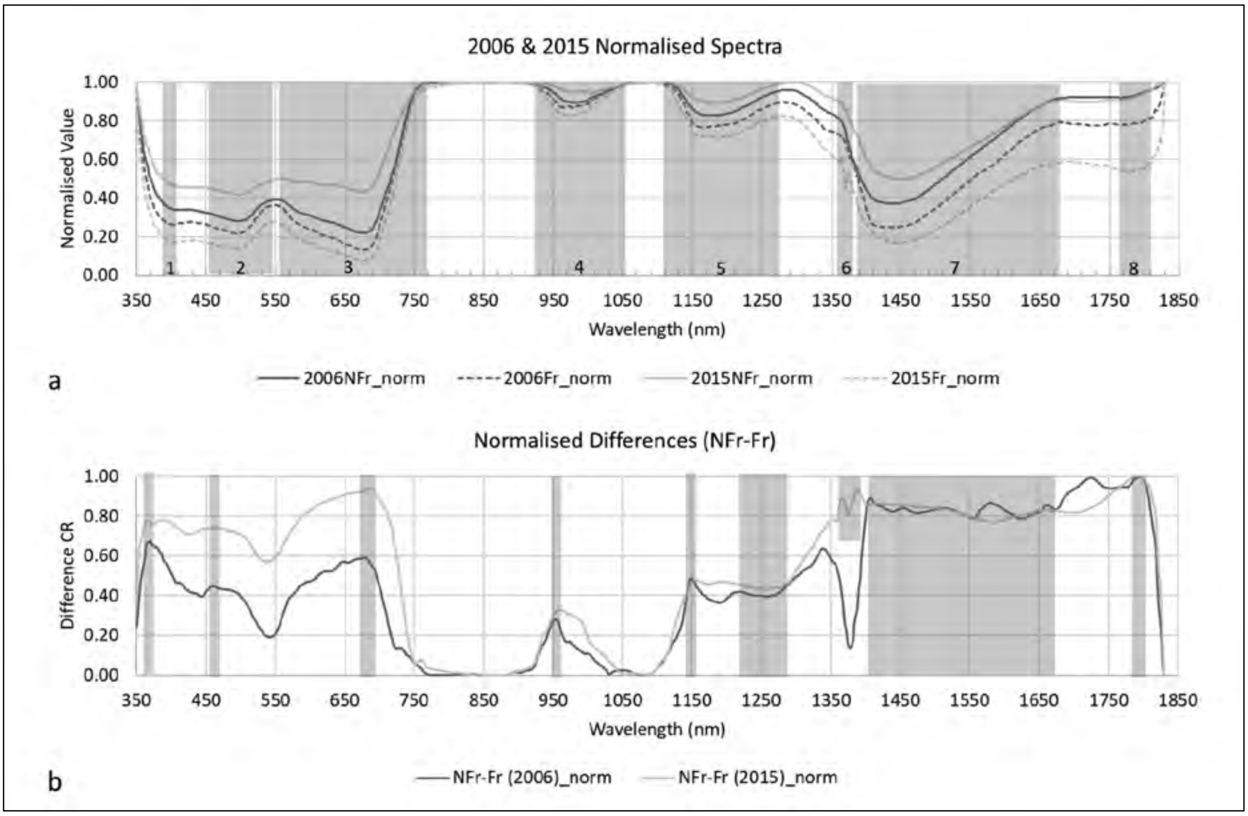

Figure 6. Spectra of wheat canopy in visible to near infrared portion of the spectrum. Two years and locations (2006, Horsham; 2015, Kewell, Victoria). (a) Spectra normalised and identification of spectral absorption regions (1-8, shaded) with differences between Fr and NFr. (b) Difference of normalised spectra (NFr - Fr) showing regions (shaded area) with potential to identify frost damage in wheat.

approximately 1220-1270nm and approximately 1400-1670nm) while reflectance values near 1800nm (Figure 6b) showed the highest difference between Fr and NFr across both years. The visible portion of the spectrum (400-700nm), although indicating similar spectral shapes between the two years, show distinct differences between the plotted lines (Figure 6b). Because photosynthesis is affected by frost (noted by the differences in Figure 6b near 450 and 670nm, where chlorophyll absorbs energy) and this changes due to many factors, it is possible that the near infrared is a more stable region of the spectrum and is more suited for frost damage detection across environmental conditions and varieties.

Spectral measurements of wheat heads

Hyperspectral measurements were taken on wheat heads subjected to frost under controlled conditions using a handheld Polypen™ (Figure 7). Results showed that there were spectral changes in

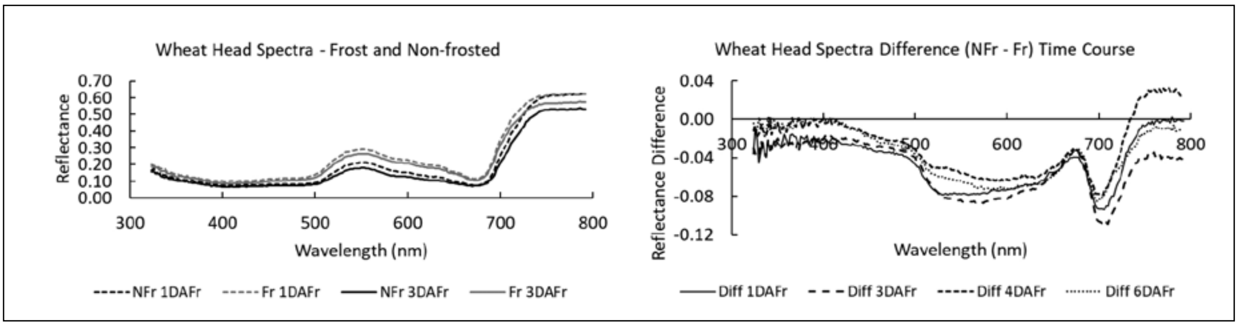

Figure 7. Spectra of wheat heads, cv Wyalkatchem^{⁽ᴰ} collected with a Polypen™. (a) One and three days after frost (DAFr) for non-frost (NFr) and frost-damaged (Fr) heads. (b) Difference between NFr and Fr heads one, three, four and six DAFr. This shows that spectra change depending on time after the frost event.

frost-affected heads even one day after a frost event (Figure 7a) but the difference in spectra (NFr - Fr) at one, three, four and six days (Figure 7b) after frost showed that the spectra changed depending when measurements were made. Although this indicates potential for a handheld device to measure frost damage in wheat heads before visual symptoms appear, this assessment may be limited to a qualitative assessment of frost damage because of spectral changes over time. The spectral differences appear to be due to changes in plant physiology after a frost.

Quantifying frost damage

As noted previously, it may be challenging to quantify the effects of frost on yield due to spectral changes after a frost, differences between varieties and varying temperature impacts to the canopy. However, if a method could be developed to measure the severity of frost damage and its impact on yield then spectral information could be used to quantitatively map frost after a frost event, allowing farmers to make decisions to cut for hay based on yield loss information. One approach that could be useful is the use of the information in the spectra to quantify yield impacts.

One full-spectrum analysis method is ‘spectral mixture analysis’. This method was used to estimate yield measured from the sampled areas (Figure 8). By comparing the measured spectrum of points where yield was collected to a library of spectral components (Figures 8a, b), the measured spectrum can be ‘unmixed’, resulting in a measure of the proportion of frost damage represented by a fraction of frost damage (Fr fraction). Here, yield was plotted against the Fr fraction (measure of frost severity) for three data sets (Figure 8c) collected at or near anthesis. Results showed that there is a frost spectral signature that can estimate yield (R^2 values from 0.58 to 0.75) within an acceptable degree of accuracy (Root mean square error (RMSE) ranged from 0.11 to 0.46t/ha) but the relationships for each data set were different. As noted previously, this could be due to differences between time after frost, cultivar or other factors. Thus, there is still more research needed to understand and measure the factors that cause frost damage and to robustly estimate yield loss.

Discussion of a multispectral approach is presented in the companion paper in these proceedings, (Nuttall et al., 2020).

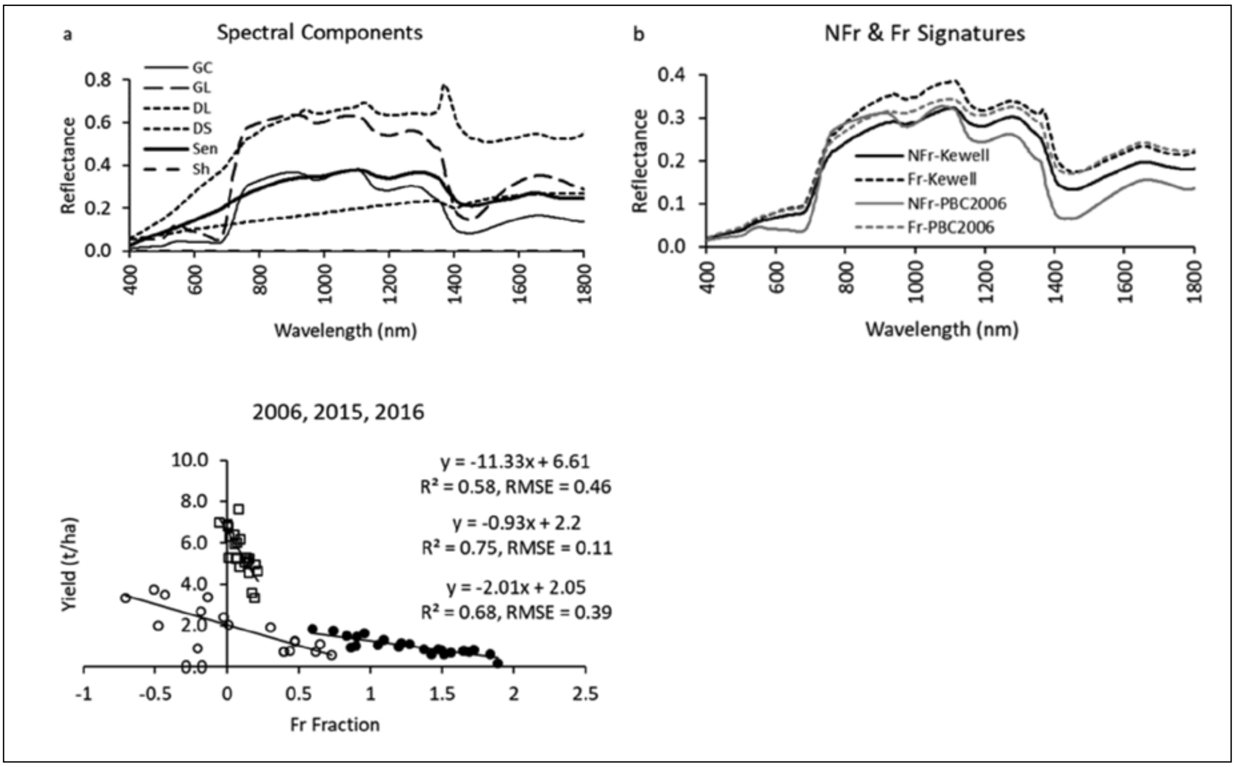

Figure 8. (a) Spectral signatures for canopy components, and (b) frost (Fr) and non-frost (NFr) canopies. (c) Frost (Fr) fraction values vs yield for three data sets using a spectral mixture analysis approach to determining frost severity and impacts to yield.

Fluorescence

Good correlations were found between some of the fluorescence indices tested and yield (Figure 9; Perry et al. 2017) or cold sums (Nuttall et al. 2018) across different experiments. The fluorescence values tracked yield across a transect in one experiment (Figure 9) and had high correlation to cold sums (r = -0.83) in another when measured on both flag leaves and heads. Advantages of this technology is that with its active light source, it can make measurements independently of sky conditions. However, the instrument is only effective when in direct contact with the plant component (leaves, heads), limiting its use to handheld measurements. Future applications may be use of fluorescence as a frost damage validation tool for crop heads or leaves.

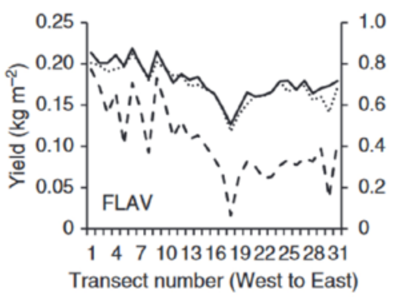

Figure 9. Corresponding grain yield and fluorometer measurements from a paddock near Kewell, Victoria in 2015 following the first observation of frost. The measurements were made along a transect of 31 rows on two dates, 9 October 2015 and 13 October 2015 (growth stages; Z61–69, Z71–75). Correlation coefficients were 0.91 and 0.90 for the two dates (Source: Figure revised from Perry et al. 2017).

Conclusions

Frost damage can be detected through sensing but cultivar, plant component, canopy structure and time after frost affect the spectral indices so that there are some approaches that look promising but currently no unique index that can consistently detect frost damage.

It appears likely that frost can be detected before onset of visual symptoms but whether this is a qualitative or quantitative assessment is still unclear.

Fluorescence seems a promising technology for frost detection but it requires direct contact with the canopy.

The most stable parts of the spectrum for a frost damage signal may be in spectral regions that cannot be currently detected by most commercially available sensors.

Non-frost damaged controls are required for research experiments.

Temperatures with frost research experiments may be more variable within experimental units than between, suggesting careful design of frost experiments is needed.

Currently there are too many technical challenges for accurate measures of crop temperature, and therefore, measuring frost damage with thermal imaging from UAVs is currently not feasible.

Mapping frost damage for the purpose of cutting hay may be feasible but these techniques still require field validation.

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Rapid detection of frost damage in wheat using remote sensing

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GRDC project code: DAV00143

Keywords

- low temperature, proximal sensors, multispectral reflectance, climate change.

Take home messages

- Applying a single frost to wheat at flowering reduced yield by 7% for every degree below zero (up to -4°C), however, this increased to a reduction by 12% for every degree below zero when applied over two consecutive nights (up to -3°C).
- Remote sensing spectral indices including normalised difference vegetation index (NDVI), normalised difference red edge (NDRE) and photochemical response index (PRI) showed significant relationships with cold load applied to wheat, however, to date no universal index for frost damage using remote sensing has been identified.
- Similar utility of these three spectral indices were observed for a survey of six commercial wheat paddocks in 2018 near Murtoa, Victoria, suggesting an opportunity for spatial management of crops when considering hay versus grain production.

Background

Frost can significantly reduce production of field crops grown in Mediterranean-type environments, where economic losses for Australian wheat is estimated at up to $360 million per year in Australia (Rebbeck et al. 2007; Watt 2013; March et al. 2015). Frost risk is predominantly managed through avoidance measures, by manipulating flowering time to avoid periods of high frost risk. However, such tactics must be assessed against the potential for heat stress and drought associated with later flowering dates. If non-destructive proximal or remote sensing technologies could make rapid, spatial assessment of frost damage (Perry et al. 2017) this could limit economic losses through timely management decisions such as zoning for crops to be cut for hay, prioritising further crop inputs, altered grain marketing strategies and improved planning of harvest logistics. While the companion paper in these proceedings (Fitzgerald et al., 2020) presents methods for frost exclusion and fundamental spectral response to frost, this paper reports on: i) the response of wheat to imposed artificial frost treatments using purpose built mobile chambers, ii) the identification of remote sensing indices linked with frost affected wheat, and iii) the utility of these proposed indices for spatial mapping of frost damage in wheat at paddock scale. Overall, the objective of this work was to investigate the ability to utilise remote sensing technologies to manage in-season frost damage in wheat.

Method

i) Wheat response to frost

Mobile frost chambers were used to examine the impact of simulated frost applied at night on wheat yield, a detailed methodology is outlined in Nuttall et al. 2018. Briefly, temperatures below 0°C were applied to wheat at head emergence and flowering in a field experiment at Horsham, Victoria during 2016. Dry ice was applied to cool the chamber in a similar pattern to a natural frost with temperature monitored at canopy level in each chamber. For the treatments at flowering, minimum temperature ranged from 1 to -3°C with frost applied either as a single night or on two consecutive nights. For the head emergence treatments, these were more severe, with temperatures down to 9°C and were applied as either single, double or triple night series. Severity of frost was calculated based on a combination of both the temperature below 0°C and the time spent below 0°C, also known as 'cold load' and measured in 'degree hours below zero'.

ii) Identifying remote sensing indices for frost damage

A range of electronic sensors were tested for their ability to identify frost affected wheat by capturing images of the crop on the day after and eight to ten days after frost application. The sensors work by measuring the light reflected off the crop canopy including; visible light (wavelengths from 400 to 700nm) as well as ultra-violet and infra-red wavelengths that are not visible to the human eye. Images were captured at various heights above the canopy and in some cases focussed on different parts of the canopy (heads, leaves, etc.). The imagery was then used to calculate a range of 'indices' which compare the light reflected at different wavelengths to give an indication of various physical and chemical characteristics of the crop. Examples include the NDVI, as well as others such as the canopy chlorophyll concentration index (CCCI), cellulose absorption index (CAI), chlorophyll index red-edge (CI), enhanced vegetation index (EVI), modified chlorophyll absorption reflectance index (MCARI), NDRE, PRI, plant senescence reflectance index (PSRI), structure insensitive pigment index (SIPI), triangular greenness index and water index (WI). The aim was to test a wide range of indices and their correlation with canopy cold load and frost damage in wheat.

iii) Paddock application of remote sensing to detect frost damage in wheat

Commercial wheat paddocks situated in a frost prone region near Murtoa, Victoria (36.620°S, 142.471°E, 139m above sea level) were monitored for frost damage in 2018. Six survey points were established in each paddock at 150m intervals along a linear transect running through the centre of the paddock, picking up the maximum variation in intra-paddock relief and likely frost severity. For monitoring crop canopy temperature, thermistors were installed at canopy (crop head) height throughout the season with sensor height adjusted as the canopy grew taller. At each site, a Stevenson screen containing a temperature logger was also installed 1.2m above the ground level, consistent with the protocol used by the Australian Bureau of Meteorology for measuring air temperature.

A six-band multispectral camera (Airphen®, Hiphen, Avignon, France) capturing light at 450, 530, 675, 730 and 850nm wavelengths, was flown over the six survey paddocks on 1 Oct 2018 using a manned, fixed wing aircraft. The imagery was acquired at approximately 9000 feet above ground level (AGL) in order to capture each paddock entirely within a single image, resulting in a spatial resolution of approximately 1m. The light reflectance spectrum (six bands) for each of the survey points were extracted from the spatial paddock images. These reflectance values were then used to compute the

Figure 1. Frost chambers a) Performance testing using visual infrared thermometer, Fluke VT02 (temperature at 32.7°F (0°C)) and b) Simulated frost being applied to wheat to determine impact on yield and ultimately the link between frost induced sterility and proximal sensor response.

subset of vegetation indices; NDRE, NDVI and PRI. At each survey point, biomass cuts (25m^2 per point) were taken at harvest for yield and quality analysis. Collectively, vegetation indices were compared with measured crop canopy load and yield across the six intra-paddock survey points for the six paddocks.

Results and discussion

i) Wheat response to frost

Simulated frost treatments

The frost chambers effectively reduced canopy temperature of wheat to below zero degrees. The simulated frosts were characterised by a rate of cooling of 2°C per hour with a duration below zero degrees of around eight hours applied during the night. For flowering frost treatments, average minimum temperatures ranged from -2.2 to -3.4°C (when applied as a single frost at each growth stage) resulting in a cold sum of 8.6 to 11.8°C.hr (< 0°C). For the treatments where frost was applied over two consecutive nights, average minimum treatment temperatures ranged from -1.4 to -2.6°C the first night and from -1.0 to -1.6°C the second night. The corresponding range in cold sum, totals over the two nights was 5.0 to 12.9°C.hr (< 0°C). For the head emergence treatments, cold loads applied over three nights were up to 161°C.hr (< 0°C) and were severe enough to cause 100% yield loss.

Cold load and crop response

For wheat grown under open ambient temperature, in the absence of naturally occurring frost (or heat wave) events during the growing season, grain-set and yield was 15890 grains per m^2 and 6.8t/ha respectively (Figure 2). Applying frost over a single night resulted in an 8.8 and 7.2% reduction in grain number and yield respectively, per degree Celsius below zero up to -4°C (Figure 2a). For those frost treatments applied over two nights, the reduction in grain number and yield increased to 15.7 and 11.8% respectively, per degree Celsius below zero up to -3°C, indicating a cumulative effect of multiple frosts. To account for both frost duration and severity, cold load was compared with yield. The response of wheat was a 2.2% reduction in grain number per °C.hr (below 0°C), which translated to a yield reduction of 1.9% per °C.hr (Figure 2b).

ii) Identifying remote sensing indices for frost damage

For the 11 indices derived from reflectance of wheat (flag leaf, head and canopy), PRI, NDVI and NDRE demonstrated significant linear relationships with frost intensity for treatments (head emergence) that were in excess of 20°C.hr <0°C (or minimum temperatures of -6.6 to -9.6°C), although the relationship was poor following frosts treatments at flowering with intensities less than 20°C.hr (Nuttall et al. 2018). This was possibly related to the limited range in cold load for the flowering treatments and any subtle impacts to crops not being detectable. Importantly, PRI showed greatest utility in its consistent relationship across both the head emergence and flowering frost treatments (Figure 3). For NDVI, although a high correlation existed for frost applied at head emergence, the anthesis response fell below the regression line compared with the earlier heading measurements, highlighting the confounding effect of senescence associated with advancing crop growth stage, on NDVI.

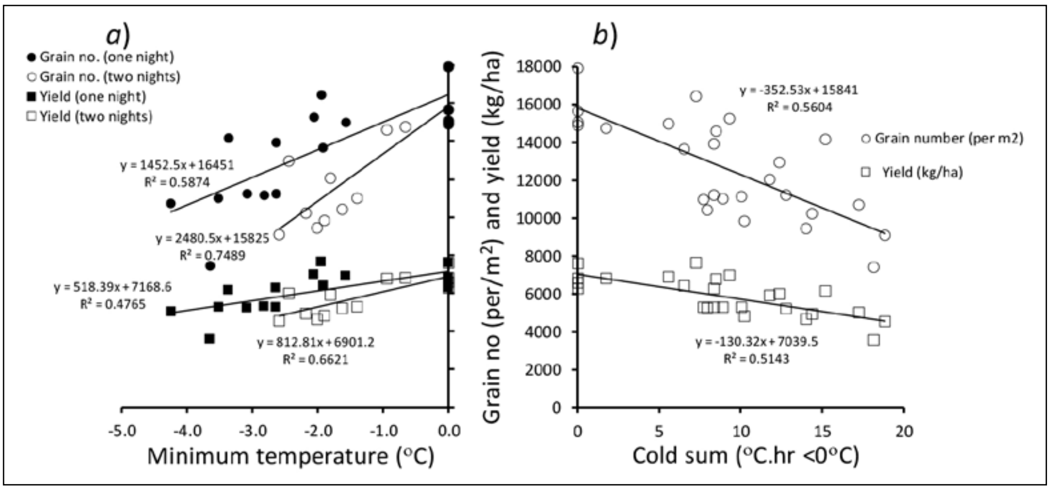

Figure 2. Relationship between wheat yield components and a) minimum temperature and b) cold sum (°C.hr < 0°C) for frost treatments.

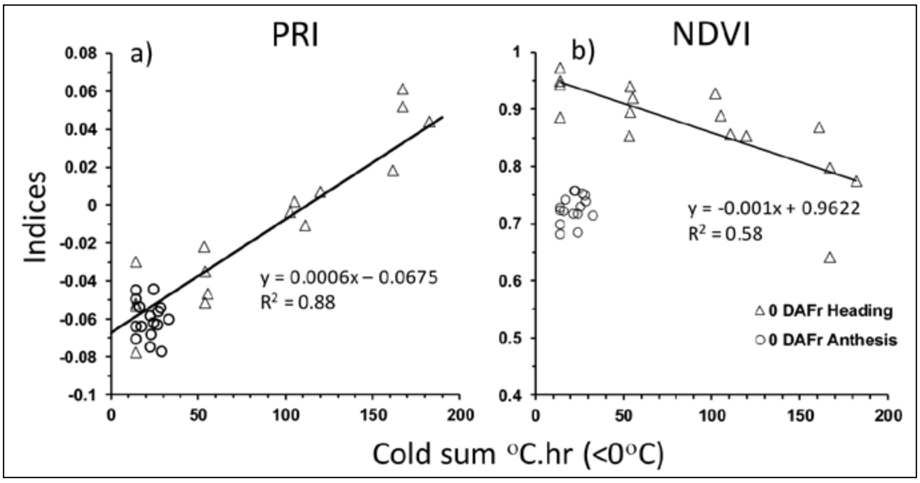

Figure 3. Reflectance derived spectral indices photochemical response index (PRI) and normalised difference vegetation index (NDVI) from wheat heads the day after frost (DAFr) treatments, applied at varying intensities and expressed as cold sums. Frost treatments were applied at the crop stages; head emergence and flowering.

iii) Paddock application of remote sensing to detect frost damage in wheat

For the six wheat paddocks surveyed in 2018, which was a decile 2 growing season, paddock averages for yield ranged from 0.4 to 1.6t/ha and ranged up to 0.2 to 2.6t/ha within any single paddock (Table 1). For the period between 15 August and 30 September there were approximately 30 nights where canopy temperatures were below 0°C, this period typically coinciding with growth stages of early stem elongation to flowering. These rolling frost events culminated in total cold load (paddock average) for this period ranging from 283 to 739 °C.hr < 0°C. Within each paddock, cold load varied substantially; in some cases, varying from 189 to 452°C.hr < 0°C across the six survey points.

Good agreement existed between intra-paddock cold load and yield, for four of the six paddocks surveyed, where there was a negative relationship for paddocks 2, 3, 4 and 5 (Figure 4). For paddock 2, the large yield range and strong negative correlation with cold load is likely linked with the substantial variation in topography across this paddock. In this case, changes in topography were associated with substantial changes in soil type; resulting in co-location of high cold loads with heavy soil types causing greater water stress in a year when growing season rainfall was decile 3. This co-location made it difficult to separate water stress from frost effects. Irrespective of this observation, a good agreement between yield and cold load was demonstrated in paddock 5, where the terrain was flat. For paddocks where there was no apparent link between yield

Table 1. Wheat yield (t/ha), minimum temperature (°C) (screen at 1.2m and crop canopy) and cold load (°C.hr < 0°C) for six commercial paddocks in 2018, Murtoa, Victoria. Intra-paddock range in values is defined in italics, which represent six points along a 750 metre transect. Minimum temperature and cold load are for the period between 15 August and 30 September.

Variable	Paddock					
	1	2	3	4	5	6
Yield	1.1	1.6	0.4	1.3	1.1	0.9
	0.8/1.3	*0.2/2.6*	*0.1/0.9*	*0.8/2.2*	*0.5/1.7*	*0.7/1.3*
Harvest index	0.21	0.27	0.11	0.19	0.26	0.22
	0.19/0.23	*0.05/0.42*	*0.04/0.18*	*0.10/0.29*	*0.17/0.38*	*0.16/0.31*
Screen min temp	-2.3	-3.7	-4.5	-3.4	-3.4	-5.2
Canopy min temp	-6.2	-5.1	-7.1	-6.3	-8.0	-9.4
	-5.2/-7.4	*-4.1/-7.3*	*-6.1/-7.8*	*-5.1/-7.7*	*-6.9/-9.1*	*-8.2/-10*
Cold load	413	283	436	423	617	739
	295/527	*189/452*	*357/496*	*310/522*	*473/745*	593/816

and cold load, it would be expected that factors other than canopy temperature (and/or soil type variation associated with topography) are having an overriding effect on yield e.g. pest and disease.

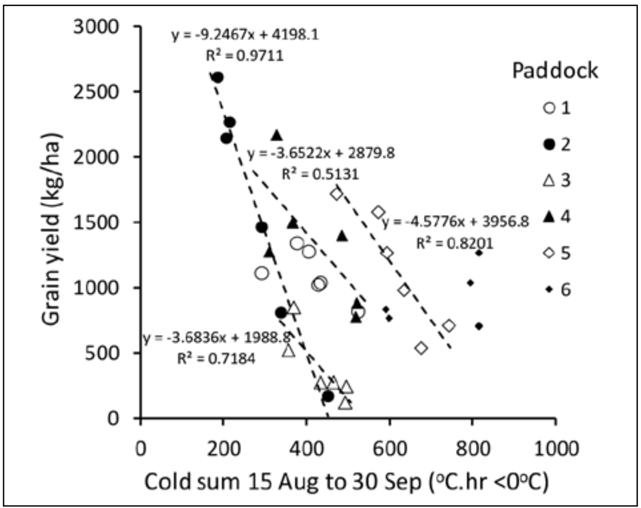

Figure 4. Intra-paddock relationship between wheat yield (kg/ha) and cold load (°C.hr <0°C) for six commercial paddocks in 2018, Murtoa, Victoria. Regression models describing intra-paddock fit between yield and cold load are for paddocks 2, 3, 4 and 5.

For paddocks 2, 3, 4 and 5, where yield and canopy cold load were correlated, there was also reasonable agreement with the reflectance indices NDRE, NDVI and PRI, these being correlated with both canopy cold load and crop yield (Table 2). For these paddocks, NDRE and NDVI were consistently negatively correlated with cold load and generally positively correlated with yield. For PRI, this relationship was less stable across paddocks when comparing cold load and yield. PRI has previously been shown to be positively correlated with cold load and negatively related to yield (Nuttall et al. 2018). The reverse pattern of PRI for paddock 5 may be due to artefact effects of previous seasons; canola stubble confounding reflectance in wave bands associated with PRI calculation, highlighting the need for ground truthing remotely sensed spatial information.

Using paddock 2 as a more detailed case study, since in this paddock there was the most consistent agreement between crop growth, cold load and indices. For this paddock, wheat yield was strongly correlated with NDRE (Figure 5a) and NDVI (Figure 5b) and negatively correlated with PRI (Figure 5c), which is consistent with the trend direction observed within controlled environment studies (Nuttall et al. 2018).

The spatial variation in PRI (or NDRE and NDVI) across paddock 2 can be used as a relative-surrogate to represent frost affected regions of crop and an opportunity for spatial management of crops for hay versus grain production (Figure 6). For 2018, the multiple heavy frosts up to crop flowering meant that this abiotic constraint is likely to have driven variation in yield across the landscape, where a single capture of remotely sensed data at flowering had utility for defining frost affected crops in four out of the six paddocks surveyed. For paddocks/regions/years where mild or discrete frost effects on crops are assessed with remote sensing tools, multiple sensor acquisitions may be required to isolate the change in crop reflectance signature associated with these short-term events. Common indices such as NDVI should also be used with caution, as their utility appears inconsistent across a range of frost related studies (Perry et al. 2017; Fitzgerald et al. 2019). This variable response may reflect the confounding effects of factors such as crop development and natural senescence, weeds and/or other constraints. The confluence of multiple indices (for example NDRE, NDVI and PRI) indicating

Table 2. Cold load, crop yield and crop spectral reflectance. Correlation (r) for reflectance-derived spectral indices taken from wheat canopies at around flowering and total cold load (°C.hr < 0°C) measured at the crop canopy between 15 August and 30 September, and wheat yield. Reflectance readings were taken on the 1 October using an Airphen® multispectral camera.

Spectral	Paddock					
	1	2	3	4	5	6
	Cold load (°C.hr < 0°C)					
NDRE	0.08	-0.98	-0.46	-0.20	-0.71	0.70
NDVI	-0.40	-0.97	-0.79	-0.23	-0.09	0.13
PRI	0.19	0.85	0.66	-0.43	-0.89	-0.54
	Wheat yield (kg/ha)					
NDRE	-0.19	0.96	0.36	0.72	0.61	0.38
NDVI	0.90	0.92	0.89	0.74	-0.06	0.50
PRI	-0.79	-0.90	-0.65	0.18	0.86	-0.19

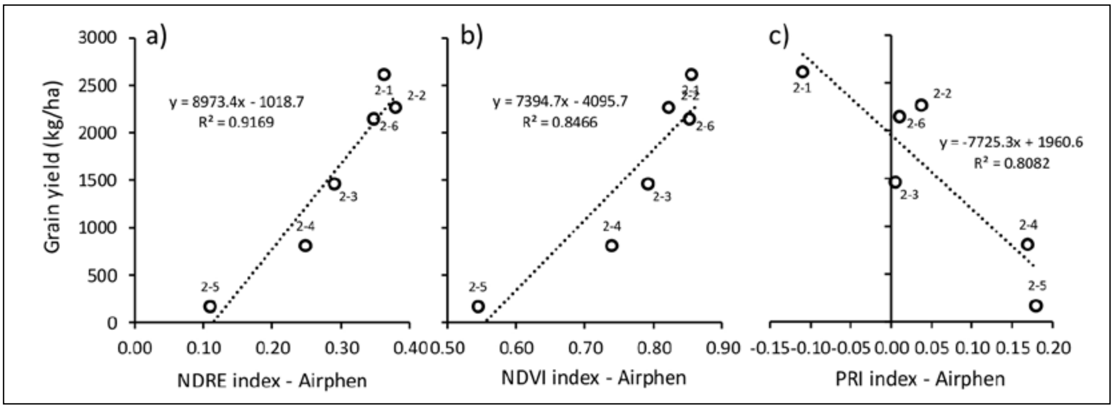

Figure 5. Relationship between wheat yield and Airphen® derived indices for a paddock (2) monitored near Murtoa, Victoria in 2018. Indices include a) normalised difference vegetation index (NDVI), b) normalised difference red edge (NDRE) and c) photochemical response index (PRI) derived from an Airphen® multispectral camera.

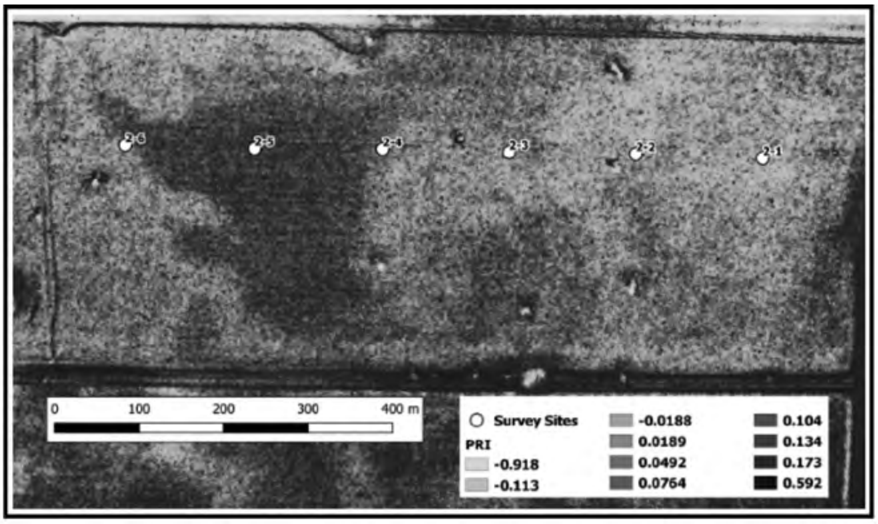

Figure 6. Spatial variation in the photochemical response index (PRI) across a wheat paddock (paddock 2) linked with crop frost damage. This represents an opportunity for spatial management of crops for hay versus grain production. Dark grey areas indicate low yielding zones and light grey areas are high yielding zones.

frost affected crops, may provide one multispectral method of estimating frost damage more reliably, or alternatively using a spectral mixture analysis approach to define new indices specifically targeted to frost response (Fitzgerald et al. 2019).

For remote sensing tools to have a practical application to industry, imagery needs to be captured at the paddock scale. For example, assessment of frost damage across whole-paddocks may be possible if several growers contract an aircraft equipped with a multi-spectral camera (e.g. Airphen®) to fly over multiple farms, making the process fast and affordable. Alternatively, spatial assessment using satellite (e.g. Sentinel 2) sensors may offer another approach, to support research and commercial opportunities (e.g. Flurosat Pty Ltd), although satellite obtained data may be limited by wave band and available indices. In both of these cases, the high-altitude platforms and large field-of-view takes away the complexity and error associated with 'stitching' overlapping images, which is required for sensors mounted on unmanned aerial vehicles (UAV) platforms. Ultimately, remote sensing tools may offer the opportunity to spatially manage frost affected crops. The next steps are to validate the proposed indices, identify other alternative indices (and determine their stability across different paddocks and seasons), quantify the economic benefit to growers and identify a commercial model that the industry may find attractive.

Conclusion

For wheat, where frost treatments were applied at flowering, grain number and yield were reduced by 8.8 and 7.2%, respectively, for every degree Celsius below zero (down to -4°C). This effect was additive over two consecutive nights. In terms of cold load, there was a 2.2 and 1.9% reduction in grain number and yield, respectively per °C.hr (below 0°C). The remote sensing spectral indices; PRI, NDVI and NDRE showed significant relationships with cold load and wheat yield over four of the six paddocks surveyed and represent an opportunity for spatial management of crops when considering hay versus grain production. Further investigation over multiple years, sites and crop growth stages is required to verify the stability and utility of these indices. Finally, the need for ground scouting to validate sensor derived information ahead of making a tactical management decision remains essential.

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Notes

Septoria tritici blotch of wheat, management strategies for the medium and low rainfall zones of south east Australia

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Keywords

- Septoria tritici blotch, *Zymoseptoria tritici*, integrated disease management, IDM, fungicides.

Take home messages

- Septoria tritici blotch (STB) has been building up in the farming system across south eastern Australia since 2010.
- *Zymoseptoria tritici* which causes STB has a long spore dispersal mechanism which allows for the spread of the disease from high rainfall to medium and low rainfall regions.
- Fungicide resistance to triazoles is ubiquitous however, active ingredients such as epoxiconazole and prothioconazole remain field effective at full rates.
- Wheat varieties with diseases ratings of moderately resistant- moderately susceptible (MRMS) reduce the need for fungicide application in medium rainfall environments.
- Risk of yield loss in medium and low rainfall environments is higher during above average rainfall years.

Background

Septoria tritici blotch (STB) of wheat is a necrotrophic disease caused by *Zymoseptoria tritici*. It is a disease of global importance and has recently been reported as the third most important disease to wheat production globally with losses ranked behind leaf rust and Fusarium head blight. The current epidemic of STB in south eastern Australia began in 2010 during numerous high rainfall years and an expansion of cropping in high rainfall zones (HRZ). This has created an environment where a large population of the pathogen survives each year to infect crops by wind dispersal in the high, medium (MRZ) and low (LRZ) rainfall environments when seasonal conditions are favourable. Outbreaks occur most years in the HRZ and were widespread during 2016 and 2017 in the Victorian and NSW medium/low rainfall zones and in Victoria/South Australia during 2019 across all rainfall zones.

Where is Septoria tritici blotch an issue?

Z. tritici has a long-range spore dispersal mechanism, which means there is always a background level of inoculum present in most regions, surviving on stubble residues and susceptible varieties. The current distribution of STB in south eastern Australia, can be seen in recent paddock surveys conducted during the 2016 and 2017 seasons which found 78 out of 80 commercial wheat crops sampled had *Z. tritici* present (Figure 1).

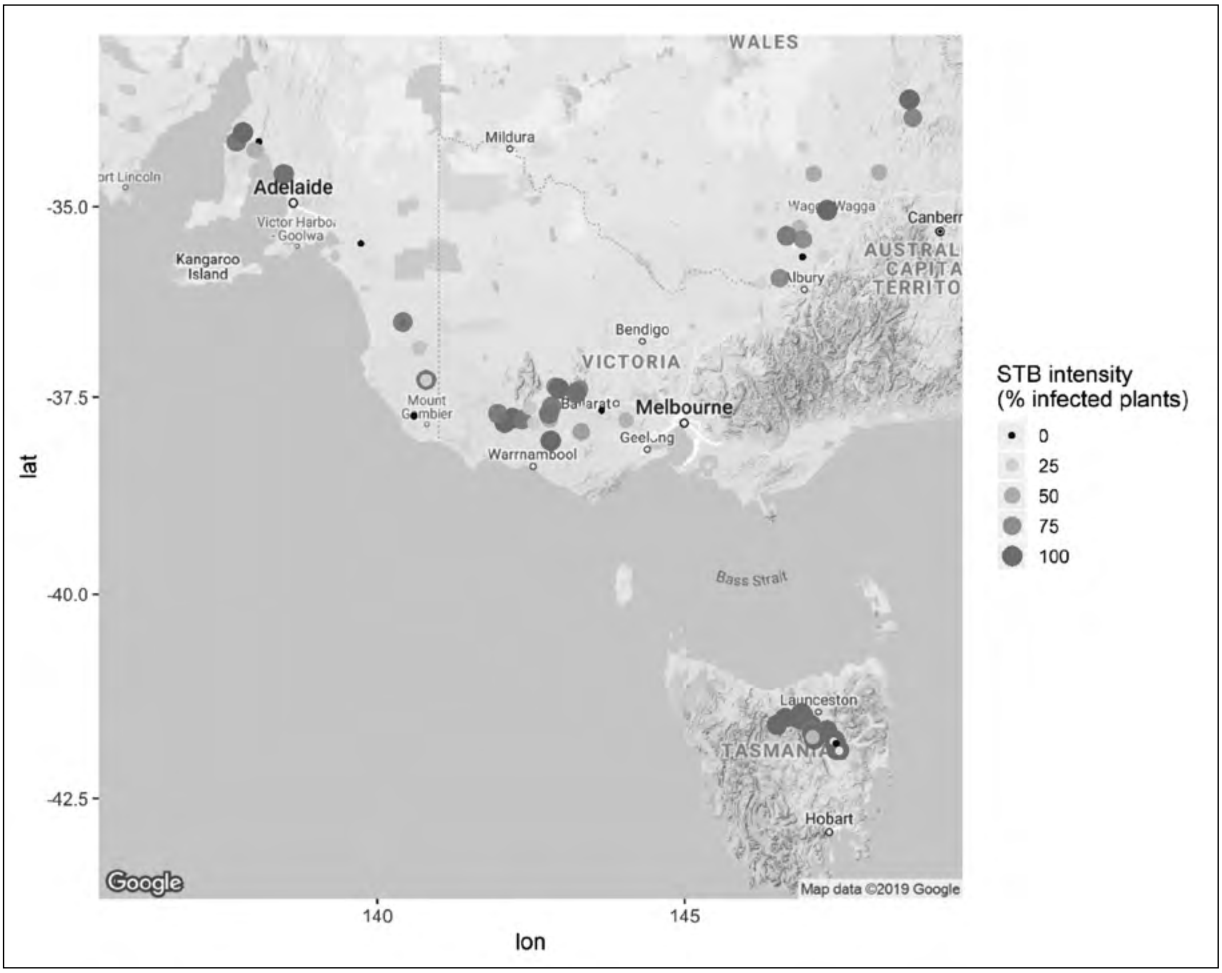

Figure 1. *Septoria tritici* blotch infection intensity in 80 paddocks randomly surveyed across the medium and high rainfall zones of south eastern Australia during 2016-2017.

STB fungicide resistance in Australia

There has been rapid selection and spread of triazole fungicide resistance in the Australian *Z. tritici* population (McDonald et al., 2019). Figure 2 shows results of a STB fungicide resistance survey conducted by NSW DPI. In 2016 the highly resistant Cyp51 isoform G1 was found predominantly in Tasmania with only a few detections at low frequency on mainland Australia. This situation changed dramatically in 2017 as seen in Figure2b, where the G1 isoform was detected at most survey sites and its frequency had increased within paddocks. This isoform contains six mutations in the Cyp51 gene which encodes an altered protein structure (isoform) that significantly reduces the ability of fungicides, such as tebuconazole, propiconazole and flutriafol to bind with the target site and kill the fungus. Prior to 2016 there was no detection of this isoform outside of Tasmania. Its detection indicates long spore dispersal is occurring between regions, which allows the rapid migration of new forms of resistance throughout south eastern Australia. Other isoforms of the Cyp51 are present in Australia but at this stage they do not cause higher levels of fungicide resistance. While our current knowledge indicates that only the triazole fungicides have been affected thus far, the increasing use of succinate dehydrogenase inhibitor (SDHI) fungicides and strobilurins means it is only a matter of time before resistance to these active ingredients is observed in Australia, as has been the case in Europe. This means reliance on fungicides alone as a control strategy is likely to fail. In the European *Z. tritici* population, the G1 isoform has been superseded by isoforms with even higher levels of triazole resistance.

Variety resistance available

Variety resistance levels listed on the National Variety Trial (NVT) website show only eight varieties that are rated better than moderately susceptible (MS) out of 82 varieties currently on the market and tested in the NVT system. The most widely grown varieties in the medium and high rainfall areas across the eastern states are rated worse than MS. Which creates a large area of crop sown

Figure 2. Map of occurrence of Cyp51 Isoform G1 in southern eastern Australia in a) 2016 and b) 2017. Green (predominantly mainland and decreasing in prevalence from 2016 to 2017) indicates absence of the G1 isoform (0%) through orange (increasing in prevalence from 2016 to 2017) to red (predominantly Tasmania) indicates G1 isoform detected in every sample from a paddock (100%).

to susceptible cultivars allowing pathogen survival every year and crops vulnerable to disease epidemic development. Recent popular varieties such as Trojan⦶, Mace⦶ and Scepter⦶ are all rated susceptible to current STB populations across eastern Australia. In the past varieties such as Yitpi⦶ provided good levels of adult plant resistance which helped reduce the inoculum levels across the medium rainfall zone in SA and parts of Victoria, thus reducing the risk of yield loss. In medium rainfall environments increasing the area sown to varieties with resistance better than susceptible ratings has a long-term positive effect on disease control.

Integrated disease management (IDM) for STB in medium rainfall environments

Decisions to manage STB in medium rainfall regions are more complex than in high rainfall regions. The practice of early sowing and stubble retention increases the chance of infection by STB. This is because the primary source of inoculum is retained in the farming landscape and early sowing synchronises the availability of susceptible hosts with ascospore release from the stubble. Growers are then reliant on fungicides to avoid yield losses. However, in contrast to high rainfall regions the

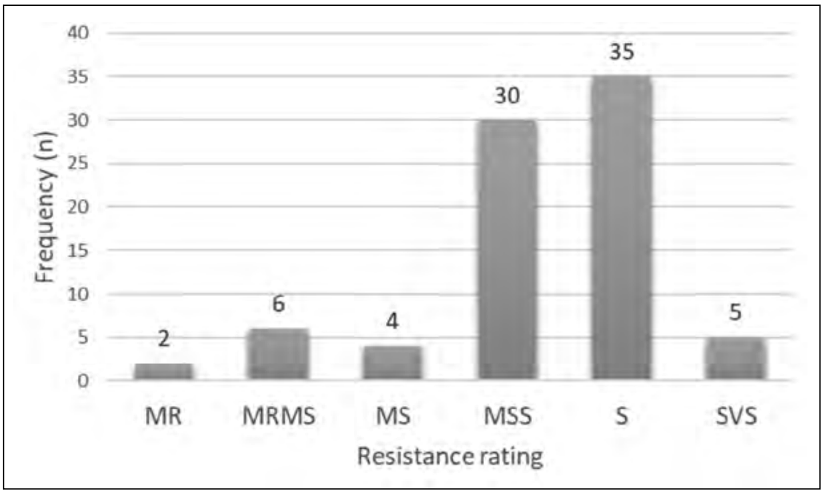

Figure 3. Frequency of National Variety Trial disease resistance ratings to STB for 2019 of 82 commercially available wheat varieties. MR – Moderately resistant, MRMS – Moderately resistant moderately susceptible, MS- Moderately susceptible, MSS – Moderately susceptible to susceptible, S- Susceptible, VS- Very susceptible.

return on using fungicides in medium rainfall regions is lower and or non-existent. This is because while infection levels can be high from seedling through to flag leaf (GS39), conditions for disease progression to continue during the booting to grain fill phase are not as frequently met. To follow are some principals to help guide practices for both fungicide resistance management and crop management:

Fungicide resistance and disease management

To achieve fungicide resistance management and disease management there are three important steps growers need to implement:

1) Stubble removal.
   a. Stubble is the source of the infection each year. By removing stubble before sowing there is a substantial reduction of pathogen population size.
   b. Reduces all isoforms irrespective of resistance and reduces the initial establishment of disease.
   c. To be effective, the removal must reduce infected stubble to very low levels, ideally below 100kg/ha of infected stubble remaining within a paddock.
   d. Do not sow wheat on wheat.
2) Variety choice.
   a. Under high disease pressure a variety rated MRMS can reduce the leaf area loss by as much as 60% compared to a susceptible – very susceptible variety (SVS).
   b. Host resistance reduces all isoforms irrespective of resistance and reduces the need for multiple canopy fungicide applications.
   c. Resistance ratings do change, so crops must still be monitored in-season for higher than expected reactions and each year it's necessary to check for updates to disease ratings.
3) Fungicide choice and use.
   a. Do not use the same triazole active ingredient more than once in a season. Do not use a strobilurin or SDHI more than once in a season.
   b. Aim for early control of disease. STB spreads up the leaf layers of the canopy through rain splash and direct leaf contact. Reducing the disease in the lower canopy slows the upward movement of disease and ultimately the leaf area lost.
   c. Follow label instructions at all times.
   d. Timing of application in the disease epidemic period is critical for getting the most out of these products.

Integrated disease management

Figure 4 illustrates the benefits of combining variety resistance, fungicides and reducing the amount of stubble inoculum for the percentage reduction in disease. In this scenario, two varieties are contrasted, Axe⒬ which is S to STB and Sunvex⒬ which is MRMS to STB grown at Wagga Wagga in 2017 under dryland conditions.

Figure 4 shows the disease development within the canopy over time in six treatments. For Axe⒬ there are obvious reductions in disease with regular application of fungicides in the protected treatment. However, when fungicides are applied only at GS31 under high disease pressure little impact is visible and the disease level remains high, similarly for the upfront treatment of fluquinconazole. Whereas when a two-spray program at GS31+GS39 is applied, disease control improves. Note that the effect of reducing inoculum in a S variety has little impact on disease progress. When the effect of the same treatments is examined with Sunvex⒬ which has higher resistance the impact is very different. In this situation the benefits of fungicide applications are less obvious, and reduction of stubble inoculum has a similar impact to the application of fungicides. This example shows that growers should look to use multiple strategies to reduce disease in their farming systems because the application of fungicides alone does not always result in improved yield outcomes in all varieties and in all years.

Conclusion

Understanding the lifecycle of STB presents opportunities for growers to be proactive about fungicide resistance and disease control. STB is a pathogen that survives from one crop to the next on the stubble left after harvest. An ideal time to take action is during this period, which should reduce the overall disease burden. In southern eastern Australia it is expected that infections of STB, particularly in the higher rainfall areas, will increase and these will require action by growers to prevent losses. However, in the medium rainfall areas early infections of crops are likely to occur but without above average rainfall from August to October these infections will present lower threats to the yield potential of crops.

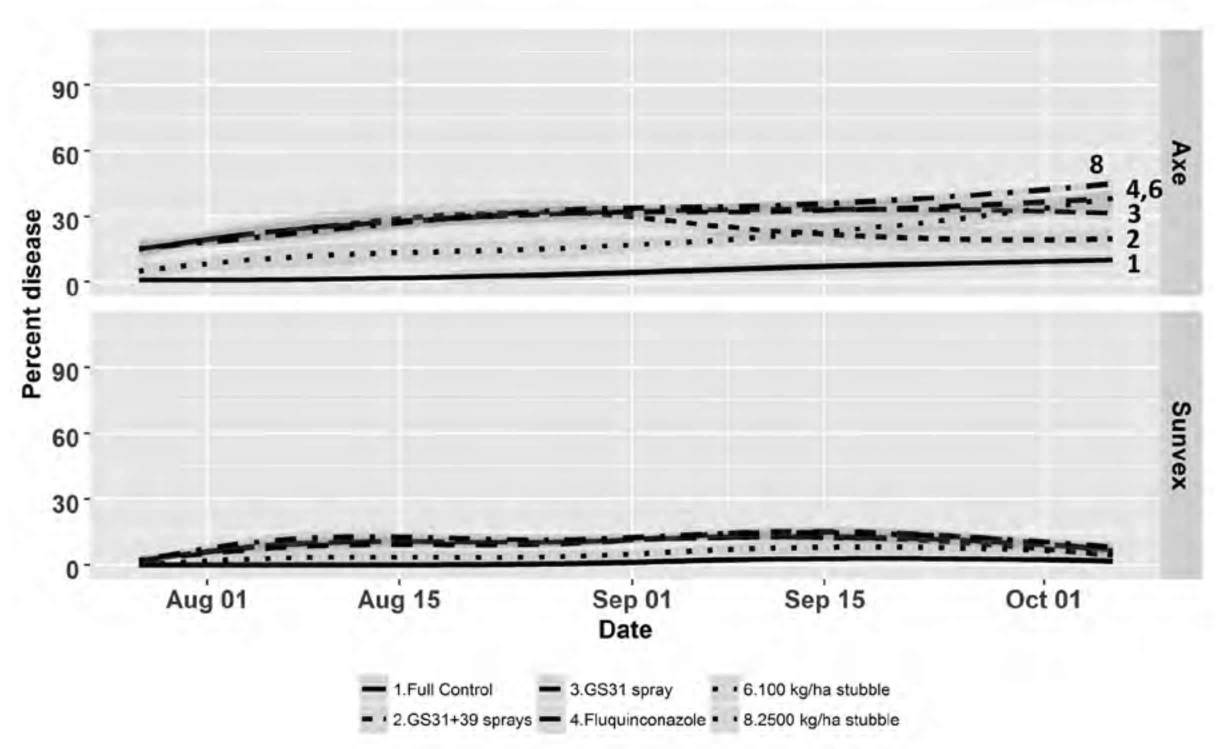

Figure 4. Trial grown at Wagga Wagga, NSW 2017. Displayed are a selection of varieties and treatments from the trial. The whole trial contained five varieties and eight treatments. The varieties displayed here are Axe⁽ᴾ and Sunvex⁽ᴾ. The treatments displayed here are 1. Full control – multiple applications of propiconazole at 500ml/ha at 250 g/l active ingredient. 2. High disease pressure (2.5 t/ha stubble) with fungicide applied at GS31 and GS39. 3. High disease pressure with fungicide applied at GS31. 4. High disease pressure and fluquinconazole applied to the seed. 6. Low disease pressure (100 kg/ha stubble) 8. High disease pressure (2.5 t/ha stubble).

Acknowledgements

The research undertaken here 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.

Members of the cereal pathology team at the Wagga Wagga Agricultural Institute (WWAI) who contribute to the fungicide resistance work; Melanie Renkin, Merrin Spackman and Beverly Orchard. Project partners Megan MacDonald and Peter Solomon at Australian National University. Samples submitted to the survey by agronomists and growers across the HRZ, MRZ and LRZ throughout south eastern Australia during 2016 and 2017.

Useful resources

http://www.grdc.com.au/~/media/Documents/Resources/Publications/Fact-sheets/FINAL-Septoria-tritici-blotch-Fact-Sheet-HR-pdf.pdf

Septoria tritici blotch experiments – southern NSW 2015 pp 148-150. In Southern NSW research results 2015. http://www.dpi.nsw.gov.au/content/agriculture/broadacre/guides/southern-nsw-research-results-2015

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Soaks are seeping across the Mallee – what can be done about it?

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Insight Extension for Agriculture.

GRDC project code: 9176969

Keywords

- Mallee seeps, normalised difference vegetation index (NDVI), seep management strategies.

Take home messages

- Seeps are rapidly growing as a result of modern farming systems, landscape and seasonal factors.
- Early identification and action are imperative and can be assisted through satellite NDVI imaging.
- Specific management strategies must be applied within recharge, discharge and interception zones to prevent the initial problem of unused freshwater developing into large unproductive saline scalds.

Background

Seeps resulting from localised, perched water tables have become a degradation issue across the cropping zones of SA and Victoria over the last 20 years and have rapidly increased over the last decade. This was highlighted in a recent survey involving 80 landholders across the Mallee region (McDonough, C. 2017). Their emergence is due to a combination of landscape, seasonal and farming system factors, leading to the waterlogging, scalding and salinisation of productive cropping ground in swales, a reduction in paddock efficiencies, and increased machinery risks.

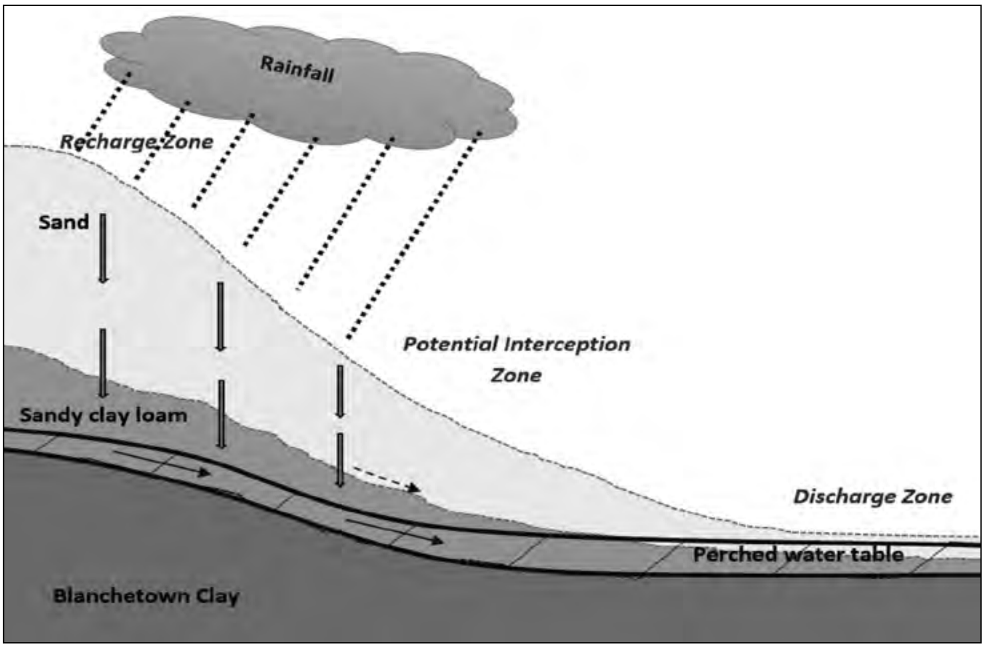

Figure 1. The formation of Mallee dune seeps near Karoonda, SA, (adapted from Hall, J. (2017) pp. 31).

Modern farming improvements toward no-till and continuous cropping have led to near total control of the previously dominant deep-rooted/perennial summer weeds like skeleton weed. This is leading to a greater storage of summer rainfall, which passes through the sandy rises with very low water-holding capacity. Figure 1 demonstrates the resulting formation of perched water tables above areas of impervious clay layers, (such as Blanchetown Clays). Water moves laterally toward lower-lying areas of the paddock and reaches the soil surface where the clay comes close to the surface in mid-slopes, or at the base of swales. This results in waterlogging, capillary rise, evaporation and salinisation over time at the discharge site.

Seeps generally begin as areas inundated with excess fresh water, which will lead to permanent salinisation and land degradation if no remediation takes place. The key to managing seeps is to identify the problem early, assess and apply appropriate management to the three key zones; recharge, intercept, and discharge areas (Figure 1):

- recharge zones – where most of the excess water is entering the system
- discharge zones – where the problems are developing at the soil surface (often in mid-slope or lower-lying areas)

  potential interception zones – where higher water use strategies can utilise the excess water before it reaches the discharge zones.

This paper presents findings and strategies resulting from several seep monitoring projects conducted over the last five years involving seven sites over six farms. Each site involves the use of moisture probes, piezometers and rain gauges with continuous data loggers. In addition, detailed landscape soil testing and treatment monitoring was used to more accurately assess the dynamics of the catchments, impacts of rainfall events and various management strategies. Growers were directly involved in developing and applying practical strategies to remediate the problems.

This research addresses many important understandings, outcomes and strategies for growers and advisors in dealing with this growing, land-degradation issue. Further results and new approaches will continue to develop as part of a collaborative project between Mallee Sustainable Farming (MSF), the GRDC, the Australian Government's National Landcare Program — Smart Farming Initiative and the SA Murray Darling Basin NRM Board.

Results and discussion

Identifying the problem

There are several key indicators that a seep area may be forming. Initially the crop below a sandy rise, or lower in a catchment area, may produce substantially higher growth or yield, due to accessing the extra moisture from the beginnings of a perched, fresh-water table. This is often more evident through drought years. It is not uncommon to find a distinct saturated layer of soil within the top 1m (sometimes slightly deeper) where this is happening. Ideally, this is the time to commence remedial action, well before it grows into a degraded soil area.

Large crop growth or yield in the developing seep is usually succeeded by ryegrass becoming thick and dominant through a cereal or pasture phase. Ryegrass tends to be more tolerant and responsive to seep conditions, persisting well into summer with a large seed set which is likely to contain a high percentage of hard seed.

As the seep areas grow it is common to find tractors suddenly sinking to their axels and causing major operational disruptions around these sites. The perched water table gets closer to the surface and bare, scalded areas will start to emerge due to anaerobic soil conditions that are detrimental to most plant growth. Depending on rainfall and landscape factors, surface ponding may occur for periods after rainfall events. This is a critical phase as, particularly over the heat of summer, as bare soil conditions will lead to capillary rise of moisture, evaporation and accumulation of salt at the surface to toxic levels for crop growth.

In recent years it has become evident that whilst wet years (such as 2010/11 and 2016) have resulted in seeps developing in these catchments, it is the drier years, with less plant growth and longer periods of heat and evaporation, that greatly exacerbate the accumulation of surface salt.

Normalised Difference Vegetation Index (NDVI) mapping has grown in prominence in recent years as a way of monitoring crop and pasture growth in precision agricultural management. NDVI images can be obtained from both drones and satellites, and essentially indicate areas of good or poor vegetative growth through spatial colour images. In 2017 a NR SAMDB project (McDonough, C. 2018a) found that strategic use of NDVI imaging can be used to identify both the formation of Mallee seep areas, as well as the potential threat to surrounding areas becoming degraded.

Consultants and growers are using numerous NDVI satellite use programs such as DataFarming and Decipher to identify areas of poor crop growth. The satellite images are convenient, free to access for the levels required, and are becoming a vital tool for seep management. A guide to the use of an NDVI mapping program is available on the MSF Mallee Seeps Website at http://www.malleeseeps.msfp.org.au/.

The key principle to reading NDVI images is to look at cloud free images over multiple dates through October to December. Soils remain wetter-for-longer in perched water table areas, resulting in extended periods of plant growth in spring. This is particularly evident in annual species, which show up clearly in contrast with normal crop areas that have already matured. Sites can then be analysed to assess the impact of seeps on the landscape.

The main advantage of NDVI imagery is that it shows the extent to which bare seep areas are likely to spread if nothing is done. In many cases it has been revealed that an easily visible bare patch of 0.2ha has the potential to quickly impact 5ha or more, due to a clear indication of excessive water and growth in the surrounding area. This provides a strong incentive for growers to take immediate remedial action, rather than observing degradation develop over time.

Viewing images throughout the growing season may also identify areas of poor crop growth which may contribute directly to recharge after rainfall. These areas can then be targeted for specific management options. Ground truthing of images, along with local grower knowledge, is vital in ensuring an accurate mapping of potential seep areas and identification of other unrelated factors influencing growth. For example, frost events can lead to crops reshooting late in the season and staying greener, for longer, in low lying areas. Also, summer crops or uncontrolled summer weeds may also present as similar NDVI image colours as seeps, as can trees or other perennial vegetation. Cloud cover and cloud shadows can cause distortions and misinterpretations, which is why it is important to view multiple images over a timeframe.

Management zone strategies

Once seeps and surrounding areas at risk have been identified, it is important to implement management strategies as soon as possible. Ideally, these should be designed to best fit within the grower's systems, with minimal disturbance to normal paddock activities. Some strategies may even lead to higher paddock productivity. However, some 'less convenient' changes may be necessary to protect a greater area of productive land heading towards total degradation and problems.

It is generally a combination of management strategies targeted in each of the recharge, discharge and interception zones is required to stop the spread of seeps and possibly bring the damaged area back into profitable production.

Recharge zone

Site monitoring shows that deep sands (often non-wetting) are the main source of excessive recharge water entering the system. Deep sands have very low water holding capacity and soil fertility and often suffer from compaction that restricts rooting

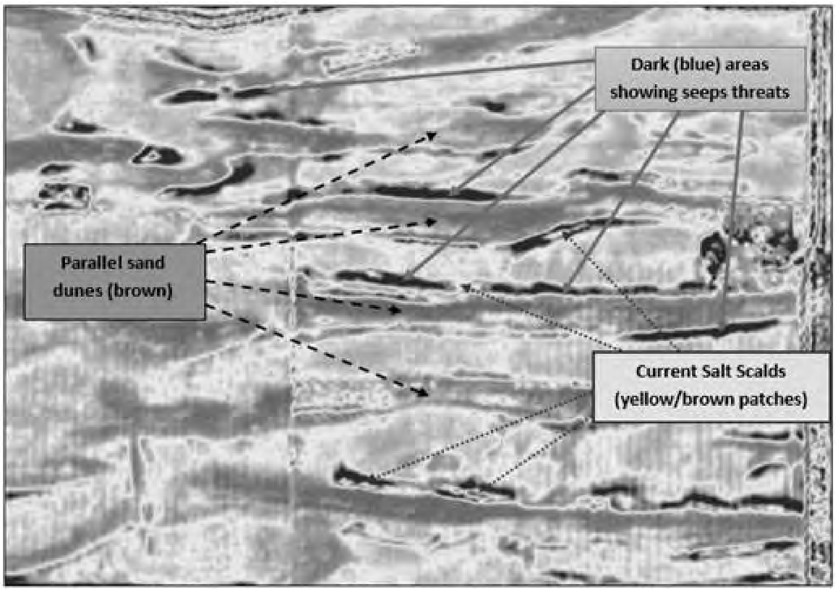

Figure 2. Normalised difference vegetation index (NDVI) map 16 October 2017 showing large areas under threat from seep degradation (dark (blue) shading).

depth. This means that even relatively small rainfall events can quickly pass through the root zones to contribute to the perched water table below.

Figure 3 illustrates the rises in water table at the mid-slope piezometer site between November 2015 and May 2018 at Wynarka, including the wet spring of 2016. The perched water table at this site is below the crop root zone, so any level rise is a direct impact of rainfall contributing recharge from the 60m of sandhill slope above the piezometer. Any fall in levels is likely due to discharge, evaporation or transpiration of the water lower in the system (particularly in the hotter summer periods), or in some cases, a bulge of water moving down the slope after a larger rainfall event. It reveals that a 40mm rainfall event raised the mid-slope water table by over 40cm. Smaller events of 12mm and 15mm during the 2017 growing season led to rises of 15-20cm. Even a sudden 7mm rainfall event in December 2016 caused a rise in water table of 10-15cm.

The key principles for managing the recharge areas is firstly to break any soil compaction, effectively increasing the plant root zone from around 20cm depth to down to 150cm (as observed at one site). This allows crops to dry out new rootzones to wilting point with benefits to crop growth and yield, while also creating a larger ‘bucket’ to fill before it starts contributing to recharge.

Soil amelioration that incorporates clay or nutritious forms of organic matter such as manures into the top 40cm often improves soil water holding capacity within this rooting zone. This was clearly evident at a Karoonda seep monitoring site, where spading in chicken manure more than doubled crop yield over a four-year period. Soil moisture probes showed excellent soil water retention within the 40cm spading depth which was utilised by the crop. This was in direct contrast to the untreated control plot which produced low yields, very little soil moisture used by crops below 30cm depth, and numerous rainfall events contributing to recharge (McDonough 2018b).

Any practical, effective and safe method of achieving soil amelioration through deep ripping, delving, spading, clay-spreading or manure/organic matter/nutrition incorporation will be beneficial in increasing crop water extraction and remediation of sandy recharge zones. Current research is developing more options for growers in this pursuit.

Some growers have decided their deep sands aren’t worth cropping and have chosen to establish permanent perennial, deep rooted pasture options such as lucerne or veldt grass. This becomes a viable option for growers with livestock in their systems, providing valuable feed options at critical times. However, care is needed in establishing pastures into adequate soil cover within favourable seasons to reduce the risk of wind erosion. In 2019, a grower at one site chemically fallowed their sandhill until sowing lucerne in August. This avoided a dry period from May to June which coincided with high winds and achieved an excellent stand as the soil warmed up in spring.

Discharge zones

The main principle for discharge zones is to try and maintain living soil cover all year around

Figure 3. Midslope (RO2 piezometer) water table rises after specific rainfall events (November 2015 to May 2018).

if possible. This greatly reduces capillary rise of moisture to the surface, and evaporation leading to surface salt accumulation, due to plant roots drawing moisture from deeper in the profile. Bare soil over the summer months and dry seasons, will lead to a rapid deterioration of soils into unproductive, saline scalds. The strategies to best manage this will depend on the development stage of the seep.

When a perched water table is in its early stages when crop yields are often increased, it is important to try and maintain cropping through these areas, without getting machinery bogged. As soon as practical after harvest, sow a summer crop in these zones to dry them out. A mixture of sorghum and millet has been successfully used over three seasons by growers near Mannum. With very little summer rainfall in this period the summer crops grew well where excess moisture was accumulating, but soon died out in the dry sandy soils surrounding the seeps. Summer crops are either cut for hay or harvested prior to seeding the winter crop.

Despite the growth of the summer crop in the discharge area, this did not lead to any yield loss in the following winter crop, as the soil continued to be recharged from higher parts of the landscape. While summer crops do not address the problem at its source, they greatly reduce soil degradation, with minimal impact on the grower within their normal cropping program. This method will only be effective long term if management strategies are also employed to address the excess water emanating from the recharge and interception zones.

For an established scald with high surface salinity or waterlogging affecting crop growth, a perennial salt tolerant pasture such as puccinellia or tall wheat grass should be considered. Ideally these can be sown with airseeders, but where heavy machinery cannot access the seep site, salt tolerant pastures can be established by spreading seed through a rabbit baitlayer and dragging harrows behind a quadbike. It has been reported that puccinellia is suitable for areas with moderately-high to very-high salinity (8 to >32dS/m), and tall wheat grass tolerates low to moderate levels (0-8dS/m, Liddicoat and McFarlane, 2007).

Current demonstrations resulted in good establishment at a variety of salinity levels, including excellent puccinellia establishment on a crystalline salt-covered scald at Wynarka. In some cases, tall wheat grass has established later in the season where puccinellia has not grown, even though they were sown together in the same seed mixture. The salt tolerant annual legume variety Messina has also been tried, but generally struggled on bare scalded sites. In addition, saltbush has been grown and grazed successfully in some seep areas, however it has not survived well in areas with periodic water inundation.

The successful establishment of pastures appears to depend on seasonal factors and more specific soil parameters not considered in previous work at more saline sites. Even slight rises in surface soil levels (i.e. raised beds????) or additions of organic matter have improved survival. Saline seeps are extremely alkaline with soil pH approaching 11 in many cases, which is toxic to most plant growth. This also needs to be considered when selecting salt tolerant species.

The MSF seeps project aims to gain a better understanding of the various mechanisms leading to saline seeps and better management decisions, by measuring soil parameters at different times throughout the seasons across different management practices. Initial success has been shown using a front-end loader to introduce a 10cm layer of sand, straw and manure to bare scalds, which improved establishment of salt tolerant grasses, and even a cereal crop at one site. These sites are being monitored over coming seasons to see if they will deteriorate over time or continue towards greater improvements.

In seep areas that have salt-scalded centres too toxic for crop growth, it is still important to employ these strategies on the less toxic edges to restrict the spread of these scalds.

Interception zone

Below the recharge zone there is a lateral subsoil flow of excess water above the impervious clay layers before it hits the discharge area (Figure 1). This area provides an opportunity to intercept and use this water before it causes problems lower in the landscape. At all monitoring sites the most successful strategy applied within this interception zone has been the strategic establishment of lucerne, with roots that penetrate deep into the perched water table to produce hay or pasture throughout the year. Lucerne effectively exploits large summer rainfall events that normally cause water recharge and is a versatile option that is familiar to growers. Figure 4 shows that each major rainfall event in the lucerne site area was quickly utilised with no evidence of recharge. This contrasts with the continuously cropped side which regularly had 60-70mm more water in the top 100cm soil passing beyond the rootzone. In the extremely wet season of 2016, the midslope lucerne was the only site to experience a reduction in the water table.

Growers are now targeting strips of lucerne (often 30-50m wide) above seep areas to intercept the lateral water flows and benefit from the productive fodder production. Even growers without livestock can boost their profits by selling lucerne hay produced off these areas. Crops can be sown through these lucerne strips, so establishing lucerne in the same direction as cereal sowing may be worthwhile, even if it takes more initial effort. While encompassing these lucerne strips within cropping paddocks may require some compromises, it is still better than losing expanding areas of highly productive land to seeps.

While growers may not wish to plant trees in the middle of cropping paddocks, these may worth considering, particularly where a fence line or laneway already exists. If planting trees close to seeps, it may be worth testing water quality to assess the level of salt tolerance required. Tree guards to protect seedlings from vermin and some early watering to ensure summer survival on deeper non-wetting sandy soils are recommended.

Innovative strategies

The MSF seeps project is currently conducting several trials and demonstrations of innovative management options, including the use of a subsoil extruder to apply organic amendments on deep sands above a seep at Alawoona. This machine applies a manure slurry behind deep ripping tines with minimal increases in erosion risk, unlike spading. Initial improvements in crop production and water use are promising.

Other trials are assessing other subsoil amelioration techniques, alternative pasture species and use of long season varieties to extend the growth period. One site is assessing the practicality of an in-ground sump and pump, just above a seep scald area, to extract water for spraying, livestock or liquid fertiliser application, however, poor water quality is presenting some challenges.

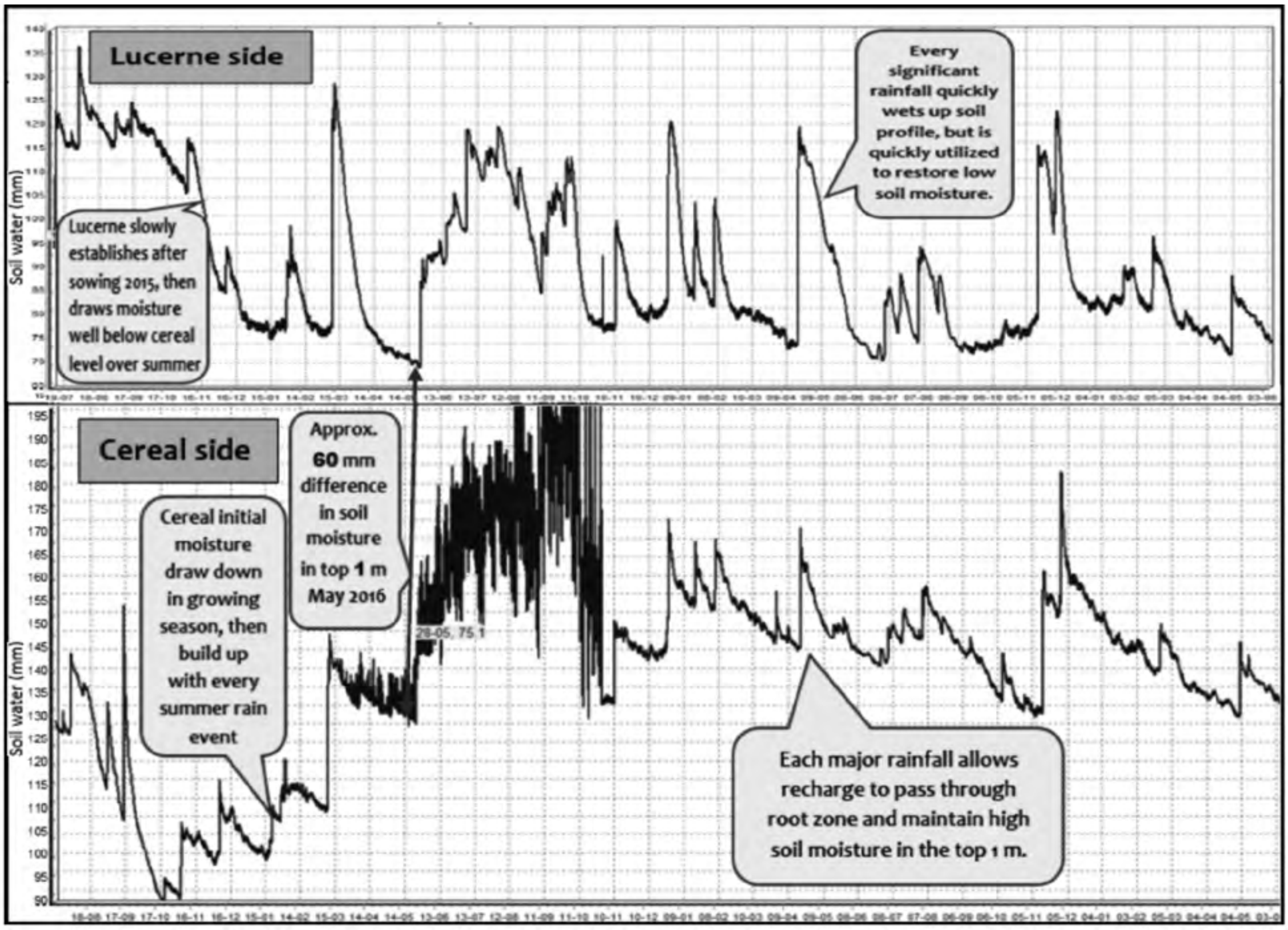

Figure 4. Comparisons of top 1m soil moisture levels in lucerne and cereal treatment areas (July 2015 to May 2018).

Conclusions

Localised seeps are a growing land degradation issue across cropping zones of southern Australia, due to a combination of landscape and seasonal factors as well as changes associated with modern farming systems. Early detection and treatment is vital to avoid rapid expansion of seep areas.

Various projects in the SA Murray Mallee have identified a number of strategies that provide practical options for growers to apply into the three critical areas of recharge, discharge and intercept zones. New technologies such as NDVI satellite imaging are providing important resources for early detection of developing seeps and the potential threat to grower's paddocks if left unmanaged. Ongoing work is refining these strategies through the MSF Mallee Seeps project to improve water use efficiencies and remediation of these issues.

Acknowledgements

The current research is a collaborative project between Mallee Sustainable Farming, the GRDC, the Australian Government's National Landcare Program — Smart Farming Initiative and the South Australian Murray Darling Basin Natural Resource Management Board. The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the author would like to thank them for their continued support.

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Maintaining wheat yield under high temperatures - how do current cultivars compare with what's coming?

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GRDC project code: US00081

Keywords

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

Take home messages

- Recent Australian wheat cultivars are heat tolerant. However, new materials developed from diverse genetic backgrounds using field-based phenotyping and genomic selection suggest that levels of heat tolerance can be substantially improved.

Introduction

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

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

Methods

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

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

All materials (>2000 lines) phenotyped in times of sowing experiments were genotyped using a 90K Single Nucleotide Polymorphism (SNP) platform and these formed the reference population for genomic selection from which all DNA marker effects were estimated. A prediction equation was developed and used to calculate genomic estimated breeding values (GEBVs) on selection candidates which were genotyped but not phenotyped. A genomic selection model that incorporated environmental covariates (for example; temperature, radiation and rainfall) directly was developed. This allowed the prediction of line performance under high temperature conditions. Environmental covariates were defined for each plot and growth development phase (vegetative, flowering and grain fill). An in-field validation of GEBV selected lines was then conducted by correlating GEBVs with field trial phenotypes. Various cycles of crosses were made among diverse lines with high GEBVs and progeny subsequently selected for high GEBV. These form the basis of our new elite heat tolerant materials.

Results

Extensive field-based phenotyping over a six-year period identified lines with superior adaptation to terminal heat stress (Figure 1). The tolerance of these materials was then confirmed in field-based heat chambers. The heat chambers were calibrated over a three-year period in replicated, triplicate plots (Table 1). Heat shock at anthesis significantly reduced yield compared to an ambient chamber and the uncovered plot. The ambient and uncovered plot were not significantly different from each other, and therefore, all future screening was conducted as paired plots (with and without heat chambers). The developed genotype-by-environment interaction genomic selection model increased genomic prediction accuracy for yield by up to 19%.

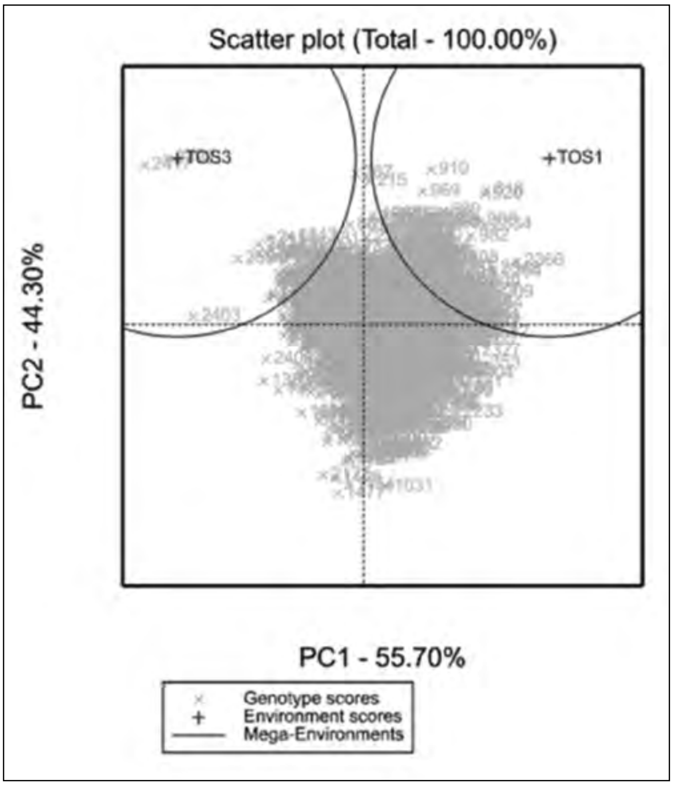

Figure 1. Genotype-by-environment interaction (GGE) biplot of yield in optimal (TOS1) and late (TOS3) sowing at Narrabri, 2013 to 2018.

The most heat tolerant Australian cultivars evaluated between 2013 to 2018 were the older varieties; Sunco, Annuello, Scout(D, Sunstate and Lang. These cultivars showed little difference in yield between times of sowing over years (Figure 2) but tended to have relatively low yield potential. However, the higher yielding, more recent varieties; EGA Gregory(D, Suntop(D and Spitfire(D tended to have reduced heat tolerance. Several recently derived pre-breeding lines

Table 1. The impact of heat chambers on yield, kernel weight, kernel number and other traits, 2013 to 2015.

Trait	Treatment			
	Ambient	Heated	No Chamber	Prob.
Yield (kg/ha)	2775 a	2248 b	2849 a	<0.001
TKW (g)	32.5	32.4	32	ns
Height (cm)	82.1	85.5	82.8	ns
Screenings%	4.09	4.89	5.13	ns
Grain number/10 spikes	49.3 a	43.8 b	48.74 a	<0.002

n.b. Means in the same row followed by different letters are significantly different.

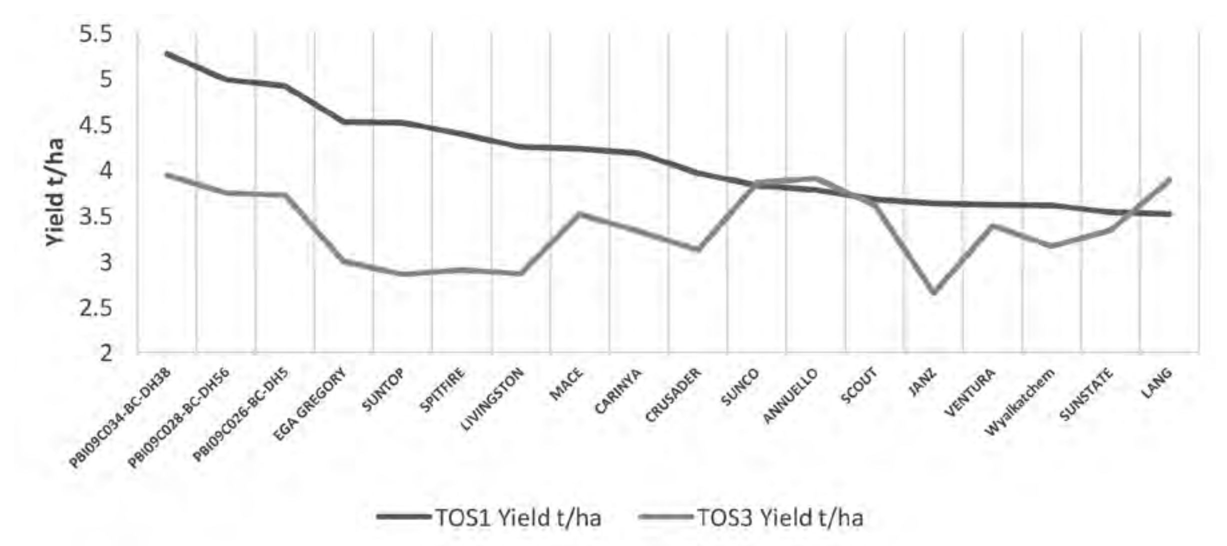

Figure 2. Yield at Narrabri (2013 to 2018) for heat tolerant lines and Australian cultivars for two different times of sowing (TOS1 and TOS2 are optimal and late sowing, respectively).

(PBI09C034-BC-DH38, PBI09C028-BC-DH56, PBI09C026-BC-DH5) have combined both high yield and heat tolerance.

A wider range of Australia cultivars, including many recent releases, was included in 2019 (Figure 3). Mustang$^{\Phi}$, Scepter$^{\Phi}$, Mace$^{\Phi}$, Sunmate$^{\Phi}$ and Borlaug$^{\Phi}$ all showed relatively high levels of heat tolerance. Mustang and Scepter combined this with high yield. The pre-breeding lines PBIC15020-0C-60N-010N and PBIC15022-0C-6N-010N, developed using genomic selection, also combined high yield with heat tolerance. Unlike Mustang$^{\Phi}$, these materials flowered later and did not escape the high temperatures during grain fill.

An important aspect of this work was the transferability of the Narrabri results to other regions of Australia. Subsets of 200 lines, selected for high GEBV, were evaluated at Merredin and Horsham to validate the strategy. A training population was necessary to allow genomic prediction models to calculate GEBVs without the need for phenotyping at other sites. The accuracy of genomic prediction for yield, trained at Narrabri, was evaluated in 2017 and again in 2018 (Figure 4). When the 2018 data were included in the estimations of GEBVs, the predictability exceeded 0.5 for both early and late times of sowing.

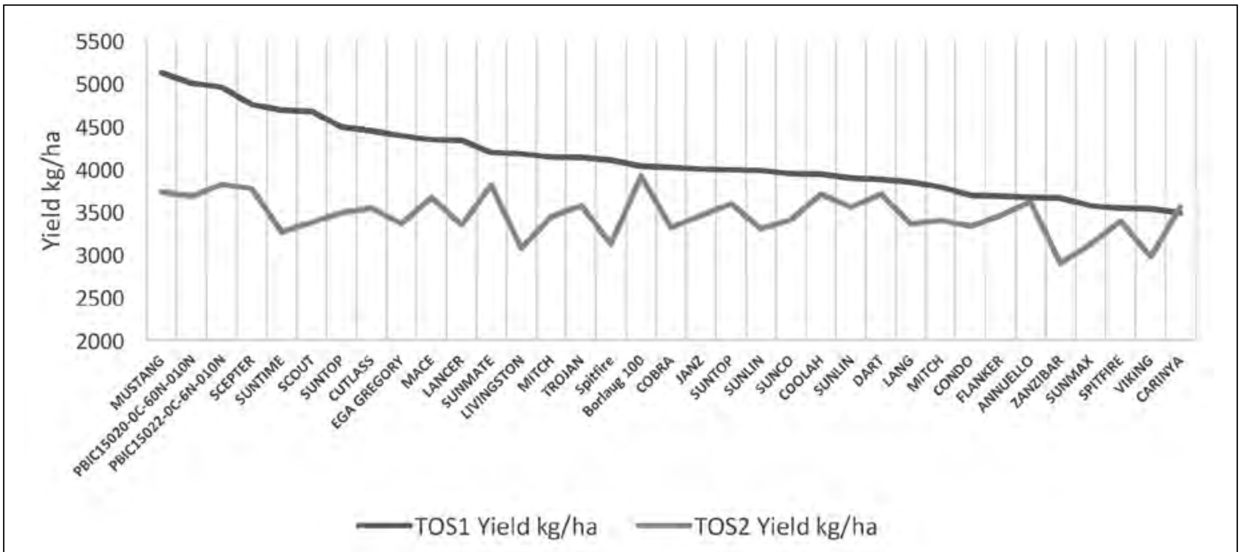

Figure 3. Yield of Australian cultivars and new heat tolerant lines at Narrabri, 2019 for two different times of sowing (TOS1 and TOS2 are optimal and late sowing, respectively).

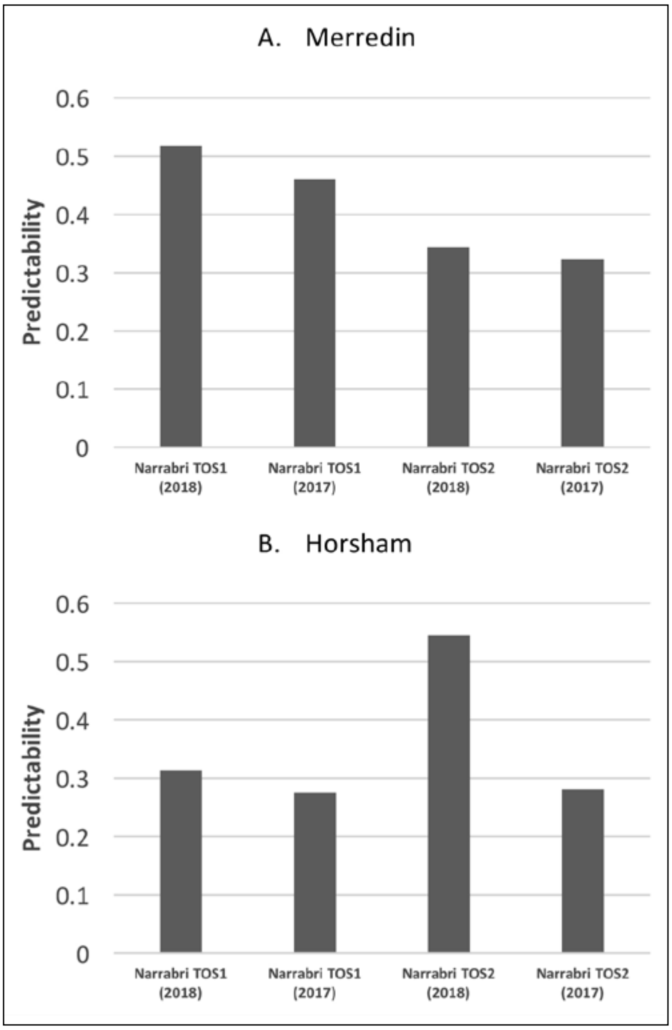

Figure 4. Accuracy of genomic prediction for yield trained at Narrabri (GEBVs calculated from five and six years of data) and validated at Merredin and Horsham in 2017 and 2018. TOS1 and TOS2 are optimal and late sowing, respectively.

Conclusion

Some recently released Australian cultivars have both the genetics of high yield and the genetics for heat tolerance. However, new pre-breeding materials developed using genomic selection offer commercial wheat breeders' new sources of diversity for both yield and heat tolerance that can be used to mitigate the effects of a warming environment. The strategy of selecting for heat tolerance at Narrabri for other regions of Australia was validated by the relatively high correlations between GEBVs and yield under heat stress at Merredin and Horsham.

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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Subsurface acidity – how far has the research advanced?

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GRDC project code: DAS1905-011RTX

Keywords

- acidity, stratification, subsurface, lime, incorporation

Take home messages

- Subsurface acidity and stratification are emerging as serious constraints to crop production across NSW, Victoria, SA and WA. Identification and treatment is being explored through multiple GRDC and State and Federal government investments.
- Traditional soil sampling strategies can lead to misdiagnosis of subsurface issues; strategic sampling at specific depth intervals is required.
- Lime rates need to be adjusted to account for subsurface pH, changes in soil texture and organic carbon content down the profile.
- Strategic incorporation/tillage can aid the efficacy of lime application for treating subsurface issues; other subsoil constraints (e.g. compaction) should be taken into consideration to maximise treatment impact, along with the risks associated with soil disturbance.
- Options for treating subsurface and stratification issues are being examined in a new GRDC project in SA.

Background

Soil pH is largely a function of soil type, rainfall and farming system, and can be inherently variable both horizontally and vertically in the profile. A soil pH_{Ca} between 5.2 and 7.5 provides optimum conditions for most agricultural crops, though plant species differ in their tolerance to acidity and alkalinity.

Whereas soil acidification is a natural process, primarily driven by the leaching of nutrients (especially nitrates) from topsoil, it is accelerated under productive farming practices. Where no lime is applied, the topsoil becomes acidified and the acidic layer spreads down the soil profile, retarding penetration of roots of acid-sensitive species, and ultimately reducing crop yield.

Subsurface acidity is the acidification of the soil below the top 10cm. The development of acidic subsurface layers can induce nutrient deficiencies and/or toxicities, limit crop responses to fertiliser application, and adversely affect root growth, water uptake, nodulation, plant vigour and the N fixation potential of acid-sensitive pulses (Burns et al. 2017b). For acid-sensitive crops like pulse legumes, rhizobia survival and nodulation are compromised at pH_{Ca} below 5.0. Acidic conditions also contribute to the suppression of organic matter breakdown and cycling of organic N within the subsurface layer (Paul et al. 2003).

Much of SA's 4.4 million hectares of productive farmland has a topsoil pH_{Ca} below 5.5 or has the potential to develop acidity (Figure 1; see colour copy of this paper on the GRDC website). The

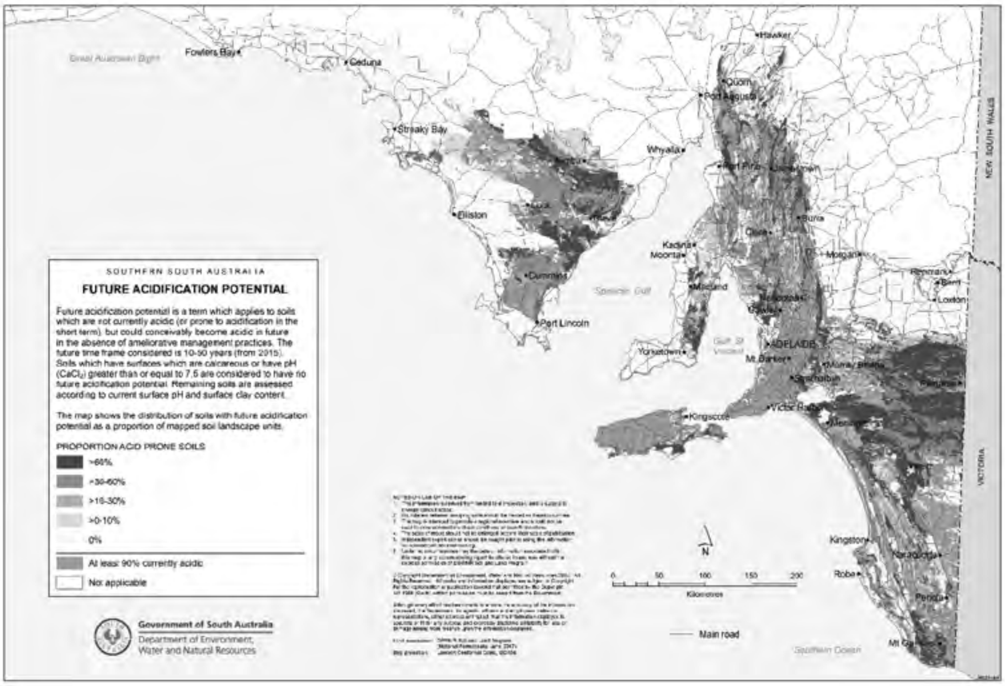

Figure 1. Map of South Australia showing areas currently affected by surface acidity (blue; see colour copy of this paper on the GRDC website) and areas at risk of developing surface acidity in the future. Note, all of these soils are also at risk of developing subsurface acidity.

potential for acidic layers at 5 to 15cm or deeper across these areas is high particularly where the A horizon is thicker than 20cm. Remedial action is required to curb its development. When it comes to subsurface acidity, prevention is better than cure.

The delineation between surface and subsurface acidity is important as monitoring and treatment options will vary, becoming increasingly complex at depth. Subsurface acidity cannot be detected with conventional topsoil sampling methods (0-10cm), and targeted sampling to depths at suitable increments is required.

There have been multiple GRDC and State and Federal government investments in recent years across NSW, Vic, SA and WA aimed at exploring subsurface acidity and its treatment. This paper serves to present a summary of that work and its relevance in the South Australian context, including recommendations for sampling and treatment. Note, this paper is an extract of a literature review being prepared for the GRDC project 'New knowledge and practices to address topsoil and subsurface acidity under minimum tillage cropping systems of South Australia' (DAS1905-011RTX). Contact Brian Hughes (Brian.Hughes@sa.gov.au) for the complete version.

Causes of subsurface acidity

The causes of soil acidification, either in the surface or subsurface layers are similar, however there are some differences.

The key environmental factors that can affect the difference in pH between surface and subsurface layers are soil fertility, initial soil pH profile before clearing, rainfall and fluctuations in soil moisture content. In duplex soils, the changing soil clay content which drives pH buffering capacity can have an impact on the speed of development of acidic subsoil layers (Paul et al. 2003). The higher soil organic matter content in surface layers may also buffer against pH changes, maintaining a higher pH than the underlying soil. Conversely, the lack of organic matter in light textured sandy subsoils can mean that severe acidity can develop quickly.

Topsoil acidification of cropping soils is largely driven by nitrification from either ammonium-based fertilisers or organic forms of N from plant residues and the subsequent leaching of nitrates. The removal of alkaline farm products is the other major contributor. Stratified acidic layers at 5 to 15cm are becoming increasingly common under no-till systems in the high and medium rainfall regions of southern Australia at the depth where N fertiliser is applied, even where topsoils have been limed (Angus et al. 2019, Burns et al. 2017a, Paul et al. 2003, Scott et al. 2017).

Subsurface acidity can occur when surface acidity goes untreated, gradually extending down the profile, and can be exacerbated by the production of acids, especially from leguminous plant roots. Plants maintain their electrostatic charge by excreting acid (H^+) where the charge of the cations taken up exceeds the charge of the anions. Non-legumes take up significant quantities of nitrate (NO_3^-) so the excess of cations over anions and acid production is usually low. By contrast, legumes generally fix most of their N internally and have a greater uptake of cations over anions. Thus, legumes produce more acidity in the deeper soil profile than non-legumes (Tang 2004).

The problem with aluminium

A key impediment to plant growth in acidic subsoils is the potential for aluminium (Al) toxicity. Aluminium is a component of many soil constituents including clays and oxides, and is also present on the surface of soil organic matter. As soils acidify, Al becomes available from the soil constituents, increasing the concentration of Al ions in the soil solution, typically once pH_{Ca} falls below 4.8. However, some soils can have low pH without Al toxicity.

High Al severely damages plant root hairs and impairs the uptake of water and nutrients. This may produce symptoms of drought and nutrient deficiency which can be difficult to relate to soil acidity and Al toxicity in the absence of soil testing data (Yang et al. 2013). Crops such as canola, barley, annual medics, lentils, faba beans and lucerne are very sensitive to Al toxicity. Often when plant roots encounter a toxic Al layer in the subsurface, the damaged roots will respond by growing sideways.

Is there a subsurface problem?

In 2019 there were various reports of patchy legume crops (faba beans, lentils and chickpeas) across SA soils that were widely considered to be alkaline. Soil testing in the patches revealed that they were no longer alkaline and a stratified acid band mostly at 5-15cm was the culprit behind the poor legume growth. Often subsurface acidity isn't uniform across whole paddocks, but rather appears in certain soil types or positions in the landscape.

Its presence is often masked by traditional 0 to 10cm soil sampling, with the alkaline 0 to 5cm layer diluting an acidic 5 to 10cm layer, resulting in an overall pH result that doesn't cause alarm. Where pH stratification and/or subsurface acidity is present, traditional soil fertility sampling may not accurately reflect pH variability and its extremes in the profile.

Crop grain yield maps and/or mid-season normalise difference vegetation index (NDVI) images, particularly in the legume phase of a rotation, can help identify 'productivity zones', or areas of good and poor plant growth that can be used to target soil sampling.

A soil pH indicator kit, purchased from your local hardware shop or plant nursery, can be used to quickly and cheaply determine whether acidity is contributing to poor plant growth, following this method:

- Use a yield or NDVI map to locate zones of 'good' and 'poor' production in a paddock.
- In each zone, dig a few holes to 40cm using a shovel or front-end loader, creating a flat vertical soil profile face.
- Apply the pH indicator liquid on the profile down to 30cm and then apply the powder and let the colour develop. Alternatively, you can use a Dig Stick soil probe (Spurr probe) to remove an intact soil core and apply the same procedure to determine the change in pH down the profile.
- Once the colour reaction is complete, use the pH colour indicator card to determine the pH down the profile and a tape measure to identify the positions of any pH changes. Any acid layers will be visible as bright green or yellow colours.
- Take a photo, including the tape measure for reference.

If acid areas have been identified using the pH indicator kit, careful soil sampling and more accurate laboratory pH and other analyses are recommended.

- Depending upon the position of the acid layer, soil depths might include: 0-5, 5-10, 10-20 and possibly 20-30cm. If the layer is more common in the 5-15cm layer the following depths may be more appropriate: 0-5, 5-15 and 15-25cm.
- Within each productivity zone, collect multiple samples from 10 to 15 cores and combine samples from each depth using a clearly labelled bucket. The number of zones (usually 2-6) that should be sampled will depend upon the variation within the paddock and its size.
- Thoroughly mix the samples for each layer depth for each zone and bag a sub-sample; send to the lab for pH_{Ca}, organic carbon % and a soil texture assessment. Aluminium (measured in $CaCl_2$) is also warranted.

Alternatively, precision soil sampling approaches, such as grid-based or on-the-go Veris® pH mapping can provide more detailed data on the variability in surface pH and possible stratification, which can identify areas of potential subsurface acidity for further sampling.

How much lime will I need?

Subsoil pH can be increased slowly over time by liming sufficiently to maintain pH_{Ca} at 5.5 or more in the top 10cm (Burns et al. 2017b, Conyers and Scott 1989, Scott and Conyers 1995). Lime rates required to achieve a target pH are influenced by the buffering capacity of the soil which is determined by the soil texture and organic matter content. The rough rules of thumb to change the pH by one unit for each 10cm depth of soil are: 2t/ha of lime for a sandy soil; 3t/ha for a sandy loam; and 4t/ha for a loam/clay loam. Where organic matter is low (common in subsurface layers and/or lower rainfall areas), rates can be substantially reduced and will have the same effect.

Lime quality is important when it comes to determining rates, with particle size (fineness) and purity (neutralising value) driving its effectiveness to counteract acidity. Recent work in SA compared different sources of lime, broadcast at 3.0 or 6.0t/ha without soil incorporation. Fine lime was found to move slightly further down the soil profile over 4 years (7 to 10cm) than coarser lime, which only moved to 5cm (Hughes and Harding 2019).

Neutralising value

The neutralising value (NV) is the carbonate component of lime that neutralises acid in the soil, and therefore, the proportion of carbonate in the liming material is important as it impacts the effectiveness of the product. The higher the NV, the greater the material's capacity to neutralise acidity. Pure calcium carbonate has a NV of 100%; good quality liming materials should have a NV greater than 80% (Harding and Hughes 2018). Lime rates need to be adjusted to reflect NV.

Registered agricultural lime suppliers are required to provide purchasers with a laboratory analysis of the neutralising value, particle size and calcium and magnesium content of their liming products.

Calculators are available to assist with lime rate decisions and assessment of lime quality from different sources (contact Brian.Hughes@sa.gov.au for a copy), though these decision support packages were developed to target surface acidity only (0 to 10cm). These calculators will be reviewed as part of the new project to calculate lime rates that account for subsurface acidity.

How can I increase lime movement in the soil?

The current industry practice of spreading lime without incorporation under no-till or zero till management is relatively ineffective at treating subsurface acidity because of the slow movement of lime down soil profiles (Burns et al. 2017). Surface applied lime is often concentrated in shallow surface layers (0 to 2.5cm) with little further downward movement in the short to medium term (Burns et al. 2017d).

Lime particles need to react with the soil and the by-products leaching into the soil. The speed at which this occurs is related to rainfall, the soils texture and buffering capacity, and the fineness of the lime. Depending on these factors, it can take anywhere from 4 to 15 years before lime applied on the surface moves beyond 10cm, but incorporation has been shown to increase liming efficacy (Conyers et al. 2003). It appears more aggressive application or incorporation methods may be needed to achieve rapid changes to pH at depth (Li and Hayes, 2017). The more vigorous the soil disturbance with lime applications, the faster subsurface acidity will be neutralised (Angus et al. 2019). Deep lime placement has been tried in several experiments with mixed results.

Strategic cultivation

Strategic cultivation with a tyned or disc implements every 4 years or more interspersed with no-till can be beneficial on a range of soil types, overcoming a number of production constraints, not just acidity. The timing of the cultivation is critical to minimise impact on soil structure and to reduce the risk of erosion. The benefits of this strategic cultivation need to be weighed against the potential cost and risks (Conyers et al. 2019). While occasional strategic tillage conflicts with the philosophical ideal of zero disturbance of soil, it may provide a tool for flexible management of weeds and pests within a conservation agriculture approach (Conyers et al. 2019).

Deep tillage and soil mixing – sandy soils

Many soils of southern Australia contain a range of physicochemical constraints, often occurring concurrently in the top and/or subsoils (Davies et al. 2019). Strategic deep tillage and/or soil mixing that extends beyond the top 10cm can be used to alleviate multiple soil constraints (for example acidity, water repellence and compaction), effectively spreading the cost and risk of incorporating lime across several soil constraint benefits and maximising the potential gains in production. Azam and Gazey (2019) demonstrated benefits to root growth and water use efficiency, doubling grain yield by incorporating lime to >30cm with a rotary spader, overcoming both acidity and compaction.

Types of deep tillage include: deep ripping (with and without inclusion plates); delving; soil mixing (spading, large offset discs); and, soil inversion (mouldboard plough, modified one-way disc plough). A summary of each approach, working depth, constraints addressed, and approximate cost can be found in Davies et al. 2019. These approaches are best suited to sandy soils and some still require validation in SA. Cultivation and deep tillage assessments will be made in this project across a range of soil types and cropping systems in SA.

Organic amendments

Organic amendments generate alkalinity as they decompose, and mixtures of lime and organic material can improve the response to lime by creating favourable conditions for the movement of lime through the soil (Butterly et al. 2018a). Organic wastes such as compost, animal manures, lime-treated sewage sludge and plant residues have been trialled and found to give some effect in reducing acidity when the wastes themselves have some alkaline content (Butterly et al. 2018b; Condon et al. 2018; Nguyen et al. 2018). Organic matter can also reduce Al toxicity, even when no pH change is detected (Antonangelo et al. 2017; Li 2018). Ongoing research in the southern region is examining the benefits of organic amendments for soil acidity and other constraints.

Conclusion

Subsurface acidity is becoming increasingly prevalent across SA's cropping land, leading to patchy plant growth and reduced grain yields, especially in pulses. Its presence often goes unnoticed until it is well developed, due to limited or inaccurate subsurface soil sampling and assessment. A strategic soil sampling approach is proposed to adequately identify stratified and subsurface bands of acidity, particularly in no-till systems. Lime application rates need to be developed that take into consideration the degree and depth of acidity, soil type and organic matter content and lime quality. Growers should consider methods to incorporate applied lime to increase its efficacy in treating subsurface issues. PIRSA is working on developing new calculators to assist lime rate decisions to treat subsurface acidity and will assess incorporation methods suited to South Australian soils.

Acknowledgements

The research reported here is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC. We'd like to thank them for their continued support.

Useful resources

Liming acid soils: https://www.youtube.com/watch?v=0bUfCwpfBxo

Legumes in acid soils: https://grdc.com.au/resources-and-publications/all-publications/publications/2018/legumes-in-acidic-soils

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iMapPESTS - Sentinel surveillance for agriculture

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Keywords

- surveillance, detection, monitoring, diagnostics, pest management, actionable information, biosecurity, area freedom.

Take home messages

- iMapPESTS is a proof of concept research project enabled by a multifaceted industry, research and government network; including GRDC.
- Through state-of-the-art surveillance and diagnostics tools and techniques, iMapPESTS aims to demonstrate how on-farm plant pest management can benefit from rapid and accurate monitoring and reporting of airborne pests and pathogens affecting all major agricultural sectors across the country.
- iMapPESTS is designed to deliver tangible benefits to the industry partners, which is why engagement and adoption is taken seriously. We want to hear from you so please get in touch with us! Visit us and get involved at www.imappests.com.au.

Background

iMapPESTS is a $21 million dollar research, development and extension (RD&E) endeavour funded from Australian Federal Government funds, through the Rural R&D for Profit Program, as well as investment from all seven plant industry Research and Development Corporations (RDCs), and in-kind contributions from national and international partner organisations including, SARDI, Agriculture Victoria and Rothamsted Research (UK), to name a few.

Over a five-year period (2017-2022), iMapPESTS aims to boost on-farm pest management through rapid and accurate monitoring and reporting of airborne pests and pathogens affecting Australia's agricultural sectors including grains, cotton, sugar, horticulture, viticulture and forestry. This will be achieved through a range of surveillance, diagnostics and engagement and adoption activities (Figure 1).

Beyond a proof of concept system, iMapPESTS will lead to enhanced pest management by providing timely information on high-priority, cross-sectoral pest and pathogen presence and abundance. Such information could be used by industry stakeholders to guide the direction or intensity of scouting efforts and pest management actions. The system could also facilitate a coordinated response to biosecurity efforts during exotic pest and disease incursions, including use in delimiting surveys and proof-of-freedom claims.

Sentinel surveillance

A key feature of iMapPESTS is the custom-designed, mobile surveillance unit called a 'sentinel' that is designed to offer automated sampling technology optimised for collecting airborne fungal spores and insects (Figure 2).

The sentinel incorporates a trailer equipped with several airborne samplers, power supply, climate sensors, telemetry, and an industrial computer to control the unit; including automated robotics to change the samplers according to the day or capture criteria, and to communicate the data.

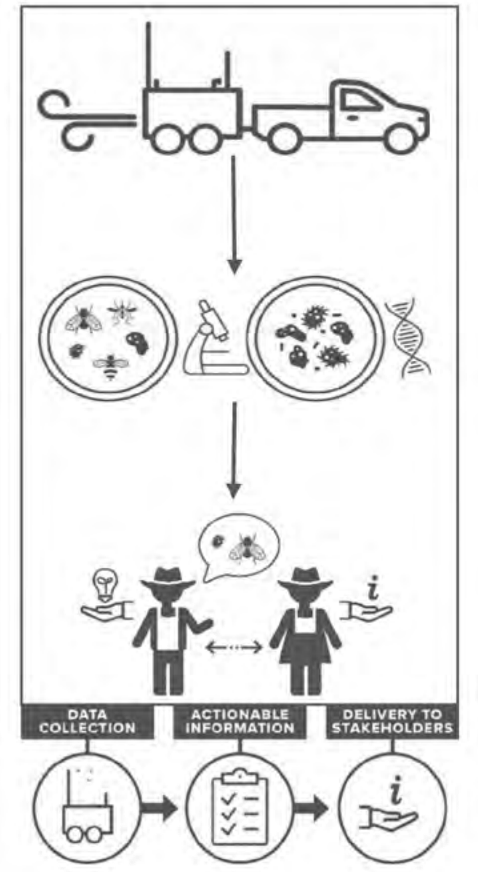

Figure 1. Schematic diagram of how iMapPESTS will boost Australia's on-farm pest management.

The sentinel features four different air sampling devices, including:

1. Two spore samplers: high volume air samplers, specifically designed to collect airborne spores;
2. A two-metre insect suction trap: to monitor localised insect dynamics;
3. A six-metre insect suction trap: ideally suited to monitor long-distance migratory insect flights; and
4. A real-time fungal pathogen monitoring system under collaboration with BioScout.

A key feature of the sentinel, and its auxiliary surveillance systems, is its ability to provide localised information that impacts a specific region, which may not apply to growing regions in other parts of the country.

After the sentinel captures airborne pests and pathogens, including many long-distance dispersal insects such as aphids and thrips, the samples are sent to laboratories for inspection and diagnosis

Figure 2. The iMapPESTS sentinel prototype (which is the first of six such units to be developed as part of iMapPESTS) situated at the Hart Field Site in South Australia's Mid North region during spring in 2019. Internal components visible when the unit is open, and solar panel array to charge its battery banks in the foreground.

of key targets by specialist entomologists and molecular diagnosticians.

Identification of industry priority targets

Laboratory analyses of the sentinel samples establishes which priority pests and pathogens are present, and in what quantities. A combination of traditional methods of identification (morphological identification) are compared against more rapid, high-throughput technologies (SARDI Molecular Diagnostics Centre) with the aim of speeding up detection for faster delivery of information to end users.

The priority airborne pests and pathogens being monitored and reported by iMapPESTS have been established in consultation with the industry partners. The current list of targets relevant to the grains industry is listed in Table 1. Many of the grains industry's targets also impact other plant industries (for example, green peach aphid), which means data and information can be provided to multiple industries concurrently. It is important to note that not all of the grains industry's targets listed in Table 1 can be identified in the sentinel samples using diagnostic techniques that are available at the present time. Validated diagnostic protocols must be established in the laboratory before these targets can be monitored and reported. The targets marked with an asterisk in Table 1 are those with available diagnostic capability to monitor and report for the grains industry.

The grains list is a subset of a broader, cross-industry list that is continually reviewed and triaged according to industry needs and capacity to accurately detect in the laboratory. As a proof of concept, the aim is to accurately and rapidly monitor and report the targets on the broader list during the life of iMapPESTS, but not to make the list as exhaustive as possible. If time and resources permit, the current broader list may be expanded to include more targets for monitoring and reporting.

Extension to industry stakeholders

Data on the presence and abundance of priority targets detected in each sentinel sample are collated in the iMapPESTS cloud-based database and overlaid with basic weather data captured by the sentinel during in-field surveillance to provide context around the pest and pathogen data. The resulting data set on pest and pathogen dynamics is then summarised, visualised and disseminated via the iMapPESTS web-based communication platform to relevant audiences in a timely manner (available at www.imappests.com.au).

The iMapPESTS website is the central point for end-users to stay up to date with RD&E outcomes, news and media, and the current location/s of the sentinels. Surveillance and diagnostics data and information relating to sentinel surveillance activities are published on the iMapPESTS website in a user-friendly format, designed to offer different levels of information to the user. Flexible and dynamic data visualisations are offered so that users can

Table 1. The list of grains targets being monitored and reported by iMapPESTS. Those marked with an asterisk are validated diagnostic assays and protocols which are currently being developed to align to morphological diagnostics; Remaining targets are at various stages of protocol design/testing and are not yet ready for reporting.

	Target type/trap method	Common name	Scientific name
1*	Insect/suction	Green peach aphid	*Myzus persicae*
2*	Insect/suction	Russian wheat aphid	*Diuraphis noxia*
3*	Insect/suction	Bird cherry oat aphid	*Rhopalosiphum padi*
4*	Insect/suction	Western flower thrips	*Frankliniella occidentalis*
5	Insect/suction	Corn leaf aphid	*Rhopalosiphum maidis*
6	Insect/suction	Rose grain aphid	*Metopolophium dirhodum*
7	Insect/suction	Green vegetable bug	*Nezara viridula*
8	Insect/suction	Green mirid	*Creontiades dilutes*
9	Pathogen/suction	Sclerotinia Stem Rot	*Sclerotinia minor, Sclerotinia sclerotiorum*
10*	Pathogen/suction	Black leg of canola	*Leptosphaeria maculans*
11*	Pathogen/suction	Blackspot of field peas	*Didymella pinodes*
12*	Pathogen/suction	Septoria	*Zymoseptoria tritici*
13*	Pathogen/suction	Botrytis Bunch Rot/Fungi Botrytis	*Botrytis cinerea*
14	Pathogen/suction	White grain disorder	*Eutiarosporella tritici-australis, Eutiarosporella darliae/ pseudodarliae.*

customise to interrogate the different aspects of the data generated, such as timing and weather events, against pest and pathogen data.

The iMapPESTS team aims to work closely with growers and industry representatives to understand the best ways to visualise and communicate pest and pathogen information to its end-users; sharing which targets the sentinel is detecting in a particular region at a given time. As the iMapPESTS network is further developed, growers, agronomists and consultants will be connected via multiple communication platforms to enable fast and efficient transfer of information to decision makers on-ground.

Has iMapPESTS commenced operations in the grains industry?

The sentinel prototype was completed in mid-2019 and its inaugural deployment for in-field tests was in the spring of 2019 where the iMapPESTS team showcased the unit, and the iMapPESTS project more broadly, at the Hart Field Day (South Australia); a key agronomic research site in South Australia's Mid North region (Figure 3). This industry-based launch of iMapPESTS provided the first opportunity to canvass industry (grains) stakeholders and marked the commencement of the first in-field trial and optimisation phase. This deployment also allowed for further testing and optimisation of its operations and downstream diagnostic workflows, as well as an opportunity to gather user feedback on pest and pathogen information products from industry stakeholders.

The outcomes of the four-week trial at the Hart Field Site are available via the iMapPESTS website, and are summarised as follows:

Insect results

The total number of each target insect counted in collected samples for each week is presented in Figures 4-7. A comparison between the 2m and 6m insect suction traps was also made (Figure 7).

For the three aphids (GPA, BCOA and RWA) a general trend of increasing winged aphid numbers can be seen in response to the maturation and dying off of host plants (for example, canola and cereals). This forces aphids to take wing in search of new green hosts. The decrease in aphid numbers in week 4 may suggest that most winged aphids have already found their new host or have died trying. The amount of green bridge available in the area will partially determine how well aphids survive over summer to reinfect crops in the new season.

Figure 3. Hart Field Day onlookers during a demonstration of the iMapPESTS sentinel presented by SARDI research scientist, Dr Rohan Kimber.

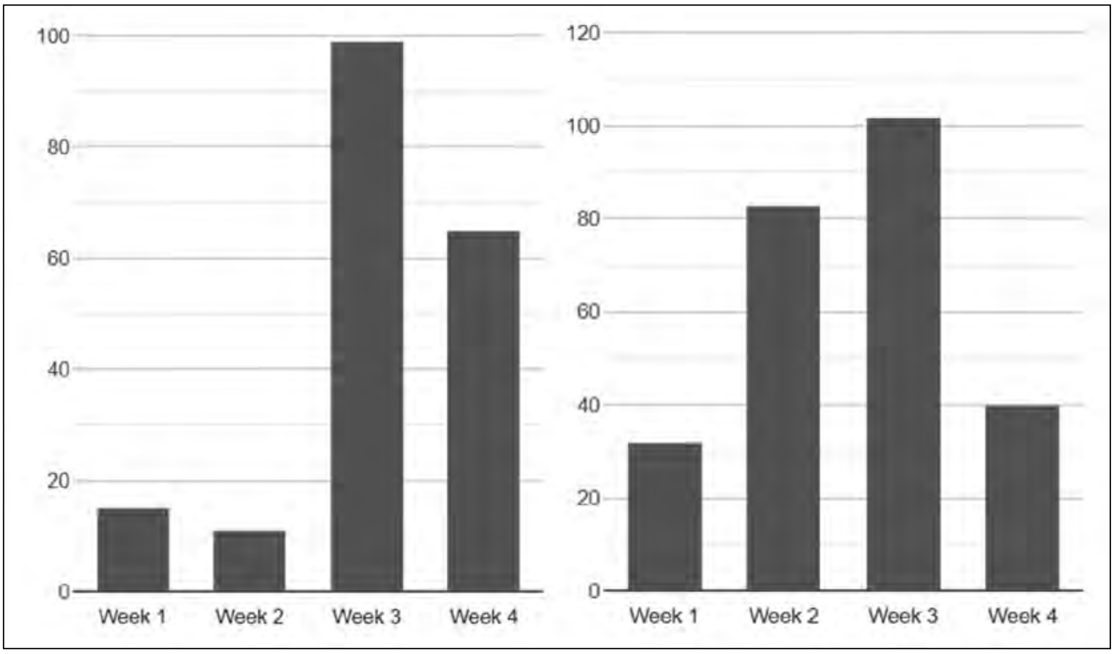

Figure 4. Total counts of green peach aphid (GPA; left) and bird cherry oat aphid (BCOA; right) by week identified in the suction trap samples during the Hart Field Site trial.

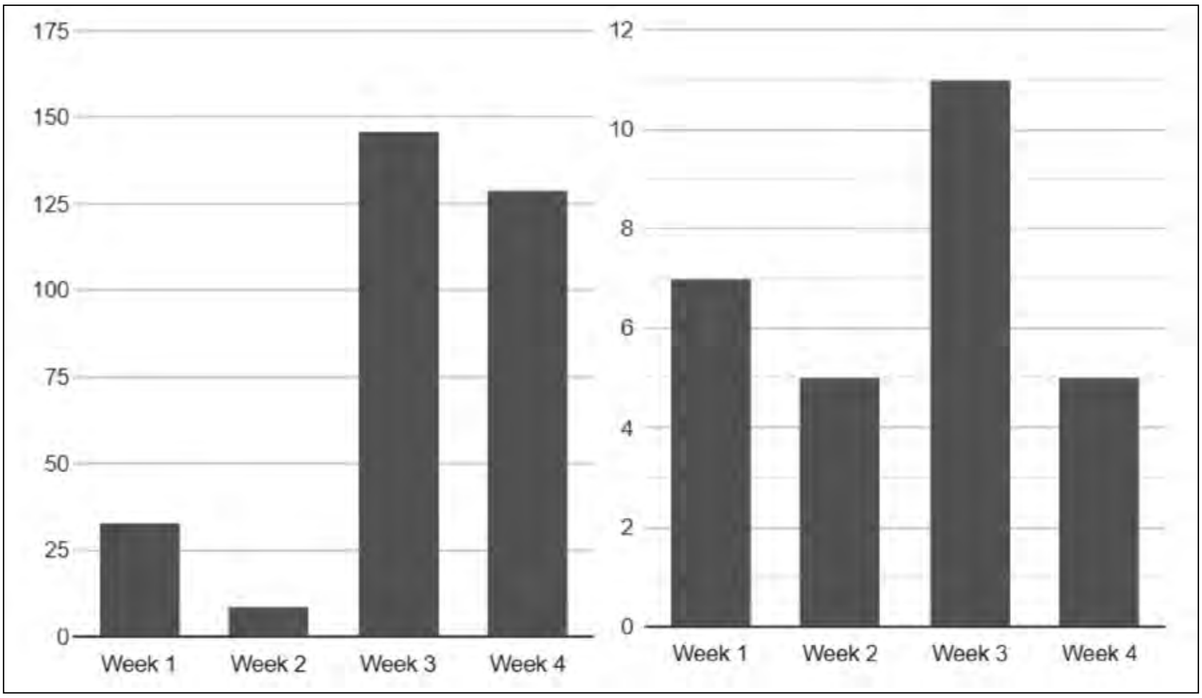

Figure 5. Total counts of Russian wheat aphid (RWA; left) and western flower thrips (WFT; right) by week identified in the suction trap samples during the Hart Field Site trial.

Western flower thrips are now ubiquitous in many Australian landscapes due to their wide host range. Whilst rarely an issue in the grains industry, they survive on some crops and build up populations that can impact on vegetable horticulture by the transmission of viruses such as Tomato spotted wilt virus. As with aphids, warm weather and the decreasing quality of host plants will prompt them to take to the air and be moved about in wind currents. In all the samples, the dominant thrips species was *Thrips imaginis* (Plague thrips) which may look like WFT but is far less damaging.

More aphids were collected in the 6m trap compared to the 2m trap. The shorter suction trap will generally provide information about the insects in the immediate paddock or property, whereas the taller 6m trap will mostly represent what is happening at a larger (potentially regional) scale.

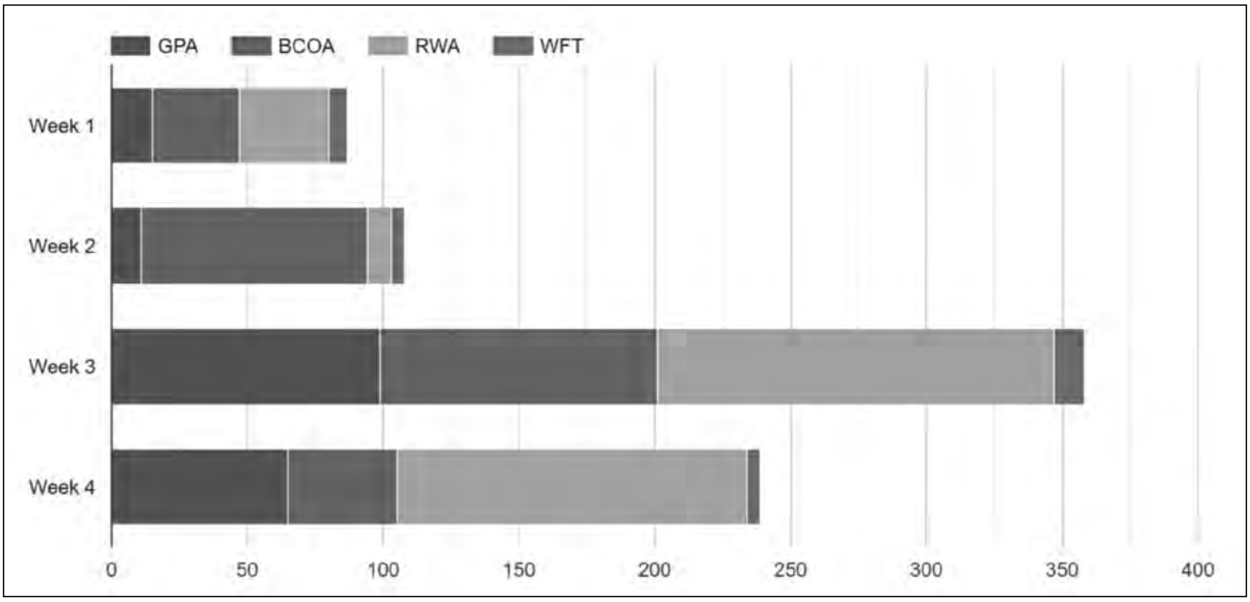

Figure 6. Relative abundance of each insect target by week identified in the suction trap samples during the Hart Field Site trial (order of display within the column bar: GPA, BCOA, RWA and WFT).

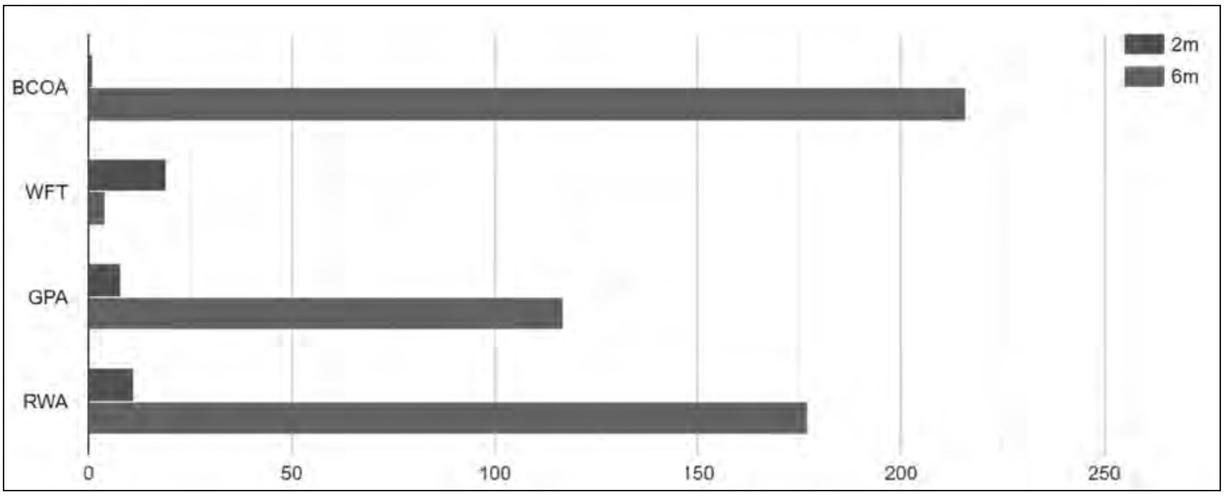

Figure 7. Total counts of each insect target identified from the 2m (top bar within each insect target) and 6m (bottom bar within each insect target) suction traps.

Insects captured from a 6m height are mostly those that have been caught up in wind currents (small insects) or are flying a migratory pattern (larger insects). Given that insect pests are well managed at the Hart site, it is not surprising that the taller trap collects higher numbers as well as a greater diversity of insects. Additionally, the two insect traps use slightly different methods of suction which may impact on the number and type of insects captured.

Pathogen (spore) results

Spore data is normalised to 100% of the maximum counts detected for each target pathogen by week and presented in bar graphs (Figures 8 and 9).

Blackleg of canola spore release increased steadily over the four-week period. This is likely driven by a rain event (10mm) prior to week 1 and a small rain event (2mm) at the end of week 2 causing subsequent spore maturation and liberation.

Maximum botrytis spore release was observed in Week 2 and Week 4. Spore release is typically driven by high humidity within crop canopy and wind events for dispersal.

Blackspot of field peas spore release increased steadily over the four-week period. This is likely driven by a rain event (10mm) prior to week 1 and a small rain event (2mm) at the end of week 2, causing subsequent spore maturation and liberation.

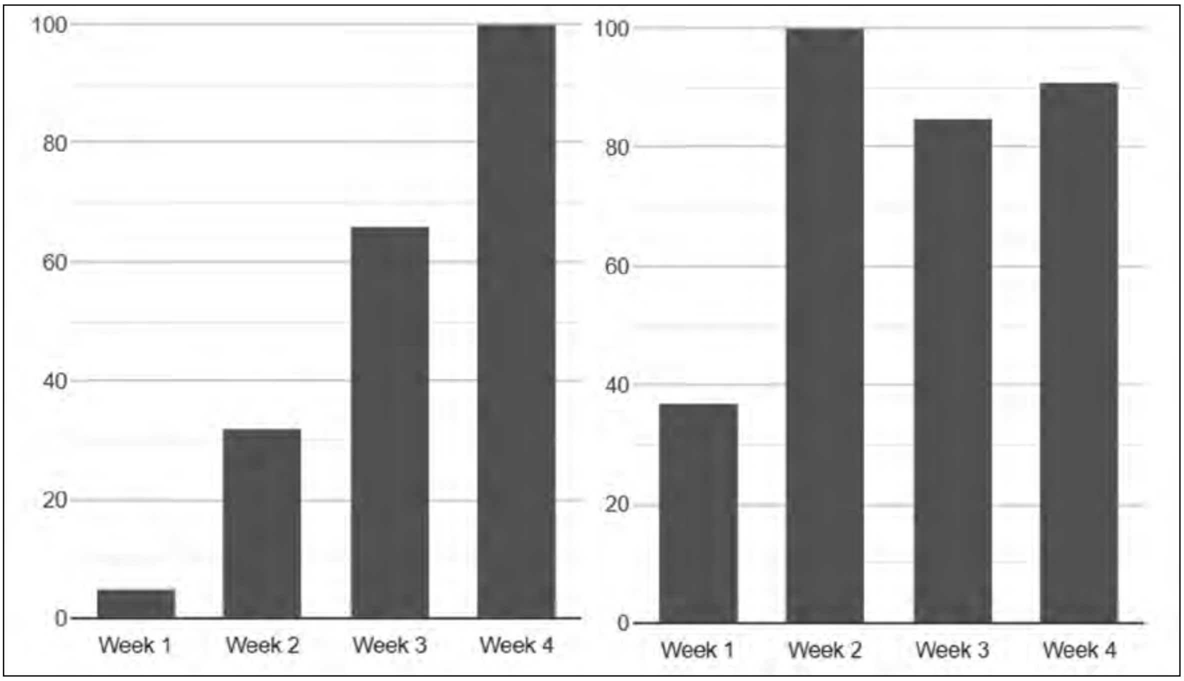

Figure 8. Total counts (normalised) of blackleg of canola (left) and botrytis grey mould (right) by week identified in the spore samples during the Hart Field Site trial..

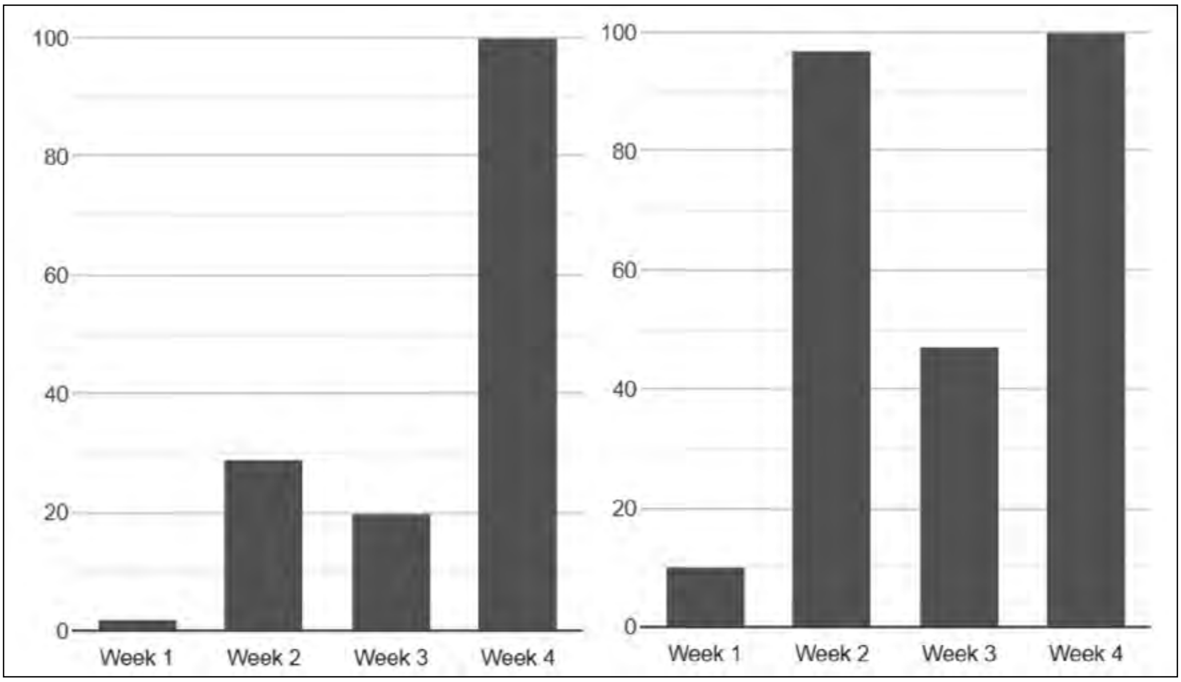

Figure 9. Total counts (normalised) of blackspot of field peas (left) and septoria (right) by week identified in the spore samples during the Hart Field Site trial

Maximum septoria spore release was observed in Week 2 and Week 4. Spore release is typically driven by leaf wetness periods, particularly from leaf debris on the soil surface.

Where is iMapPESTS now?

In mid-November 2019, a second trial phase of the sentinel prototype commenced at the Nuriootpa Research Station in South Australia's Barossa Valley.

The results of this viticulture-focussed trial will be made available via the iMapPESTS website at the trial's completion in late January 2020. Solutions are being explored on how to produce more detailed and informative visualisation products for the Nuriootpa trial data to communicate to industry, including Grafana (the open observability platform) and other similar solutions.

The production of a second sentinel is also currently underway. Once that sentinel is completed (February 2020) it will be deployed for a testing and optimisation phase in Northern Queensland for approximately three months. The wet and humid conditions during the wet season will provide valuable learning opportunities that can be incorporated into subsequent sentinel designs (and, ultimately, demonstrate broad scale application and impact of the sentinels).

What's on the horizon for iMapPESTS?

From mid-2020, additional sentinels will commence construction and once delivered will be deployed at strategic sites across the country in collaboration with industry partners. At each site, pilot user groups will be formed to capture user feedback and continuously improve outputs and outcomes generated across iMapPESTS.

A detailed deployment plan is currently being developed for each sentinel spanning the remainder of the term of iMapPESTS. With limited time and resources and the aim of demonstrating cross-sectoral impact, the aim is to spread efforts across as many industries as possible and prioritise relative high-risk targets. This strategy will demonstrate to each of the industry partners, the application and utility of the different tools and technologies that are being explored within iMapPESTS.

For more information about iMapPESTS, and to stay up to date on where and when the sentinels will be deployed in your region, please visit the website (www.imappests.com.au).

Acknowledgements

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The research undertaken in this project was 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.

Useful resources

iMapPESTS website: www.imappests.com.au

BioScout, realtime monitoring technology: www.bioscout.com.au

Hart Field Site website: www.hartfieldsite.org.au

Data Effects (data visualisation): www.dataeffects.com.au

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Notes

Notes

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Final session Day 2

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.

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Impact of climate change on southern farming systems

Peter Hayman.

SARDI, Climate Applications.

GRDC project code: : RnD4Profit-16-03-007 Forewarned is forearmed

Keywords

- climate change, adaptation, climate variability.

Take home messages

- It is important to consider both climate variability and climate change.
- The projections show a continuation of the warming and drying that has been seen in the southern grains belt. The confidence in the trends and projections is higher for temperature than rainfall.
- Adaptable, information-rich farming systems are needed. This includes understanding phenology, making the most of rainfall that falls at any time of the year, responding to seasonal variability, vigilance for pests and disease and an appropriate level of optimism.

Background

In 2019, Australia experienced the driest year on record (drier than 1902) and warmest year on record (half a degree hotter than 2013 and 2 degrees hotter than 1961-90 reference period). Many in the southern grains region have been through a series of very difficult years. This poses the obvious question as to what to expect in the coming decades? Should the recent past be interpreted as the challenges of our variable climate or how much is a manifestation of what is to come with climate change? The simple answer is that there are components of both variability and change with higher confidence for trends and projections of warming than drying. It is important to think clearly about the interaction between climate variability and climate change, cycle and trend, hot spell and warming, drought and drying, a run of poor seasons and increased aridity.

As a general observation, rural communities are much more aware of year-to-year and decade – to-decade variability in climate compared to urban communities. Some commentators remarked that, for urban communities, water restrictions during the Millennium drought (2002 to 2009) provided an abrupt realisation of vulnerability to climate. Following from this shock, there seemed to be greater acceptance of climate change. For rural communities, the deep understanding of past runs of poor years and good years leads to a greater emphasis on variability and a caution or suspicion about attributing events to climate change. This is mainly because variability is part of lived experience and understanding passed down from parents. An additional factor is that because the climate plays such an important part in livelihoods, discussing a negative trend is confronting. While some might say that when a crop runs out of water or is hit by a heat event that the distinction between variability and change doesn't matter, I disagree. A neighbour saying that they have had enough and are selling up because of drought (variability) is quite different to saying they are leaving due to increased aridity (long term and ongoing change). The central point for the grains industry (and wider society) is that we need to shift the conversation from either variability **or** change, waves or tides to a respectful conversation on variability **and** change, waves **and** tides.

Climate variability and climate change – waves and tides; cycles and trends

Climate variability is the year-to-year changes in seasonal conditions due to the internal forcing of the climate system (for example, El Nino Southern Oscillation (ENSO) or Indian Ocean Dipole (IOD)). Many grain growers are aware of these major drivers of climate. GRDC has invested in the Climate4Profit and the R&D for Profit project, working with the Bureau of Meteorology (BoM) on climate extremes. More effective management of seasonal variability is well recognised as one of the most effective ways to manage long term risk.

Climate change is manifested as a longer-term trend due to external forcing that comes from astronomy (distance from the sun), volcanoes and changes to levels of green-house gases. Human induced climate change or the enhanced greenhouse effect refers to the changes in the radiative properties of the atmosphere due to human activity. Earlier reports of the Intergovernmental Panel on Climate Change (IPCC) stated that the warming of the climate system is unequivocal. The fifth and most recent assessment report states; 'Human influence on the climate system is clear' and assess that there is a 95 to 100% probability that human influence was the dominant cause of global warming in the last 50 years. The attribution of the cause of warning increases confidence in the trend and indicates that the future depends on choices made by the global community.

A simple but powerful analogy used by the late eminent climate scientist Stephen Schneider is to consider a vulnerable system (like a grain crop) being impacted as a sandcastle with waves (climate variability) and tides (climate change). Following any damaging climate event such as drought, fire, heatwave or flood, the question is often posed as to how much can be attributed to climate change (the tide) and how much to climate variability (the wave). It is almost always the wave that destroys the sandcastle, but on a rising tide the waves do more damage. Another analogy for the same purpose is a man walking in a consistent direction (trend) with a dog on a lead (variation) (https://www.climate.gov/teaching/resources/dog-walking-weather-and-climate).

Although Guy Debelle, deputy governor of the Reserve Bank didn't use analogies of sandcastles or dogs, in 2019 in his speech on monetary policy that distinguished between shocks and trends he noted that economists were used to considering climate shocks (such as a cyclone destroying most of the banana crop or low production due to drought). These climate shocks are treated as temporary and discrete rather than a trend. He posed the question 'What if droughts are more frequent, or cyclones happen more often? The supply shock is no longer temporary but close to permanent. That situation is more challenging to assess and respond to (https://www.rba.gov.au/speeches/2019/sp-dg-2019-03-12.html). This involves looking back to interpret the recent past and accessing information on what climate science is projecting for the future.

Looking back at trends in the climate

In 2019 the BoM, CSIRO and FarmLink were funded by the Commonwealth Government in a $2.7M project to develop regional weather and climate guides for all natural resource management regions across Australia. These guides compared the weather records of the last 30 years (1989 to 2019) with the previous 30 years (1959 to 1989) (http://www.bom.gov.au/climate/climate-guides/). GRDC was consulted on the design of the information (https://groundcover.grdc.com.au/story/6447986/southern-nsw-growers-get-up-to-date-climate-outlooks/).

The main conclusions for the Northern and Yorke Peninsula regions of South Australia (SA) are as follows:

- Annual rainfall has been relatively stable.
- There have been seven years drier than average and nine wetter.
- There has been a decrease in rainfall in the autumn months.
- Winter rainfall has been reliable; summer rainfall has been unreliable.
- There have been more frosts and they have been coming later.
- There have been more hot days, with more consecutive days above 40°C.

The recent past has been dominated by the extensive Millennium Drought (2002 to 2009) which can be shown in Figure 1 rainfall across South East Australia. The drought ended with widespread rain from the 2010 La Nina. The only other wet year since the Millennium Drought has been the negative IOD of 2016. The wet springs of 2010 and 2016 were reasonably well forecast in winter by the BoM. Some, but not all of the dry springs were forecast.

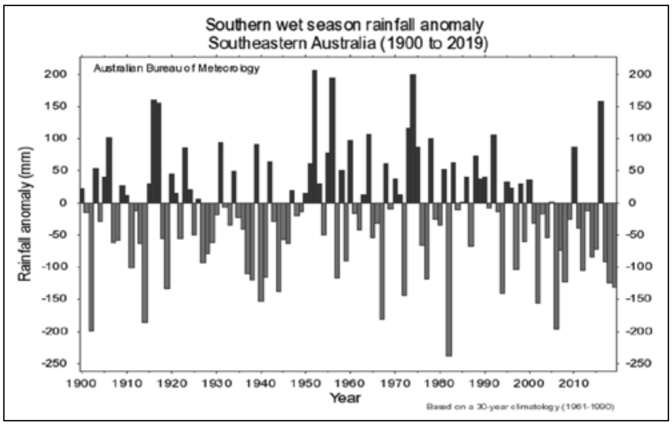

Figure 1. April to November rainfall for south eastern Australia (line from Newcastle to Ceduna) (Source: Bureau of Meteorology).

GRDC has invested in a large project titled 'Forewarned is Forearmed' with the BoM to improve the forecast and management of extreme events on a multi-week to seasonal time scale. Another investment in a project led by Agriculture Victoria with input from SARDI and Federation University has funded the Break newsletters and produced a local climate tool where anyone can check the impact of climate drivers on their rainfall (https://climatetool.forecasts4profit.com.au/)

Looking forward with climate change projections

The first climate change projections for Australia were prepared for the Greenhouse 1987 conference and since then projections have been released by CSIRO in 1990, 1991, 1992, 1996 and 2001, 2007 and 2015 (Whetton et al. 2016).

Current projections for Australia are available at the Climate Change in Australia website (https://www.climatechangeinaustralia.gov.au/en/). The SA Government also provides climate change projections (https://data.environment.sa.gov.au/Climate/SA-Climate-Ready/Pages/default.aspx)

Key findings from the Climate Change in Australia report for the southern grains belt include:

- Average temperatures will continue to increase in all seasons (very high confidence).
- More hot days and warm spells are projected with very high confidence. Fewer frosts are projected with high confidence.
- By late in the century, less rainfall is projected during the cool season, with high confidence. There is medium confidence that rainfall will remain unchanged in the warm season.
- Even though mean annual rainfall is projected to decline, heavy rainfall intensity is projected to increase, with high confidence.
- A harsher fire-weather climate in the future (high confidence).
- On annual and decadal basis, natural variability in the climate system can act to either mask or enhance any long-term human induced trend, particularly for rainfall in the next 20 years.

The Climate Change in Australia report compared 70 global climate models. All models show future warming in all seasons of the year. In contrast, there is a disagreement between model projections for annual and seasonal rainfall. Figure 2 shows

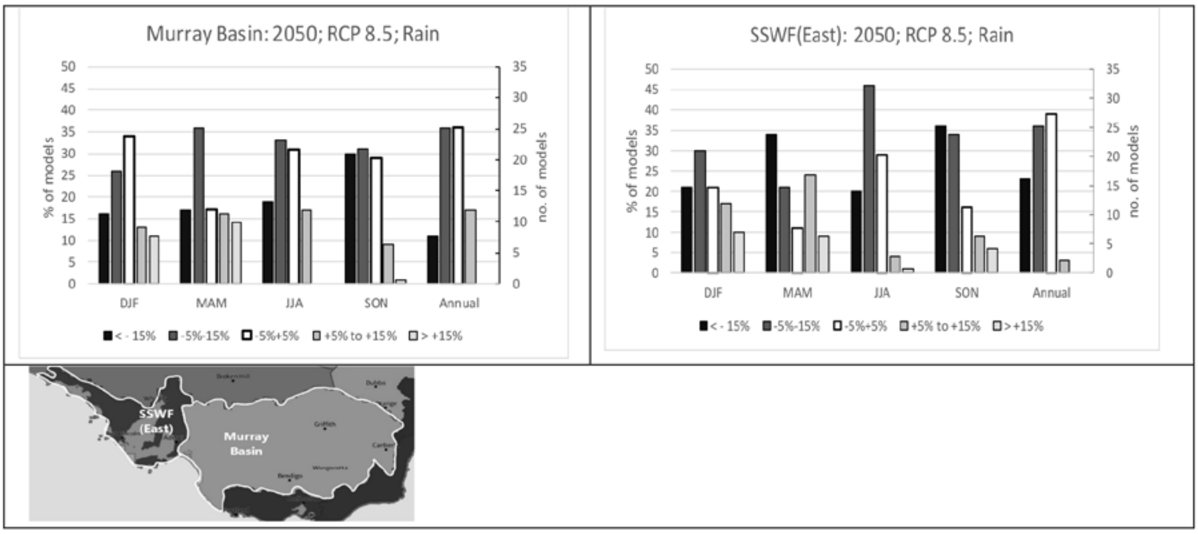

Figure 2. Climate projections for seasonal and annual rainfall changes for 2050 using a high emission Representative Concentration Pathway (RCP) 8.5 for the Murray Basin region (left) and SA to the west of Mt Lofty Ranges (right). Y-axes show data as the % of models (primary) and number of models (secondary) from the full 70 models. Data from the Climate Change in Australia website.

the number of models in different categories of wetter or drier futures. Using the annual columns for the Murray Basin as an example; the white bar represents no change (-5% to +5% by 2050) and this is the result for about a third of the 70 models. The bars to the left of the white bar show a third projecting moderate drying (-5% to -15%), eight models show severe drying (>15%). The bar to the right of the white bar indicates 12 of the 70 models show a moderate wetting (+5% to 15%). Summer (DJF) and autumn (MAM) show the widest spread but there are more models showing drying than wetting. Winter and spring show more pronounced drying with the strongest projection of drying in spring. The SA grains belt to the west of the Mt Lofty Ranges is covered by the Southern and South West Flatlands (SSWF). There are more models showing drying for this region.

In 2018, the National Environmental Science Programme (NESP) built on the 2015 Climate Change in Australia Report producing a summary document on long term trends and future projections for rainfall in Southern Australia (http://nespclimate.com.au/wp-content/uploads/2018/12/ESCC-NESP-Southern-Australia-6pp-WEB.pdf). The report concludes that the general drying trend over southern Australia over the past 50 or so years is likely to continue in the future. Key findings are as follows:

1. The intensification of the subtropical ridge (Pepler et al. 2018)– the pattern of cooler wetter winters and hot dry summers is driven by annual progression of the subtropical ridge from a summer position of 40°S (between mainland and Tasmania) and a winter position of 30°S (Maree SA, Bourke NSW). There is more confidence in the intensification (higher pressures) across southern Australia than a consistent latitudinal shift.
2. A trend towards positive Southern Annular Mode (SAM) (Lim et al. 2016). A positive SAM indicates a contraction of westerly winds and reduced winter rainfall for southern mainland Australia (and wetter summers). The impact of SAM on winter drying is more pronounced on the southern edge of the continent.
3. An increase in extreme ENSO and IOD events leading to greater variability (Power et al. 2018).
4. After assessing the 70 models used in the Climate Change in Australia report, Gross et al. (2017) used 15 models that best represented rain-bearing circulation for southern Australia. These 15 models showed a stronger drying especially in the winter.

In late October 2019 a group of 15 Australian climate scientists held a workshop on the science of extreme event attribution. In this context, attribution addresses the role of anthropogenic climate change in modifying the likelihood, intensity, duration or frequency of a particular extreme event. Table 1 is a qualitative assessment of the ability of the latest climate models to represent specific extremes (model capability), the quality and length of the observational record for extremes (observations) and the level of physical understanding of how anthropogenic forcing influenced the extreme (understanding). The percent of disagreement amongst the 15 workshop participants represents approximately the number of participants expressing ‘strong disagreement’ (https://view.joomag.com/bamos-vol-32-no4-december-2019/0270132001576909864).

It is important to note that these are qualitative rankings from a workshop and are more usefully interpreted as relative rankings rather than objective ratings of confidence. The lower level of

Table 1. Qualitative assessment of the ability of the latest climate models to represent model capability, observations and understanding.

Event	Model capacity	Observational record	Understanding	Percent disagreement
Extreme cold	High	High	High	0%
Extreme heat	High	High	High	0%
Marine heatwaves	High	High	High	0%
Fire relevant fuel	Low	Low	Medium	0%
Fire weather	Low	Medium	Medium	10%
Extreme rain	Medium	High	Medium	10%
Drought	Medium	Medium	Low	40%

understanding of the process of drought and the high level of disagreement with the rankings on drought indicate that this in an area of active debate and research. It would be a mistake to interpret the lack of understanding or agreement as an indication that rainfall won't change.

The role of human induced climate change in the catastrophic bushfire summer of 2019/20 has gained worldwide attention. There is widespread acceptance of the warming, but there is less clarity on the lack of rainfall. The extreme drought leading up to the summer was consistent with the positive IOD and the positive SAM and these can be considered drivers of variability or waves. However, there may be some indication of longer-term trends or a tide. In a response to the Guardian newspaper on 13 January 2020, Professor Matthew England, UNSW Climate Change Research Centre said: 'These modes of variability are not changing in a way that's good for south-east Australia… we are stacking the dice for the chances of these extreme drought years because of the changes in the [IOD and SAM] modes.' https://www.theguardian.com/environment/2020/jan/13/explainer-what-are-the-underlying-causes-of-australias-shocking-bushfire-season

Exposure, sensitivity and adaptive capacity of the southern grains industry

Returning to the earlier analogy of a sandcastle by the beach, some sandcastles are more vulnerable than others. The vulnerability of a natural or managed system to climate can be considered as the difference between impact and adaptive capacity (Figure 3). In this simple diagram (Figure 3), the impact of climate is the result of exposure and sensitivity. A high value horticultural crop in a glass house is **sensitive** to climate, but not **exposed** whereas a slow growing rangeland shrub is **exposed** but less **sensitive**. Recent seasons have highlighted that the grains industry in Australia is both exposed and sensitive to adverse climatic conditions such as drought, frost and heat. In a managed system such as cropping, adaptive capacity includes the varieties, equipment, chemicals and know-how in dealing with the variable and changing climate. Impressive crops produced under difficult circumstances in recent years show the high degree of adaptive capacity within the Australian grains industry.

In Table 2 the broad concept of climate change is broken down into components of seasonal heat, extreme heat, frost, seasonal rainfall, extreme rain events and changes to carbon dioxide (CO_2) levels. This allows comment on the level of confidence from climate science on the exposure, confidence on crop science on sensitivity, and agronomy on management (Hayman, O'Leary and Meinke, 2019).

There are some changes such as increase in mean temperature where the confidence from both climate science on projections and agricultural science on impacts are high. This contrasts with changes to rainfall where the confidence in the projections is lower, but the impacts on cropping of changes to rainfall are very well understood. The interaction between these six aspects of climate change is important but uncertain. For example, elevated carbon dioxide is likely to partially offset some of the impacts of a decline in rainfall, but it is less clear how a drier, but carbon dioxide enriched future will respond to a heat wave.

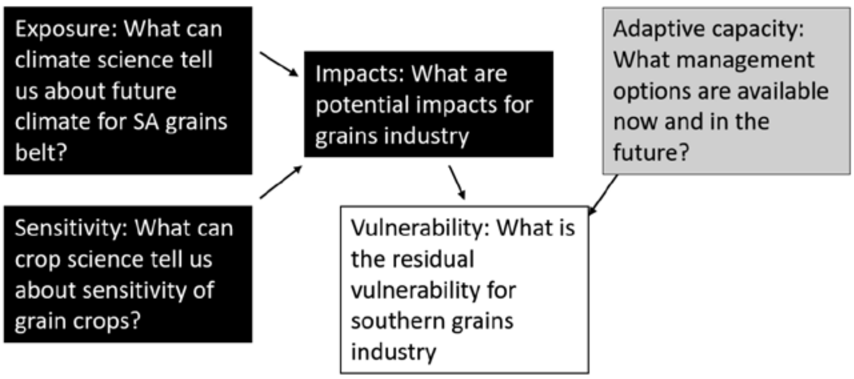

Figure 3. Vulnerability is determined by impacts and adaptation. (see Turner 2013 for review and critique of frameworks).

Table 2. Components of climate change and commentary regarding exposure, sensitivity and adaptive capacity (Source: Hayman, O'Leary and Meinke, 2019).

1. Increased mean temperature	
Confidence from climate science (exposure)	**Very high** All parts of the southern grains region have warmed and are expected to warm in the future. Because inland regions are drier, they are expected to warm faster than coastal regions. The greatest trends in warming across most of the region has been in spring, this may be largely due to a decline in spring rainfall.
Confidence of impact from crop science (sensitivity)	**High** confidence that the rate of crop development will increase. Growth rates for winter crops will increase in cooler months and regions. Higher temperatures contribute to a modest increase in potential evapotranspiration. Hot conditions can contribute to more challenging conditions for crop emergence. Increased mean temperature will change the weed and disease spectrum.
Management options (adaptive capacity)	Understanding the drivers of crop development can be used to better match varieties to the climate. In a warmer world, slower maturing varieties will develop more quickly. GRDC is investing in ongoing work on measuring and modelling the phenology of cereals and pulse crops in the current and future climates. This analysis includes the interaction of water stress with the timing of heat and frost events. Stubble retention will reduce evaporation and keep the seedbed cooler. CSIRO is investigating the role of long coleoptile wheat varieties.
Residual vulnerability	**Low vulnerability** to warming over coming decades provided that grain growers have access to crops with appropriate development. Vulnerability to warmer seasons will be greatly increased if growing season rainfall was to decline and warming is associated with heat waves.
2. Changes to heatwave frequency and intensity	
Confidence from climate science	**High** confidence that in a warmer world the weather patterns that bring heat to the grains belt will result in more intense heat waves. Confidence is lower on how the weather patterns that set up the hot spells will change.
Confidence of impact from crop science	**Moderate** understanding of the impact of heat on different phenological stages and thresholds for different crops grown in the field and how these impacts are modified by soil moisture. There is ongoing R&D investigating the impact of heat spells at critical stages of cereals and pulses.
Management options	Optimising flowering time of available winter crops and breeding crops that can tolerate high heat loads.
Residual vulnerability	**High vulnerability** to an increase in spring heat events for all dryland winter crops but especially pulse crops. Spring heat events are more damaging when combined with low soil moisture. In cooler than normal springs water use efficiency (WUE) tends to be higher than expected. This suggests moderate heat events might be imposing a cost in most years.
3. Changes to frost frequency and intensity	
Confidence from climate science	**Low** – a perceived paradox that, despite warming, the frequency and intensity of frost has increased in some regions of the southern grains belt. This may be simply due to dry springs or other drivers related to synoptic patterns. It remains unclear whether this trend is due to decadal variability or increased greenhouse gases. The more rapid crop development due to warmer conditions can contribute to frost risk.
Confidence of impact from science	**Moderate to low** – although impact of extreme frost at critical times can be obvious, the exact link between crop minimum temperature recorded in the Stevenson screen and damage to crops is noisy. Frost damage is poorly represented in simulation models.
Management options	Understanding the frostier parts of the landscape and matching land use (for example, livestock on river flats). Using the small amount of variation in frost susceptibility between wheat varieties and greater variation between winter crops (for example barley is less susceptible than wheat). If sowing early (for example, in April) selecting a longer season variety, delaying flowering by sowing time and variety choice seems to be ineffective because of the damage from heat and drought.
Residual vulnerability	Although there is less confidence on the likelihood, there is **high vulnerability** to any increase in frost severity and frequency for many parts of the grains belt. Agronomists working with frost affected farmers refer to both a direct cost of frost damage and an indirect psychological impact on decision making.
4. Changes to seasonal rainfall	
Confidence from climate science	**Moderate** confidence in drying in southern winter growing season, especially spring. **Lower** confidence for other seasons.
Confidence of impact from crop science	**Very high**. There are extensive studies that provide a good basis for understanding water productivity of major crops. Growers and agronomists are highly aware of the impact that the timing and amount of rainfall has on yield and profitability.
Management options	More effective storage of water prior to the growing season and then using the water as efficiently as possible by matching sowing time and cultivar to the environment. The impact of dry autumns can be partially offset by sowing part of the cropping program into dry soil. Many southern region grain farmers have improved their water use efficiency by summer weed control, stubble retention and timely sowing. Some growers are using seasonal climate forecasts to adjust their operations.
Residual vulnerability	**Very high vulnerability**. Although grain growers are highly skilled at managing low rainfall environments, the ongoing profitability of enterprises relies on capturing good seasons and are strongly affected by drier seasons. In medium to higher rainfall parts of the southern grains belt a substantial increase in drier than average growing seasons would greatly reduce confidence in management of input levels. Drier conditions would also reduce the amount of higher return and higher risk broadleaf crops.

Table 2 cont. Components of climate change and commentary regarding exposure, sensitivity and adaptive capacity (Source: Hayman, O'Leary and Meinke, 2019).	
5. Changes in the intensity of rainfall	
Confidence from climate science	**High**. A warmer atmosphere contains more energy and will hold more water. This leads to intensification of the hydrological cycle which further increases variability. There is lower confidence in changes to weather systems that bring high or low intensity of rainfall.
Confidence of impact from crop science	**High** confidence in the impacts of changes to daily intensity. The SA grains belt has numerous low intensity falls (< 5mm) which tend to be inefficient as most of the rainfall wets the surface and is lost in evaporation. A moderate increase in intensity will improve efficiency of soil water gains. An increase in large falls (>20mm) is likely to lead to runoff and erosion and cause problems for operations such as sowing and harvest.
Management options	Stubble retention and other erosion management especially on sloping sites. Many grain growers are using short term weather forecasts to plan operations. This planning leads to improved efficiency and reduces the likelihood of runoff of agricultural chemicals.
Residual vulnerability	**Low vulnerability.** A modest increase in the intensity of rainfall will be beneficial. There are risks of water erosion but these can be managed with stubble retention which has high levels of adoption and co-benefits of reducing wind and water erosion risk and increasing productivity
6. Elevated levels of carbon dioxide	
Confidence from climate science	**Very High.** Future emissions depend on policy and technology. Although the exact concentration is difficult to predict, there is high confidence that future levels will be higher than present.
Confidence of impact from crop science	**High** for growth and yield of crops but **lower** for longer term cropping systems (soil carbon C and N) and grain quality components (for example, protein and its various end use requirements). The growth rate of weeds, pests and disease will also change with elevated CO_2.
Management options	Changes in CO_2 cannot be considered separately from temperature and water supply, and plant breeding advances cultivars suitable to present day conditions by default. In the future there is likely to be deliberate selection of varieties that respond more positively to elevated CO_2. Monitoring of changes to pests and disease and revising nutrition will be essential.

Conclusion

The southern grains industry will continue to deal with a climate that varies year to year and has a warming and most likely a drying trend. Adaptable, information-rich farming systems are needed. Some of the important steps for agronomists and leading farmers are:

- Understand crop phenology –matching variety to environment. GRDC is investing in projects to better characterise phenology.
- Make the most of out of season rainfall.
- Manage the variable seasons through soil moisture monitoring and the use of seasonal climate information.
- Be vigilant for changes to pests and disease.
- Be an informed user of climate science.

Being an informed user of climate science is not easy as there is a vast amount of information. It is also difficult to come to terms with a message that increasingly points to a more challenging future. The southern grains industry is exposed and sensitive to climate, but it also has a high level of adaptive capacity. Not only has there been substantial performance in good seasons, the capacity to produce in difficult seasons is impressive. It is important to maintain an appropriate level of optimism. As Puri and Robinson (2007) put it, 'optimism is like red wine, a glass a day is good for you, but a bottle a day can be hazardous'. From my observations, one of the most effective ways to achieve the appropriate level of optimism, learning and social support is through farming systems groups.

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What is your cost of Harvest Weed Seed Control?

Peter Newman.

WeedSmart.

Keywords

- harvest weed seed control, HWSC, cost, weed control.

Take home messages

- There is no single answer as to which HWSC tool is best. It depends!
- The Estimated Cost of HWSC model aims to give you the most accurate estimate of cost of HWSC based on what we know now.
- The total cost per hectare can be relatively small when all things are considered.
- Give the model (https://ahri.uwa.edu.au/whats-the-cost-of-hwsc-for-you/) a run with your numbers and see what you find.

Introduction

How much does it cost to run a car? It depends. Some cars are expensive to buy but have low maintenance and fuel costs, whereas others are cheaper to buy but guzzle the fuel and need a lot of work to keep them on the road. Harvest weed seed control (HWSC) is just the same. We need to look a bit deeper than the up-front capital cost to get the full story.

The do it yourself narrow windrow burning chute seems cheap at the time, but what is the true cost of this type of HWSC? The answer is, it depends on several factors!

The short answer: HWSC costs $7 to $19 per hectare and there are only minor differences in the cost between the various tools.

The slightly longer answer: For a large farm with lower yielding crops the cost is $7-$10/ha. For a small farm with higher yielding crops the cost is $18-$20/ha.

The whole story: The cost of HWSC depends on a whole range of factors that differs from farm to farm. AHRI have developed an interactive model that enables you to input your details and obtain the best cost estimate for different HWSC methods. The model can be downloaded from the September 2019 AHRI insight (https://ahri.uwa.edu.au/whats-the-cost-of-hwsc-for-you/).

Table 1 demonstrates an example output from the model along with some details explaining all of the assumptions used in the model.

Table 1. Cost ($/ha) of various harvest weed seed control (HWSC) tools. Data from the Estimated Cost of HWSC model. (https://ahri.uwa.edu.au/whats-the-cost-of-hwsc-for-you/). This data represents farms of different sizes and crop yields, all harvested with one harvester.

Crop Area (ha)	Crop Yield	Seed Terminator cost ($/ha)	Vertical iHSD cost ($/ha)	Redekop SCU cost($/ha)	Chaffline cost ($/ha)	Chaff deck cost ($/ha)	Narrow windrow burn cost ($/ha)
2000	Low	$11.76	$9.66	$11.06	$9.94	$11.01	$22.21
2000	High	$19.14	$17.04	$18.44	$19.07	$20.14	$40.47
4000	Low	$7.56	$6.51	$7.21	$9.76	$10.38	$22.19
4000	High	$14.94	$13.89	$14.59	$18.89	$19.51	$40.46

n.b. crop area is 50% cereal, 25% legume and 25% canola.

Table 2. Assumptions used in the model to generate the results presented in Table 1.

	Low yield	High yield
Cereal	2t/ha	4t/ha
Legume	1.2t/ha	2.5t/ha
Canola	1.2t/ha	2t/ha
Reduction in harvest capacity due to mill	0%	10%
Harvest speed	12ha/hour	8ha/hour
Mill life	400 hours	400 hours
Harvest cost for harvester + chaser bin	$400/hour	$400/hour
Extra fuel to run a mill	0.5L/tonne grain	0.5L/tonne grain

Table 1 shows that the lowest cost of HWSC is achieved by larger farms with generally lower yields. This is because the capital cost of HWSC is spread out over a larger area, the nutrient removal costs are lower due to the lower yields, and harvest is not slowed by the mills due to the lower yields. In contrast, the highest cost of HWSC is associated with smaller farms with higher yields. In general, there's only a relatively small difference in cost between all of the HWSC tools except for narrow windrow burning, which is always the most expensive due to the highest nutrient cost. The 'bale direct' tool was not included in this comparison, but in general it is a very high cost and can be profitable if a large market for straw bales exists close to the farm.

Capital cost

The capital cost of HWSC tools are always quickly quoted, but it's important to remember that this is only part of the picture. Table 3 gives an estimate of the capital cost of the various tools but as the laws of competition come into play, these values will most likely change.

Nutrients

One of the most important, and sometimes overlooked costs of HWSC is the value of the nutrients contained within the crop residue that is removed in the process.

Table 3. Approximate capital costs of various harvest weed seed control (HWSC) tools.

HWSC tool	Capital cost
Narrow windrow burning chute	$500
Chaff line chute	$500 to $5000
Chaff deck	$17,000 to $20,000
Vertical iHSD	$90,000 fitted
Seed Terminator	$120,000 fitted
Redekop	$110,000 fitted
Bale direct (baler + Glenvar system)	$340,000

In 2011, the amount of nutrients found in a range of chaff cart dumps and narrow windrows was measured (Table 4). Nutrient analysis was conducted by CSBP, Western Australian fertiliser distributor.

Research by Dr. Michael Walsh has shown that chaff yield averages about 33% of grain yield. In other words, if you are harvesting a 1t/ha wheat crop, approximately 333kg of chaff will be diverted into the chaff cart or chaff line or seed impact mill. This assumption was used to calculate the value of nutrients per tonne of grain harvested (Table 5).

Table 5. The value of the nutrients contained in harvest residue per tonne of grain harvested based on 2019 fertiliser prices

	Value of nutrients in chaff per tonne of grain harvested
Cereal	$5.46
Legume	$7.38
Canola	$6.37

Table 4. Average nutrient content in chaff from chaff cart dumps in 2011 in Western Australia.

	Nitrogen	Potassium	Phosphorus	Sulphur
	units N per t chaff	units K per t chaff	units P per t chaff	units S per t chaff
Cereal	5	8	0.5	0.5
Legume	10	8	0.6	1
Canola	7	8	0.6	2

n.b. Legume = lupin

Nutrient spread

For chaff lining and chaff decks, the residue is not removed from the paddock but is placed in narrow zones that are not available to the whole crop, so it is assumed that the nutrients are lost. The nutrient cost of seed impact mills is assumed to be zero as the pulverised crop residue is returned to the field. However, if the mill cannot evenly redistribute these nutrients, perhaps this cost needs to be included. When observing the mill, it's important to consider if it's achieving an even spread.

Cost of ownership

To calculate the cost of purchasing a HWSC tool, depreciation and interest rate are added together and multiplied by the capital cost. This value is then divided by the hectares harvested by each harvester to give a $/ha cost. Consultants generally use a figure of 10% depreciation per annum for agricultural machinery (some machinery depreciates faster and some slower). At this point in time there is no measure of how fast weed impact mills depreciate, and therefore, the average of 10% is used. Interest rate is included in the cost of purchasing as there is an opportunity cost for the money used to purchase the tool.

Harvest cost

The cost of harvest is important because if the HWSC tool slows the time taken to harvest the crop, there is an increase in the cost of harvest per hectare.

Growers should estimate their own harvest cost and it should include depreciation, fuel, labour, repairs and maintenance, interest, etc. Also don't forget to include the cost of running the chaser bin as part of the harvest cost.

Reduction in harvest capacity

Some of the HWSC tools can slow harvest, although a wide range of stories have been reported from farmers. Most farmers with chaff carts comment that they do not slow harvest at all, whereas some farmers say they slow harvest a little bit by perhaps 5%. The seed impact mills can slow harvest if the harvester is limited by its horsepower. Some farmers chip the engine to boost horsepower and report no reduction in harvest capacity. In general, in lower yielding crops where horsepower is not limiting there is no reduction in harvest capacity with the use of HWSC tools. In higher yielding crops, 5 to 10% reduction in capacity is common, with some growers reporting as much as a 25% reduction.

Fuel

There are a range of extra fuel costs quoted for seed impact mills and chaff carts. The figure of 0.5L/tonne of grain harvested of extra fuel for the mills is assumed in the model. Growers interviewed for this study, quoted anywhere from 0.3L/t grain to 1.5L/tonne of grain.

Wearing parts of impact mills

Assuming the cost of wearing parts in impact mills is a moving target, now, due to the emphasis the manufacturers of the mills are placing on product development to reduce wear rates. A pair of mills costs in the order of $9000 to $11,000 to replace. Mill life can be anywhere from 150 to 700 hours with 400 hours being the current average. At 400-hour mill life and $9500 for a new set of mills, this works out to be roughly $3/ha.

Repairs and maintenance (R&M)

To estimate this cost, it is best to check with the seller of the machine. Values used in the model are an educated guess for all of the HWSC tools.

Other benefits of residue retention

There are benefits to the soil biology and moisture from retaining crop residue, however an accurate figure to use was not found.

Grazing chaff cart dumps, chaff lines and chaff deck with sheep

Grazing chaff can be both beneficial to the sheep and is likely to redistribute some of the nutrients back over the paddock. These benefits may negate some of the cost of these tools and in some cases may result in the HWSC tool being free; particularly in cases where grazing chaff dumps or lines reduces the cost of supplementary feeding of sheep.

Conclusion

There is no single answer as to which HWSC tool is best. It depends! The Estimated Cost of HWSC model aims to give you the most accurate estimate of cost of HWSC based on what we know now. Even though there can be a big difference in capital cost between the HWSC tools, the total cost per hectare can be relatively small when all things are considered. Give the model a run with your numbers and see what you find. The model can be downloaded at: https://ahri.uwa.edu.au/whats-the-cost-of-hwsc-for-you/

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THE 2017-2020 GRDC SOUTHERN REGIONAL PANEL

JANUARY 2020

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CHAIR - JOHN BENNETT

Based at Lawloit, between Nhill and Kaniva in Victoria's West Wimmera, John, his wife Allison and family run a mixed farming operation across diverse soil types. The farming system is 70 to 80 percent cropping, with cereals, oilseeds, legumes and hay grown. John believes in the science-based research, new technologies and opportunities that the GRDC delivers to graingrowers. 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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DEPUTY CHAIR - MIKE MCLAUGHLIN

Mike is a researcher with the University of Adelaide, based at the Waite campus in South Australia. He specialises in soil fertility and crop nutrition, contaminants in fertilisers, wastes, soils and crops. Mike manages the Fertiliser Technology Research Centre at the University of Adelaide and has a wide network of contacts and collaborators nationally and internationally in the fertiliser industry and in soil fertility research.

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Peter is a farmer at Mudamuckla near Ceduna on South Australia's Western Eyre Peninsula. He uses liquid fertiliser, no-till and variable rate technology to assist in the challenge of dealing with low rainfall and subsoil constraints. Peter has been a board member of and chaired the Eyre Peninsula Agricultural Research Foundation and the South Australian Grain Industry Trust.

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Jon has worked in agriculture for the past three decades, both in the UK and in Australia. In 2004 he moved to Geelong, Victoria, and managed Grainsearch, a grower-funded company evaluating European wheat and barley varieties for the high rainfall zone.
In 2007, his consultancy managed the commercial contract trials for Southern Farming Systems (SFS). In 2010 he became Chief Executive of SFS, which has five branches covering southern Victoria and Tasmania. In 2012, Jon became a member of the GRDC's HRZ Regional Cropping Solutions Network.

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Fiona has been farming with her husband Craig for 21 years at Mulwala in the Southern Riverina. They are broadacre, dryland grain producers and also operate a sheep enterprise. Fiona has a background in applied science and education and is currently serving as a committee member of Riverine Plains Inc, an independent farming systems group. She is passionate about improving the profile and profitability of Australian grain growers.

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Lou is a farmer based at Lameroo in the Southern Mallee of South Australia. Along with her parents and partner, she runs a mixed farming enterprise including export oaten hay, wheat, barley a variety of legumes and a self-replacing Merino flock. After graduating Lou spent 3 years as a sales agronomist where she gained valuable on-farm experience about the retail industry and then returned to her home town of Lameroo. She started her own consultancy business three years ago and is passionate about upskilling women working on farms.

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Richard along with wife Lee-Anne, son Will and staff, grow wheat, canola, lentils and faba beans on some challenging soil types at Warooka on South Australia's Yorke Peninsula. They also operate a self-replacing Murray Grey cattle herd and Merino sheep flock. Sharing knowledge and strategies with the next generation is important to Richard whose passion for agriculture has extended beyond the farm to include involvement in the Agricultural Bureau of SA, Advisory Board of Agriculture SA, Agribusiness Council of Australia SA, the YP Alkaline Soils Group and grain marketing groups.

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Michael runs a collaborative family farming enterprise at Nile in the Northern Midlands of Tasmania (with property also in northern NSW) having transitioned the business from a dryland grazing enterprise to an intensive mixed farming enterprise. He has a broad range of experience from resource management, strategic planning and risk profiling to human resource management and operational logistics, and has served as a member of the the High Rainfall Zone Regional Cropping Solutions Network for the past seven years.

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Kate is a partner in a large grain producing operation in Victoria's Southern Mallee region. Kate and husband Grant are fourth generation farmers producing wheat, canola, lentils, lupins and field peas. Kate has been an agronomic consultant for more than 20 years, servicing clients throughout the Mallee and northern Wimmera. Having witnessed and implemented much change in farming practices over the past two decades, Kate is passionate about RD&E to bring about positive practice change to growers.

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Andrew is a forth generation grain grower and is currently the Managing Director and Shareholder of Lilliput AG and a Director and Shareholder of the affiliated Baker Seed Co - a family owned farming and seed cleaning business. He manages the family farm in the Rutherglen area, a 2,500 ha mixed cropping enterprise and also runs 2000 cross bred ewes. Lilliput AG consists of wheat, canola, lupin, faba bean, triticale and oats and clover for seed, along with hay cropping operations. Andrew has been a member of GRDC's Medium Rainfall Zone Regional Cropping Solutions Network and has a passion for rural communities, sustainable and profitable agriculture and small business resilience.

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Nicole Jensen is GRDC General Manager for the newly created Genetics and Enabling Technologies business group. Nicole brings a wealth of experience in plant breeding and related activities arising from several roles she has held in Australia and internationally in the seed industry including positions as Supply Innovation Lead with the Climate Corporation - Monsanto's digital agricultural flagship, Global Trait Integration Breeding Lead for Monsanto.

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BASF Agricultural Solutions

Farming today is more complex than ever before with the unpredictability of the weather, control of pest and weeds, market price development, scarcity of natural resources. These challenges demand BASF to continue its commitment to creating innovative solutions for growers, supporting them with the task of nurturing a hungry planet.

BASF has been creating chemistry for over 150 years and with a broad portfolio of fungicides, insecticides, herbicides and seed treatments, we help farmers to sustainably increase the yields and the quality of their crops. By nurturing a culture of global innovation in alignment with our local customers' needs, our technologies aim to ensure that crops grow healthier, stronger and more resistant to stress factors, such as heat, drought or frost.

We also offer a range of smart solutions for pest problems in urban and rural areas. From products to protect buildings from termites to rodent control products with a softer environmental profile, we help our customers to keep their homes, food establishments, and businesses clean and pest-free.

Bayer

At Bayer, we work to shape agriculture through breakthrough innovation for the benefit of farmers, consumers and our planet.

Bayer has been investing in Australian agriculture for almost 100 years, supplying leading brands backed by expert advice in the areas of seeds and plant biotechnology, crop protection and non-agricultural pest control. Our spirit of innovation and curiosity means we are always looking to develop more advanced solutions to environmental and commercial challenges to shape Australian agriculture.

On and off the farm, we work closely with our customers, our business and research partners and the wider community to improve the security of our food and fibre supplies and our overall quality of life. This great tradition is also our commitment to the future – entirely in line with our mission: science for a better life.

InterGrain

As an Australian cereal breeding leader, InterGrain breeds broadly adapted Australian Barley and Wheat varieties for growers. Our highly successful wheat and barley breeding programs are designed to target the major cereal growing regions of Australia.

Our focus is breeding differentiated cereal varieties tailored to the Asian export market and we are globally recognised for our proven capability in the delivery of quality malting barleys and udon noodle wheats.

InterGrain's shareholders are the WA State Government (62%) and GRDC (38%). InterGrain employs 40+ staff and has offices in Perth and Horsham. We also have marketing staff based in Northam, Adelaide and Wagga Wagga.

Trade display supported by

Nufarm

We're big and small. Our business is large, stable and built on solid, established values.

And we're small enough to be quick, agile and fueled by innovative ideas. We know where and how to provide value to our customers. Our products include proven active ingredients, packaged to deliver practical solutions for progressive producers and retailers. Relationships drive our approach to customer service. We work hard to make business simple, streamlined and fun.

We're Nufarm and we're proud to be a partner in Australian agriculture.

For more information, contact your local Nufarm Territory Manager.

Pioneer® seeds Australia

At Pioneer we understand the best leaders serve. We believe we have a unique responsibility to help improve grower's operations, promote good stewardship through the value chain and advance the science of agriculture in Australia. We do this by delivering improved seed genetics and inoculant products to farmers, producing and distributing high-quality seed and supporting our customers by sharing knowledge of our products and agronomic practices. Pioneer has been operating in Australia for more than 40-years, serving customers with integrity, unmatched agronomic knowledge and solutions to help them succeed. Because when you partner with Pioneer, we are with you from the word GO. www.pioneerseeds.com.au

Seed Force

Seed Force has been operating in Australia since 2006, with a strong proprietary seed business based on local R&D from its global plant breeding linkages.

This includes a cornerstone shareholding from RAGT Semences, one of Europe's largest seed companies with a large $80Mpa investment in plant breeding across 24 species including forage grasses & legumes, brassicas, cereals and oilseeds.

Seed Force has established itself as an innovative business pushing the boundaries of plant genetics. This has seen significant gains in the area of yields, feed quality and water use efficiency.

To date the company has commercialised performance leading varieties of annual, italian ryegrass, forage brassicas, lucerne, cocksfoot, tall fescue, sub-clover, forage oats and forage sorghum.

More recently Seed Force has released hybrid winter Clearfield and spring TT canola and new barley and wheat varieties into the Australian market under the RGT prefix.

Seednet

Seednet is a national seed commercialisation business dedicated to the grains industry.

We commercialise a wide range of cereal and pulse varieties for plant breeders across Australia.

New varieties in 2020 are Leabrook barley, PBA Royal kabuli chickpeas and PBA Amberley faba beans.

For enquiries in SA, VIC and southern NSW contact Stuart Ockerby on 0448 469 745 or visit www.seednet.com.au

UPL

The fifth agrochemical company in the world, after the acquisition of Arysta LifeScience, UPL is a global leader in global food systems.

The new UPL offers an integrated portfolio of both patented and post-patent agricultural solutions for various arable and specialty crops, including biological, crop protection, seed treatment and post-harvest solutions covering the entire crop value chain.

With a revenue of US$3.14 billion, UPL is now present in 130+ countries.

We have market access to 90% of the world's food basket and are focused on ushering growth and progress for the complete agricultural value chain including growers, distributors, suppliers and innovation partners.

The new UPL is a solutions company. It's about what we can do with our customers, with farmers, with the whole network to drive world agriculture to the next level.

Prefer to provide your feedback electronically or 'as you go'? The electronic evaluation form can be accessed by typing the URL address below into your internet browsers:

www.surveymonkey.com/r/Adelaide-GRU

To make the process as easy as possible, please follow these points:

- Complete the survey on one device
- One person per device
- You can start and stop the survey whenever you choose, **just click 'Next' to save responses before exiting the survey**. For example, after a session you can complete the relevant questions and then re-access the survey following other sessions.

2020 Adelaide GRDC Grains Research Update Evaluation

1. Name

ORM and/or GRDC has permission to follow me up in regards to post event outcomes

2. How would you describe your main role? *(choose one only)*

- ❑ Grower
- ❑ Agronomic adviser
- ❑ Farm business adviser
- ❑ Financial adviser
- ❑ Communications/extension
- ❑ Grain marketing
- ❑ Farm input/service provider
- ❑ Banking
- ❑ Accountant
- ❑ Researcher
- ❑ Student
- ❑ Other* (please specify)

Your feedback on the presentations

For each presentation you attended, please rate the content relevance and presentation quality on a scale of 0 to 10 by placing a number in the box (**10 = totally satisfactory, 0 = totally unsatisfactory**).

DAY 1

3. Australia's grain industry in 2030 - a look into the future: *Ross Kingwell*

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

4. New herbicides - the best integration to prolong their impact: *Roberto Busi*

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

Concurrent sessions: please circle the session you saw, and review its content relevance and quality

5. 11.05 am	**Latest strategies in canola disease control** *Steve Marcroft*	**New pasture opportunities for low rainfall mixed farms** *Ross Ballard*	**The hows and whys for deep ripping sandy soils** *Brian Dzoma*	**A sensor-based approach to improved N decision making** *Rob Bramley*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

6. 11.45 am	**Frost mitigation - investigating agronomic options** *Mick Faulkner*	**The 10 key lessons from the Optimising Canola Profitability project** *Andrew Ware*	**Potassium and sulphur - the known knowns and the known unknowns** *Rob Norton*	**Problem weeds - management to minimise impact** *Gurjeet Gill*	**None**

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

7. 12.25 pm	**The health report: pulse disease update** *Mohsen Khani, Sara Blake* and *Blake Gontar*	**Use of chemicals and residues arising** *Gerard McMullen*	**New pasture opportunities for low rainfall mixed farms** *Ross Ballard,*	**A sensor-based approach to improved N decision making** *Rob Bramley*	**None**

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

LUNCH

8. 2.00 pm	**New changes and future opportunities within NVT** *Rob Wheeler*	**The hows and whys for deep ripping sandy soils** *Brian Dzoma*	**Break crop selection in low rainfall environments - one size does not fit all** *Sarah Day*	**The health report: pulse disease update** *Mohsen Khani, Sara Blake* and *Blake Gontar*	**None**

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

9. 2.40 pm	**Problem weeds - management to minimise impact** *Gurjeet Gill*	**The 10 key lessons from the Optimising Canola Profitability project** *Andrew Ware*	*On the couch with Roberto & Ross*	**Frost mitigation - investigating agronomic options** *Mick Faulkner*	**None**

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

10. 3.20 pm	**Potassium and sulphur - the known knowns and the known unknowns** *Rob Norton*	**Break crop selection in low rainfall environments - one size does not fit all** *Sarah Day*	**Latest strategies in canola disease control** *Steve Marcroft*	**New changes and future opportunities within NVT** *Rob Wheeler*	**None**

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

11. Student session: Hyperspectral sensing for the prediction of nitrogen, water and salt content in wheat: *Brooke Bruning*

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

12. Student session: Herbicide resistant common sowthistle and prickly lettuce: dispersal, seed biology and management considerations in lentils: *Alicia Merriam*

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

13. International grain markets - long term trends: *Cheryl Kalisch Gordon*

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

DAY 2

14. Early risers session: Assessing the value in soil and plant testing: *Sean Mason*

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

Concurrent sessions: please circle the session you saw, and review its content relevance and quality

15. 9.00 am	**Seeder strategies for non-wetting soils** *Jack Desbiolles*	**New strategies to manipulate flowering date and yield** *Kenton Porker*	**Cereal disease wrap up** *Hugh Wallwork*	**Latest research for improving management of snails** *Helen Brodie*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

16. 9.40 am	**Integrating new chemistries in the field** *Chris Preston, Chris Davey* and *Brian Lynch*	**Spotlight on pulses** *Penny Roberts*	**Rapid post-event frost damage assessment - can it be achieved?** *Glenn Fitzgerald* and *Audrey Delahunty*	**Septoria - no longer only an issue for the high rainfall zone** *Andrew Milgate*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

17. 10.50 am	**Soaks are seeping across SA - what can be done about it?** *Chris McDonough*	**Improving the heat tolerance of wheat** *Rebecca Thistlethwaite*	**Septoria - no longer only an issue for the high rainfall zone** *Andrew Milgate*	**Latest research for improving management of snails** *Helen Brodie*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

18. 11.30 am	**Spotlight on pulses** *Penny Roberts*	**New strategies to manipulate flowering date and yield** *Kenton Porker*	**Subsurface acidity - how far has the research advanced?** *Melissa Fraser*	**Cereal disease wrap up** *Hugh Wallwork*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

19. 12.10 pm	**Soaks are seeping across SA - what can be done about it?** *Chris McDonough*	**Seeder strategies for non-wetting soils** *Jack Desbiolles*	**Eye on active plant pests** *Rohan Kimber*	**Rapid post-event frost damage assessment - can it be achieved?** *Glenn Fitzgerald and Audrey Delahunty*	**None**

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

20. Predicted climate change impacts on southern farming systems & how we should act: *Peter Hayman*

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

21. What's the cost of HWSC for you? *Pete Newman*

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

Your next steps

22. Please describe at least one new strategy you will undertake as a result of attending this Update event

23. What are the first steps you will take?

e.g. seek further information from a presenter, consider a new resource, talk to my network, start a trial in my business

Your feedback on the Update

24. This Update has increased my awareness and knowledge of the latest in grains research

Strongly agree	Agree	Neither agree nor Disagree	Disagree	Strongly disagree
❑	❑	❑	❑	❑

25. Do you have any comments or suggestions to improve the GRDC Update events?

26. Are there any subjects you would like covered in the next Update?

Thank you for your feedback.