GRAINS RESEARCH UPDATE

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

Bendigo

Ulumbarra Theatre,
Gaol Road

#GRDCUpdates

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Bendigo GRDC Grains Research Update
convened by ORM Pty Ltd.

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GRDC Welcome – Bendigo 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, Bendigo.

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

The Victorian 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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The Farmers2Founders Ideas Program is designed for primary producers in the agri-food and fibre industry with an idea for a new business, an agtech or foodtech invention, or who are working on a value-added product.

We have already graduated our first group of 12 producer-led teams from the Ideas Program in 2019 and we are now looking to help the next batch of 12 get started! Over 12 weeks, F2F provides the producer-led teams with funding, coaching, tools and networking. We help them work out if their tech or value-added product idea is worth pursuing to the next stage of commercialisation. To fit in with core farming business commitments, the program is largely delivered remotely, with in person workshops at the kick-off in March and then at the 8-week point.

This program is a great fit for primary producers who:

- Have a business, tech or product idea they want to explore
- Have a team of 1-4 people
- Can commit ~ 5 hours per week over the 12-week period
- Are available to attend the workshops in March and at the 8-week point (travel funding provided)
- Are willing and enthusiastic to embark on a new venture journey

Whether you are a primary producer, a supplier or service provider to producers, or you think you know someone who would be interested in participating in the Ideas Program – we look forward to hearing from you and sharing our passion for supporting Australia's agrifood and fibre industry.

Farmers2Founders (F2F) is a world-first innovation program tailored to producers that equips them to act as frontline innovators and supports them to develop entrepreneurship & technology capabilities, so they can solve critical industry challenges.

Farmers2Founders.com

Ulumbarra Theatre

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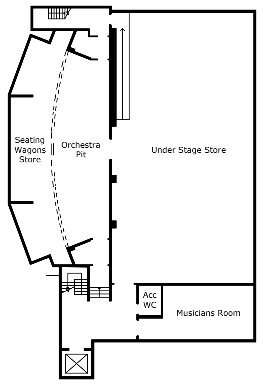
3 Cloak Room
4 Box Office
5 Central Hall
6 Ground Floor Foyer
7 Bar
8 Female Toilet
9 Male Toilet
10 Accessible Toilet
11 Vestibule
12 Stalls Seating

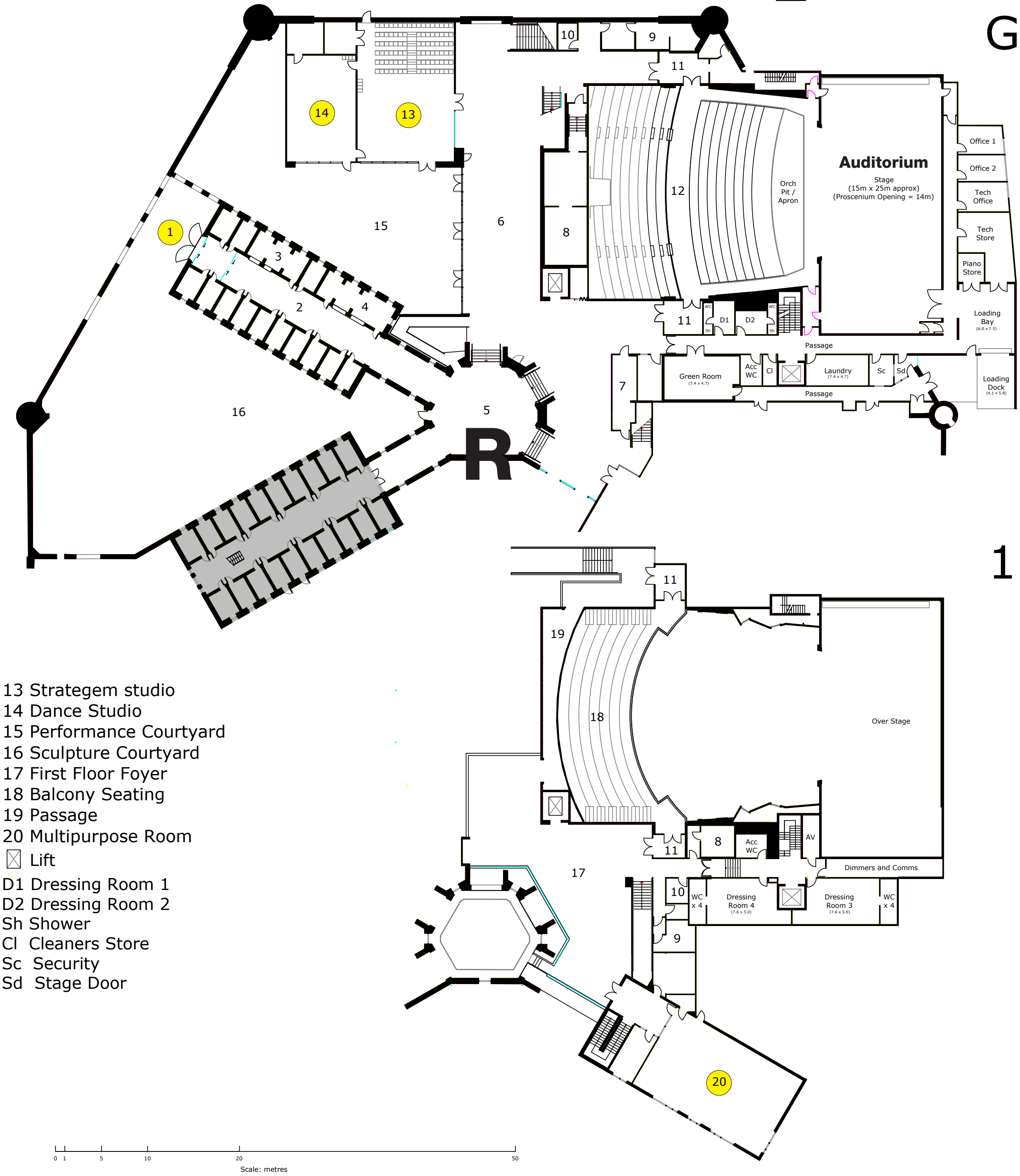
The GRDC Grains Research Update is being hosted in the Bendigo Ulumbarra Theatre this year.

Please enter then venue at **Point 1** on the map.

Please walk down the hall until you reach the registration desk at Point **R**.

Presentations are in the **Auditorium**, **Room 13**, **14** and **20**. Trade & catering are at **Point 6** and **15**.





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GRDC Grains Research Update BENDIGO

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GRDC Grains Research Update BENDIGO

PROGRAM DAY 1 - FEBRUARY 25th

8.55 am	**Announcements**	*ORM*
9.00 am	**Welcome and GRDC update**	*GRDC representative*
9.20 am	**A look into the future - capitalising on barley market opportunities** - P15	***Mary Raynes,*** *AEGIC*
10.00 am	**Understanding pre-emergent herbicide availability, selectivity and persistence** - P17	***Mark Congreve,*** *ICAN*
10.40 am	**Morning tea**	

CONCURRENT SESSIONS (40 minutes including time for room change)

(R = session to be repeated)

	Auditorium	Dance Studio	Strategem Studio	Multipurpose Room
11.10 am	**Assessing the value in soil and plant testing (R)** - P31 ***Harm van Rees,*** *Cropfacts Pty Ltd*	**The risks and rewards of growing pulse crops in the LRZ (R)** - P37 ***Michael Moodie,*** *Frontier Farming Systems*	**Improving the outcomes of oaten hay in the rotation (R)** - P43 ***Courtney Peirce,*** *SARDI*	**The continuing evolution of HWSC options (R)** - P49 ***Mike Walsh,*** *University of Sydney*
11.50 am	**Better pastures, better crops - best management of pastures in a mixed farming system (R)** - P59 ***Tim Condon,*** *Delta Ag*	**Stubble and nutrient management to build soil carbon - challenges and opportunities** - P69 ***BP Singh,*** *NSW DPI*	**Management tweaks making a difference with canola and lentil establishment success rates (R)** - P79 ***Glenn McDonald,*** *University of Adelaide*	**Latest strategies in canola disease control (R)** - P87 ***Steve Marcroft,*** *Marcroft Grains Pathology*
12.30 pm	**2020 cereal disease update (R)** - P97 ***Grant Hollaway*** *and* ***Mark McLean,*** *Agriculture Victoria*	**Eye on active plant pests** - P107 ***Rohan Kimber,*** *SARDI*	**The risks and rewards of growing pulse crops in the LRZ** - P37 ***Michael Moodie,*** *Frontier Farming Systems*	**The continuing evolution of HWSC options** - P49 ***Mike Walsh,*** *University of Sydney*

1.10 pm **LUNCH**

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

	Auditorium	Dance Studio	Strategem Studio	Multipurpose Room
2.10 pm	**Problem weeds - management to minimise impact (R)** - P117 ***Gurjeet Gill,*** *University of Adelaide*	**Improving the outcomes of oaten hay in the rotation** - P43 ***Courtney Peirce,*** *SARDI*	**Management tweaks making a difference with canola and lentil establishment success rates** - P79 ***Glenn McDonald,*** *University of Adelaide*	**2020 cereal disease update** - P97 ***Grant Hollaway*** *and* ***Mark McLean,*** *Agriculture Victoria*
2.50 pm	**Latest strategies in canola disease control** - P87 ***Steve Marcroft,*** *Marcroft Grains Pathology*	**Aphid and insecticide resistance management in oilseed and pulse crops** - P133 ***Marielle Babineau,*** *cesar*	**Better pastures, better crops - best management of pastures in a mixed farming system** - P59 ***Tim Condon,*** *Delta Ag*	**Biology of nitrogen release from pulses** - P143 ***Gupta Vadakattu,*** *CSIRO*
3.30 pm	**Insect pest control - are you advising for today or the future?** - P125 ***Kelly Angel,*** *BCG,* ***Greg Toomey,*** *Nutrien Ag Solutions and* ***Craig Drum,*** *Dagro*	**Problem weeds - management to minimise impact** - P117 ***Gurjeet Gill,*** *University of Adelaide*	**Assessing the value in soil and plant testing** - P31 ***Harm van Rees,*** *Cropfacts Pty Ltd*	**Latest research for improving management of snails** - P151 ***Greg Baker,*** *SARDI*

4.10 pm **AFTERNOON TEA**

4.40 pm **Developing a nationally validated model to predict flowering time of wheat and barley** - P161 — ***Max Bloomfield,*** *student*

4.50 pm **How will rising atmospheric CO_2 concentrations affect the uptake of phosphorus in crop species?** - P171 — ***James O'Sullivan,*** *student*

5.00 pm **Biosecurity status update on the top 5 nasties** - P177 — ***Dale Grey,*** *Agriculture Victoria*

5.10 pm **Hitting production targets in the UK amidst a highly regulated environment** - P183 — ***Keith Norman,*** *Keith Norman Consultancy Ltd*

5.50 pm **COMPLIMENTARY DRINKS & FINGER FOOD IN THE TRADE DISPLAY AREA**

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GRDC Grains Research Update BENDIGO

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PROGRAM DAY 2 - FEBRUARY 26th

8.15 am **EARLY RISERS: Everything you want to know and ask about crop diseases heading into 2020**

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

	Auditorium	Dance Studio	Strategem Studio	Multipurpose Room
9.00 am	**Canola roots and water use - big is not always best (R)** - P197 ***John Kirkegaard,*** *CSIRO*	**Estimating in-crop N mineralisation in current cropping systems (R)** - P205 ***Katherine Dunsford,*** *Agriculture Victoria*	**Spotlight on pulses (R)** - P207 ***Jason Brand*** *and* ***Garry Rosewarne,*** *Agriculture Victoria*	**Soil acidity - sampling and lime incorporation under review (R)** - P209 ***Lisa Miller,*** *SFS*
9.40 am	**Integrating new chemistries in the field (R)** - P217 ***Chris Preston,*** *University of Adelaide*	**The hows and whys for deep ripping sandy soils** - P221 ***Michael Moodie,*** *Frontier Farming Systems and* ***Chris Saunders,*** *University of SA*	**Earwigs - an appetite for destruction or are they beneficial?** - P233 ***Matthew Binns,*** *CSIRO*	**Rapid post-event frost damage assessment - can it be achieved? (R)** - P249 & P259 ***James Nuttall*** *and* ***Eileen Perry,*** *Agriculture Victoria*
10.20 am	**MORNING TEA**			
10.55 am	**High Rainfall Zone research forum:** **Addressing the yield gap - local hyper-yielding project** **Pulse agronomy trials in HRZ** **Canola yield improvement** - P183, P197, P267 & P269 ***Jon Midwood,*** *SFS,* ***Keith Norman,*** *Keith Norman Consultancy Ltd (UK),* ***James Manson,*** *SFS and* ***John Kirkegaard,*** *CSIRO*	**Deep ripping - does it work for all situations?** - P281 ***Roger Armstrong,*** *Agriculture Victoria*	**The health report: pulse disease updatew (R)** - P287 ***Josh Fanning,*** *Agriculture Victoria and* ***Sara Blake,*** *SARDI*	**Soil acidity - sampling and lime incorporation under review** - P209 ***Lisa Miller,*** *SFS*
11.35 am		**Estimating in-crop N mineralisation in current cropping systems** - P205 ***Katherine Dunsford,*** *Agriculture Victoria*	**Integrating new chemistries in the field** - P217 ***Chris Preston,*** *University of Adelaide*	**Rapid post-event frost damage assessment - can it be achieved?** - P249 & P259 ***James Nuttall*** *and* ***Eileen Perry,*** *Agriculture Victoria*

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

	Auditorium	Dance Studio	Strategem Studio	Multipurpose Room
12.15 pm	**Use of chemicals and residues arising** - P297 ***Gerard McMullen,*** *National Working Party on Grain Protection*	**Canola roots and water use - big is not always best** - P197 ***John Kirkegaard,*** *CSIRO*	**The health report: pulse disease update** - P287 ***Josh Fanning,*** *Agriculture Victoria and* ***Sara Blake,*** *SARDI*	**Spotlight on pulses** - P207 ***Jason Brand*** *and* ***Garry Rosewarne,*** *Agriculture Victoria*

12.55 pm **LUNCH**

1.35 pm **Food and diet trends affecting the grains industry** - P303 ***Sara Grafenauer,*** *Grains and Legumes Nutrition Council*

2.15 pm **Breaking through the big yield constraints - where to next?** - P309 ***James Hunt,*** *La Trobe University*

2.50 pm **CLOSE AND EVALUATION**

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

LOOK AROUND YOU.

1 in 5 people in rural Australia are currently experiencing mental health issues.

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The GRDC supports the mental wellbeing of Australian grain growers and their communities. Are you ok? If you or someone you know is experiencing mental health issues call *beyondblue* or Lifeline for 24/7 crisis support.

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www.beyondblue.org.au

beyondblue
Depression. Anxiety.

Lifeline
13 11 14
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Lifeline
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Looking for information on mental wellbeing? Information and support resources are available through:

www.ifarmwell.com.au An online toolkit specifically tailored to help growers cope with challenges, particularly things beyond their control (such as weather), and get the most out of every day.

www.blackdoginstitute.org.au The Black Dog Institute is a medical research institute that focuses on the identification, prevention and treatment of mental illness. Its website aims to lead you through the logical steps in seeking help for mood disorders, such as depression and bipolar disorder, and to provide you with information, resources and assessment tools.

www.crrmh.com.au The Centre for Rural & Remote Mental Health (CRRMH) provides leadership in rural and remote mental-health research, working closely with rural communities and partners to provide evidence-based service design, delivery and education.

Glove Box Guide to Mental Health
The *Glove Box Guide to Mental Health* includes stories, tips, and information about services to help connect rural communities and encourage conversations about mental health. Available online from CRRMH.

www.rrmh.com.au Rural & Remote Mental Health run workshops and training through its Rural Minds program, which is designed to raise mental health awareness and confidence, grow understanding and ensure information is embedded into agricultural and farming communities.

www.cores.org.au CORES™ (Community Response to Eliminating Suicide) is a community-based program that educates members of a local community on how to intervene when they encounter a person they believe may be suicidal.

www.headsup.org.au Heads Up is all about giving individuals and businesses tools to create more mentally healthy workplaces. Heads Up provides a wide range of resources, information and advice for individuals and organisations – designed to offer simple, practical and, importantly, achievable guidance. You can also create an action plan that is tailored for your business.

www.farmerhealth.org.au The National Centre for Farmer Health provides leadership to improve the health, wellbeing and safety of farm workers, their families and communities across Australia and serves to increase knowledge transfer between farmers, medical professionals, academics and students.

www.ruralhealth.org.au The National Rural Health Alliance produces a range of communication materials, including fact sheets and infographics, media releases and its flagship magazine *Partyline*.

ifarmwell growing farmers' wellbeing | Black Dog Institute | Centre for Rural & Remote Mental Health | CORES™
Rural & Remote Mental Health | Heads up Better mental health in the workplace | National Centre for Farmer Health | National Rural Health Alliance Ltd

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A look into the future – capitalising on barley market opportunities

Mary Raynes.

AEGIC.

Notes

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Notes

Understanding pre-emergent herbicide availability, selectivity & persistence and how we can use this knowledge to predict behaviour of new herbicides

Mark Congreve.

Independent Consultants Australia Network.

GRDC project code: ICN1811-001SAX

Keywords

- pre-emergent herbicides, solubility, binding, incorporation, persistence, breakdown.

Take home messages

- Chemical properties dictate herbicide;
    - persistence & mobility
    - Photolysis & volatility
    - Solubility
    - Binding co-efficient (K_{oc})
    - Half-life (DT_{50})
- Know your soil type (soil texture, pH, any hard pans or changes at depth).
- Seeder set-up is very important to minimise seed and herbicide contact.
- Understand the role of soil microbes.
- Develop a plan that doesn't rely on any single pre-emergent herbicide.

Background

Over the last 20-30 years, resistance to many post-emergent herbicides has developed to the stage where many growers are now again heavily reliant on pre-emergent herbicides as the foundation of weed control programs. This is especially the case with annual ryegrass.

During this timeframe we have also seen a change in farming practice. Most paddocks now have zero or minimum tillage, with implications for the position of weed seeds in the soil and the ability to incorporate pre-emergent herbicides.

These factors have resulted in the development of 'incorporate by sowing' (IBS) technology which allows for 'grass killing' herbicides, several of which are toxic to the cereal crop, to be used at planting in crops such as wheat and barley.

To achieve acceptable weed efficacy with minimal crop injury, users benefit from understanding the chemical properties of pre-emergent herbicides and how they interact within their micro-environment.

This paper discusses the main factors affecting pre-emergent herbicide availability, the importance of correct positioning of herbicide in the soil, and how to avoid carryover and crop damage the following year.

From 2020, numerous new pre-emergent herbicides will become available to Australian grain growers. Understanding the factors that influence pre-emergent herbicide availability will enable users to better predict how these herbicides will behave in their farming system.

Background information

This GRDC Grains Research Update paper briefly outlines the most important factors that influence pre-emergent herbicide behaviour. Users seeking more information on the behaviour of herbicides are directed to

https://grdc.com.au/resources-and-publications/resources/herbicide-behaviour In particular, the publication 'Soil Behaviour of Pre-emergent Herbicides' and the associated videos, which expand on the concepts outlined in this paper.

Factors affecting pre-emergent herbicide behaviour and availability

Application of pre-emergent herbicides is targeted at the soil surface, with incorporation by sowing (IBS) or follow up incorporation moving the herbicide into the soil profile, where it is then available for uptake via weed seeds. Many factors influence how herbicides enter the soil and what happens once in the soil (Figure 1).

A wide range of pre-emergent herbicides are available for use Australian grain growers. There are significant differences in the chemical properties of these herbicides, so it is important to understand how they differ and the impact on each loss pathway.

Interaction with stubble

Pre-emergent herbicides are typically applied with a standard boom spray, with the target being the soil surface. As would be expected, higher volumes of stubble in the paddock will intercept a greater percentage of the applied spray.

It is important to understand if spray deposited on stubble can be washed off with subsequent rainfall or whether it will be difficult to remove from stubble once it has dried. To predict the ability to wash off stubble we need to understand the herbicide solubility and the absorption (binding) coefficient (K_{oc}). Herbicides such as trifluralin, with low solubility and strong absorption to organic matter, will be almost impossible to remove from stubble after the spray has dried, so herbicide deposited on the

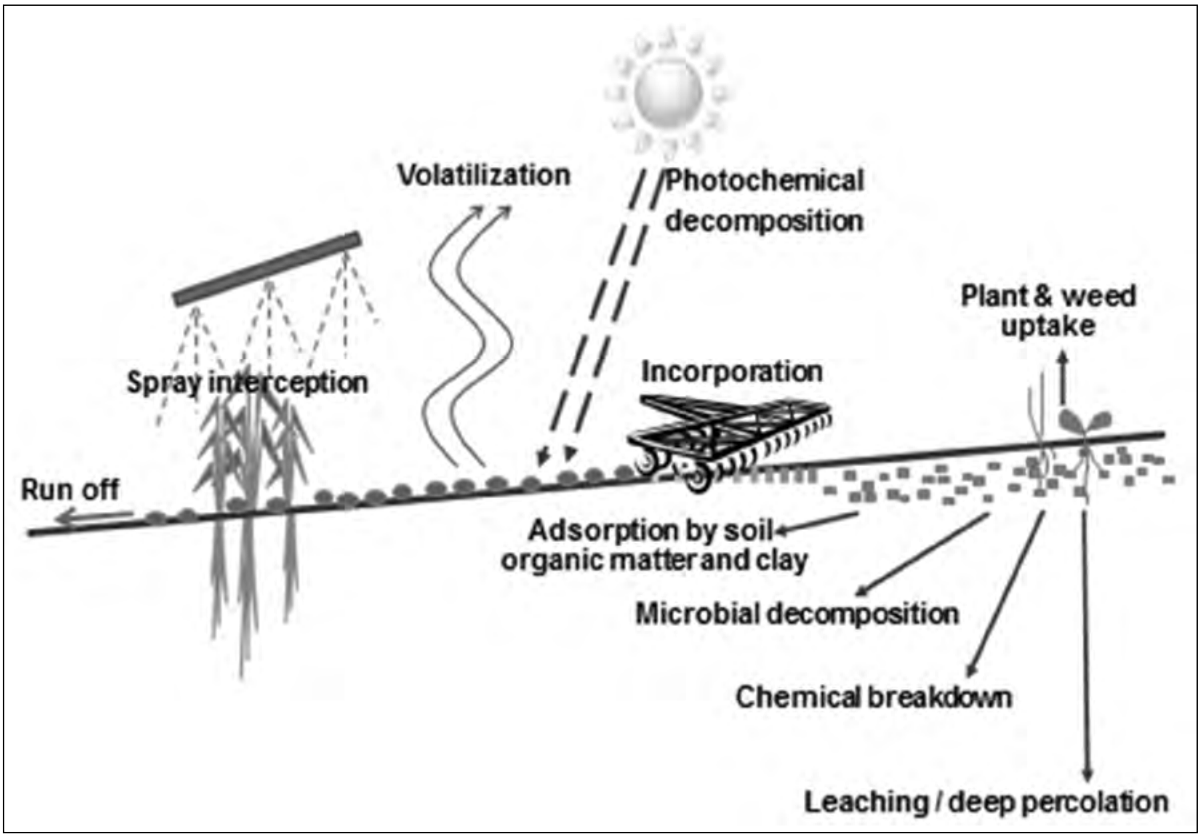

Figure 1. Key loss pathways for pre-emergent herbicides.

Table 1. Relative herbicide affinity for binding to stubble.

Tight binding.	Relatively tight binding.	Low mobility.	Some mobility.	Mobile.
Won't wash off stubble after spray has dried.	More difficult to wash off stubble after spray has dried.	Requires significant rainfall to remove from stubble.	Will wash off stubble with adequate rainfall.	Relatively easy to wash off stubble.
pendimethalin	prosulfocarb	diuron	atrazine	Group B
trifluralin	tri-allate	flumioxazin	simazine	Group I
		propyzamide	terbuthylazine	metazachlor
		napropamide	pyroxasulfone	s-metolachlor
		isoxaben		

stubble is effectively 'unavailable' for weed control. At the other extreme, herbicides with very high solubility and very weak binding to organic matter, for example Group B (Acetolactate synthase (ALS) inhibitors), will wash off stubble and into the soil following the next significant rainfall event. Other herbicides fall somewhere in between, depending upon their chemical properties.

Two new pre-emergent herbicides are expected to be available in 2020. Overwatch® (bixlozone) is a Group Q herbicide and Luximax® (cinmethylin) is expected to be initially allocated to Group Z. Based on published chemical properties of these new herbicides, it is predicted that they will most likely be included into the 'some mobility' group (Table 1).

Where stubble is no longer standing (for example; knocked down by grazing or chaff lining) this is likely to increase spray interception and further reduce the ability of the herbicide to reach the soil. In these situations, users would be best advised to select a mobile herbicide that will be easier to wash through stubble.

When using pre-emergent herbicides that are less likely to wash off stubble, there are several tactics that can be employed during the spraying operation to reduce the proportion of herbicide captured by stubble. These include:

- Travel with the rows, ideally with a cross breeze.
- Use large (very coarse or greater), solid droplets.
- Reduce nozzle spacing to 25cm.
- Lower boom height as far as practical (double overlap to be maintained at top of stubble, weeds, crop or soil – whichever is highest)
- Narrow fan angle (for example; 65° or 80°).
- Travel speed <16km/hr, and/or backward facing nozzles.
- Increase water rates. As a guide, minimum carrier volume of:
  - o 60L/ha - no stubble.
  - o 80L/ha - light stubble.
  - o 100L/ha - moderate stubble.

The use of water sensitive paper to pre-check herbicide deposition on the soil surface is highly recommended.

Loss pathways before entering the soil – photodegradation and volatilisation

Some herbicides are subject to degradation by ultra-violet light on the soil surface prior to incorporation. This can be a significant loss pathway for certain herbicides particularly when applied to no-till fallows in summer. However, when applied in autumn prior to planting winter crops and incorporation follows soon after application, this loss pathway is generally not significant.

Certain herbicides can be subject to losses from volatilisation, as some of the applied herbicide may transition into a gaseous phase after the spray has dried and then be lost to the atmosphere. While there are many factors that affect the rate at which volatilisation occurs, it is often useful to look at the vapour pressure of the herbicide as this can show relativity between herbicides. As a general principle, the higher the vapour pressure, the more urgent it is to have the herbicide incorporated into the soil before losses become significant. Volatility losses from herbicides with a vapour pressure below 1mPa @ 20-25°C is generally insignificant.

Of the pre-emergent herbicides used in grain crops, trifluralin is the most sensitive to losses due to volatility. Trifluralin has a relatively high vapor pressure, very low solubility and tight binding to soil and organic matter. This means that rainfall is not useful for incorporation and trifluralin requires mechanical incorporation soon after application.

Table 2. Published vapour pressure of pre-emergent herbicides commonly used in grains production

Herbicide	Vapour Pressure (mPa @ 20 or 25°C)
tri-allate	12
trifluralin	9.5
cinmethylin	8.1[A]
s-metolachlor	3.7
pendimethalin	3.3
prosulfocarb	0.79
flumioxazin	0.32
napropamide	0.22
terbuthylazine	0.152
most other pre-ems used in Australian grain crops	Less than 0.1

(Source: Pesticide Properties Database https://sitem.herts.ac.uk/aeru/ppdb/en/index.htm
[A] Luximax® Public Release Summary https://apvma.gov.au/node/55631)

The rate of trifluralin loss prior to incorporation is difficult to quantify, as there are many factors that influence this (Table 3).

It is important to understand that where volatility losses are significant, they may not be noticed via compromised weed control in the immediate weeks after application. Often, 'enough' herbicide will still make it into the soil to achieve weed control for the first few weeks after application. Excessive losses to volatility prior to incorporation are most likely to be expressed as a shorter effective residual life of the herbicide.

Achieving weed control and crop selectivity

Most herbicides effective against annual ryegrass can be toxic to winter cereal crops should the herbicide be taken up by the crop. It is important that the herbicide is positioned where it will come into contact with the weed seed, but not into contact with the cereal crop seed and/or emerging shoot/roots. To provide weed control and crop safety we need to understand herbicide mobility in the soil and the positioning of herbicide in relation to the weed and crop seeds.

Mobility in the soil

Mobility in the soil depends on the herbicide solubility and the absorption (binding) coefficient (K_{oc}), soil texture and the level of soil moisture.

Herbicides with low solubility and strong binding to soil and organic matter (i.e. high K_{oc} value) will tend to remain close to the soil surface. These herbicides are well suited to IBS application, in that the herbicide can be physically positioned away from the crop seed and will largely remain close to where it was incorporated (see section to follow on IBS). While this improves crop safety, it also means that the less mobile herbicides will not control weed seeds germinating in the crop row where the herbicide has been physically removed from the planting line.

Conversely, more mobile herbicides (high solubility, low K_{oc} value) will be primarily positioned with the soil moisture and will move both horizontally and vertically in the soil profile with soil water movement. Rainfall after application will distribute these herbicides more widely in the soil, including potentially around the crop seed, with crop injury often observed when this occurs.

Soil type/texture and soil moisture also influence movement in the soil. 'Heavy' soils, or soils with high organic matter, have more physical binding sites and smaller air spaces between soil particles. This means that any herbicide movement is likely to be less in these soil types. Whereas in 'light' or 'sandy' soils, it is likely that all herbicides may move further than in a heavier soil. Risk is higher when heavy rainfall occurs soon after application in a light soil.

Table 3. Factors influencing trifluralin volatility loss.

Conditions where losses are minimal	Conditions increasing speed of loss and reducing length of residual control
• Cooler temperature	• Warmer temperature
• Dry surface at application	• Moist surface at application
• Still conditions	• Wind/breeze blowing across the surface
• Rapid mechanical incorporation	• Delayed incorporation (>24 hours)
• Good incorporation	• Poor incorporation e.g.
o Well set up tine seeder	o Poor soil throw from tine seeder
	o Low disturbance disc seeder
	o Cloddy soil

Table 4. Herbicide mobility in the soil.				
Tight binding.	Relatively tight binding.	Low mobility.	Some mobility.	Mobile.
pendimethalin trifluralin	prosulfocarb tri-allate	diuron flumioxazin propyzamide napropamide isoxaben	atrazine simazine terbuthylazine pyroxasulfone	Group B Group I metazachlor s-metolachlor
Will stay relatively close to soil surface (unless physically moved, or excessive rainfall soon after application). Suits IBS (incorporate by sowing) with tines.				Will move horizontally and vertically with soil moisture. More likely to come in contact with the crop seed = higher potential for crop injury.

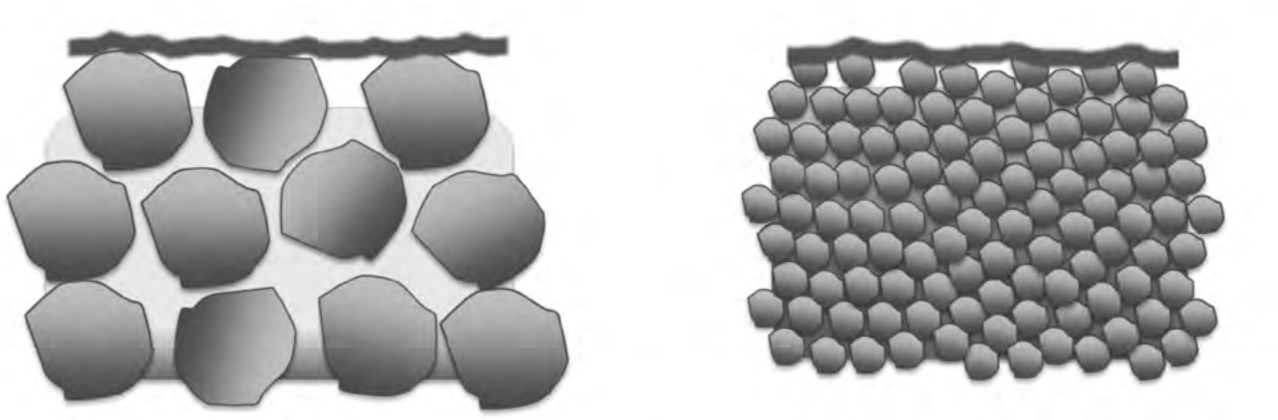

Figure 2. Lighter soil types (left) have more air spaces between soil colloids, resulting in greater potential for herbicide movement and less binding. Herbicide movement will be less on heavier soil types (right).

Where the herbicide is applied to a dry soil profile and there is a significant rainfall event after application, all herbicides are likely to move further than expected with a wetting front that is moving quickly down the soil profile. Conversely, if the soil moisture profile is relatively 'full' at application, herbicide movement is likely to be slower following the incorporating rainfall; allowing more time for soil binding to reach an equilibrium.

Where are the weed seeds?

Where zero till farming is practiced, it is likely most of the grass weed seeds will be very close to the soil surface (Figure 3). This is important for effective weed control when using immobile herbicides that are incorporated via the IBS technique. With IBS application, herbicide treated soil in the planting line is thrown into the interrow (see section to follow on IBS) leaving an area of 'untreated' soil along the planting line in which the crop can emerge. Where the weed seeds are on the soil surface, these will also be thrown out of the planting line with a correctly setup tine seeder.

Where a paddock has been cultivated in recent years, it should be expected that weed seeds will be distributed throughout the soil to the depth of tillage. Should an immobile herbicide be used, and a tine seeder used to throw the herbicide away from the planting line, then it is likely that weed seeds at the bottom of the planting furrow will establish along the planting row.

Crop and weed physiology

The ability to use the IBS technique in winter cereals is further enhanced by the differences in crop physiology between wheat and barley and other grass weeds (Figure 4).

With most grass weeds (and some grass crops) the mesocotyl elongates during germination, pushing the herbicide sensitive coleoptile node and secondary roots towards the surface, and into the

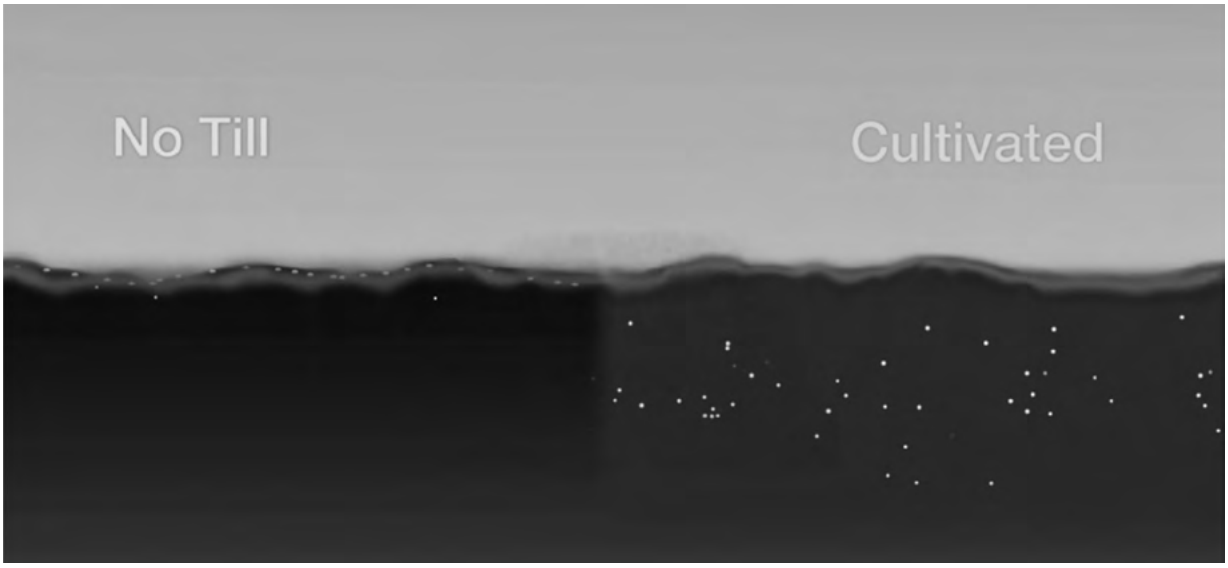

Figure 3. Location of weed seeds in the soil profile (weed seeds represented by dots).

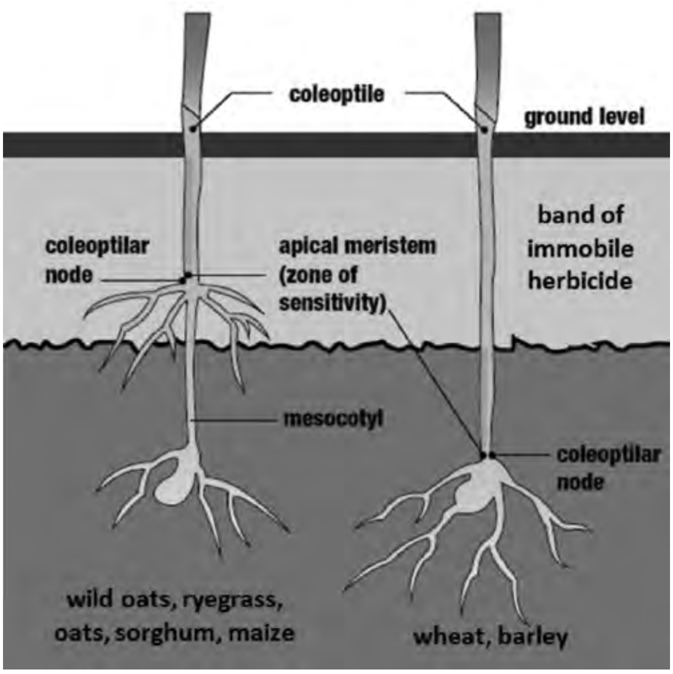

Figure 4. Differences in mesocotyl elongation is important for herbicide separation in wheat and barley (Adapted from Hall, Beckie & Wolfe (1999). How Herbicides Work)

zone of herbicide (Figure 4). The mesocotyl does not elongate in wheat and barley, thus keeping the coleoptile node lower in the soil profile and allowing for vertical separation from the immobile herbicide at the soil surface.

Principals of IBS application of immobile herbicides

Australia has developed the IBS application technique using knife points and press wheels (Figure 5), to allow relatively immobile 'grass killing' herbicides to be positioned away from the wheat or barley crop. This technique relies on:

- Weed seeds being close to the soil surface, and therefore also thrown into the interrow with the pre-emergent herbicide.
- Seeder setup and soil conditions that ensure herbicide treated soil is thrown from the planting line, yet not into the adjacent crop row.

This requires close attention to seeder setup, and this should be carefully monitored and adjusted during planting with changes to soil type, level of stubble and soil moisture.

Herbicide persistence

Persistence in the soil varies considerably between different herbicides. The length of persistence is a function of the speed of degradation and the application rate.

Understanding the herbicide half-life in the soil is useful in predicting length of control and likelihood of carry-over issues the following season. Herbicide half-life is normally presented as an average and a range of DT_{50} values (days of time for 50% of the herbicide to dissipate) when measured across several trials, environmental conditions and soil types.

Herbicides with an average DT_{50} of < 30 days are generally considered to be relatively non-persistent and usually have minimal plant-back constraints the following season. In order for these 'non-persistent' herbicides to be able to provide weeks/months of residual control, the application rate typically needs

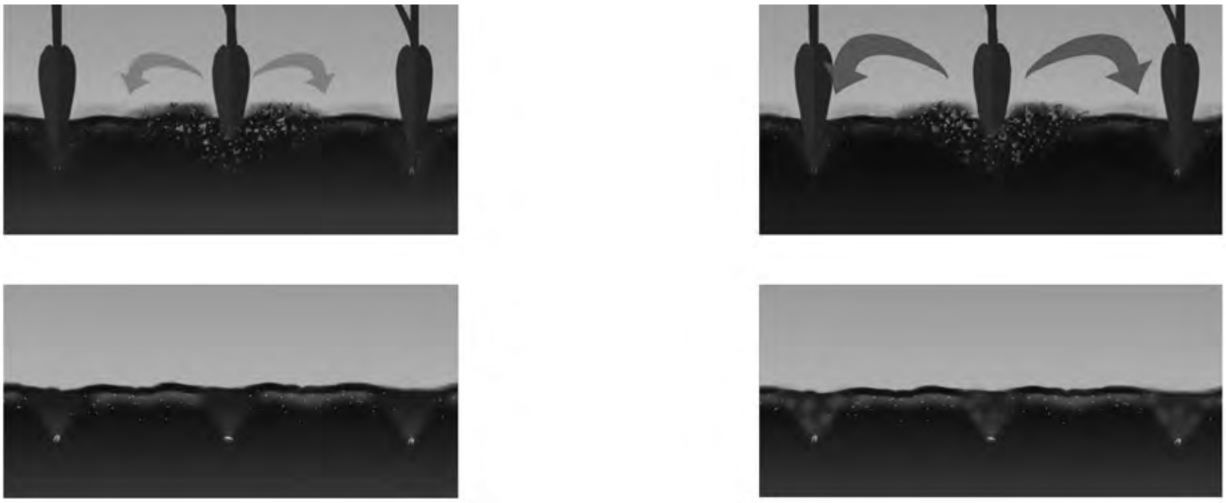

Figure 5. Correct IBS using knife points (left) removes herbicide treated soil and weed seeds from the planting line. Excessive soil throw (right) can result in unacceptable crop damage.

Table 5. Comparison of half-lives (DT_{50}) of certain pre-emergent herbicides.

Average DT_{50}	Classification			
< 30	Non-persistent	Unlikely to have plant back constraints the following year. To achieve extended residual, relatively high application rates are required.	metazachlor	prosulfocarb
			imazamox	flumioxazin
			s-metolachlor	pyroxasulfone
			terbuthylazine*	
30 to 100	Moderate	Plant-back constraints likely to be required. Often there is considerable variability on different soil types and under different climatic conditions	chlorsulfuron*	clopyralid
			tri-allate	cinmethylin
			propyzamide	atrazine*
			napropamide	diuron
			picloram	simazine*
			imazapyr!	bixlozone
>100	Persistent	Long re-cropping intervals will exist to sensitive crops.	pendimethalin	isoxaben
			trifluralin	imazapic!

** Persistence extended in alkaline soils; !Persistence extended in acidic soils.*

to be very high in relation to what is required to kill the weed, as they will be quickly breaking down over time (Figure 6).

Herbicides with longer half-lives (higher DT_{50} values) will typically provide longer, but often more variable persistence. These herbicides are likely to have plant-back constraints on the label.

Herbicide breakdown

A small number of herbicide groups have non-microbial degradation pathways that significantly contribute to herbicide breakdown. Hydrolysis is typically the primary pathway in the degradation of sulfonylurea and triazine herbicides. For these herbicides, the hydrolysis reaction requires adequate soil moisture and a neutral or acidic soil pH. As soil pH becomes more alkaline, the speed of this hydrolysis pathway slows and may stop completely. Should hydrolysis stop, the slower microbial breakdown becomes the degradation pathway for these herbicides.

The primary degradation pathway for most herbicides is microbial degradation. Sustaining soil microbe populations requires;

- Organic carbon (stubble) as a food source,
- oxygen (for aerobic species),
- a neutral pH (preferable),
- suitable temperature (not limiting in spring/summer), and
- moisture.

As a result of these requirements, microbe numbers are usually highest in the top 10-15cm

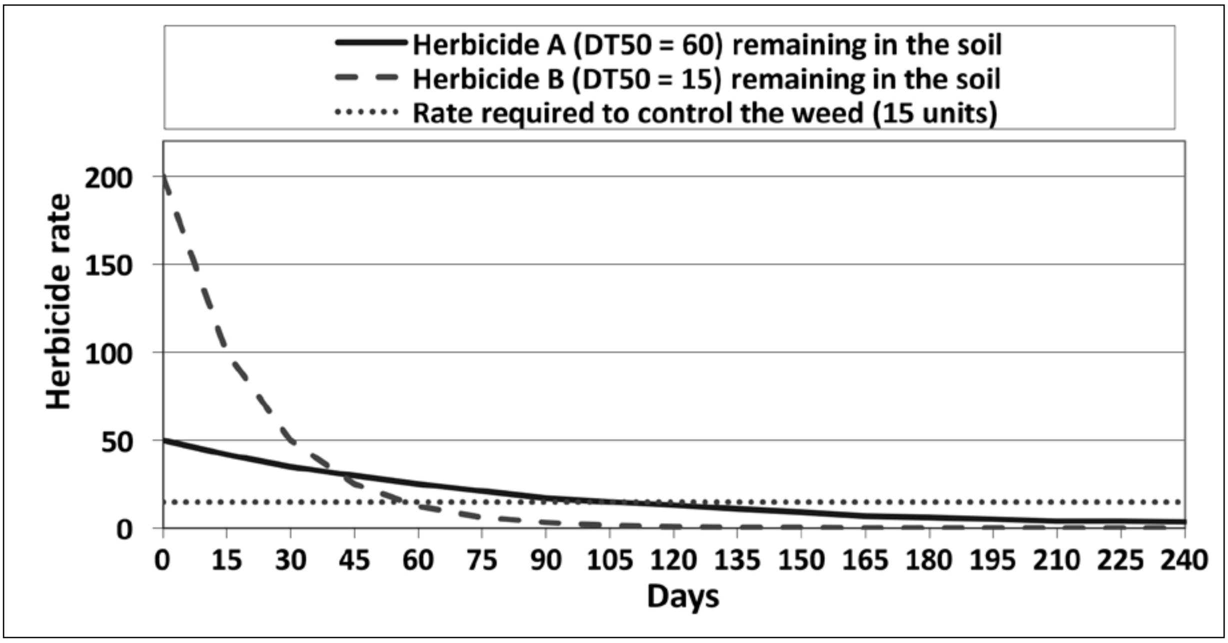

Figure 6. Comparison in the length of persistence (days) of short persistent herbicide (DT50 = 15 days) and a moderate persistent herbicide (DT50 = 60 days).

and rapidly decline further down the soil profile. Microbial numbers respond rapidly to temperature and soil moisture. In cold winters, little microbial activity will occur, regardless of soil moisture. In spring/summer, very high microbial activity is likely if there is moisture in the soil profile. Where the soil is dry, microbial activity is reduced and minimal herbicide breakdown will be occurring.

Highly mobile herbicides, with moderate to long persistence, (for example, some Group B and Group I herbicides) typically cause the most problems in terms of carry-over in following seasons. This can be made worse if there is a soil impediment at depth that prevents the herbicide from leaching right through the soil profile (for example; a plough pan, significant change in soil texture or pH).

In this situation, the mobile herbicide will disperse through the soil profile with in-season rainfall. If there is a soil impediment at depth, some herbicide will concentrate above this impediment. Rainfall over the following spring/summer will sustain microbial populations near the soil surface and this will degrade herbicides residues near the surface, however herbicide lower in the profile may not be fully degraded due to low levels of microbial activity at depth. Where a sensitive crop is planted the following season it often establishes well, providing the herbicide residue in the planting zone has fully degraded. Crop effects are then seen later in the crop as roots reach the herbicide remaining at depth.

Herbicides with residual soil activity and the capacity to affect subsequent crops have recommendations on their label on recommended intervals before re-cropping. More advanced labels also have information on the amount of rainfall required during this period to reduce the risk. Understanding that these intervals and rainfall requirements are linked with microbial degradation, it is clear to see that the pattern of rain within this period can also influence the level of microbial degradation. Prolonged periods of drought/dry conditions, interspersed with short periods of very wet conditions, particularly when it is cool, could meet label requirements for herbicide breakdown., However this may not allow adequate microbial activity for herbicide breakdown to safe levels to occur.

Enhanced microbial degradation

Where multiple applications of the same herbicide are made in the same paddock, the microbial species that degrade that herbicide may build up in numbers which leads to the faster degradation of subsequent applications (Figure 7). While this is likely to reduce carry-over problems the following year, it will also result in substantially reduced length of weed control.

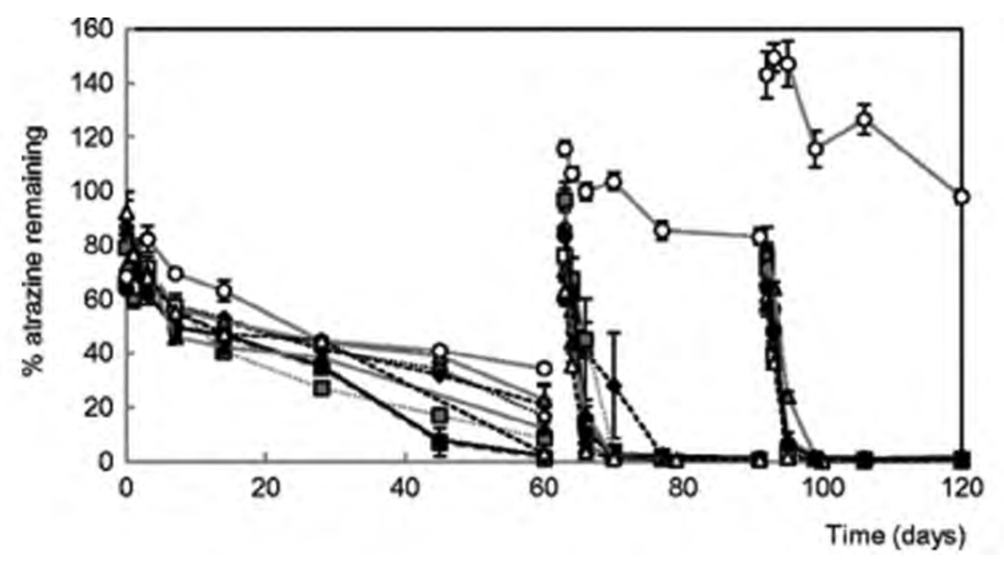

Figure 7. Atrazine applied three times to a range of soils that had no history of triazine use for at least five years prior to the first application. (Source: Yale et al. (2017)).

2020 and beyond

Grain growers have access to a wide range of very useful pre-emergent herbicides with more herbicides to come to market in the next few years. Understanding the chemistry of these herbicides is important to understand how to best use these products in your soils and farming system.

It is likely that Sakura®, Boxer®Gold/prosulfocarb, propyzamide, trifluralin and tri-allate will continue to underpin many ryegrass management programs in winter grain crops for the foreseeable future.

Three 'new' pre-emergent herbicides for grains were introduced in 2017 to 2018. Two of these herbicides; Butisan® (metazachlor) and Devrinol® (napropamide) are Group K herbicides targeting ryegrass in canola. While the third; Gallery® is a unique Group O herbicide that targets wild radish in wheat, barley and triticale.

Two new pre-emergent herbicides targeting annual ryegrass are expected to be available in 2020. Overwatch® (bixlozone) is from the seldom used Group Q mode of action and will be registered for use in wheat, barley and canola. Luximax® (cinmethylin) is registered for use in wheat and will be initially placed into Group Z.

Three to six other pre-emergent herbicides are currently being evaluated in field trials (mostly from existing modes of action) and some of these are likely to come to market in the next two to five years.

With several new 'tools' being added to the pre-emergent 'toolbox' it presents a great opportunity for growers and their agronomists to rethink their herbicide rotation plans. Where possible, incorporate as many different pre-emergent herbicides as possible into a five-year cropping rotation and avoid using any herbicide more than twice in a five-year period. This will reduce the potential selection for herbicide resistance, while also reducing the likelihood of enhanced microbial degradation.

Conclusion

The chemical properties of pre-emergent herbicides play a significant role in determining herbicide persistence and mobility in the soil. In particular, an understanding of the herbicide's solubility, propensity to bind to soil and organic matter (Koc), half-life (DT50) and losses from photolysis or volatility will assist in predicting how the herbicide will perform in the field in relation to weed control, crop safety and carry-over.

An understanding of the chemical properties helps users to select herbicide(s) that are most appropriate for their soil type and prevailing weather conditions. These properties will also guide the need for crop and herbicide separation and the best strategies to achieve this.

Herbicide degradation, and potential carry over to following seasons is most likely to be dictated by microbial activity in the soil and the climatic conditions supporting this activity.

With several new pre-emergent herbicides becoming available in the next few years, now is an extremely important time to revisit long-term herbicide rotation plans and develop programs that incorporate all appropriate pre-emergent options. Reducing overuse of any single mode of action should delay herbicide resistance, while also providing better weed control by avoiding accelerated microbial degradation.

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.

Useful resources

https://grdc.com.au/resources-and-publications/resources/herbicide-behaviour

https://grdc.com.au/SoilBehaviourPreEmergentHerbicides

https://grdc.com.au/rotational-crop-constraints-for-herbicides

https://www.diversityera.com/courses/pre-emergent-herbicides-101

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Concurrent session Day 1

Soil and plant testing for profitable fertiliser use

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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.

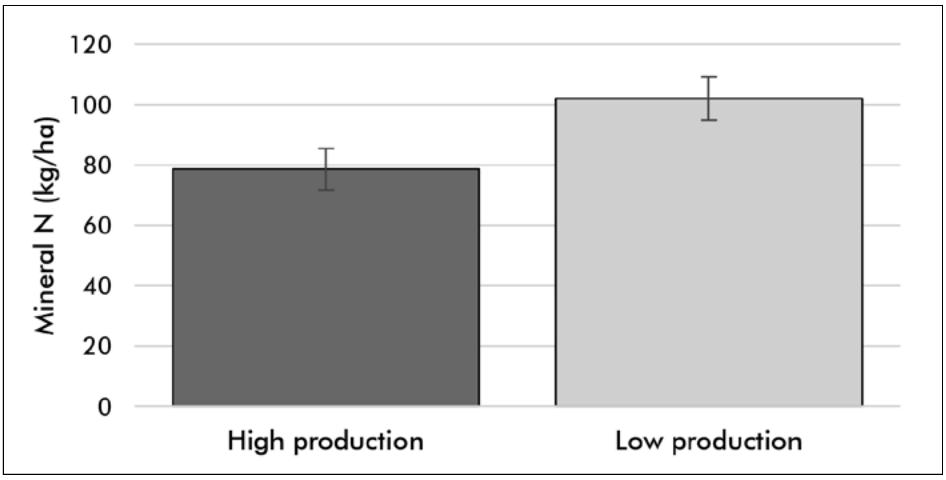

Figure 1. Overall soil mineral N status across the project area (GRDC Southern region) for allocated 'high production' and 'low production' zones within paddocks before the 2019 sowing season. Error bars represent standard error across all sampling sites in each zone.

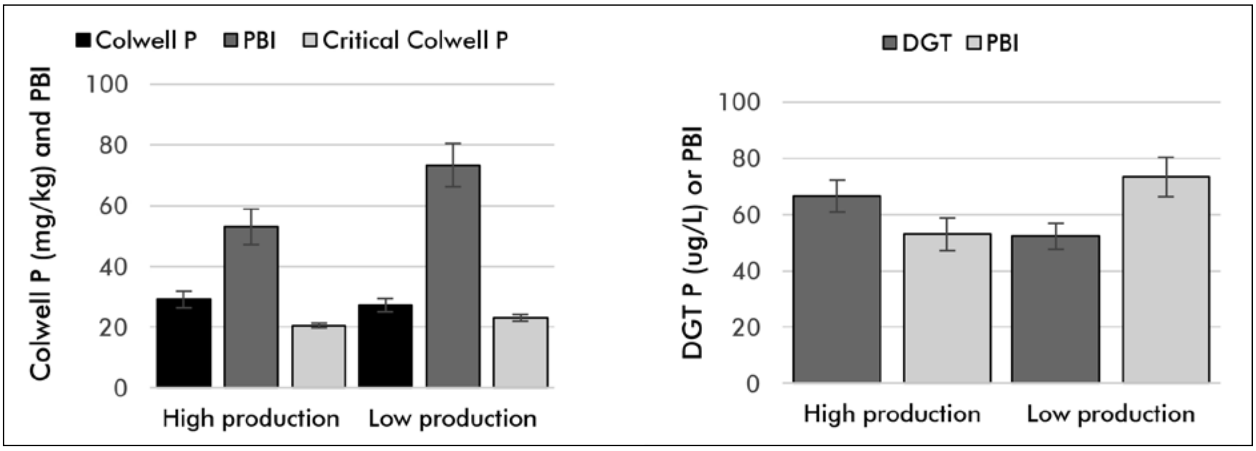

Figure 2. Overall soil P status across the project area for allocated 'high' and 'low' production zones within each paddock as assessed by Colwell P (left) and DGT (right) together with PBI for each zone. Error bars represent standard error across all sampling sites in each zone.

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⁽ᵈ⁾ 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.

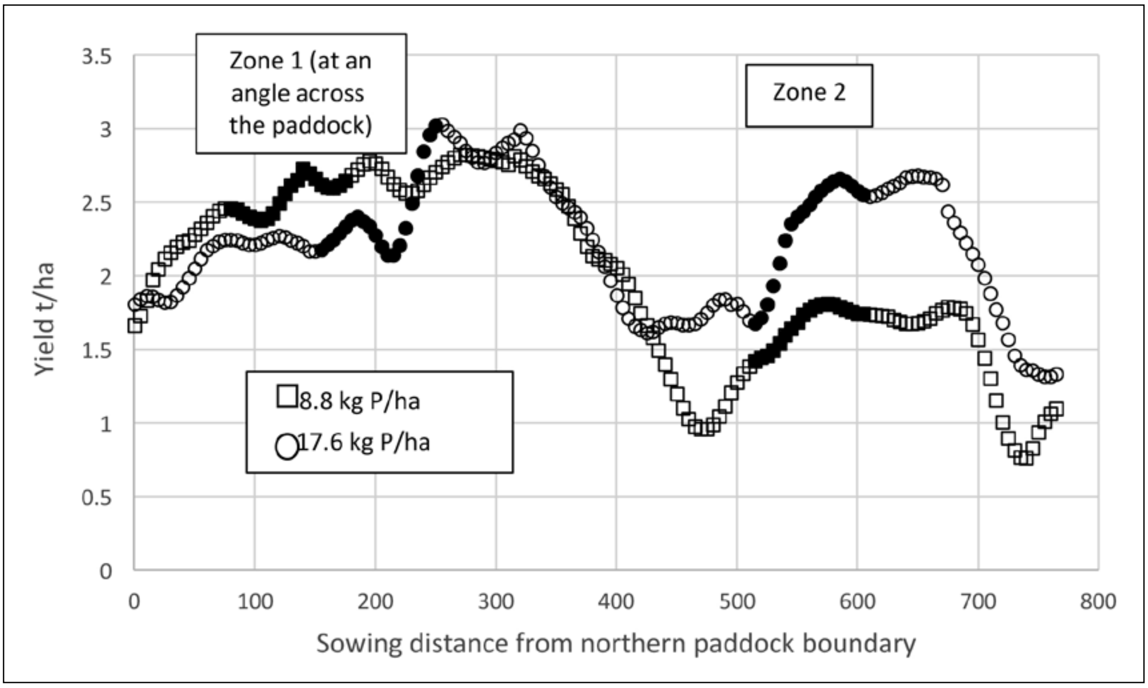

Figure 3. Strip yield (t/ha) for two rates of fertiliser P applied across two soil sampling areas. Solid black circles and squares indicate the yield achieved within the soil sampling areas for Zone 1 and 2.

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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The risks and rewards of growing pulse crops in the low rainfall Mallee cropping region

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Keywords

- field pea, vetch, lentil, faba bean, chickpea, lupin, crop sequence, gross margin.

Take home messages

- Season has the greatest impact on productivity with yields almost four times greater in a high rainfall year (decile 8-10), than in a low rainfall season (decile 2-4).
- The highest, and least variable grain yields were achieved on sandy loam – loam soil types, with up to 60% lower productivity, and high yield variability obtained on both heavy and sandy soils.
- Monte Carlo simulation using @Risk showed that lentils had both the greatest profit potential and lowest financial risk of all pulse crops over the long term.
- Chickpea and field pea are expected to have a negative gross margin in more than 30% of years but a high gross margin (>$500/ha) is expected in nearly one in five seasons.

Background

Grain producers have become more proficient atThe adoption of pulse crops in low rainfall cropping regions such as the Mallee is increasing in response to recent research demonstrating the benefits of break crops to Mallee crop sequences. McBeath et al. (2015) measured cumulative break crop effects of over 1t/ha in wheat crops following the break phase at Karoonda in the South Australian (SA) Mallee. This research primarily attributed the break benefit to beneficial effects on the cycling and supply of nutrients. Moodie et al. (2017) reported cumulative break crop benefits of 0.5 to 1.5t/ha and increased profit up to $100/ha per year by including break crops such as pulses in low rainfall crop sequences, relative to maintaining continuous wheat.

While the farming system benefits of pulse crops are clear, there is a lack of regionally available data to support grower decisions on the most profitable pulse crops to select. This study compared pulse crop productivity and profitability on four major soil types in the Mallee region, to identify the most appropriate option for local farming systems. This research aims to provide growers with information on the relative productivity and profitability of legume break crops in this low rainfall region.

Method

Field trials

One current commercial variety of each of six pulse crops, of interest to growers in the low rainfall Mallee region, were compared over three seasons (2015-2017) on four regionally important soil types. The pulse crops used were; field pea (PBA Wharton), vetch (Rasina), lupin (PBA Barlock), lentil (PBA Hurricane XT), faba bean (PBA Samira) and chickpea (Genesis 090).

The trials were located at Waikerie (-34.26°S 140.00°E) and Loxton (-34.53°S 140.53°E). At each site, two trials were located on contrasting soil types within the same paddock. A brief description of each of the four soil types is provided below:

- Loxton flat — red loam located in a swale.
- Loxton sand — deep yellow sand located on the top of an east-west dune.

- Waikerie flat — heavy red-grey soil with limestone present 20-30cm below the surface.
- Waikerie sand — red sandy loam located mid-slope.

Each trial was sown after the break of the season into moist soil, to ensure successful rhizobial inoculation. Trials were sown on the following dates in each season:

- 2015: Loxton, 28 April; Waikerie, 1 May.
- 2016: Loxton, 26 May; Waikerie, 30 May.
- 2017: Loxton, 5 May; Waikerie, 9 May.

Each treatment at each site was managed independently to ensure it reached its potential. Agronomic management differences included herbicide choice, fertiliser rates and fungicide and pesticide applications. All trials were machine harvested across multiple dates in each season to ensure grain yield was measured soon after crops matured and to minimise losses.

Seasonal conditions

Figure 1 shows the annual rainfall received at Loxton and Waikerie for each of the three trial years. In 2015 and 2017, rainfall was generally below average, with growing season rainfall (GSR) at Loxton decile 5 and 3 respectively. At Waikerie GSR was decile 3 and 2 for 2015 and 2017 respectively. Both seasons had good April rainfall allowing for timely sowing in early May. In 2016, both sites received exceptional GSR, especially in spring, with a decile 10 GSR recorded at Loxton and decile 8 GSR at Waikerie.

Profit risk modelling

A gross margin analysis was undertaken using Monte Carlo simulation with the Microsoft Excel add-in @Risk. Gamma distributions (which defined the long-term yield probability) were created for the grain yield of each crop using the 12 soil type x season yield outcomes that were generated by field trials (Table 1). Log logistic distributions of grain price were developed for each crop using long-term (2003 – 2017) average January grain price from the Farm gross margin and enterprise planning guide (Rural Solutions). The yield and price distributions were used to undertake 5000 iterations, generating a new gross margin distribution for each crop. The parameters for each crop used to create the Gamma yield and Log logistic price distributions in @Risk are provided in Table 1.

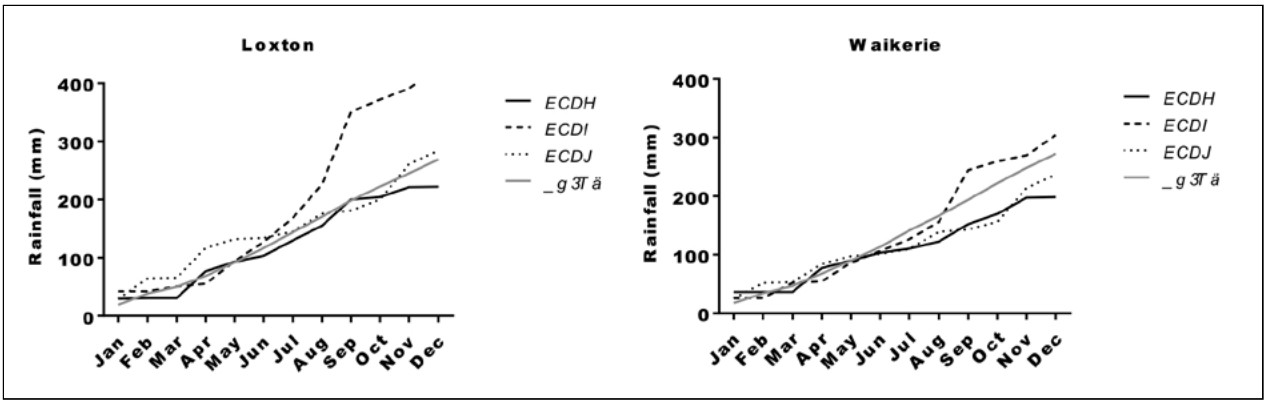

Figure 1. Cumulative annual rainfall for Loxton and Waikerie locations for the three trial years (2015-2017) and the long-term average (LT Av).

Table 1. Parameters for fitting Gamma distributions for grain yield and Log logistic distributions for grain price in @Risk to represent pulse crops in the Mallee region.

Crop	Gamma Grain Yield Distribution			Mean (t/ha)	Log Logistic Price Distribution		
	Mean ($/t)	Alpha	Beta		5th Percentile ($/t)	Median ($/t)	95th Percentile ($/t)
Field Pea	1.45	1.152	1258.180	322	211	305	484
Lupin	1.12	1.867	598.802	276	197	270	374
Chickpea	0.77	1.46	529.101	609	288	600	960
Lentil	1.08	1.653	653.594	684	401	630	1136
Faba Bean	0.95	1.393	684.931	386	246	370	576
Vetch	1.14	1.942	584.795	431	313	500	600

Results and discussion

Productivity

Field pea was the best yielding pulse crop, with an average yield of 1.3t/ha over all soil types and seasons. All other crop types averaged between 1 to 1.1t/ha, except for chickpea which had an average grain yield of 0.8t/ha.

There was a high level of variation in break crop yields both between seasons and between soil types. For example, the average yield of all break crops in 2016 was nearly four times greater than in 2015 and 2017 (Table 2). The pattern of rainfall and temperatures within years was also important. In 2015, a hot and dry spring favoured crops with early maturity — field peas, vetch and lentils produced the highest average yield. In contrast, frosts in August and September and significant rainfall in October 2017 favoured later maturity crops, with chickpea and lupins producing the highest yields.

Pulse crops were most productive on the loamy soil of the Loxton flat site, with all pulse crops averaging 1.45t/ha for the three seasons. However, average pulse crop yield on the sandy soil at Loxton were only 60% of those achieved on the loam, despite the sites being located just 250m apart. Lentils, chickpea and faba bean performed particularly poorly on the sandy soil, producing 50% of the grain yield achieved on the better soil type. At Waikerie, the best production was on the sandy loam soil (Waikerie sand) with an average yield of 1.1t/ha across all crops and seasons. In comparison, the average yield at the Waikerie flat site was 0.9t/ha. However, performance at this site was highly variable with seasonal conditions, being almost as productive as the Loxton and Waikerie sand sites in 2016 but extremely poor in 2015 and 2017.

Profit risk modelling

Monte Carlo simulation showed that lentils are not only the most profitable break crop but are also the least risky (Table 3). The average gross margin for lentils is $500/ha, with a negative return from growing lentils expected in only 14% of seasons. Vetch was the next most profitable break crop with an average gross margin of $300/ha. However, vetch as grain is predominantly sold for seed to plant fodder and hay crops. And while there have been some high prices received for vetch in recent years, the grain market is limited and becomes easily flooded, which is not reflected in the @Risk simulation.

Chickpea and field pea had similar profitability and risk outcomes, with both having simulated mean long-term gross margins of $217/ha. Both crops had similar risks of not achieving a break-even gross margin (33-36%), and an 18% probability of the gross margin exceeding $500/ha. Despite both crops having a similar profitability and risk profile, our observations from the trials were that they could be complementary within a farm enterprise mix. Field peas matured early and tended to perform well in frost-free situations with terminal drought and/or

Table 2. Pulse crop grain yields (t/ha) on four Mallee soil types for three seasons (2015-2017). Mean grain yield ± Standard Error of the Mean (SEM) is provided in the table.

Year	Site	Chickpea	Faba bean	Lentils	Lupin	Vetch	Field Pea
2015	Loxton Flat	0.43±0.09	0.83±0.11	0.96±0.11	0.71±0.11	0.77±0.14	0.58±0.21
	Loxton Sand	0.22±0.03	0.55±0.05	0.64±0.05	0.60±0.09	0.86±0.03	0.71±0.05
	Waikerie Flat	0.05±0.03	0.29±0.03	0.47±0.07	0.20±0.07	0.19±0.02	0.16±0.18
	Waikerie Sand	0.45±0.01	0.46±0.04	0.82±0.07	0.49±0.05	0.69±0.04	1.21±0.03
	Average (all sites)	0.29	0.53	0.72	0.50	0.63	0.66
2016	Loxton Flat	1.55±0.36	2.92±0.33	3.13±0.45	2.88±0.32	2.84±0.25	3.02±0.48
	Loxton Sand	0.65±0.08	1.50±0.18	0.88±0.16	2.06±0.15	2.03±0.09	1.67±0.64
	Waikerie Flat	1.15±0.06	1.65±0.15	2.53±0.05	1.81±0.35	1.81±0.31	3.58±0.07
	Waikerie Sand	2.48±0.07	1.66±0.20	1.90±0.21	1.55±0.15	2.19±0.13	3.25±0.15
	Average (all sites)	1.46	1.93	2.11	2.07	2.22	2.88
2017	Loxton Flat	1.01±0.15	0.93±0.18	0.86±0.14	1.27±0.25	0.78±0.11	0.73±0.11
	Loxton Sand	0.36±0.05	0.18±0.12	0.31±0.07	1.18±0.04	0.68±0.07	0.4±0.07
	Waikerie Flat	0.39±0.07	0.37±0.06	0.28±0.04	0.25±0.19	0.33±0.09	0.29±0.06
	Waikerie Sand	0.51±0.10	0.10±0.07	0.20±0.04	0.46±0.08	0.47±0.10	0.60±0.07
	Average (all sites)	0.57	0.39	0.41	0.89	0.57	0.50
	Average (all years)	0.77	0.95	1.08	1.12	1.14	1.35

Table 3. Mean gross margins for pulse crops and the probability of gross margin which are less than $0/ha or greater than $500/ha, generated with @Risk simulations.

Crop	Mean ($/ha)	Probability <$0/ha	Probability $0 - $500/ha	Probability >$500/ha
Lentil	498	14%	49%	38%
Vetch	300	16%	63%	22%
Chickpea	217	36%	47%	18%
Field pea	217	33%	60%	18%
Lupin	132	29%	66%	5%
Faba bean	114	44%	46%	10%

high levels of heat in spring. Conversely chickpea matured late and performed well at sites which were frosted in early spring and in situations where soil moisture was available late in the season.

Lupin and faba bean had lowest simulated long-term gross margins of $132/ha and $114/ha respectively. Faba bean are also the riskiest crop and are not expected to break even in 44% of seasons. The downside risk of lupins is comparable to field pea and chickpea, but lupins has the lowest probability of achieving a high gross margin of more than $500/ha. This is due to low long-term price outcomes for lupins relative to other pulse crops.

Conclusion

Overall, most pulse crops had similar productivity potential, however the yields achieved in any one season were highly influenced by seasonal conditions (including the amount and distribution of seasonal rainfall, frost and heat events) and soil type. Season had the greatest impact on productivity, with yields almost four times greater in a high rainfall year (decile 8-10), than in a low rainfall season (decile 2-4). Pulse crop yields also varied by up to 60% between soil types. The highest and least variable pulse crop grain yield were achieved on sandy loam – loam soil types, with lower productivity and high yield variability obtained on both the heavy and sandy soils. As each of these soil types are encountered within a typical Mallee paddock, management options to improve pulse productivity and reliability on these constrained soils are required.

Monte Carlo simulation showed that lentils had both the greatest profit potential and lowest financial risk of all pulse crops over the long term. Vetch, chickpea and field pea are expected to generate long term gross margins of more than $200/ha. Chickpea and field pea are expected to have a negative gross margin in more than 30% of years, however a high gross margin (>$500/ha) is expect in in nearly one in five seasons. This information will allow Mallee growers to make more informed selections of the most appropriate pulse crops for their farming system.

Acknowledgements

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Useful resources

www.msfp.org.au

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Rural Solutions SA farm gross margin and enterprise planning guide: http://solutions.pir.sa.gov.au/news/news/newspaper_items/2014/farm_gross_margins_and_enterprise_planning_guide_2015

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National hay agronomy - improving the outcomes of oaten hay in the rotation

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Keywords

- oaten hay, hay quality, hay yield, time of sowing, nitrogen.

Take home messages

- Results from 2019 indicate that oats can achieve similar or higher biomass than wheat (Scepter⁽ᵈ⁾) and barley (Compass⁽ᵈ⁾).
- Growers have access to oat cultivars with similar development speeds to Compass⁽ᵈ⁾ barley and Scepter⁽ᵈ⁾ wheat and are likely to flower within a similar frost risk window.
- Early May sowing of oats in 2019 achieved higher total biomass and hay yield than oats sown late May/early June in three different environments.

Background

The National Hay Agronomy (NHA) trial is a new four-year project supported by AgriFutures Australia, focusing on improving the quality of export hay in Australia. The project is being led by Georgie Troup from the Department of Primary Industries and Regional Development (DPIRD), Western Australia (WA) and includes collaborators from SARDI and Hart Field Site in South Australia (SA), Agriculture Victoria and Birchip Cropping Group in Victoria (Vic) and Department of Primary Industries NSW in New South Wales (NSW).

The core agronomy component of the NHA focusses on developing updated guidelines for export oaten hay that optimise variety selection, seeding date and in-crop nutrition requirements for SA, WA, Vic and NSW. Trials commenced in 2019 and will continue for the next two seasons at Hart in the Mid-North of SA, Muresk in WA, Kalkee in Vic, and Yanco in NSW. These trials are investigating the influence and interaction between oaten hay variety, sowing date and nitrogen to provide best practice guidelines for growers to maximise both yield and hay quality.

The 2019 season was defined by spring drought, and areas in South Australia were hit by numerous frosts in early Spring damaging cereal crops (Rural Solutions SA, 2019). These seasonal conditions coupled with a strong domestic demand for fodder, highlighted the benefit of hay including oaten hay as a risk management strategy. Additional investment from SA Grain Industry Trust Fund (SAGIT) benchmarked oaten hay cultivars with the productivity of barley and bread wheat in frost prone landscapes.

Oaten hay varieties

Durack⁽ᵈ⁾

Durack⁽ᵈ⁾ is a very early maturing, moderately tall, dual purpose (milling OAT2 in WA, hay) variety. It has good lodging resistance but is susceptible (S) to very susceptible (VS) to stem rust in SA and Vic, and has variable resistance (resistant (R) to S) to leaf rust; depending on pathotype. It has excellent grain quality with high protein levels, and good hay yield; although care needs to be taken to cut at the correct growth stage to achieve highest hay quality.

Brusher⁽ᵈ⁾

Brusher⁽ᵈ⁾ is a tall, early to mid-maturity hay variety with good hay quality and yields, commercialised by Australian Exporters Company (AEXCO). It has improved stem and leaf rust resistance than Wintaroo⁽ᵈ⁾ and suits low rainfall areas.

Carrolup

Carrolup is a mid-maturity, moderately tall, dual purpose variety (milling grain and hay) mainly grown in WA, with lower grain yield than milling varieties Bannister$^{\phi}$ and Williams$^{\phi}$. It has similar maturity to Yallara$^{\phi}$.

Forester$^{\phi}$

Forester$^{\phi}$ is a very late maturing variety, adapted to high rainfall and irrigated cropping regions. It has excellent early vigour, a good foliar disease resistance package, and good hay colour but does not resist hot dry winds as well as earlier maturing varieties. Seed is available from AGF seed.

Koorabup$^{\phi}$

Koorabup$^{\phi}$ (tested as line 05096-32) was released in 2019 and commercialised by AEXCO. It is a mid-tall hay variety developed for the WA market. It has improved Septoria resistance compared to other current hay varieties, and good rust and bacterial blight resistance.

Mulgara$^{\phi}$

Mulgara$^{\phi}$ is a tall, mid maturity hay variety commercialised by AEXCO. It is R to stem nematode, has improved resistance to stem rust and bacterial blight compared with Wintaroo$^{\phi}$. Hay quality is similar to Wintaroo$^{\phi}$ with excellent hay colour and the inherent ability to resist brown leaf tipping at hay cutting.

Williams$^{\phi}$

Williams$^{\phi}$ is a tall, dual purpose (milling grain and hay) variety commercialised by Heritage Seeds, released in WA but also suited to eastern Australia. It has better Septoria resistance than the other milling varieties and high grain yields. Hay quality is similar to Wintaroo$^{\phi}$ but yield is slightly lower than the other hay varieties and care should be taken with seeding density as its main issue is stem thickness.

Wintaroo$^{\phi}$

Wintaroo$^{\phi}$ is a tall, mid maturity hay variety with good hay yield and quality, and it resists brown leaf tipping. It is S to stem rust, and moderately susceptible (MS) to leaf rust. It is more prone to lodging compared with other hay varieties.

Yallara$^{\phi}$

Yallara$^{\phi}$ is a mid-maturity, medium-tall, dual purpose (milling grain and hay) variety commercialised by Seednet. It has good hay quality and thin stems suitable for the export market. It is moderately resistant (MR) to stem rust, and R to leaf rust.

Kingbale$^{\phi}$

Kingbale$^{\phi}$ is a tall, mid-maturity hay variety with improved tolerance to soil residues of imidazolinone herbicides. Preliminary data shows that Kingbale $^{\phi}$ has a similar disease and agronomic profile to Wintaroo$^{\phi}$. The original breeding work was undertaken by Grains Innovation Australia and it is being commercialised by Intergrain, with commercial seed available in 2021 subject to 2019 field testing results, and an APVMA herbicide registration.

Methods

NHA Core agronomy trial

The aim of this trial was to investigate variety performance, seeding dates and in-crop nutrition to develop guidelines for achieving optimum performance for export oaten hay in SA.

- Location: Hart; SA, Kalkee; Vic, Yanco; NSW and Muresk; WA.
- Varieties: Nine oat varieties (listed in the preceding section, excluding Kingbale$^{\phi}$)
- Management treatments:
    - o Two times of sowing (TOS), early May and late May/early June.
    - o Three nitrogen (N) rates (30kg N/ha, 60kg N/ha or 90kg N/ha) for all varieties, and YallaraA, Mulgara$^{\phi}$ and Wintaroo$^{\phi}$ also had an additional three N treatments of 10kg N/ha, 120kg N/ha and 150kg N/ha to ensure N management matched typical growers' practice (Note: starting soil for the overall site was 67kg of N/ha and starting soil moisture was negligible).
    - o N treatments were split with two-thirds applied at seeding, and one-third applied six weeks after seeding when the plants were tillering. This split was according to current best practice for hay to achieve good early vigour, plant establishment and thin stems.
    - o Plots were sown at a target seeding density of 320 plants/m^2.

Expansion sowing date trials

The aim of this trial was to improve the productivity of oats for both grain and domestic hay in frost prone landscapes.

- Location: Lameroo in the Mallee (LRZ) and Tarlee in the Mid-North (HRZ)
- Varieties:
  - o At both sites; Carrolup was replaced with Kingbale⁽ᵈ⁾.
  - o One barley (Compass⁽ᵈ⁾) and one wheat (Scepter⁽ᵈ⁾) variety were included for comparison.
- Management treatments
  - o At all sites in SA (Lameroo, Hart and Tarlee), varieties were sown at two times, either early May (6 May, 3 May and 1 May, respectively) or late May/early June (28 May, 5 June and 31 May, respectively).
  - o At Lameroo one N rate was used, which was calculated on starting soil N and expected hay yields, which equated to 45kg N/ha at Lameroo and 80kg N/ha at Tarlee. The targeted seeding rate at Lameroo was 240 plants/m^2 and 320 plants/m^2 for Tarlee.

Plots were sown as 6 rows (9 inch row spacing) by 10m with 1.75m spacing between plots. The Hart site was N responsive with a low starting N. All plots received the same rate of N applied as DAP with additional N applied as urea to achieve N treatment rates. No pesticides were applied in the 2019 season at Hart due to a lack of disease or pest pressure. Growth stage of varieties were monitored from heading, and hay cuts were taken for each plot (four rows x one metre) when the variety reached watery ripe (Zadoks 71). Hay was cut by hand atb 15cm height above the ground before being dried for two days at 60°C, and then measured for hay yield. Hay cuts were then ground to <1mm, and hay quality determined by near infrared (NIR) technology.

Results and discussion

2019 Season

The rainfall during the 2019 season at Lameroo and Tarlee was below average, with Lameroo recording a decile three year for May to October growing season rainfall (GSR 196mm) and a decile one year for annual rainfall (218mm), and Tarlee recording a decile one year for GSR (215mm) and annual rainfall (255mm). In 2019, Hart received 161mm of growing season rainfall (GSR) and 188mm annual rainfall, resulting in a decile one year and very low hay yields for the season. There was minimal rainfall resulting in dry soil prior to the season break of 13.4mm on the 9th of May. There were some significantly different responses to applied N treatments at Hart but they were small. The increase in N from 30kg N/ha to 60kg N/ha increased biomass yields when sown in early May (3.0t/ha to 3.6t/ha, Lsd 0.4t/ha), however there was no increased biomass as a result of increasing applied N above 30kg N/ha when the crop was sown in early June. This result is unsurprising as both the availability of applied N, and the plants ability to uptake applied N would have been low in 2019, due to the reduced in-season rainfall and shortened growing season. It will be interesting to see the response to N over the next two years in hopefully more representative seasons.

Hay quality data is currently being analysed and will be provided in the presentation at the Bendigo 2020 GRDC Grains Research Updates.

Oat development differences

Due to the dry conditions experienced at Hart, many varieties flowered in the boot which made flowering date observations difficult. This is a problem in some varieties as it is likely to influence hay quality by increasing the curing time from hay cut to baling. Cut dates were similar at Hart and Lameroo. In general, cut dates were seven to 14 days after flowering depending on the variety. Table 1 shows the dates and number of days until mid-flowering at both Lameroo and Tarlee and can be used to estimate hay cut timing. The spread in flowering date between oat varieties, except for Forester⁽ᵈ⁾ is about three weeks when sown early-May, or two weeks when sown late-May. Durack⁽ᵈ⁾ was the earliest flowering variety, flowering and being cut for hay at a similar time as Compass⁽ᵈ⁾ (barley) and on average, flowering a week before all other varieties. Several of the early-mid maturing oat varieties (Mulgara⁽ᵈ⁾, Brusher⁽ᵈ⁾, Williams⁽ᵈ⁾) flowered and were cut for hay at a similar date to Scepter⁽ᵈ⁾ (wheat). Forester⁽ᵈ⁾ is a very slow developing variety and did not flower under all environments. In lower rainfall areas, both the early-May and late-May sown Forester⁽ᵈ⁾ were cut on the same day at flowering after observing a halt in biomass growth over the previous two weeks. Forester⁽ᵈ⁾ is unlikely to be a suitable variety for the low-medium rainfall environment of SA.

Table 1. Date of mid-flowering (Zadoks 65) and in brackets; days from sowing to flowering for both sites and sowing dates in 2019.

Sowing date	Lameroo		Tarlee	
	6 May	28 May	1 May	31 May
Compass$^{(b)}$	28-Aug (114)	20-Sep (112)	1-Sep (123)	20-Sep (112)
Scepter$^{(b)}$	14-Sep (131)	28-Sep (123)	14-Sep (136)	28-Sep (123)
Durack$^{(b)}$	1-Sep (118)	15-Sep (110)	1-Sep (123)	20-Sep (112)
Williams$^{(b)}$	8-Sep (125)	27-Sep (122)	11-Sep (133)	28-Sep (120)
Mulgara$^{(b)}$	10-Sep (127)	25-Sep (120)	11-Sep (133)	28-Sep (120)
Brusher$^{(b)}$	11-Sep (128)	25-Sep (120)	9-Sep (131)	27-Sep (119)
Yallara$^{(b)}$	12-Sep (129)	23-Sep (118)	8-Sep (130)	29-Sep (121)
Wintaroo$^{(b)}$	12-Sep (129)	30-Sep (125)	20-Sep (142)	3-Oct (125)
Kingbale$^{(b)}$	18-Sep (135)	30-Sep (125)	21-Sep (143)	3-Oct (125)
Koorabup$^{(b)}$	19-Sep (136)	29-Sep (124)	20-Sep (142)	30-Sep (122)
Forester$^{(b)}$	22-Oct (169)	N/A*	10-Oct (162)	25-Oct (147)

**Forester$^{(b)}$ flowered inconsistently in some parts of the plot but a decision to cut was made for the same time as the 6 May time of sowing. Both Lameroo plots were cut on 22 October.*

Table 2. 2019 hay yields (t/ha) for all SA sites.

Sowing Date	Hart		Lameroo		Tarlee	
	3 May	5 June	6 May	28 May	1 May	31 May
Compass$^{(b)}$	-	-	6.3 ^{bcde}	6.2 ^{bcde}	10.5 ^{bcd}	10.7 ^{bc}
Scepter$^{(b)}$	-	-	5.4 ^{efgh}	5.2 ^{fgh}	11.0 ^{bc}	9.4 ^{defgh}
Koorabup$^{(b)}$	3.6 ^{b}	2.4 ^{ef}	6.0 ^{cdef}	5.1 ^{fgh}	10.0 ^{cde}	8.7 ^{fghi}
Brusher$^{(b)}$	3.8 ^{ab}	2.4 ^{ef}	7.2 ^{ab}	5.4 ^{efgh}	9.9 ^{cdef}	8.5 ^{ghi}
Durack$^{(b)}$	3.7 ^{b}	2.4 ^{e}	7.3 ^{a}	5.9 ^{defg}	9.1 ^{efg}	7.9 ^{i}
Forester$^{(b)}$	1.9 ^{g}	1.1 ^{h}	5.2 ^{fgh}	4.5 ^{h}	10.2 ^{bcde}	8.2 ^{hi}
Mulgara$^{(b)}$	3.9 ^{a}	2.6 ^{d}	6.7 ^{abcd}	5.8 ^{defg}	12.3 ^{a}	10.0 ^{cde}
Williams$^{(b)}$	3.3 ^{c}	2.0 ^{fg}	6.2 ^{cde}	4.6 ^{h}	10.1 ^{cde}	8.6 ^{ghi}
Wintaroo$^{(b)}$	3.9 ^{a}	2.5 ^{de}	6.7 ^{abcd}	5.4 ^{efgh}	10.4 ^{bcd}	9.5 ^{defg}
Yallara$^{(b)}$	3.8 ^{ab}	2.6 ^{d}	7.0 ^{abc}	5.9 ^{defg}	11.0 ^{bc}	9.9 ^{cdef}
Carrolup	3.3 ^{c}	2.6 ^{d}	-	-	-	-
Kingbale$^{(b)}$	-	-	6.0 ^{cdef}	5.0 ^{gh}	11.4 ^{ab}	9.1 ^{efgh}
Lsd ($p \leq 0.05$)	0.4 (0.2 within same TOS)		0.9 (0.9 within same TOS)		1.2 (1.0 within same TOS)	

Within a site, varieties that have different letters indicate significant differences in hay yield ($p \leq 0.05$)

Hay yields

At all three sites (Hart, Lameroo and Tarlee), hay biomass was maximised from early May sowing (Table 2). At Lameroo, Compass$^{(b)}$ when sown either early or late May, produced similar hay yield to the best performing early May sown oats. At Tarlee, neither Compass$^{(b)}$ nor Scepter$^{(b)}$ could match the hay yield of the best performing oats. Although there is not much variation in cutting date between most of the varieties, earlier maturing varieties (Durack$^{(b)}$, Brusher$^{(b)}$, Mulgara$^{(b)}$, Yallara$^{(b)}$), particularly at Lameroo in the low rainfall region, performed best. At Tarlee, Mulgara$^{(b)}$ from early May sowing was the highest yielding variety with Kingbale$^{(b)}$ also yielding similarly. Kingbale$^{(b)}$ the new Imi-tolerant variety yielded well from early May and similar to Wintaroo$^{(b)}$ at each site, as expected.

Conclusion

Although this is only the first year of trials for the National Hay Agronomy project, we have been able to get some baseline data on the performance of oaten hay. There are several oat varieties that will flower in a similar window to both Compass$^{(b)}$ and Scepter$^{(b)}$. Most oat varieties are of the fast to mid-fast development speed and will flower from an early May sowing date within a two to three-week period in September. At all three sites oaten hay yields were maximised from earlier sowing and were similar to those achieved with wheat and barley.

Due to the low rainfall experienced in 2019, hay yields were very low at Hart, and there were limited differences between varieties, except for Forester⁽ᵇ⁾ which was too slow in its phenology to be suitable for export oaten hay in this environment. Hay quality is still to be analysed so it remains to be seen whether the quality of hay can be maintained from earlier sowing.

Acknowledgements

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Useful resources and references

Rural Solutions SA, 2019, Crop and Pasture Report South Australia, PIRSA, November 2019, available at https://www.pir.sa.gov.au/primary_industry/crops_and_pastures/crop_and_pasture_reports

https://grdc.com.au/2020-south-australian-crop-sowing-guide

https://www.agric.wa.gov.au/oats/2019-oat-variety-sowing-guide-updated

http://aexco.com.au/producing-quality-oat-hay/

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The continuing evolution of HWSC systems

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GRDC project code: US00084

Keywords

- chaff lining, chaff grazing, harvest weed seed control, impact mills.

Take home messages

- Chaff grazing increases annual ryegrass emergence by removing chaff residues.
- Widespread adoption of harvest weed seed control (HWSC) is driving the development of impact mill technology.
- There is a need for independent testing of new impact mill systems.

Background

Since the introduction of chaff carts in the early 1990s there has been ongoing development of harvest weed seed control (HWSC) systems where growers can now choose from six general approaches; chaff carts, narrow windrow burning, chaff lining, chaff tramlining, bale direct and chaff impact mills. The adoption of HWSC systems has increased dramatically over the last decade with the recognition of the weed control benefits from the long-term use of these systems. With most Australian growers now using some form of HWSC, there is demand for new and more refined user-friendly systems. At present the most popular systems are chaff lining and chaff tramlining as they are relatively cheap and simple to install, there is no requirement for after-harvest treatment, and they are suitable for mixed farming systems. Similarly, impact mill systems for chaff processing are also increasing in popularity. The advantage of the latter approach over other HWSC systems is that weed seeds are destroyed during harvest along with the retention and dispersal of all harvest residues. Over the last five years industry research and development efforts have focussed on the refinement of current impact mill systems and the development of new systems. This paper aims to provide an update of recent research and development activities with chaff lining, chaff tramlining and chaff impact mills.

Methods

Influence of grazing on chaff lines

The impact of sheep grazing on annual ryegrass emergence from chaff lines was assessed in a field trial near Marrar, NSW, about 40km north of Wagga Wagga from November 2018 to April 2019. Wheat plant samples were collected from 20 quadrats (1m x 35cm) on 19 November 2018, the day before harvest, for the determination of wheat biomass and grain yield. Samples were collected in five (1m x 35cm) quadrats in each of four harvester swaths (12m wide) and placed in separate bags. After oven drying for 48hrs at 70°C, dry weights were recorded. These wheat plant samples were then threshed with the grain collected and weighed to determine yield.

To determine the amount of chaff production, five collection trays (75cm x 35cm) were placed in each swath on the path of the chaff line immediately prior to harvest. As each swath of wheat crop was harvested, the chaff samples were collected in these trays resulting in 20 samples. After harvest the collected chaff was placed into paper bags. These were then oven dried at 70°C for 48hrs, then weighed. This chaff material was sieved with annual ryegrass seed collected and counted to determine a seed number/m chaff line.

To examine the impact of grazing on annual ryegrass emergence from chaff lines immediately after harvest (26 November 2018) exclusion cages (five) were placed on each of the four chaff lines. This allowed for five replicates of each of the four harvester swaths, for a total of 20 exclusion cages.

The paddock was continuously grazed by sheep without any supplemental feed from 14 December 2018, until the end of the trial on 22 April 2019. No herbicides or pesticides were used on the paddock throughout the duration of the trial.

Following a dry summer period, rainfall at the end of March/start of April 2019 stimulated the germination and emergence of annual ryegrass. Annual ryegrass emergence was counted on 9 April in 1m chaff line lengths inside the exclusion cages and on adjacent chaff lines outside of the exclusion cages. Chaff samples were collected from the grazed and ungrazed areas from five randomly chosen cages and adjacent areas.

All chaff collections were made by measuring 1m lengths of chaff line for the grazed and ungrazed areas. Collected samples were placed in a paper bag and oven dried at 70°C for 48hrs then weighed. Chaff samples were then sieved to collect and count the ryegrass seed remaining in the chaff.

One-way analyses of variance were performed on chaff biomass, annual ryegrass seed number and annual ryegrass seedling emergence data with means compared using LSDs (P=0.05).

iHSD and seed terminator evaluation

A Western Australian grower at Newdegate has two identical Case harvesters (8230), one fitted with an integrated Harrington Seed Destructor (iHSD) and the other with a Seed Terminator (ST). The seed destruction efficacy of these impact mills was evaluated during the harvest of a 2.4t/ha wheat crop on 16 December 2017.

Seed preparation

Annual ryegrass seeds were dyed by immersing in a 2% edicol dye (blue (iHSD) and red (ST)) solution for 15 minutes then spread on paper towel to dry overnight, this would allow the seed to be differentiated from the native seed after processing. Ten replicated seed lots of 5000 seed were counted out for blue dyed and red dyed seed. The viability of dyed seed lots was established prior to testing by placing three replicates of 100 seed on 0.6% (w/v) agar-solidified in petri dishes in a temperature-controlled laboratory at 25/15°C and 12hr photoperiod. Over 28 days, geminating seed were counted and removed. Seeds were classified as viable if they germinated. Seeds were also considered viable but dormant if they did not germinate but did not decay. This test established the proportion of viable seed in the seed lots used for testing.

Harvest procedures

During the harvest of 10m long by 14m wide areas of wheat crop, 5000 annual ryegrass seeds were introduced through a 10cm diameter tube mounted directly over the top of the left hand mill of either the iHSD or ST. Seed introduction commenced after the mill had started to process chaff material. A 0.5mm nylon mesh bag was attached to the outlet chute of the mill to collect the processed chaff material exiting the mill.

At the end of each plot the threshing and cleaning systems were operated until the harvester was empty and there was no material exiting. The collected chaff material was then transferred into a separate woven poly bag and the mesh bag reattached to the mill outlet. Harvester speed throughout testing was approximately 5km/h. Annual ryegrass seed destruction efficacy was tested in ten plots each (replicates) for the iHSD and ST systems.

Chaff sample processing

Chaff samples were weighed before any further processing was undertaken.

To examine the effects of mill type on the size distribution of chaff fractions the chaff sample from each mill was mixed thoroughly and then a 1kg subsample was collected for sieving. Each subsample was passed through six hand sieves in descending order of mesh size: 11, 7, 3, 2, 1 and 0.5mm. Using a method practised by Guzzomi et al (2017), the sieve was shaken by hand, twice per second for two minutes, turning the sieve 90° every 30 seconds. The chaff remaining on each sieve was collected and weighed.

All chaff samples were then manually sorted to retrieve dyed annual ryegrass seed and seed fragments. Collected fragments were then weighed and stored until all chaff samples had been sorted. Once all samples were sorted the viability of seed and seed fragments was determined by allowing them to germinate on 0.6% (w/v) agar-solidified in plastic trays (17cm x 12cm x7cm). Germination was counted after 14 days and 28 days with remaining seed fragments checked for viability as described previously.

Single and vertical impact mill testing

Similar procedures were used to test the efficacy on annual ryegrass seed of the single (for class 6 and 7 harvesters) and vertical mill systems during wheat crop harvest at Corrigin 2017 (single mill) and Broomehill 2018 (vertical mill). Prior to testing, 12 plots were marked out in an area of wheat crop that was free of annual ryegrass. Plot length was 20m, with plot width determined by harvester width, 10m at Corrigin and 12m at Broomehill. To test the weed seed kill when the mills were operating under different loads, plots were harvested at three speeds. The mill systems were tested at three harvester speeds (8, 10 and 12km/h at Corrigin and 4, 6 and 8km/h at Broomehill) with four replicates for each speed. The respective speeds chosen represented when the harvesters were operating below capacity, at capacity and above capacity.

During the harvest of each plot, dyed germinable annual ryegrass seed (5000) were introduced into the mill through a 5cm diameter plastic tube using the same procedures described above for the impact mill testing.

Collected chaff samples were processed at Charles Sturt University, Wagga Wagga to determine the level of seed survival for each plot. Subsamples (100g) were collected from the well mixed bags of chaff. These samples were spread thinly across the surface of trays filled with potting mix. A light covering of potting mix was spread over the chaff material. To ensure the germination of any surviving annual ryegrass seed, trays were watered daily to maintain soil moisture near field capacity. Each day over a four week period annual ryegrass seedlings were counted and removed.

Results and discussion

Influence of grazing on chaff lines

The establishment of chaff lines during harvest using a 12m front resulted in the concentration of a high amount of chaff from a relatively low yielding wheat crop. The narrow (35cm) chaff lines established during harvest using a chaff lining system produced chaff lines with 274g chaff/m row which was equivalent to 8.5t/ha of chaff (Table 1). This level of wheat chaff has been shown in pot trials to have only a small suppressive effect on annual ryegrass emergence (approximately 5-10%) (Ruttledge et al. 2018).

Over-summer grazing resulted in a 38% reduction ($P<0.05$) in chaff biomass (equivalent of 3.2t/ha) compared to the ungrazed chaff lines. With little or no rainfall over the summer-autumn period there was little or no chaff decomposition resulting in no difference ($P>0.05$) in chaff amounts present at harvest and in the ungrazed chaff lines in autumn (Figure 1). Thus, even with a low yielding wheat crop the concentration of chaff in lines enabled the consumption of a substantial amount of chaff biomass by grazing sheep.

Table 1. Wheat biomass and grain yield at harvest and the amount of chaff concentrated in narrow rows during harvest. Number in brackets represent standard error (n=20).

Wheat Biomass (t/ha)	Grain Yield (t/ha)	Chaff (g/m chaff row)
2.44	0.61	273.87
(0.09)	(0.03)	(18.47)

Very high numbers of annual ryegrass seed were collected and concentrated in narrow windrows during harvest. There was an average of 2237

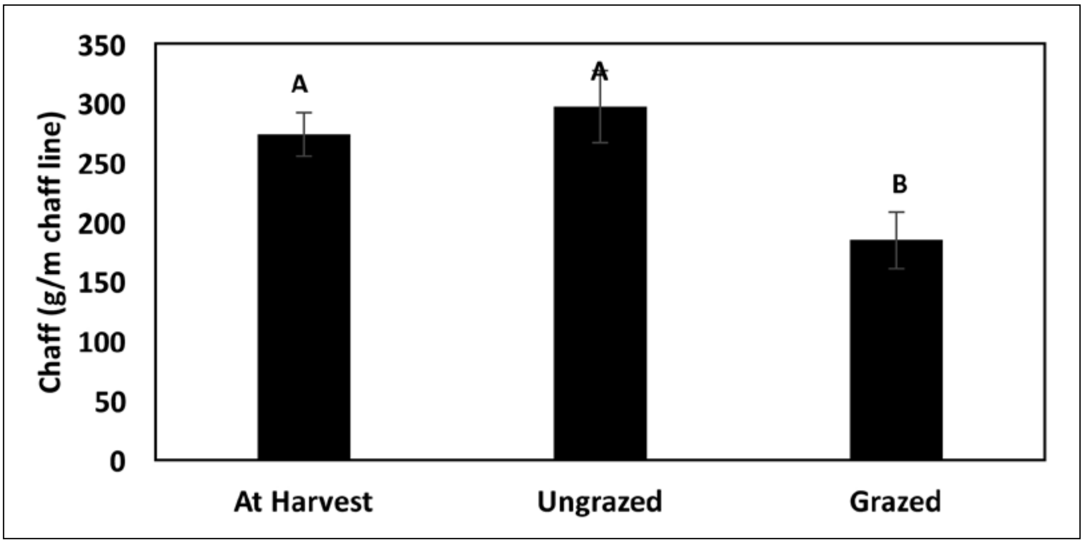

Figure 1. Chaff biomass weights collected during trial. Bars represent standard error (n=20 for harvest, n=10 for ungrazed and grazed, respectively). Different letters indicate significant differences (P=0.05).

annual ryegrass seeds per m/chaff row (Figure 2). In autumn at the end of the trial annual ryegrass seed numbers were reduced to 364 and 302 seeds per m/chaff row in the grazed and ungrazed treatments, respectively. Thus, regardless of grazing treatment there were similar amounts of seed loss of approximately 85%. Annual ryegrass seed concentrated in chaff material at harvest migrates though that material to the soil surface over summer (Walsh and Powles, 2007) and therefore, is unlikely to be consumed by grazing livestock. With little or no rainfall recorded over this period in this region it is likely that seed predation and not seed decay was the most likely cause for these seed losses (Spafford Jacob et al., 2006).

Annual ryegrass emergence was greater on the grazed chaff lines due to the removal of chaff material. Annual ryegrass emergence of 84 plants/m^2 in the grazed chaff lines was substantially higher ($P<0.05$) than the seven plants/m^2 recorded in the ungrazed chaff lines (Figure 3). With similar levels of annual ryegrass seed present on the soil surface, the 13-fold decrease in emergence is likely due to the influence of the chaff material remaining in the ungrazed treatments. This approximate 90% reduction in emergence is substantially higher than the levels previously observed in pot trials for this level of wheat chaff (Ruttledge et al. 2018).

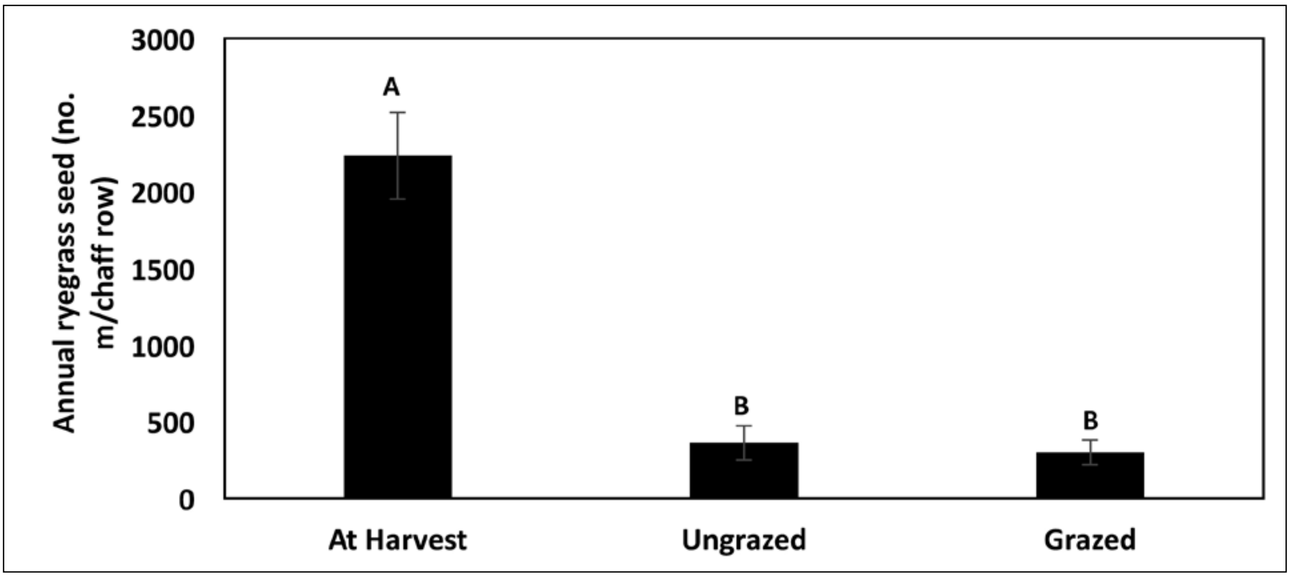

Figure 2. Annual ryegrass seed numbers present in chaff in autumn. Bars represent standard error (n=20 for at harvest, n=10 for ungrazed and grazed). Different letters indicate significant differences (P=0.05).

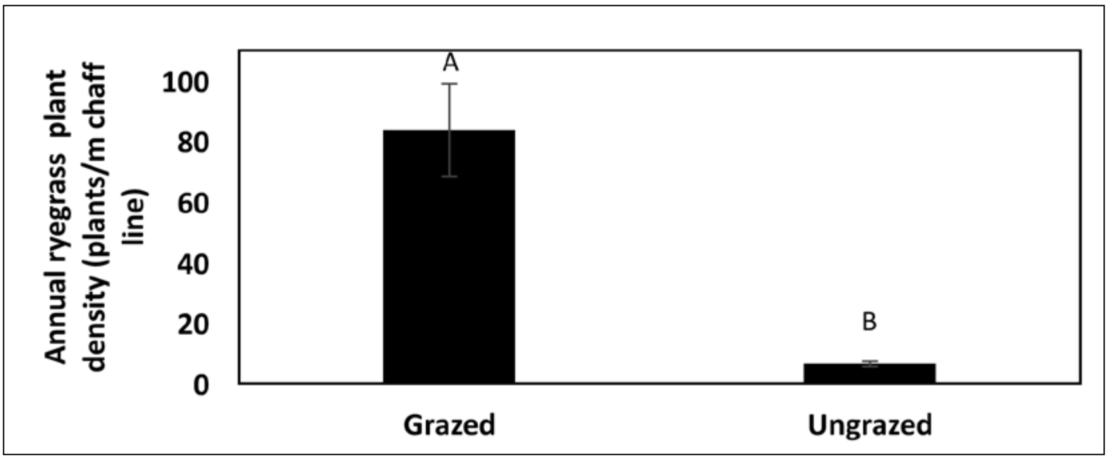

Figure 3. Annual ryegrass seedling emergence, grazed versus ungrazed. Bars represent standard error (n=20). Different letters indicate significant differences (P=0.05).

iHSD and seed terminator evaluation

Chaff output

Much lower amounts of chaff material were collected from the ST than the iHSD during the harvest of equivalent areas of similar yielding wheat plots. Approximately 40% less wheat chaff was collected exiting the ST than the iHSD (Figure 4). On average there was approximately 3.5kg of chaff collected from the exit chute of the ST compared to 6.4kg collected from the iHSD during the harvest of a 10m long by 14m wide wheat plot. With a lower baffle height (approximately 10cm) in the ST system it is possible that much less chaff material entered the ST. It is also possible that the action of ST resulted in a high proportion of fine material that was not collected by the 0.5mm mesh bags used to collect the processed chaff during testing.

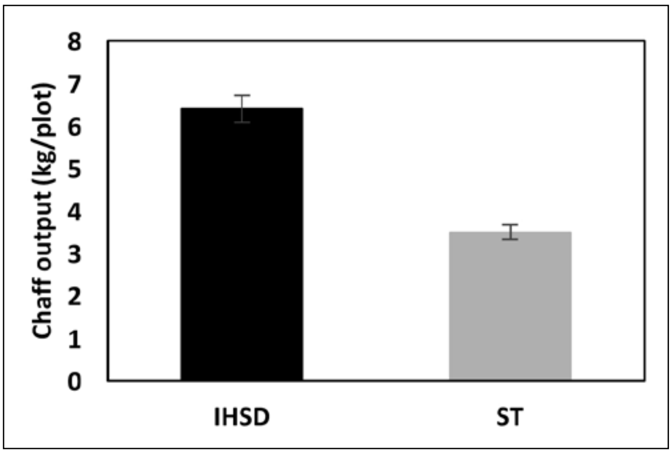

Figure 4. Amount of processed chaff collected from the outlet from one of the iHSD and ST mills during the harvest of a wheat plot (10m length x 14m width). Bars represent standard error for the mean of 10 replicates.

Processed chaff fraction sizes

The action of the ST resulted in generally more finely processed chaff material than the iHSD (Figure 5). There were greater proportions of chaff material in the smaller fraction sizes (< 2mm) of chaff processed by the ST compared to chaff processed by the iHSD. This indicates that the ST processed the chaff material to a greater extent than the iHSD.

The larger amount of annual ryegrass seed fractions recovered from the iHSD processed chaff further indicates the higher degree of processing by the ST but also the possibility that less ryegrass seed entered the ST. There was approximately 5g of dyed annual ryegrass seed fractions recovered from chaff processed by the iHSD compared with 0.8g recovered from ST processed chaff (Figure 6). The increased processing by the ST (Figure 5) may have contributed to the difficulty in recovering seed fractions. It is also possible that with less chaff material passing through the outlet (Figure 4), not all introduced annual ryegrass seed passed through the mill.

The efficacy of the ST was slightly greater than the iHSD with both systems producing very high (>95%) levels of annual ryegrass seed kill. Annual ryegrass seed kill was 95% for the iHSD and slightly higher for the ST at 99% (Figure 7). The very low standard errors highlight that these high seed kill levels were consistent across all replicates.

Impact mill developments and the need for independent testing

Since the introduction of the initial impact mills there has been considerable and ongoing

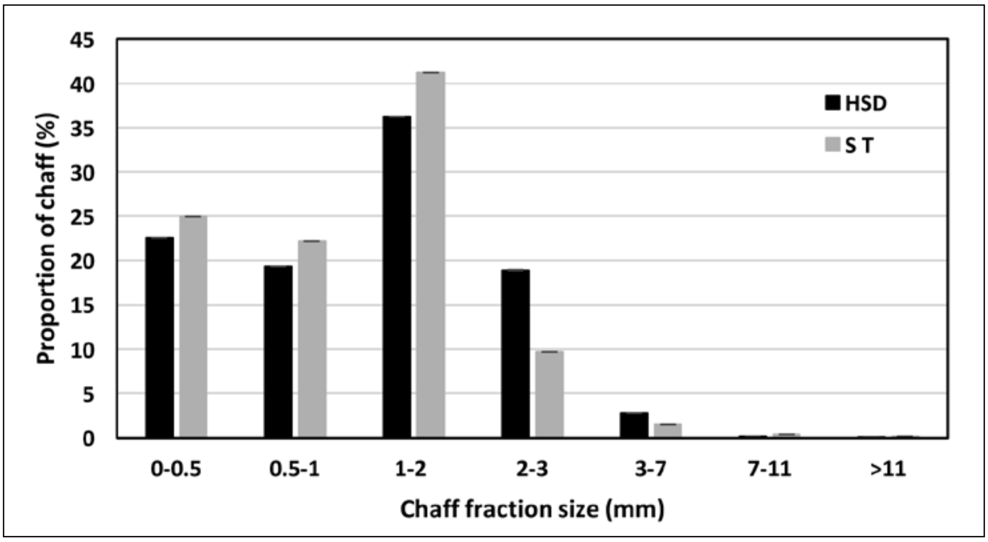

Figure 5. Distribution of chaff fraction sizes for iHSD and ST processed chaff material. Bars represent standard error for the mean of 10 replicates.

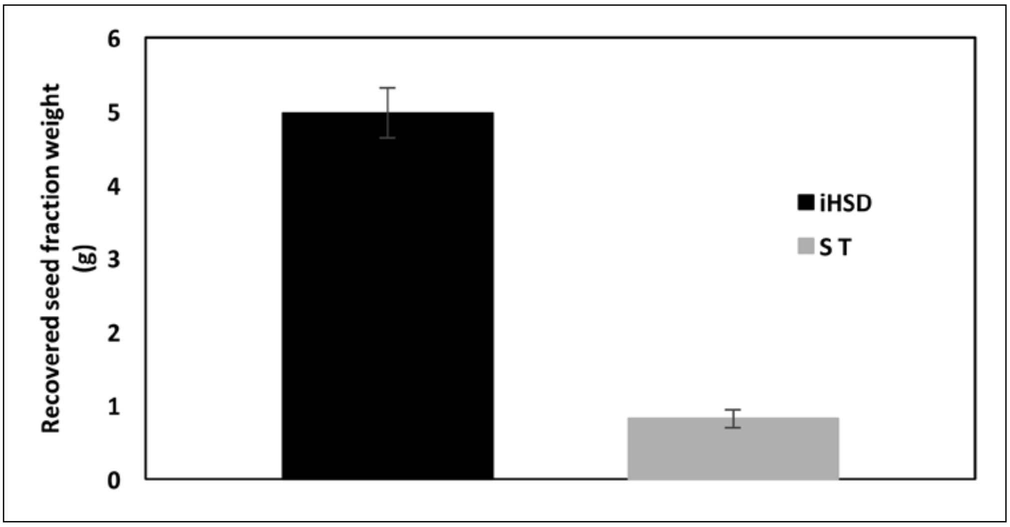

Figure 6. Weight of seed fractions manually recovered from processed chaff collected from the outlet of a single iHSD and ST mill during the harvest of a wheat plot (10m length x 14m width). Bars represent standard error for the mean of 10 replicates.

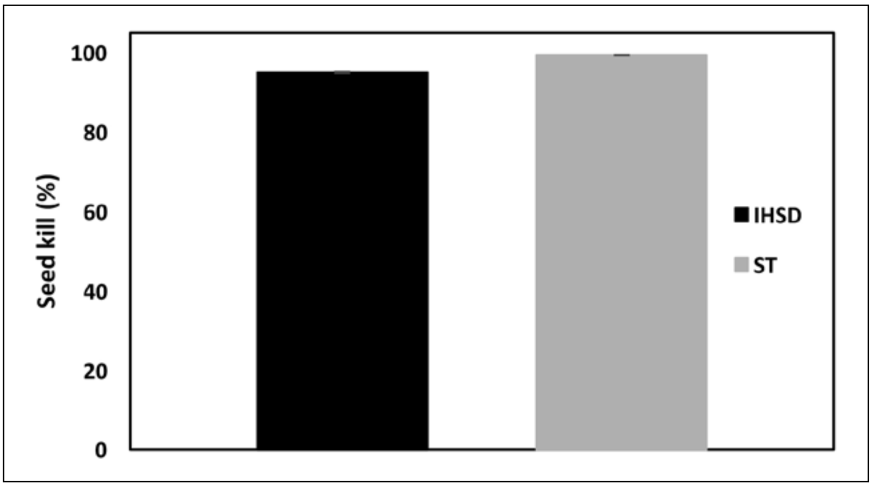

Figure 7. Proportion of seed that was killed by the action of the iHSD and ST harvest of a wheat plot (10m length x 14m width). Bars represent standard error for the mean of 10 replicates.

development that is increasing the range of available options.

Single mill system

The single mill system maintained high levels of annual ryegrass seed kill during wheat crop harvest. Annual ryegrass seed kill was consistent (94 to 96%) across all three indicating that mill performance was not severely affected by harvester load (Figure 8). These results highlight the ability of the single mill to effectively process chaff material for class 6 and 7 harvesters.

Vertical mill system

When tested across all three operating speeds the vertical mill maintained high (approximately 98%) levels of annual ryegrass seed kill (Figure 9) equivalent to previously recorded levels for horizontally mounted mills (Walsh et al. 2018). These results indicate that mill alignment (vertical versus horizontal) does not interfere with mill efficacy.

New mill systems - The continued interest

Seed Control Unit

In 2018 Redekop® introduced a twin impact mill system, with seed control unit that is incorporated with their MAV straw chopper system. The Redekop system is similar in design to the iHSD and ST twin mill systems with circular rows of bars on spinning base plates and fixed top plates. At present this system has only been installed on John Deere harvesters. It is believed that the intention is for this system to be available through John Deere as an optional extra when purchasing a new harvester.

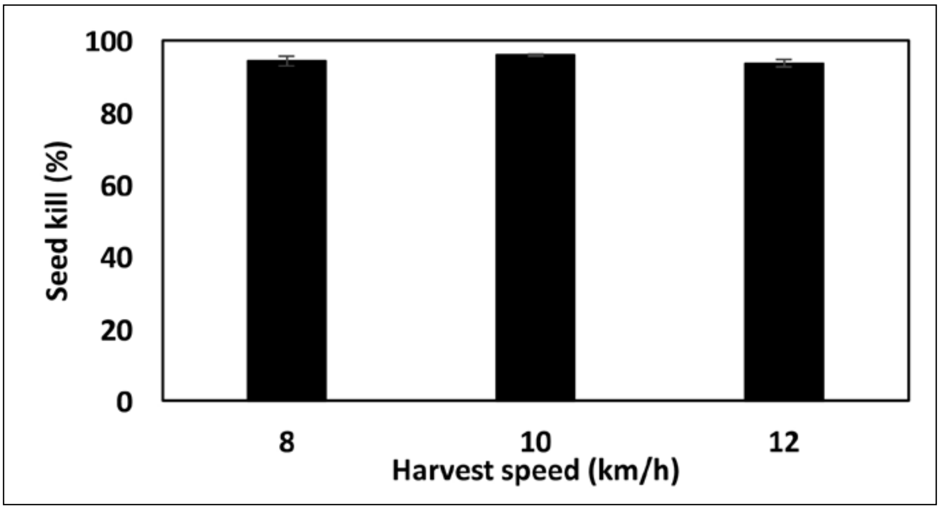

Figure 8. Annual ryegrass seed kill by a single iHSD mill system on a class 7 header during the harvest of wheat as influenced by increasing harvester speed. Bars represent standard error for the mean of four replicates.

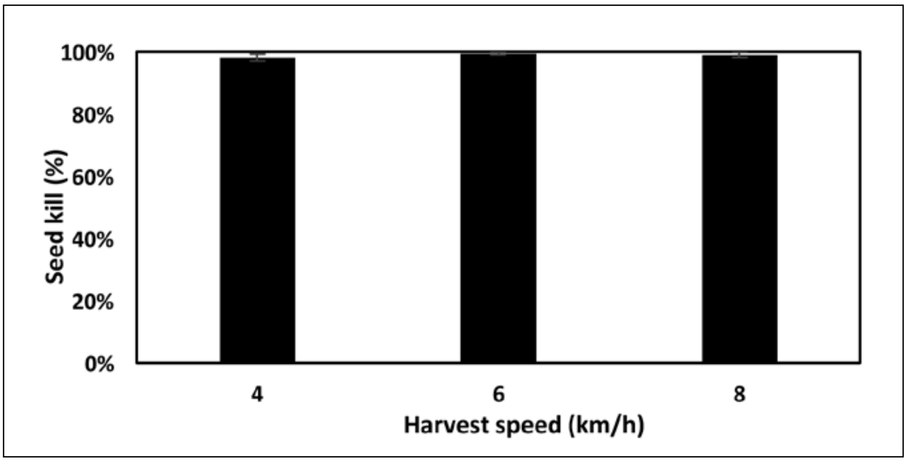

Figure 9. Annual ryegrass seed kill of a vertically mounted iHSD mill during the harvest of wheat as influenced by increasing harvester speed. Bars represent standard error for the mean of four replicates.

At present there is no independent testing data available for this system, however Redekop testing indicates high weed kill efficacy of approximately 98%.

Figure 10. Photo of Redekop® twin impact mill system.

Tecfarm WeedHog

After four years of development, in 2019 Tecfarm have made significant progress with their impact mill system. This machine represents a radical shift in impact mill design from the currently available systems. The WeedHog design is focused on the principles of reduced energy requirement and low cost. Tecfarm test results indicate that an 80% seed kill for annual ryegrass can be consistently achieved, with room for improvement. Independent testing is planned for the 2020 harvest. Tecfarm have indicated that they intend to have a limited number of units available to Western Australian growers for the 2020 harvest.

Recognised standard for testing impact mills

As the weed seed control efficacy of impact mills cannot be readily observed there is a need for the development of a testing standard for current and new impact mill systems. The efficacy of impact mills on weed seeds needs to be confirmed by a recognised standard testing procedure. This testing is required to provide growers with confidence in knowing the efficacy of an impact mill system which cannot be readily observed in the field. With many weed species, such as annual ryegrass persisting from a viable seedbank, the efficacy of impact mills in targeting weed seeds during the grain crop harvest will potentially remain unknown for many years by growers relying on visual observations. Without some assurance of the efficacy of an impact mill system, understandably there will be doubts about seed kill efficacy when visual responses are not readily observed.

Conclusion

The increasing interest in HWSC systems in general continues to drive the research and development on new and existing HWSC systems in line with grower preferences. These efforts now appear to have resulted in the development of new and more durable impact mill systems. With the adoption of impact mill systems now reaching significant levels there is a need to establish a recognised testing standard to provide growers and the industry a level of confidence in their efficacy.

Acknowledgements

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Allison Chambers and the Charles Sturt University students who spent many months manually sorting through chaff samples looking for annual ryegrass seed.

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Better pastures — better crops: Management of pastures in a mixed farming system

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ΦExtra technical comment by Protech Consulting Pty Ltd

Keywords

- pasture, lucerne, perennial grasses, annual legumes, nutrition, weeds, transition, tillage, pH-acidity, persistence, winter cleaning.

Take home messages

- Pastures rebuild organic carbon (C) and soil nitrogen (N) reserves.
- Pastures provide opportunities to reduce the weed seed bank prior to cropping.
- To achieve these benefits, the pasture must be dense, productive and persistent.
- Soil test - ensure that all nutritional issues are addressed at establishment and across the entire pasture phase, in particular phosphorus (P), sulphur (S) and molybdenum (Mo).
- pH stratification and subsoil acidity have the potential to severely compromise pasture production.
- Legumes must have effective rhizobia nodules fixing N.
- Winter cleaning is a highly effective management practice for weed control and lasting crop rotational benefits in terms of N and cereal root diseases.
- Match pasture type to desired outcome and utilisation potential.

Background

Across the southern NSW cropping belt, there has been a multitude of research projects conducted and papers written about this very topic. The biological processes and farming systems effects are very well understood, however a large amount of this research was carried out in the 1990s and as this decade came to a close, one paper concluded that 'the relevance of pasture-crop rotations is decreasing as sheep numbers decline and cropping area increases' and in 2001 this same paper identified that 'there has been little attention paid to the long term consequences of continuous cropping around the issues of nitrogen, weeds, residues, tillage, lime and gypsum' (Angus, Kirkegaard and Peoples, 2001). So fifteen to twenty years on, what has changed?

- Continuous cropping area has increased.
- Crop rotations are longer on the more arable zones of mixed farms.
- Canola is the dominant break crop.
- There is not a stable, reliable pulse crop being widely grown in southern NSW.
- Organic N levels have declined under long term cropping.
- Weeds are an ongoing issue.
- Direct drilling using KPPW seeders, and retaining stubbles are common practice.
- pH stratification and acidic subsoils are a constraint.
- Phosphorus stratification is not well understood.

- More recently livestock enterprises have reached new profitability levels, often higher than cropping and with less risk. Mixed farmers are capitalising on the synergies of grazing crops, pastures and cash crop systems.
- Well managed pastures are one of the key drivers of the profitability, sustainability and resilience of these systems.

It is this last bullet point that is the focus of this paper and in particular, how well a well-managed pasture phase will deliver significant benefits to the subsequent cropping phase. The main areas of discussion are on:

- Pasture types on typical mixed farms.
- The positive impacts that pastures have on the soil resource.
- Long term weed seed bank management.
- Transitioning from pasture to crop and from crop to pasture.

A typical mixed farm

This is a very difficult thing to describe given the significant variation in farm size and enterprise mix across the region. Table 1 attempts to standardise the typical differences from west to east.

Just as describing the typical farm is difficult, so too is describing a typical pasture. By far the dominant species are lucerne, sub clover and arrowleaf clover. Moving east as rainfall increases, perennial grasses are included in the majority of mixes and the pasture phase is longer.

Whatever the mix utilised from this diverse range of pasture species and varieties, the key to bringing the many positive benefits available from the pasture phase across to the subsequent cropping phase is to use the pasture that is best suited to each particular paddock and manage to ensure that it is dense, persistent and productive for the entire time that it is there.

The impact of pastures on the soil resource

Pastures are recognised as providing a long term benefit both in terms of soil structure and soil fertility. There are two major nutritional benefits that flow from a pasture phase to the cropping phase — residual organic N and an increase in soil C levels. A well-managed legume based pasture can fix between 100 and 200kg/ha of N annually. This number is highly correlated to shoot dry matter produced. As a rough rule of thumb, the research indicates that most legumes fix between 15 and 25kg of N/t of dry matter. This is, of course, dependent on effective nodulation. Pasture type also influences the subsequent supply of N mineralisation into the crop rotation as shown in Figure 1.

Table 1: Comparable area breakup of mixed farms across the region.

	West < 450 mm		Middle 450 - 550 mm		East > 550 mm	
Ha	2,000		2,000		2,000	
Crop	1,800	90%	1,300	65%	1,000	50%
Grazing crop		nil	390	*(30% of crop)*	400	*(40% of crop)*
Pasture	200	10%	700	35%	1,000	50%
dse/ha	1,000	5.0	10,000	9.2	15,000	10.7

Table 2: Typical pasture species used across the region.

	West < 450 mm	Middle 450 - 550 mm	East > 550 mm
Species used	Lucerne	Lucerne & Chicory	Lucerne & Chicory
	Sub & Medic	Sub & Medic	Perennial Grasses
	Annual clovers	Annual clovers	Sub & Medic
	Vetch	White clover	Annual clovers
		Prairie grass	White clover
			Prairie grass
Phase years	2 to 4	3 to 5	5 to 10

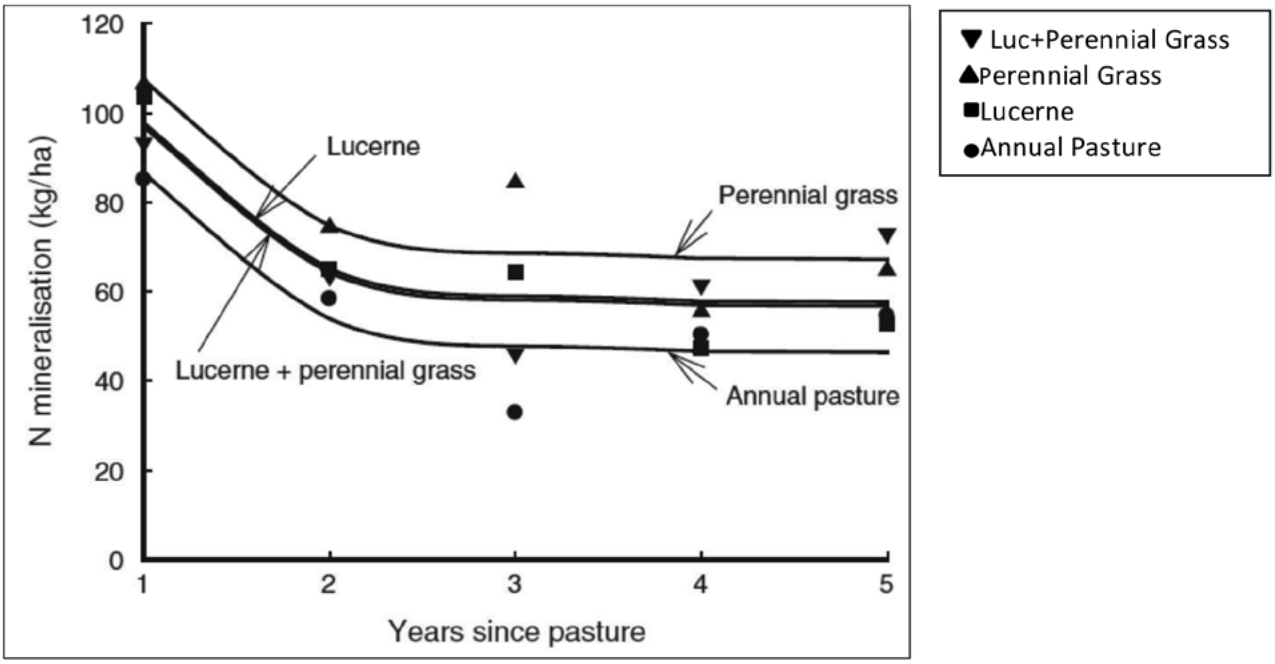

Figure 1. N mineralisation rates in relation to previous pasture type and the number of years since the pasture phase. *Source: Angus, Bolger, Kirkegaard, Peoples, 2006.*

Building up the soil organic pool improves soil structure and provides more regulated soil water holding capacity and nutrient cycling and is a very slow biological process. Long term research at Harden by CSIRO researchers John Kirkegaard and Clive Kirkby has shown that long term cropping (stubble retained — direct drill) uses around 50kg/ha of soil organic C per year, whilst a pasture phase can increase C levels by 200 to 550kg/ha per year, by far the fastest way to significantly rebuild organic C levels.

However, to do this, the pasture must again be productive. Recent research by Dr Yin Chan NSWDPI (Chan, *et al.* 2010) has shown that fertility is vital to drive this process. Without sufficient P and S, the available C and N in the pasture residues cannot be converted to stable humus, increasing the organic N and C pools in the soil (Kirkby, *et al.* 2014).

Another significant benefit is that deep rooted perennial pastures, such as lucerne and chicory, have the ability to improve macroporosity well into the subsoil layers with the initial benefit of creating higher infiltration capacity, as well as greater access to deeper water and nutrients for subsequent crops (McCallum, *et al.* 2014). In our region, chicory is particularly useful for penetrating acidic subsoils. The downside to this, as was very evident across the millennium drought, was that these deep rooted perennials can also de-water the subsoil, with negative impacts on subsequent crops. However, once this deep water is gone, it is gone so this short term impact is significantly outweighed by the long term residual benefits of greater macroporosity, particularly if a farm is being transitioned to a controlled traffic farming (CTF) system to reduce compaction. Of note, tap rooted crops could not achieve the same effect.

Weed seed bank management

The pasture phase provides a number of opportunities for significantly reducing weed seed banks.

These include:

- Fodder conservation, hay and/or silage.
- Spray topping and/or fallowing.
- Pasture cleaning with grazing and herbicides.

Table 3: Residual root channels increase infiltration rates into the subsoil.

Prior Pasture	Temora NSW		Birchip VIC
	Infiltration Rate mm/hr	Macropores > 2.0 mm	Infiltration Rate mm/hr
Annual Crops	2	68	3
Lucerne	10	225	6

Source: McCallum, et al. 2014.

Table 4: Expected levels of ryegrass control from different management strategies.

Tactic	Ryegrass control level (%) likely (range)
Mowing + Crash grazing	95 (90-98)
Hay, silage, green manure	90 (80-98)
Strategic grazing	75 (30-95)
Winter cleaning	90 (80-98)
Spray topping to reduce grasses	75 (50-90)
Spray fallowing — double knock	90 (80-98)

Source: Roundup Ready canola resistance management plan.

Ideally, pasture density will be high enough to outcompete weeds in the first instance, which can be easily achieved with the right establishment program using an appropriate sowing rate and species mix. Then towards the end of the pasture phase, implement a strategy that achieves zero weed seed set for the two years prior to returning to the cropping phase.

A typical strategy would be to reduce the seed set by 70-80 % in year one with strategic crash grazing, fodder conservation or spray topping, followed by a winter clean in year two, then finally an early fallow in year three.

Given that the aim is to achieve 100% weed control with winter cleaning and fallowing, it is worth discussing these strategies in greater detail.

Winter cleaning involves using grazing and herbicides to control a range of broadleaf and annual grass weeds, including capeweed, radish, fumitory, mustards, milk thistle, prickly lettuce, ryegrass, barley grass, brome grass, wild oats and vulpia.

The process is to:

- Graze the paddock very hard to bare it right out (golf fairway short).
- Apply a herbicide mix of Gramoxone® and Simazine[Φa] a (plus broadleaf herbicide).
- An alternative herbicide option is propyzimide[Φb].

[Φa]Gesatop is not registered for use on capeweed, radish, fumitory, mustards, milk thistle or prickly lettuce. [Φb]Label states not registered for use on capeweed, radish, fumitory, mustards, milk thistle, prickly lettuce, ryegrass, barley grass, brome grass or wild oats.

The main mix is applied immediately after the stock are removed and just ahead of a rain front. To gain maximum control, the paddock must be grazed very short. It can be warranted to apply a low dose of gramoxone® after grazing to reduce any residual bulky areas that stock cannot reach, prior to applying the main herbicide mix a week later.

It needs to be noted that this strategy is very hard on the desirable species in the pasture. It will take at least eight weeks for the pasture to rebuild dry matter levels back to grazing levels. This requires winter stocking rates to be managed accordingly, which is an example of where the synergies of having grazing crops available elsewhere on the farm are highly beneficial.

There is also an added proven benefit from winter cleaning which is increased N supply to the subsequent crops, along with control of cereal root disease pathogens if a cereal is to be the first crop in the rotation. **Winter cleaning in the year prior to cropping has been shown to increase canola yields by 80% in canola and 40% in wheat in year one with significant increases in the order of 10-15% for the subsequent three years (Harris et al., 2002).**

Fallowing the pasture phase out is another weed control opportunity not to be missed. To maximise the level of control, use robust herbicide rates and fallow early. This application can be followed with some grazing to reduce the bulk to a manageable level for cultivation if required, with the aim of maintaining ground cover over the summer period. If any weeds survive the initial glyphosate based application, then a double knock with Gramoxone® can also be used.

Table 5: The effect of timing of removal of lucerne prior to cropping on soil mineral N, wheat N uptake and grain yield at Junee Reefs, NSW.

Timing of lucerne removal months	Soil Mineral N 0.0 - 2.0 m Kg N/ha	Wheat Shoot N Uptake Kg N/ha	Grain Yield t/ha
2	59	86	3.8
4	111	109	5.0
6	206	137	5.9

Source: Angus et al., 2000.

Fallowing in early spring will also allow a greater potential for capturing spring rainfall and conserving nutrients for the subsequent crop. To maximise this opportunity, the fallow must be kept weed free and ground cover maintained over the summer period.

Transitioning — from pasture to crop

There is no standard point of transition. The timing is highly variable from farm to farm, ranging from a set rotation to when the pasture declines to a point where it is no longer productive. Over the course of time, lucerne and other perennials tend to thin out to the point where they become vulnerable to invasion by annual weeds, which dictates when the paddock is returned to crop. Ideally, the pasture would be fully productive, providing a significant grazing resource, and providing weed control options and building soil resources right up to the point it is removed.

Prior to removal, regular soil testing will indicate the fertility status of the paddock. If pH levels have declined, then the appropriate rate of lime should be applied to raise the pH of the top 10.0cm to at least 5.5 $CaCl_2$. When the opportunity arises in late summer to early autumn, the paddock can be strategically cultivated to fully incorporate the lime. This strategic cultivation can have other benefits as described in the Mark Conyers' paper in these proceedings.

With the aim of achieving two years of complete weed control prior to cropping, an alternative strategy is to drill a forage cereal, such as oats into the thinning pasture stand, crash grazing and applying a knockdown first, spray topping when the grasses go to seed and crash grazing in year one followed by a complete fallow in the spring of year two.

Transitioning — from crop to pasture

Again there is no standard point of transition, often being dictated by the cropping returns dropping off, as a result of declining fertility, lower yields, higher costs and often a buildup of weeds. A preferable option is to rotate the paddock back to pasture without a weed burden compromising pasture establishment.

Getting this transition right and establishing a dense productive pasture are critical for achieving the benefits outlined previously. There are a range of issues to consider:

- Nutrition - P, S and Mo.
- Acidity.
- Weeds, insects and diseases.
- Establishment technique – undersowing or direct seeding.

Nutrition

Often setting the paddock up for the pasture phase from a nutritional aspect is overlooked. It is assumed that things were right for the cropping phase so they will be right for the pasture. Two recent projects looking at legume performance have highlighted that things may not be as they seem.

Firstly, the GRDC supported, NSWDPI project (DAN00191) 'Boosting pulse crop performance on acid soils' (Burns, Norton and Tyndall, 2016) has identified that pH stratification is a significant issue for pulse crop nodulation and performance. They found it reasonable to conclude that the presence of undetected, but severely acidic layers is likely to be a major factor responsible for inconsistent 'performance' of acid-sensitive pulses on slightly acid (pH $CaCL_2$ >5.0) and moderately acid soils (pH $CaCL_2$ 4.6 to 5.0) of the medium and high rainfall zones. Pasture production would be expected to be compromised in the same way, significantly reducing immediate performance and carryover benefits.

Secondly, another project 'The Trouble with Sub', funded by the Riverina Local Land Services (LLS) in conjunction with many collaborators, surveyed 81 clover paddocks in the spring of 2015 across the Riverina and south west slopes region.

Some key findings from this project were:

- Legumes comprised 48% of the pasture base.
- Only 23% of paddocks had sub clover with good nodulation.
- Nodulation in 45% of paddocks was poor.
- 22% of paddocks had pH issues in the topsoil layer with Al% > 5.0 %.
- 40% of paddocks had a subsoil pH issue with the pH $CaCl_2$ of the 10-20cm layer being < 4.5. Only 4% of paddocks had a history of Mo in the past 10 years.
- 61% of paddocks have a history of fertiliser applications.

Phosphorous drives overall pasture production by boosting the legume content which fixes more N which drives pasture growth. The critical level of Colwell P to maximise pasture production depends on the desired stoking rate, soil type and environment as outlined in Figure 2. This issue is comprehensively covered in the publication, 'Five easy steps to ensure you are making money from superphosphate" (Simpson *et al.* 2009).

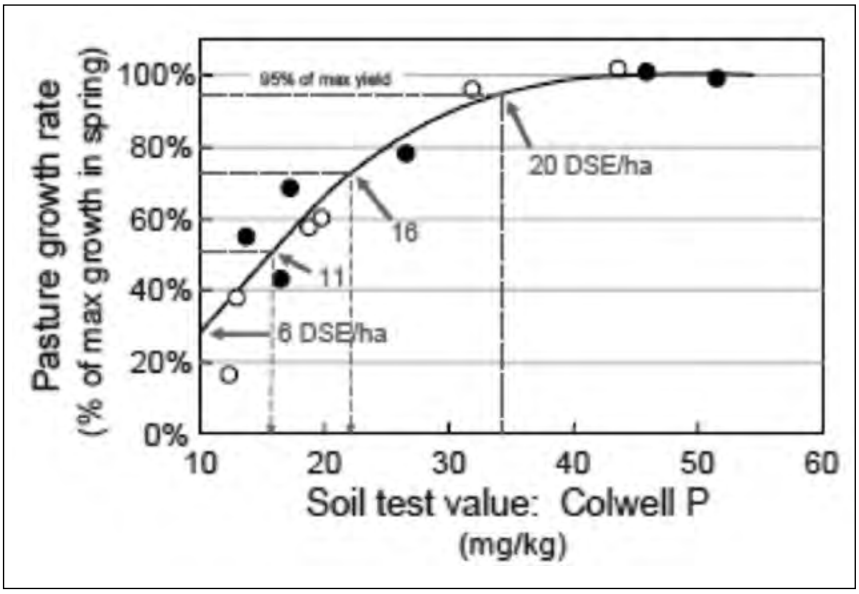

Figure 2. Critical soil phosphorus values relative to stocking rate.
Source: Five easy steps to ensure you are making money from superphosphate (Simpson et al. 2009).

The current standard practice on most mixed farms is to build the P level of the paddock across the cropping phase with annual monoammonium phosphate (MAP) inputs, then let it run down through the pasture phase. As pasture phases become longer (greater than three years), regular soil testing to monitor P, S and pH is recommended. A typical program that aims to maintain an ideal level of pH, P, Mo and S for pasture and crop production is illustrated in Table 6.

MAP applied @ 90kg/ha to all crops, with Single Super applied @ 120kg/ha in 2010.

The key message here is to ensure that all nutritional issues are fully considered. Soil test regularly, and a top up lime application and strategic incorporation may be required, along with an application of Mo to ensure conditions are suitable for legume pasture production. More regular P and S applications may be required as well.

Weeds, insects and diseases

All need to be managed, with the industry having a good understanding of this. Some new pests such as earwigs and slugs need to be considered as they can completely and quickly bare out large areas of establishing pastures, the effects of which carry right through the pasture and well into the next cropping phase. More careful attention also needs to be paid to the emerging weed problems of prickly lettuce and milk thistle, particularly in the year prior to pasture establishment, as these weeds can be hard to control in some pasture mixes. It is also advisable to be very cautious of the plant back periods that must be observed for herbicides such as Lontrel™ for control of these weeds. In general, it is important to refer to the label of any herbicide used prior to sowing the pasture to ensure that there will be no risk of **residual herbicide** carry over effects. In particular, group B herbicides such as Atlantis® which are being more commonly used to manage wild oats in cereals as well as chemistry used on Clearfield crops. Some more common herbicides and their plant backs are listed in Table 7.

Table 6: Soil testing, lime/pH, P, S and Mo management over a 20 year period.

PADDOCK Windmill	DATE	P	S	pH CaCl2	Al %	OC %	Lime Yr	Rate t/ha	Yr Gyp	Year Mo
Crop 97 - 01	09/11/1997	6		4.9	2.2	0.8	98	2.7	98	98
Past 02 - 03	20/03/2000	21	7.8	6.0	1.0	1.3				
Crop 04 - 07	19/01/2004	18	4.7	5.6		1.2			05	07
Past 08 - 13	15/01/2009	25	3.1	5.3	1.1	1.3				
Crop 14 - Current	30/01/2014	30	7.0	5.1	2.5	1.4	15	1.0	15	15

Table 7: Plant back periods for various herbicides prior to pasture establishment.

Product	Plant back in months	
	Lucerne	Sub Clover
Lontrel Adv	9	9
Intervix	10	10
Spinnaker	10	10
Atlantis OD	21	21
Sakura	21	9

Note: As there are also often rainfall and soil type requirements that affect these periods, refer to the label.

Establishment technique

Regionally there are two methods of establishing pastures:

1. Under a cover crop
2. Direct seeding.

There is always considerable debate about which method is best practice without a clear outcome. There are many research papers that show that cover cropping increases the risk of pasture establishment failure, and reduces the pasture biomass production in the year after establishment as shown in Table 8.

However, the whole farm economic analysis from this same research project concluded that there was no difference in the probable farm cash balance at the end of a decade between pasture establishment techniques. Hence, across the region the dominant method (greater than 80%) of pasture establishment is under a cover crop. There are, however, some clear directions that come from this research.

- Use a low cover crop seeding rate, relative to environment.
- Lucerne and chicory based pastures are more likely to establish.
- Perennial grasses, such as phalaris, fescue and cocksfoot are more likely to fail.
- Short term straight annual legumes are best direct seeded.
- Short term, three year 'rebuilding pastures' are best established without a cover crop.

From experience and observation, there are several rules of thumb that can be followed to reduce the risk of establishment failure:

Cover crop choice —Firstly considering species, crops that finish early in the spring will give the pasture the chance to utilise spring rains for improved establishment. Short season barley and wheats are therefore popular choices. Canola is also being used more widely where weeds are not an issue. Then within species there are options on what is the most competitive crop. For example, the wheat varieties Condo⁽ᴾ⁾ and Spitfire⁽ᴾ⁾ are quick, erect and low tillering.

Time of sowing — Plan to get the undersowns in right at the front of the cover crop sowing window to improve establishment opportunities and avoid heat stress in spring. This is where the wheat variety Lancer⁽ᴾ⁾, which is very slow and poorly competitive through the winter may have a place, to allow very early establishment of the undersown pasture as opposed to a high tillering tall variety like Gregory⁽ᴾ⁾ which should be avoided.

Direction of sowing —It is now recognised that sowing in an east -west direction significantly reduces weed competition in the inter-row. **To improve the growth and establishment of the undersown pasture, sow in a north-south direction.**

Pasture type, seasonal conditions and outlook — If sowing perennial grass based pastures in a dry autumn with the forecast of a dry spring, do not use a cover crop, or consider not sowing the pasture at all.

Environment — in low rainfall environments (< 400mm), use cover crops with caution.

Case study

This short case study is an actual example of how the introduction of a pasture phase can rebuild fertility and get on top of a significant weed burden on a mixed farm in the mid rainfall belt on the southwest slopes of NSW.

Table 8: Difference in biomass production in the year after establishment.

Year & site	Species	No Cover Crop t/ha DM	Plus cover crop t/ha DM	% Reduction
2009 Yerong Creek	Lucerne	20.9	14.4	31
	Phalaris	8.3	2.6	69
	Chicory	13.8	7.0	49
2009 Ariah Park	Lucerne	7.5	4.3	43
	Phalaris	5.4	0.7	87

Source: Hayes et al., 2015

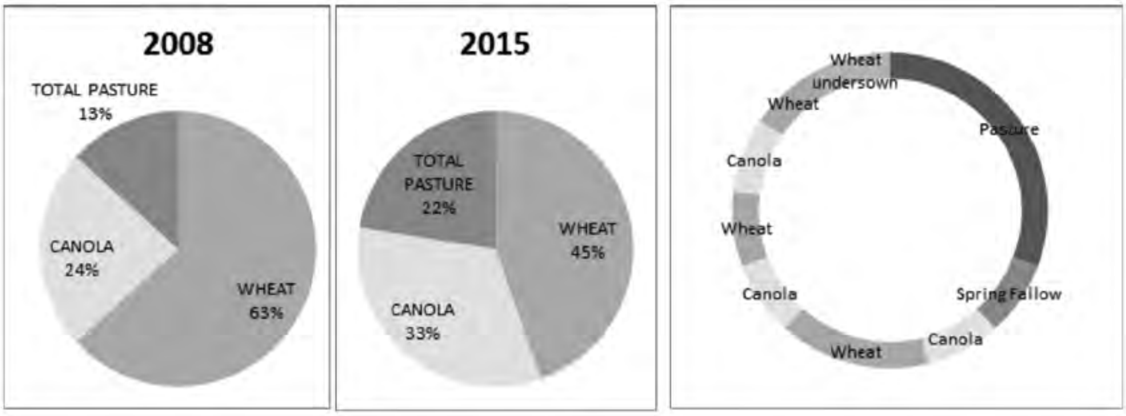

Figure 3. The change in rotation on the case study farm. Current is five years' pasture, canola, wheat, wheat, canola, wheat, canola, wheat, wheat undersown with lucerne and clover pasture.

A 1,000 hectare block was purchased in 2005. The block had been continuously cropped for the previous 15 years. The rotation was changed from 100% crop to 70% crop with 30% pasture because of ryegrass and poor fertility. Paddocks are now cropped for seven years and out to pasture for four or five years. Pastures are lucerne clover based and are winter cleaned in year 2/3, have hay made in year 4 (the year prior to being spring fallowed) and spring fallowed in year 5, then come in through triazine tolerant (TT) canola, followed by wheat with Sakura®. Winter cleaning was predominantly gramoxone/simazine/Tigrex®, but now also includes propyzimide .

The canola area now varies between 33% and 45% of crop area depending on the grain market outlook. Winter cleaning and narrow windrow burning have been critical in getting the ryegrass back in control. In the past, without pasture on this farm achieving the protein levels in wheat over 9.5 — 10.0 % did not happen very often. For the 2016 harvest, the wheat yields ranged from 4.0t/ha of APW1 on the last of the long term crop paddocks, up to 5.8t/ha of AH2 on the paddock's second crop after a pasture phase.

Summary

A pasture phase can deliver substantial and lasting nutritional benefits well into a subsequent cropping phase, as well as providing the opportunity to drive weed seed banks to very low levels. To achieve these outcomes, the pasture must be dense, productive and persistent. The pasture phase is the ideal opportunity to address soil constraints that are limiting production and rebuild soil N and organic C levels. A rigorous process of soil testing, identifying all the issues then addressing them with the appropriate addition of required nutrients and/or ameliorants is just as important as the selection of the most appropriate pasture species, variety, seeding rate and establishment technique. Well-managed productive pastures provide significant synergies to a mixed farm — firstly in terms of a major fodder resource for the livestock enterprises and secondly, by providing a range of tangible benefits that enhance the sustainability and profitability of the subsequent cropping phase.

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Notes

Stubble and nutrient management to build soil carbon – challenges and opportunities

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Keywords

- soil organic matter, stable organic carbon fractions, carbon isotopes, low and high wheat stubble, clay-rich and clay-poor soil, organo-mineral interactions.

Take home messages

- Preserving or enhancing soil organic matter stocks is critical to sustainable agriculture, due to its key role in soil health, plant productivity and building resilience. Stubble return with strategic nutrient inputs ('integrated stubble-nutrient management') has been proposed as a measure to build soil organic matter in cropped soils.
- The supply of extra nutrients along with wheat stubble enhances stocks of stable soil carbon if wheat stubble input is high (12t/ha), which is unlikely under rainfed conditions in normal seasons. At more common rates (less than or equal to 4t/ha), there may be no benefit on improving stable soil organic matter through the integrated stubble-nutrient management.
- Where stubble input is high, the addition of extra nutrients considerably enhances microbial biomass, potentially leading to build-up of stable organic matter, especially in clay soils.

Background

There is growing recognition of the benefits of soil organic matter (SOM) for maintaining productivity and carbon sequestration. Managing crop residue, such as straw residues together with input of nutrients, commonly known as 'integrated stubble–nutrient management', is a topic of interest to growers aiming to improve SOM, soil structure, microbial growth, and available nutrients to support crop production (Kirkby et al. 2016). SOM originates from the decay of plant materials (such as crop stubble, dead roots), animal wastes, and microbes. SOM is composed of several fractions; living microbial biomass (BIOM), readily degradable (labile) particulate organic matter (POM), and slowly degradable, humified organic matter (HOM), (Figure 1).

Cereal stubble has low concentrations of nutrients including nitrogen (N), phosphorus (P), and sulphur (S), although some nutrients may be released from existing SOM during the decay of stubble after its incorporation in the soil (Sarker et al. 2019). The addition of extra nutrients from fertilisers, along with the return of nutrient poor stubble in soil, may stimulate microbial activity and decrease nutrient mining by microorganisms while preserving existing SOM. Hence, integrated stubble–nutrient management may enhance the decay of stubble and increase microbial biomass and carbon-use efficiency (Fang et al., 2018a), with potential to convert a greater quantity of stubble-derived carbon (C) into stable SOM fractions (Kirkby et al. 2013; Kirkby et al. 2016).

Currently, there is limited understanding of the impact of combined inputs of wheat stubble and nutrients (N, P, S) and the effects of 'normal' and higher rates of nutrients on stubble-derived C in SOM fractions, and the consequential implications for long-term C storage in different soil types. To better predict responses of C cycling and storage following the return of crop residues to the soil, greater understanding of the role of stubble and nutrient management in SOM formation and stabilisation is needed. In agricultural soils, adoption of integrated stubble-nutrient management may enhance the conversion of labile organic matter inputs into more stabilised SOM. This process known as ‘humification’, keeps more C stored in soil with implications for economic benefits via the ‘carbon economy’ (e.g. soil carbon credits).

There is some evidence that balancing nutrient inputs to match the C-to-nutrient ratio of SOM can improve the stabilisation of stubble-C in a fine fraction pool (<0.4mm) (Kirkby et al. 2013; Kirkby et al. 2016). However, less is known about the effect of supplementary nutrients (N, P, S) on the conversion of stubble/straw into different SOM fractions with varied stabilities. As detailed in Figure 1, a C-isotope technique was applied in an eight-month laboratory study to directly quantify the partitioning of residue-C (δ^{13}C-enriched) in physically-defined and modelling-relevant SOM fractions. To harness the benefits of returning stubble together with extra nutrients in farming systems, we need to identify;

- The nutrient supply value of wheat stubble, plus the release of additional nutrients from existing SOM after the input of stubble, which may save some fertiliser costs.
- The effectiveness of adding extra nutrients together with wheat stubble (the amounts may be low or high, depending on grain yield in different rainfall conditions) to enhance the transformation of wheat-stubble-C into stabilised humified SOM fractions.
- The effect of soil type on the incorporation of stubble-derived C into stable SOM fractions.
- The role of ‘integrated stubble-nutrient management’ in enhancing residue-C mineralisation and microbial biomass with implications for C sequestration in stable SOM fractions.

Methodology

In this study, two different soils were collected from two separate long-term, grain-based, farming system trials at Condobolin (New South Wales), and Hermitage (Queensland). A red soil (Red Chromosol) was collected at Condobolin and a cracking clay soil (Vertosol) at Hermitage (Table 1).

Tables 2 and 3 report relevant soil properties of the two field sites, as well as total C and nutrient contents of the wheat stubble used in this study.

Table 1. . Site descriptions for Condobolin (NSW) and Hermitage (QLD) for the long-term trials.

Location	Condobolin Ag research station (NSW)	Hermitage research station (QLD)
Treatment sampled	Conventional tillage — long fallow wheat, short fallow wheat under-sown with pasture and subsequent three-year grazed pasture (annual medics and lucerne).	Conventional tillage — mainly wheat cropping phases with stubble retained and 90kg urea-N per hectare.
Trial established	1998	1968
Climate	Hot, semi-arid climate; non-seasonal precipitation	Subtropical; summer-dominant precipitation
Soil	Sandy clay loam (Chromosol)	Clay (Vertosol)

Table 2. Properties of the soils at the trial sites. Values in brackets are standard errors (n=3).

	$pH_{1:5\ water}$	Sand (%)	Clay (%)	Organic carbon (t/ha)	^{13}C (‰)	Total N (t/ha)	Total P (t/ha)	Total S (t/ha)
Red Chromosol	5.8	61.7	26.9	7.1	–24.7	0.5	0.25	0.11
	(0.2)	(2.0)	(0.8)	(0.5)	(0.1)	(0.1)	(0.03)	(0.01)
Vertosol	7.3	15.2	62.6	12.4	–19.2	0.8	0.63	0.13
	(0.1)	(1.2)	(0.3)	(0.2)	(0.2)	(0.1)	(0.02)	(0.02)

Table 3. Properties of wheat stubble used in this study. Values in brackets are standard errors (n=3).

	Organic carbon (kg/t)	^{13}C (‰)	Total N (kg/t)	Total P (kg/t)	Total S (kg/t)
Wheat residue	435.2 (4.7)	494.0 (2.1)	4.0 (0.1)	1.9 (0.1)	0.24 (0.02)

Soil sampling, laboratory incubation and analyses

Soil samples were collected in May 2015 from the long-term conventional tillage treatments, during the crop pre-sowing stage at both field sites. The soils were gently sieved to less than six millimetres then incubated for eight months, with or without incorporation of chopped wheat stubble residues (less than 2mm), under controlled soil moisture and temperature conditions.

Wheat stubble residues were applied at 0, 6.7 and 20.0g/kg soil, corresponding to respective no, low (4t/ha) and high stubble loading rates (12t/ha). These stubble loading rates are typical for low and high rainfall seasons. Applications were made to a shallow depth of 5cm with a bulk density of 1.2g/cm^3 (Fang et al., 2018a). A laboratory incubation experiment containing seven treatments for each soil was set up at 22°C (Table 4).

Quantities of N, P, and S additions were calculated on the assumed nutrient requirements of an additional 10 or 30% of wheat residue to become stable SOM, which was based on the commonly-observed C-to-nutrient ratio of SOM; C: N of 12:1, C: P of 50:1, and C: S of 70:1 (Kirkby et al. 2013).

The soils amended with stubble and nutrients were incubated for eight months under a controlled environment. Soil samples or soil-residue mixtures were adjusted to 60% of maximum water holding capacity and packed in containers to 1.2g/cm3 bulk density and placed in 1.2L enclosed buckets. Subsamples of soil-residue mixture and the control soils were removed at 126 and 245 days, air-dried and sieved for analyses.

To quantify the distribution of wheat residue-C (δ^{13}C 494‰, C-content 43.5%), two-pool ^{13}C-isotope modelling was employed (Fang et al. 2018a,b). This is expressed as a percentage of added residue-C, into total CO_2, microbial biomass carbon (MBC), and various modelling-relevant SOM fractions (pools).

Soil density and particle size fractionation

A combined density and particle size fractionation of soil samples was conducted, separating SOM into labile and stable C fractions (Golchin et al. 1994; Herath et al. 2014). Figure 1 illustrates the physical fractionation to separate SOM into different C fractions, which were analysed for C% and δ^{13}C (Fang et al. 2019).

Results and discussion

Impact of stubble-nutrient management on residue and microbial carbon

Over 245 days, the total stubble residue-C mineralisation ranged from 480 to 610kg CO_2-C per tonne of residue-C. This is equivalent to 48–61% of residue-C mineralised across all the stubble and nutrient treatments (Figure 2).

- At high stubble loads (12t/ha), residue-C mineralisation was different for the two soil types studied. In the Chromosol, the residue-C mineralisation was the same for both the nil and high nutrient input treatments, and greater for the low nutrient input. The Vertosol showed no difference in residue-C mineralisation between different nutrient supply levels.
- At low stubble loads (4t/ha), nutrient addition had no impact on residue-C mineralisation, and MBC in either of the two soils (Figures 2 and 3).

Nutrient inputs at the high stubble load increased MBC in both soils, except at the end of the monitoring period (day 245). Microbial biomass was significantly higher in the Vertosol than the Chromosol and decreased over time across all treatments (Figure 3). The proportions of total MBC

Table 4. Description of the residue and nutrient (N, P and S) input treatments, and the expected additional stabilization of residue-C in SOM. The nutrients were added by ammonium nitrate (N), monopotassium phosphate (P), and ammonium sulphate (S).

No	Treatments*	Wheat stubble t/ha	N	P	S	Fertiliser cost $/ha	Expected C stabilization [1] %
			kg/ha				
1	Res0_0nut	0	0	0	0	0	0
2	Res4_0nut	4	0	0	0	0	0
3	Res4_Lnut	4	15	3.6	2.6	28	10
4	Res4_Hnut	4	45	10.8	7.7	85	30
5	Res12_0nut	12	0	0	0	0	0

[1] *The low and high nutrient inputs (C, N, P and S) were based on the expectation of additional 10% or 30% of residue-C that would be converted to stable SOM (C: N of 12:1, C: P of 50:1, and C: S of 70:1).*

**Abbreviations; Res0 = control soil with no residue and no nutrient inputs, Res4 = residue rate at 4t/ha, Res12 = residue rate at 12t/ha, 0nut = no nutrient input, Lnut = low nutrient input level, Hnut = high nutrient input level. Wheat stubble (4t/ha = 18,00kg C/ha; 12t/ha = 5,400kg C/ha.*

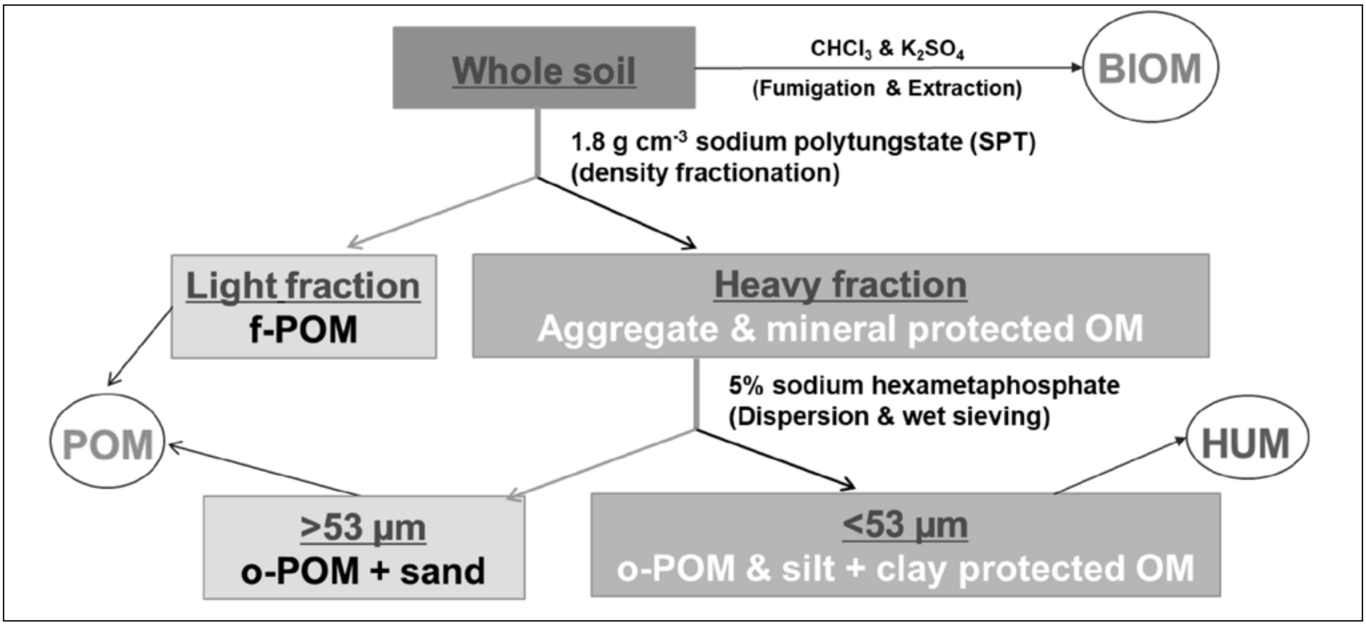

Figure 1. The density-size fractionation process used to separate five soil carbon pools; light fraction (free particulate organic matter, f-POM), heavy fraction (aggregate and mineral protected OM), >53µm fraction (occluded particulate organic matter, o-POM), and <53µm fraction (silt-clay mineral associated OM). POM = particulate organic matter, HUM = humified organic matter and BIOM = microbial biomass.

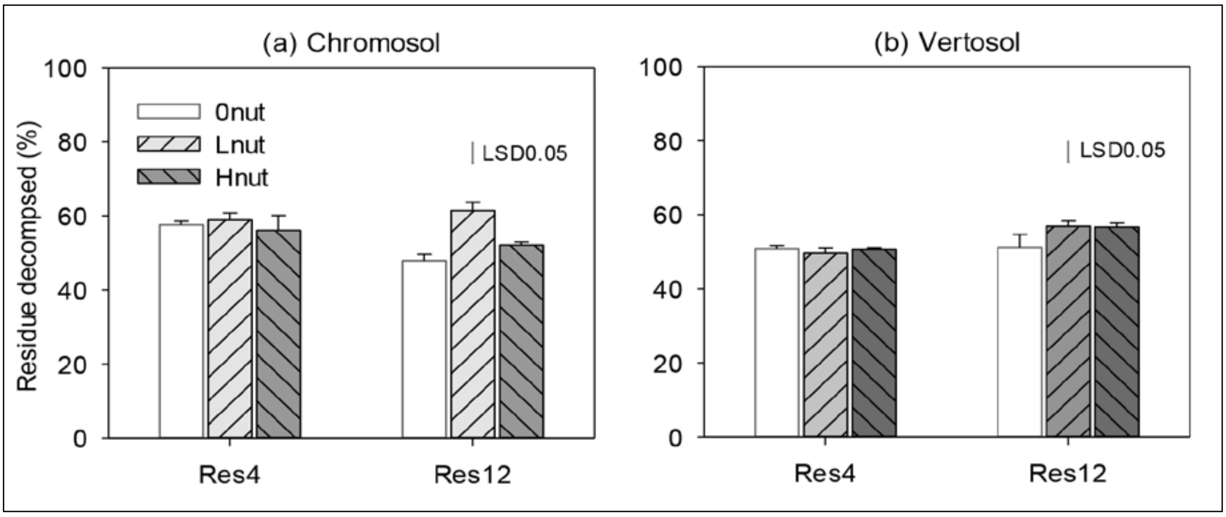

Figure 2. Residue carbon decomposed in the Chromosol (a) and Vertosol (b) over the 245-day incubation period. Error bars represent standard errors of the mean (n=4). Res4 = residue rate at 4t/ha, Res12 = residue rate at 12t/ha, 0nut = no nutrient input, Lnut = low nutrient input level, Hnut = high nutrient input level. Red lines on top of bars represent least significant differences at 5%.

derived from residue were higher (45–76%) in the high stubble-residue than the low-stubble residue treatments (24–54%) (data not shown; Fang et al. 2018a).

The lack of effects of nutrients on residue-C mineralisation at the low stubble load rate (4t/ha) was likely due to two reasons. Firstly, considerable nutrients may be released from the stubble and SOM, (10-12t N/ha, 12-36t P/ha and 10-14t S/ha as described in Table 5), following the stimulation of microbial activity and mineralisation of residues and existing SOM after the input of stubble in the soils (Singh et al. 2017; Sarker et al. 2019). Secondly, simpler organic molecules may have expedited the release of mineral-bound SOM and dissolution of protective mineral surfaces, mobilising nutrients (P, S) beyond the input of nutrients from stubble residues (Guppy et al. 2005; Keiluweit et al. 2015; Singh et al. 2017; and Sarker et al. 2019). That is, simpler organic molecules of low-molecular-weight are produced during the decay of stubble residues in the soil.

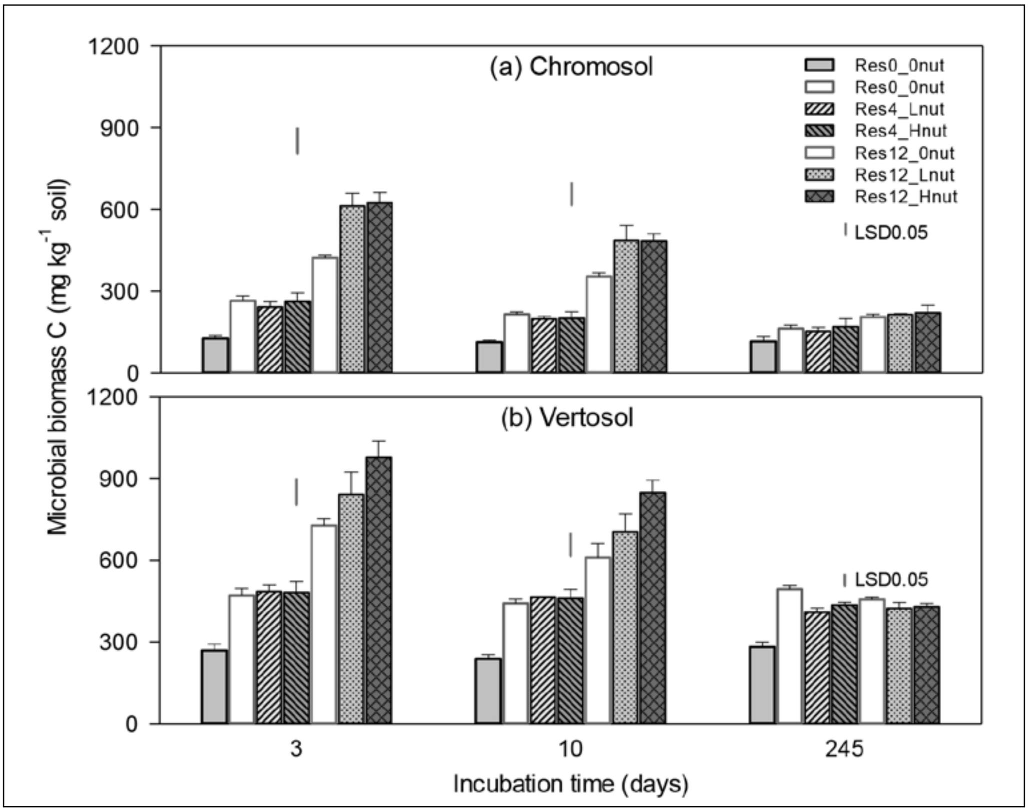

Figure 3. Microbial biomass carbon in the Chromosol (a) and Vertosol (b) after three, 10 and 245 days of incubation period. Error bars represent standard errors of the mean (n=4). Abbreviations; Res0 = control soil with no residue and no nutrient inputs, Res4 = residue rate at 4t/ha, Res12 = residue rate at 12t/ha, 0nut = no nutrient input, Lnut = low nutrient input level, Hnut = high nutrient input level. Red lines on top of bars represent LSD (least significant differences at 5% level) for the combinations of soil, residue and nutrient inputs at each time point.

Hence, nutrients released from the residue and soil reserves were sufficient at the low stubble rate to support microbial growth and activity.

Where stubble load is high however, nutrient availability became a limiting factor for the biological degradation of the C-rich and nutrient-poor wheat residue (C: N: P: S ratio of 1850:17:8:1 as described in Table 3). The results of lower MBC without nutrient supply at the high stubble rate suggest that the potential release of nutrients from the stubble residue, SOM decomposition, and soil mineral reserves (via dissolution-desorption processes) may not be sufficient to satisfy fast microbial growth (Figure 3). However, the extra nutrient supply at the high stubble loads increased MBC (Figure 3) and enzyme activities (Fang et al. 2018b), thus enhancing stubble decay and production of microbial residues while lowering nutrient mining from existing SOM (Fang et al. 2018a,b).

Impact of stubble-nutrient management on distribution of stubble carbon

Results show that after 245 days, 43–54% of the stubble-C remained in SOM fractions, in both soils (Table 6). Of this, 22–41% of stubble-C was in the light fraction (f-POM) and 14–20% in the

Table 5. Nutrient release following wheat residue incorporation (at different rates per hectare).

kg/ha	Red soil (Chromosol) (Condobolin, New South Wales)		Cracking clay soil (Vertosol) (Hermitage, Queensland)	
	Residue 10t/ha	Residue 4t/ha vs. 12t/ha	Residue 10t/ha	Residue 4t/ha vs. 12t/ha
Nitrogen	30	12 vs. 36	25	10 vs. 30
Phosphorus	30	12 vs. 36	90	36 vs. 108
Sulphur	25	10 vs. 30	35	14 vs. 42

Note: for simplicity, results are averaged across different farming systems. See the detailed results in Singh et al. 2017 https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/enhancing-availability-of-nutrients-from-soil-organic-matter-and-crop-residues.

heavy fraction (o-POM plus silt-clay SOM). Further sequential separation of the heavy fraction revealed 8–15% of residue-C was distributed to silt-clay OM and 4–6% to o-POM, after 245 days. This study found that the supply of extra nutrients at only the high stubble rate (12t/ha), increased the incorporation of residue-C into the silt-clay SOM in both soils. That is, at the high stubble rate the net humification efficiency increased from 8% to 11% in the Chromosol, and from 11% to 14% in the Vertosol across both nutrient input treatments. At the low stubble rate, different nutrient inputs (compared to no nutrient treatment) had no impact on the humification efficiency of SOM, such as in the heavy fraction and silt-clay SOM.

Following the input of nutrients at both low and high rates, the enhanced incorporation of high stubble residue-C to the stable SOM fraction (silt-clay) was possibly related to the high MBC in the soils (Fang et al. 2018a) (Table 6 and Figure 2). The high MBC may have stimulated turnover and formation of microbial residues/products, with potential for their incorporation into the stable SOC fractions (Hagerty et al. 2014). Moreover, when compared with no-nutrient, the decrease of stubble-C content in the labile pool (f-POM) via the supply of extra nutrients, could be due to the accelerated breakdown of crop residues by microorganisms. This would likely lead to the higher incorporation of microbial residues in the silt-clay fraction (Fang et al. 2018a). Under the low stubble rate (4t/ha) however, there was no significant impact of adding extra nutrients in any SOM fractions (Table 6; Figure 1). There was also no evidence that SOM increased with stubble retention and additional nutrients at eight trial sites, after three and five years across south-eastern Australia, under a continuous cropping system in the low to medium rainfall zone (van Rees et al. 2017).

In the current study, soil type also affected the incorporation of residue-C in the heavy or silt-clay fractions. For example, 20% higher residue-C was incorporated in the silt-clay SOM in the Vertosol than Chromosol. This higher incorporation of residue-C is in agreement with previous findings that more residue-C would have been retained in reactive clay-rich soils (Jenkinson, 1977). This could be mainly attributed to greater stabilisation of microbial residues in the Vertosol than the Chromosol, because of higher residue-derived MBC (Fang et al. 2018a,b) and higher clay content (Table 1), or clay type (e.g. smectite- versus kaolinite-dominated) (Kopittke et al. 2018).

Overall, the results suggest that stubble residue-C was rapidly mineralised and utilised by microorganisms only in the high stubble treatment with high extra nutrients which aimed to actively achieve the C-to-nutrient ratio of stable SOM. The process of rapid microbial biomass growth and turnover may have facilitated the incorporation of microbial residues in the stable SOM fractions (Figure 4).

Table 6. The proportional distribution of added residue-carbon in soil fractions in two different soils, including light fraction (LF; f-POM), heavy fraction (HF; aggregate and mineral protected OM), occluded particulate organic matter (o-POM), silt-clay protected organic matter (silt-clay OM).

Soil type	Treatments*	f-POM (%)	HF (%)	o-POM (%)	Silt-clay SOM (%)
Chromosol	Res4_0nut	24.5 (2.5)	17.1 (0.5)	6.0 (0.7)	11.4 (0.3)
	Res4_Lnut	29.7 (1.4)	16.1 (0.2)	5.9 (0.7)	12.1 (0.9)
	Res4_Hnut	28.6 (3.2)	17.4 (0.6)	5.9 (0.3)	11.2 (0.8)
	Res12_0nut	40.8 (1.4)	13.9 (0.3)	6.1 (0.9)	8.3 (0.3)
	Res12_Lnut	22.1 (2.0)	17.1 (0.5)	5.1 (0.8)	11.5 (0.1)
	Res12_Hnut	31.2 (1.4)	15.9 (0.8)	5.5 (0.6)	10.9 (0.6)
Vertosol	Res4_0nut	27.0 (1.0)	19.2 (2.1)	4.5 (0.2)	14.3 (1.3)
	Res4_Lnut	31.4 (0.4)	19.2 (1.8)	4.7 (0.3)	15.2 (1.7)
	Res4_Hnut	27.3 (0.9)	19.0 (1.2)	4.2 (0.6)	15.4 (0.1)
	Res12_0nut	29.7 (2.8)	16.3 (1.3)	5.8 (0.9)	11.1 (1.0)
	Res12_Lnut	25.4 (1.5)	18.1 (1.2)	4.6 (0.9)	12.9 (0.3)
	Res12_Hnut	24.0 (1.1)	19.5 (1.0)	4.5 (0.4)	13.9 (0.7)
	$LSD_{0.05}$	5.1	3.0	1.8	2.5

**Abbreviations: Res4 = residue rate at 4t/ha; Res12 = residue rate at 12t/ha; 0nut = no nutrient input; Lnut = low nutrient input level; Hnut = high nutrient input level. The values in the brackets are standard errors of the mean (n=3). $LSD_{0.05}$ = least significant differences at 5%.*

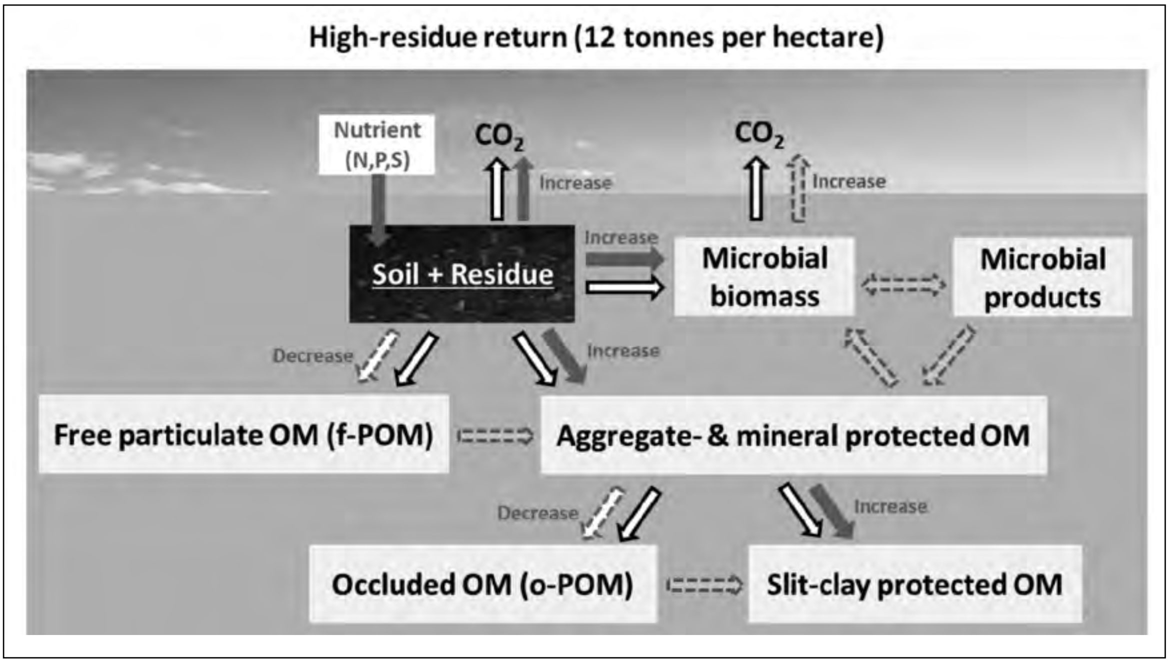

Figure 4. A conceptual model showing the allocation of wheat stubble carbon in physically-defined soil organic matter fractions in two contrasting soils, (Red Chromosol, and cracking clay Vertosol), at high stubble rate (12t/ha), influenced by nutrient input. See Fig. 1 for soil C fractions. Black and blue arrows represent the flux without or with nutrient input, respectively.

Both soils exhibited the same trend of residue-C distribution in the fractions. Extra nutrients increased residue-derived CO_2 respiration and microbial biomass, that is, the flow of cycling, turnover and stabilization of microbial biomass and products (as represented in Figure 4 by orange arrows) (Fang et al. 2018b). The partitioning of residue-C in soil C fractions at low-residue rate (4t/ha) was not impacted by the extra nutrients; hence, a conceptual figure for that treatment is not presented.

Conclusion

- This incubation study demonstrated the interaction of varying inputs of wheat stubble and nutrients influenced residue-C mineralisation, microbial biomass, and incorporation of residue-C in SOM fractions.
- The majority (48–61%) of added stubble-C was mineralised in eight months in the red Chromosol, and cracking clay Vertosol.
- Only at the high stubble input (12t/ha), adding both low or high amount of nutrients increased residue-C mineralisation and microbial biomass, leading to stabilisation of residue-C in the heavy fraction, including silt-clay (humified) fraction in both soils (Vertosol > Chromosol).
- At the low stubble residue input (4t/ha), there is no effect of extra nutrients on residue-C mineralisation, microbial biomass, and labile or stable C fractions in both soils.
- Gentle mixing of crop stubble in the soil (such as shallow tillage) has the potential to mobilise nutrients from SOM and soil surfaces, particularly P and S, beyond their actual contents in the residues (Singh et al. 2017; Sarker et al. 2019).
- Applying extra nutrients with low or normal stubble quantities is not effective for building stable soil C stocks, in cereal-based farming systems. However, extra nutrients appear beneficial for enhancing soil carbon where large amounts of stubble are produced.
- This study was performed under an ideal soil moisture condition in the laboratory, and it is recommended that the carbon sequestration potential in stable SOM fractions be validated under field situations (particularly under high rainfall zones, with high stubble yields).
- This study shows the importance of considering the impacts of stubble management and nutrient availability on microbial activity, as this will determine the extent of stubble decomposition, formation of stable SOM, and mobilisation of soil nutrients for plant growth.

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Resources

GRDC update paper regarding the nutrient value from crop residue and soil organic matter; https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/02/enhancing-availability-of-nutrients-from-soil-organic-matter-and-crop-residues

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Notes

A survey of crop establishment in canola and lentil — what have we learnt?

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Keywords

- crop emergence, sowing, sowing depth, time of sowing, stubble cover.

Take home messages

- Crop establishment among commercial crops is variable and improvements can be made in many cases.
- Improving establishment may lead to saving in seed costs.
- Establishment of canola and lentil is influenced by different factors.
- While some factors are outside the control of growers, there are a number of simple changes that can be made to maximise establishment.

Background

Germination and establishment is a critical period in crop growth. Firstly, germination and establishment determine the plant population, which influences the level of early crop vigour, competitiveness against weeds and yield. Secondly, the evenness of establishment influences the level of interplant competition. Early work on seedling emergence indicated that seedlings that emerged early had a competitive advantage over those that emerged later (Knight, 1983; Soetono and Donald, 1980; Gan et al., 1992). A uniform plant stand can reduce interplant competition and result in significant increases in yield (Yang et al., 2014) but the benefits of this tend to be greatest at low plant populations (Kemp et al., 1983; Sattorre, 1999, Kristensen et al., 2008).

There is relatively little information on the levels of crop establishment currently achieved in commercial crops. This paper summarises the results of a survey of crop establishment in canola and lentil in the southern and western GRDC zones and considers some of the factors that have contributed to variation in establishment. The aim of the survey was to provide benchmark data for current practices and identify the factors that most strongly affect establishment to inform future research.

Method

Commercial crops were surveyed in South Australia (SA), Victoria, Tasmania and Western Australia (WA) in 2018 and 2019. The crops targeted were canola, lentil and faba bean in the southern region and canola, lupin and wheat in the western region. This paper will only report on the results for canola and lentil.

In each paddock, five sample sites were randomly selected. At each location, seedling numbers were counted in two adjacent rows along a 3m length of row. The cumulative distance between 30 adjacent seedlings in each row was measured to estimate mean interplant distance. Seedling depth was measured by cutting seedlings at the soil surface, excavating the seed and measuring the vertical distance from the seed to the cut surface. The amount of stubble cover was assessed by comparison with standard photographic charts. A sample of the seed used to sow the crop was collected to measure mean seed weight and germination percentage.

A questionnaire was distributed to growers to gather information on the seeding equipment used, how it was set up and the management of the paddock and crop. Crop establishment percentage was estimated from the plants/m^2 and the seeds/m^2 sown. Uniformity of crop establishment was measured by the co-efficient of variation (CV) in plant number and interplant distance.

In a small number of paddocks, more intensive sampling of crop establishment was conducted to assess the variation in plant number and seedling depth across the width of a seeder bar. Measurements were taken from the left, middle and right sections of the seeder at two locations in the paddock. At each position the number of seedlings per 3m or row was counted, and the depth of seed placement was measured at seedlings approximately every 30cm along the row.

Results and discussion

Seeder age and set up

The median age of the seeders was six years in the southern region and eight years in the western region. Disc seeders were used by 13% of the growers. Inter-row sowing was practised by 54% of growers. All the growers used press wheels however only 22% of growers knew the specific pressure at which the press wheels were used, and among those there was a great variety in responses. The most common pressure reported was 10kg (by six growers) but values ranged from 5kg to 130kg. Good seed-soil contact is important for germination, but these results suggest there is a lack of information on what are appropriate pressures to use, to optimise the performance of press wheels under different conditions.

Separate delivery of seed and fertiliser was more commonly used by growers in the western region (83%), while in the southern region roughly half the growers used a single delivery system. Most growers in the southern and western regions sowed seed in a single row rather than using paired rows. The average depth of the furrow cut (mean ± SEM) was similar for canola (61 ± 6.0mm) and lentil (62 ± 6.5mm).

Sowing rates and crop establishment

The average sowing rate over all sites for canola was 2.7kg/ha (range; 1.4 to 4.0 kg/ha) and 48 kg/ha for lentil (range; 35 to 60 kg/ha). On average, growers sowed 60 to 70 seeds/m^2 for canola and 118 seeds/m^2 for lentil (Table 1). Crop establishment averaged 51% in canola in the western region to 82% in lentil. Lentil showed less variation in plant number and interplant distance than canola — the median CV for interplant distance was 145% in lentil and 160% in canola. The corresponding median CVs for plants/m^2 were 20% in lentil and 25% in canola.

Table 1. The mean number of seeds/m^2 sown, establishment (%) and seedling depth for canola and lentil in the southern and western regions. The values are shown as mean ± standard error of the mean (SEM) and the number of paddocks in the sample is shown in parentheses.

	Canola	Lentil
Seeds/m^2 sown		
Southern	61 ± 4.1 (30)	118 ± 4.5 (18)
Western	71 ± 9.9 (6)	
Establishment (%)		
Southern	67 ± 4.1 (29)	82 ± 5.0 (17)
Western	51 ± 5.8 (6)	
Seedling depth (mm)		
Southern	22 ± 1.3 (38)	35 ± 2.4 (24)
Western	19 ± 1.3 (9)	

Mean germination for all the seed samples submitted was 88% in canola and 90% in lentil. Growers who indicated they adjusted their sowing rate for seed size and/or germination percentage did not achieve significantly better establishment than growers who didn't. However, the method of calibration appeared to influence establishment, with manual calibration tending to result in poorer establishment compared to using the seeder's control system. Establishment following manual calibration was 63 ± 5.1% in canola and 79 ± 6.1% in lentil, compared to 72 ± 9.2% and 99 ± 11.2% with the control system. The specific reason for this difference is unclear but it was a consistent effect in both crops. Among the canola paddocks, establishment was higher in hybrid varieties (72 ± 5.9%, n = 20) than in open pollinated varieties (60 ± 6.9%, n=14), which most likely reflects the greater vigour of the hybrid seed.

Inter-row sowing did not significantly affect establishment in canola (Table 2). Most lentil crops were inter-row sown and their establishment was

Table 2. Crop establishment (%) in two crops classified by sowing method. Crops were either sown between (inter-row) or not between (non-inter-row) previous crop rows, with a separate or single seed/fertiliser delivery system or in single or paired rows. The values are shown as the mean ± SEM and the number of paddocks in the sample is shown in parentheses.

	Canola	Lentil
Sowing		
Inter-row	62 ± 4.1 (17)	85 ± 5.9 (14)
Non inter-row	67 ± 8.2 (15)	73 ± 3.2 (2)
Shoot type		
Separate	70 ± 7.2 (17)	92 ± 6.2 (11)
Single	57 ± 4.0 (15)	65 ± 1.4 (5)
Seeding rows		
Paired	74 ± 10.7 (2)	76 ± 1.6 (2)
Single	64 ± 6.7 (19)	68 ±2.6 (6)

higher compared to crops that were not sown between the rows. However, this result needs to be interpreted cautiously because of the very small number of crops (two paddocks) that were not inter-row sown.

Separating seed and fertiliser delivery improved establishment in both crops (Table 2). The potentially harmful effects on germination and seedling growth of having seed and fertiliser close to one is well known and this effect can be exacerbated under dry conditions. Having separate delivery systems is an effective way of maximising establishment.

Using paired rows rather than sowing in a single row also tended to improve establishment, although there were fewer paddocks in this comparison (Table 2). Using paired rows will increase the seed bed utilisation (SBU), which will help reduce interplant competition within the row and mitigate any potentially harmful effects of fertiliser.

Canola establishment in the southern and western regions region was lowest on sandy soils and in the southern region it tended to increase with the clay content (Table 3). Lentil was less sensitive to texture. There was no consistent effect of soil properties (pH, EC and ESP%) on emergence.

Management practices and establishment

Time of sowing was an important influence on establishment in canola and wheat. Establishment improved with later sowing into May (Figure 1). This effect may have been associated with the dry autumn over the southern and western region in 2018, which resulted in many crops being sown dry or under marginal soil moisture. This was supported by the relationship between rainfall and establishment in canola. Rainfall received in the four weeks centred on the time of sowing was positively related to establishment percentage ($r = 0.39$, $P = 0.05$, $n = 25$) and the uniformity of establishment, measured as the CV for plants/m^2 (r - -0.41, $P = 0.044$, $n = 25$).

In canola, there are clear yield advantages to early sowing, so delaying sowing to improve establishment is counterproductive. However, the survey indicated there was a trade-off between sowing time and establishment, which seemed to be driven in part by rainfall. The survey confirmed that the risk of poor establishment in canola increases as soil moisture declines. It was also noted in the survey that most of the canola there was staggered emergence (that is, multiple canola growth stages), which is likely to have been largely affected by variation in soil moisture.

Lentil responded very differently to canola. Sowing date had no effect on crop establishment in lentil even though the range in sowing dates was similar to canola. High rainfall around sowing tended to reduce establishment percentage and decrease the uniformity of establishment. Per cent establishment was negatively correlated with rainfall received after sowing ($r = -0.58$, $P = 0.02$, $n = 15$) and total rainfall received in the two weeks prior to and after sowing ($r = -0.64$, $P<0.01$, $n= 25$). The CV for plant number was positively correlated with rainfall after sowing ($r = 0.47$, $P = 0.08$, $n = 15$).

Table 3. Establishment (%) of canola and lentil on soils with different textures. The values are shown as mean ± SEM and the number of paddocks in the sample is shown in parentheses.

Soil texture class	Canola		Lentil
	Southern	Western	Southern
Sand	55 (1)	30 (1)	
Sandy loam	60 ± 14.8 (3)	56 ± 6.1 (3)	96 ± 25.3(2)
Loamy sand	67 ± 11.2 (4)	54 ± 9.7 (4)	80 ± 6.8 (6)
Loam	67 ± 11.5 (5)		104 ± 13.1 (3)
Silty loam	75 ± 17.8 (6)		63 (1)
Clay loam	75 ± 7.8(8)		70 ± 6.9(2)

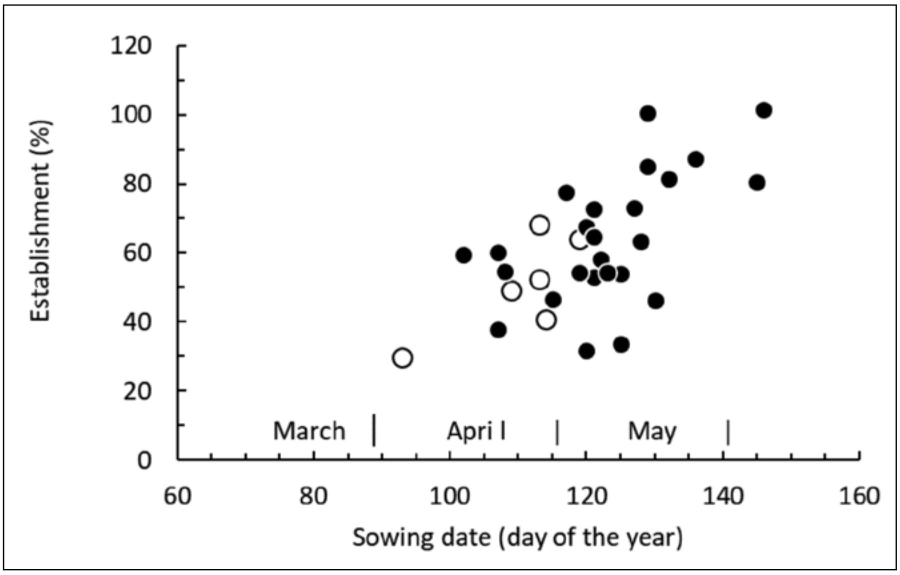

Figure 1. The relationship between sowing time and crop establishment in canola in the southern region (●) and the western region (O).

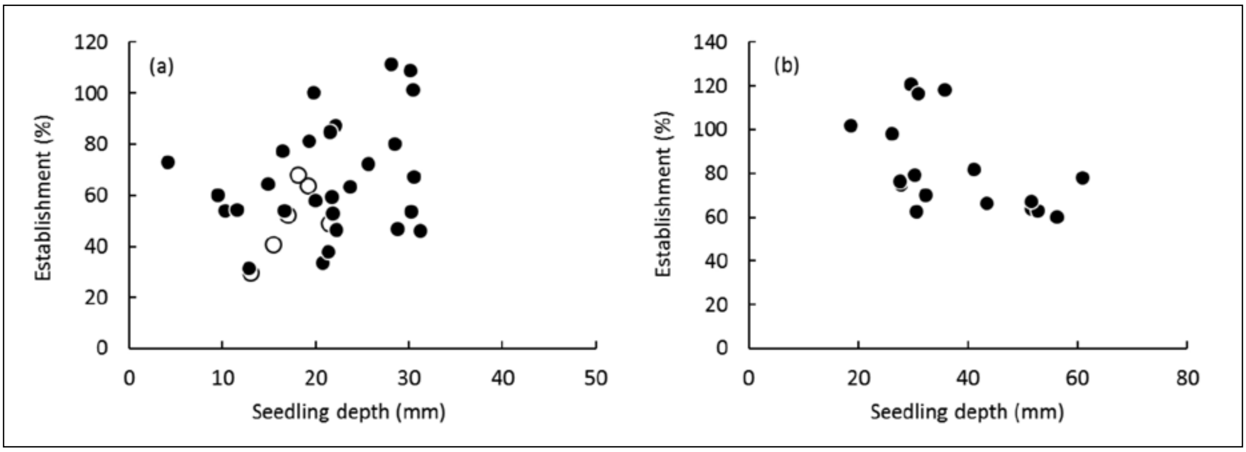

Figure 2. The relationship between seedling depth and establishment in (a) canola and (b) lentil in the southern region (●) and the western region (O).

Although variable, sowing to about 30mm improved establishment in canola in both the southern and western regions (Figure 2). It is likely that with the dry autumn in the survey area, there was insufficient moisture in the surface soil for high germination rates and growth of seedlings. In contrast, lentil establishment benefited from shallower seed placement, but the range of sowing depths was greater than that in canola.

High stubble loads at sowing tended to reduce emergence of canola (Figure 3) but the relationship was not strong. There was no effect of stubble cover on emergence in lentil. Emergence in both lentil and canola was sensitive to the condition of the surface soil (Figure 4) with emergence being lower as surface structure became poorer.

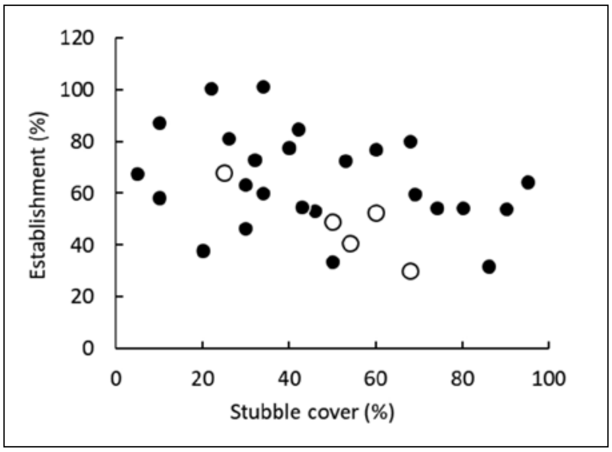

Figure 3. The relationship between the visual assessment of stubble ground cover and establishment in canola in the southern region (●) and the western region (O).

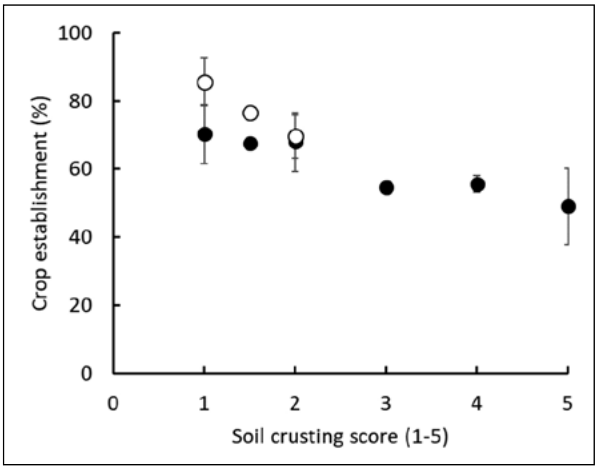

Figure 4. The relationship between assessment of surface crusting and emergence in canola (●) and lentil (O) in the southern region. Error bars are the standard errors of the means. Surface crusting was assessed visually based on a set of images; 1 well structured, no crusting; 2 moderate crusting; 3 severe crusting; 4 cultivated cloddy surface; 5 cultivated, good tilth. The number of paddocks on which the data are based ranged from one and 10.

The survey data suggests that emergence in lentil is less sensitive than canola to a number of management practices and appears to be a more robust crop in this respect. The risk of poor establishment in canola is increased with shallow sowing under low soil moisture, high stubble loads and where surface structure is poor. The impact of reduced emergence on yield will depend on the degree to which plant number is reduced and how well the canola crop can compensate for low plant densities. Recent sowing rate trials suggest that at a yield level of about 1.5t/ha, populations of 20plants/m^2 may not result in significantly lower yields compared to higher plant densities (Ware, 2018; McDonald et al., 2019).

Variation across seeders

The average values for plant number and seedling depth were similar at the two sampling sites in each paddock, but this belies the variability across seedling rows. There was considerable variation in the number of plants established and the depth of seed placement across a seeder (Figures 5 and 6). The average CV for plant number were 42% (SA site) and 33% (WA site), compared to an overall CV for canola of 25% across all the sites. Similarly, the average CV for seedling depth were 25% (SA) and 27% (WA), while the survey average for canola was 17%.

Comparison of paddocks with good and poor establishment

While variation in crop establishment in canola and lentil was high among the surveyed paddocks, there were some growers achieving high and relatively uniform establishment. The features of paddocks that recorded high establishment (>80%), and poor establishment (<50%), are shown in Table 3, where results confirm a number of the trends observed in the survey.

In canola, better establishment was measured in later-sown crops, where there was slightly less stubble cover, slower sowing speeds and when there was more rainfall. In lentils however, sowing time and stubble cover were not related to establishment. In this case, higher establishment was associated with shallower depth of seed placement and when there was less rainfall after sowing.

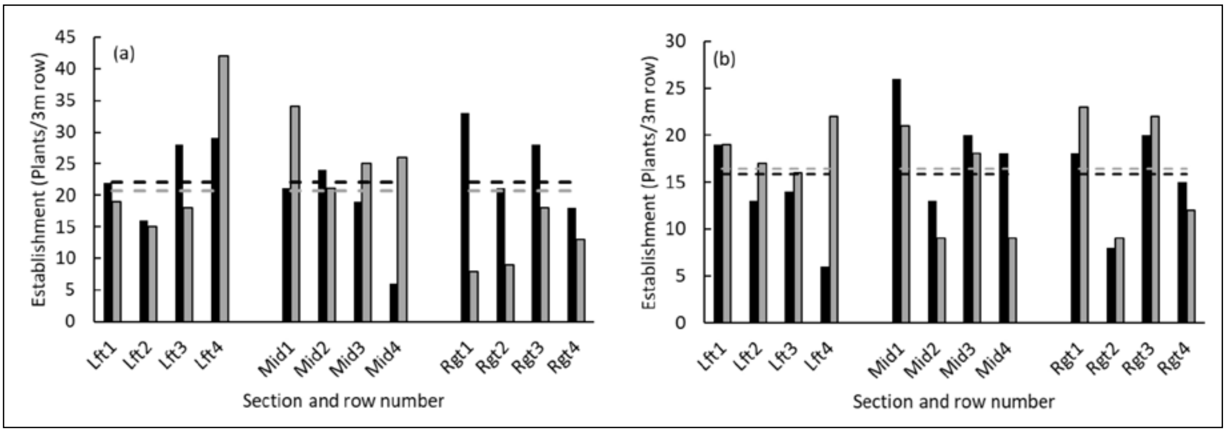

Figure 5. The variation in plant number of canola across the seeder bar in a paddock in (a) the mid North of SA (Flexicoil ST820) and (b) Corrigin, WA (Flexicoil PTX 601). The measurements were taken from adjacent rows in three sections of the seeder (left, middle and right), and from two locations in the paddock (black and grey bars). The horizontal lines are the average values for each location.

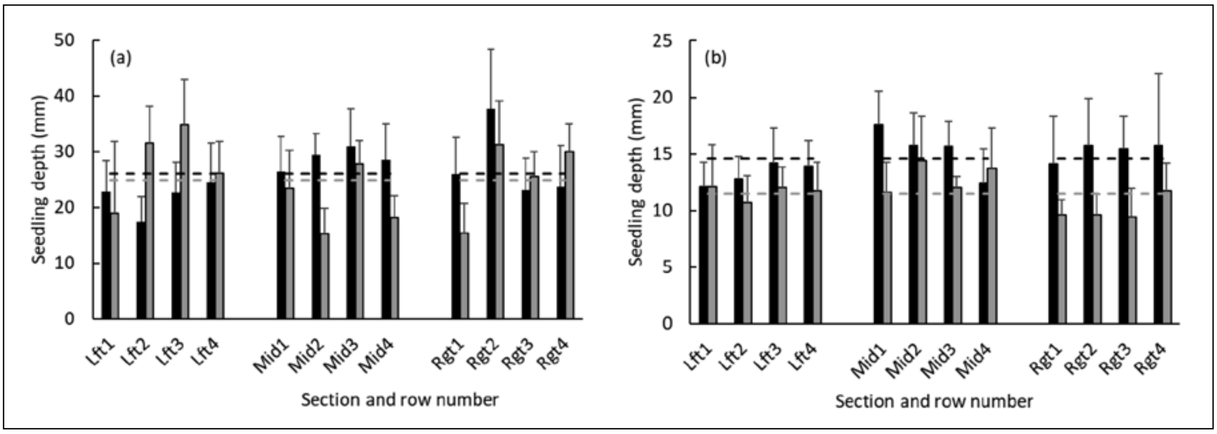

Figure 6. The variation in seedling depth of canola across the seeder bar in a paddock in (a) the mid North of SA (Flexicoil ST820) and (b) Corrigin, WA (Flexicoil PTX 601). The measurements were taken from adjacent rows in three sections of the seeder (left, middle and right), and from two locations in the paddock (black and grey bars). The horizontal lines are the average values for each location and the error bars are the standard deviations within each row.

Table 4. The average values of paddock and site characteristics from paddocks where high (>80%) and poor (<50 or <60%) establishment was measured in canola and lentil in the survey in 2018.

	Canola		Lentil	
	Est >80%	Est <50%	Est >80%	Est <60%
Seeder age (year)	9 ± 2.0	7 ± 1.9	7 ± 1.0	6 ± 2.1
Stubble cover (% ground cover)	34 ± 7.5	49 ± 10.3	70 ± 5.6	64 ± 5.9
Sowing date	16 May ± 3d	29 April ± 3d	3 May ± 6d	1 May ± 7d
Sowing speed (km/h)	8 ± 0.3	10 ± 0.6	10 ± 0.8	11 ± 0.8
Furrow depth (mm)	57 ± 13.5	54 ± 15.8	68 ± 7.3	47 ± 6.0
Seedling depth (mm)	25 ± 1.6	21 ± 2.1	30 ± 3.2	45 ± 3.9
Rainfall (mm)				
14 days before sowing	24 ± 8.8	11 ± 2.3	9 ± 3.6	10 ± 2.8
14 days after sowing	20 ± 4.2	5 ± 5.6	4 ± 2.1	13 ± 3.4
Seedbed moisture content at time of assessment (% v/v)	21 ± 1.7	20 ± 1.2	14 ± 5.7	23 ± 4.1

Conclusion

The survey highlighted the variation in crop establishment that occurs within a paddock and between paddocks. However, a number of growers are achieving high establishment and relatively uniform crop stands, which suggests improvements are feasible. The key outcomes from this survey to date are;

- Establishment in canola was lower and more sensitive to sowing conditions than lentil and this is where greater improvements can be achieved.
- The age and make of the seeder are less important than how it is set up and the conditions in the paddock at sowing.
- Maintaining good soil surface structure to minimise crusting will assist with better seedling emergence (through stubble retention or management of sodicity for example).
- Know your seeder. Factors under the control of growers that can influence establishment include; seeder set-up and operation (careful calibration), separating seed and fertiliser and increased SBU, sowing speed and sowing depth.
- Dry sowing - rainfall at sowing was more important to establishment in canola than in lentil, and early sowing will reduce establishment without adequate rainfall around the time of sowing. This is an inevitable trade-off that growers face with early sowing under dry conditions, but sowing rate trials suggest that as long as there are 20-30plants/m^2 there may not be a significant yield penalty in canola.

Acknowledgements

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

We thank the many growers who collaborated with the survey and the assistance of the Leibe Group, the Facey Group, the Corrigin Farm Improvement Group and the McKillop Group in conducting the survey.

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Notes

Blackleg – new seed treatment, stubble management and fungicide resistance

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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

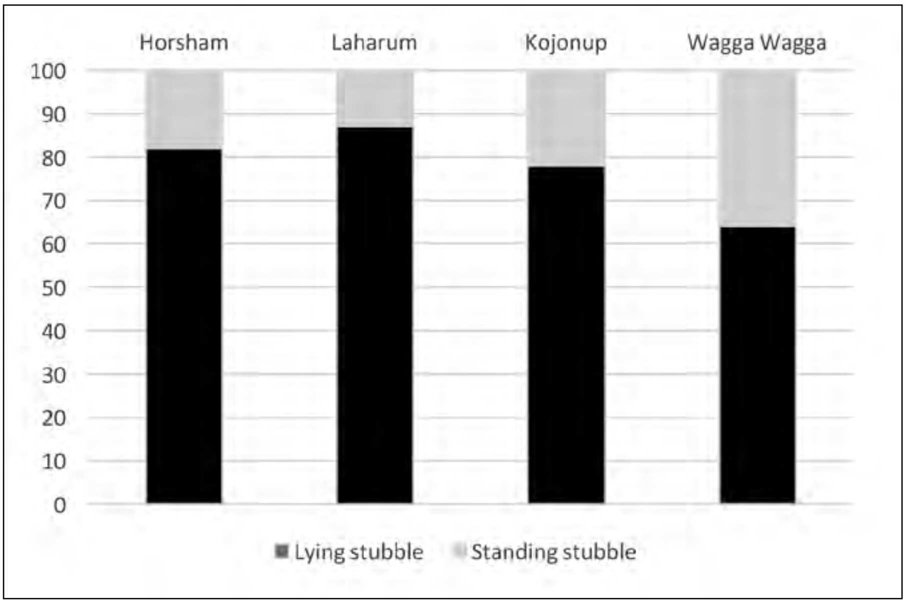

Figure 1. Proportion of total spores from specific stubble types and sections produced over a growing season for four sites in 2018.

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).

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

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.

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

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 and ARC-linkage, the authors would like to thank them for their continued support.

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)

www.nvt.com.au

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Cereal disease update 2020

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GRDC project codes: DJP1907-001RTX, DAW1810-007RTX, DJP1907-004RTX, DJP1907-002RMX, DJP1905_002SAX, CUR00023, CUR1905-001SAX

Keywords

- stripe rust, net form of net blotch, NFNB, oat diseases, decision support app, fungicide resistance.

Take home messages

- The proactive use of different management options in combination (such as variety selection, paddock selection and appropriate fungicide use), provides proven sustainable and economic control for both root and foliar diseases.
- A new strain of stripe rust is important to durum wheat and some bread wheats with new ratings published in the 2020 Victorian Disease Guide.
- A new decision support tablet-based app will help in the management of stripe rust.
- Recent reports of fungicide resistance in cereal pathogens highlight the importance of avoiding fungicide use that increase the likelihood of resistance development.

Background

The good start to the 2019 season favoured early foliar disease development but did not continue as dry spring conditions mostly limited further disease progress. Despite this dry finish to the season, field experiments by Agriculture Victoria demonstrated yield losses of 8 to 18% due to net form of net blotch (NFNB) in the Wimmera and Mallee when highly susceptible cultivars were planted, infected stubble was present, and fungicides not applied. This highlights the importance of implementing disease management strategies to minimise yield losses.

Cereal disease management in 2020

Cereal diseases will require proactive management prior to and during the 2020 season. A disease management plan should consider the variety disease rating (consult a current disease guide) and inoculum loads within a paddock (stubble and soilborne diseases) and the district (consider any green bridge). A fungicide strategy should be developed for each crop, based on identified risks and being mindful of avoiding over-reliance on, or overuse of, fungicides. Diseases can be cost effectively controlled when a proactive management approach is used.

Wheat stripe rust

During 2019 there was a late outbreak of stripe rust in wheat crops, particularly in the variety LRPB Trojan⫽ due to the occurrence of a new pathotype. This late outbreak caused concern about the merits of fungicide applications late in the season. A new stripe rust app, StripeRust Wheat Management (StripeRustWM), will help with difficult decisions around in-crop fungicide control.

Rust pressure is expected to be relatively low during 2020 given the hot and dry conditions during December. These conditions have provided an effective control of the green bridge thus reducing rust carry over into the 2020 season. This reduced risk from rust can be factored into 2020 rust management plans.

A new stripe rust pathotype

During 2019, there were reports of stripe rust in the wheat varieties LRPB Trojanϕ and DS Bennettϕ at higher than expected levels. These reports were most likely related to a new stripe rust strain (pt. 198 E16 A+ J+ T+ 17+) that was first detected in 2018. It was isolated from Victoria and Tasmania later in 2018, and in 2019 from NSW (four isolates), Victoria (two isolates), and Queensland (one isolate). This pathotype is a simple mutational derivative of pt. 134 E16 A+ J+ T+ 17+, that is, from the 'Western Australian' family of stripe rust pathotypes, with added virulence for the differential Suwon 92/Omar. Given that the resistance of Suwon 92/ Omar has not been fully characterised, The University of Sydney is currently undertaking studies to fully understand the implications of this new pathotype.

Data collected from the field during 2019 by NSW DPI and AgVic, as part of the GRDC's National Variety Trials (NVT) disease rating project, indicated that this new pathotype has implications for several wheat varieties, such as DS Bennettϕ and LPB Trojanϕ and to a lesser extent Devilϕ, Illaboϕ, DS Darwinϕ, Emu Rockϕ and Hatchet CL Plusϕ. There were also implications for several durum varieties, such as DBA Spesϕ, DBA Lillaroiϕ, DBA Vittaroiϕ and EGA Bellaroiϕ.

The ratings published in the 2020 Victorian cereal disease guide have been updated and consider this as well as the other pathotypes known to occur in Victoria. It is important to always consult a current disease guide due to changes such as these.

Decision support for stripe rust control: StripeRustWM

A new tablet-based app, StripeRustWM, has been developed to support in-crop decision making for the management of stripe rust of wheat. The app is based on the already successful BlacklegCM and SclerotiniaCM apps that are widely used in canola. StripeRustWM estimates potential losses using information including variety resistance

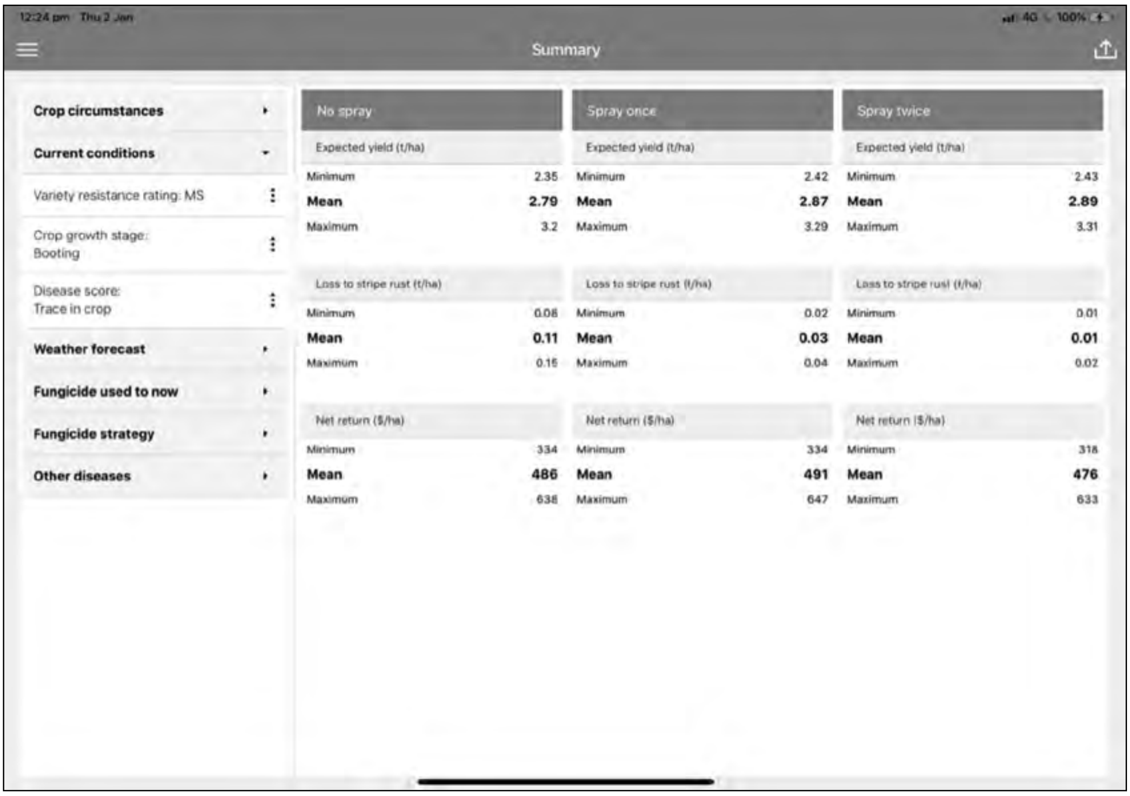

Figure 1. The summary view from StripeRust Wheat Management (StripeRustWM) comparing expected yield, loss to stripe rust and net return for the cases where fungicide is not applied, is applied once, or is applied twice.

rating, plant growth stage, fungicide history, presence of rust either within the crop or the district, climatic conditions, expected yield and economics. StripeRustWM was developed using data and information from the last 30 years' national pathology research projects. The app will be updated annually with the latest research findings so that new information can be utilised by industry as soon as available.

StripeRustWM is designed to be quick to use in the field, to guide profitable decisions about stripe rust management. It has a straight-forward user interface that asks for inputs that can be readily estimated by agronomists.

Figure 1 illustrates the StripeRustWM app interface, where a trace of stripe rust has been detected in a crop with a resistance rating of moderately susceptible (MS), at the booting growth stage. The output shows that a marginally higher net return would be expected if fungicide was applied to the crop once, compared with not spraying. The net return would probably be lower if the crop were sprayed twice.

An alternate presentation of the StripeRustWM app is shown in Figure 2, illustrating the range of possible outcomes, as a probability, from a single fungicide application. This reflects the variable nature of a biological system where a range of outcomes are possible. It shows the relative likelihood of positive and negative returns from the spray based on different environmental conditions and yield potentials.

StripeRustWM is available at no cost for iPads or Android tablets from the Apple App Store or Google Play — search for 'StripeRustWM'.

Net form of net blotch

Net form of net blotch (NFNB) is becoming a common foliar disease of barley in Victoria due to the adoption of susceptible varieties such as RGT Planet⁽ᵈ⁾ and moderately susceptible varieties such as Compass⁽ᵈ⁾. A survey of 80 barley crops across Victoria during 2019 found NFNB in 11% of paddocks. Severity was relatively low, ranging between 1 to 15% of leaf area infected, which was due to proactive fungicide strategies and/or dry spring conditions not favouring NFNB development. This level, however, serves as a warning for potential damage in conducive seasons.

During 2020, the risk of loss due to NFNB will be greatest where susceptible varieties are sown into barley stubble from either of the last two years. NFNB is seed and wind-borne, and therefore can establish in crops where there is no recent paddock history of barley. A new NFNB strain virulent on Spartacus CL⁽ᵈ⁾ has been found in SA

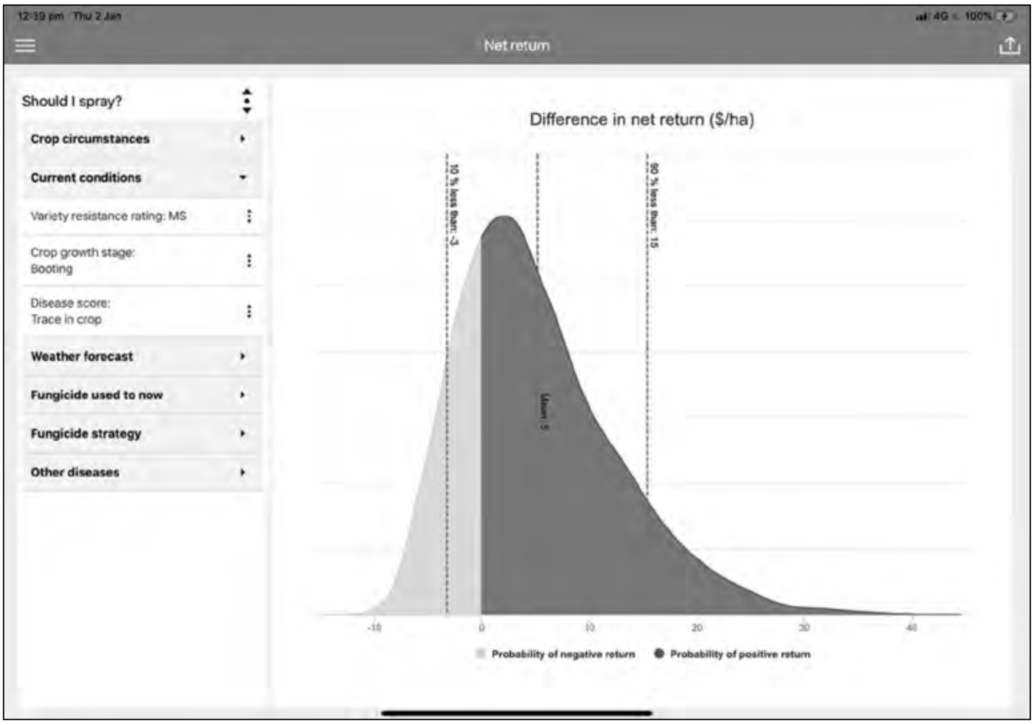

Figure 2. The net return view from StripeRust Wheat Management (StripeRustWM) showing the distribution of expected net return resulting from a single fungicide application.

and is likely to spread and become established in Victoria. In SA, the Centre for Crop and Disease Management (CCDM) researchers have identified resistance to fluxapyroxad (a member of the Succinate Dehydrogenase Inhibitors (SDHI) group of fungicides), the active ingredient in the seed treatment Systiva®, and tebuconazole. Subsequently these fungicides may no longer be reliable options for NFNB control (see section on fungicide resistance below for more details). While the initial discovery of resistance occurred on the Yorke Peninsula, SA, the extent of the distribution is likely to increase with time.

Fungicides will be an important part of NFNB control in susceptible varieties. Previous research has shown that two fungicide applications can be effective for NFNB management. Either seed applied Systiva® followed by foliar application at Z39-55, or two foliar applications at Z31 and Z39 or Z55 are effective. Earlier applications tend to be more effective in shorter season environments and later applications in longer, high rainfall environments. It is important to rotate fungicides with different modes of action to minimise the chance of resistance developing.

In general, susceptible crops with a yield potential of 5t/ha or more are at risk of substantial economic losses, especially during a wet spring. Experiments conducted in the Victorian Mallee and Wimmera during 2019 demonstrated that NFNB was severe, with up to 70% of leaf area affected at grain fill (Figure 3), up to 18% grain yield loss and reductions to grain plumpness (Tables 1, 2 and 3) in the very susceptible breeding line VB9613. The partially resistant varieties had less infection and grain yield loss than VB9613. RGT Planet$^{(l)}$ is rated susceptible to very-susceptible (SVS), and had up to 11% infection and 5% grain yield loss while all other varieties had less than 5% leaf area infected at the end of the season. This illustrates that avoiding growing highly susceptible varieties, such as those rated as susceptible to very-susceptible (SVS), or worse, to NFNB, will significantly reduce potential losses and the need for fungicide intervention. In general, NFNB should be managed in susceptible varieties where disease levels are moderate and yield potential is above 5t/ha. It is also likely that NFNB can cause economic losses where yield potential is between 3 to 5t/ha and there are wet spring conditions. Experiments are being conducted during 2020 to investigate this further.

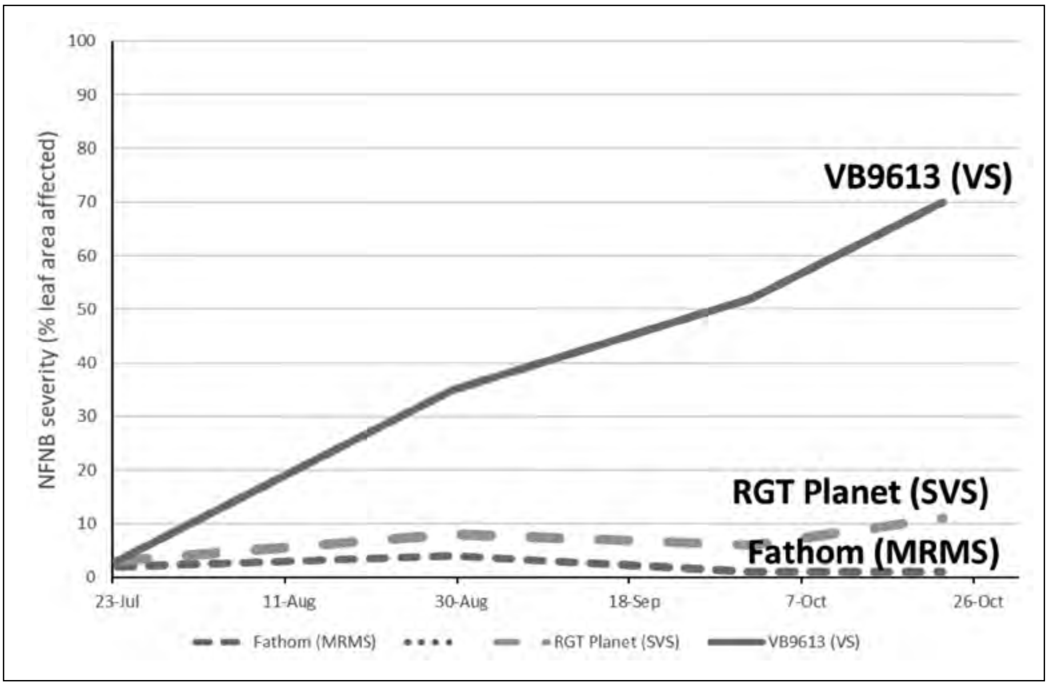

Figure 3. Severe net form of net blotch infection developed in breeding line VB9613, rated susceptible to very-susceptible (SVS), compared to moderate and low infection in RGT Planet$^{(l)}$ (SVS) and Fathom$^{(l)}$ moderately resistant to moderately susceptible (MRMS) at Birchip during 2019.

Table 1. Net form of net blotch severity (% leaf area affected) and grain yield of eight barley varieties grown at Birchip during 2019.

Variety	Rating#	Disease severity (%) 22 October 2019 (Z85)		Grain Yield (t/ha)		
		NFNB	SFNB	Dis.[A]	Fung.	% Loss
Banks(b)	MR	1	5	5.6	5.5^{ns}	0
Fathom(b)	MRMS	1	0	5.3	5.4^{ns}	2
Commander(b)	MS	1	5	4.9	5^{ns}	2
SakuraStar(b)	MS	1	0	5.4	5.5^{ns}	2
Spartacus CL(b)	MSS	1	10	6.2	6.4^{ns}	3
Alestar(b)	S	3	0	5.3	5.6*	5
RGT Planet(b)	SVS	11	10	6.5	6.7 ^{ns}	3
VB9613	VS	70	0	4.2	5.1*	18
P=		<0.001	-	-	-	-
LSD (0.05)=		2.9	-	-	-	-

[A] Dis. = Disease - 1kg infected stubble, no fungicides; Fung. = no stubble, Systiva® + Prosaro® at Z31 and Z39.

** = Significant at 5%; ns = not statistically significant when the fungicide and disease treatments are compared.*

 # rating = moderately resistant (MR), moderately susceptible (MS), moderately resistant – moderately susceptible (MRMS), moderately susceptible – susceptible (MSS), susceptible (S), susceptible – very susceptible (SVS), very susceptible (VS).

Table 2. Effect of net form of net blotch on grain quality for eight barley varieties grown at Birchip during 2019.

Variety	Rating#	Screenings (%<2.2mm)			Retention (%>2.5mm)		
		Dis.[A]	Fung.	% Increase	Dis.	Fung.	% Loss
Banks(b)	MR	3	5^{ns}	0	76	77^{ns}	1
Fathom(b)	MRMS	2	2^{ns}	0	91	90^{ns}	0
Commander(b)	MS	3	4^{ns}	1	84	83^{ns}	0
SakuraStar(b)	MS	5	4^{ns}	1	76	79^{ns}	3
Spartacus CL(b)	MSS	3	2^{ns}	1	76	79^{ns}	3
Alestar(b)	S	4	3^{ns}	1	76	78^{ns}	2
RGT Planet(b)	SVS	3	4^{ns}	0	75	73^{ns}	0
VB9613	VS	10	5*	5	28	45*	17

[A] Dis. = Disease - 1kg infected stubble, no fungicides; Fung. = no stubble, Systiva® + Prosaro® at Z31 and Z39.

** = Significant at 5%; ns = not statistically significant when the fungicide and disease treatments are compared.*

 # rating = moderately resistant (MR), moderately susceptible (MS), moderately resistant – moderately susceptible (MRMS), moderately susceptible – susceptible (MSS), susceptible (S), susceptible – very susceptible (SVS), very susceptible (VS).

Table 3. Net form of net blotch severity, frost damage and grain yield of eight barley varieties grown at Horsham during 2019.

Variety	Rating#	NFNB severity (%LAA) 22 October 2019 Z85	Frost damage (%)	Grain yield (t/ha)		Loss (%)
				Dis.[A]	Fung.	
Banks(b)	MR	1	5	5.5	5.5	0
Fathom(b)	MRMS	1	5	6.3	6.5	3
Commander(b)	MS	3	30	5.7	5.5	0
SakuraStar(b)	MS	1	5	5.9	5.9	0
Spartacus CL(b)	MSS	1	2	6.3	6.4	2
Alestar(b)	S	2	8	5.2	5.0	0
RGT Planet(b)	SVS	9	2	5.7	6.0*	5
VB9613	VS	47	2	4.8	5.2**	8
P=		<0.001	-	-	-	
LSD (0.05)=		3.2	-	-	-	

[A] Dis. = Disease - 1kg infected stubble, no fungicides; Fung. = no stubble, Systiva® + Prosaro® at Z31 and Z39.

*** = statistically significant at 5%, * = Significant at 5%; ns = not statistically significant when the fungicide and disease treatments are compared.*

 # rating = moderately resistant (MR), moderately susceptible (MS), moderately resistant – moderately susceptible (MRMS), moderately susceptible – susceptible (MSS), susceptible (S), susceptible – very susceptible (SVS), very susceptible (VS).

Foliar diseases of oats

Foliar diseases are a major constraint on milling oat production in south eastern Australia. Surveys identified red leather leaf (RLL), caused by the fungus *Spermospora avenae*, as the most common and severe foliar disease in south eastern Australia. It is restricted to the medium and high rainfall zones as it is favoured by wet and cool conditions.

During 2019, bacterial blight was common across all rainfall zones but was generally at low levels that were unlikely to cause significant loss. However, given the right seasonal conditions there is potential for it to cause losses.

Experiments conducted in the Wimmera during 2019 demonstrated that RLL caused up to 13% (0.5t/ha) grain yield loss in susceptible varieties (Table 4). Yallara$^{\oplus}$ was the worst affected, while Mitika$^{\oplus}$ and Williams$^{\oplus}$ were also affected. Growers should grow moderately susceptible (MS) or better rated varieties to reduce losses. Most of the infection was on the flag -2 leaves and lower. Greater losses are possible during wet weather conditions that favour greater infection on the top two leaves.

There are no fungicides registered for control of RLL in oats. We investigated fungicides registered for use in oats for potential suppression and control. We found that fungicides suppress RLL but do not provide complete control. Previous research showed that each foliar fungicide application provided 5-7% reduction in RLL severity in the Wimmera. Greater response has been observed in the high rainfall zone. This was illustrated by the fungicide treatment in Table 4 which shows up to 11% RLL infection following three applications of propiconazole. Previous research has shown that foliar fungicide applications at Z25 and Z31 are most effective as they coincide with early disease development, while application at Z39 can provide benefits during seasons with wet springs.

Growers should avoid sowing oats into paddocks with oat stubble from previous years as this is the main source of infection. RLL can also be seed-borne, so it is important to monitor all crops and apply fungicides if necessary.

Fungicide resistance

Fungicide resistance is an important issue for the management of diseases in cereals. During the last 20 years fungicides have provided cheap and reliable control of many fungal diseases, but their frequent use has resulted in a selection pressure which favours pathotypes that have mutations for fungicide resistance. Subsequently, there are increasing reports of diseases displaying reduced fungicide sensitivity and fungicide resistance. It is important that the agricultural industry adopts strategies that reduce reliance on fungicides to ensure their longevity.

During 2019, there were several reports of fungicide resistance in cereal diseases across Australia. The most significant was the identification of fungicide resistance in barley net form of net blotch (NFNB) to fluxapyroxad (a member of the SDHI group of fungicides) in the seed treatment Systiva®. This resistance was confirmed by the fungicide resistance researchers from the Centre for Crop and Disease Management at Curtin University in collaboration with SARDI in samples taken from multiple paddocks across the Yorke

Table 4. Red leather leaf (RLL) severity and grain yield of six milling oat varieties in response to disease and fungicide treatments near Horsham during 2019.

Variety	Rating#	Red leather leaf (RLL) severity (% leaf area affected)				
		16/8 Z32		Grain yield (t/ha)		
		Dis.[A]	Fung.	Dis	Fung	Loss (%)
Kowari$^{\oplus}$	MS	14	7	4.2	4.2^{ns}	0
Bilby$^{\oplus}$	MS	14	8	3.7	3.9^{ns}	5
Bannister$^{\oplus}$	MSS	16	8	3.9	4.1^{ns}	5
Williams$^{\oplus}$	MS	15	7	3.8	4.2*	9
Mitika$^{\oplus}$	S	16	10	4.0	4.4*	9
Yallara$^{\oplus}$	SVS	20	11	3.3	3.8*	13
P=		<0.001	0.034	-	-	-
LSD (0.05)=		2.138	2.629	-	-	-

[A] *Dis. = Disease - 1 kg infected stubble, no fungicides; Fung. = no stubble, propiconazole at Z25, Z31 and Z39.*

\# *rating = moderately resistant (MR), moderately susceptible (MS), moderately resistant – moderately susceptible (MRMS), moderately susceptible – susceptible (MSS), susceptible (S), susceptible – very susceptible (SVS), very susceptible (VS).*

Peninsula in South Australia. Whilst testing for resistance to SDHI fungicides, a very high level of resistance to tebuconazole (used as an indicator of resistance within the DMI group of fungicides) was also detected in all 15 paddocks tested across the YP. Testing so far has focused on the YP but given the widespread dispersal of airborne spores it is possible that spores of the dual-resistant pathotype of NFNB will have been dispersed during 2019 and may be present across a wider area, albeit at a low level during 2020. Further field testing is planned for 2020.

This development and spread of fungicide resistance for NFNB is likely to have been enhanced with the sowing of susceptible barley varieties into infected barley stubbles and the repeated use of fluxapyroxad (Systiva®) and a narrow range of DMI fungicides. This incidence highlights the importance of not becoming over-reliant on a single option for disease control.

The agricultural industry can slow the development of fungicide resistance and thus protect the longevity of the limited fungicides available by adopting the following disease management strategies;

- Use a range of control strategies to minimise disease development, including;
  - avoid growing highly susceptible cultivars
  - use crop rotation to avoid planting into paddocks with disease present
  - manage the green bridge for diseases such as mildew and rust.
- Use seed and/or fertiliser treatments, if available, to suppress early disease development.
- Avoid unnecessary fungicide use.
- Use fungicide mixtures formulated with more than one mode of action.
- Do not use the same active ingredient more than once within a season.
- Adhere to label recommendations.

New fact sheets

Several new fact sheets have been released recently that provide current and useful information for the management of diseases in cereals. Links to each of the new fact sheets can be found in the 'useful resources' section at the end of this report.

Cereal disease guide

The 2020 Cereal disease guide published by Agriculture Victoria provides current variety ratings for all recently released and commonly grown cereal varieties in Victoria, using the latest disease resistance ratings from the NVT. The ratings reflect the disease strains of importance in Victoria. As the strains of disease do change over time it is always important to consult a current version of the guide.

Crown rot

A new GRDC fact sheet has been published on the identification and control of crown rot. In seasons conducive to crown rot (such as those with a dry spring) losses greater than 20% are common in wheat crops grown in paddocks with medium to high crown rot levels. As there are no in-crop control options available, the fact sheet recommends the use of soil testing to identify risk prior to planting.

Root lesion nematode

The latest information on the management and control of root lesion nematodes has been published in a GRDC fact sheet. It highlights the advantages of using soil testing to determine nematode levels within paddocks to enable the planning of rotations to minimise losses.

Spot form of net blotch in barley

A fact sheet on the identification and management of spot form of net blotch in barley is due for release by GRDC in early 2020. This disease can cause yield losses greater than 20% in susceptible varieties during wet seasons, when crops are planted into paddocks with infected stubble. The fact sheet highlights the potential yield losses from the disease and the important control strategies to minimise losses.

Seed treatment guide

SARDI has published the 2020 guide to cereal seed treatments, which lists all the registered seed and fertiliser treatments available to assist with disease control.

Conclusion

In the absence of proactive disease control, yield losses due to diseases can be greater than 20%. Therefore, it is important to develop plans to effectively manage cereal diseases this season. Disease management plans should consider paddock and variety selection and, where the risk warrants it, the proactive use of fungicides that avoid overuse to protect their longevity.

Acknowledgements

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Useful resources

Current Victorian cereal disease guide:

http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/plant-diseases/grains-pulses-and-cereals/cereal-disease-guide

Root lesion nematode fact sheet:

https://grdc.com.au/root-lesion-nematode-southern

Crown rot fact sheet:

https://grdc.com.au/crown-rot-southern

Cereal seed treatment guide, 2020:

https://pir.sa.gov.au/__data/assets/pdf_file/0005/237920/Cereal_seed_treatments_2020.pdf

Spot form of net blotch fact sheet:

Check the GRDC web site for an early 2020 release.

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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.

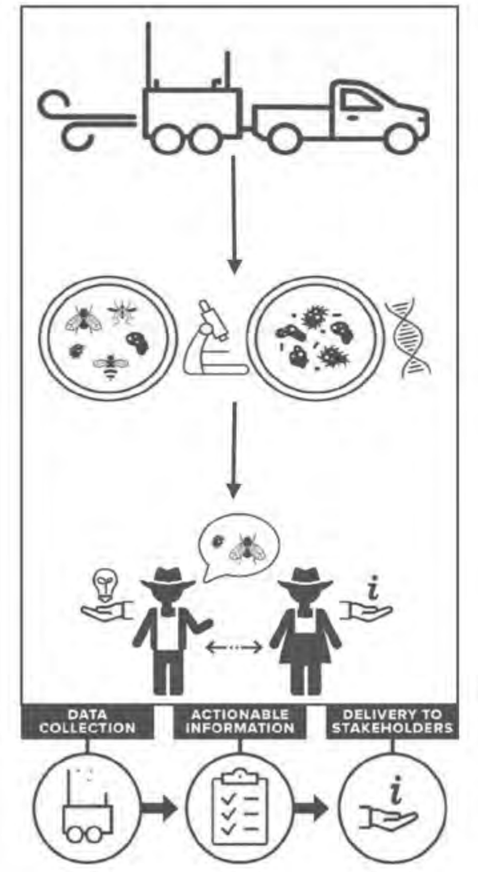

Figure 1. Schematic diagram of how iMapPESTS will boost Australia's on-farm pest management.

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.

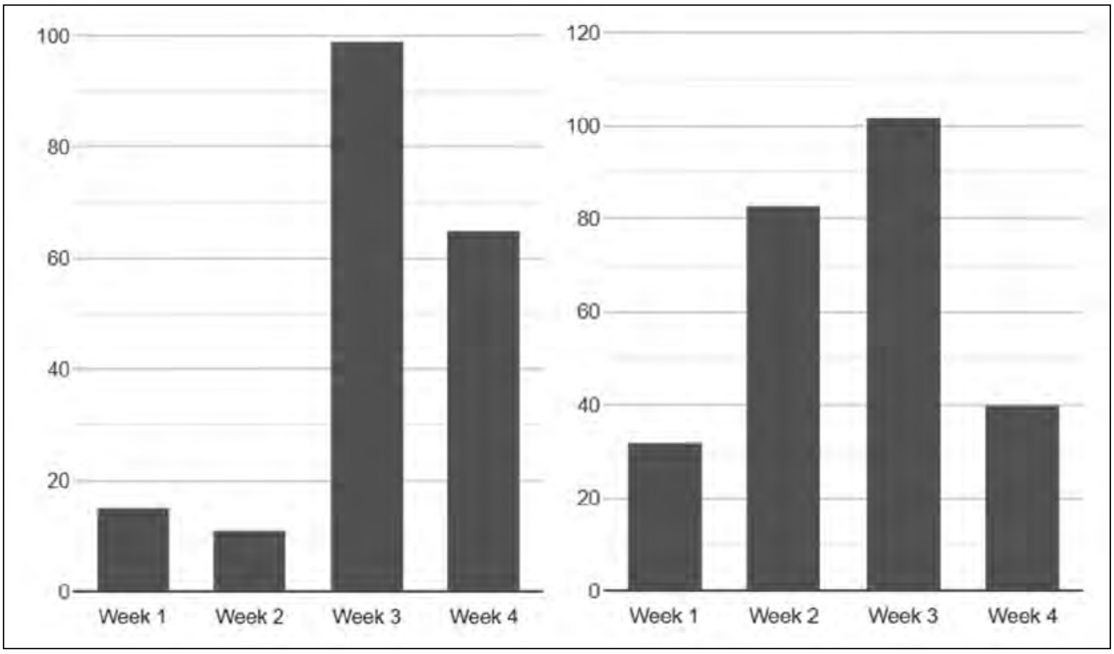

Figure 4. Total counts of green peach aphid (GPA; left) and bird cherry oat aphid (BCOA; right) by week identified in the suction trap samples during the Hart Field Site trial.

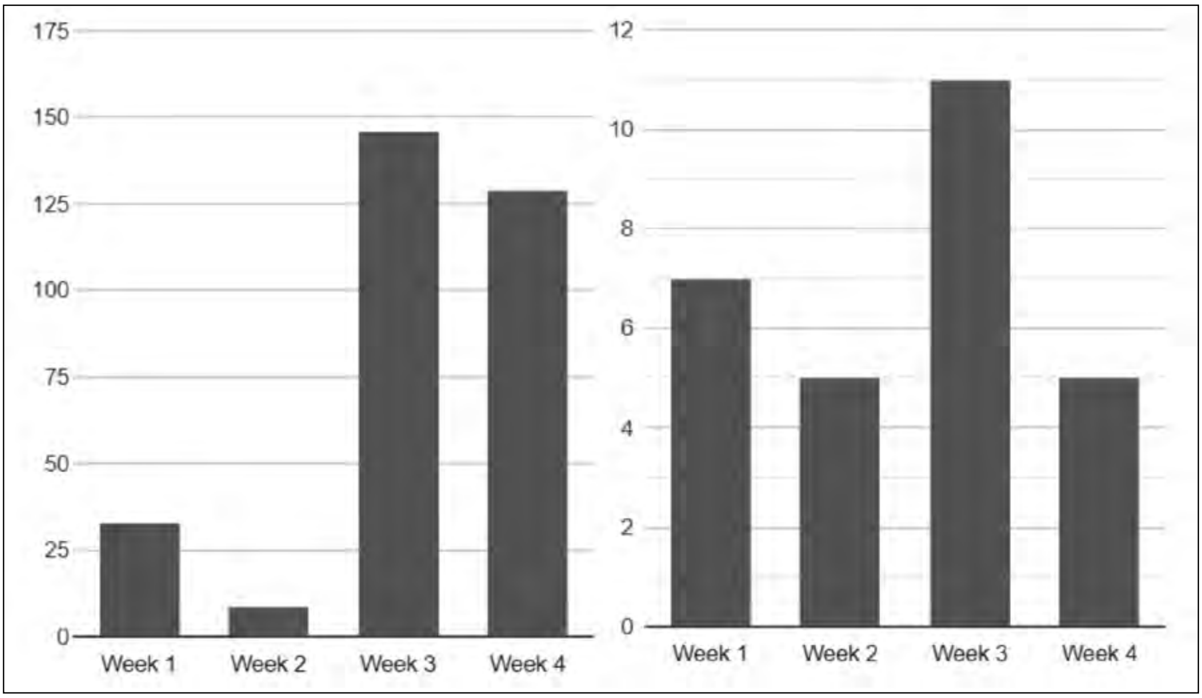

Figure 5. Total counts of Russian wheat aphid (RWA; left) and western flower thrips (WFT; right) by week identified in the suction trap samples during the Hart Field Site trial.

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.

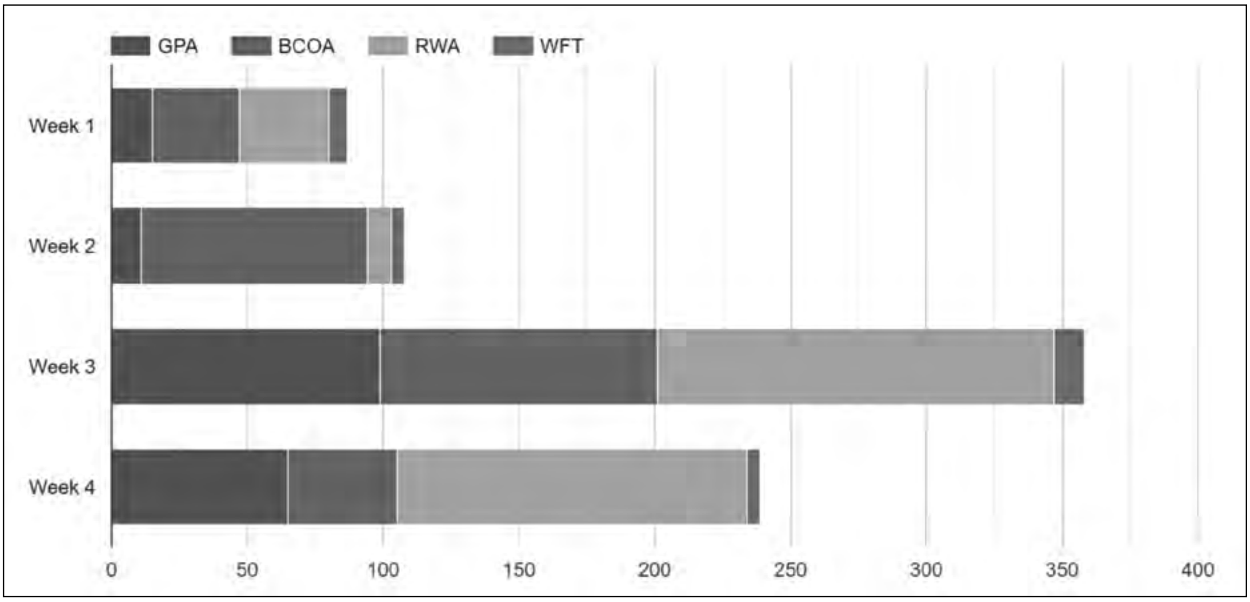

Figure 6. Relative abundance of each insect target by week identified in the suction trap samples during the Hart Field Site trial (order of display within the column bar: GPA, BCOA, RWA and WFT).

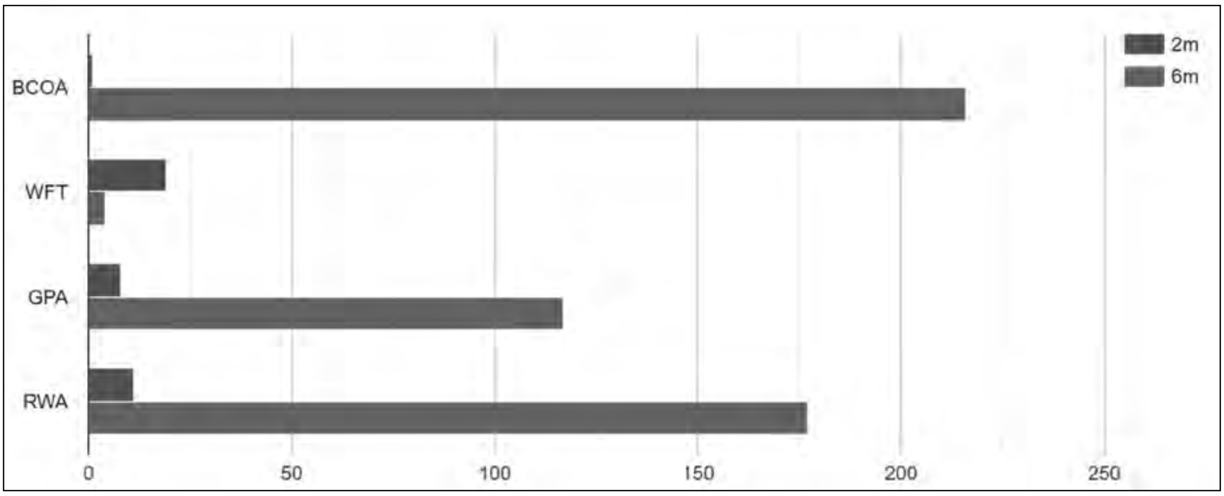

Figure 7. Total counts of each insect target identified from the 2m (top bar within each insect target) and 6m (bottom bar within each insect target) suction traps.

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.

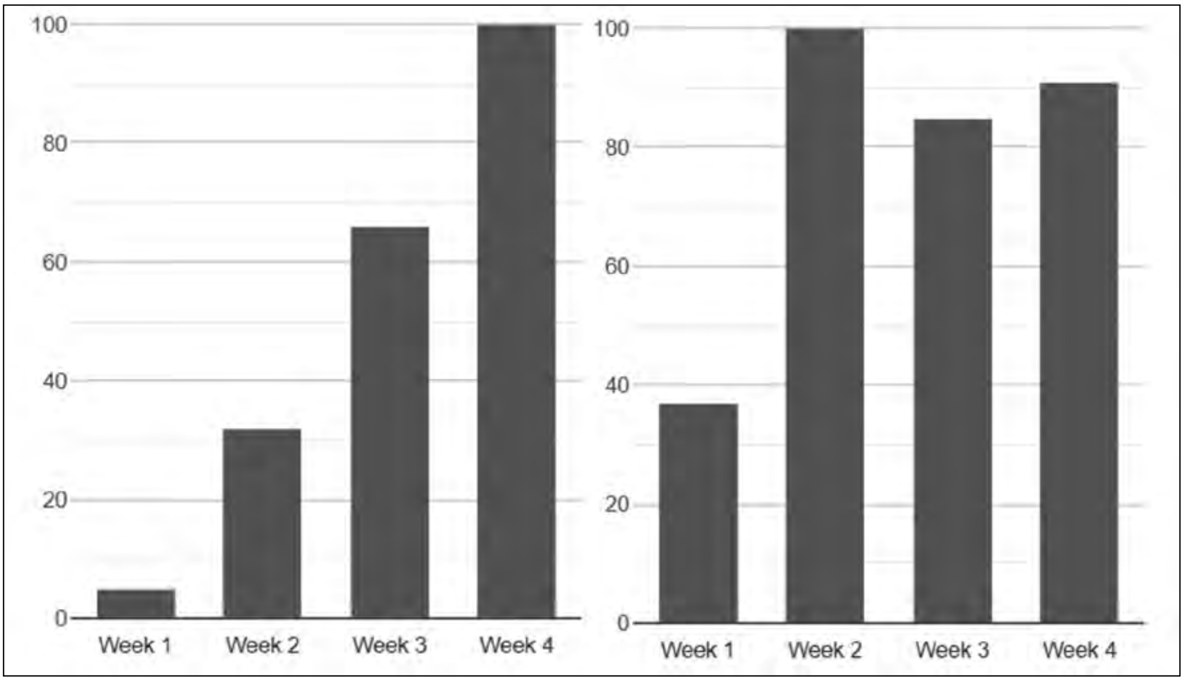

Figure 8. Total counts (normalised) of blackleg of canola (left) and botrytis grey mould (right) by week identified in the spore samples during the Hart Field Site trial..

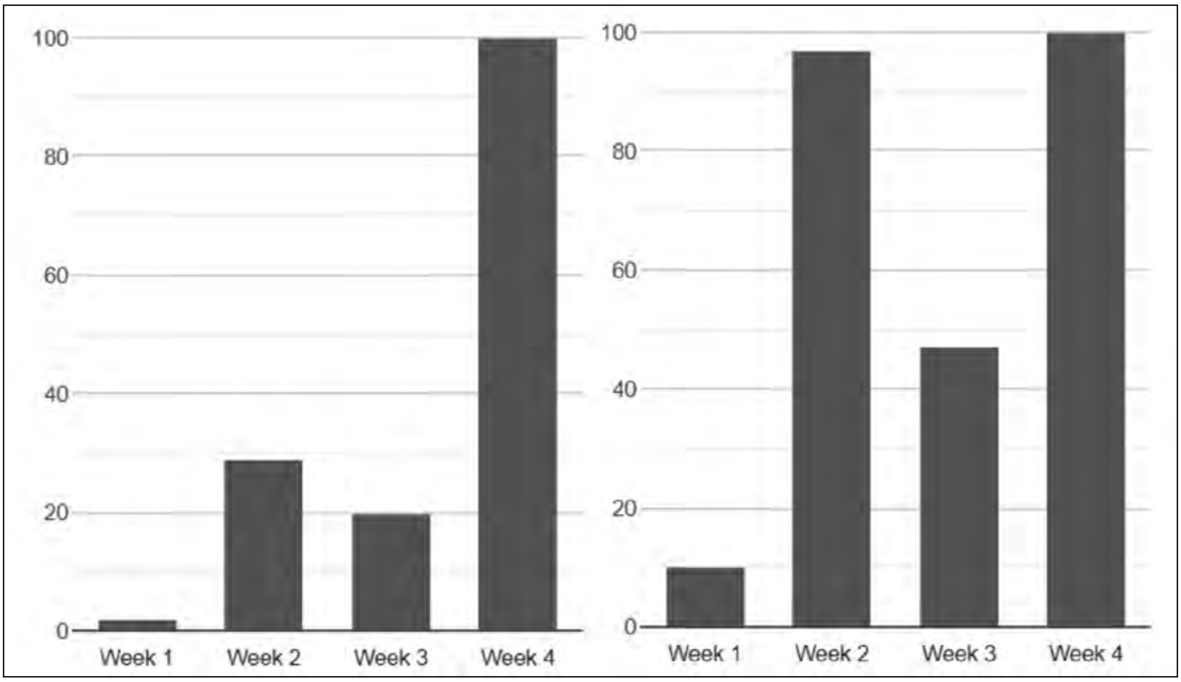

Figure 9. Total counts (normalised) of blackspot of field peas (left) and septoria (right) by week identified in the spore samples during the Hart Field Site trial

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

iMapPESTS is supported by Hort Innovation, through funding from the Australia Government Department of Agriculture as part of its Rural R&D for Profit Program and Grains Research & Development Corporation, Sugar Research Australia, Cotton Research & Development Corporation, Wine Australia, AgriFutures Australia, and Forest and Wood Products Australia.

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

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

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GRDC project code: 9175134

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⦸)	Wheat (Scepter⦸)	Barley (Spartacus CL⦸)
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)

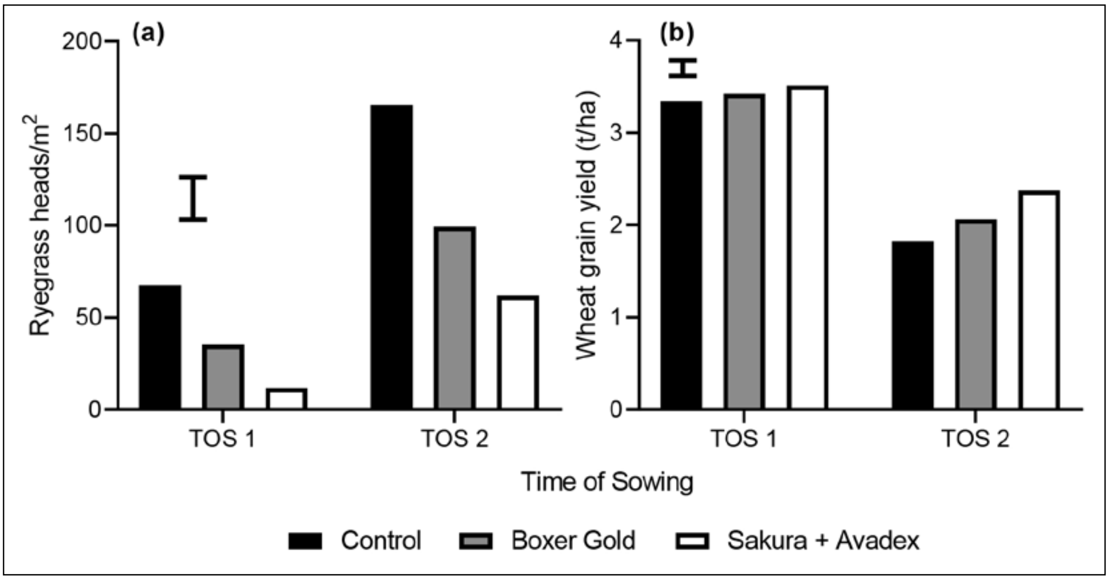

Figure 1. The effect of time of sowing (TOS) and herbicide treatments on ryegrass head density (a), and wheat grain yield (b), at Washpool in 2019. The error bars represent LSD (P=0.05).

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

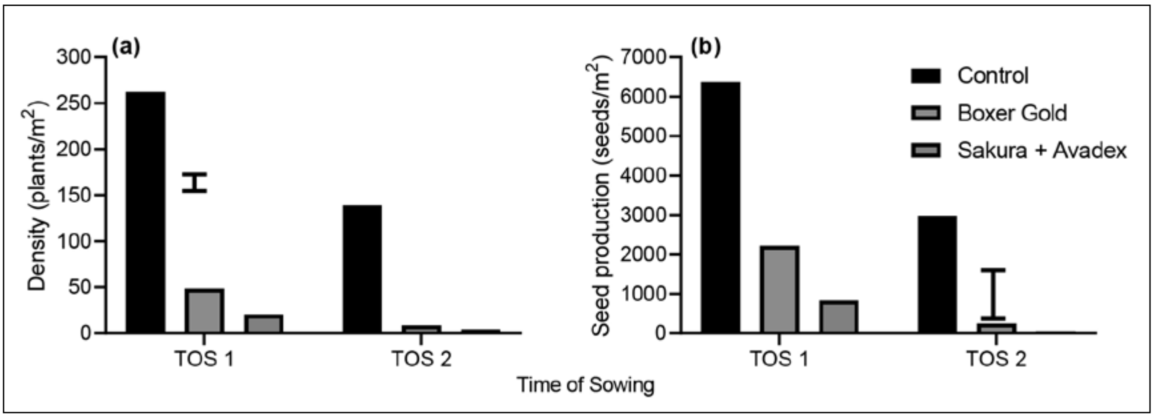

Figure 2. The effect of time of sowing (TOS) wheat and herbicide treatments on in-crop ryegrass plant density (a), and its seed production (b), at Minnipa in 2018. The error bars represent LSD (P=0.05).

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.

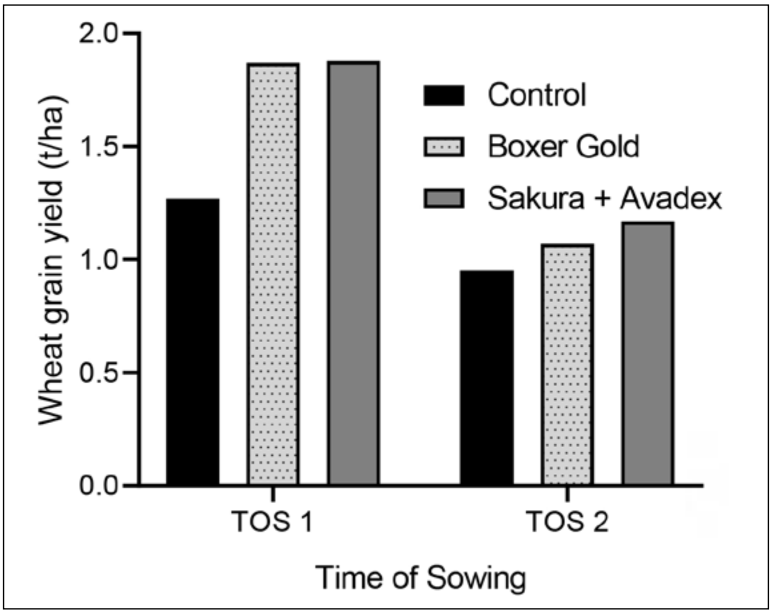

Figure 3. The effect of time of sowing (TOS) wheat and herbicide treatments on wheat grain yield at Minnipa in 2018.

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

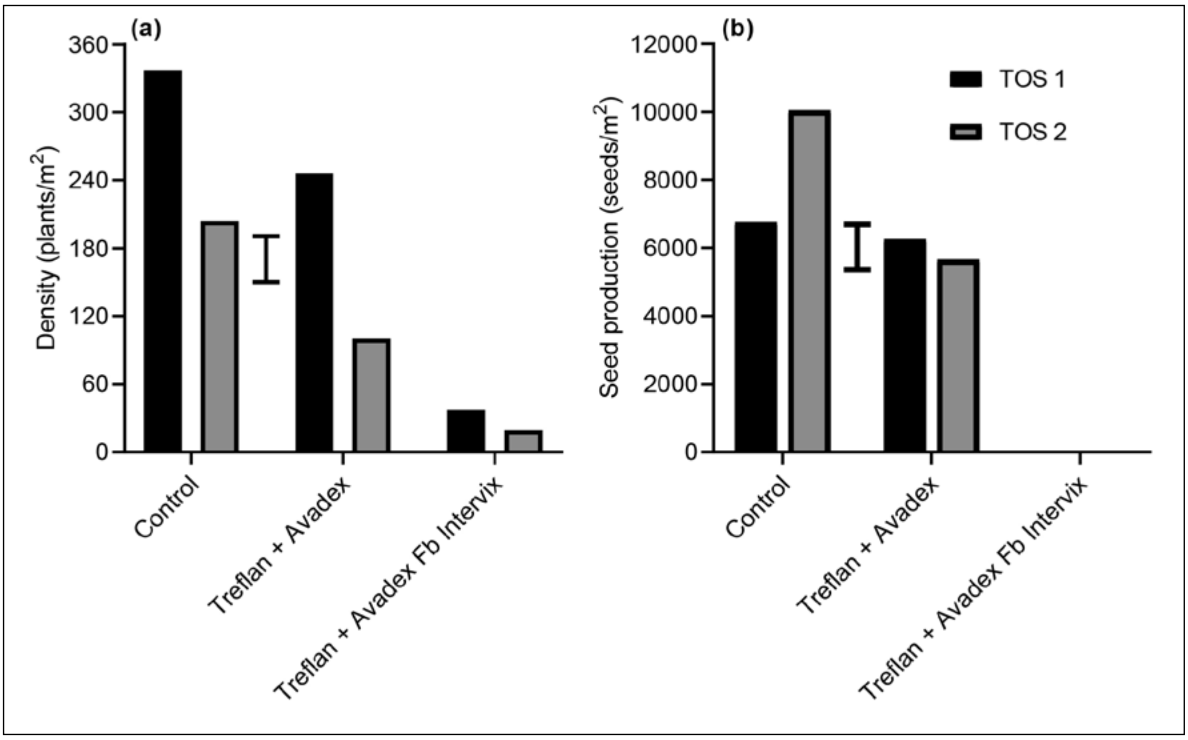

Figure 4. The effect of sowing time and herbicide treatments on brome grass plant density (a), and brome grass seed production (b), at Marrabel in 2018. The error bars represent LSD (P=0.05).

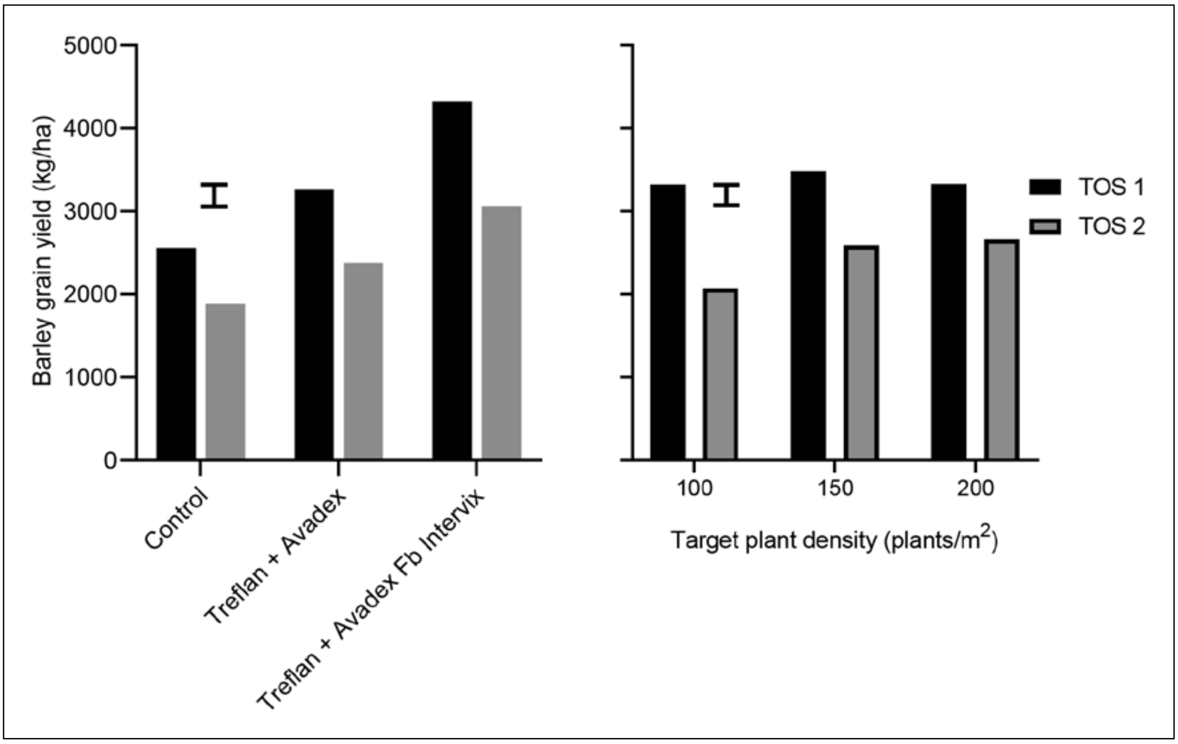

Figure 5. The effect of sowing time and herbicide treatments on barley grain yield (a), and sowing time x seed rates on barley grain yield (b), at Marrabel in 2018. The error bars represent LSD (P=0.05).

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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Insect pest control – are you advising for today or the future?

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GRDC project code: BWD1805-006SAX

Keywords

- insecticide resistance, adviser, integrated pest management, IPM, neonicotinoid, pesticide.

Take home messages

- There is a strong social dynamic at play when it comes to adoption of sustainable pest management strategies that must be better understood in order to curb the threat of increasing cases of insecticide resistance.
- The adviser has an important role to play in facilitating long term sustainability of farming enterprises; they need to have a 'for the future' focus.
- Motivators other than profit, such as responsibility for land and environment and pride in quality products, are likely to be important behavioural drivers that should be identified and considered within extension frameworks.
- Insecticide resistance management needs to have a foundation in long-term planning rather than short-term decision-making to achieve sustainability benefits.

Background

How old are you? Sorry! Perhaps that is an inappropriate question! But we have a very good reason for asking. There is a good chance that when you were born, your parents or family friends were farming in a very different way. Turn to the person closest to you. Share what you know about how insect pests were managed when you were born. Once you have done that, share with your colleague what pests would have been difficult to manage due to insecticide resistance. You may now have a sense for how much the situation has changed…

Insecticide resistance has been documented as far back as 1914 in the US with reports of farmers experiencing increasing difficulty in controlling an apple orchard pest, San Jose scale, with sulphur-lime. By the mid-1940s, 11 cases of resistance to inorganic insecticides had been documented, and with the introduction of the first organic insecticide (DDT) to the market in 1942 it was not long before housefly resistance was documented in 1947. Since that time, resistance to organic synthetic insecticides has been reported at an increasing rate for most of the chemicals introduced to the market. Globally, there are now more than 580 documented cases of invertebrate pests evolving resistance, and 331 unique compounds for which one or more species have evolved resistance.

The Australian grains industry has an ongoing reliance on limited chemical control methods; particularly the cheaper broad-spectrum chemistries. Therefore, managing insecticide resistance is a major challenge. Currently, insecticide resistance in Australian grains (excluding the grain storage pests) is established in redlegged earth mites (*Halotydeus destructor*), green peach aphid (*Myzus persicae*), diamondback moth (*Plutella xylostella*) and corn earworm (*Helicoverpa armigera*) (McDonald et al. 2019).

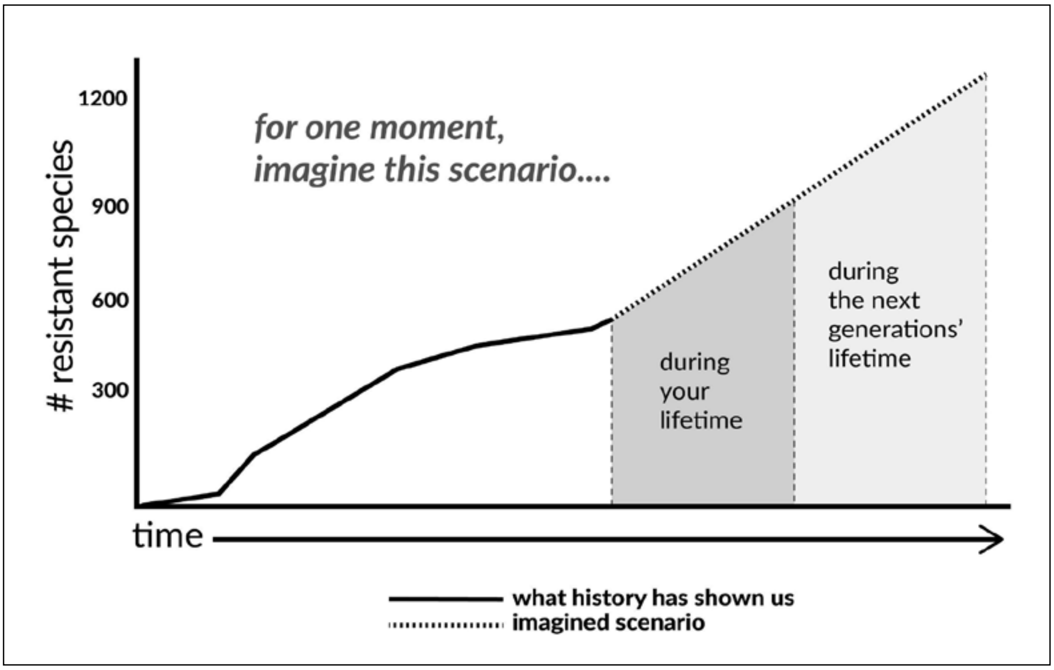

Figure 1. Historical development of insect resistance and expected future projections.

Now imagine that the scenario posed in Figure 1 has become our truth. Throughout your lifetime the insecticides that you buy have become less and less reliable each year. Pest control becomes more like a coin flip. How does it make you feel? What has led to this situation?

Values and vision - how can we avoid our worst imaginings?

The GRDC investment 'Supporting the sustainable use of insecticides and local on-farm implementation of integrated pest management strategies in the southern region' was initiated in response to the ever-increasing threat of resistance evolution within key pest species in the southern cropping region and more broadly. The Birchip Cropping Group, **cesar**, SARDI, QDAF, and C-Qual Agritelligence are collaborating to improve industry understanding of insecticide resistance issues, and to develop clear steps to manage resistance in key pests.

We are far more familiar with the evolution of herbicide resistance compared to insecticide resistance. Insect pests are often a sporadic problem within a region, and therefore, are not considered as serious an issue as herbicide resistance. At the annual Crop Protection Forum 2019, run by cesar in partnership with the Australian Herbicide Research Institute and the Centre for Crop Disease Management, researchers, industry bodies and advisers identified insecticide resistance as a sleeping giant with the potential for devastating effects on the Australian grains industry. Why?

The intermittent nature of many insect pests in broadacre agriculture, and knowledge base gaps among the research community and agriculturalists, can result in management becoming complacent and reactive. When management does occur, the application of broad-spectrum, non-selective sprays from a limited selection of mode of action (MoA) groups means that we put immense selection pressure on both the pest intended, as well as those that are not a priority issue but 'lurk in the shadows'.

To more proactively address this issue, we cannot ignore current challenges in relation to invertebrate pest control, and particularly the management of pesticide resistance, which must be considered when investigating how behaviours may be influenced. These can include, but may not be limited to:

- Growing operations are often large and mechanised.
- The climate is variable, making it difficult to judge the risk of a pest outbreak, and increasing business risk.
- Export requirements for grain quality are extremely stringent, with zero tolerance for live invertebrates.

- Uptake of Insecticide Resistance Management Strategies (IRMSs) and the principles in these IRMSs is slow.
- An increased reliance on seed dressings, which are often neonicotinoids, and the possibility of stronger neonicotinoid restrictions on use in future. This also includes possible future restrictions on other chemical classes.

This project aims to realign the way messages are conveyed about insecticide resistance management, and more generally, about good insecticide stewardship. To date, a number of publications have been produced that highlight the current situation and risks we face, in particular with key pests such as redlegged earth mite, green peach aphid, diamondback moth and to a lesser extent the threat posed by cotton bollworm (refer to the Resources Section within this paper).

Understanding the social dimension

When you stand in an elevator, do you turn to face the doors after you enter or just before you leave (Figure 2)? It is likely your answer will be the former. The floor buttons are usually near the doors and you want to keep an eye on who walks in. It makes sense. But, what about the social element at play? How much is logic and efficiency, and how much is habit, risk aversion and social expectation?

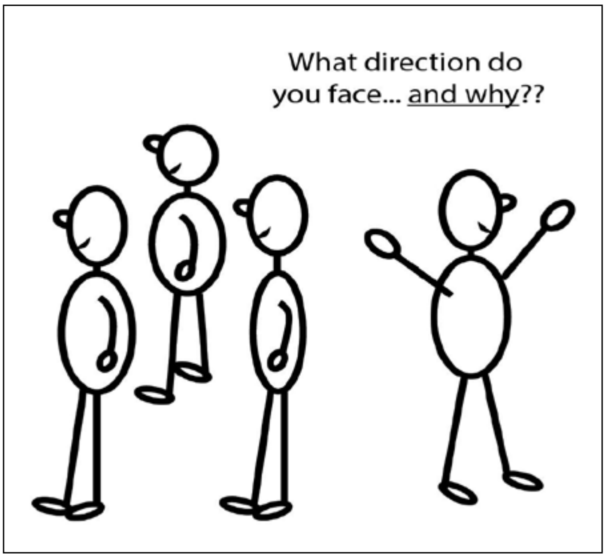

Figure 2. What direction do you face?......... and why?

There is a crucial social dimension at play when it comes to changing behaviours and practices. Cummins (2007) highlights four major factors that influence adoption of new advice and technologies:

1. The personal and situational (values, motivations, attitudes, financial situation) ;
2. the pathway of information delivery (eg. Eg.trusted source of information, style and format of extension etc.);
3. technology characteristics (complexity of adoption and associated reasons); and
4. farmer capacity to change (including risk aversion, innovativeness and ability).

Other studies have also highlighted grower characteristics and facilitating factors that influence adoption of new technologies or practices. Findings from these studies include:

Appetite for risk

Appetite for risk is likely to influence motivation to adopt new practices, with the variable Australian climate making it difficult to judge the risk of a pest outbreak. In addition, export requirements for grain quality have a zero tolerance for live invertebrates, further motivating growers to take a perceived low risk approach. However, compiled survey data by Zhang et al. (2019) indicates that grain growers with a history of achieving high yields tend to be more likely to take the risk of adopting a new technology than those that achieve lower yields. Further, Zhang et al. (2019) found that growers with a greater sense of control over farm risks are more likely to take proactive measures to manage crops.

The cost of doing business

Input costs are, of course, significant motivating factors. Large farming operations make regular pest monitoring time expensive, and broad-spectrum chemistry is widely available and often cheaper than more selective options. For cereals, organophosphates and pyrethroids account for >85% of all estimated insecticide applications. In legumes, pyrethroids are by far the most widely used mode of action. Pyrethroids, organophosphates and neonicotinoids are also widely applied in canola crops within Australia (Umina et al. 2019).

Keeping it simple

A 2013 study by Llewellyn points out that 'Growers with a relatively strong preference for keeping their farming operations simple are less likely to adopt practices that add complexity, such as spatial management. Convenience and simplicity for farm managers are likely to be an increasingly important determinant of the relative advantage of new practices.'

A trusted source

Trusted local advisers are extremely important sources of knowledge and heavily influence crop management decisions. Zhang et al. (2019) has shown that high yielding grain farms were more likely to source information from fee for service advisers as a trusted knowledge broker, than low yielding grain farms. The strong link between independent agronomy advice and uptake of new practices was also identified by Llewellyn (2013). However, use of and access to advisory support can vary between regions.

Knowledge pool

The education level of staff does influence attitude towards adoption of new practices. Having staff with a university level of education is correlated with greater knowledge seeking behaviour, such as attendance at extension events (Zhang et al. 2019). Zhang et al. also demonstrated that having staff with a university level of education was correlated with a higher likelihood of using a fee for service adviser (as opposed to a retail agronomist) and higher relative yield.

Ability and resources

The ability of a farm enterprise to trial new practices and evaluate the benefits of the practice is influenced by the regularity of the pest, cost, rotational strategy, understanding/knowledge of farm staff, access to advice, motivation and skill set of the farm decision maker(s). As suggested by Llewellyn (2013), management capacity and capital constraints are a major consideration in the ability of an operation to uptake new technology. Thus, farm business structures (for example; joint ventures versus independent operations) are an important consideration in the speed at which certain new technologies (precision agriculture) are integrated into farm operations.

Technology type

Australia does not have access to some of the high potential new technologies currently employed overseas. However, Australian grain growers are experienced in keeping on top of certain research and development (R&D) outputs, such as varietal developments and adopting promising varieties quickly. Adoption of automated monitoring technologies and integrated data storage systems are other examples of areas that are being embraced by many Australian growers, although a large number of growers remain limited in ability to adopt these practices due to unreliable mobile data coverage (Zhang et al. 2017).

Comfort and confidence

Prior work by Llewellyn (2002) has shown that R&D information is more effective at influencing grain grower perceptions if there is a low level of associated variance and uncertainty. Further, tools or advice that can be shared with a high level of certainty will stand a greater chance of being adopted if they relate to a topic towards which growers feel a high level of uncertainty.

Prioritisation and attitudes

In terms of invertebrate pest management, the importance that growers place on employing new strategies to manage pests, relative to other crop management issues, such as weeds, must be considered. Zhang et al. (2019) identified distinct differences in how weed management is viewed in comparison to invertebrate pest management. In terms of maximising yield, growers reported that the three key practices that need to be done well are weed control, nutrition and sowing at the right time were essential to good wheat yields (53%-84% of respondents). Pest control was only regarded as a concern for maximising yield by 0-1% of respondents.

Results

Why do you farm? Our investigation into value drivers

Understanding the characteristics of growers who are more likely to adopt new practices is extremely useful for enabling change. However, value drivers (personal motivators) provide the basis for these characteristics. At the commencement of this project it was decided to re-assess how call-to-action messaging was delivered. To undertake this, it was important to understand what value drivers should be considered as a priority when attempting to motivate growers to do (or view) something differently. Therefore, at the outset of this project the team took a deeper look into the value drivers behind why growers farm and what would drive them to adopt a new practice, with a key objective of using findings to aid the project team in developing extension outputs that appeal to these motivators.

Two activities were undertaken to obtain insights into the motivations and the values of growers within the target audience. The first was a series of focus groups held across the GRDC Southern Region. The second was to conduct a short survey designed by Cultural Dynamics Strategy & Marketing Ltd that reveals what they refer to as 'Values Modes'. With a basis in principles captured by Maslow's Hierarchy, Values Modes™ was designed using empirical data, gathered from large population surveys to identify 12 discrete psychographic types, to capture values that underpin the decision-making processes of most individuals.

Led by the Birchip Cropping Group and Bruce Howie of C-Qual Agritelligence, the investigation highlighted interest in the employment of more sustainable practices across the industry.

Why do growers love farming?

Results from the study revealed some of the key reasons growers farm (Table 1). These focussed on four areas including:

1. Responsibility for land and environment.
2. Continuity of farming and family tradition.
3. Rewards and demonstration of success.
4. Passion for agriculture and pride in quality products.

However, in the case of agricultural research, the primary benefit usually pitched to growers around adopting new practices is tied into increased financial returns, whether through yield increases, improved profitability or greater efficiencies, etc. While these benefits are important and should be made evident, they are often not the primary trigger for stimulating interest in a new concept or motivating a change in practice. Sometimes we need to look at the long-term impacts, and motivators to realise and convey that short-term financial gains may risk unintended long-term consequences if not managed carefully.

Results were analysed by UK business Cultural Dynamics to evaluate individual and community values, resulting in respondents being placed in categories or value modes that sit within three overall motivational levels based on Maslow's hierarchy of needs. From this analysis, there was a strong representation of responses within the 'Pioneer' group (81%). 'Pioneers' are likely to have characteristics of high level of self-awareness, ethical behaviours and willingness to push boundaries and as such are the most likely to explore new ideas and practices, particularly if they are likely to contribute to a better environment. There needs to be some consideration to the relatively small sample size investigated here, however other research with larger sample sizes have suggested that Australian growers generally have a higher representation in the 'pioneer' group (40.1%) compared with other countries such as the UK and Europe (pers. comm.).

Table 1. Summary of motivations expressed by growers at each focus group.

Lake Bolac	Birchip	Naracoorte	Hart
Continue family tradition	Satisfaction in running a family farm	Long family history of family farming	Continue family tradition
Love farming - variety and challenges	Enjoy growing things	Passion for agriculture	Love farming
Continuity	Pass the land on no worse, hopefully better	Continuous learning	Future opportunities for the family
Environmental improvement especially now with children	Rewards from meeting the challenges of our environment	Maintaining healthy and sustainable farm	Leave the farm better for the next generation
Satisfying and rewarding	Care of the soil	Big picture, responsible environmental management	Maintain the legacy and hope to make a living out of it
Always being challenged by whatever comes around the corner	Meeting the challenges of every new season	Satisfaction of success Producing quality products	Enjoy the challenge and want to keep improving
Enjoy new ideas but becoming more cautious	Pushing boundaries	Doing things right	Doing the best with what we have
Achieve financial goals	Can make income from what I love	Profitability of a good family enterprise	Try to be profitable amidst the seasonal challenges
Independence - working for yourself	Working outdoors and in the crop	Love being outdoors	
	Trying new things and new research	Give back through producing	
	Producing quality, market ready produce with safe methods	Seeing crop develop to maturity is exciting	
	Analysis and interaction of systems		
	Decisions on the fly		

**It is important to note the repeated usage of the words 'continue' and 'challenge'. These words should be targeted in the planning and delivery of extension and communications to best relate to the key audiences.*

Focus groups readily identified that, particularly amongst those who demonstrate a low level of implementation of integrated pest management (IPM) practices, broad-spectrum sprays are too frequently applied as cheap, 'safe' options or as low-cost risk mitigators. Despite good levels of commitment to IPM practices, several focus group attendees did accept that on occasions they found themselves taking that route. This might happen through pressure of work, seasonal conditions or crop condition that did not warrant a more expensive, selective spray. Even so, the general feeling was that the low cost, prophylactic approach is inconsistent with their approach to IPM. It is interesting that the same concerns did not manifest regarding the use of seed treatments. To some extent, seed treatment has become the IPM practitioner's convenient, prophylactic treatment. Although there were some concerns about resistance, there was a very strong reluctance to manage seed treatments with the same level of commitment as they seek to do with foliar sprays.

This investigation also indicated that growers tend to experience 'decision paralysis' because they are faced with an overload of content, and it emphasised the importance of local advisers as trusted sources of information.

The role of the adviser

The role of the adviser has shifted a lot over time. At one stage, growers would often review advisers' recommendations and would ultimately make their own decisions. However, as the scale of farms has increased, this role has shifted to what we recognise today as a role with increased decision-making influence in crop management, and many farm businesses retain a 'trusted' adviser. This was identified by grower focus groups where it was suggested that advisers are a key source of information. This means a significant proportion of decision risk is passed to advisers, and as such it could be seen that advisers now have their own reputation to protect.

It is careless to generalise, as some advisers will advise growers to try new practices and take new risks, but it is likely that the amount of risk an adviser is willing to take will be dependent on the individual. The less risk the adviser is prepared to take, the more likely they will act early to manage pest issues, and the more quickly they will aim to achieve a good result; as such broad-spectrum, non-selective insecticide options will tend to be selected.

When it comes to insect management, taking a risk comes at the cost of high crop losses if things do not go to plan. As such it is paramount that the adviser has a good understanding of the threats on the farm and how these threats may impact on rotational choices. However, there would also be value in the adviser sitting down with the grower to come up with the long-term strategy and align management with sustainability goals and key motivators for the client, as well as identifying risks and rewards. The role of advisers in supporting adoption of long-term sustainable approaches to grain growing should not be understated.

The panel session

While this project included focus groups and surveys to investigate grower value drivers, the important topic of adviser value drivers and challenges remains to be explored using a structured approach. This session will be a first step in delving into this topic and will launch an exploration of how advisers can support transformational change in insect management. It will address questions such as:

- What are the key hurdles and respective actions that advisers, with a long-term view, consider will reduce the pressure on the small selection of insecticides we have available?
- How do advisers align their approach with the long-term views of the farming unit?
- How do they look to change the focus from here and now (this cropping season) to the future?
- Why do you recommend practice 'A' over practice 'B'? In what situations do you provide advice wearing a long-term hat?
- What are the key hurdles to be overcome by advisers in order to make long term decisions with clients?
- How can advisers effectively focus on both the here and now (this cropping season) and the long-term? What is the appetite (and ability) to take a long-term view?

These questions will be explored within the context of a future risk: loss of a product of importance, such as the neonicotinoid seed treatment; imidacloprid. We will also discuss limitations on the status quo and why it will not support farmers in achieving sustainable practices in the long-term.

Conclusion

When it comes to insecticide resistance management, there is a strong social dynamic at play around adoption of sustainable pest management strategies that must be better understood in order to curb the threat of increasing cases of insecticide resistance. To foster this, there needs to be a strong understanding of the key parties involved in on-farm decision making and advisers need to realise they have an important role to play in facilitating long term sustainability of farming enterprises; they need to have a 'for the future' focus.

There are many issues however, that limit the adoption of a long-term view and can include seasonality of pests, limited options for management, and demands for high quality products with minimal if any damage from insects or presence of live insects in marketable produce. Extension materials need to acknowledge these challenges, but also recognise that motivators other than profit, such as responsibility for land and environment and pride in quality products, are likely to be important behavioural drivers that should be identified and considered within extension frameworks.

Ultimately all parties; growers, advisers and markets must recognise that insecticide resistance management needs to have a foundation in long-term planning rather than short-term decision-making to achieve sustainability benefits and limit the continued rapid evolution of resistance in key pest species.

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Useful resources

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Aphid and insecticide resistance management in oilseed and pulse crop

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GRDC project codes: CES00003 (2016-2019), CES2001 (2020-2023)

Keywords

- green peach aphid, oat aphid, insecticide resistance, neonicotinoid, sulfoximines, biosecurity.

Take home messages

- A high number of green peach aphid populations are resistant to pyrethroids, carbamates, organophosphates, and neonicotinoids.
- Multiple green peach aphid populations from a specific region are resistant to sulfoximines (sulfoxaflor, Transform®) due to an unknown resistance mechanism.
- Significant differences in pyrethroid sensitivity were found between populations of oat aphid.
- The green peach aphid insecticide resistance management strategy has been updated and should be consulted by growers and advisers.
- Rotate available insecticide modes of action (new modes of action to be registered in coming years).
- Controlling green bridges around paddock and sowing into standing stubble is recommended.
- Proper identification of aphid species is necessary to assess risk of resistance and choice of insecticide to be used.
- Monitoring of aphid predators and parasitoids allows chemical-free control of insecticide resistant aphids.

Background

Aphids are major crop pests throughout the world, attacking a broad range of crops through direct feeding, and as a vector of viral diseases. In Australia, the cost of aphid injury has been estimated at $200-$400 million per year. The green peach aphid (*Myzus persicae*, GPA) has evolved resistance to a wide range of commonly used insecticides. There is a need to develop resistance management strategies that minimise the risk of increased resistance evolution, focus on targeted use of pesticides and include non-chemical options.

In Australia, the oat aphid (*Rhopalosiphum padi*) causes feeding injury which can reduce cereals yield by 6%, with the damage caused by aphid-vectored viruses reducing yield of cereal crops by up to 30%. Aphid control in these crops is achieved almost exclusively with chemical insecticides, and there is growing concern about insecticide resistance evolution in multiple aphid species.

Method

This project documented the frequency and spread of insecticide resistance in GPA through a national insecticide resistance surveillance program throughout Australia. Over 400 GPA populations were screened for resistance to carbamates, organophosphates, synthetic pyrethroids, neonicotinoids and sulfoximines. Screening was completed using optimised phenotypic methodologies, newly developed molecular markers for GPA populations and testing over multiple known genetic resistance mechanisms. The assessment of resistance was based on genetic screening of alleles for *MACE, kdr,* super-*kdr*, as well as amplification of the *E4* esterase gene, and finally the CYP6CY3 (P450) copy number, which confer resistance to carbamates, pyrethroids, organophosphates, and neonicotinoids. The risk of incursion and local evolution of the sulfoximine and neonicotinoid-resistant mutation (known as "R81T") has been evaluated and investigated through predictive modelling and a large network of field traps, followed by genetic testing for this mutation.

An extensive review of resistance risk in aphid species other than GPA was also completed. New knowledge was developed regarding the risk of resistance evolution in grain aphids and based on risk profiles and considerable base-line sensitivity data was established for multiple insecticides for two species deemed to be at risk of resistance evolution in Australia; the cowpea aphid and oat aphid. Nine field populations of oat aphid were collected from localities representing the major grain growing regions of Australia; Tamworth (TMW), Picola (PIC), Dookie (DOK), Pimpinio (PIM), Back Valley (BKV), Adelaide (ADE), Manjimup (MNJ), Capel (CAP) and Katanning (KAT). Toxicity data for each population was established against four insecticide classes (organophosphates, synthetic pyrethroids, carbamates, neonicotinoids).

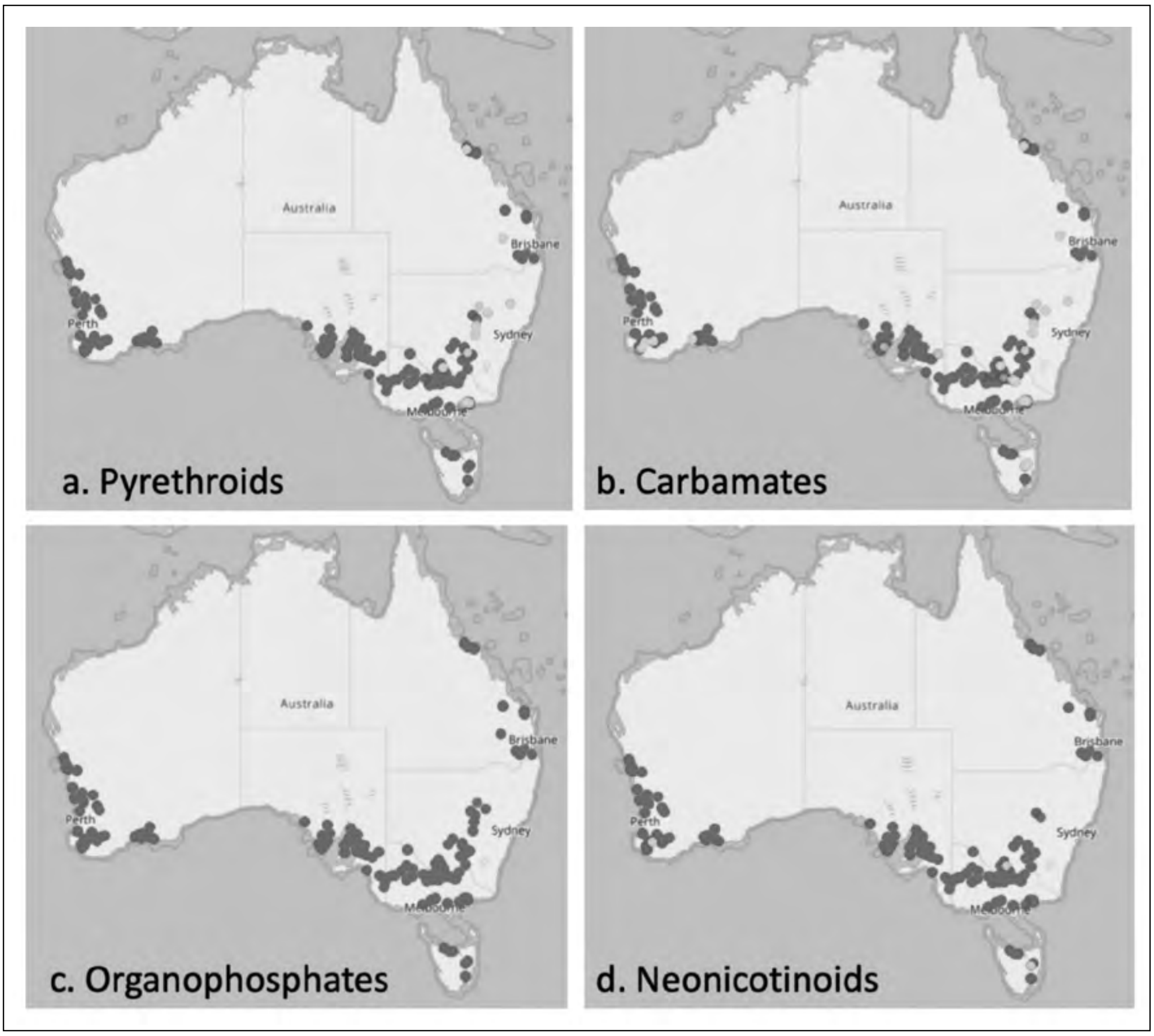

Figure 1. Insecticide resistance maps of green peach aphid collected during 2017/2018 for pyrethroids, carbamates, organophosphates, and neonicotinoids. Red dots represent resistant population location, green represent susceptible population location.

Results and discussion

Green peach aphid resistance monitoring

Insecticide resistance maps show that resistance is commonplace; almost all (>90%) populations tested showed resistance to carbamates, pyrethroids, organophosphates and neonicotinoids (Figure 1).

Genotyping has revealed GPA from many field-collected populations are resistant clones, possessing resistance to organophosphates, carbamates, pyrethroids and neonicotinoids. The use of pyrethroids and pirimicarb (even at high rates) will not provide control against these populations. Interpreting resistance-testing results for organophosphates is more complex. The amplified carboxyl-esterase mechanism leads to organophosphate resistance in GPA. This mechanism is unusual because it is regulated by DNA methylation and can be 'switched on' in response to environmental conditions such as weather events or pesticide exposure. As a result, aphids carrying the *E4/FE4* gene amplification can quickly adapt to survive organophosphates. The GPA populations that have this gene amplification are expected to have a moderate level of resistance (5- to 20-fold) to organophosphates; including dimethoate, omethoate and chlorpyrifos. A baseline sensitivity of spirotetramat and cyantraniliprole has demonstrated high sensitivity in all GPA populations tested (de Little et al. 2017a).

For neonicotinoids, a subset of populations was screened using phenotypic laboratory bioassays as well as testing for the overexpression of the P450 monooxygenase CYP6CY3 detoxifying gene. Low-level resistance was found across most field-collected populations. Under field conditions, this resistance mechanism is likely (although not confirmed) to shorten the length of protection offered by neonicotinoid-based seed treatments on canola. Importantly however, complete chemical field failures are unlikely given the low level of resistance exerted by the overexpression of the CYP6CY3 gene (de Little et al. 2017b).

A sensitivity shift was also identified to sulfoximines in a small number of GPA populations collected from Western Australia (WA) around the Esperance region. Four population had significantly higher tolerance to sulfoxaflor, based on LC50, compared to other populations and the susceptible control (Figure 2). The resistance factor was 7, 8, 10, 23 for Cascade1, Cascade2, Munglinup1, and Munglinup2, respectively. These represent resistance to dosage below the field rate.

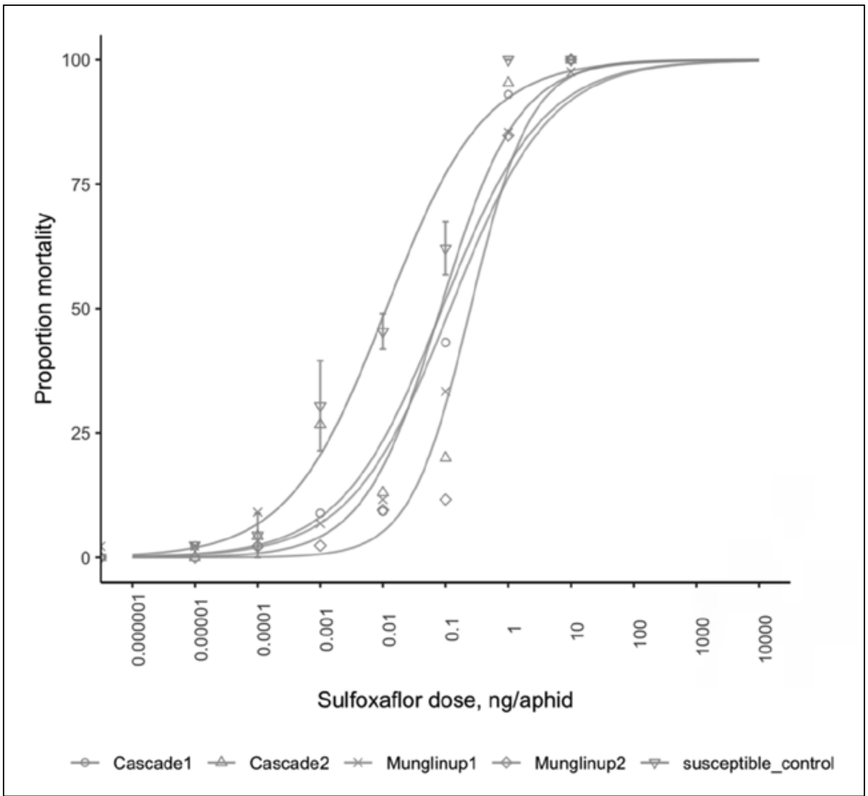

Figure 2. Dose response of sulfoxaflor for four GPA populations and the susceptible control.

Table 1. Sulfoxaflor resistance ratio (RR) over time for four GPA populations collected from the Esperance region in 2018.

	INITIAL RESISTANCE RATIO (RR)	3-4 MONTHS LATER RR	9-11 MONTHS LATER RR
Cascade1	7	7	7
Cascade2	8	4	5
Munglinup1	10	6	6
Munglinup2	23	6	0

Within nine to eleven months of the original phenotypic assay, Munglinup2 showed a significant decrease in sulfoxaflor tolerance, while Cascade1, Cascade2 and Munglinup1 remained at the same sensitivity level as before (Table 1). Recently, Wang et al. (2018) selected a strain of *M. persicae* for resistance to sulfoxaflor in the laboratory, which showed 199-fold resistance after 45 generations compared with the starting population. The mechanism responsible for this laboratory-selected resistance has not yet been elucidated. Interestingly, Wang et al. (2018) found a significant decrease in aphid survival rate, longevity, fecundity and duration of production compared with the susceptible strain, suggesting strong fitness penalties. Perhaps this, at least partly, explains the results observed for Munglinup2.

None of the known mechanisms of resistance to other modes of action explained the sulfoxaflor sensitivity shift observed. Overseas, the mutation R81T, present in the loop D region of the β-1 subunit of the nicotine acetylcholine receptor gene, is present in European GPA populations and results in sulfoxaflor resistance (resistance ratio of approximately 70). This mutation was screened in the above population and was not observed. The changes in resistance ratios observed in our study potentially points to a metabolic mechanism yet to be identified.

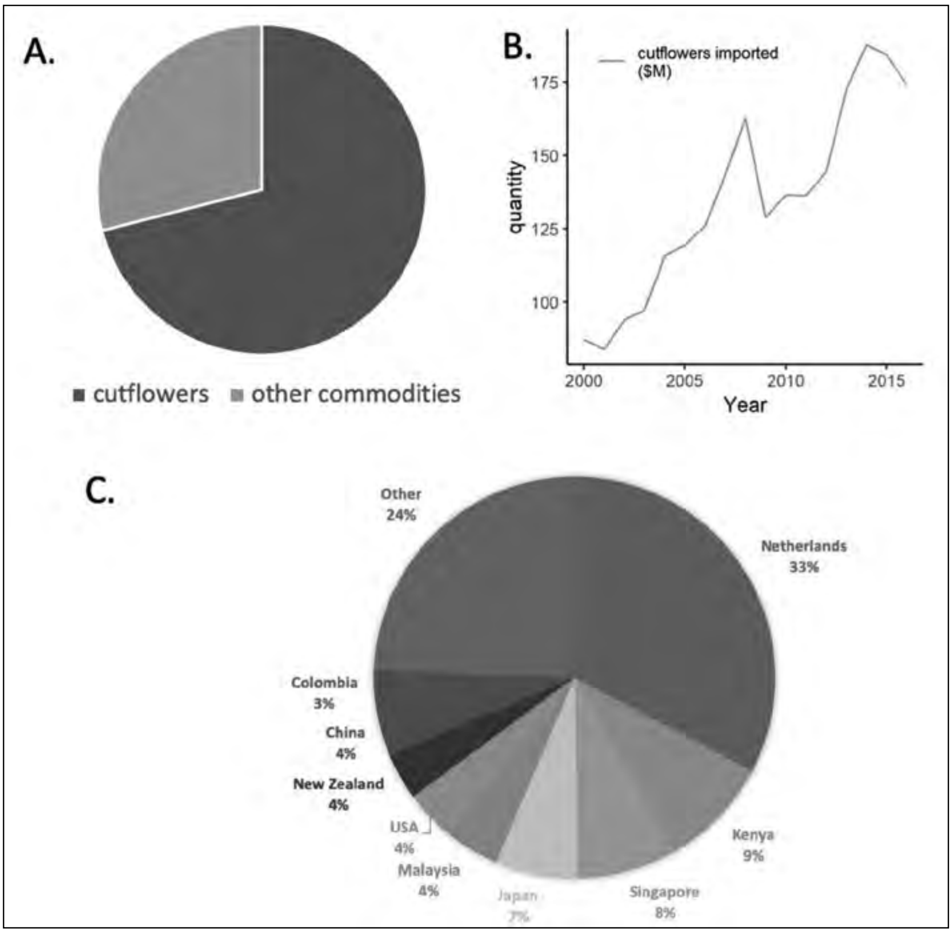

Figure 3. Biosecurity interception and risk from the overseas GPA R81T resistant genotype. A). GPA border interceptions in Australia from 2000-2017, B). Quantity of cut flowers imported into Australia from 2000-2016, C). Top 10 cut flower supplier countries into the Australian market.

Table 2. Total number of traps deployed per state, with the number of GPA carrying the R81T mutation (resistant) or not carrying the R81T mutation (susceptible).

STATE	NO GPA	GPA SUSCEPTIBLE	GPA RESISTANT	TOTAL TRAPS
NEW SOUTH WALES	18	21	0	39
QUEENSLAND	9	0	0	9
SOUTH AUSTRALIA	25	19	0	44
VICTORIA	54	29	0	83
WESTERN AUSTRALIA	12	112	0	124
TOTAL	118	181	0	299

Scientific literature was reviewed to determine the locations of GPA carrying resistance alleles at the target site R81T loci. DNA extraction techniques and modified, previously established diagnostic tests were used to examine GPA samples from Europe and China. The tests found GPA carrying the R81T mutation in many countries, and importantly, several Chinese provinces. Fifteen years of data were collated and analysed on GPA interceptions in Australia (port of entry, port of origin), along with trade volumes of host produce that could be carrying GPA (for example; cut flowers, leafy vegetables, etc.). Border interceptions of GPA in Australia are strongly associated with imported cut flowers (Figure 3A). Simultaneously, imports of cut flowers into Australia have doubled from 2000 to 2016 (Figure 3B). Of the top ten suppliers of imported cut flowers to Australia, China supplies 4% of imports and is known to possess GPA with the R81T mutation. However, given the high dispersal capacity of GPA and the spatial proximity of the Netherlands to France (known to possess GPA with the R81T mutation), there is also a high risk associated with cut flowers imported from the Netherlands. The Netherlands accounts for 33% of all Australian cutflower imports (Figure 3C).

The domestic risk of evolution of further neonicotinoid resistance, such as the R81T mutation, was modelled based on sales data of neonic products by regions (Cushen et al., submitted). The results showed that the grain growing areas of Tasmania, New South Wales (NSW) and WA showed increased risk of local evolution of R81T based on high purchase volume of neonicotinoid-based chemicals.

The R81T mutation was not found in any Australian GPA (Table 2). The consequences of R81T would be significant to the grains industry; rendering all neonicotinoids ineffective, as well as conferring cross-resistance to sulfoximines. Of the 299 yellow sticky traps that were processed across most of

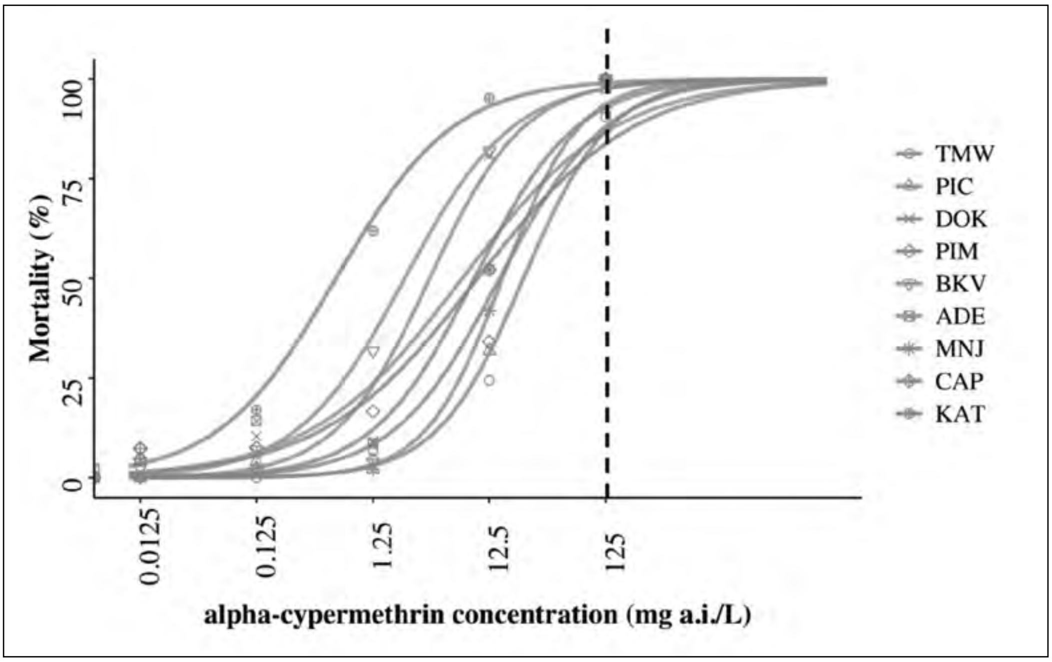

Figure 4. Dose response curves after exposure to alpha-cypermethrin for 48hrs for oat aphid populations collected from Tamworth (TMW), Picola (PIC), Dookie (DOK), Pimpinio (PIM), Back Valley (BKV), Adelaide (ADE), Manjimup (MNJ), Capel (CAP) and Katanning (KAT). Dotted line represents the field rate.

the Australian grain growing regions, GPA were detected on 181 or 60% of traps (Table 2). Most GPA detections occurred in southern Australia. Of the 181 GPA positive samples, all were negative for the R81T mutation, supporting the notion that Australia is presently free of this resistant biotype (Maino et al. in preparation).

Variations in oat aphid baseline sensitivity

For three of the chemical classes tested (organophosphates, carbamates and neonicotinoids), there were no differences in the nine oat aphid population responses. However, for pyrethroids, a widely used insecticide class in Australia, there are statistically significant differences between several aphid populations (Figure 4). After 48hrs, there was a significant difference in dose response curves between populations ($\chi^2 = 166.84$, df = 8, p = 0.002) for alpha-cypermethrin (Umina et al. in preparation). The *R. padi* population from KAT responded differently to aphids from TMW (p = 0.006), MNJ (p = 0.03) and PIC (p = 0.02). Aphids from these three populations were less sensitive to alpha-cypermethrin compared with KAT (Figure 4). The LC_{50} values across all nine populations ranged from 0.6 to 24.57mg a.i./L. The field rate of alpha-cypermethrin (125 mg a.i./L) controlled 98%, 93% and 90% of aphids from ADE, MNJ and TMW, respectively. For the remaining six populations, the field rate was adequate in supressing 100% of individuals after 48 hrs.

The previous insecticide baseline sensitivity on Australian oat aphid populations had not detected significant variation in response to pyrethroids (Clouston et al. 2016). These data highlight the impending pest management challenges growers could encounter and will be important for future monitoring of insecticide responses of *R. padi* in Australia.

Practical implications for oilseed and pulse crop aphid management

The research presented above leads to key implications in aphid management.

1. **Aphid species identification:** Each aphid species will show different levels of resistance (or sensitivity) to different insecticides; for example, GPA have widespread resistance to organophosphate, neonicotinoids, carbamates and pyrethroids, while oat aphid have lower sensitivity to pyrethroids. Therefore, the proper identification of aphid species in a paddock is crucial to determine the risk of resistance, and therefore, the selection of management strategies. This key step helps to optimise inputs (financial, labour, time) for efficient management.
2. **When dealing with GPA, always follow the GPA Insecticides Resistance Management Strategy (IRMS).** The research outcomes from this project have informed the update of the GPA IRMS available at the GRDC website www.grdc.com.au/GPAResistanceStrategy . This strategy outlines the regionally relevant management strategies for dealing with GPA .
3. **Rotating insecticides' modes of action.** This recommendation applies especially to GPA, which has been demonstrated to have a high propensity to evolve insecticide resistance to multiple chemical classes. To start with, an assessment of the efficacy of chemicals being used on GPA in a paddock should be performed, followed by the identification of insecticide classes that have not been used so frequently and therefore could be added in the chemical yearly plan. Currently, there are five modes of action registered against GPA in broadacre crops. Our research has shown that Australian GPA populations have decreased sensitivity to sulfoximines and low-level of neonicotinoid resistance. The resistance to organophosphates is very variable. This indicates that, if no previous resistance to these three classes has been observed locally, these three classes can remain in the chemical rotation. Research conducted by cesar as part of this project has shown high efficacy of new insecticide classes against GPA. These insecticides are currently undergoing registration process led by the appropriate chemical registrant.
4. **Consult if reduced insecticide efficacy on aphids is suspected.** Growers should report and consult their advisers if experiencing insecticide efficacy reduction or failure and/or are suspecting insecticide resistance. More targeted strategies can be deployed depending on the aphid species. The extension and research team at cesar publishes PestFacts South-East which informs the industry and growers about pest issues. For this purpose, **cesar** is keen to receive reports from the field regarding resistance issues. The team at cesar is always available to provide advice and conduct resistance testing if necessary.

5. **Control aphids in green bridge and sow into standing stubble (when possible).** Based on their lifecycle, GPA will remain in the surrounding area of a recently harvested paddock and this population will serve as a reservoir to infest newly sown crops. In the case of insecticide resistant GPA, it is key to eliminate them from the area. Sowing into standing stubble is a method that reduces the visual cues from migrating GPA and reduces infestation. Reducing the total numbers of aphids in a field allows for easier and faster management of the aphids and reduced statistical risk of resistance development.
6. **Monitor activity of aphid predators and parasitoids.** The multiple resistance observed and the high number of GPA populations with a resistant phenotype found in this project compromises chemical management options. There are several aphid predators and aphid parasitoids that can effectively control GPA, susceptible and resistant, in a chemical-free environment. These natural enemies will often move in when the GPA population numbers are higher, and therefore, there is a short lag between high GPA numbers and increased activity of natural enemies. Natural enemies can be identified using the GRDC back pocket guide (www.grdc.com.au/BPG-BeneficialInsects-SW). Additionally, insecticides that are less toxic to beneficial insects can be found in the GRDC Insecticide Resistance guide (https://grdc.com.au/insecticide-resistance-in-the-southern-region). Purchase of specific insect natural enemies can be made through a few companies and released into an area.

Conclusion

An increased number of GPA populations were observed, both in time and in geography, showing resistance to pyrethroids, organophosphates, carbamates and neonicotinoids. Multiple GPA populations from a specific region showed low-level resistance to sulfoxaflor. The newly reported cases of low-level resistance to neonicotinoids and sulfoxaflor were not associated with the domestic evolution or the incursion from the highly resistant genotype R81T. Both the risk of local evolution and biosecurity risk of incursion of the R81T genotype are estimated to be high, warranting continued surveillance. This study also reports a decreased sensitivity of oat aphid population to pyrethroids. Key recommendations regarding aphid management emerge from this research. Accordingly, the management strategy regarding insecticide resistant populations of GPA has been updated and published for growers and advisers to consult.

Aphid management, and the potential for aphid insecticide resistance management, should include proper aphid species identification, rotation of insecticides modes of action, consulting when observing reduced chemical efficacy and suspected resistance, year-long aphid control in the green bridge, and monitoring of aphid natural enemies.

Acknowledgements

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Useful resources

http://cesaraustralia.com/sustainable-agriculture/pestfacts-south-eastern/

www.grdc.com.au/GPAResistanceStrategy

https://grdc.com.au/CropAphidsBackPocketGuide

www.grdc.com.au/BPG-BeneficialInsects-SW

https://grdc.com.au/insecticide-resistance-in-the-southern-region

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Notes

Biology of nitrogen release from pulses

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GRDC project codes: CSP00186, CSA00050, DAQ00192

Keywords

- grain legumes, pulses, mineralisation, immobilisation, soil microorganisms, nitrogen.

Take home messages

- All grain legume (pulse) crop residues generally have higher concentrations of nitrogen (N) and lower C to nitrogen ratio than cereal crops.
- The rate and timing of availability of N from pulse stubble to the following crops is determined by stubble decomposition rate and N immobilisation (tie-up) by soil micro-organisms.
- N mineralisation/tie-up processes after pulse crops can differ significantly to that after cereal and canola in terms of the (i) timing of release of N from residues (for example; during summer versus early into the following crop), (ii) magnitude of N tie-up during the seedling phase and (iii) the availability of fertiliser N to the cereal crop after a pulse crop.
- In low fertility soils, the combination of N release from pulse crops and N from fertiliser sources is required to maximise productivity benefits in the following crops.

Background

During the last decade, the effect of increasing intensification of cropping systems on the ability of grain legumes as rotational crops to sustainably reduce N inputs and increase N use efficiency (NUE) in non-leguminous crops following legumes has not been fully explored. It is generally considered that soil mineral N after both pasture and grain (pulses) legumes is higher than after cereals or canola crops. However, the magnitude of this benefit is found to vary for different legumes, especially for grain legumes (pulses) where it is strongly dependent on location and season. For example, Peoples et al. (2017) observed that on average the soil mineral N from legume crops was 35kg N/ha but varied from 11kg N/ha to 89kg N/ha based on experiments in eastern and southern Australia.

Stubble retention can provide benefits through changes in soil physical, chemical and biological properties. Soil biota play a key role in several essential biological functions where carbon (C) inputs from plant roots and crop residues form the essential supply of C (energy source) and nutrients for biological activities. Changes in the short-term flux of labile soil organic matter (SOM) pools (for example; dissolved OM and particulate OM due to stubble retention and crop rotation also influence biological N cycling and N availability. The concentrations of soil mineral N observed at the beginning of a growing season represent the net effect of different biological processes such as (i) residue decomposition, SOM cycling and N mineralisation by microbes, (ii) N tie-up by microbes, (iii) losses through leaching and gaseous losses and (iv) N uptake by weeds that either favour or reduce the accumulation of plant-available soil mineral N.

Therefore, in most Australian agricultural soils C inputs through above- (stubble) and below-ground (roots) plant residues have a major influence on populations of biota and their activities.

Recent research has indicated that cereal stubble mainly acts as a source of C for microbial activity thereby influencing N availability and may not be considered as a significant source of N to the following crops (Gupta et al. 2017). Our understanding of the fate of organic inputs from grain legume residues in terms of their decomposition, release of nutrients and soil OM build-up is yet to be fully explored. This paper presents a brief summary of what is known about the biology of pulse crop residues and N release in a cropping system.

Crop residues as a source of C and nitrogen

Crop residues (stubble) are one of the major inputs of OM into the soil and are the primary sources of C (energy source) for soil microorganisms (biota) both in agricultural and natural systems, particularly in low OM Australian soils. Stubble generally contains approximately 42% of C (dry weight basis) and a large portion of it is biologically available (labile) in the short-term (less than three years). Retention of stubble after harvest would also contribute to the conservation of nutrients that have been taken up by the plant within the cropping system. All plant residues are basically composed of the same primary building blocks (cellulose, hemicellulose, protein, lignin and lipids) albeit in different proportions, leading to the formation of SOM. For example, amino acids represent a key pool of C and N in soil, and their availability to plants and microorganisms has been implicated as a major driver in regulating biological functions such as SOM cycling and N transformations. Although plants also provide key inputs of belowground C and nutrient inputs through root exudation and turnover, aboveground stubble inputs are considered a major contributor of OM into the soil. With a harvest index of 34±2%, grain legume crops (pulses) add aboveground residues ranging from 1.4t/ha to 10t/ha which provides 1t of C/ha to 3.9t of C/ha for use by soil biota (Table 1). The amount of C inputs from stubble for faba bean and lupin was generally higher (averaging 2.1-3.1 tonnes of C/ha) and lower for lentil and mung bean crops (averaging 0.96-1.13 tonnes of C/ha).

The amount of nutrients in pulse stubble at harvest depends upon crop type, soil fertility, nutrition received through fertilisers and nutrients removed in the grain. Average concentrations of N in the stubble from different pulses are given in Table 1. The N content of harvest-shoot residues for different pulses are generally higher (0.8-1.2%) than for either cereal (0.4±0.06) or canola (0.7±0.06%) stubble. Therefore, pulse residues generally have lower C:N ratios (43:1 to 65:1) compared to that for cereal and canola residues (Table 1). At maturity, leaf material from legumes (generally representing 8-10% of residues) has a greater concentration of total N, soluble organic C and N and lower C:N ratio than stems. Additionally, N concentrations are highest for brown manure (BM) residues with the lowest C:N ratios compared to the same crops where grain was harvested. Previous research has shown that in addition to the aboveground residues, belowground nodulated roots also contribute a significant amount of C and N, which varies depending upon legume type and location (People et al. 2017; McNeill 1998, GRDC project UWA196WR). For example, belowground N at peak biomass of pulses grown at Goomalling in Western Australia (WA), measured using ^{15}N labelling method, represented 40-50% of crop N for faba bean, lupin and chickpea crops. Overall, it was suggested that net inputs of legume N from the total crops at harvest ranged between 52-330kg N/ha for pulses (grain harvested) and 210-323kg N/ha for BM crops (Peoples et al. 2017).

Since the growth and N fixation by legumes vary depending on crop season and soil type, care should be taken in estimating the amount of N benefit from the crop residues in specific fields and regions.

Decomposition of pulse stubble:

Decomposition rates of legume residues is generally faster than that of cereal and canola residues (van Vliet et al. 2000). Results from a field experiment in South Australia (SA) indicated significant differences in mass loss of lupin (70%; decomposition rate k = 0.0045 % mass loss per day) and wheat (40%; decomposition rate k=0.0014 % mass loss per day), one year after harvest (Figure 1a & b). Similar findings were reported for lupin (20%) and wheat (15%) residue decomposition during summer months in WA (van Vliet et al. 2000). Differences in chemical composition in terms of soluble organic C and N; C:N ratio are considered the main contributors for the variation in decomposition rate, although other properties such as % cellulose, % lignin and polyphenol concentrations have also been shown to influence stubble decomposition. A general trend of reducing C:N ratio was seen in both the legume and wheat residues although C:N ratio of legume residues were always lower than that for wheat residues (Figure 1c).

In addition to residue quality, stubble decomposition and nutrient release patterns are influenced by climatic factors (especially moisture and temperature) and soil factors such as aeration, microbial biomass (MB) and nutrient status.

Table 1. Comparison of estimates of above ground potential C and N inputs derived from crop (shoot) dry matter and C and nitrogen residue N remaining after individual legume (pulse) species grown for grain or brown manure (BM).

Region	Legume crop	Shoot residues (t/ha)	Harvest Index	Carbon (%)	Nitrogen (%)[1]	C:N ratio	C inputs (tonnes C/ha)	N inputs (kg N / ha)
NSW/SA/Vic (Peoples et al. 2017)	Field pea (n=7)	3.70 (1.4-6.3)	0.34	47.5	0.78	61	1.76	29 (11-49)
	Chickpea (n=6)	3.20 (1.9-4.6)	0.30	47.5	0.86	55	1.52	27 (16-39)
	Lupin (n=6)	4.60 (1.9-6.4)	0.34	45.7	1.01	45	2.10	47 (19-65)
	Lentil/Vetch (n=2)	2.40 (2.3-2.5)	0.43	47.0	0.85	55	1.13	21 (20-21)
	Faba bean (n=5)	5.30 (2.2-9.2)	0.36	45.0	1.20	38	2.39	64 (26-110)
Northern farming systems (Bell L, CSIRO; unpublished)	Field pea (n=5)	4.69 (1.6-10.1)	0.37	45.0	0.85	56	2.11	40 (14-86)
	Chickpea (n=8)	3.60 (1.2-6.5)	0.37	47.5	0.86	55	1.71	31 (10-55)
	Faba bean (n=4)	6.87 (4.7-9.2)	0.39	45.0	1.05	43	3.09	72 (49-96)
	Mung bean (n=4)	2.18 (1.4-2.4)	0.20	44.0	0.80	55	0.96	17 (11-19)
NSW/SA/Vic (Peoples et al. 2017)	Vetch BM[3] (n=2)	5.25 (5.1-5.4)		45.0	2.72	17	2.36	165 (139-147)
	Field pea BM (n=2)	8.00 (6.3-9.8)		47.5	2.30	21	3.80	223 (145-225)
	Lupin BM (n=1)	8.40		45.7	2.28	20	3.84	207
	Wheat[2]	1.00	0.35	45.0	0.42	107	0.45	4.2
	Canola[2]	1.00	0.18-0.30	45.0	0.70	64	0.45	7.0

Notes: 1Percentage N values for legume stubble for the Northern Farming system experiments are estimated from published data;2Percentage N and harvest index values for wheat and canola are estimated from published data; 3No grain was harvested for BM crops, terminated with herbicide in mid-spring before grain maturity. Numbers in parenthesis represent range of values reported in the literature.

Soil moisture influences microbial activity and N cycling processes near residues by directly affecting the microbial populations and their composition under water stress, and directly affecting the transport of dissolved organics and mineralised materials from residues. Indirectly, soil moisture influences soil aeration status. It has been reported that optimum moisture level of N mineralisation ranges between 45% to 60% water filled pore (WFP) space and at greater than 60% WFP denitrification can dominate due to sharp transition to O_2-limiting conditions. The maximum decomposition rate of crop residues is generally reported to occur between 30 °C to 35°C and minimum temperature for decomposition activity is approximately 5°C. Therefore, decomposition of crop residues and N mineralisation under Australian conditions is generally higher during summer (provided soil moisture is optimum) and lower during the winter season.

Interactions with microorganisms and management effects:

Crop residue decomposition is mainly driven by soil microorganisms, although through direct and indirect interactions a complete food-web of soil organisms is involved. As soil microorganisms depend on residues for energy and cellular growth, stubble decomposition also affects soil microbial composition and activity. Soil fauna facilitate the decomposition of residues by acting as biocatalysers enhancing directly and indirectly the function of microorganisms through fragmentation and incorporation of stubble into soil, particularly in no-till systems.

Microorganisms responsible for stubble decomposition are diverse and their composition varies with residue quality, soil type and management. The level of MB is mostly higher with legume residues compared to that on wheat residues, especially during the early periods of decomposition (van Vliet et al. 2000). Significant differences in the composition of microbes were observed colonising legume stubble compared to wheat and canola residues (Figure 2). For example, colonisation by proteobacteria (fast growing microbes) was greater on legume residues (lower C:N ratio) compared to that on wheat residues (higher C:N ratio). The nutrient contents of pulse stubble are positively correlated with microbial activity and physiological diversity thereby influencing decomposition rate. Residue management in terms of incorporation technique, amount and time of incorporation can affect the composition and populations of microorganisms, thereby influencing decomposition rates. Incorporation of stubble and cutting it into small pieces increases the contact between stubble and soil microorganisms and the availability of soluble organic C and N. This modifies which type of microbes proliferate, and consequently the rate of decomposition and N release. Reduced tillage generally promotes greater proportion of fungi compared to incorporated stubble which promotes bacterial domination, with consequences to timing of N release.

Nitrogen release - mineralisation and immobilisation:

The release of N from crop residues and its availability to subsequent crops is a product of the rate of decomposition, mineralisation and immobilisation (microbial tie-up) processes. The conversion of organic N in the residues into inorganic N (nitrate N) available for plant uptake involves multiple biological processes mediated by different microbial functional groups. Some of these processes include residue decomposition (degradation of polyphenols and cellulose), proteolysis (conversion of proteins into amino acids) and nitrification (conversion of ammonium into nitrate). The abundance of different functional groups of N cycling microbes was found to be greater near legume residues and in soils following legume crops (Phillips et al. 2015; Gupta 2016). The net release of N from pulse residues with narrower C:N ratios is greater and quicker compared to that from cereal crop stubble. Also, net N mineralisation is greater from BM crops compared to grain harvested pulses (Peoples et al. 2017). However, the

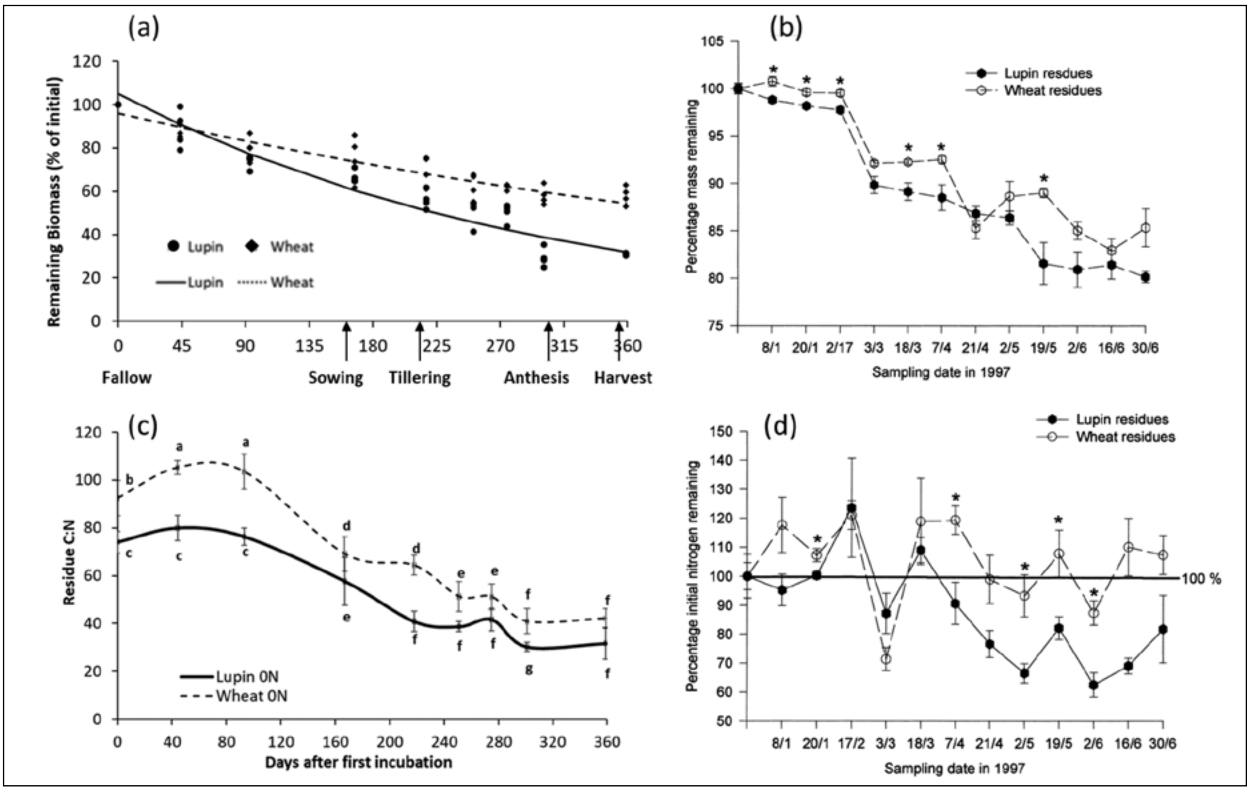

Figure 1. The decomposition of lupin and wheat residues presented as biomass remaining as % of initial stubble residues in (a) field experiments at Karoonda, SA (Source: Muschietti-Piana, P, unpublished) and (b) field experiments at East Beverley, WA (Source: van Vliet et al. 2000) in litter bag experiments. (c) Residue C:N ratio in the Karoonda experiment and (d) changes in % N in the lupin and wheat residues during the six months of field incubation experiment at East Beverley, WA.

magnitude varies depending upon stubble load and agronomic factors such as tillage including the time of removal and type of stubble. For example, for BM crops the timing of crop termination during the growing season and its treatment would affect the decomposition, mineralisation and release of N into soil mineral N pool.

Soil microbial biomass; the mass of living components of soil OM, is both a source and sink of biologically mediated nutrients. The amount of MB associated with residues (both legumes and cereal stubble) and especially in soil after legume crops is generally higher resulting in greater immobilisation of N (Figure 3). Immobilisation of N by MB during the early phases of decomposition has been observed with both legumes and cereal residues resulting in lower soil mineral N levels. Legume residues with lower C:N ratio immobilise to a lesser extent hence release N faster compared to that with cereal residues (Figure 1d). Fungi can translocate residue-derived C into the underlying soil while simultaneously translocating soil and fertiliser derived inorganic N up into the litter layer (Figure 1d). This stubble induced immobilisation could initially lower fertiliser N recovery efficiency by crops (Figure 2b), however N tied-up in MB is released with microbial turnover and due to faunal grazing of microbes, hence becomes available for crop uptake later in the season. Therefore, potential early N supply to crops could be improved by combining legume and fertiliser N, particularly in lower fertility soils (Muschietti-Piana et al. 2019).

Overall, the net release of N from legume residues is faster than that from cereal residues. This contributes to the general observation of higher mineral N in the soil profile at the end of the fallow period after legumes compared with cereal crops (Gupta 2016; Peoples et al. 2017). But due to the involvement of a multitude of factors related to residue, soil and the environment, the net release of N from crop residues, including pulses, could result in no observable increase in soil mineral N levels following summer months. For example, results from several Northern farming systems

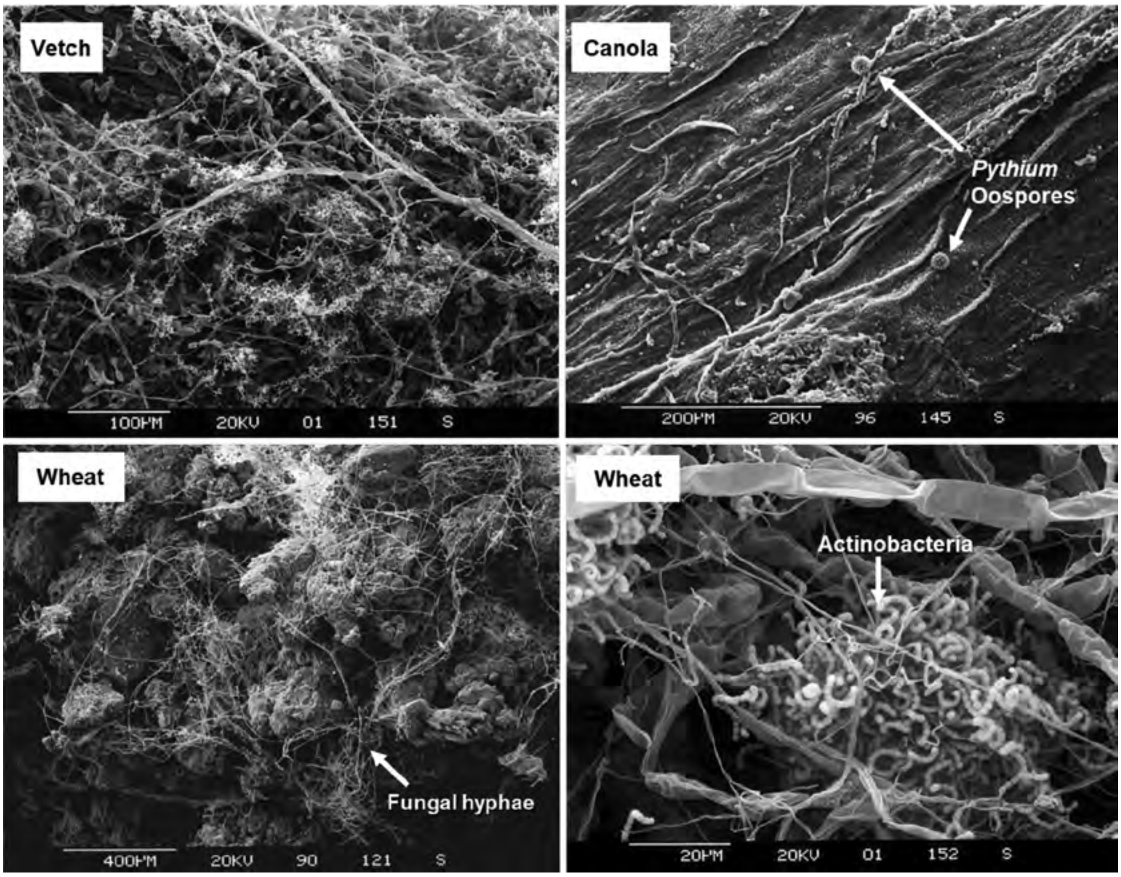

Figure 2. Photos of crop residues taken using a scanning electron microscope (SEM) showing the various types of microorganisms colonising stubble from vetch, canola and wheat crops. Extensive colonisation of nitrogen rich vetch residues by bacteria and fungi. Fungi and actinobacteria were the dominant microflora colonising wheat residues whereas fungal growth on canola residues was less and limited to specific fungi such as Pythium species.

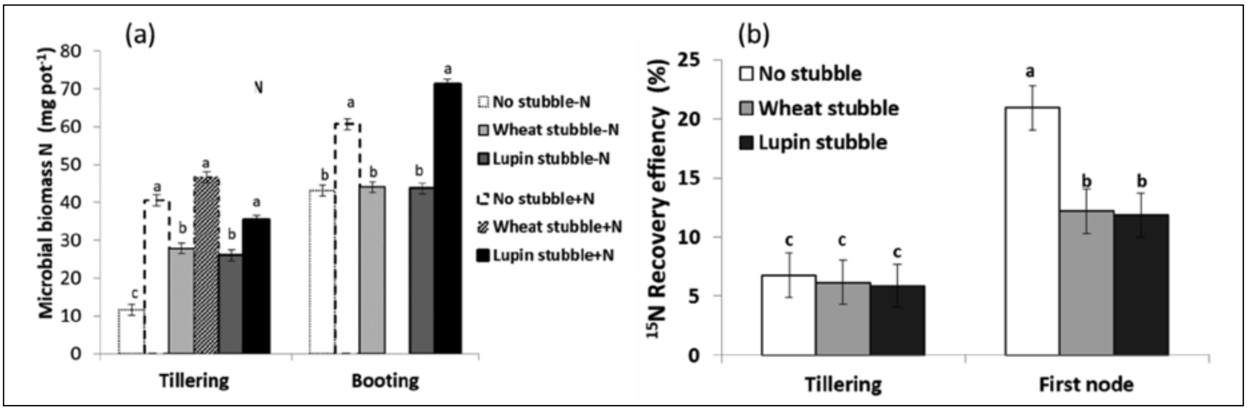

Figure 3. Effect of lupin and wheat stubble and N fertiliser application on (a) microbial biomass N in the surface 10cm soil at different growth stages. Within tillering, different letters indicate significant differences for the interaction between the 'stubble treatment' and 'fertiliser N' (DGC test, $p<0.05$). At booting, different letters indicate significant differences between treatment (DGC test, $p<0.05$). (b) 15N fertiliser recovery efficiency by wheat; different letters indicate significant differences for the interaction between 'stubble treatment' and 'growth stage' (DGC test, $p<0.05$).

experiments during the 2015 to 2018 seasons indicated, no increase in soil profile mineral N levels following fallow after chickpea crops compared to that after wheat, in seven out of the 15 experiments (Bell L, GRDC project CSA00050). A wide range of pre-sowing soil mineral N values; 10-90 (35±20kg N) have been reported (Gupta 2016; Peoples et al. 2017). Nitrogen released from legume crop residues during summer months, when there is no plant uptake is less prone to leaching. Overall, apparent recovery of 30±10% of legume residue N by the following wheat crops was observed over 20 legume treatments in dryland experiments conducted in eastern Australia (Peoples et al. 2017). Whereas, cereal stubble is not a major source of N for following cereal crops and should be seen as a source of C for microbial activity. In no-till systems, only 1-6% of the N requirement of cereal crops is derived from the previous year's wheat stubble (Gupta et al. 2017).

Although N concentration and C:N ratio of plant material is suggested as the most robust indices of residue quality, plant materials containing high concentration of recalcitrant C or lignin and polyphenols could also limit N mineralisation. The lateral roots and shoots of all legumes are expected to mineralise most rapidly given the low C:N ratios and less recalcitrant fractions, whereas wheat and canola shoots and wheat and lupin main roots might be expected to mineralise slower. Lignin to N and soluble polyphenols and polyphenol to N, polyphenol plus lignin to N ratios have also been suggested as indices of residue N release. Thus, no single index could characterise the quality of plant residues for their effect on all soil biological processes and N release.

Currently, there is very little information for decomposition rate and consequent N release rates (for example; temporal changes in mineralisation versus immobilisation) and the role of changes to soil microbiology for pulse residues in the different Australian grain growing regions, in particular under the intensive cropping and conservation agriculture systems currently practised.

Conclusion

Factors affecting N release after pulse crops include (i) amount of shoot residue biomass at the end of the growing season, (ii) N content and quality (e.g. C:N ratio) of the legume residues, (iii) environmental conditions; mainly rainfall over the fallow period before the next crop and (iv) soil microbial composition following the legume crop. The amount of aboveground plant biomass from different pulses not only limits the amount of C inputs for microbial activity but also limits potential N inputs from legume plant biomass. As the quality and N content of pulse crop residues defines the amount of N added to the system it consequently influences the N mineralisation and tie-up (immobilisation) processes. The rate and timing of the availability of N from pulse stubble to the following crop is determined by the rate of decomposition and immobilisation (tie-up) by the soil micro-organisms. However, the significance of these effects varies depending upon stubble load, time and type of burning and other agronomic factors.

Acknowledgements

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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.

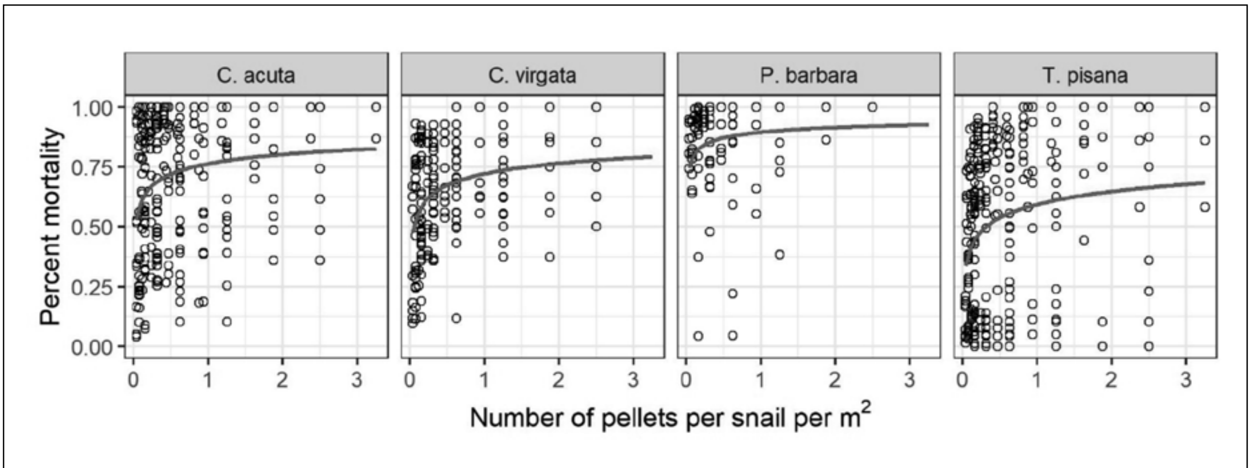

Figure 1. Mortality response versus density of pellets per snail per m^2 for four snail species (*Cochlicella acuta, Cernuella virgata, Prietocella barbara* and *Theba pisana*). Plots show pooled data for nine field cage trials with three different bait products. Circles represent mean mortality per 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.

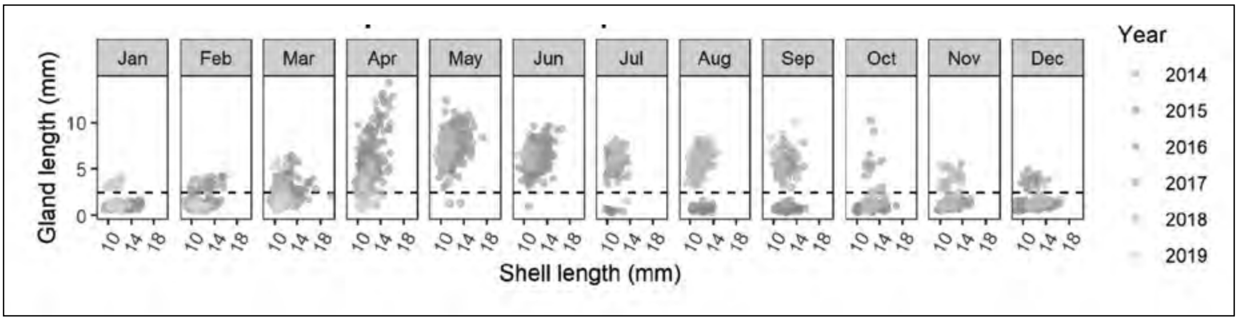

Figure 2. The seasonal reproductive cycle of common white snails at Palmer SA, shown by changes in the size of albumen glands over time. Each point represents one snail.

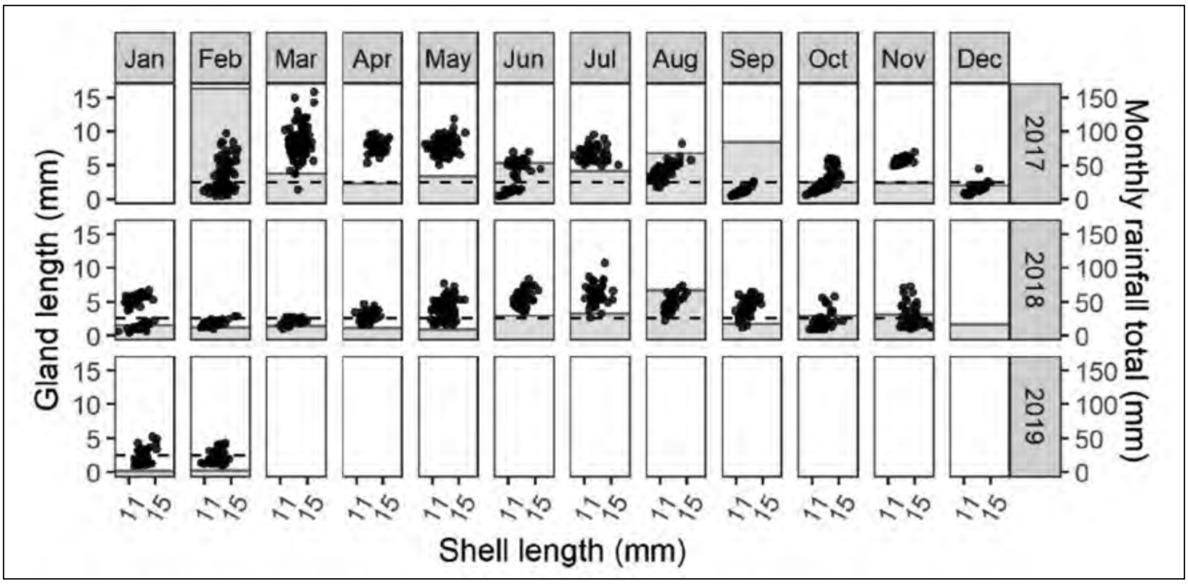

Figure 3. The seasonal reproductive cycle of common white snails at Gairdner WA together with total monthly rainfall (shading). Note that gland enlargement commenced in February of 2017 coinciding with high summer rainfall, compared to May of 2018 coinciding with a dry start.

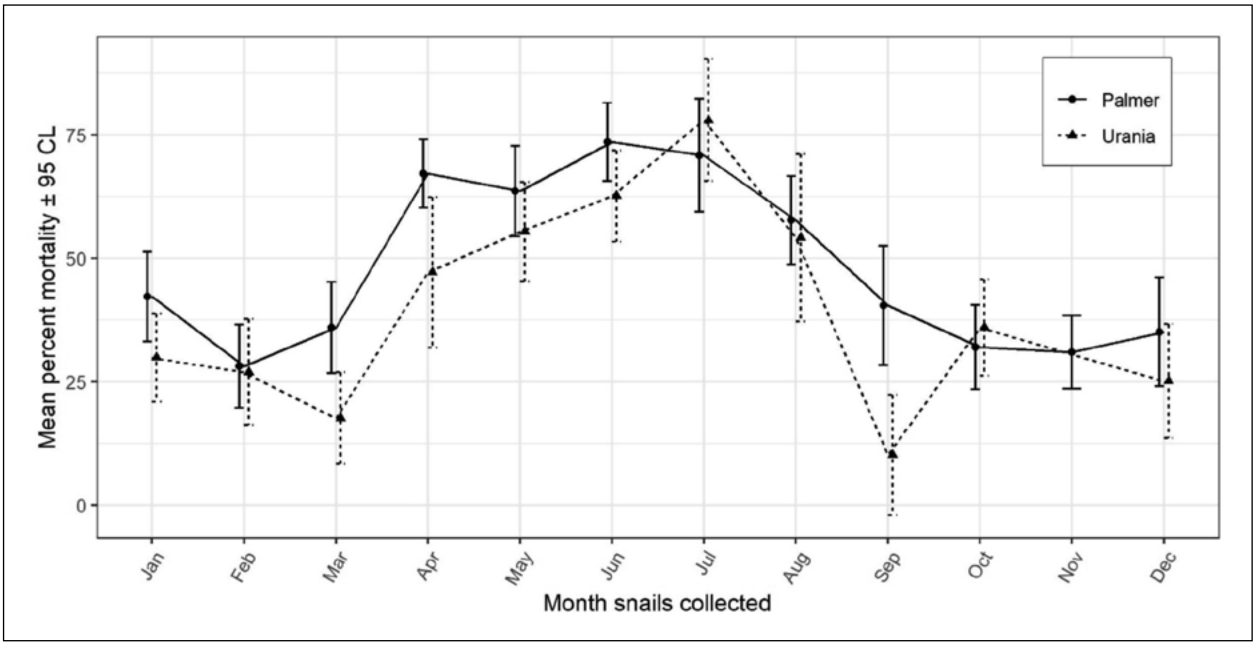

Figure 4. Mortality of common white snails exposed to Metarex baits in laboratory trials, for snails collected in each month of the year. Results from samples taken at Palmer include combined data for 2016-2019; Urania includes combined data for 2018-2019.

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.

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

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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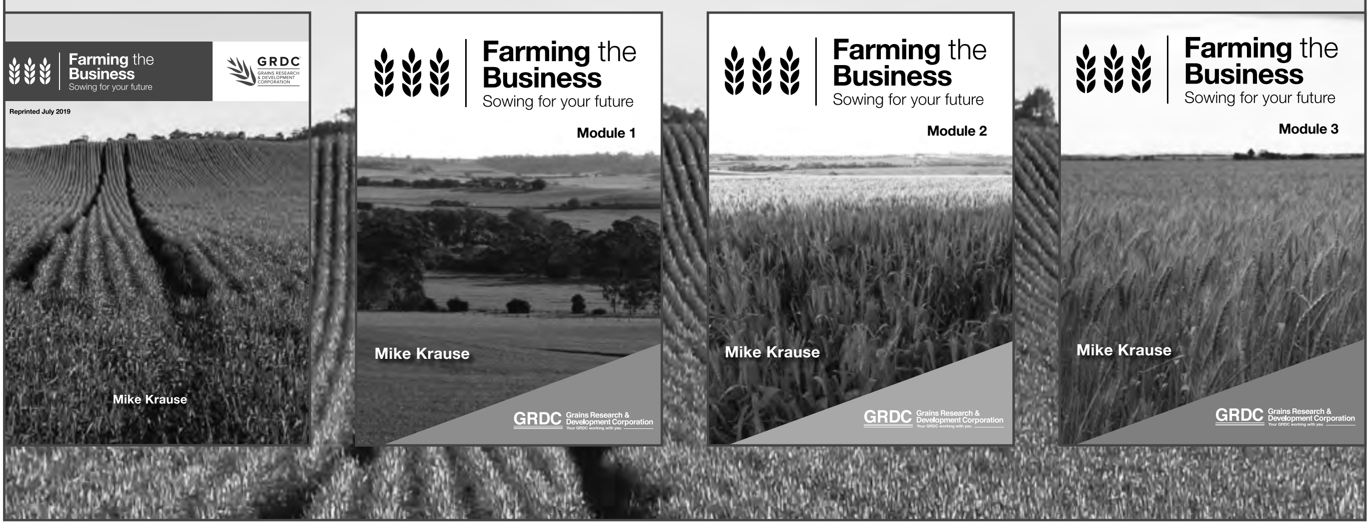

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Developing a nationally validated model to predict flowering time of wheat and barley

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GRDC project code: 9175445

Keywords

- time of sowing (TOS), optimal flowering period, crop modelling.

Take home messages

- The GRDC national phenology initiative has been established to better predict flowering time of wheat and barley across the major cropping regions of Australia.
- A total of 64 wheat and 32 barley genotypes, selected for their diverse phenology, are being genotyped and phenotyped under different controlled conditions to parameterise the model. The same genotypes are also being grown and phenotyped at five field sites (two × WA, SA, NSW, VIC) across eight times of sowing to validate the model.
- The initiative will deliver a web-based tool through the National Variety Trials (NVT) website where growers and advisors can plan cultivar × time of sowing decisions for their specific environments. This will become available in 2022, with new cultivars being added as they are released.

Background

Wheat and barley must flower during an optimal period to maximise yield. The optimal flowering period (OFP) for a given environment can be defined as the period when risks of frost and insufficient biomass accumulation (from early flowering), and heat and drought (from late flowering), are minimised (Flohr et al 2017; Hunt et al 2019). Limiting these abiotic stresses during the reproductive phase leads to increased fertility and grain number on spikes, a longer grain-filling period and hence increased yield. The length and duration of the OFP is dependent on the environment. Hot low rainfall environments generally have an earlier and shorter OFP (late August to mid-September across <1-2 weeks). More temperate high rainfall environments will have a later and longer OFP (mid-September to late October, 2-3 weeks) (Flohr et al 2017; Liu et al 2020).

Interactions between the genotype (cultivar) sown, the environment it is being grown in and management practices — specifically time of sowing (TOS) — determine when flowering will occur in the field.

Cultivars develop at different rates in the field depending primarily on the alleles they carry. Occurring at five major development gene loci in wheat (*Ppd-B1, Ppd-D1, Vrn-A1, Vrn-B1* and *Vrn-D1*), and four in barley (*Ppd-H1, Ppd-H2, Vrn-H1* and *Vrn-H2*). These major genes determine a cultivar's response to two environmental factors, temperature and photoperiod (day length). Temperature is the main environmental factor and daily mean temperatures between approximately 0°C and 35°C are conducive to progressing development (Porter and Gawith 1999). Cultivars carrying sensitive alleles at some, or all, of the VRN gene loci, will develop faster following an extended period of cool temperatures (i.e. winter, termed vernalisation; Trevaskis et al 2003). Cultivars with sensitive alleles at all *VRN* gene loci must experience vernalisation to progress from the vegetative to reproductive phase and are termed 'winter habit type'. Conversely, cultivars that progress from the vegetative to reproductive phase regardless of whether they experience vernalising conditions or not are termed 'spring habit type'. Most wheat varieties grown in Australia are spring types with moderate to no vernalisation response. It is also widely accepted that the spring type barley cultivars available to Australian growers have little to no response to vernalisation. In addition to habit type, cultivars vary in development rate due to response to photoperiod. Cultivars with sensitive alleles at the *PPD* gene loci will increase development rate as the days get longer, whereas photoperiod-insensitive cultivars will develop at a similar rate regardless of day length (Scarth and Law 1984). Variation in phenology of spring habit cultivars is largely dependent on this, and cultivars that are sensitive to photoperiod will accelerate development rate as the days start to get longer in early spring.

Traditionally spring habit cultivars are sown in southern Australia following the autumn break around late April to early May. These accumulate biomass over winter, flower between late August and mid-October (depending on location) and are harvested in early summer. However, the timing of the autumn break has become more variable and in-season rainfall has declined and become more variable since 1997 (Cai et al 2012), meaning that the traditional sowing window is no longer always suitable. According to records in the Yield Prophet® database, 78% of the 4149 paddocks across Australia between 2008-2015 showed cultivars sown outside of their optimal sowing windows, reducing national wheat and barley yield by an estimated 12% per annum (Flohr et al 2018). Growers therefore require a greater suite of cultivars with a broad range of phenological diversity that can be sown when there are opportunities anywhere from early March to mid-July. These opportunities could involve sowing slow developing winter wheat cultivars early, when stored soil moisture from fallow or early autumn rainfall events allow (Hunt et al 2019), through to sowing fast, vigorous spring types when the rainfall break is late (early to mid-winter). The benefit of early sown winter wheat is the stable flowering time from a wide range of times of sowing (Flohr et al 2018). Breeding explicitly for varying combinations of alleles of the major development genes that govern responses to temperature and day length, into a diverse range of parent material, could also lead to diversity in cultivars to be grown in different environments from a broad range of sowing times, while still ensuring crops flower during the OFP.

There is currently no accurate way to predict flowering time from a wide range of sowing times across the diverse environments of the Australian grain belt, especially at point of release of new cultivars. This is because breeding companies lack the resources or agronomic expertise to conduct experiments across many environments and sowing dates, to define accurate sowing windows for new cultivars. Instead, growers must rely on their own trial and error and agronomist's advice, which can take multiple seasons to get right.

Recent advances have been made in crop modelling (Brown et al 2013; Zheng et al 2013) and genomics (Wang et al 2014), and molecular markers have been developed to identify alleles of major development genes (Eagles et al 2009). This has created an opportunity to synergise agronomy, genetics and genomics and crop modelling. This project combines these disciplines and aims to improve accuracy in predicting development for current and newly released wheat and barley cultivars across the Australian grain belt from a broad range of sowing times. It will do this by improving and developing parameters of the wheat and barley models in the Agricultural Production Systems sIMulator: Next Generation (APSIM Next Gen; Holzworth et al 2014), which will be informed through phenotypic data from controlled environment experiments, molecular marker information and/or genomic information. Phenology of cultivars will be recorded across eight TOS in Western Australia (WA), South Australia (SA), New South Wales (NSW) and Victoria (VIC)—capturing the full range of early to late times of sowing and diverse environments of the major production areas—and data will be used to validate the model. A preliminary validation of the wheat model is also being conducted on 14 genotypes using field experiment data from previous GRDC investments.

By 2022 a web-based platform will be deployed through the NVT website (https://www.nvtonline.com.au/), running patched point climate datasets from nearby weather stations and the APSIM Next Gen wheat and barley models. This tool will allow growers and advisors to better inform decisions when selecting cultivars and TOS, with the flowering periods being estimated for a range of scenarios (below average, average and above average growing temperatures, etc.). Newly released cultivars will be added as they become available.

Table 1. Wheat cultivars selected to the Australian Phenology Panel, their habit, qualitative development speed and, where available, CSIRO Sunstate near-isogenic lines (NILs) with matched alleles at the *PPD1* and *VRN1* gene loci.

Cultivar	Habit	Qualitative development speed	Matched NIL pair
Youngᶲ	Spring	Very fast	CSIROW077
Axeᶲ	Spring	Very fast	CSIROW105
Emu Rockᶲ	Spring	Very fast	
H45ᶲ	Spring	Very fast	
LRPB Gauntletᶲ	Spring	Fast	CSIROW029
LRPB Spitfireᶲ	Spring	Fast	Sunstate
Macev	Spring	Fast	CSIROW005
LRPB Catalinaᶲ	Spring	Fast	CSIROW011
EGA Hume	Spring	Fast	CSIROW027
LRPB Scoutᶲ	Spring	Fast	Sunbee
Wyalkatchemᶲ	Spring	Fast	
Janz	Spring	Fast	
Peakeᶲ	Spring	Fast	
LRPB Crusaderᶲ	Spring	Fast	
Suntopᶲ	Spring	Fast	
Ellisonᶲ	Spring	Mid-fast	CSIROW018
LRPB Trojanᶲ	Spring	Mid-fast	CSIROW002
Grenade CL Plusᶲ	Spring	Mid-fast	
AGT Scytheᶲ	Spring	Mid-fast	CSIROW023
Merindaᶲ	Spring	Mid-fast	
Scepterᶲ	Spring	Mid-fast	CSIROW005
Ouyen	Spring	Mid-fast	
Derrimutᶲ	Spring	Mid-fast	
EGA Wills	Spring	Mid	
Magentaᶲ	Spring	Mid	
EGA Gregoryᶲ	Spring	Mid	CSIROW003
Cutlassᶲ	Spring	Mid	
Yitpiᶲ	Spring	Mid	
Calingiri	Spring	Mid	
Mitchᶲ	Spring	Mid	CSIROW102
LRPB Lancerᶲ	Spring	Slow	CSIROW029
Braewood	Spring	Slow	
Bolacᶲ	Spring	Slow	
Strzeleckiᶲ	Spring	Slow	CSIROW003
Beaufortᶲ	Spring	Slow	
Forrestᶲ	Spring	Very slow	
Sunbri	Spring	Very slow	CSIROW087
EGA Eaglehawk	Spring	Very slow	
Kellalac	Spring	Very slow	
Sunlambᶲ	Spring	Very slow	
Longswordᶲ	Winter	Fast	CSIROW007*
Whistler	Winter	Fast	
LRPB Kittyhawkᶲ	Winter	Mid	CSIROW021
Rosella	Winter	Mid	CSIROW021
EGA Wedgetailᶲ	Winter	Mid	CSIROW073
Manningᶲ	Winter	Slow	

**no longer a pair based on most recent genotyping.*

Method

Genotype selection

The Australian Phenology Panel (from herein termed 'the panel') of 64 wheat (Table 1) and 32 barley (Table 3) genotypes were selected for controlled environment phenotyping and field validation. Of the wheat genotypes, 47 are elite commercial cultivars chosen for their popularity among growers and diversity in phenology expressed in the field. The diversity of phenology is linked largely to the variation in alleles of the major *PPD* and *VRN* development genes. As such, each cultivar carries a unique allele combination across the five major genes except for a few cultivars with matching combinations where phenology in the field is different. The other 17 are experimental near-isogenic lines (NILs) bred from a Sunstate background (GRDC project CSP00183) to vary in alleles at the five major gene loci (Steinfort et al 2017). The NILs were selected to match allele combinations with the commercial cultivars where available. An additional four commercial cultivars and a breeding line (Table 2) were included for controlled environment phenotyping, to conduct an initial validation of the wheat model with field data from other current and past GRDC investments.

Of the 32 barley genotypes (Table 3), 30 are commercial cultivars selected for their diversity in phenology within the Australian germplasm. Two are NILs in a low earliness *per se* (EPS) background with winter and spring habit. Three additional cultivars have been included for controlled environment phenotyping (Table 4).

Table 2. Additional wheat genotypes selected for initial model validation, their habit and qualitative development speed.

Cultivar	Habit	Qualitative development speed
Condoⓓ	Spring	Fast
LRPB Nighthawkⓓ	Spring	Very slow
Illaboⓓ	Winter	Mid-fast
ADV08.0008	Winter	Mid
DS Bennettⓓ	Winter	Mid-slow

Table 3. Barley cultivars selected to the Australian Phenology Panel, their habit and qualitative development speed.

Cultivar	Habit	Qualitative development speed
Biereⓓ	Spring	Very fast
CSIROB3	Spring	Very fast
Compassⓓ	Spring	Fast
Groutⓓ	Spring	Fast
Keel	Spring	Fast
Rosalindⓓ	Spring	Fast
Spartacus CLⓓ	Spring	Fast
Stirling	Spring	Fast
Fathomⓓ	Spring	Mid-fast
Alestarⓓ	Spring	Mid
Bassⓓ	Spring	Mid
Baudinⓓ	Spring	Mid
Dash	Spring	Mid
Fleetⓓ	Spring	Mid
Flindersⓓ	Spring	Mid
Grangerⓓ	Spring	Mid
RGT Planetⓓ	Spring	Mid
Schooner	Spring	Mid
Scopeⓓ	Spring	Mid
Shepherdⓓ	Spring	Mid
Banks	Spring	Mid-slow
Commanderⓓ	Spring	Mid-slow
Lockyerⓓ	Spring	Mid-slow
Capstan	Spring	Slow
Franklin	Spring	Slow
Gairdner	Spring	Slow
Navigatorⓓ	Spring	Slow
Oxford	Spring	Slow
Westminsterⓓ	Spring	Slow
CSIROB1	Winter	Very fast
Urambieⓓ	Winter	Fast
Cassiopee	Winter	Slow

Table 4. . Additional barley cultivars, their habit and qualitative development speed.

Cultivar	Habit	Qualitative development speed
Mundah	Spring	Fast
Unicorn	Spring	Very fast
Yagan	Spring	Fast

Controlled environment phenotyping

Two experiments (one wheat, one barley) were designed to phenotype the 69 wheat and 35 barley genotypes. They were grown in eight (four for wheat, four for barley) controlled environment treatments at La Trobe University, Bundoora, VIC. The four controlled environments (as decribed in Bloomfield et al 2018) were selected to completely deprive and/or saturate critical photoperiod and vernalising conditions, as follows;

- short days, not vernalised (SN)
- short days, vernalised (SV)
- long days, not vernalised (LN)
- long days, vernalised (LV).

Each environment was a randomised complete block design with three replicates, randomised in R (R Core Team 2018). Short day photoperiods were eight hours and long days were 17 hours. Artificial lights (a combination of florescent tubes and incandescent bulbs) were used in each controlled environment and produced approximately 300µmol/m^2/s at pot height. Seeds of each genotype were pregerminated in petri dishes for 48 hours to break potential dormancy. In non-vernalised treatments, two seeds of each genotype were sown per 90mm olive pot and grown at a constant temperature of 22°C. After one week, they were thinned to one plant per pot. Plants in vernalised treatments were sown in seedling trays and grown in a Thermoline TRHL Series (Thermoline, Wetherill Park, Australia) temperature and humidity-controlled cabinet for eight weeks at 5°C. Photoperiods in the cabinet were also 17 (LV) or eight (SV) hours with artificial light from 8 × 54W T5 lamps producing 160µmol/m^2/s. Seedlings of each genotype were then re-potted into 90mm olive pots and transferred to a controlled environment room set at 22°C with short (SV) or long (LV) photoperiods.

Phenotypic data were recorded from emergence to anthesis. Recorded on each plant were emergence date, progressive leaf number as Haun stage (main stem; Haun 1973), final leaf number (main stem), heading dates of wheat (main stem and 50% of culms), awn peep dates of barley (main stem and 50% of culms) and anthesis dates (main stem and 50% of culms). Leaf number was recorded twice per week and plants were monitored daily for final leaf number, heading (wheat), awn peep (barley) and anthesis.

Air and soil temperature were recorded at 30min intervals in each environment using Tinytag Plus 2 model data loggers (Gemini Data Loggers, Chichester, UK) with soil probes attached.

APSIM Next Gen parameters

The simulations are performed on APSIM Next Gen (Holzworth et al 2014) to predict flowering time for wheat and barley cultivars across the Australian grain belt. The model predicts development with the ‘phenology’ component of the Plant Modelling Framework (PMF) developed by Brown et al (2014). For wheat, the phenology component of the PMF advances through a series of phases from sowing though to ripening (see detailed description in Brown et al 2018), while this project focusses on phases from sowing to anthesis. Once a phase reaches a target (enough days above a minimum day length, accumulated vernal time, accumulated thermal time, or a combination of some or all) in one phase, the model will progress to the next. The lengths of phases vary between cultivars. Responses to extremes of photoperiod and vernalisation in the controlled environments determine the main parameters. For example, a winter type must accumulate vernal time (enough cold days over an extended period) to progress from the emergence (vegetative) phase into the stem elongation (reproductive) phase. A spring type with little to no vernalisation requirement will progress based mostly, or entirely, on accumulated thermal time. At present, the barley model uses the same critical temperature values as the wheat model because of their similar responses to thermal accumulation, however this is to be investigated further. The important traits to parameterise a cultivar are progressive, and final, leaf numbers in the four controlled environments.

Field validation

Design

Field experiments were conducted in 2019 and are being repeated in 2020. Five field sites were selected to assess variation in major grain producing environments of Australia. The sites are Wagga Wagga NSW (35.05°S, 147.35°E), Yan Yean VIC (37.54°S, 145.09°E), Callington SA (35.07°S, 139.05°E) and Merredin (31.49°S, 118.21°E) and Dale WA (32.21°S, 116.76°E). The panel was sown at eight times of sowing targeting 1 and 15 March, April, May and June. A partially replicated (p-rep) design (Cullis et al 2006) was used with the eight TOS blocked separately due to experimental constraints — meaning blocking structure is confounded with the TOS treatment. Partial replication was imposed on 90 genotypes (60 wheat and 30 barley), with the remaining six genotypes used as controls. The genotypes Spartacus CL$^{\phi}$ and RGT Planet$^{\phi}$ were the controls for barley, and the genotypes Scepter$^{\phi}$, LRPB Lancer$^{\phi}$, Manning$^{\phi}$ and Beaufort$^{\phi}$ were the controls for wheat. Genotypes were not blocked by crop type. Different sets comprising 25% of the cultivars were replicated in each TOS block in order to obtain better overall replication of the genotypes. In total, for the eight TOS blocks, 88% of the cultivars were replicated 10 times and 12% of the cultivars were replicated nine times. The controls were replicated 12 times.

While the replication proportions were consistent for all sites, the layouts differed. At locations Merredin, Callington and Yan Yean, each TOS block comprised 15 columns (ranges) × eight rows, with a complete trial layout of 15 columns × 64 rows. At locations Wagga Wagga and Dale, each TOS block comprised 12 columns (ranges) × 10 rows, with a complete trial layout of 12 columns × 80 rows. Plot size was three rows × approximately 2m with a target density of 50 seeds per linear meter of row. Different randomisations were used for each site and year combination. Row spacing was as per district practice at each site (25cm at Wagga Wagga, 22cm spacing at Merredin and Dale, 22.8cm at Callington and 20cm at Yan Yean). Plots were sown in a north-south direction with 100kg/ha MAP + Flutriafol. Pesticides and fertilizer were applied as needed throughout the season. Earlier times of sowing were irrigated with 25mm of water after sowing to establish the crop, and then kept topped up to Decile 3 of the lowest rainfall site (Merredin).

Experimental conduct

Seed was bulked up and treated with Fluxapyroxad (Systiva®, BASF) and Imidacloprid (Gaucho®, Bayer) by Kalyx (Kalyx, Young, NSW) at the GRDC NVT site near Young, NSW in 2018. Genotypes used in the field experiments in 2019 are as in Table 1 and 3, except that Grout$^{\phi}$ was replaced by RGT Accroc at Wagga Wagga and Callington in 2019.

Sites were monitored twice per week from the first TOS until heading/anthesis was complete in the last plot. Emergence, heading (wheat) and awn peep (barley) were observed on all plots, while leaf number as Haun stage, final leaf number and anthesis were measured on a subset of cultivars (wheat: Axe$^{\phi}$, Beaufort$^{\phi}$, Cutlass$^{\phi}$, EGA Gregory$^{\phi}$, LRPB Kittyhawk$^{\phi}$, LRPB Lancer$^{\phi}$, Mace$^{\phi}$, Manning$^{\phi}$, Scepter$^{\phi}$, LRPB Trojan$^{\phi}$, Suntop$^{\phi}$; barley: Commander$^{\phi}$, Compass$^{\phi}$, Fathom$^{\phi}$, RGT Planet$^{\phi}$, Spartacus CL$^{\phi}$, Urambie$^{\phi}$) in TOS one, four and eight. Emergence was recorded on 1m of the centre row of each plot until stable. Heading was recorded on 10 plants in the centre row of all wheat plots until 100% of culms had headed. Awn peep was recorded on 10 plants in the centre row of all barley plots until 100% of culms had awns peeping. Leaf number and final leaf number were recorded on three plants in the centre row outside of the marked 10 plants in the subset mentioned above. Anthesis was recorded on 10 randomly selected heads outside of the marked 10 plants until 10 heads had flowered (yellow anthers extruding or in the floret) in the subset mentioned above. Observations were recorded on the FieldPrime software developed by CSIRO (https://compbio-pi.csiro.au/fieldprime/).

Climate data was logged at all sites on weather stations at 30-minute intervals, measuring air temperature and photosynthetically active radiation at 1.2m, soil temperature at 3cm below ground and leaf temperature in Scepter$^{\phi}$ plots in TOS one, four and eight. Dates and quantities of rainfall and irrigation were recorded at all sites.

Genetics and genomics

All wheat lines were genotyped using high throughput DNA extraction and KASP markers to identify alleles of the major *PPD* and *VRN* development genes (outlined in Bloomfield et al 2018). Barley lines have not yet been genotyped. Further analysis with 90K SNP data was conducted (through GRDC project CSP00183 and this project) to identify additional markers important for development. These markers will be utilised to further parameterise the models.

Statistical analyses of controlled environment experiments

Temperature data recorded at 30-minute intervals was used to calculate accumulated thermal time. Two-way analysis of variance (ANOVA) in the GENSTAT 19 software package (VSN International Ltd, Hemel Hempstead, UK) was used to analyse thermal time to flowering assuming a split-plot design with randomised blocks and environment as whole-plot and genotype as subplot.

Preliminary results and discussion

Controlled environment experiments

At present, the 69 wheat genotypes have been phenotyped in all four environments. The 35 barley lines have been fully phenotyped in the LN and LV environments and are currently being phenotyped in the SN and SV environments. Only results from six diverse wheat cultivars will be shown here. As expected, thermal time to flowering varied significantly between genotypes and environments (Figure 1). All genotypes experienced a significant photoperiod response (difference between SV and LV). Very fast spring types (for example, Emu Rock⁽ᵈ⁾) experienced no significant response to vernalisation (difference between LN and LV). For the mid to slow developing spring types, significant decreases in time to flowering were varied. Some genotypes significantly responded to vernalisation, photoperiod and a combination of the two (for example, LRPB Trojan⁽ᵈ⁾, Scepter⁽ᵈ⁾ and Beaufort⁽ᵈ⁾), compared to others (such as LRPB Lancer⁽ᵈ⁾) which responded significantly to photoperiod but only to vernalisation when photoperiod was short. Winter types (for example, LRPB Kittyhawk⁽ᵈ⁾) showed a lot of variation in time to flowering in all environments except LV (results not shown). Significant differences in time to flowering between genotypes with matching alleles at the major PPD and VRN gene loci was also observed (results not shown). This warrants the further exploration into genomic and genetic information being carried out to identify other important genes associated with flowering time.

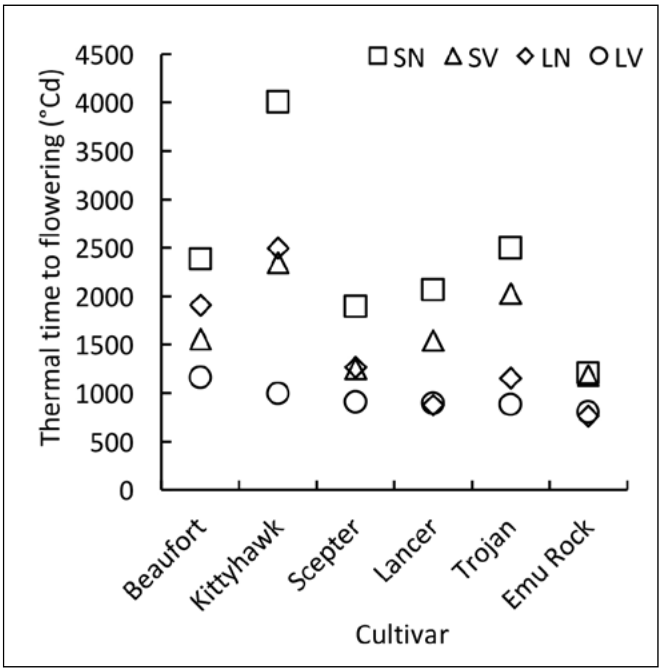

Figure 1. Mean thermal time from emergence to flowering of six wheat genotypes (G) under controlled environment (E) conditions, including; short days, not vernalised (SN); short days, vernalised (SV); long days, not vernalised (LN); and long days, vernalised (LV). Lsd ($p = 0.05$) = 268 for the two-way interaction between E and G.

Initial model validation

Using only controlled environment phenotypic data to parameterise it, the wheat model has performed well so far in simulating heading and/or flowering date of 47 genotypes used in field experiments in other GRDC investments (results not shown). The model was able to explain 72% of the variation in heading or flowering days after sowing across sowing dates from 14 March to 12 August and 46 sites. In its early stages the model is performing well overall. Estimated heading and flowering times are being simulated accurately for some cultivars, for example; Axe⁽ᵈ⁾, Derrimut⁽ᵈ⁾, H45A and LRPB Kittyhawk⁽ᵈ⁾. However, inaccurate predictions have tended to be from overestimating heading and flowering times, for example; Cutlass⁽ᵈ⁾, Magenta⁽ᵈ⁾, Scepter⁽ᵈ⁾. The model has only underestimated heading and flowering for Longsword⁽ᵈ⁾, so it is possible that correcting the model for overestimations will remedy the issue for most cultivars. Further model improvements are discussed below.

Field validation and model improvements

One year of climate and phenotypic data from the five sites has now been collated. This will be tested against the model using the controlled environment parameters. Wheat genotypes will be modelled and validated, but barley genotypes cannot be modelled and validated until the controlled environment experiments have concluded.

It is hypothesised that model performance will be enhanced by deriving parameters from genetic and genomic information. Genome wide analyses are identifying new SNP markers important for flowering time and will be able to explain the variation in addition of the major PPD and VRN genes.

Conclusion

The National Phenology Initiative has brought together a multi-organisation and multi-disciplinary team to synergise research agronomy, data science and crop modelling, and genetics and genomics. The initiative aims to improve the accuracy in predicting flowering time of wheat and barley cultivars across the major cropping regions of Australia, including newly released cultivars. It does this by assessing a cultivar's development in response to combinations of saturating and limiting vernalisation and photoperiod conditions as well as identifying alleles of important genes associated with development and flowering time. This data is used to parameterise the APSIM Next Gen wheat and barley phenology models. Multiple field experiments are being run over two years to capture a wide range of early to late times of sowing and diverse environmental conditions of major cropping environments. Model performance will be validated and improved using phenology data collected from the field trials. So far, an initial model of 47 wheat cultivars has explained 72% of heading and flowering when validated against field experiment data from a range of previous GRDC investments using only controlled environment data to parameterise the model. It is expected that further parameterisation with genetic and genomic information will improve the predicting capability of the APSIM Next Gen phenology models. Once tested and validated, this will be delivered as a web-based tool in 2022 through the NVT for growers and advisors to better inform cultivar × time of sowing decisions. New NVT listings will be added to the tool as they become available.

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How will rising atmospheric carbon dioxide concentrations affect phosphorus uptake in crops?

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Keywords

- phosphorus-utilisation efficiency, phosphate, high carbon dioxide, CO_2, climate change.

Take home messages

- Elevated atmospheric carbon dioxide (CO_2) concentrations can increase crop growth when sufficient phosphorus (P) is supplied.
- Crop are better able to acquire non-labile P under elevated CO_2 through increased root length in wheat and enhanced phosphatase activity in white lupin.
- High P-fixing soils may need increased P inputs so that the crops grown on these soils realise their increased crop yield potentials induced by elevated CO_2.

Background

Rising atmospheric CO_2 concentrations otherwise known as elevated CO_2, leads to an increase in C-fixation by crops. This elevated CO_2-induced increase in C-fixation leads to greater plant biomass and crop yields where nutrient supply is not limiting (Leakey et al. 2009). With increased plant biomass and yields under elevated CO_2, it is anticipated that nutrient demand will increase, particularly for nitrogen (N) and phosphorus (P). There has been extensive work exploring the effects of elevated CO_2 on N dynamics in cropping systems but only limited work that looks at the effects on P dynamics (Lam et al. 2012; Jin et al. 2017). In highly weathered Australian soils that have high P-fixing capacity, P is one limiting plant nutrients in cropping systems and inputs of fertiliser P are an important driver of yield and profits (Kooyman et al. 2017).

Some crop species have adapted to acquire P from soils, despite its low availability to other species (Vu et al. 2010). Physiological adaptations are mechanisms which modify the rhizosphere environment and include exudation of organic acids and plant-derived phosphatases, and acidification. Morphological P acquisition traits involve increasing root length, altering root morphology and increasing the root-to-shoot ratio, enabling a greater soil volume to be exploited for P uptake. For example, wheat and faba bean have been shown to alter their root architecture in response to P deficiency, whereas species such as white lupin (*Lupinus abus* L.) upregulate exudation of organic acids and/or phosphatases to utilise non-labile P (Lyu et al. 2016). Elevated CO_2 can affect both physiological and morphological adaptation due to increased belowground C allocation and possibly increased P demand. For instance, it is widely known that elevated CO_2 enhances root length in a range of crop species, thus enabling crops to exploit a greater volume of soil. Furthermore, root exudation is also anticipated to increase as plants will have an excess of C that can be released as organic acids. The extent to which elevated CO_2 will increase a plant's access to P under elevated CO_2 is unknown particularly in crop species with contrasting P acquisition strategies.

As elevated CO_2 generally increases crop yields, it is unknown if plants will require more available P in the soil to realise these yield increases. One method to determine the P demand of a crop species under elevated CO_2 is to apply increasing amounts of P to

P-deficient soils. By generating a P response curve, the amount of P in the soil required to achieve maximum yield of a particular crop species can be determined. Furthermore, the present study examined if P or atmospheric CO_2 is limiting yield.

Method

Trial 1

Five crops (a wheat line without citrate exudation, a wheat line with citrate exudation, white lupin, faba bean and canola) were grown in a P-deficient Chromosol from Hamilton with a Bray-P of 5.1mg/kg. The two wheat lines were identical with the exception of a *TaMATE1B* gene, which confers a constitutive citric acid transporter (Han et al. 2016). Crop species such as white lupin rely strongly on exudation of organic acids and phosphatases for P acquisition whereas faba bean displays a balance between physiological and morphological P adaptations. Plants were grown inside CO2-controlled growth chambers under 20°C/16h days and 18°C/8h nights. The ambient and elevated CO_2 concentrations were 400ppm and 800ppm, respectively. Seventy days after sowing plant shoots were harvested and roots were removed from the soil. Rhizosphere soil was collected for phosphatase analysis.

Trial 2

This trial aimed to generate a P response curve for wheat. The plants were grown in two soils that contrasted in their P-fixing capacity. The high P-fixing soil was a Ferrosol and the low P-fixing soil was a Sodosol. The Ferrosol and Sodosol had P buffer index of 1095mg P/kg and 76mg P/kg, respectively and were both limed to a pH of 6. After addition of basal nutrients, increasing P rates were applied to each soil based on a previous incubation study (data not shown). The soil was transferred to columns (10cm x 30cm) with each containing 3kg of air-dry soil. The soils were pre-incubated for seven days and pre-germinated wheat seeds (*Triticum aestivum* L. cv. Yitpi⁽ᴰ⁾) were sown. Growing conditions were identical to Trial 1. After five weeks, shoots and roots were harvested, and bulk soil was collected.

Measurements

Shoots and roots were oven dried at 70°C for two days then ground and digested in nitric-perchloric acid. The P concentration in the digests was determined using malachite green or ICP-OES.

Statistical analysis

A two-way analysis of variance (ANOVA) was performed using GENSTAT (version 19; VSN International, Hemel Hempstead, UK) to compare different treatments and their interactions. Differences between means were determined using the least significant differences (LSD).

Results and discussion

Elevated CO_2 enhanced total P uptake in canola and white lupin, but decreased P uptake in wheat without citrate exudation (by 18%) and faba bean (29%). It did not affect the P concentration in the shoot of citrate-exuding wheat, but decreased P concentration by 21% in non-citrate exuding wheat line (Table 1). The increase in P uptake in white lupin under elevated CO_2 may be explained through enhanced root exudation and increased phosphatase production which increased access to non-labile P sources. As elevated CO_2 can increase C fixation through photosynthesis, there may be more carbohydrates transferred below-ground and more organic acids (such as citric and malic acid) exuded from the root. The importance of organic acid exudation is outlined in the wheat lines where a lack of citric acid exudation led to a decrease in P uptake under elevated CO_2, whereas the wheat genotype that possessed the *TaMATE1B* gene was able to sustain P uptake under elevated CO_2. Furthermore, as elevated CO_2 increases P demand and uptake, up-regulation of phosphatase activity can also occur, leading to mineralisation of organic P in soil (data not shown).

Elevated CO_2 did not affect shoot dry weight across all crop species in Trial 1 which could be due to low soil P availability limiting the promotion of plant growth under elevated CO_2. This is confirmed by the data in Table 2 where elevated CO_2 did not significantly increase the shoot dry weight of wheat at very low P rates. Results therefore suggest that crop yields will not benefit from elevated CO_2 in soils with low P availability. These results are supported by Jin et al. (2012) who showed no increase in soils without P addition.

Through regression analysis, maximum shoot yield in Trial 2 was calculated to occur at 260mg P/kg and 350mg P/kg soil in the Ferrosol for ambient and elevated CO_2, respectively. This indicates that P supply may need to increase to benefit from the increased yields induced by elevated CO_2. In the Sodosol, the calculated P rate at which maximum

Table 1. Shoot dry weight, P concentration and P uptake of wheat without citrate exudation (wheat –citrate), wheat with citrate exudation (wheat +citrate), white lupin, faba bean and canola grown for 70 days under ambient (A) and elevated (E) CO_2.

Species	CO_2	Shoot dry weight (g/plant)	Shoot P (mg/g)	Shoot P uptake (mg/plant)
Wheat -citrate	A	2.80	2.17	6.03
	E	2.75	1.70	4.93
Wheat +citrate	A	2.69	2.68	7.35
	E	2.84	2.63	7.47
White lupin	A	2.83	1.44	3.64
	E	3.26	1.64	5.49
Faba bean	A	5.71	2.74	15.56
	E	4.92	2.22	10.97
Canola	A	3.61	1.78	6.58
	E	4.15	2.28	10.15
Significance level (LSD P=0.05)				
CO_2		>0.05	>0.05	>0.05
Crop species		<0.001 (0.602)	<0.001 (1.29)	<0.001
CO_2 × P Rate		>0.05	0.059 (0.58)	0.008 (2.51)

Table 2. Shoot dry weight, P concentration and P uptake of wheat grown in a Ferrosol or a Sodosol with increasing P application rates. Plants were grown for 35 days either under ambient (A) or elevated (E) CO_2.

CO_2	P rate (mg P/kg)	Shoot dry weight (g/plant)	Shoot P (mg/g)	Shoot P uptake (mg/plant)	P rate (mg P/kg)	Shoot dry weight (g/plant)	Shoot P (mg/g)	Shoot P uptake (mg/plant)
	Ferrosol				Sodosol			
A	0	0.08	1.26	0.10	0	0.08	1.57	0.12
E		0.08	1.49	0.12		0.13	1.66	0.22
A	50	0.30	2.44	0.73	10	0.17	3.02	0.52
E		0.36	2.48	0.88		0.19	2.55	0.49
A	100	0.48	2.04	0.96	20	0.18	3.51	0.62
E		0.60	2.40	1.44		0.23	3.46	0.81
A	200	0.84	3.72	3.12	40	0.27	4.26	1.13
E		1.18	3.39	4.09		0.29	4.06	1.19
A	300	0.98	3.67	3.60	60	0.27	4.43	1.19
E		1.12	3.71	4.14		0.29	4.54	1.30
A	500	1.06	4.40	4.72	80	0.30	5.33	1.58
E		1.51	4.63	6.77		0.35	5.14	1.81
A	800	1.13	5.82	6.59	150	0.42	5.75	2.44
E		1.34	5.93	7.98		0.58	5.80	3.37
A	1500	1.08	8.49	9.18	300	0.73	6.46	4.72
E		1.58	8.59	13.70		0.90	5.35	4.79
A	2500	1.11	10.66	11.79	500	0.70	6.90	4.83
E		1.51	10.55	15.80		1.00	5.76	5.75
Significance level (LSD P=0.05)								
CO_2		<0.001 (0.09)	>0.05	0.002 (0.42)	CO_2	<0.001 (0.03)	<0.001 (0.09)	0.004 (0.18)
P Rate		<0.001 (0.18)	<0.001 (1.29)	<0.001 (1.88)	P Rate	<0.001 (0.07)	<0.001 (0.19)	<0.001 (0.38)
CO_2 × P Rate		>0.05	>0.05	>0.05	CO_2 × P Rate	0.01 (0.11)	<0.001 (0.26)	>0.05 (0.54)

shoot yield occurred was similar between ambient and elevated CO_2, occurring at around 280mg P/kg. Elevated CO_2 significantly increased the shoot yield by 28% in the Sodosol when P supply was at marginally deficient and adequate levels. This was associated with increased in root length and P uptake under elevated CO_2 (data not shown). The contrasting result between the Ferrosol and Sodosol is not clear but could be related to the diffusive supply of P (Mason et al. 2013) as the Sodosol may have some physical constraints. Given this, methods such as diffusive gradient in thin films (DGT) would be advantageous in estimating plant available P when compared to the conventional extraction methods used in this experiment.

Conclusion

Elevated CO_2 enhances P uptake in a P-deficient soil when the crop species grown are those that rely on organic acid exudation and phosphatase production. Furthermore, increased root length exhibited under elevated CO_2 aids in P acquisition and further enhances P uptake, particularly in low P-fixing soils.

Elevated CO_2 increased P requirements for the maximum biomass production of wheat plants grown in high P-fixing soils but not of those grown in low P-fixing soils.

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The top five exotic nasties to have on your watch list

Jemma Pearl, Luise Fanning and Dale Grey.

Agriculture Victoria.

Keywords

- biosecurity, exotic, pests, diseases, weeds.

Take home messages

- Khapra beetle, Karnal bunt, Wheat stem rust pathogen Ug99, Lupin anthracnose and Barley stem gall midge are all exotics that are risks to the Victorian grain industry.
- Thirty-four key exotic pests, diseases and parasitic weeds can be found in the 2020 edition of the CropSafe guide to exotic pests and disease of grain available soon at: http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/cropsafe-program

Background

Exotic pests and diseases are those not yet found in a region. The pests and diseases described in this update paper are all exotic to Victoria If they do gain entry, many will pose a significant threat to Victoria's cropping industry, valued at over $1.8 billion (ABARES 2014-15). Some will also prevent access to our important overseas markets. Preventing pests and diseases from gaining a foothold, and quickly identifying and eradicating localised outbreaks, is critical to protecting the Victorian grains industry.

CropSafe is a critical tool in identifying potential exotic pests and disease threats to Victoria's grains industry. Agriculture Victoria delivers the CropSafe program in collaboration with a number of major agribusiness companies. Together, this cluster incorporates approximately 80% of Victoria's agronomists. CropSafe has a network of over 200 experienced agronomists continually looking for new pests and diseases. This means Victorian growers can be far more confident that their grain crops are free of exotic pests. The CropSafe program has streamlined sample receipt, analysis, reporting and record keeping.

The 2018 CropSafe general surveillance survey resulted in CropSafe agronomists reporting on over 1.9 million hectares, which is approximately half of the estimated 3.2 million hectares of grain crop in Victoria. Crops are inspected three to ten times (five times on average) during the growing season, depending on the crop type and scouting program required for crop pest and disease management. The Agriculture Victoria Chief Plant Health Officer relies on surveillance data for market access related area-of-freedom claims.

The CropSafe program maintains its rigor through continued communication and a range of extension products. This ensures that the agronomists in the network and the wider industry understand key pests and diseases that are of greatest risk to Victorian grain growers. Growers and agronomists can find the key 34 pests, diseases and parasitic weeds that are threats to the Victoria grains industry in the recently updated 'CropSafe – guide to exotic pests and diseases of grain' booklet. A link to the electronic version of the booklet can be found in the Useful resources section within this paper.

For sampling material and instructions (including plastic specimen bags and plastic vials) or information on joining CropSafe, contact Luise Fanning on (03) 4344 3111 or crop.safe@agriculture.vic.gov.au.

The success of CropSafe was acknowledged with a National Biosecurity Award in March 2017.

Top five exotics for Victorian Grain Growers

Khapra beetle – Trogoderma granarium

Khapra beetle can cause losses of up to 75% from direct feeding. Infested grain also becomes contaminated with beetles, cast skins and hairs from larvae, which can be a health risk and are difficult to remove from grain storage structures and transport vessels.

Organism

Larvae can grow up to 7mm long, are reddish brown in colour and darken as they mature. They have characteristic long hairs all over their body, especially at the rear end and can survive without food for over 12 months.

Adults are 2mm to 3mm long and 1mm to 2mm wide, brownish in colour with a smooth oval shaped body. There are three transverse bands (markings) of pale coloured hairs on the wing covers.

Host range

A beetle pest of stored grain and dry foodstuffs worldwide. The larvae of Khapra beetles are serious pests of oilseeds, damaged and whole cereals and, to a lesser extent, pulses. The adults rarely, if ever, eat or drink.

Method of spread

Khapra beetles are spread through the movement of stored grain and products or as contamination of seed, machinery and straw.

Where?

Khapra beetle is found in Africa, India, Russia and many middle Eastern countries.

Figure 1. Adult Khapra beetle *(copyright Simon Hinkley and Ken Walker, Museum Victoria)*

Karnal bunt – Tilletia indica

Wheat grains develop dark discolouration at the pedicel or 'embryo' end of the grain. The discolouration progresses along the grain until it is entirely discoloured. The infection is difficult to detect on the plant. Infected grain has a distinct fishy smell, making it unacceptable for human consumption. Symptoms on the grain may be confused with black point, a physiological disorder common after wet conditions at harvest. Grain discolouration may also be caused by other fungi, so samples should be sent to a laboratory.

Host Range

Triticum spp., including *Triticum aestivum* and *Triticale*

Method of spread

Spores of the fungus survive in grain (seed), soil for up to five years and cereal trash. It can be spread by movement of seed, soil, wind, on machinery and anthropogenically.

Conditions favouring disease

The spores require free water in the soil to germinate. Air temperature ranging from 10°C minimum to 26°C maximum, with high humidity above 75% relative humidity during heading and flowering, is required for infection.

Where?

First detected in India and now found in many middle Eastern countries. Confined to specific areas of South America, South Africa and the USA. If Karnal bunt became established in Australia, access to over 45 markets would be significantly reduced.

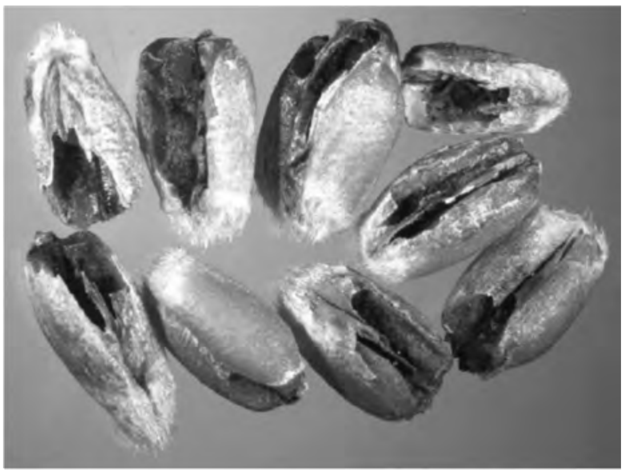

Figure 2 . Grain seed infection. Source Simon Hinkley and Ken Walker, Museum Victoria.

Wheat stem rust pathogen – Puccinia graminis forma specialis tritici, pathotype Ug99

Symptoms are the same as other wheat stem rust pathotypes. Elliptical blisters on the stems and leaves running parallel to the long axis. These blisters break open after a couple of days to reveal a mass of rust-coloured spores.

If stem rust is detected on a wheat line which is thought to be resistant, samples should be sent for testing.

Send samples to:

Australian Cereal Rust Survey
University of Sydney,
Australian Cereal Rust Survey,
Reply Paid 88076,
Narellan, NSW, 2567

Host range

Wheat and other cereal crops.

Method of spread

Wind, contaminated clothing, machinery and tools.

Where?

Several stem rust pathotypes are present in Australia and resistant varieties of wheat have been bred to limit crop losses. This new pathotype was discovered in Uganda in 1999, and is now found in Kenya, Ethiopia, Sudan, Yemen and Iran.

Figure 3. Symptoms of race Ug99 on wheat grains. *Source David Mowbray (CIMMYT).*

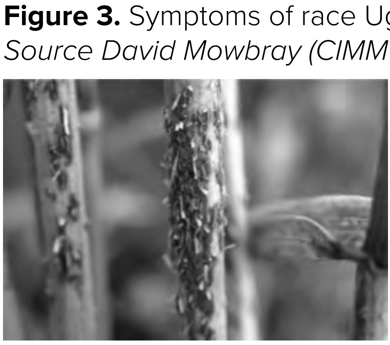

Figure 4. Symptoms of race Ug99 on stem. *Source David Mowbray (CIMMYT).*

Lupin anthracnose – Colletotrichum lupini (formerly known as Colletotrichum gloeosporioides)

Seedlings can develop lesions on the hypocotyl or cotyledons. Stem lesions are very distinctive and are oval shaped up to 2cm long and contain spore masses which are pink to orange. These cause the stem to collapse on one side and bend to produce a 'shepherd's crook' symptom. Further rainfall will allow infection progress to infect pods and seeds. Symptoms are most noticeable during flowering. Lupin branches die back in mature plants, eventually causing their death.

Pods can develop lesions which also result in the twisting and distortion of pods. Pod infection can result in nil seed set or infected seed. Lesions on pods also develop brightly coloured spore masses which vary in colour from pink to white.

Infected lupin seeds can be discoloured or symptomless. Discolouration of seed can also be caused by another fungal disease, brown leaf spot, caused by the fungal pathogen *Pleiochaeta setosa*.

Host range

Lupinus spp.

Method of spread

The pathogen can spread into new areas when infected seed and trash are carried by trade, farming practices, animals or birds. Short distance spread within a crop is via water-splash of spores during rain or irrigation.

Conditions favouring disease

C. lupini can survive over summer on infected trash and seed. Wet conditions in winter favour germination of infected seed and disease establishment. Frequent rainfall during flowering favours spread of the disease within crops and development of shepherd's crook symptoms.

Where?

The disease is widespread throughout Western Australia and has not been observed in South Australia in the last decade, despite widespread outbreaks in the late 1990s. An outbreak of anthracnose occurred in New South Wales in 2016, but this was contained, and the disease was declared eradicated in 2019.

Figure 5. Stem infection on albus lupins. *Source Kurt Lindbeck, NSW Department of Primary Industries.*

Figure 6. Early stem infection. Source Kurt Lindbeck, NSW Department of Primary Industries.

Barley stem gall midge – Mayetiola hordei

Feeding damage on cereal plants from *Mayetiola hordei* can cause leaf discolouration, from a darker green to bluish green or slowing of new growth in seedlings. Plants are often stunted, and tillers can become weakened, causing plants to lodge. The main identifying feature of Barley stem gall midge is the formation of pea-sized galls (swellings of the plant tissue) at the base of the host plant between the leaf sheath and stem.

Organism

Gall midge larvae have a long-lived larval stage specialised for feeding, whereas adults are short lived and generally only last one to two days, during which time they do not feed but mate, find suitable host plants and lay eggs. Small numbers of eggs are laid indiscriminately on numerous host plants. Up to 400 eggs are laid per lifetime. Larvae undergo three instars growing up to 3mm to 4mm in length.

The second instar becomes a puparium within which the non-feeding third instar, pupa and adult develop. Larvae are initially pale red in colour and become milky white as they mature. Adults are small, mosquito-like flies about 2mm to 4mm long, have one set of wings with a few weak veins and beaded, elongated antennae.

Host range

The preferred host of *M. hordei* is barley (*Hordeum vulgare*) but it will also feed on oat (*Avena sativa*), wheat *(Triticum aestivum*) and rye (*Secale cereale*). Stem galls are produced almost exclusively on barley but occasionally on oat, wheat and rye.

Method of spread

Adults spread by actively flying throughout the crop or using wind current. Long distance dispersal also occurs by 'hitchhiking' on machinery, clothes and plant materials.

Where?

Barley stem gall midge originated in Tunisia. Its range has expanded through North Africa and has been recorded in European countries; Spain, UK and France.

Figure 7. The white larva and the dark brown pupa of the Barley stem gall midge. S*ource ICARDA.*

Acknowledgements

Thank you to Kurt Lindbeck (NSW DPI) and the Agriculture Victoria Chief Plant Health Officer Unit for their contribution of content and expertise.

Useful resources

CropSafe – guide to exotic pests and diseases of grain 2020 found here:

agriculture.vic.gov.au/agriculture/grains-and-other-crops/cropsafe-program

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Cereal production in the United Kingdom (UK) with regulation, resistance and a changing climate

Keith Norman.

Independent Agritech Consultant; Keith Norman Consultancy Ltd..

Keywords

- regulation, resistance, yield plateau, yield gap, remote sensing, soil health, soil nutrition, fungicides, immune enhancers, semiochemicals, robotics, big data.

Take home messages

- Reliance on conventional pesticides will diminish from the effects of regulation and resistance.
- Plant breeding and genetics have a vital part to play in the sustainability of crop production.
- There are many emerging applied technologies that will underpin the sustainability of future crop production.

Regulation

The European Union (EU) has one of the most heavily regulated agricultural industries globally. The United Kingdom (UK)'s agrochemical (Agchem) market is affected by all of the following regulations:

- Regulation 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).
- Regulation 1107/2009 on the Placing on the Market of Plant Protection Products (PPPR). Aims to draft 'specific scientific criteria for the determination of endocrine disrupting properties'. Deadline was originally 2013, the criteria were adopted only in 2018.
- Regulation 528/2012 on Biocidal Products (BPR).
- Regulation 2018/605 Endocrine Disruption.
- Regulation 2000/60 Water Framework Directive.

In 1993, the EU launched a review of approximately all of the 1000 active substances in the EU.

Each substance had to be evaluated with respect to human health (consumers, farmers, local residents and passers-by) the environment, groundwater, and non-target organisms, such as birds, mammals, earthworms and bees. This review program was finalised in March 2009. Some manufacturers decided not to submit dossiers. Some products were no longer profitable, or the active substances would not pass the stricter safety testing requirements. Only 26% of the actives survived the review.

Table 1. Active ingredients that are no longer available.

Chlorothalonil	Carbendazim	Diquat	CIPC	Fenoxaprop
Neonicotinoids	Methiocarb	Flupyrsulfuron	Flurtamone	Flusilazole
Fenpropimorph	Fluazifop	Iprodione	Isoproturon	Linuron
Glufosinate	Ioxynil	Paraquat	Permethrin	Picoxystrobin
Mecoprop	Omethoate	Simazine	Tepraloxydim	Terbutryn
Quinoxyfen	Quizalofop	Tralkoxydim	Tridemorph	Vinclozolin
Thiamefoxam	Thiram	Desmedipham	Dimethanamid	Gamma HCH

Active Ingredients that are considered high risk of being removed in the next two to three years:

Fungicides	Epoxiconazole, Tebuconazole, Cyproconazole, Metconazole, Mancozeb.
Herbicides	2,4-D, Bifenox, Carbetamide, Chlortoluron, Clopyralid, Fluroxypyr, Glyphosate (Austria, France and Germany have already announced a ban), Metazachlor, MCPA, Pendamethalin Propyzamide.
Insecticides	Cypermethrin, Deltamethrin, Esfenvalerate, Thiacloprid, Metaldehyde.

What have been the effects of this more stringent system?

Tougher regulation has led to manufacturers submitting less actives for approval.

During the 1990s over 120 new actives were submitted for approval, but this has reduced to less than 40 in the last decade.

Because of the more stringent criteria the costs of bringing a new active to market has increased from $184m in 2000 to $286m (current). Maximum Residue Levels, Ecotox, Environmental Chemistry and Toxicology are some of the significant costs of registering a new product.

There is a much greater threat of resistance development due to fewer modes of action being available for fungicide, herbicide and insecticide options, and therefore, increased selection pressure on what remains.

Active ingredients (AIs) with a single site of action are more favoured in the new system and are more vulnerable to forming resistance than the broad-spectrum multiple site of action AIs.

The manufacturer pipeline of new actives does not seem likely to deliver a wide range of replacement AIs.

Biological controls are in their infancy and are not ready for scale up. They are also very poorly understood and early indications of their performance reliability is hugely variable and weather dependent.

What are UK growers doing to mitigate the dwindling stock of effective plant protection products?

Strategies used by UK growers to mitigate dwindling stock of effective plant protection products:

- Choosing varieties with greater disease resistance.
- Seeding later which reduces disease potential.
- Being more selective of where they grow crops on the farm. They don’t grow crops on areas with heavy weed burdens, or inherently less productive areas due to topography, soil type, drainage, etc. Environmental payments are going to take the place of subsidies, the details are yet to be announced.
- Growing more barley and less wheat. It’s cheaper to grow and yields are sometimes as good as wheat.
- More spring cropping; which enables an increase in use of non-selective grass weed herbicides and spreads autumn workload.
- Spring beans, spring barley and maize for anaerobic digestors have had the most significant increases.
- The Environmental Land Management Scheme will replace subsidies and will generate income on less favoured areas for crop production.
- Reduce the area of combinable crops and rent land out for potato, sugar beet and vegetables on short-term agreements.
- Greater use of high-technology monitoring tools. For example, DNA fungal spore detectors, insect suction traps, remote sensing using unmanned aerial vehicles (UAVs), satellites, etc.
- Decision support modelling is being developed to use the information from the new Internet of Things together with location, weather, cultivars and the growth period.
- Investigations into the many biological products coming onto market is beginning to take place. In the last three years, registration applications for biologicals have been greater than conventional chemistry.

Resistance in the UK

Resistance is becoming more widespread and at a faster rate of development than ever before. The following are examples of major resistances UK growers are having to manage.

Fungicides	Herbicide	Insecticide
Septoria	Blackgrass	Grain aphid
Mildew	Ryegrass	Peach Potato Aphid
Light Leaf Spot	Poppy	Cabbage Stem Flea Beetle
Potato Blight	Chickweed	Pollen beetle
	Mayweed	Pea and Bean Weevil

Repeated use of a smaller number of active ingredients adds more selection pressure to the remaining options.

Over the last 20 years, we have seen the efficacy of triazoles in a protectant and curative capacity drop significantly from > 90% from when they were first introduced to approximately 30% today.

In more detailed studies, the EC_{50} (effective concentration) of the two key triazoles; epoxiconazole and prothioconazole have steadily increased from 0.01ppm to 5ppm for epoxiconazole, and from 0.001ppm to 1.5ppm for prothioconazole.

It is common to find the coexistence of between five to eight resistant populations in the one field. Not only are there mutations to the CYP51 protein that the triazoles bind to, but there are also two other types of resistance becoming commonplace; an over-expression gene whereby the mutated protein amplifies to greater levels than normal. There is also a mutation that affects the Efflux pump mechanism, whereby the Septoria cells actively pump out the fungicide from within to minimise the effect of the fungicide on them.

Likewise, we are seeing a marked reduction in the efficacy of succinate dehygrogenase inhibitors (SDHIs). From 2015 to 2019, their average performance had dropped from >90% to approximately 60%

The increase of resistance to pyrethroids is also concerning, especially now that neonicotinoid seed treatments are no longer permitted. It is estimated that between 30-50% of grain aphids (English Grain Aphid, *Sitobion avenae*) now carry the KdR gene. This is also reflected in the decrease of the area sown to oilseed rape due to the lack of control of the Cabbage Stem Flea beetle (*Psylliodes chrysocephalus*). Oilseed rape (OSR) grown in the UK has dropped from 758,000ha in 2012 to an estimated 483,00ha for harvest 2020.

Autumn 2019 saw the arrival of the first barley yellow dwarf virus (BYDV) resistant wheat from RAGT, a variety called Wolverine. Wolverine's resistance originates from a goat grass, *Thinopyrum intermedium*, a distant wheat relative. A genetic segment from Thinopyrum containing the resistance gene Bdv2 has been translocated onto a wheat chromosome via an Australian research line known as TC14.

Myzus persicae is totally resistant to pyrethroids causing problems for virus control in potatoes and sugar beet There are two BYDV resistant barley varieties and six TuMV resistant OSR varieties on the market presently.

Grass weed herbicide resistance, principally black grass and ryegrass, is a significant problem on approximately 1M hectares of wheat (50% of the UK hectarage) Both target site and enhanced metabolic resistance coexist within fields. We are beginning to see resistance building with some of the residual chemistry too; flufenacet and pendimethalin.

Of greatest concern is the observation of some blackgrass populations now becoming insensitive to doses of 540g/ha of glyphosate which would normally have been effective.

Finally, there are four broadleaved weed species that are now resistant to sulfonylurea herbicides, they are poppy (*Papaver somniferum*), chickweed (*Stellaria media*), mayweed (*Matricaria*) and sowthistle (*Sonchus asper*).

The Yield Plateau

The phenomenon of the 'yield plateau' extends further than just the UK. A similar situation exists in other countries of Western Europe. From 1980 to 1996, UK wheat yields improved rapidly; by an average of 0.10t/ha per year. Since then, yields have stagnated, increasing by only 0.05t/ha per year.

No single agronomic factor has had a clear dominant influence on trends in UK wheat yields over the last 30 years. A proportion of the lost yield improvement remains unexplained, with aspects of climate change being amongst the likely causes. Plant breeding has continued to deliver genetic improvement.

Several theories have been put forward as to why yield has plateaued such as soil health, soil management and cultivations, compaction from heavier machinery, suboptimal nitrogen (N) and sulphur use, pesticide resistance, sowing dates and seed rates.

The Yield Gap

There is a considerable 'yield gap' between average UK wheat yields, currently approximately 8.5t/ha and the top achieving growers. In 2019, the top Yield Enhancement Network (YEN) of growers reported an actual yield of between 14t/ha to 16t/ha, with the world record still set at 16.5t/ha.

According to YEN, 75% of yield variation is influenced by the farm's physical characteristics, crop husbandry, the agronomist and the farmer. High biomass and ear numbers are essential for high yields. The foundation period; seeding to GS31, is a very important period and crop development within this period is very heavily influenced by soil management, nutrition and good root development.

Moisture retentive soils are key to ensuring grain fill is optimum. There is a positive association with organic amendments, particularly slurry and digestate. Site, weather and husbandry factors have a bigger influence than variety choice, and therefore, varieties should be chosen for quality traits, end markets, disease resistance and standing ability rather than just yield.

There is a positive association with soil pH and with straw incorporation. The association with N fertiliser rate is very strong.

Early indication is that phosphate (P) grain content is also correlated to yield, the critical value for grain P = 3200mg/kg.

There is a negative association with liquid N probably due to the scorching of the crop if it is applied in the wrong conditions. Because high biomass and ear numbers are important, plant growth regulator (PGR)-use has a strong positive association with yield. High straw N% and soluble stem carbohydrate reserves were considered very important to maintain photosynthesis during grain filling.

New technologies being introduced

There are several new technologies being developed which will hopefully increase production potential.

Plant breeding and genetics

The first BYDV resistant wheat and barley in the UK has previously been discussed within this paper. However, there are also exciting developments using a Synthetic Hexaploid breeding approach whereby one of the three wheat genomes, the D genome, is being replaced from other sources of material resulting in greater yields, and greater resistance to biotic and abiotic stress.

Work at the John Innes Centre is also looking at producing grains with increased length and width, thereby increasing the 'sink' for higher yields. Other attributes are also being researched, for example; longer spikelets that produce approximately 20% more grains, a branched ear producing 50% more grains, etc.

Advances in genetic marker-assisted speed breeding, whereby up to six generations can be achieved per year through controlled environment and Light Emitting Diode (LED) technology are enabling more rapid translation of genetic discovery into elite lines.

Remote sensing

There are many new capabilities being developed to assist the farmer and agronomist to manage crops more effectively, many of which are satellite based.

Monitoring of crop health through normalised difference vegetation index (NDVI) measurements, biomass measurements, Green Area Index, crop growth rate, plant stress are all operational and enable farmers/agronomists to target their time more effectively by targeting the inspection of problem areas of paddocks rather than general field walking.

Hyperspectral, pre-symptomatic disease signatures are currently being developed in Controlled Environment conditions by Hummingbird Technologies.

Ground Penetration Radar is now available from satellites and has the capability of penetrating soils up to 1m. This technology has the capability of detecting compaction in subsoils, as well as soil moisture for irrigation scheduling purposes.

Another form of remote sensing; Synthetic Aperture Radar, is an active wavelength which has the potential to penetrate cloud and can also deliver information in the dark.

Field based spore sensors that can be primed to detect the DNA of multiple diseases from the surrounding air are also being developed and would be another key feature in the early detection and intervention of disease ingression. Portable LAMP assay kits are now becoming available whereby growers can take leaf samples and look for the presence of pathogen DNA on recently emerged leaves.

Another approach is a 3D printed spore trap being developed by the University of Manchester and Sony. A mimic leaf is embedded with sensors that look for the presence of disease enzymes that are used to penetrate the vascular system of the plant and wreak havoc, or pressure sensors to detect the appressorium (pegs) that some diseases; such as rust, use to enter the leaf surface.

Soil health and nutrition

Volatile Organic Compounds (VOCs) are the basis of a new infield technology being developed by PES technologies. The small detector, about the size of a matchbox, is filled with soil and the VOCs that are detected give an indication of the key indicators of soil health.

Variable rate N capabilities are now commonplace with the more progressive farmers.

The age-old debate as to whether to put more or less N on the poorer parts of the crop rages on. A new product from Hummingbird technologies enables growers to test the option of inversing the approach to N at the click of a box. In practical terms, if extra N applied on the lower biomass areas of the crop hasn't produced a positive effect, then less will be applied on the second split, thereby optimising gross margins.

More knowledge is being developed regarding optimum nutritional thresholds during the key stages of crop development. Tissue and grain testing are becoming a more reliable method to test nutrient levels compared to soil testing.

Infield soil sensors are starting to make an appearance. The Terralytic soil probe has 26 sensors and measures soil moisture, salinity, and N, phosphorus (P) and potassium (K) at three different depths, as well as aeration, respiration, air temperature, light, and humidity

The Terramap, which is a small measuring device fitted to an all-terrain vehicle (ATV), measures four naturally emitted isotopes - Caesium-137 (Cs), Uranium-238 (U), Potassium-40 (K) and Thorium-232 (Th). There are approximately 800 reference points per hectare. In comparison, grid sampling map layers have only a single data point per hectare. Strategic soil samples are taken from each paddock and then the scan data and soil sample results are combined and processed to produce up to 21 high-definition soil property layers; P, K, magnesium (Mg), pH and % of clay, sand, silt, calcium, sodium, manganese, boron, copper, molybdenum, iron, zinc, sulphur, organic matter (OM), salinity (CEC) and plant available water are all delivered.

Fungicides, immune enhancers and semiochemicals

After a long time, two new fungicides have arrived on the UK market this season. The first is Revysol® (mefentrifluconazole), a new type of triazole, an isopropanol-Azole, which has been a top performer in AFD trials this year. The second is awaiting imminent approval, InatreqTM from Corteva which is based on a fermentation product of a soil borne Streptomyces bacteria. This has a very similar mode of action as the strobilurins; it acts on complex 3 of the mitochondria.

Plant immune enhancers have been introduced into the market, but their use in terms of timing, dose and frequency is still to be determined. They are based on both systemic acquired resistance and induced systemic resistance. They work by stimulating the salicylic and jasmonic acid pathways. If successful in their development, they could be an important part of a resistance management program

Semiochemical technologies are also currently being developed. An example is; jasmonic acid which naturally repels insects and tricks insects into believing the host is decaying and under attack, and therefore, the plant would not make a viable host.

Others disrupt the mating cycle of insects by confusing the male insect so that it is unable to find a female to mate with. This reduces pest populations.

Attractants can also be used to lure insects into traps containing insecticides. These can be used in conjunction with evolving 'smart trap' technologies whereby insect species are identified and counted, enabling more effective insect control management strategies.

Alternatives to herbicides

The future of glyphosate still hangs in the balance following the current approval period which ends in 2022. Various other techniques are being investigated, for example; the use of pelargonic acid, laser weeding and electronic weeding.

Hight voltage weeding, while very effective and quick in the resulting kill, still must overcome the practical difficulties of generating enough tractor mounted voltage to optimise width and speed of travel.

Laser weeding, whether by robots or boom mounted is more appropriate for wide-row horticulture crops rather than broadacre commodity crops.

Pelargonic acid as a standalone product is not as active on weeds as glyphosate but can considerably enhance the effect of low rates of glyphosate. It has a high application rate of 20-30L/ha which has implications for application and storage

Robotics

There is a lot of activity in this area, but most of the technologies are going to be more suited to horticulture/top fruit crops rather than broadacre commodity crops. Fruit sizing, colour detection and picking are all being developed as well as laser weeding.

The Small Robot Company is developing a partnership of robots – one detects, the other implements. They have a philosophy of 'per plant' establishment and management which they believe will replace conventional methods.

Big data

Finally, 'big data' is a direct consequence of the Internet of Things in agriculture. I don't think we have yet seen the full extent of the advantages of the use of 'big data'. A new UK government funded Agritech Centre, Agrimetrics is developing new services for farming that utilise 'big data'.

Data, at a global level, is on an exponential rate of use, and has increased from 30-40 zettabytes from 2019 to 2020 (1 Zb = 1 trillion gigabytes).

Omnia, a GIS service on offer from Hutchinsons can analyse multi- layers of crop information to give more insight into the output potential of a specific paddock. Yield data from combines, soil sampling, etc. can be compared across many seasons and variable rate applications adjusted accordingly.

Useful references

Regulation (EC) 1107/2009 on the Placing of Plant Protection Products on the Market,

http://www.europarl.europa.eu/RegData/etudes/STUD/2018/615668/EPRS_STU(2018)615668_EN.pdf

European Commission, Communication from the Commission to the Council and the European Parliament - Community strategy for endocrine disrupters - A range of substances suspected of interfering with the hormone systems of humans and wildlife, COM (1999)706 final, 1999. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:51999DC0706

Registering a Pesticide: http://www.pesticides.gov.uk/guidance/industries/pesticides/topics/pesticide-approvals/pesticidesregistration/ ; registering-a-pesticide.htm

Pesticides Usage Survey:
https://secure.fera.defra.gov.uk/pusstats/surveys/

Fungicide resistance action group
https://ahdb.org.uk/frag

Insecticide resistance action group
https://www.irac-online.org/

Weed resistance action group
https://ahdb.org.uk/wrag

Yield Plateau – report commissioned by AHDB
https://ahdb.org.uk/Tags/Yield%20Plateau

Yield enhancement network (YEN), connects agricultural organisations and farmers who are striving to improve crop yields:
https://www.yen.adas.co.uk/

AHDB Fungicide Performance, independent information on the efficacy of fungicides against key diseases in wheat, barley and oilseed rape:
https://ahdb.org.uk › fungicide-performance

Tissue derived optimum nutrient thresholds for wheat: https://www.lancrop.com/

Teralytic Wireless NPK soil probe and an analytics platform: https://teralytic.com/

Terramap – passive, gamma-ray detection technology providing high-definition mapping of all common nutrient properties:
https://www.omniaprecision.co.uk/terramap/

Omnia Precision:
https://www.omniaprecision.co.uk/

Small Robot Company: https://www.smallrobotcompany.com/meet-the-robots#weed-killing

Hummingbird Technologies, crop data analytics using satellites, fixed wing and drones:
https://hummingbirdtech.com/

Electronic weeding: https://zasso.com/

Agrimetrics, provides data, tools and services to agrifood businesses: https://agrimetrics.co.uk/

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Notes

GRAINS RESEARCH UPDATE

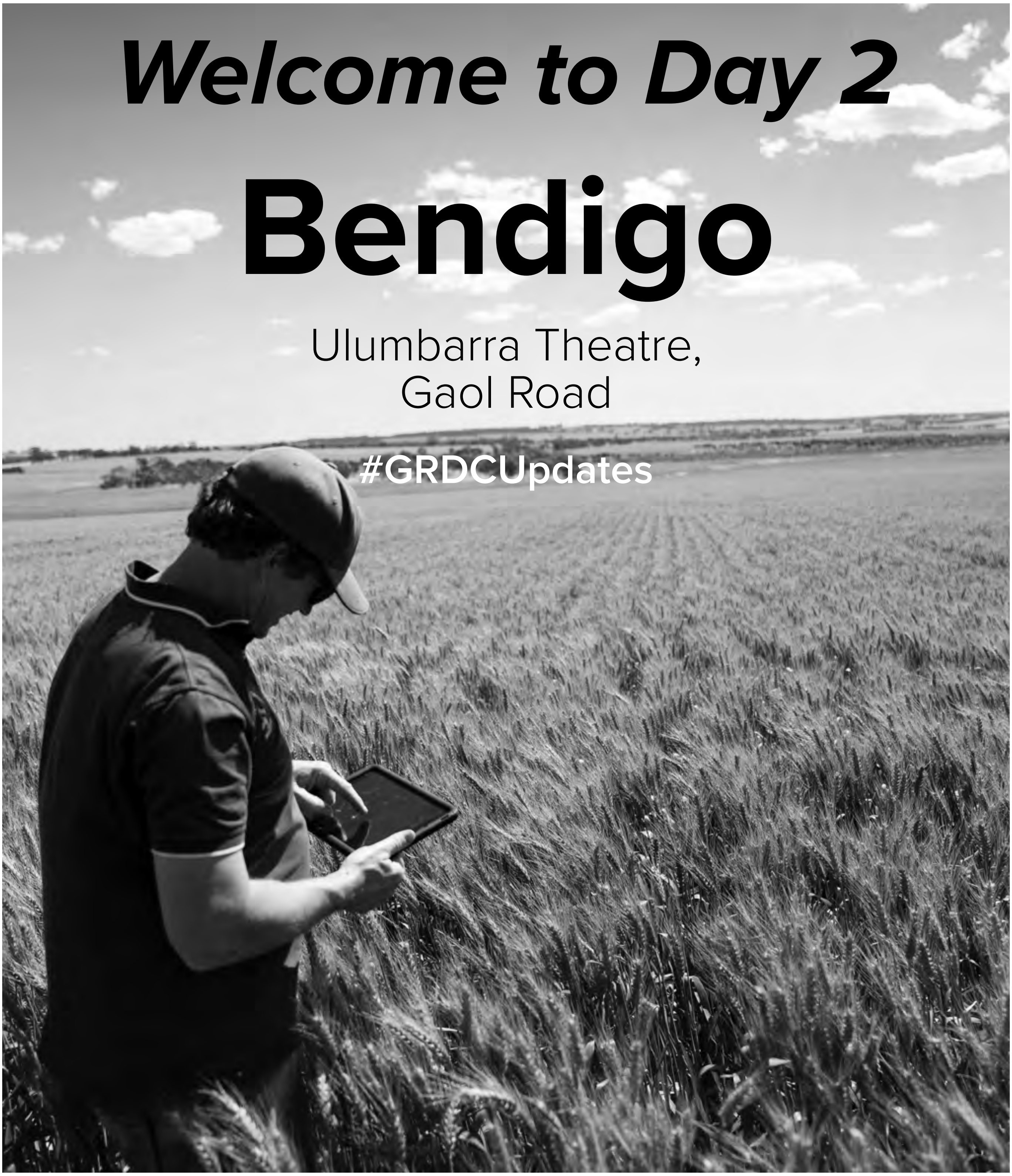
GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

Welcome to Day 2

Bendigo

Ulumbarra Theatre,
Gaol Road

#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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GRDC Grains Research Update BENDIGO

PROGRAM DAY 2 - FEBRUARY 26th

8.15 am **EARLY RISERS: Everything you want to know and ask about crop diseases heading into 2020**

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

	Auditorium	Dance Studio	Strategem Studio	Multipurpose Room
9.00 am	**Canola roots and water use - big is not always best (R)** - P197 ***John Kirkegaard,*** *CSIRO*	**Estimating in-crop N mineralisation in current cropping systems (R)** - P205 ***Katherine Dunsford,*** *Agriculture Victoria*	**Spotlight on pulses (R)** - P207 ***Jason Brand*** *and* ***Garry Rosewarne,*** *Agriculture Victoria*	**Soil acidity - sampling and lime incorporation under review (R)** - P209 ***Lisa Miller,*** *SFS*
9.40 am	**Integrating new chemistries in the field (R)** - P217 ***Chris Preston,*** *University of Adelaide*	**The hows and whys for deep ripping sandy soils** - P221 ***Michael Moodie,*** *Frontier Farming Systems and* ***Chris Saunders,*** *University of SA*	**Earwigs - an appetite for destruction or are they beneficial?** - P233 ***Matthew Binns,*** *CSIRO*	**Rapid post-event frost damage assessment - can it be achieved? (R)** - P249 & P259 ***James Nuttall*** *and* ***Eileen Perry,*** *Agriculture Victoria*
10.20 am	**MORNING TEA**			
10.55 am	**High Rainfall Zone research forum: Addressing the yield gap - local hyper-yielding project Pulse agronomy trials in HRZ Canola yield improvement** - P183, P197, P267 & P269 ***Jon Midwood,*** *SFS,* ***Keith Norman,*** *Keith Norman Consultancy Ltd (UK),* ***James Manson,*** *SFS and* ***John Kirkegaard,*** *CSIRO*	**Deep ripping - does it work for all situations?** - P281 ***Roger Armstrong,*** *Agriculture Victoria*	**The health report: pulse disease updatew (R)** - P287 ***Josh Fanning,*** *Agriculture Victoria and* ***Sara Blake,*** *SARDI*	**Soil acidity - sampling and lime incorporation under review** - P209 ***Lisa Miller,*** *SFS*
11.35 am		**Estimating in-crop N mineralisation in current cropping systems** - P205 ***Katherine Dunsford,*** *Agriculture Victoria*	**Integrating new chemistries in the field** - P217 ***Chris Preston,*** *University of Adelaide*	**Rapid post-event frost damage assessment - can it be achieved?** - P249 & P259 ***James Nuttall*** *and* ***Eileen Perry,*** *Agriculture Victoria*

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

	Auditorium	Dance Studio	Strategem Studio	Multipurpose Room
12.15 pm	**Use of chemicals and residues arising** - P297 ***Gerard McMullen,*** *National Working Party on Grain Protection*	**Canola roots and water use - big is not always best** - P197 ***John Kirkegaard,*** *CSIRO*	**The health report: pulse disease update** - P287 ***Josh Fanning,*** *Agriculture Victoria and* ***Sara Blake,*** *SARDI*	**Spotlight on pulses** - P207 ***Jason Brand*** *and* ***Garry Rosewarne,*** *Agriculture Victoria*

12.55 pm **LUNCH**

1.35 pm **Food and diet trends affecting the grains industry** - P303 ***Sara Grafenauer,*** *Grains and Legumes Nutrition Council*

2.15 pm **Breaking through the big yield constraints - where to next?** - P309 ***James Hunt,*** *La Trobe University*

2.50 pm **CLOSE AND EVALUATION**

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

Canola's deep roots - agronomy to capture benefits and manage legacies

John Kirkegaard[1], Mel Bullock[1], Tony Swan[1], Julianne Lilley[1] and Rohan Brill[2].

[1]CSIRO Agriculture and Food, Canberra; [2]NSWDPI, Wagga Wagga.

GRDC project code: CSP00187

Keywords

- early sowing, winter canola, rooting depth, water uptake, crop sequence.

Take home messages

- Canola has a deep root system that can penetrate soil faster (~2cm/day) and for longer than wheat.
- Earlier sown, slower developing canola crops can access deep stored water to out-yield later sown varieties if subsoil water is available, AND the spring is dry.
- Managing crop sequence and summer fallows to improve deep-stored water and nitrogen (N) will capitalise on the higher yield potential of earlier-sown canola and reduce risk.
- High yielding, early-sown crops can leave a legacy of dry, N-depleted subsoil, which may require changes to crop sequence and management to avoid yield penalties.

Background

Canola is generally believed to be more sensitive to drought than cereals. However, in the recent dry 2018 and 2019 seasons, the success of early-sown hybrid varieties with robust Nitrogen (N) rates at several sites has been surprising. Many people assumed that the vigorous, early canola growth would exhaust soil water rapidly, create terminal stress and reduce grain yield – but this has not been the case. Recent studies of canola root growth and water use in the GRDC Optimised Canola Profitability Project (OCPP), provide an explanation, related to the capacity of early-sown canola to grow deep roots and capture deep stored water to support higher yield.

The benefits of early-sown, slow-developing canola crops over later-sown, fast-maturing varieties are less likely in the absence of deep stored water, or when in-crop rain is plentiful. In addition, dry subsoils that may be left as a legacy of the high yielding, early-sown canola crops, may persist if the summer is dry. This can limit the yield potential of following crops. Adjustments to crop choice, sowing date and N fertiliser management may be required to reduce the risk of low yields and to maximise profit across the cropping sequence. Grazing early-sown crops can be a strategy to offset some of the risk, as growing biomass in winter is far less risky than filling grain in spring.

This paper discusses root growth, water use and yield potential of earlier-sown, slow-developing canola crops and how to best manage them within the crop sequence to improve profit and reduce risk.

Canola is a deep-rooted crop – when soil conditions permit

Brassica species including canola (*Brassica napus*) are generally known to have a capacity for deep rooting. In Europe Brassica are often used as cover crops or catch crops, to capture nitrate from deep soils to prevent leaching. In the absence of restrictive soil layers, the root system has demonstrated potential to reach deep soil layers in excess of 2m, with most studies in the literature reporting maximum rooting depths for canola of 1.5 to 2.4m (Dresbøll et al. 2018; Lisson et al. 2007). Differences in maximum rooting depth between canola and other crop species are often misinterpreted based on the different lengths of the vegetative period. For example, in Canada, Merrill et al. (2002) reported maximum rooting depths for safflower of 1.64m and canola of 1.14m. However, when corrected for the different season lengths of each crop (113 days and 86 days respectively), root penetration rates were more similar (1.45cm/d and 1.33cm/d).

On red loam soils in southern NSW, the roots of perennial plants such as lucerne are known to reach depths beyond 4m, while research on annual spring wheat and canola crops involves coring to only 1.5 - 1.8m. Most crops sown in mid-May have maximum rooting depths in that range, and while canola roots occasionally protrude from the bottom of 2.0m soil cores on deep red soils, maximum rooting depths have not been investigated. Renewed interest has developed in the rooting depth of canola following the 2011 introduction of March-sown winter canola as a dual-purpose crop, and the success of slower-maturing spring hybrids sown in April. In 2018 and 2019, soil cores were taken to a depth of 4.5m on a deep red soil at Greenethorpe, NSW, to determine the potential depth of canola roots, with a focus on earlier-sown hybrid varieties.

Canola roots can grow down at 2cm per day

In 2018, the estimated root penetration rate for two varieties sown in early April; Archer, and early May; Nuseed Diamond, was similar —1.5cm/d before the start of flowering, and between 0.7 and 1.7cm/d after the start of flowering (Table 1). In 2019 three varieties were sown onto fallow in March, April and May and all had root penetration rates of 2.3 to 2.6cm/d before flowering. The May-sown variety (which had deepest roots within coring depth after flowering) had a post-flowering root penetration rate of 1.2cm/d. An earlier study of winter canola in 2014 at another site also had an early root penetration rate of 2.0cm/d between March and June. These studies demonstrate that canola roots can penetrate soil at around twice that of wheat before flowering (wheat was ~1.2 cm/d on similar soils; Kirkegaard and Lilley 2007). Being indeterminate, canola also continues to grow roots down after flowering, while wheat rooting depth changes little after flowering. As a result, canola can achieve maximum rooting depths of >2m when sown in May. This can increase to 3 to 4m when slower maturing varieties, with longer vegetative stages, are sown in March or early April on deep loam soils.

Subsoil water use by deep roots

In circumstances where subsoil water has been stored over summer, deep rooted, early-sown canola can utilise the deeper water to produce higher yield. In the 2018 Greenethorpe experiment; Archer, sown on 4 April, had roots that were ~100cm deeper than Nuseed Diamond at harvest (3.2m cf 2.2m) and had extracted an extra 33mm of water from the soil during the dry spring (Figure 1). Archer's increased rooting capacity was confirmed with more detailed root measurements possible in the Rhizolysimeter at Wagga Wagga. Archer had consistently deeper roots than Nuseed Diamond at every growth stage recorded throughout the season (Pitt et al. 2019).

Frequency of yield benefits from deep water use

In the 2018 Greenethorpe experiment, early-April sown Archer and May-sown Nuseed Diamond flowered at the same time. Archer extracted an additional 33mm of water from the deep soil below 2m during the terminal drought (total seasonal rainfall 185mm) and generated a higher yield of 2.9t/ha compared to 1.7t/ha for Nuseed Diamond (Table 2). This represents a very high efficiency usage of deep stored water at 36kg/ha/mm. In an irrigated

Table 1. Root penetration rate and maximum rooting depth of canola varieties measured on red loam soil at reenethorpe, NSW.

Year	Variety	Sowing date	Root penetration rate (cm/day)		Maximum root depth (m)
			Pre-flowering	Post-flowering	
2018	Archer	4 April	1.4	1.7	3.2+
	Nuseed Diamond	7 May	1.6	0.7	2.2
2019	Hyola®970CL	19 March	2.3	NM	4.5+
	Pioneer®45Y91CL	18 April	2.6	NM	3.9+
	Pioneer®43Y92CL	14 May	2.4	1.2	3.4
2014	Hyola®971CL	15 March	2.0	NM	*(1.6m on 6 June)*

NM = not measured as roots could not be accurately sampled (too deep, or unable to core).

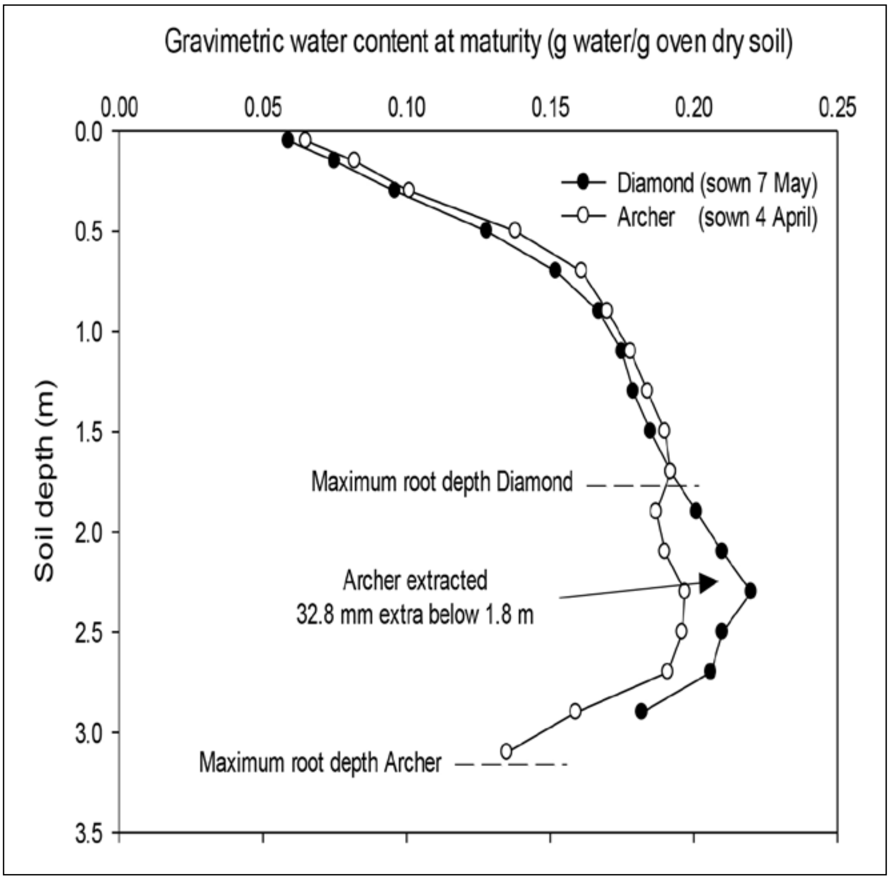

Figure 1. Residual soil water at harvest, following a terminal drought in 2018, showed deeper rooting and increased deep water use in an early April sown canola variety (Archer) compared with May-sown variety (Nuseed Diamond) with similar flowering dates (Kirkegaard et al. 2020 in press).

treatment, with 100mm of additional water supplied after flowering (total water supply 285mm), a similar yield benefit from deeper roots was observed even at this higher yield level (3.7t/ha vs 2.3t/ha). Biomass at flowering was similar for both Archer and Nuseed Diamond in the two water treatments, because additional irrigation was applied after the start of flowering. This demonstrates that the benefits of accessing deeper water can occur under a range of seasonal conditions and yield potentials.

Variety comparisons across a greater range of sites in 2017 and 2018 show an average yield advantages of around 0.4t/ha in yield ranges from 1.5 to 3.5t/ha (Figure 2). In very dry seasons (<1.5t/ha) there was no yield advantage, presumably because yield potential was low. At sites where fallow rainfall was low (<150mm), and in-crop rainfall was high (>250mm), there was less reliance on stored water and higher yields (>3.5t/ha), and also little yield advantage from earlier sowing systems (Brill et al.

Table 2. Growth and yield benefits of early-sown, slow maturing canola at Greenethorpe in 2018 under two different seasonal water supplies. WUE was calculated for dry treatment only.

Water supply	Variety	Sowing	Flowering Biomass	Yield	Maturity Biomass	Harvest Index	WUE (Yield/ET)
Dry (185mm)	Archer	4 April	8.4	2.9	10.8	0.27	10.7
	Nuseed Diamond	7 May	4.3	1.7	6.7	0.25	7.8
Wet (285mm)	Archer	4 April	8.0	3.7	14.3	0.26	-
	Nuseed Diamond	7 May	4.5	2.3	9.1	0.25	-
LSD (0.05)	Variety		0.9	0.3	1.1	0.01	-
	Water		ns	0.3	1.1	ns	-
	Water x Var		ns	ns	ns	ns	-

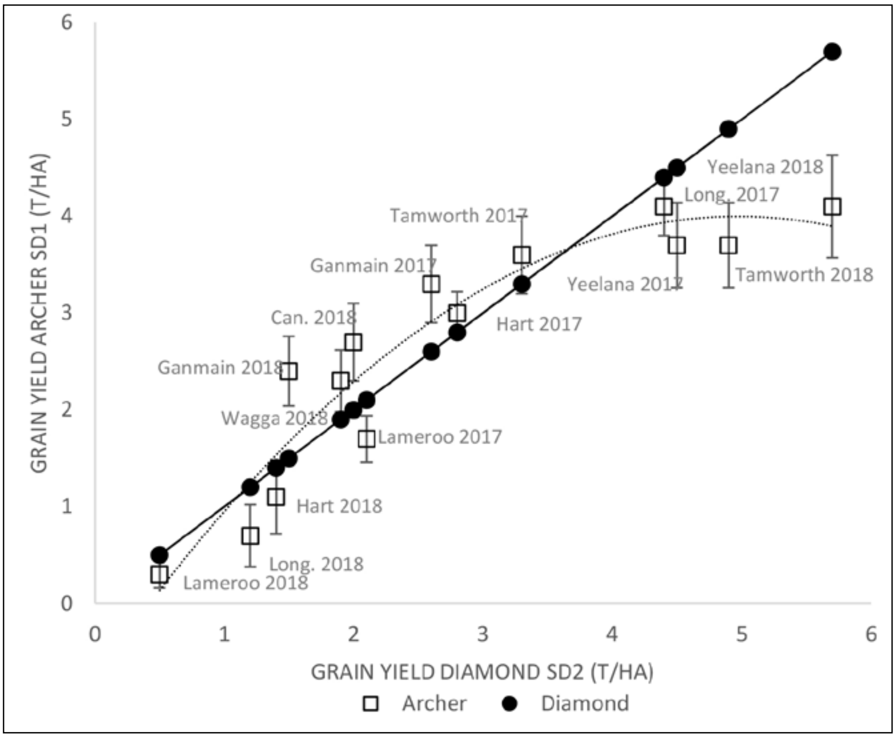

Figure 2. Grain yield of Archer sown early (early to mid-April) compared with Nuseed Diamond sown at its optimal time (late April to mid-May). Error bars indicate LSD (P=0.05). Can. = Canowindra. Long. = Longerenong (from Brill et al. 2019).

2019). On the deep red loams in southern NSW, the combination of factors including; availability of deep stored water after good summer fallow rain; soils that facilitate deep root growth; AND a terminal drought period that calls upon subsoil water, can drive the yield advantage of earlier-sown, slow-maturing crops.

Observations were repeated at two sites in 2019; Greenethorpe and Wallacetown, to compare hybrids sown on different dates but with similar flowering dates (Table 3). At both sites and under both water regimes at Wallacetown, the earlier-sown varieties had higher biomass at flowering and higher yield (average benefit 0.7t/ha). Root and water uptake measurements (at Greenethorpe only) confirmed that the earlier sown variety 45Y91 had deeper roots (Table 1) and increased water uptake from depth (data not shown), consistent with the 2018 results.

Table 3. Benefit of earlier sowing on the yield of hybrid varieties at two sites in 2019.

Site	Variety	Sowing date	Biomass (t/ha)		Yield (t/ha)
			Flowering	Maturity	
Greenethorpe(291mm)	Pioneer®45Y91 (CL)	18 April	10.7	12.2	2.4
	Pioneer®43Y92 (CL)	14 May	8.7	8.9	1.7
Wallacetown Dry (228mm)	Pioneer®45Y91 (CL)	4 April	10.0	10.2	2.5
	Pioneer®44Y90 (CL)	18 April	7.5	8.3	1.8
	Nuseed Diamond	2 May	5.9	6.8	1.1
Wallacetown Wet (308mm)	Pioneer®45Y91 (CL)	4 April	11.3	14.2	3.6
	Pioneer®44Y90 (CL)	18 April	8.6	11.2	2.8
	Nuseed Diamond	2 May	7.1	9.9	2.4

Wallacetown water regimes; dry; wet - an extra 80mm added by drippers in March.

Agronomy to capture the benefits of deep water

Capitalising on the potential of earlier-sown, deeper rooted crops on suitable soils depends upon good agronomy (https://grdc.com.au/resources-and-publications/all-publications/publications/2019/20-tips-for-profitable-canola-central-and-southern-nsw). Good agronomy includes the following key elements:

- **Crop sequence choice** – preceding grain legumes (grain or manure), chemical fallow (with adequate residue), or crops cut for hay can increase the amount of residual water available for subsequent early-sown crops compared to crops harvested for grain. This varies with season, but in 2018 and 2019 these treatments had 10-50mm extra water compared to harvested wheat or canola crops. These options can significantly reduce the risk of early-sown canola, as water is stored at depth and available in the critical period. Table 4 summarises the various pros and cons of different options to precede early-sown canola.
- **Summer fallow management** – strict summer weed control and maintenance of residue cover will increase infiltration of heavy storms, slow evaporation during summer and preserve moist seedbeds, which can provide an average of 40kg N and 40mm water/ha. Higher stubble loads will retain moisture in the surface for longer, to facilitate earlier sowing in late March or early April.
- **Early sowing with the right variety** – capitalising on stored water and N requires selection of a suitable variety that will hit the optimum flowering period from the selected sowing date. Typically, this means sowing winter types in late summer and early autumn, slow-spring types from late March to mid-April, mid-spring types in mid-April to early May and fast-spring types late April to mid-May. This will achieve the optimum flowering date to minimise the combined risks of frost, heat and water stress.
- **Ensure adequate N to achieve the target yield** – early-sown, hybrid varieties with higher yield potential, will have a higher N requirement to drive biomass and achieve high yield. Ensure the crop has 70-80kg N/ha for every t/ha of expected seed yield. Sowing canola after a legume or a long fallow will increase available N and reduce the need for high rates of N application.

Table 4 summarises the pros and cons of the various options to precede early-sown canola crops, highlighting that water is not the only aspect of the farming system influenced by crop choice.

Agronomy to manage the legacy of dry soils after high yielding, early-sown crops

Early-sown, high yielding crops can leave a legacy of drier and N-depleted soils in seasons where the spring is dry. This was seen in 2018 and 2019 in much of southern NSW and northern Victoria (Figure 1). If subsequent rainfall during summer fallow is low, and fails to refill the soil profile, it may be necessary to reconsider the crop sequence plan, or the intended sowing date of subsequent crops, in order to avoid high risk scenarios.

A current farming systems project is investigating improving the management of legacy effects where a range of crop sequence choices are combined with early-and later-sown crops with different N management. This project is examining the productivity, profitability and risk of different management options. Table 5 shows the residual plant available water and mineral N to 2m depth following a range of crops at Greenethorpe in 2018. Early-sown winter canola had no plant available water left in the top 2m, while the other crops options had between 24 and 57mm of stored water left in the profile. Legumes also left a legacy of increased soil mineral N. The different rooting depth and water use patterns of these crops may provide opportunities to plan sequences where high value legumes can be grown in sequence with early-

Table 4. A summary of the impacts of different preceding crop choices to precede early-sown canola crops (the more stars the better for each aspect).

Sequence option	Residual soil water	Nitrogen	Ground cover	Weed control	Relative
profit					
Grain legume	***	***	***	***	***
Legume hay	****	**	*	****	****
Legume brown manure	****	*****	****	*****	*
Cereal grain	*	*	*****	*	****
Cereal hay	**	*	*	***	*****
Long fallow (with cover)	*****	***	variable	****	*

Table 5. Residual plant available water (mm) and mineral Nitrogen (N) (kg/ha) at harvest to a depth of 2m following a range of different crop options at Greenethorpe in the dry year of 2018.

Crop	2018 sowing date	Rooting depth (cm)	Plant available water (mm)	Mineral N (kg/ha)
Winter canola (grazed)	3 April	370	0	24
Spring canola (hybrid, grain)	17 April	340	42	16
Spring canola (OP-TT, grain)	7 May	220	24	28
Winter wheat (grazed)	4 April	340	42	31
Spring wheat (grain)	7 May	185	24	39
Lentil	8 May	150	48	79
Chickpea	8 May	150	46	129
Fababean	9 May	150	57	103

sown, deep-rooted grazing crops. Benefits include both capitalising on water and N left by the legume and reducing the risk of negative legacy effects after early-sown crops, by sowing a less water-demanding crop.

Conclusion

On red loam soils in southern NSW, early-sown, slow-developing canola varieties have roots that grow deeply. These varieties can take advantage of deep soil water to produce more biomass and offer greater yield potential than faster maturing varieties sown later in the season — even in seasons with a dry spring. The notion that early-sown, vigorous hybrids may set themselves up to fail in a dry spring seems unfounded, at least when stored soil water is available at depth. The combination of early-sowing and hybrid canola was particularly successful at sites with a high proportion of fallow rainfall to in-crop rainfall.

Success with earlier-sown crops in the sequence requires management to increase the likelihood of deep stored water and N prior to these highly profitable crops, as well as attention to the legacy of drier, N-depleted subsoils that may follow. Strategies to be considered include; adjustments to crop sequence to utilise crops less dependent on deep water for yield (such as grain legumes of barley); or crops that provide grazing options on mixed farms. A greater awareness of plant available water throughout the cropping season provides the platform for better decision making.

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Useful resources

https://grdc.com.au/resources-and-publications/all-publications/publications/2019/20-tips-for-profitable-canola-central-and-southern-nsw)

http://www.agronomyaustraliaproceedings.org/

https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/deeper-roots-may-improve-the-water-use-of-early-sown-canola

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Estimating in-crop nitrogen mineralisation in modern cropping systems

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This paper was under review at the time of publication of proceedings and can be found in full at https://grdc.com.au/resources-and-publications/grdc-update-papers

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Advances in herbicide tolerance in pulses

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This paper was under review at the time of publication of proceedings and can be found in full at https://grdc.com.au/resources-and-publications/grdc-update-papers

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Acidity – soil sampling and lime incorporation under review

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Southern Farming Systems.

GRDC project code: DAN00206, 9176971

Keywords

- lime, soil acidity, soil pH, aluminium, tillage.

Take home messages

- Highly acidic layers between 7 and 30cm soil depth may not be detected by only sampling the 0-10cm depth.
- Recommended soil layers for pH monitoring are 0-10cm, 10-20cm and 20-30cm. Testing 0-5cm is also important if sowing acid sensitive plants and you are unsure of your soil pH profile.
- Regular liming and keeping the topsoil pH above 5.5 allows lime to move to below 10cm depth but this process is slow, even in high rainfall zones
- Strategic one-off incorporation of lime is the fastest way of ameliorating highly acidic soil layers, especially at depth

Background

Grain producers have become more proficient at Soil acidity is a common and emerging issue in most soil types. Soil acidity results from failure of growers to replace the alkalinity lost through product removal (e.g. grain, hay, mild, meat and wool), use of nitrogen (N) fertilisers and N leaching. Soil sampling protocols have largely been designed to determine nutrient supplies in the 0-10cm layer, and not necessarily to detect subsoil acidity, which can occur in deeper layers. As a result of poor detection of acidity, especially in the subsoil, most lime decisions haven't accounted for the slow build-up of soil acidity deeper within the soil profile.

Slow movement of lime, no-till farming systems and surface applications have had little effect on acidic layers deep within the soil profile. Infrequent applications of lime have raised soil pH in the top part of the soil but have left highly acidic layers at depths — often at 5 to 15cm. Incorporation of topdressed lime was once a widely accepted practice, however the move to no-till farming systems means incorporation is now uncommon. With the recent evidence of subsoil acidification, several questions are often asked; Do we need to incorporate lime and if so, what are the best ways to do this? And, how do we incorporate while minimising any damage to soil structure and maintain trafficability across paddocks?

A new SFS project with funding from GRDC and the National Landcare Program involves partners across the high rainfall zone in Tasmania, Gippsland and in southern South Australia (SA). The project is focused on finding ways to speed up the movement of lime and help improve the precision of where lime is applied. This paper reports on the soil sampling required to detect soil acidity and whether it's necessary to incorporate lime.

Basics of soil acidity

Soil acidity is measured by soil pH, which refers to the concentration of hydrogen ions in the soil solution. The scale is logarithmic, so small changes in pH can mean large changes in the amount of hydrogen in the soil. All soil pH results in this paper were measuring using a calcium chloride extract which is approximately 0.7 units lower than the pH water test. This is used for reporting on soil acidity due to its consistency across seasons and reliability in neutral to acidic soils.

The desirable soil pH in the 0-10cm layer is at least 5.0 or 5.5 for acid sensitive pulses, and at least 4.8 in the subsurface and subsoil. Low soil pH and excessive hydrogen ions impact root growth, uptake of water and nutrient availability (such as N, phosphorus, potassium, sulphur, calcium, magnesium and molybdenum), and decrease soil microbial activity. As a result, N fixation by rhizobia, organic matter breakdown and cycling of nutrients are all reduced in acidic soils. In addition, aluminium becomes soluble at a pH of 4.8 in many soils and becomes increasingly toxic to root growth as pH falls. Most feeder roots are in the top 5 to 20cm of soil, so having good pH in this layer is critical. The deeper roots are important for accessing soil moisture, particularly at grain fill when topsoils have dried out.

Diagnosing soil acidity

Soil acidity develops slowly over many years and crop symptoms such as slow or reduced growth go unnoticed. Also soil pH varies across the paddock and if acid sensitive plants are sown such as lucerne, faba bean or barley, poor patches often show up. Areas of soil acidity are difficult to detect by eye and soil sampling and testing is the best method for diagnosis.

The standard soil testing depth for fertiliser decisions is 0-10cm, and deeper testing is sometimes included for N - 10-20, 20-30cm or deeper. Among 200 paddocks tested by SFS in the Corangamite and Glenelg Hopkins catchments, the main acidity issues have been at 0-10cm and 10-20cm (Table 1). Sandy soils have a low pH buffering capacity and small additions of acid cause a large drop in pH, which is why acidity shows up first in sandy patches. Where the clay content is high, the soil pH tends to be neutral to alkaline, which in SW Victoria commonly occurs at 20-30cm. Combining soil from 10-30cm, which is sometimes recommended for subsoil sampling of nutrients, can mask acidity issues at 10-20cm.

Table 1. Mean soil pH(Ca) of 100 different farming enterprise paddocks in both Corangamite and Glenelg Hopkins catchments in SW Victoria, taken in 2018 and 2019 (Miller 2019, Debney 2019).

Depth (cm)	Corangamite 2018 pH (Ca)	Glenelg Hopkins 2019 pH (Ca)
0-10	4.9	4.9
10-20	5.0	4.8
20-30	5.3	5.1

If you detect low pH (<4.8) at 20-30cm, then test 30-40cm and so on, to build a picture of pH throughout the soil profile. This allows you to target areas to monitor.

Where there is limited history of lime applications, the soil pH profile is often relatively uniform. For example, Table 2 shows the soil pH profile at the Drysdale site, with no lime history, which has a consistent soil pH down to 20cm. The detection of soil acidity is more complex when lime has been applied, because this creates stratification and a favourable pH layer often confined to the top 5cm of soil. Note the difference of 1.2pH units between the top and bottom 5cm increments at Drysdale.

Soil testing in 5cm increments is somewhat laborious and expensive but it provides the greatest detail of pH stratification and knowledge of acid barriers. This is recommended when you are planning to sow acid sensitive legumes. At Hamilton for example, lucerne was established in a paddock

Table 2. Soil pH(Ca) at Hamilton and Drysdale sites, at different soil depths with and without surface lime. Two soil sampling strategies (in 10 or 5cm increments) were compared.

Testing method	Depth (cm)	Hamilton Lucerne	Drysdale 2014 (no lime history)	Drysdale 2018 following lime in 2014
10cm increments	0-10	4.9	4.2	5.2
	10-20	*	4.4	4.6
	20-30	*	4.9	5.0
5cm increments	0-5	5.9	4.3	5.6
	5-10	3.9	4.0	4.4
	10-15	4.4	4.3	4.4
	15-20	4.9	4.5	4.6

that had been recently limed, but large patches died out after three months. Further testing showed a soil pH of 4.9 at 0-10cm (Table 2), however, 5cm increment testing showed a pH of 3.9 at 5- 10cm and 4.1 at 10-15cm (McCaskill et al. 2009).

Increment testing at 5cm depths is difficult as you need to extract intact cores and split them into increments. It's ideally done when there is soil moisture so samples hold together, but not so sticky that they can't be pushed out of the coring device. Lubricants can be used which don't interfere with soil pH. For this reason, many agronomists like to extract soil cores using a dig stick, or open facing coring device, and apply pH field test indicator along it to give a quick pH guide of the soil profile.

Where to sample in the paddock?

Precision or grid sampling is a tool that can be used to help identify variability through pH mapping. Analysis of 350 paddocks and found the average range in pH values with paddocks was 0.95 units, ranging from 0.1 to 3.2pH units (Barlow et al. 2019). This means that with an average pH in the paddock of 5.0, pH might vary from 4.1 to 5.9. When sampling paddocks, different land management units or soil types need to be sampled separately. The Fertcare® soil sampling guide is an excellent reference and provides information on separating out zones of different soil types and unrepresentative areas.

For general monitoring, a zigzag pattern across the paddock gives a good representative sample, lowers risk of bias, and is easy enough to do (Table 3). The straight-line transect is not quite as reliable, as you could potentially follow a pateern (e.g. a feeding line of sheep). Use GPS reference points to identify transects for future monitoring, and for monitoring trends.

For decisions about the use of variable-rate lime, precision sampling divides broadacre paddocks into one to two hectare grids and takes eight samples within each grid along a 120 to 160m transect. Whilst statistical models may suggest more intensive sampling may be needed to inform site specific management, the costs can become prohibitive and may not be practical.

Do we sample in the row, or outside it, or both?

American research was used to inform sampling patterns where fertiliser banding occurs (Kitchen et al. 1990). Recommendations are based on row spacing. For example, for 30cm row spacings, one core from the sowing row should be combined with eight from the inter row soil to get a true average of the soil. in the absence of research on what is applicable in relation to soil acidity sampling in modern farming systems, which potentially use deep banding of fertiliser, the above recommendation remains the best advice.

Deep banding of N can cause acidification at the placement site. Unlike ammonium-based fertilisers, deep banding of urea itself does not cause net acidification unless N is converted to nitrate and leached. Deep banding is not yet a widespread practice but monitoring pH at the depth and location of where the N is being placed is probably worthwhile — especially if is beyond 10cm.

pH mapping and variable rate – is it worth it?

Soil pH mapping involves more intense sampling and identification of zones of difference to tailor lime rates to reach a target pH. VR lime application may appeal to growers if it offers cost savings by reducing the amount of lime needed compared to a blanket rate application. There is also potential for reallocation of lime, so the poor areas get more, and/or a more even pH distribution is created. pH mapping assists growers and agronomists to identify problem areas and provides greater information to make more informed decisions about the rates of lime needed across the paddock.

The question of pH variability and economic benefits of high cost intensive point sampling was investigated by Agriculture Victoria (GRDC project DAV00152), who investigated pH and

Table 3. Fertcare®'s soil sampling paddock/block sampling patterns and attributes.

Pattern	Repeatability for monitoring	Labour efficiency	Ability to automate	Likelihood of representative sample	Reducing risk of bias
Transect	*****	*****	*****	***	***
Zigzag	*****	****	*****	****	****
Cluster	*****	****	***	**	**
Uniform grid	**	**	**	*****	*****
Random	*	**	*	*****	****

Note: As the sampling characteristics improve the number of asterisks assigned increases (Source: Gourley and Weaver, 2019).

lime responses in 10 paddocks in the high rainfall cropping zone. A discounted cash flow model was used to compare a high cost 'precision strategy' involving grid soil pH mapping and variable rate lime applications to low-cost traditional sampling, testing and uniform applications across the paddock. Cost assumptions included commercial production of a grid map at $16/ha (including laboratory analysis of two top-soil samples per ha) and VR lime application costing approximately $4/ha more than normal spreading.

Findings showed that nine out of 10 sites had a greater Net Present Value (NPV) when the precision strategy was employed compared to applying the traditional strategy, but only when an acid sensitive pulse was included in the rotation, such as faba bean (Stott et al. 2019). The size of the additional net returns ranged from 2% to 14% for the case study paddocks examined. NPV was low when the precision strategy was applied at the Seaspray site, which had a mean pH (Ca) of 4.2 and a co-efficient of variation (CV) of 4.8% — exhibiting less variation than most sites. Eight of the 10 sites had considerable variation with a CV ranging from 6.2 to 11.9%. However, the traditional uniform strategy had a higher NPV for all 10 sites when a more acid tolerant rotation was used, such as barley-wheat-canola.

This analysis indicated that if the paddock has a pH >4.5 and a CV >4%, and high-value acid-sensitive crops are planned in rotation, then the net returns from precision pH mapping and variable rate liming would be superior to traditional methods (Stott, pers. comm.).

Do we need to incorporate lime?

The decision to incorporate lime or leave it on the soil surface is dependent on where the acidity issue is and how fast you need to ameliorate soil acidity, given that lime moves approximately one to 2cm per year at best. In the examples given below it can take up to 20 years to address acidity down to 30cm. If soil pH is poor at 5cm and beyond, and you are using acid sensitive or high value crops, then incorporating lime helps ensure establishment and additional yield. Currently, deep-banded acidity is not easy to implement and considered a poor investment (Conyers et al. 2019).

There are two long-term lime trials that provide evidence of how higher rates and frequent applications of surface applied lime have addressed subsurface acidity without incorporation. Firstly, a trial near Wagga Wagga ran for 23 years, with a starting pH of 4.1 (0-10cm) and 4.2 (10-30cm). This trial involved applying superfine lime every six years, which reached and maintained soil pH above 5.5 in the surface 0-10cm after 11 years (Li et al. 2019). Only after this occurred did alkalinity leach into the layers below. Another finding of this trial indicated the acidification rate at 10-20cm was very low (0.005 pH units per year) suggesting not a lot of lime is needed at depth to match and exceed the acidification rate. Soil pH under the lime treatments increased at 0.04 pH units per year as the alkali moved vertically over time. This was a sandy soil, and high clay content soils will have higher pH buffering capacity, slower soil pH amelioration rate and will require higher rates of lime to change pH.

In the sandy soils of WA, several acidity trials have been monitored over the long-term. A trial at Wongan Hills was established in 1994 and tracked pH change after recurring applications of surface applied lime (Azam et al. 2019). The sandy soil was limed three times over the 23-year period and had higher soil pH throughout the top 30cm compared to the untreated control. This was achieved by maintaining soil pH above 5.5 in the top 10cm, allowing movement of alkalinity to the subsurface soil. However, a large proportion of the applied lime was undissolved and still sitting in the top 4cm, mainly from the most recent applications of lime. In this case the undissolved lime was related to its coarseness. When the acid soil particles react with the edge of the lime partciles, the surrounding pH increases until it reaches pH (Ca) 5.4 when dissolution slows and stops as the soil becomes alkaline. The pH adjacent the soil needs to further acidify before the lime starts dissolving again. Through incorporation, this lime was further distributed through the profile to correct acidity and achieve greater grain yields.

Although topdressing lime on the soil surface can address deeper acidity, it is far better to avoid subsoil acidity in the first place by maintaining topsoil pH (Ca) at 5.5 or above.

The pros and cons of incorporation

Some downsides of incorporation include additional costs, reduced trafficability, and potential negative effects on soil structure. Mark Conyers, former NSW Agricultural research scientist discussed the results of a strategic tillage project at the 2017 Bendigo GRDC Update. Conyers acknowledged that repeated tillage is not ideal and while tillage should be minimised, a strategic 'one-off tillage' or lime incorporation can address agronomic or soils issues and will not undo 20 to 30 years of no-till. In the worst cases on red and grey clays of southern NSW, he found that strategic tillage

Table 4. Summary of Southern Farming Systems lime application method trials (Miller 2016 and Miller 2018).

Site and establishment time	Method	Issues and lime type	Effect on plant establishment	Effect on yield
Stawell Jan 2019	1. Offset discs to mix lime to 10cm. 2. Offset discs with deep ripping with/without lime placed in acid layers at 25 and 50cm spacing. 3. No till surface lime.	At ripping, the combination of deep ripping at 25cm spacing and offset discs caused the soil to completely lose its structure. Fine grade lime used.	Significant (S) decline in canola establishment in offset disc treatment compared to other treatments ($p<0.05$, LSD 6 plants/m^2)	Canola no significant (NS) difference in yield from treatments, but nil lime yielded lowest (0.1 to 0.2t/ha) compared to other treatments
Skipton Apr 2019	1. Tynes to mix lime to 10cm. 2. Deep ripping following with/without surface liming. 3. No till surface lime.	In winter, farm tractor sank leaving trench in one area. SW lime used.	S decline in deep rip treatment with lime compared to surface only applications ($p<0.05$, LSD 29 plants/m^2)	2019 wheat harvest results unavailable at paper submission
Mt Mercer Apr 2019	1. Tynes to mix lime to 10cm. 2. Deep ripping following with/without surface liming. 3. No till surface lime.	Ripping brought up sodic clods of soil and basalt boulders. SW lime used.	NS difference of Triticale between treatments. High variation across plots	NS yield differences between treatments or trends shown in 2019
Rokewood Jan 2018	1. Offset discs to mix lime to 10cm. 2. Offset discs to mix lime plus deep rip placement of lime. 3. Offset discs to mix lime with deep rip only. 4. No till, surface lime.	No issues with 50cm ripping spacing or other treatments. Fine grade lime used.	S decline in lupin establishment 2018 with offset discs plus deep rip (no lime) treatment compared to other treatments ($p<0.05$ LSD 1.4 plants/m^2). S decline in 2019 with wheat in deep ripping treatments versus no till surface lime ($p<0.1$, LSD 19.8 plants/m^2).	NS difference between tillage treatments in 2018 and 2019 but no till had lowest yield (approximately 0.2t/ha) compared with other treatments
Inverleigh April 2016	1. Offset discs to 15cm. 2. Deep ripping with lime placed in rip lines 38cm spacing. 3. No till, surface lime.	None. SW lime used.	No observed difference.	NS differences between incorporated and top-dress treatments in 2016, 2017, 2018. In 2017 highest rate of lime (5t/ha) increased wheat by 0.24t/ha above standard 2.5t/ha ($p<0.05$, LSD 0.23)
Drysdale April 2016	1. Offset discs to 10cm. 2. Deep ripping with lime placed in rip lines 75cm spacing. 3. No till surface lime.	None. SW lime used.	No observed difference.	Tillage method was NS in 2016. No harvest 2017. In 2018 highest rate of lime (5t/ha) increased yield by 0.6t/ha above standard 2.5t/ha ($p<0.05$, LSD 0.57). Tillage method NS but 0.3t/ha higher than no till methods

set soil structure back by two to four years, and that adding fresh residues, green manures or a pasture phase hastened the recovery. Additionally, strategic tillage either did not affect yields, or improved them (Conyers et al. 2017).

Conyers et al. 2019 outlines the main agronomic reasons for tillage, one of them being to incorporate lime, overcome stratification and correct deeper acidity. Ignoring a deep acidity problem just to maintain soil structure may not be prudent. Soil structure is improved with organic matter breakdown, microbial and earthworm activity and fine roots — all of which will be restricted in acid soil layers.

Trafficability after incorporation is a concern in the high rainfall zone. Deep ripping earlier in the year may help decrease soil moisture and dry out rip lines to reduce trafficability issues. This can be beneficial where winter waterlogging can be an issue, but it may increase the risk of erosion. By leaving tillage later in the season, soil moisture might also affect the result, with soil smearing on clay soils rather than mixing or shattering. There are also concerns about tillage in sodic subsoils — bringing sodic soil to the surface might cause poor structure, surface sealing and reduce plant establishment.

What incorporation methods can be used?

The incorporation method most suitable depends on where the acidity is located in the profile and what other agronomic constraints could be addressed in the one operation. Agronomic constraints might include treating compaction, re-distribution of nutrients, soil borne diseases slugs/snails, and burying weed seeds.

Not all tillage methods are effective at mixing lime and vary with their effects on soil structure and trafficability. Burns and Norton 2018 report the ineffectiveness of the Speedtiller®, set to a depth of 8-10cm, where 4t/ha of fine grade lime applied over five years was still confined to the shallow surface soil (0-5cm), leaving a pH of 4.4 and a 4.2 from 5 to 10cm. Light harrowing has also had poor results (Scott and Coombes, 2006).

SFS have used different methods of lime incorporation, with results and issues shown in Table 4. The results from trials are indicating some reduction in establishment using tillage treatments in the first year following incorporation, compared to no-till. However, by harvest time the yields from incorporation methods tended to be either the same, or slightly higher than the no-till treatments — especially after the first year. With shallow soil acidity at 15-20cm depth, the use of offset discs or a tined implement to mix lime to 10 or 15cm is preferred, with lime rates capable of raising pH to 5.5 so lime can move further downwards if required. Tined or offset disc implements have created few issues and the paddocks have been trafficable afterwards.

Deep ripping has been used to address acidity down to 30cm depths. Ripping on 50cm spacings between tines is suitable for addressing deep acidity as it can create preferential pH pathways for roots to follow. However, this leaves areas un-limed between the rip lines which will continue to acidify. For this reason, lime still needs to be applied across the paddock and either surface applied or incorporated in a separate pass. Experimental implements with the capacity to band lime within the acid soil layers have proven difficult to use of a broad scale.

A NSW DPI purpose-built machinery was used at subsoil acidity trials in Victoria. Deep ripping with rip lines 25cm apart was used at Stawell after being validated at Ferndale, NSW in a subsoil acidity trial. Deep ripping placed lime about 10 to 12cm either side of the rip line and 25cm rip spacing allows intersection of lime. However, the combined ripping at 25cm spacing followed by offset discing to incorporate lime at 10cm overworked the light sandy soil, causing loss of structure and traction.

Conclusion

Being able to identify areas of soil acidity in three dimensions (i.e. spatially across the paddock and down the soil profile) supports more informed decision making regarding suitable lime strategies, especially if acid sensitive legumes (e.g. faba bean or lucerne) are part the rotation.

Subsurface acidity issues are most likely to occur from 7-20cm and can be missed through standard 0-10cm sampling methods. Therefore, sampling at 0-10cm, 10-20cm and 20-30cm sampling is recommended as a first step. In some cases, further sampling in 5cm increments may be warranted for a more detailed investigation.

Incorporation of lime gives rapid amelioration of acid topsoil layers and will move into deeper layers over a period of 5-10 years provided the top-soil pH is kept above 5.5. However, the time frame to treat subsoil acidity and the loss of yield while waiting for surface applied lime to reach the subsoil, makes it an economically unattractive choice when the subsurface acidity is severe.

Incorporation of lime through some form of strategic tillage can address subsoil acidity constraints and increase yields, especially for acid sensitive or high value crops.

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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.

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Recommendations for ripping deep sandy soils of the Mallee

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GRDC project code: CSP00203

Keywords

- deep ripping, sandy soils, soil amelioration, penetration resistance, Mallee, soil constraint, organic matter, fertiliser placement, inclusion plates, machinery design, forces.

Take home messages

- Consistent first-year yield responses to deep ripping have been measured on Victorian Mallee sandy soils, with yield benefits commonly 0.5 to 1.0 t/ha in the first season following deep ripping.
- Short-term yield responses to deep ripping in the dry years tested have not been improved through additional inputs of fertiliser or organic matter (OM) on sandy soils in the Victorian Mallee.
- There are opportunities to optimise tine spacing, power requirements and operating costs of ripping and inclusion operations, through improving our understanding of the interaction between soil loosening, shank design and working depth.

Background

Sub-optimal productivity is commonly reported for the deep sands that make up 20 to 30% of the cropping soils in the low rainfall Mallee region of Victoria (Unkovich, 2014). There is evidence of unused soil water, despite an apparent absence of constraints commonly associated with sandy soils (such as non-wetting or acidity). Diagnostic studies of local constraints have pointed to low abiotic and biological fertility in the subsoil layers, and to the physical restriction of rooting depth, as the most likely constraints to production on sands in the Victorian Mallee.

There is considerable interest in strategic deep tillage with/without agronomic amendments (fertilisers, organic amendments) aimed at overcoming physical constraints and increasing water and nutrient supply within the soil profile. Strategic deep tillage includes ripping or deep soil mixing and inversion operations (i.e. spading, Plozza Plow) to depths of 30cm and more. To explore this further, replicated trials have been established across four sites in the Victorian Mallee; Ouyen (2017), Carwarp (2018), Kooloonong (2019) and Tempy (2019), with further sites to be established in 2020. These trials are part of the research and validation work within the GRDC project; 'Increasing production on sandy soils in the low-medium rainfall areas of the southern region' (CSP00203). The trials are a collaboration between Frontier Farming Systems with Mallee Sustainable Farming, CSIRO and UniSA.

Although the benefits of deep ripping in deep sandy soils have been recognised previously, there is a need to understand where ripping can most reliably lead to yield benefits, how benefits can be maximised over multiple seasons, and which sands are more or less likely to respond. There are opportunities to optimise machinery set-up and operating parameters (e.g. speed, depth, fuel consumption) and to understand how tine design influences constraints within the profile over multiple seasons. Improving this information will help inform grower decision making to better target soil amelioration practices.

Method

Deep ripping trials

Nutrient placement (Ouyen, 2017-19)

This trial investigated three key fertiliser factors; the depth of placement (surface band at 7.5cm deep, deep band at 20cm deep and deep ripped band at 30cm deep), the nutrient source (N only or a package of N, P, K, S, Zn, Cu, and Mn) and the frequency of addition (all in 2017, or an annual approach of equivalent total input) supplying 90kg N/ha in total. All plots received an annual baseline addition of 20kg N/ha as di-ammonium phosphate (DAP) at sowing and top-dressed application of ammonium sulphate during tillering. The trial was sown to Spartacus barley in 2017, Kord Wheat in 2018 and Spartacus barley in 2019.

Organic matter placement (Carwarp, 2018-2019)

This trial compared the impact of physical intervention alone (deep ripping, spading or a combination of the two), to physical intervention combined with incorporation into the surface soil or deep placement of lucerne hay at 6t/ha (Table 1). For incorporation, lucerne hay was spread on the soil surface before spading with Farmax spader supplied by Groocock Soil Improvement (http://www.spaders.com.au/). For deep subsoil placement, the same lucerne material was pelletised and metered at a controlled rate behind the rip tine at depth. Deep ripping operations at 30 or 60cm depth were completed with a Tilco® ridged shank at 56cm spacing. The trial was sown to Spartacus barley in the fist season (2018) followed by Razor Wheat in the second year (2019).

Deep ripping with organic matter (Tempy, 2019)

The Tempy trial was sown to Barley in 2019 and comprised of five treatments to compare deep ripping only with inclusion plates and OM addition (details below). All deep ripping treatments were implemented to a depth of 50cm with a tine spacing of 56cm. The OM used was a chicken litter compost blend, applied at 5t/ha (https://www.peatssoil.com.au), in the following treatments;

- control (undisturbed)
- deep ripping (50cm) with rigid shank (Tilco)
- deep ripping (50cm) with inclusion plate (Tilco) operating 150mm below soil surface
- deep ripping (50cm) with inclusion plate (Tilco) plus OM surface applied
- deep ripping (50cm) with OM deep placed behind the ripping shank.

Break crop response to deep ripping and organic matter (Kooloonong, 2019)

The Kooloonong trial was established for a range of break crops; lupin, lentil and chickpea. Each trial comprised of four treatments arranged in a factorial design;

- +/- deep ripping (50cm depth with tine spacing of 56cm)
- +/- surface OM application at 5t/ha (chicken litter compost blend https://www.peatssoil.com.au).

Optimising deep ripping operations

Complementing these and other agronomic field trials, University of South Australia researchers are using computer simulation and field validation to understand how different equipment, design, set-up and operating parameters affect the performance of deep tillage strategies. Computer simulations have highlighted that forward (driving) speed was likely to have a large impact on the burial performance of commercially available inclusion plates. A range of experimental inclusion plates were manufactured and compared to a standard commercially available plate at two operating speeds in a trial near Caliph, SA Mallee, in June 2019. The soil type was a red sand with an average soil bulk density of 1.6g/cm^3 from 0-400mm depth, and an average moisture

Table 1. Treatments included in the organic matter (OM) placement trial at Carwarp, established 2018.

Treatment	Physical disturbance	Depth of disturbance (cm)	OM addition (6t/ha lucerne)	Depth of OM placement (cm)
Control	Nil	Nil	+/-	Surface
Spade	Rotary spade	30	+/-	Surface-30
Deep rip_30	Deep rip	30	+/-	30
Deep rip_60	Deep rip	60	+/-	60
Deep rip_30/60	Deep rip	60	+/-	30+60
Spade + deep rip_60	Rotary spade + deep rip	30+60	+/-	Surface-30 + 60

content of 3% over the same depth range. The validation of the surface layer burial was carried out by applying a blue layer of sand to the surface in front of the tine (Figure 1).

The draught forces required to pull the standard ripper tine and each of the inclusion plates was also measured using a RIMIK brand pull-meter. The pull-meter was used between two tractors (a draught tractor pulling a free-wheeling, ripper operating tractor) to avoid side and vertical loading, ensuring that the load cell measured pure tension with no side-loading.

The research also aimed to quantify the impact of shank working depth and design on soil loosening performance in the compacted sandy soils. Tines tested included with and without wings (Figure 2), and measurements included differences in relevant draught forces and soil disturbance profiles. After ripping operations, face pits were excavated across the direction of travel to visualise and refine the loosened cross-sectional area (Figure 3). Digital image analysis was used to quantify the profile area loosened across different test treatments.

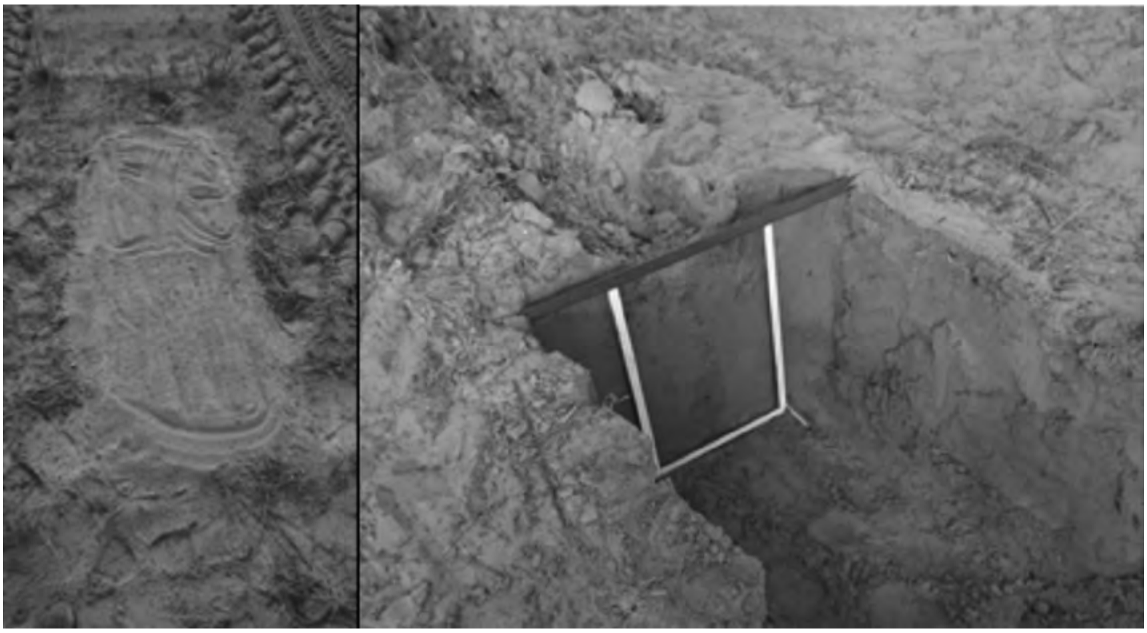


Figure 1. Blue sand applied to the surface to validate soil burial behind inclusion plates.

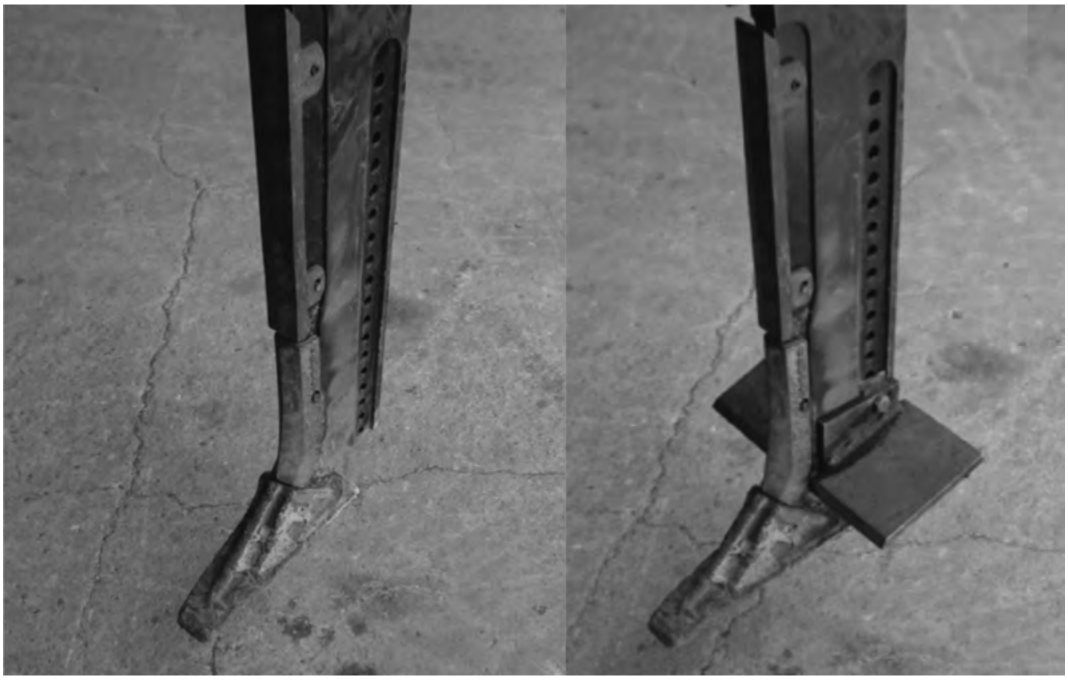


Figure 2. Ripper tine (left) and ripper tine with wings (right).

Figure 3. Excavated pit with a white rope defining the boundary of the loosened soil.

Results and discussion

Yield response to deep ripping

The first three years of the project (2017-2019) have seen low rainfall seasons in the Victorian Mallee. Average growing season rainfall generally ranges from 180mm-230mm in this region, however as shown in Table 2 growing season rainfall at all trial sites has been well below this long term expected rainfall.

Table 2. Growing season rainfall at each site

Site	Growing Season Rainfall (mm)		
	2017	2018	2019
Ouyen	123	93	88
Carwarp		56	75
Tempy			126
Kooloonong			100

Despite below average rainfall throughout the first three years of the project, positive yield benefits have been observed following deep ripping across all four trial sites in the first season. At the Ouyen trial (2017, year 1) deep ripping at ~30cm provided a yield benefit of 0.8t/ha over the control and the pre-drilled fertiliser treatments (Figure 4). This result reflected a reduction in penetration resistance measured under the deep ripped treatments (Figure 5). Pre-drilling fertiliser at 20cm depth did not reduce the sands penetration resistance, as the narrow tine and knifepoint used had a slotting effect and did not disrupt soil strength, unlike the deep ripping implement (Agroplow deep ripping shank with a wide foot).

Following the single ripping event at Ouyen in 2017, significant yield benefits were observed for two subsequent seasons, but not in the third season, providing a cumulative benefit of 1.5t/ha. Where ripping was repeat applied on an annual basis, positive yield responses were observed in all three seasons (Figure 4), with cumulative benefit over the control of 2t/ha.

In the first year of the Carwarp trial, mechanical disturbance to 30cm by rotary spading or deep ripping resulted in additional grain yield of 0.5t/ha compared to the unmodified control yield of 0.55t/ha (Figure 6). Deeper ripping to 60cm did not provide a significant yield increase over working to a depth of 30cm only. These responses were observed under very dry conditions, with only 75mm of rainfall post sowing. Another drought was encountered in 2019 with similar low rainfall during the growing season and very little rainfall over the summer fallow. Consequently, a negative yield effect of 0.5-0.6t/ha was observed in treatments where deep ripping was conducted to 60cm in the previous season. The mechanism of this result is not clear and is still being explored.

In 2019, new sites were established at Kooloonong (Figure 7) and Tempy (Figure 8) demonstrating yield gains across several crop types. Comparing grain legumes at Kooloonong, deep ripping significantly increased the yield of lupin, lentil and chickpea by 0.4, 0.4 and 1.0 t/ha respectively. At Tempy, deep ripping provided a 0.7t/ha increase in barley yield over the control, however adding inclusion plates did not provide any advantage over deep ripping with a ridged shank tine.

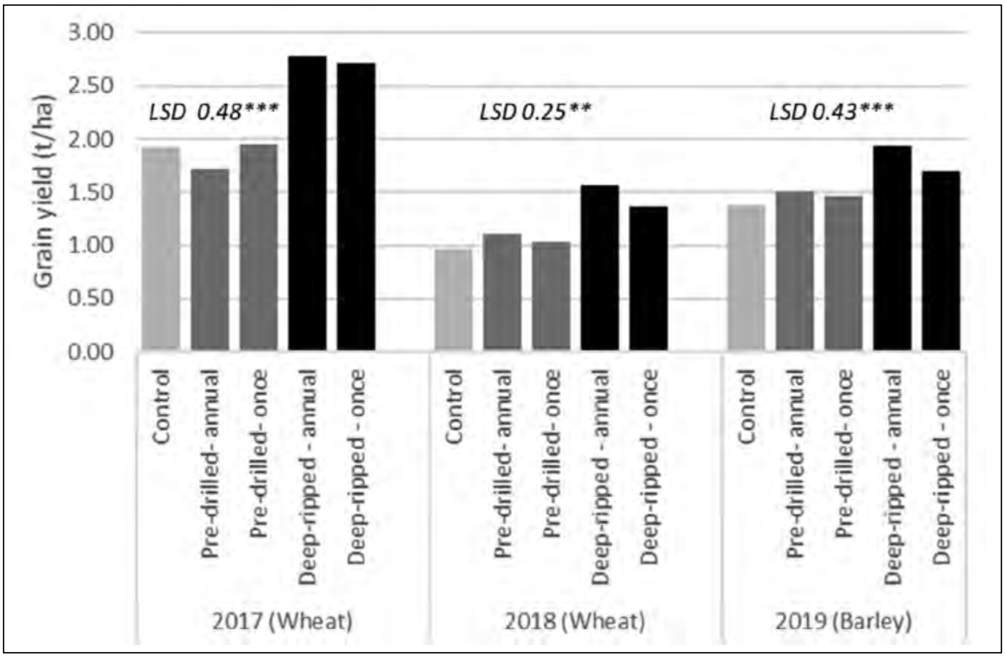


Figure 4. Grain yield (t/ha) response at Ouyen to pre-drilling or deep ripping implemented prior to sowing in (once) or in each season (annual). Only the control treatments are presented which all had equivalent rates and placement of nutrient.

While deep has provided clear benefits across these four trial sites, the addition of inputs such as OM or additional fertiliser did not show consistent and/or economic benefits under dry trial conditions. Improving inputs over and above good agronomic practice through subsoil placement (30cm or deeper) of nitrogen or a broader nutrient package (P, K, S, Zn, Mn, Cu) did not provide a yield benefit at Ouyen. A sister trial at Ouyen looking at the incorporation of organic inputs with rotary spading showed a positive response to the addition of chicken litter and compost (Moodie et al. 2019). However, this effect was unable to be replicated with similar organic inputs at the Tempy and Kooloonong sites in 2019. Lucerne hay was used as an organic source at Carwarp with no positive yield impacts observed across the first two, albeit very dry, years of the trial.

Optimising deep ripping operations

There is considerable interest in ripper modification and/or fitting inclusion plates to the back of the ripping shank. Inclusion plates aim to improve subsurface fertility by creating a void behind the ripping shank, into which the topsoil, surface residues and surface spread amendments fall.

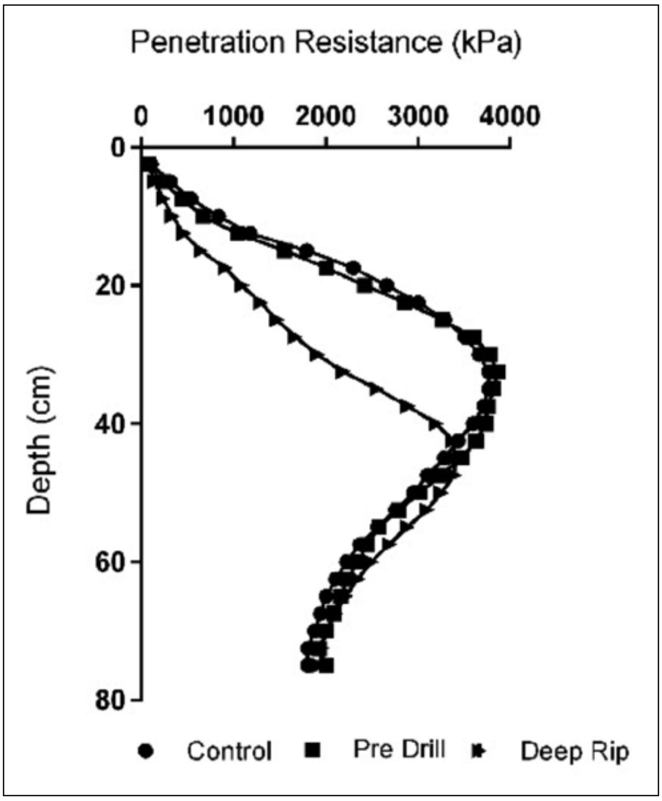


Figure 5. Penetration resistance (kPa) measured at the Ouyen site in 2017 for the control, pre-drill and deep rip treatments.

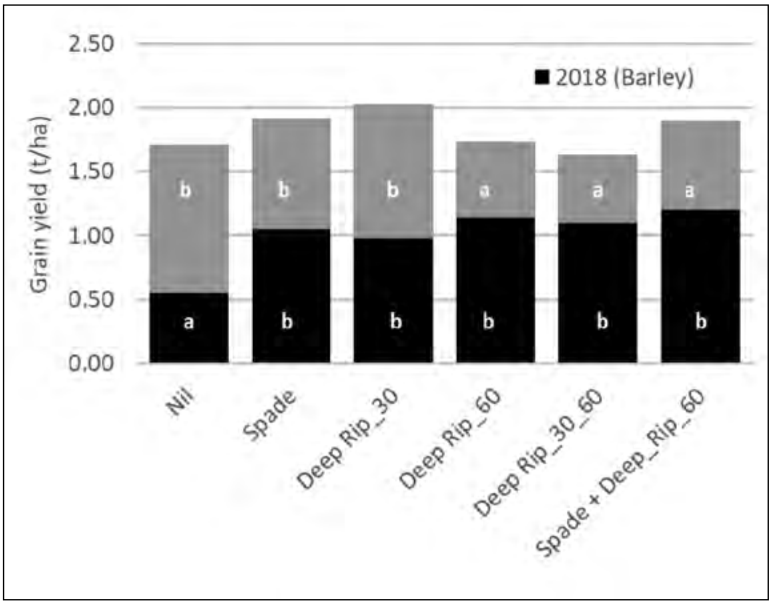


Figure 6. Grain yield (t/ha) response at the Carwarp site to deep ripping and spading treatments without organic matter (OM) addition over two seasons (2018 and 2019).

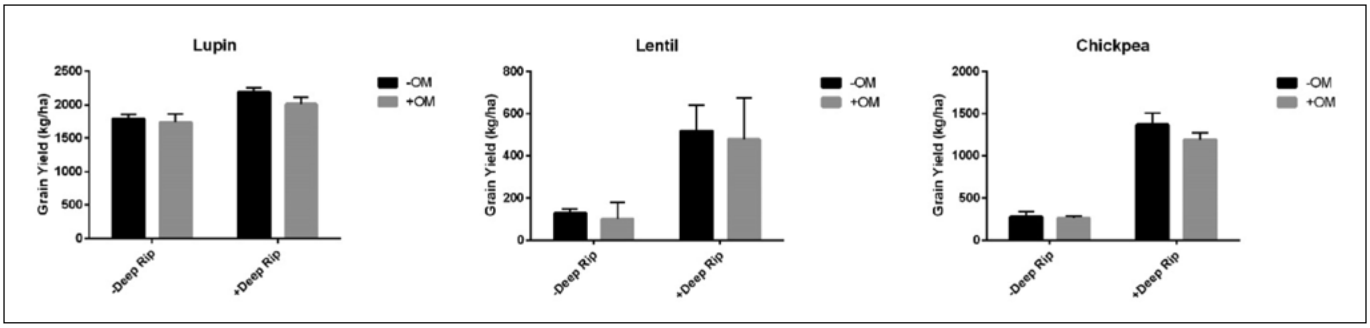


Figure 7. Grain yield of lupin, lentil and chickpea at Kooloonong in 2019 in response to deep ripping and organic matter (OM) addition. Error bars are standard error of mean (SEM).

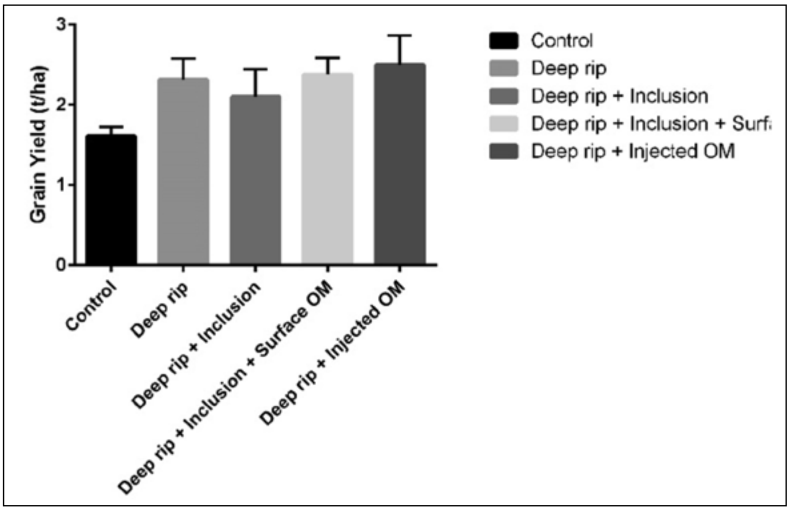


Figure 8. Grain yield of barley in response to treatments implemented at Tempy in 2019. Error bars are standard error of mean (SEM).

Incorporation of surface material behind a standard (290mm high x 300mm side wall length) commercial inclusion plate is greatly affected by speed of operation, where higher speeds lead to lower burial (Figure 9). Modification of inclusion plates, such as increasing the length of the side wall (150mm length extension on standard plate), can lead to improved burial at higher speeds, as illustrated in Figure 10. Further modification to the plate (390mm high and 600mm side wall length) improved depth and quantity of included surface layer (Figure 11).

In relation to the draught forces, adding inclusion plates led to an increase in the force required to pull

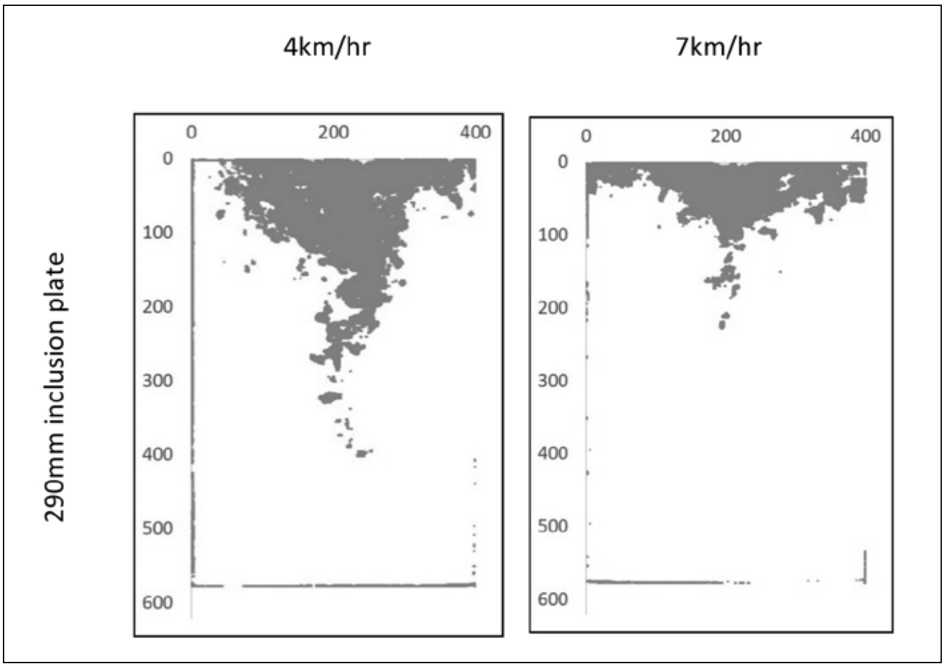


Figure 9. Topsoil inclusion using a standard 290mm high x 300mm side wall length inclusion plate at 4km/h and 7km/h.

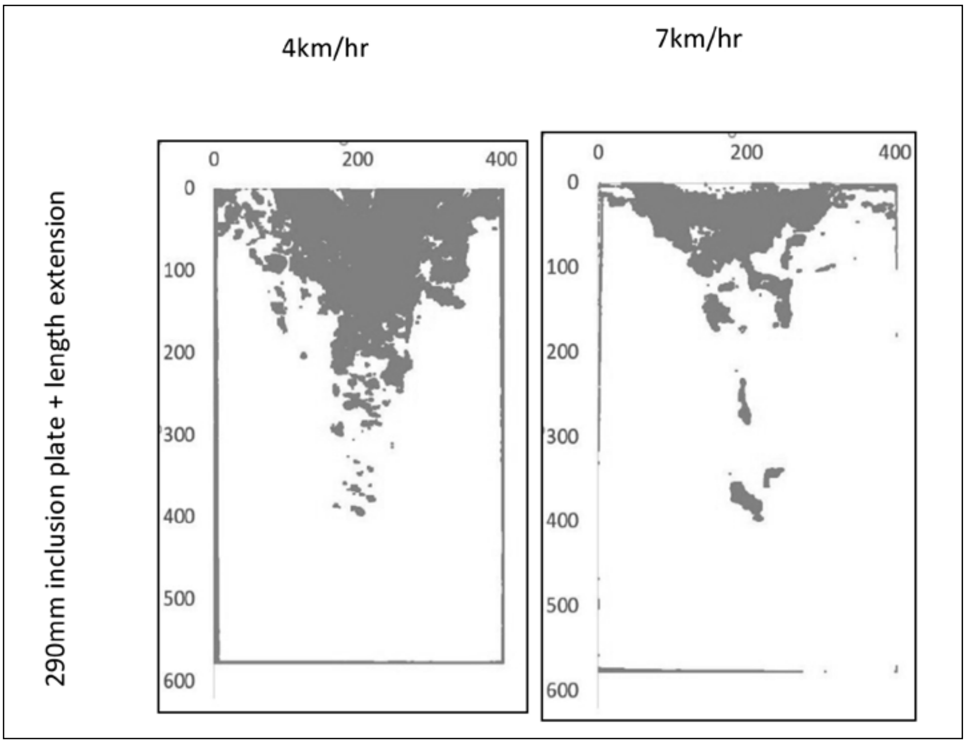


Figure 10. Topsoil inclusion using a 290mm x 450mm side wall length inclusion plate with 150mm length extension at 4km/h and 7km/h.

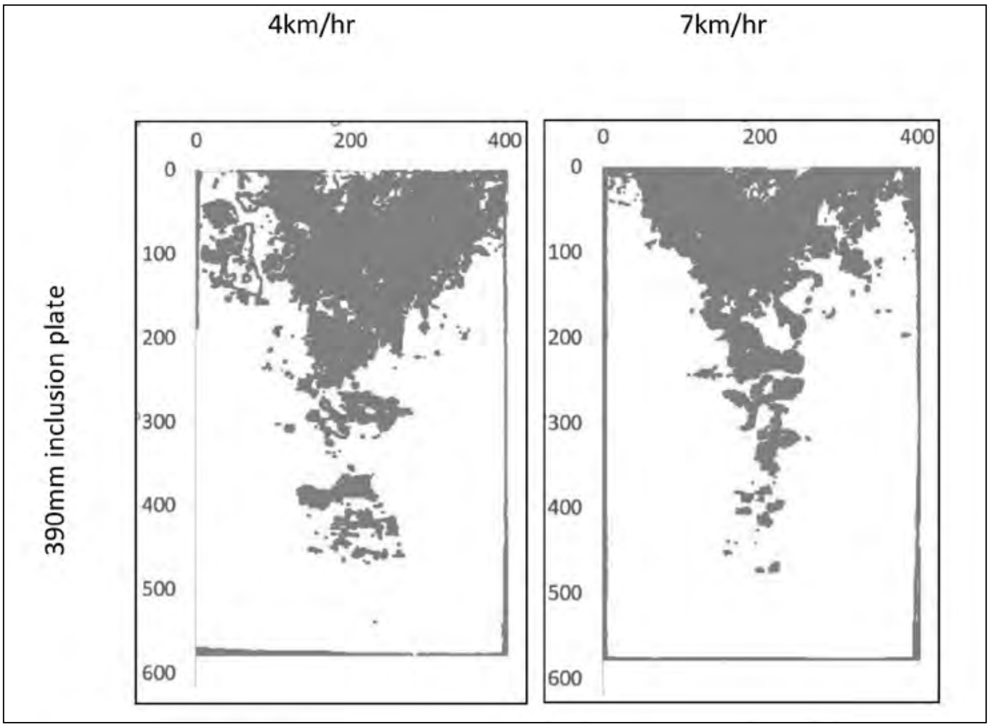
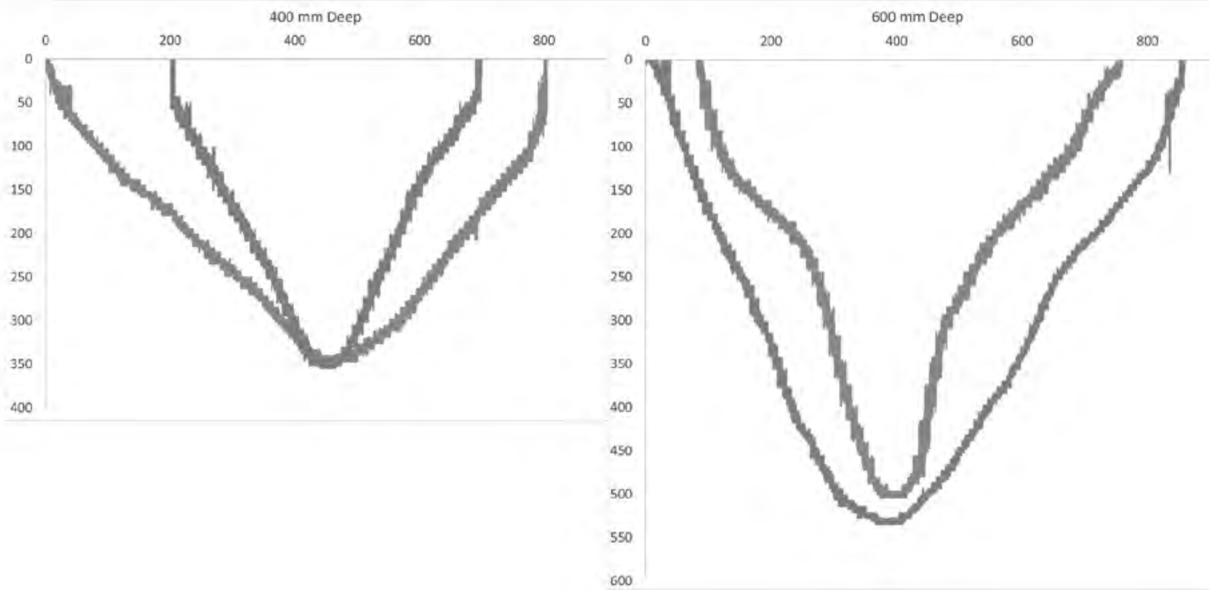


Figure 11. Topsoil inclusion using a 390mm high x 600mm side wall length inclusion plate with 150mm length extension at 4km/h and 7km/h.

the ripper. Increases in the draught forces were in the order of 40%, but the larger inclusion plates for improved burial only increased the draught force by an additional 12% and 15% at 4km/h and 7km/h respectively. Increasing draught forces correlate directly to increases in tractor power and fuel requirements associated with the operation.



(A) 400mm ripper profiles; blue without wings, orange with wings

(B) 600mm ripper profiles; blue without wings, orange with wings

Figure 12. Comparing ripper loosened area, without (A) and with (B) the addition of wings.

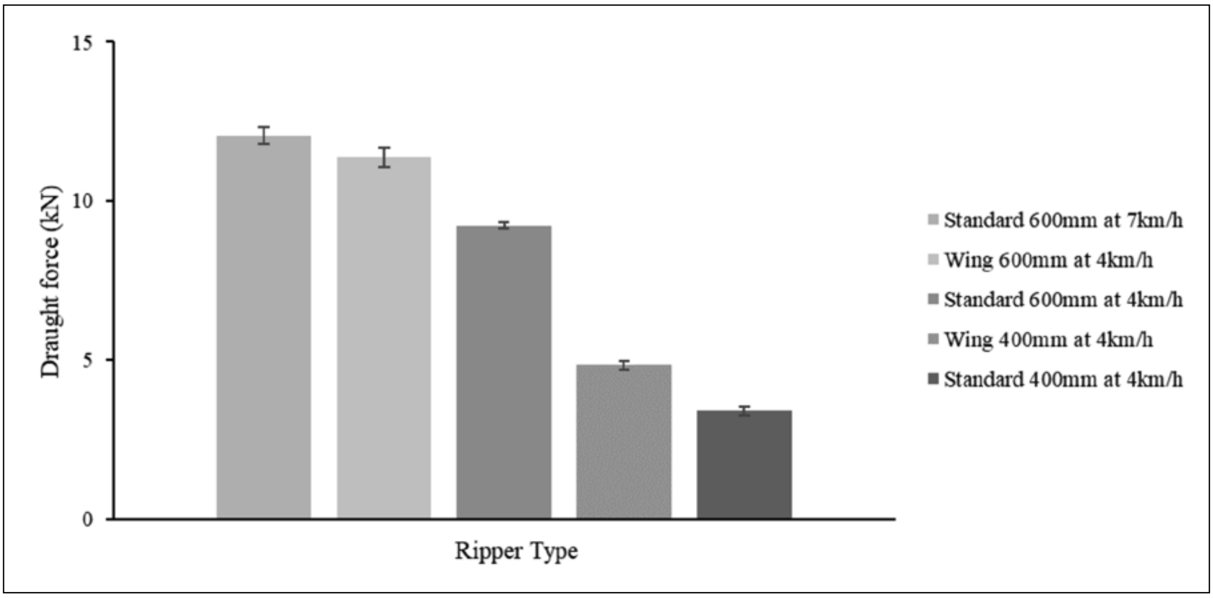


Figure 13. Draught force of ripper tines, with and without wings.

Ripping shank design and working depth will influence the soil loosening impact, power requirements, and the cost of ripping. Adding an experimental wing to the ripping shank increased loosening areas by about 49% to 53% when the operating depth was 400mm and 600mm, respectively (Figure 12). Increasing working depth from 400 to 600 mm increased the area of loosened soil by about 70% (Figure 12). Considering power and cost implications when working at 600mm depth, the additional wing increased soil loosening by ~50%, while the draught force increased by only 24% (Figure 13). Improving our understanding of the interaction between soil loosening, shank design, and working depth will help optimise tine spacing, power requirements and operating costs.

Conclusion

The primary constraints to crop water-use in deep sandy soils of the Victorian Mallee appear to include physical barriers to root growth, which restrict uptake of water and nutrients from the subsoil layers. Acidity, strong repellence, and subsoil toxicity were not primary constraints at the focus research sites in this project. Provided there is reliable subsoil moisture, ripping to a depth beneath hard compacted layers provides a good starting place for growers aiming to improve under-performance.

Deep ripping alone provided more consistent yield responses compared to combined approaches, looking to physically ameliorate compaction and boost profile fertility through incorporation of high N organic amendments, although the seasons were drier than average when nutrient responses are expected to be minimal. Before undertaking a deep ripping program, growers should assess the type and depth of the constraint, and choose a ripper which can work into, and under, the compacted and consolidated layers. In some cases deeper ripping operations requiring greater draught are more costly than shallower tillage and do not necessarily lead to higher yield benefits.

In our experiments, the use of inclusion plates for burial of surface material did not provide consistent yield benefits above ripping alone, but significantly increased draught and operational costs. There are opportunities to optimise tine spacing, power requirements and operating costs of ripping and inclusion operations through improving our understanding of the interaction between soil loosening, shank design, and working depth.

Acknowledgements

This research is a collaborative project between the GRDC, CSIRO, the University of South Australia, the SA state government through Primary Industries and Regions SA, Mallee Sustainable Farming Inc, AgGrow Agronomy and Trengove Consulting. 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.

UniSA also acknowledge GRDC / DAFWA project (DAW00243) for supporting the computer simulations and Tilco Engineering for supplying modified inclusion plates.

Useful resources

Think strategically before ripping into sandy soils: https://grdc.com.au/news-and-media/news-and-media-releases/south/2019/4/think-strategically-before-ripping-into-sandy-soils

Advice to match design of inclusion plates to soil type for optimum effect: https://groundcover.grdc.com.au/story/6384234/keys-to-undertaking-deep-ripping-with-inclusion-plates/

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Notes

Notes

Earwigs - an appetite for destruction or are they beneficial?

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Keywords

- earwig, canola, lifecycle.

Take home messages

- Adult European earwigs are present all year, but eggs and juvenile earwigs are only present from April to November.
- European earwigs can cause significant damage to canola, lucerne, lupins and in some cases, lentils.
- The potential for damage to emerging crop seedlings by adult European earwigs exists, although it is dependent upon the timing of germination and egg laying. During mid-late season, earwigs can act as a predator of aphids, potentially contributing to their control.
- Multiple earwig species have been detected in grain crops, most of which are not associated with crop damage. It is therefore important to correctly identify which species is present in a paddock before taking any action.

Background

There are at least 80 species of earwigs (Dermaptera) present in Australia (Haas 2018). Recent work using a combination of morphological and molecular data has identified ten different species of earwigs in grain crops (Stuart et al. 2019). These species are comprised of introduced and native earwigs, and there is limited information on the native earwigs. Many of the native species are potentially beneficial species and appear to be region specific (Stuart et al. 2019). However, reports of earwig outbreaks and damage to canola, cereals and pulse crops, have been increasingly recorded in Victoria (Vic), New South Wales (NSW), South Australia (SA), and southern Western Australia (WA). Factors that influence the risk of earwig outbreaks and crop damage are not well documented.

The most dominant and widespread species in Australian crops is the European earwig (*Forficula auricularia*) (Hill et al. 2019) which consumes a variety of foods (plants, invertebrates, fungus, detritus), acting beneficially through the consumption of crop pests in some fruit orchards (Quarrell et al. 2017). However, the European earwig has been observed as an irregular pest of grain crops in Australia (Murray et al. 2013). Despite being introduced into Australia over a century ago (Quarrell et al. 2018), there has been little research conducted on crop damage from European earwigs in Australia. Furthermore, the potential beneficial activities of the European earwig in grain crops have not been explored.

The two dominant native earwig species found in grain crops are *Labidura truncata* and *Nala lividipes* (unpublished data). Research has shown *L. truncata* to be predatory (Horne and Edward 1995), although its importance as a beneficial in grain crops has not been explored. *Nala lividipes* is a pest of Queensland cereals (Hargreaves 1970), although it is unclear if this is also the case in southern Australia, or if it feeds on canola. Increased stubble retention and the associated increase in organic matter within the soil may be linked to increase in-field earwig populations. However, studies that examine the factors affecting the risk of crop damage from pest earwigs, as well as management options to minimise crop damage, are limited.

Methods

Lifecycle monitoring of the European earwig

To establish the life cycle of European earwigs within a grains production context, grain crops (canola, wheat, oats) at five commercial farms were examined, two in Vic and three in SA. Sampling at these sites was undertaken over a period of seven days each month from September 2016 to December 2018. During each sampling period two types of traps were used; shelter traps in the form of cardboard rolls inserted into PVC pipe, and pitfall traps containing 100% propylene glycol. Three pitfall traps were installed two meters apart at four sampling locations (>30m apart) per site, with at least one sampling location being placed at the paddock edge for a total of 12 pitfall traps. Pitfall traps were used to capture earwigs during times of activity (i.e. foraging for food at night).

At each of the four sampling locations within the field, three cardboard rolls were placed complementary to the pitfalls to determine abundance (12 rolls in total). The cardboard roll traps were placed within an inter-row parallel to the stubble row, two meters from the pitfall traps. Roll traps were collected after seven days. Additionally, to establish movement of earwigs into vegetation adjacent to field sites, two rolls were placed in the canopy of four trees per site (eight tree rolls) using wire to tie the rolls to branches. The use of cardboard rolls allowed the collection of live earwigs during times of inactivity (being nocturnal, earwigs use the rolls for shelter during the day).

European earwigs (*F. auricularia*) comprised 75% of earwigs collected (unpublished data), and so laboratory processing first involved separating them from the other earwig species that were captured. Part of the species separation process involved confirmation via molecular work with comparisons to published sequence data (Stuart et al. 2019). Adult and nymphal stages of F. auricularia were identified using head width, the number of antennal segments and wing bud development as described in Crumb et al. (1941). As earwigs are sexually dimorphic, sex was identified using the shape of the cerci (Crumb et al. 1941) and earwigs were categorised as male, female or gynandromorph.

Damage and management of the European earwig in canola

On 23 April 2019, 8m by 1.8m plots of canola were sown into wheat stubble on a 0.5ha paddock on the Ginninderra research station near Canberra ACT (latitude -35.203571, longitude 149.083316). The plots were randomly allocated to different seed treatments; fipronil, imidacloprid or untreated. All seed was planted at the rate of 2.7kg/ha, and all seed was treated with Jockey® Stayer® for blackleg control. The plots around the edges of the paddock were assigned as a buffer, roughly 10m in width. Every second 1.8m row was also assigned as an internal buffer.

On 23 May 2019, seedling establishment was measured in the fipronil/imidacloprid/untreated plots by counting the number of seedlings. At this time the European earwigs had either laid eggs or were preparing to lay eggs, but no juveniles had yet hatched. By mid-June, second instar earwig nymph activity was detected using a modified wildlife camera (Spartan SR1 IR) and damage was seen over the next couple of weeks. On 24 June 2019 the damage to the plots of canola was assessed by estimating biomass loss in each experimental plot by measuring the area of plant damage.

Exclusion/inclusion cages

Following sowing on 23 April 2019, 100 enclosures were constructed to keep earwigs out or in, depending on the treatment. These open-top enclosures were 1m x 1.2m in area, made from corflute sheets buried 30cm into the ground, which was affixed to wooden stakes (driven 50cm into the ground) by screws and liquid nails. Both the inside and outsides of each corner was sealed using Selleys® silicon sealer. Tanglefoot was applied to the top 10cm of the corflute around the enclosure to prevent crawling insects getting in or out. This method of using tanglefoot barriers was previously used to successfully exclude/include European earwigs on tree branches to study aphid predation (Mueller et al. 1988).

Inside each enclosure, before earwig introduction, the existing wheat stubble in the paddock was manipulated so that there were three stubble loads: bare, 2t/ha (2T) and 5t/ha (5T). In addition to this, three water treatments were assigned: Low (exclusion of direct rainfall), Medium (natural rainfall) and High (additional artificial rainfall applied throughout the season).

Earwig manipulation occurred after all enclosures were constructed, whereby any earwigs within the plots were removed and added to a population of earwigs collected from the 1ha area. In total, 3000 *Forficula auricularia* were collected and sorted, after which forty second-instar juveniles were added to each of the 50 plots assigned to have earwigs the following morning and given a cardboard roll trap as shelter.

Laboratory trial – effects of crop growth stage and earwig life-stage on the damage done to a range of crops by European earwigs

Microcosm containers (600ml BioPak® Biocups) were used to which 250ml of soil was added. The soil mix used was 3 parts sandy loam soil: 2 parts sand: 1 part potting mix. The top layer of soil over the seeds is sandy loam soil only, sieved to create a 1cm topsoil layer. Each microcosm was watered on Monday, Wednesday and Friday ensuring a moist surface. Each cup contained four crop seedlings which were grown at 18°C, 12:12 L:D from untreated seed.

This experiment was run four times to capture multiple earwig life-stages. The earwigs used for this experiment were captured from a property near Elmore (latitude -36.4863, longitude 144.5513) which were acclimatised at 18°C for three nights. On day 0, the earwigs were introduced following the treatments in Table 1. All treatment combinations were used with 5 replicates each. The experiment was run for 14 days at 18°C 12:12 L:D.

Table 1. Treatments used for European earwig crop feeding experiment.

Earwig life-stages	2nd instar juvenile, 4th instar juvenile, summer adults, winter adults
Crop types	Lucerne, canola, lupin, lentil, wheat, oat, chickpea
Crop growth stages	1st and 2nd as defined by Lancashire et al. (1991)

Laboratory trial – effects of aphid presence and density on the damage done to canola by European earwigs

Forty microcosm containers (Biocups) were set up using the same methods as for the crop feeding trial described previously. Each cup contained four canola seedlings which were grown to the third growth stage as defined by Lancashire et al. (1991), at which point the experiment was started. The earwigs used for this experiment were 4th instar juvenile European earwigs collected from Ginninderra experimental station on the 25 October 2019. Cabbage aphids were also collected at this time. These earwigs were acclimatised at 18°C and starved for three nights, though they were provided with moisture. On day 0 (28 October 2019), the earwigs and aphids were introduced following the treatments in Table 2 each replicated five times. Aphids were added first and allowed three hours to establish themselves on the seedlings, only apterous aphids were used. In addition to this, a small (3cm x 3cm) piece of moist paper towel was placed onto the soil surface as shelter for the earwigs. The experiment was run for 14 days at 18°C 12:12 L:D.

Table 2. All treatment combinations used for European earwig aphid feeding experiment

4th instar European Earwigs	Cabbage aphids
Two individuals present	0
Two individuals present	50
Two individuals present	250
Two individuals present	500
Absent	0
Absent	50
Absent	250
Absent	500

Scoring was done at day 1, 3, 7 and 14. On each occasion, treatments were scored for the number of earwigs, number of aphids, earwig plant damage (1-10, 10 being stem snipped), aphid plant damage (% curled/discoloured leaves), number of canola seedlings, and photographed from 20cm above the soil surface.

Laboratory pilot trial – feeding preferences of the two major native earwig species (Labidura truncata and Nala lividipes)

Twenty-four microcosm containers (Biocups) were used and set up using the same methods as for the crop feeding trial described previously. The crop seedlings were grown to the third growth stage as defined by Lancashire et al. (1991), at which point the experiment was started. The earwigs used for this experiment were adult black field (*Nala lividipes*) and common brown (*Labidura truncata*) earwigs collected from Ginninderra experimental station on the 6 November 2019. Green peach aphids (GPA) were also collected at this time. These earwigs were acclimatised at 18°C and starved for three nights, and again provided moisture. On day 0 (9 November 2019), earwigs and aphids were added following the treatments described in Table 3 and each replicated three times. Aphids were added first and allowed three hours to establish themselves on the seedlings, only apterous aphids were used. In addition to this, a small piece of moist paper towel was placed onto the soil surface as shelter for the earwigs. The experiment was planned to run for 14 days at 18°C 12:12 L:D but extended to 42 days when no plant feeding was observed. Scoring was done as in the previously described experiment.

Table 3. All treatment combinations used for native earwig feeding experiment.

Adult Earwigs	Crop type	Green Peach Aphids
Two Nala lividipes	Canola	0
Two Labidura truncata	Canola	0
Two Nala lividipes	Canola	250
Two Labidura truncata	Canola	250
Absent	Canola	0
Two Labidura truncata	Wheat	0
Two Nala lividipes	Wheat	0
Absent	Wheat	0

Results and discussion

Lifecycle

The lifecycle of the European earwig *(F. auricularia)* was investigated over the course of two years, with 25 000 specimens captured from five sites.

The timing of the peak abundance of each lifestage was relatively consistent across each of the five sites, for which the data was combined to determine the proportion of each lifestage expected to be observed for each month of the year (Figure 1). The initial brood of eggs was observed in nests during April to July, with peak numbers of first and second instar nymphs observed in July. Third instar numbers peaked in October, while fourth instar numbers peaked before this in September. This is potentially due to earwigs moving out of the paddocks and into nearby trees when they reached fourth instar in September and October. Adult earwig numbers were shown to peak in November/ December and remain abundant until the following March.

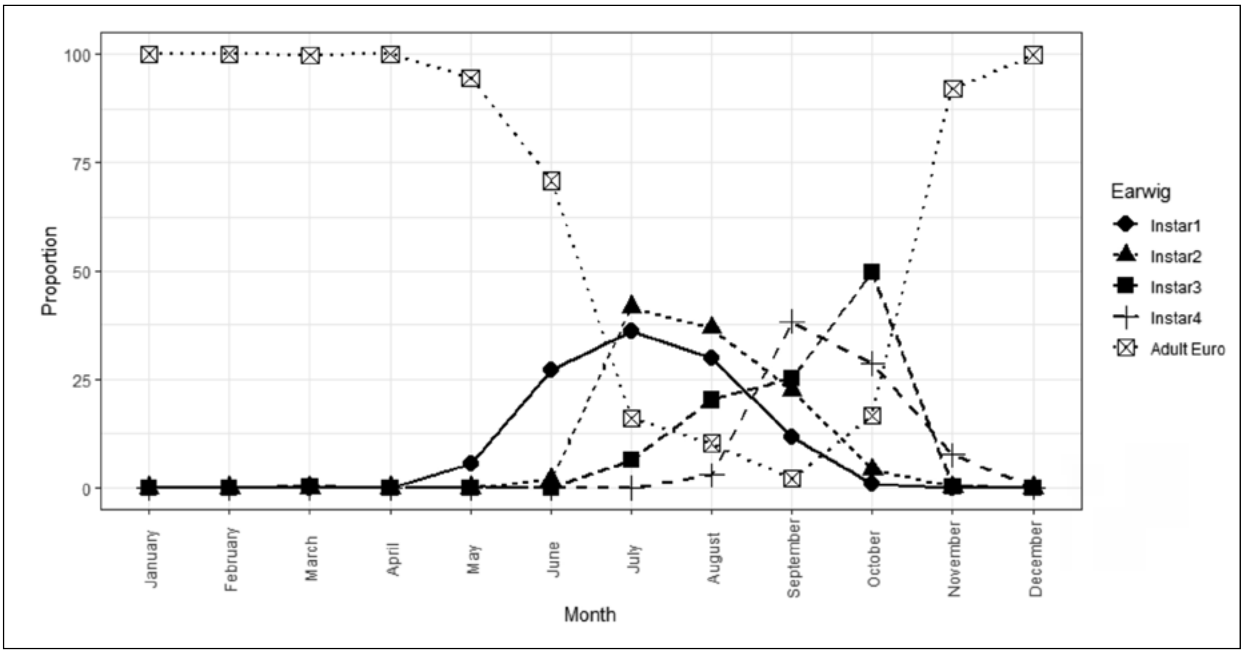

Figure 1. The lifecycle of the European earwig in grain crops. This figure shows the combined proportion (%) data of each *F. auricularia* lifestage from two years of sampling at five sites across Victoria and South Australia. Adults are present all year, but juveniles are only present from April to November.

Detailed lifecycle data for *F. auricularia* has enabled orchard growers worldwide to preserve or increase earwig numbers and thereby take advantage of their beneficial behaviors to protect orchards from pest insects (Nicholas et al. 2005; Quarrell 2013). Conversely, using this lifecycle data for grain crops may allow better prediction of the risk of crop seedlings to earwig attack, and if necessary, optimise timing of management tactics to reduce earwig numbers by targeting the appropriate life stages.

Damage and management

Early season

No significant difference was found in seedling establishment a month after sowing between seed treatments (p=0.25). Generally, canola is sown and starts growing several weeks before the European earwig eggs hatch. As such, the severe damage caused by juveniles may be avoided during the plant's most vulnerable stage unless sowing occurs late. However, adults will be present at this time and have the capacity to cause seedling damage (**cesar**, unpublished data), though there is a window of a few weeks where the adult female is underground caring for her eggs and not feeding. For this particular trial, the canola germinated as the females stopped feeding and started laying eggs. Thus, only very mild and occasional earwig damage was seen, not enough to have much effect on seedling establishment. Of course, there are many cases when earwigs can be damaging in autumn months. Although preliminary, these trials point to a complexity of factors at play that influence timing of events and thus impact the likely damage caused to emerging crop seedlings by European earwigs.

Once the earwig juveniles had hatched and reached second instar, significant damage started to occur to the canola (Figure 2). The damage caused by earwig nests at the 4 to 5 true leaf stage was significant ($p<0.05$) depending on the seed treatment used (Figure 3). Fipronil provided significantly more protection over untreated and imidacloprid treated seed, while imidacloprid seemed to result in no significant improvement over untreated seed in terms of earwig damage. In laboratory studies, both imidacloprid and fipronil prevented earwig damage during the time in which the treatment remained active (**cesar**, unpublished data). However, fipronil caused significant mortality in earwigs whereas imidacloprid did not (imidacloprid only acted as a feeding repellant). Potentially, fipronil is more effective in the long term due to the initial reduction in earwig numbers. Thus, as seen in this field trial, damage occurred after the imidacloprid seed treatment had worn off and there were significantly fewer ($p<0.05$) earwig nests found in the fipronil treated areas.

In this experiment, the overall average biomass loss per plot at this stage was 0.17% for fipronil and about 1% for untreated/imidacloprid. This is with an average of eight 'nesting spots' for the untreated/imidacloprid treatment compared to 1.6 'nesting spots' for fipronil; each 'nesting spot' represents

Figure 2. Damage to canola by second instar earwig juveniles. This is typical for canola that is in very close proximity to a European earwig nest, the white arrow (left) points to where the nest was found. The black arrow (right) points to an image of second instar earwigs feeding observed from about 11:00pm to 2:00am.

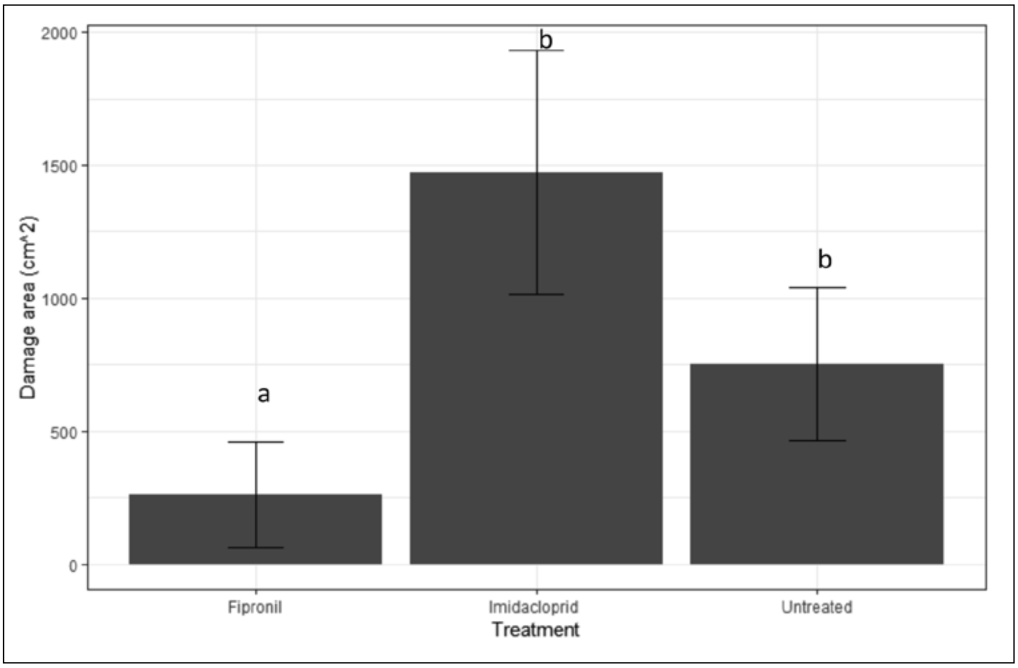

Figure 3. Total area of earwig damage measured in each 8m x 1.8m plot at the 4- to 5-true leaf canola growth stage. Bars represent the means with +- standard error. Letters represent similar means at $p<0.05$ based on an ANOVA.

either one earwig nesting location (Figure 2) or several in close proximity. The damage does not seem to spread much further than 30cm from an earwig nest during the pre-bolting growth stage of canola. This suggests that while the damage to the plant is apparent, it won't necessarily impact overall biomass or yield. This result is from one paddock only, and so additional data is required to assess how damage and biomass/yield loss scales with increased earwig nest densities in order to establish economic thresholds.

Mid-season – aphids

By late August, aphids started to colonise the canola plants. Green peach aphids were observed low on the plant and cabbage aphids were observed higher, mostly on the buds and spreading down the stems. Aphids were counted at four time points, and a negative binomial regression model was fitted to the data at each time point, testing the effects of earwig presence, water treatment, stubble load and seed treatment on aphid abundance (Figure 4). For 9 September 2019 and 6 October 2019 the results show a significant earwig presence and water interaction ($p < 0.05$). There were significantly more aphids in the non-earwig plots than the earwig plots, although this was only the case for the low water treatments ($p < 0.05$). For the third time point, 18 October 2019, aphid numbers were significantly higher ($p < 0.05$) where earwigs were absent, and there was no significant water effect. Stubble load and seed treatment had no significant effects on aphid numbers ($p > 0.1$) at any of these time points. The final time point, 1 November 2019, had too many aphid zero values for model convergence, and could not be reliably assessed. These results suggest that European earwigs may help control aphids.

Late season – pod damage

Non-aphid pod damage only occurred from 1 November 2019 when the aphid populations had declined. No significant difference ($p = 0.37$) in pod damage was found between earwig treatments. Earwig pod damage (Figure 5) is very similar to diamondback moth damage, of which there were moderate numbers present. This makes it difficult to assign damage directly to the earwigs; however given the fact that less than 0.5% of pods had this damage, and given the damage was only superficial, it is unlikely that European earwigs in the density that was used will cause much damage when present at this point in the season.

Harvest

The harvest biomass is the total dry weight of the entire canola biomass within an experimental plot. Seed weight is the weight of all seed produced within a plot after cleaning. This seed will be processed further during 2020 to look for differences in oil content. An ANOVA was used to look at all experimental treatment combinations and

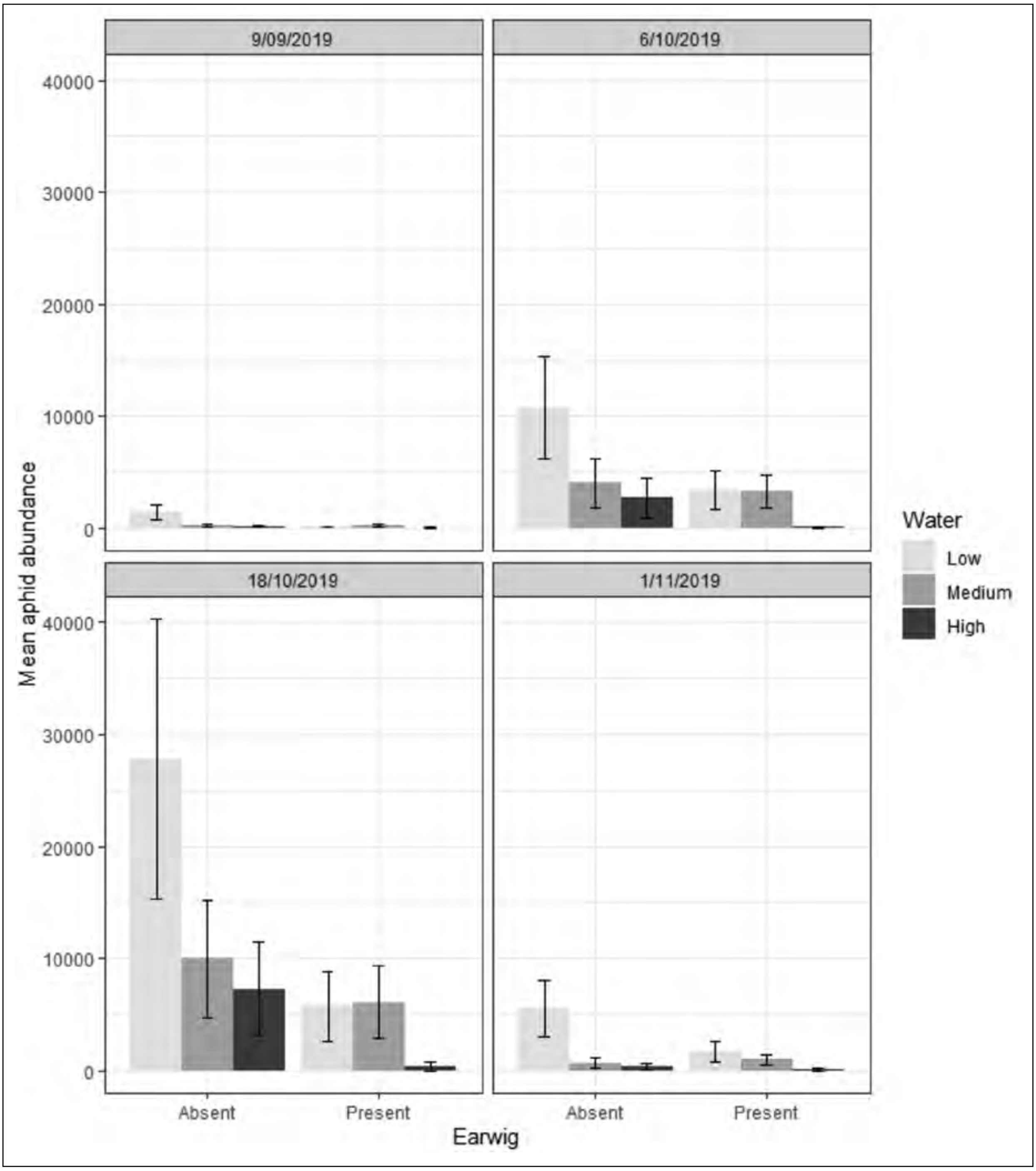

Figure 4. Aphid abundance over time, showing the interaction between water treatments and European earwig presence/absence treatments.

associated interactions. Interactions were tested but none were significant ($p > 0.1$). Significantly higher biomass was found in the plots containing earwigs than those without earwigs ($p < 0.05$). This was not what was expected early in the season, as the earwigs caused obvious damage to the plants. However, it may reflect earwig effects on other crop pests such as aphids when they arrive later in the season. As expected, the highest biomass was obtained from the plots that received a 'high' water treatment (Figure 6). The highest biomass was also found in plots that received a 'bare' stubble treatment, no difference was found between 5T and 2T treatments (Figure 7).

The differences in plant biomass did not appear to translate to total seed weight in this experiment (Figure 6; Figure 7). No significant differences were found in seed weights across any of the treatments ($p > 0.05$), further processing will be done in 2020 to obtain seed oil content.

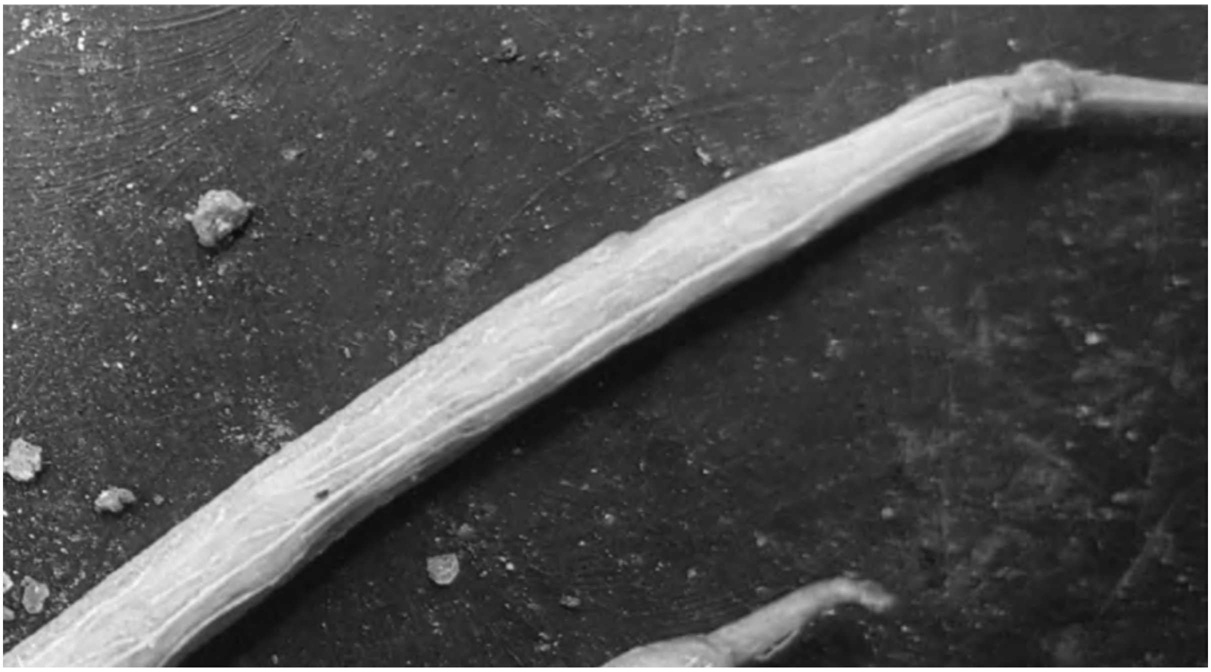

Figure 5. Example of the chewing damage done by European earwigs to canola pods.

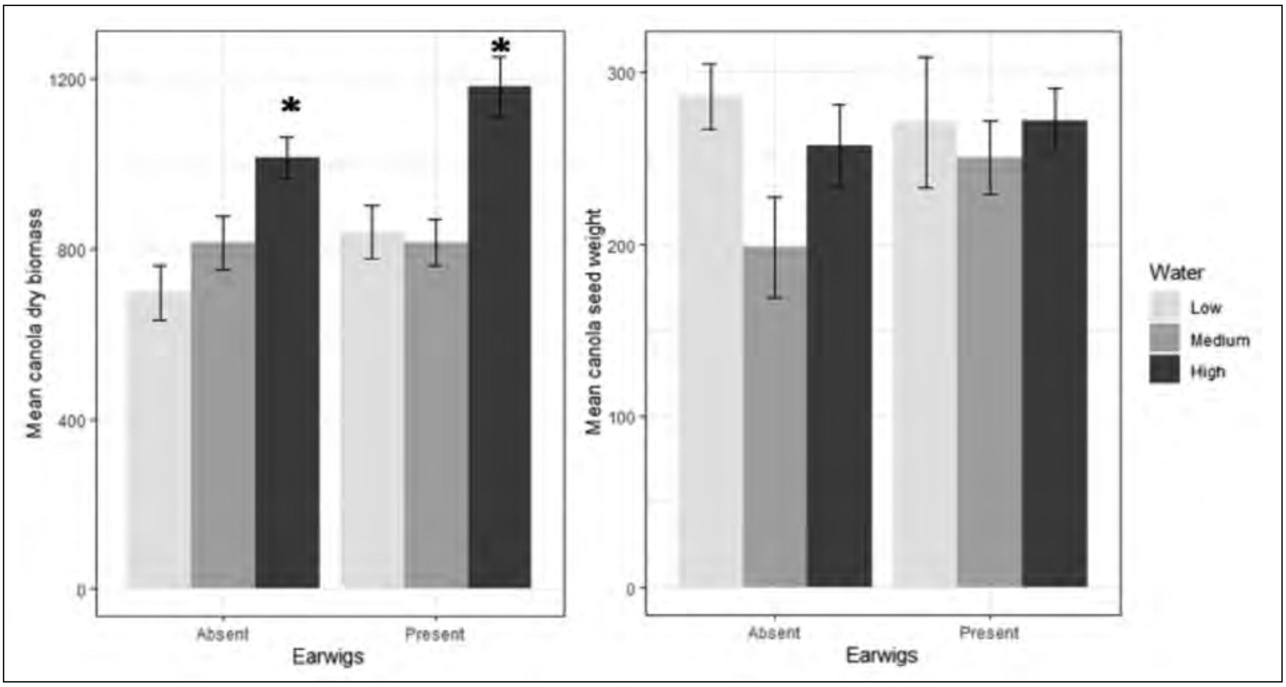

Figure 6. The effects of earwig presence and water treatment on total canola biomass (left) and total seed weight (right) measured in grams. Asterisks indicate significant ($p < 0.05$) differences within the earwig groups.

The effect of seed treatment on harvest biomass was significant ($p < 0.05$). The effect is consistent with what was recorded early in the season, greater biomass was measured from Fipronil treated seeds than both untreated and imidacloprid (Figure 8). The biomass of untreated and imidacloprid treated seed was not significantly different. Fipronil and imidacloprid treated plots all received 2T/ha stubble and medium water, so the interactions with stubble/ water could not be assessed. This was done to reduce the number of treatment combinations, making construction more feasible.

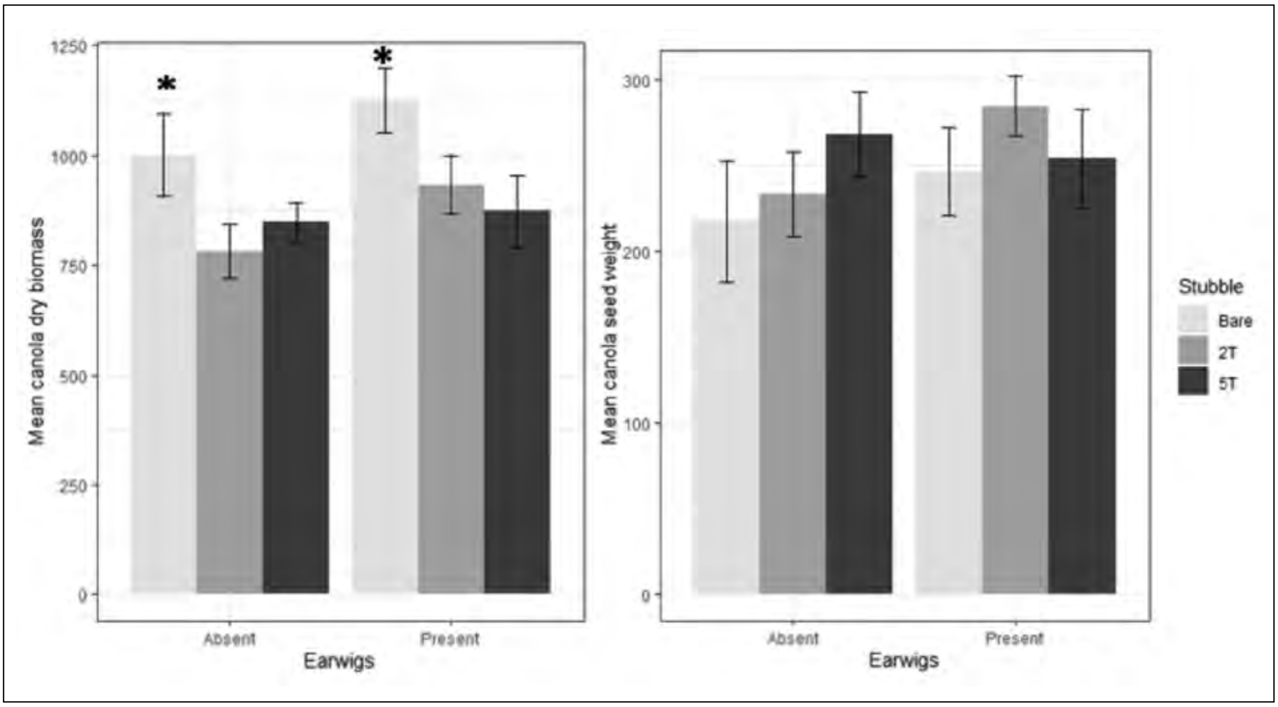

Figure 7. The effects of earwig presence and stubble treatment on total canola biomass (left) and total seed weight (right) measured in grams. Asterisks indicate significant ($p < 0.05$) differences within the earwig groups.

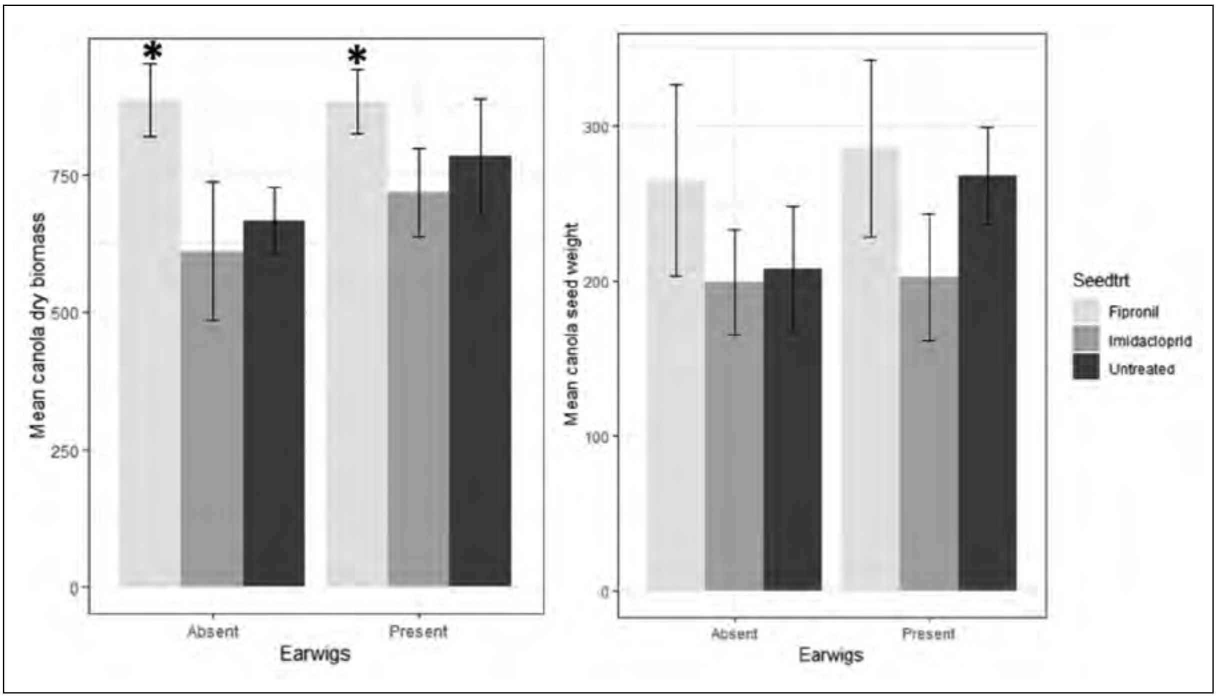

Figure 8. The effects of earwig presence and seed treatment on total canola biomass (left) and total seed weight (right) measured in grams. Asterisks indicate significant ($p < 0.05$) differences within the earwig groups.

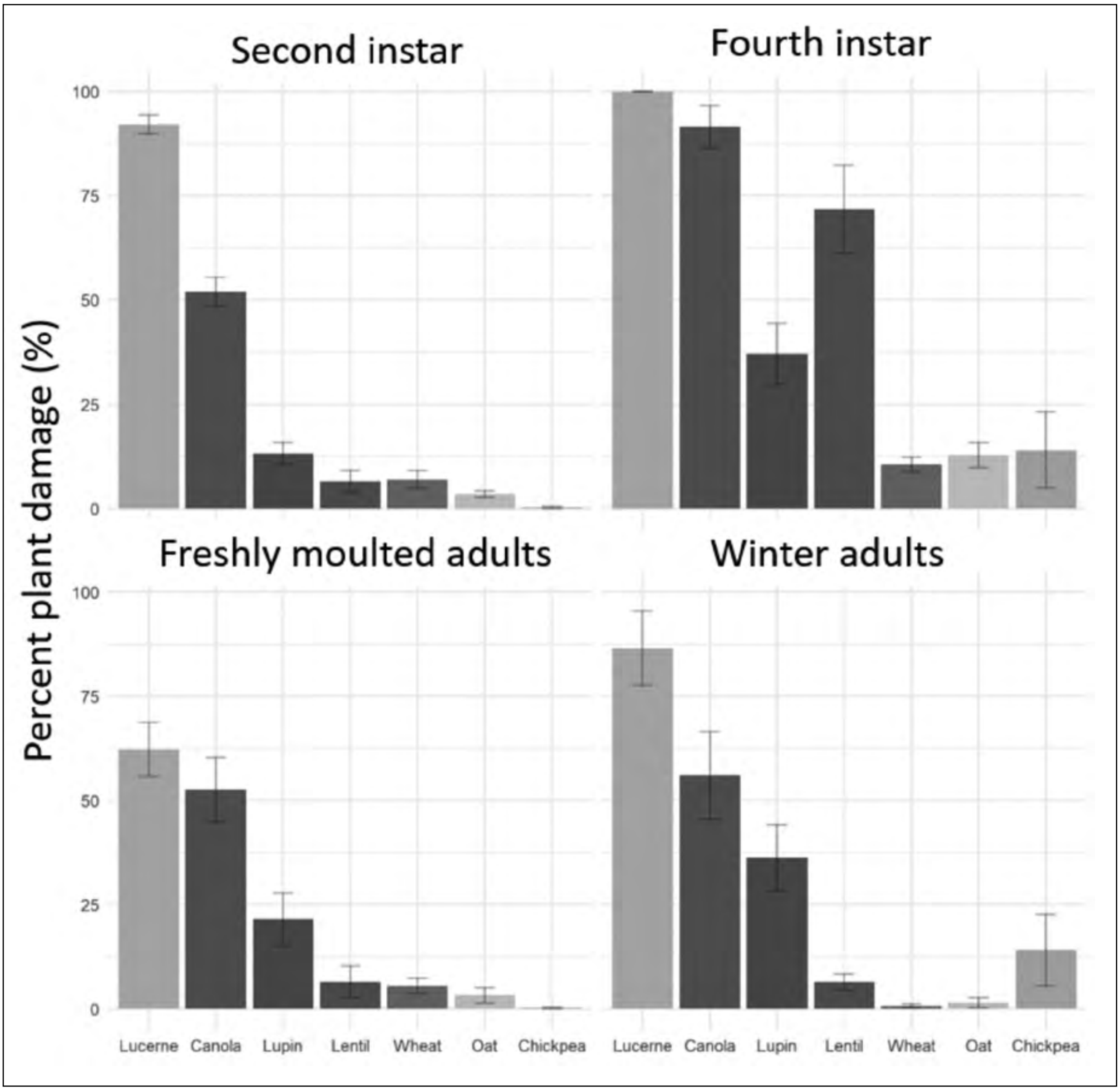

Figure 9. Mean damage by treatment and life stage for days after treatment (DAT) 14 and 1st growth stage with standard errors shown.

Again, the biomass results did not carry over to the seed mass. The effect of seed treatment on seed weight was not significant ($p > 0.05$).

Laboratory trial – effects of crop growth stage and earwig life-stage on the damage done to a range of crops by European earwigs

European earwigs caused the most damage to lucerne, canola, lupins, and lentils. The most damaging earwig life-stage appears to be fourth instar juveniles, this was also the only life-stage that caused significant damage to lentils (Figure 9; Figure 10). The difference in percentage damage to plants between plant growth stages was expected, a lower percentage of damage was scored on the mature plants (Figure 10).

Laboratory trial – effects of aphid presence and density on the damage done to canola by European earwigs

Earwigs started damaging the canola in the no-aphid and 50 aphid treatments from Day 1 (Figure 11). The aphids in the 50 treatment were entirely consumed by Day 1 (Figure 12). The canola in the 250 and 500 aphid treatments was not damaged until Day 7 (Figure 11). The aphids in the 250 and 500 treatments were entirely consumed by Day 7 (Figure 12).

These results show that European earwigs will readily feed on canola when no other food is available. However, if there are large enough numbers of aphids present, the earwigs will not damage the canola at all until the aphids have been consumed.

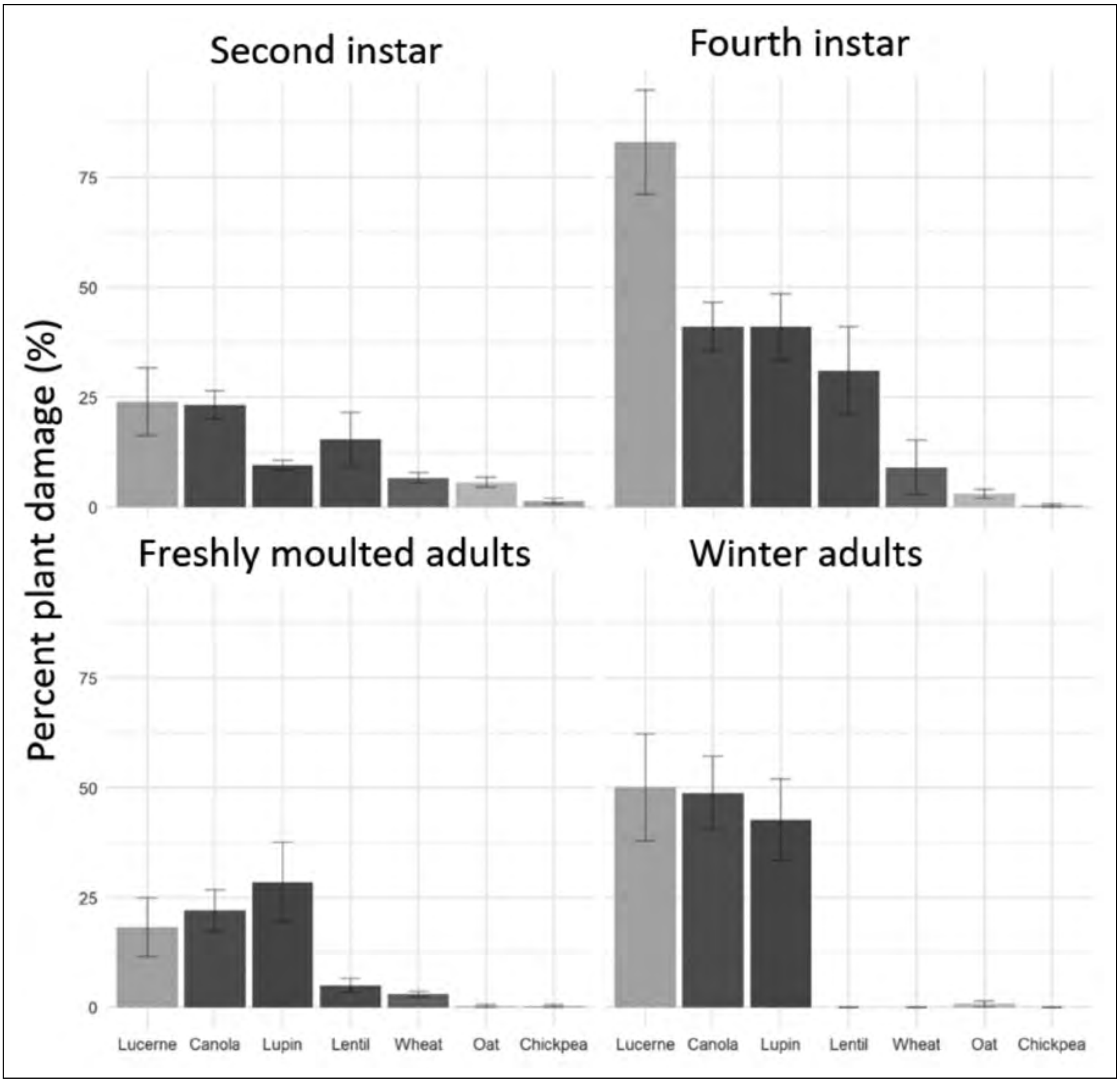

Figure 10. Mean damage by treatment and life stage for days after treatment (DAT) 14 and 2nd growth stage with standard errors shown.

Laboratory pilot trial – Feeding preferences of the two major native earwig species: Labidura truncata and Nala lividipes

After running the experiment for 42 days, there was no damage by native earwigs to any of the canola or wheat plants. The earwigs remained alive throughout this duration but did not appear to feed on plant material. The aphids were consumed entirely over one night by the *L. truncata* and over two nights by the *N. lividipes*.

Conclusion

European earwigs are generally not regarded as a pest in grain crops internationally (other than occasional harvest contamination), and potentially play a beneficial role in pest management (Sunderland and Vickerman 1980). However, it is clear from damage reports that they can cause damage in Australian crops, particularly in canola. European earwigs have the capacity to cause damage throughout the entire season. The nesting phase begins around April, which is often when canola is sown. Prior to nest establishment, adult earwigs are actively feeding, and can cause damage to emerging seedlings if the crop starts germinating at that time. However, there is a period of several weeks where the female earwig is confined underground caring for her eggs and crop feeding is less likely to happen. After the eggs have hatched and the juveniles start developing, significant damage to canola can occur which can be particularly harmful if the plant is still small and vulnerable. Hence, the timing of earwig feeding activity and crop vulnerability is likely to be an important predictor of crop damage.

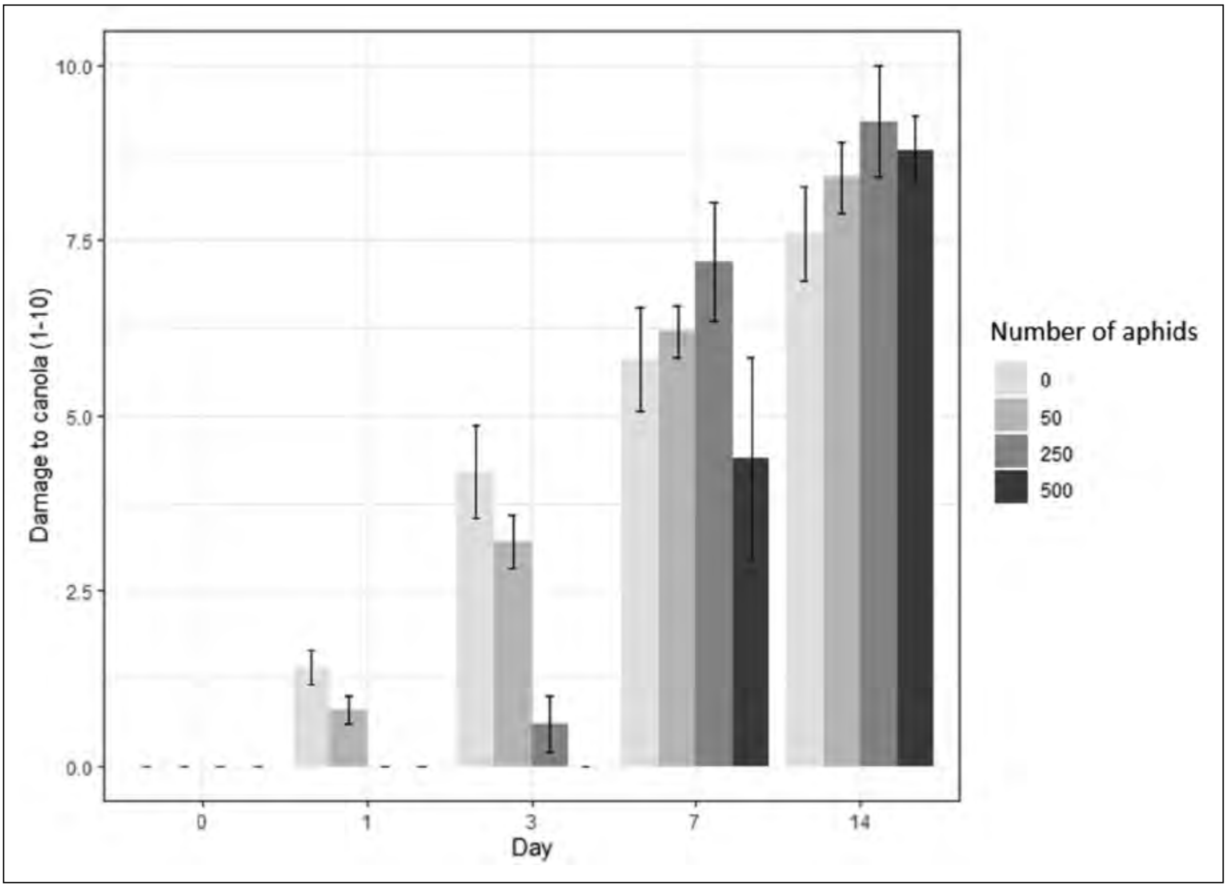

Figure 11. Damage done to canola by European earwigs when varying numbers of aphids are present (1-10 scale). Day refers to the number of days after the earwigs were introduced to the microcosm.

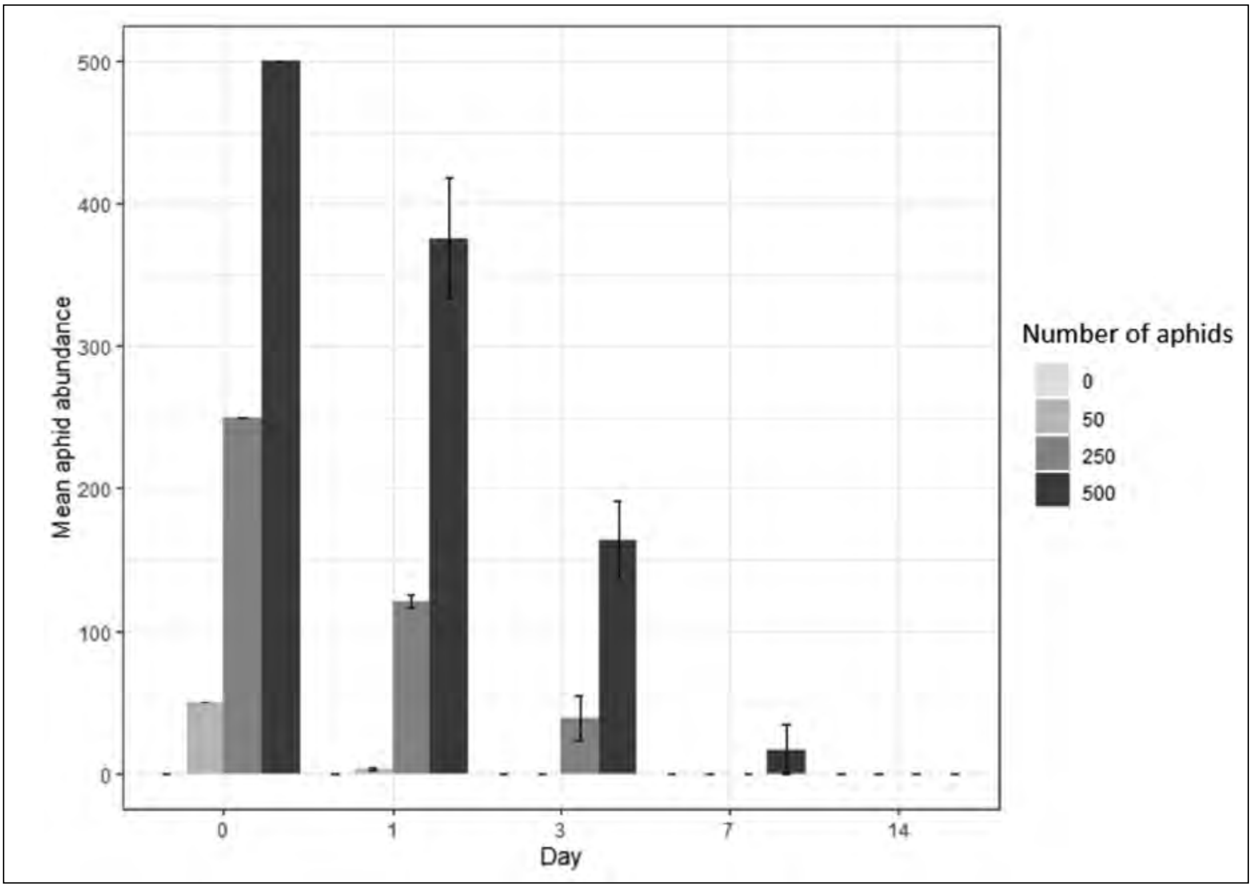

Figure 12. Aphid population over time when earwigs are present, day refers to the number of days after the earwigs were introduced to the microcosm.

European earwigs only have one generation per year (with potentially two broods per female), and they don't travel very far to feed as young juveniles. Once a nest is established, it is likely that the canola near the nest will be damaged, but the earwigs within that nest are likely to cause minimal damage to other parts of the crop. Extensive damage will be the result of many nests becoming established across large areas of the paddock. Monitoring for nests from April until June will allow for management before the earwigs reach the more destructive second instar stage from late June.

The role of European earwigs throughout the season is complex, and there are clear interactions with other invertebrates. We have demonstrated in laboratory tests that European earwigs will readily damage canola presented in isolation. However, when presented with canola that had been inoculated with aphids, the earwigs did not damage the canola at all until they had consumed the aphids. Aphid monitoring in the field suggests that earwigs may play a role in aphid suppression mid-late season. The importance of this role, and how earwig densities might interact with aphid densities and crop damage, are still unknown.

The accurate identification of species in the crop is the most important predictor of crop damage. Of the three dominant species found in canola, only European earwigs are confirmed as causing damage, while *N. lividipes* and *L. truncata* appear to have beneficial value. *Nala lividipes* is primarily reported as a pest of Queensland sorghum and maize during summer (Hargreaves 1970). However, we have confirmed that *N. lividipes* will not cause damage to canola or wheat; additional crops will be tested in 2020.

Our data so far suggests that the damage per earwig nest is spatially limited, but very high numbers distributed across a paddock will need to be controlled. So far, the data obtained around control methods is limited. The preliminary results of our trial suggest that fipronil might be useful as a seed treatment in areas with a history of earwig problems, although this pest is not listed on the current registered claims. There are reports suggesting cracked grain baits containing chlorpyrifos can be useful, these could be mixed with an attractant such as linseed oil. Due to the beneficial aspects of earwigs, reducing populations unnecessarily may have consequences for future crops. Therefore, before taking action, it is important to properly identify which species of earwig is in the field, how dense the population is, and how eliminating it may negatively impact the control of pests such as aphids.

Acknowledgements

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Useful resources

www.grdc.com.au/GRDC-FS-Earwigs

http://cesaraustralia.com/sustainable-agriculture/pestnotes/insect/European-earwig

https://grdc.com.au/resources-and-publications/all-publications/publications/2019/insect-pests-of-establishing-canola-in-nsw

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Notes

Notes

Quantification of frost damage in grains using remote sensing

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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 5-10 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. For example, decisions on when and how much of the crop to cut for hay could then be made. 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, thereby reducing costs.

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

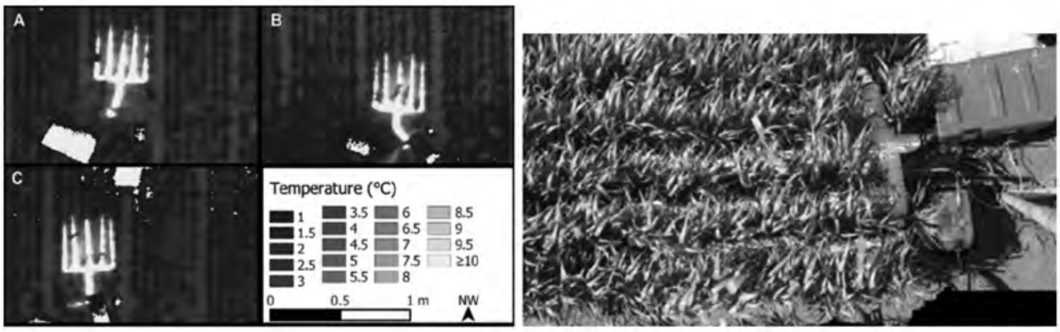

Figure 2. (left) Thermal image of the plot heater effect acquired from a UAV and (right) Close-up picture of diesel plot heater (Stutsel et al., 2019b).

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 Fr and NFr wheat heads and leaves (Murphy et al., 2019) 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., 2019). The technique compares the mixed spectra

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.

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.

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., 2019) 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 to detect frost damage across canopy, leaves and heads were: 419-494nm and 670-675nm. Areas outside the range of the laboratory analysis include those noted in Fig. 7b in blue. 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

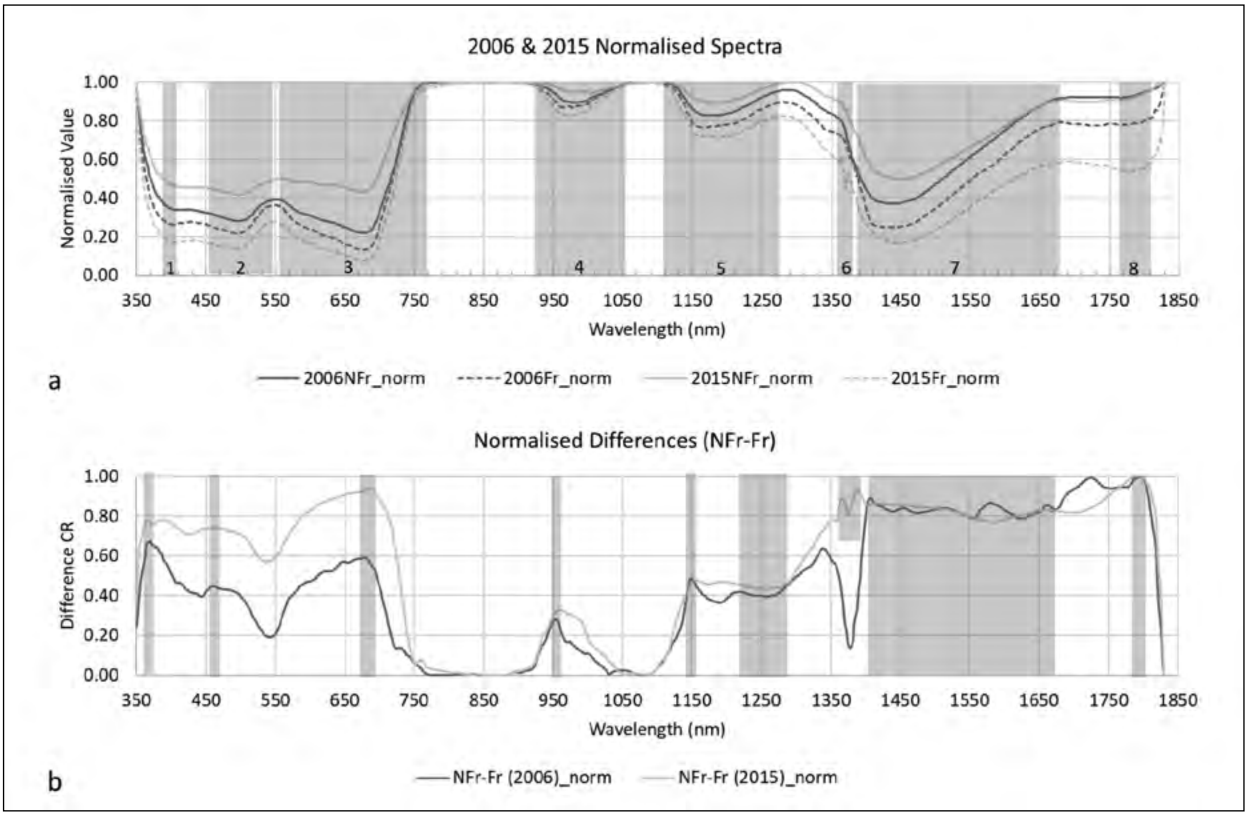

Figure 6. Spectra of wheat canopy in visible to near infrared portion of the spectrum. Two years and locations (2006, Horsham; 2015, Kewell, Victoria). (a) Spectra normalised and identification of spectral absorption regions (1-8, shaded) with differences between Fr and NFr. (b) Difference of normalised spectra (NFr - Fr) showing regions (shaded area) with potential to identify frost damage in wheat.

stable regions in the infrared (e.g., ~1220-1270nm and ~1400-1670nm) while reflectance values near 1800nm (Fig. 7b) 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 (Fig. 7b). Because photosynthesis is affected by frost (noted by the differences in Fig. 7b 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).

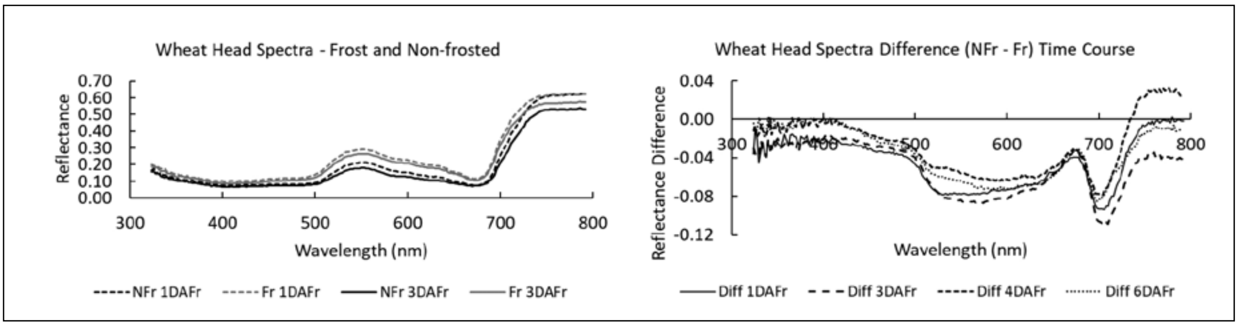

Figure 7. Spectra of wheat heads, cv Wyalkatchem$^{\text{(D)}}$ collected with a Polypen™. (a) One and three days after frost (DAFr) for non-frost (NFr) and frost-damaged (Fr) heads. (b) Difference between NFr and Fr heads one, three, four and six DAFr. This shows that spectra change depending on time after the frost event.

Results showed that there were spectral changes in 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).

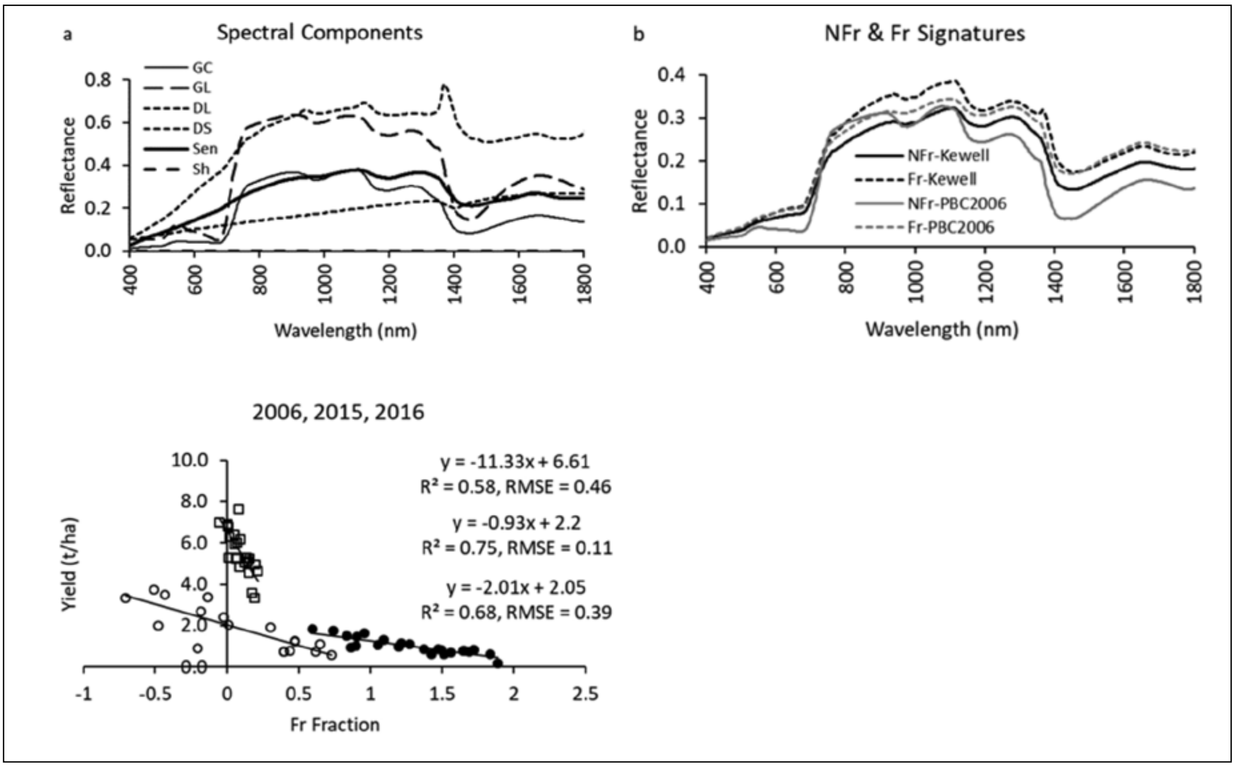

Figure 8. (a) Spectral signatures for canopy components, and (b) frost (Fr) and non-frost (NFr) canopies. (c) Frost (Fr) fraction values vs yield for three data sets using a spectral mixture analysis approach to determining frost severity and impacts to yield.

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.

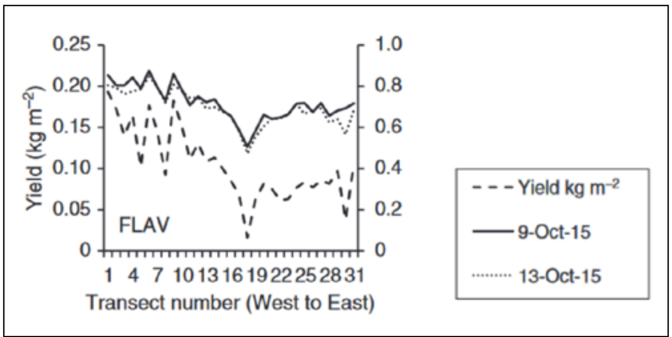

Figure 9. Corresponding grain yield and fluorometer measurements from a paddock near Kewell, Victoria in 2015 following the first observation of frost. The measurements were made along a transect of 31 rows on two dates, 9 October 2015 and 13 October 2015 (growth stages; Z61–69, Z71–75). Correlation 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.

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. Other support was provided by Agriculture Victoria/ Department of Jobs, Precincts and Regions and co-author, Bonny M Stutsel, was supported by an Australia Government Research Training Program (RTP) award and a GRDC PhD top-up award.

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Notes

Notes

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 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.

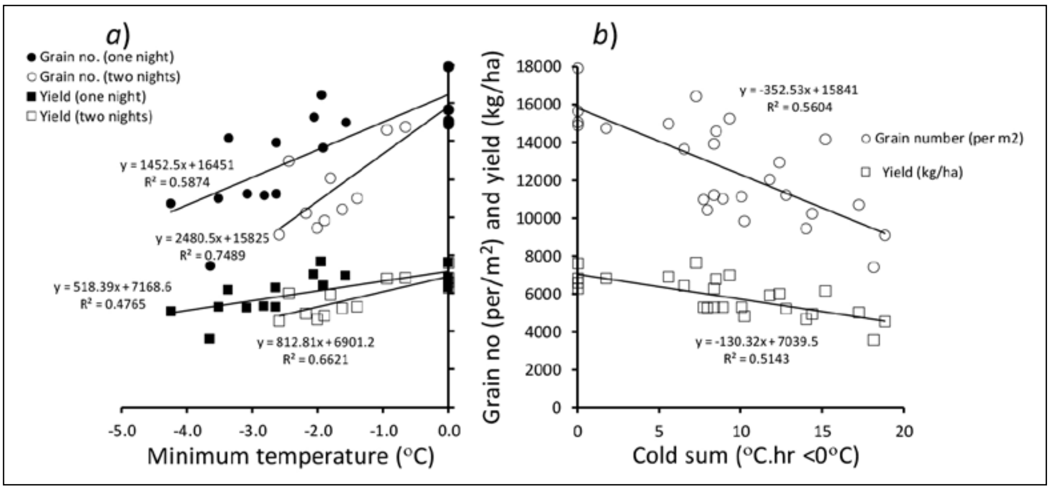

Figure 2. Relationship between wheat yield components and a) minimum temperature and b) cold sum (°C.hr < 0°C) for frost treatments.

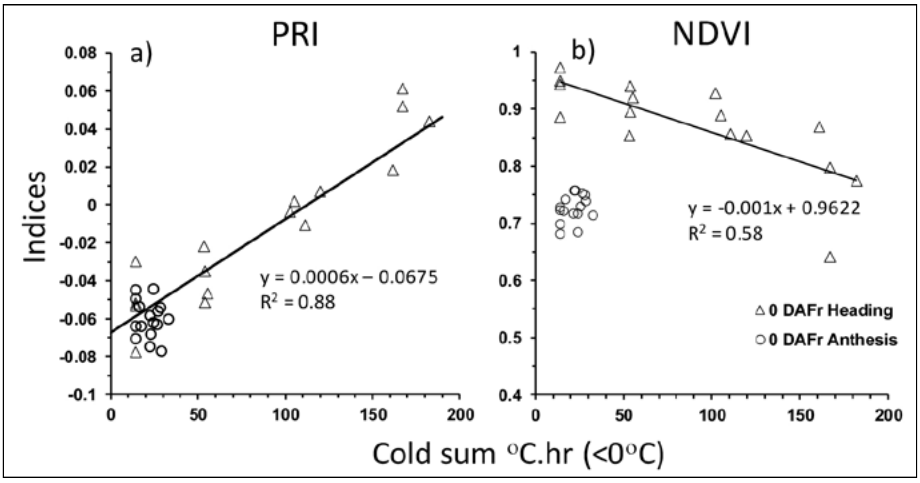

Figure 3. Reflectance derived spectral indices photochemical response index (PRI) and normalised difference vegetation index (NDVI) from wheat heads the day after frost (DAFr) treatments, applied at varying intensities and expressed as cold sums. Frost treatments were applied at the crop stages; head 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.

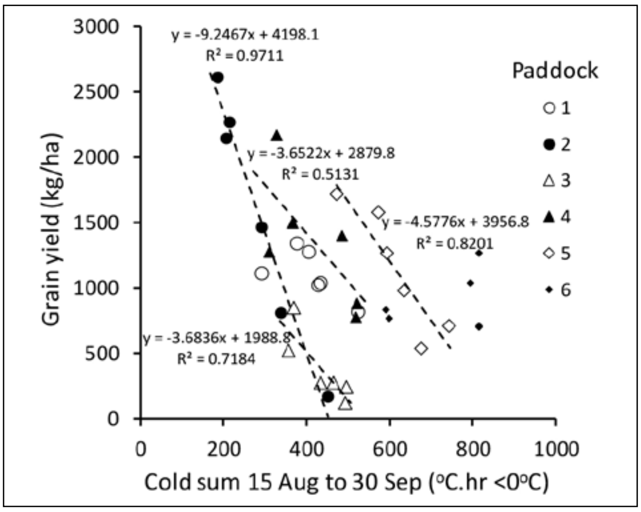

Figure 4. Intra-paddock relationship between wheat yield (kg/ha) and cold load (°C.hr <0°C) for six commercial paddocks in 2018, Murtoa, Victoria. Regression models describing intra-paddock fit between yield and cold load are for paddocks 2, 3, 4 and 5.

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

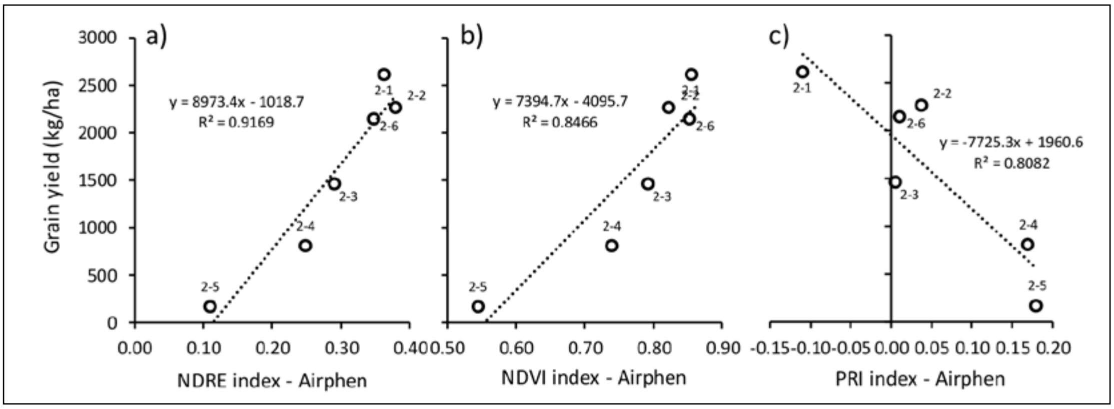

Figure 5. Relationship between wheat yield and Airphen® derived indices for a paddock (2) monitored near Murtoa, Victoria in 2018. Indices include a) normalised difference vegetation index (NDVI), b) normalised difference red edge (NDRE) and c) photochemical response index (PRI) derived from an Airphen® multispectral camera.

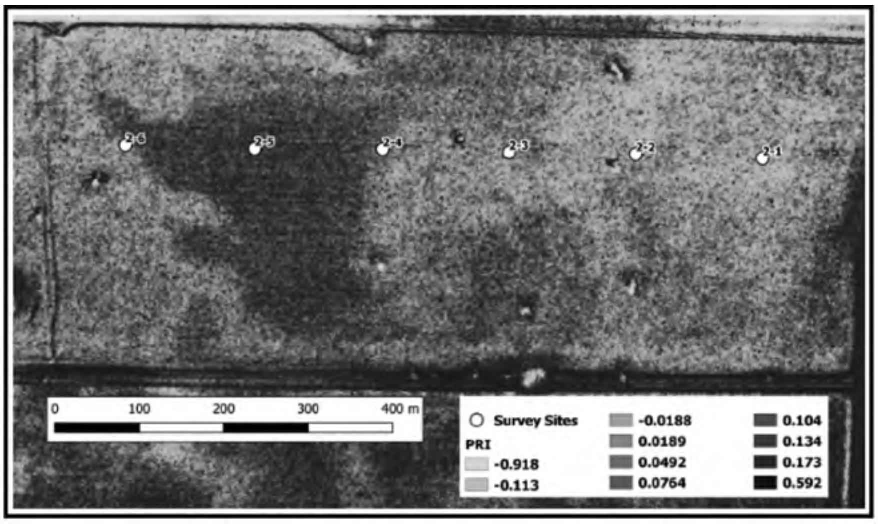

Figure 6. Spatial variation in the photochemical response index (PRI) across a wheat paddock (paddock 2) linked with crop frost damage. This represents an opportunity for spatial management of crops for hay versus grain production. Dark grey areas indicate low yielding zones and light grey areas are 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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Addressing the yield gap – local hyper-yielding project

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Overcoming key agronomic constraints to faba bean production in the Victorian high rainfall zone

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Keywords

- pulse, faba bean, high rainfall zone (HRZ), fungicide, canopy management, acid soils, sowing rate, acid-tolerant rhizobia.

Take home messages

- Acid-tolerant strains of Group F rhizobia increased the nodulation of faba beans on acidic soils (pH<5.0 $CaCl_2$) with low background rhizobia at Chatsworth and Rokewood, Victoria, but optimal nodulation rates were not achieved.
- After a late break, with adequate chemical fungal disease control, PBA Samira⚔ faba bean grain yields at Tarrington, Victoria, increased as targeted plant density was increased from five to 45 plants/m^2. However, the gross margin only increased from five to 35 plants/m^2.
- Genetic resistance and fungicides increased disease control and yield of faba beans, in a high disease-pressure year at Tarrington in 2019, however more than just disease control contributed to grain yield.
- PBA Amberley⚔ is more resistant to chocolate spot than PBA Samira⚔ and PBA Zahra⚔, but still benefitted from chemical fungal control at Tarrington in 2019.

Background

In Victoria, faba bean plays a supporting role to canola as a break crop. From 2014 to 2019, 386, 000 hectares were sown to canola, compared with the 95, 000 hectares sown to faba bean (ABARES 2019). Nevertheless, the contribution of faba bean to farming systems is expected to increase with continued improvement in from agronomy and breeding. Growing pulses such as faba beans provides benefits to farming systems that are not available with canola alone. Benefits include a potential reduction in nitrogen (N) inputs in crops following the nitrogen-fixing legume, an extra pest and disease break in canola-cereal systems, and the opportunity for a double-break from cereals to control problem weeds such as annual ryegrass.

Several constraints to faba bean production in the Victorian high rainfall zone (HRZ) limit its incorporation into farming systems. Two key agronomic constraints are considered in this paper; poor nodulation in acid soils and disease pressure in humid crop canopies. Addressing these constraints would increase faba bean profitability and potentially contribute to their increased adoption in the region.

Faba bean and their associated Group F rhizobia are more susceptible to soil acidity than canola (Burns 2018), a particular challenge for the Victorian HRZ. A recent report showed that of 100 paddocks surveyed, 62% had a soil pH ($CaCl_2$) of less than 5.0 in the 0-10cm layer, and 52% of sites were less than 4.8 in the 10-20cm layer (Debney 2019). Acid-tolerant rhizobia strains have been identified in response to this challenge (Ballard et al. 2018).

Faba bean are suited to the HRZ as the most waterlogging-tolerant pulse species of those grown in Victoria, however, they are also susceptible to foliar fungal disease (GrowNotes 2017), which is prevalent in the moist canopies. It is known that higher crop plant densities increase the risk of fungal disease by increasing canopy humidity, especially in early-sown crops. This has been factored into the recommended sowing rates, targeting 20 plants/m^2 with early sowing and up to 30 plants/m^2 for later sowing (GrowNotes 2017). Little work has been done, however, to test these recommendations since 2011. Since that time, several varieties have been released with longer growing seasons and greater disease resistance to key fungal diseases like chocolate spot (for example; PBA Samira⁽ᴰ and PBA Zahra⁽ᴰ). In older recommendations, mid-April is considered a very early sowing date (GrowNotes 2017). More recently, many growers begin sowing faba bean in the first week of April. New fungicide products are also available. It is unknown whether the recommendations for faba bean canopy management should be adjusted to reflect these changes.

Method

Acid-tolerant rhizobia for increased nodulation in acid soils

Two acid-tolerant rhizobia strains (SRDI969 and SRDI970) and the commercially available strain WSM1455 were cultivated and supplied by South Australian Research and Development Institute (SARDI), Adelaide, as peat. These were made into a peat slurry by grower hosts and applied to faba bean seed at the standard rate, then sown on the same day with a commercial seeder at 130 kg seed/ha. Two replicates of each treatment were sown in the following order; no inoculant, commercial strain, SRDI969, SRDI970. A third strip with no inoculant was sown at the end to check for cross-contamination between treatments.

The trial at Chatsworth was sown on 13 May 2019 into moist soil, whereas the trial at Rokewood was sown on 26 April 2019, about one week before a significant rain event. The soil pH of each site is presented below in Table 1. At eight weeks after crop emergence, ten plants were collected along each strip and the nodules were counted on the intact root systems.

Table 1. Soil pH of on-farm inoculation trials at two sites in Victoria in 2019.

Site	pH $CaCl_2$	
	0-10cm	10-20cm
Rokewood, Victoria	4.51	4.77
Chatsworth, Victoria	4.98	4.63

Canopy management to optimise yield potential

Two small-plot trials were sown at a research site in Tarrington to test canopy management; one testing the effect of time of sowing (TOS) and sowing rate on yield, and the other testing cultivar choice and fungicide program on disease control and yield.

Table 2. Sowing rates used for target plant densities.

Grain size (g/100 seeds)	Germination rate (%)	Establishment rate (%)	Target plant density (plants/m^2)	Sowing rate (kg/ha)
66	95	85	5	41
			15	124
			25	206
			35	289
			45	371

Table 3. Fungicides applied to a sowing date x plant density faba bean trial at Tarrington, Victoria in 2019.

Date applied	Product	Rate/ha	Active ingredient rate/ha
30 July 2019	Veritas®	1L	Tebuconazole 200g
			Azoxystrobin 120g
3 September 2019	Mancozeb 750 ®	1kg	Mancozeb 750g
	Carbendazim 500	500mL	Carbendazim 250 mL
26 September 2019	Aviator Xpro® [A]	600mL	Prothioconazole 90g
			Bixafen 45g

[A] *This application of Bixafen + Prothioconazole was off label for experimental purposes only.*

The trial that tested TOS and sowing rate was set up as a random complete block design with a split-plot factorial treatment structure and eight replicates organised in four TOS blocks. It was sown with PBA Samira(b) on 26 April and 16 May 2019. These treatments emerged by 20 May and 4 June 2019, respectively, over three weeks after the sowing date, due to the late start to the season. Sowing rates were calculated based on the grain size, the germination rate and an estimated establishment rate of 85% (Table 2). The fungicide program that was applied to all treatments is presented in Table 3.

For this trial, the gross margin (GM) was calculated based on the PIRSA 2019 Gross margin guide. The price of sowing seed was changed to $1.70/kg of seed and the cost of sowing was calculated for each sowing rate treatment. The yield data for each plot was used to calculate freight cost and End Point Royalties ($3.85/t yield for PBA Samira(b)). Yield components were examined by collecting 15 branches per plot then counting the number of pods per tiller before removing the seeds and weighing grain biomass.

The trial that tested variety and fungicide program was set up as a random complete block design experiment with four replicates and a split-plot factorial treatment structure. This included six cultivars and four fungicide programs, where treatments were blocked by fungicide program. It was sown on 26 April and emerged by 20 May 2019 due to a late start to the season. Varieties used and their resistance rating to foliar fungal disease are presented in Table 4. Fungicide programs are outlined in Table 5. Visual disease scores were done in October and November, assessing chocolate spot incidence as a percent of leaf area affected per plot.

Table 4. Varieties and their resistance to Aschochyta blight and chocolate spot used in a variety x fungicide faba bean trial at Tarrington, Victoria in 2019 (Fanning et al. 2019).

Variety	Aschochyta blight		Chocolate spot (Botrytis)
	Pathotype 1	Pathotype 2	
PBA Amberley(b)	RMR	RMR	MR
PBA Zahra(b)	R	MRMS	MS
PBA Samira(b)	RMR	RMR	MS
PBA Rana(b)	R	MRMS	MS
PBA Marne(b)	RMR	MRMS	S
PBA Bendoc(b)	RMR	RMR	S

Key; R = resistant, MR = moderately resistant, RMR = resistant-moderately resistant, MRMS = moderately resistant – moderately susceptible, MS = moderately susceptible, S = susceptible.

Table 5. Fungicide treatments in a variety x fungicide faba bean trial at Tarrington, Victoria in 2019. Table 6 provides the trade name and rate of chemicals applied for each treatment where the rates were the same across treatments.

Growth stage	Early flower only	Old chemistry only	District practice	Complete control[A]	Date
5 node		Mancozeb @2.2 kg/ha	Carbendazim [B]	Disease free [A]	30-Jul
Early flower	Bixafen + Prothioconazole	Mancozeb @2.2 kg/ha	Mancozeb @1kg/ha + Carbendazim		3-Sep
Mid flower			Mancozeb @1kg/ha + Chlorothalonil		17-Sep
Mid pod		Mancozeb @2.2 kg/ha	Mancozeb @1kg/ha + Chlorothalonil		30-Oct

[A] The complete control treatment is a rotation of fungicides applied to ensure minimal to no disease as a control in the experiment.

[B] Carbendazim is currently permitted for application on beans under a temporary permit (PER13752).

Table 6. The active ingredients, trade names and rate of chemicals used in a variety x fungicide faba bean trial at Tarrington, Victoria in 2019.

Active Ingredient	Trade name of chemical used	Rate (mL/ha)
Carbendazim	Carbendazim 500	500
Bixafen + Prothioconazole	Aviator® Xpro®	600
Mancozeb	Mancozeb 750	Rates vary, see Table 5
Chlorothalonil	Chlorothalonil 720	1400

Results and discussion

Acid-tolerant rhizobia for increased nodulation in acid soils

Acid-tolerant rhizobia increased nodulation in on-farm trials at both Chatsworth and Rokewood in 2019 (Table 7). The low nodulation rate in Nil control treatments shows that there was little to no background rhizobia in these acidic paddocks, where a legume had not been sown for several years. Slightly more nodulation was seen in the nil control check plots, (where a strip was sown with un-inoculated seed after the other treatments were sown), compared to the Nil control treatments. This suggests that there was minimal cross-contamination between treatments.

At Chatsworth, there were 10-15 more nodules per plant in acid-tolerant rhizobia treatments compared to the commercial strain treatment. This was also two to three times greater than the grower's paddock, where seed was inoculated with peat slurry at the standard rate (albeit from a different source to the commercial strain treatment used in the trial). However, the nodulation rate of 37 to 43 nodules per plant in the acid-tolerant treatments is still below what is considered optimal nodulation (50 nodules/plant).

At Rokewood the average level of nodulation was much lower than Chatsworth. This could be partly due to the earlier sowing date in very dry soil, the seed treatment with Thiram and Thiabendazole (P-Pickel T) fungicide (which is known to affect nodulation), and/or the greater level of waterlogging in this paddock during May. Regardless, acid-tolerant rhizobia slightly increased nodulation over the commercial strain treatment. The grower's paddock however, had much greater nodulation. This grower inoculated the seed with a standard rate of peat slurry inoculant and sowed with a standard rate of granular inoculant, which would increase the number of rhizobia bacteria present in the soil during bean root growth. The purpose of using acid-tolerant rhizobia in acidic soils is also to increase the number of rhizobia bacteria, but it appears that in the harsher conditions of the Rokewood paddock, doubling the rate inoculant achieved this end to a greater extent than the acid-tolerance trait.

These on-farm trials demonstrate that acid-tolerant rhizobia can improve nodulation in acid soils (pH<5.0 $CaCl_2$) with low background rhizobia levels under differing environmental conditions. However, these strains did not achieve optimal nodulation rates by themselves. Appropriate liming programs to control soil acidity, targeting a pH of > 5.5, are also importantalong with using higher inoculation rates.

Canopy management to optimise yield potential

Effect of time of sowing and plant density on yield

In the TOS x plant density trial, faba bean establishment was slightly greater than the targeted plant densities. However, consistent and significant differences were achieved between sowing rate treatments (Table 8). Emergence date and plant density affected canopy structure. Due to the late break in the 2019 season, emergence date is presented rather than sowing date, to more accurately reflect the growing season at this site. Earlier emerged treatments were significantly taller, as were higher plant densities, but later emerging treatments reached a plateau in crop height from 25 plants/m^2. The height to the lowest pod was increased from 20cm above the soil surface to 35cm from the lowest to the highest plant density. Treatments with lower plant densities compensated for the reduction in plant number by setting more grain-filled pods, containing a larger grain biomass per tiller.

Data shows that changing the plant density and emergence date can create substantial changes to the canopy structure of faba bean. Changes to plant height and structure were more pronounced with earlier emergence date, but changes to grain yield components (per branch) were only affected by plant density. Although not observed in this trial year, earlier sowing with high plant densities may increase the risk of lodging in some seasons.

Table 7. Nodulation from on-farm demonstrations testing faba bean rhizobia strains

	Chatsworth (pH 4.8 $CaCl_2$)		Rokewood (pH 4.6 $CaCl_2$)	
	Nodules/plant	s.e. (n=10)	Nodules/plant	s.e. (n=10)
Nil control	0.4	0.3	0.9	0.6
Commercial strain	28.5	4.3	5.3	1.0
Acid-tolerant strain 1	37.4	4.1	8.3	2.0
Acid-tolerant strain 2	43.3	5.1	11.3	1.7
Nil control check	12.5	2.8	4.2	1.5
Grower practice	14.7	4.1	29.9	4.5

Table 8. Effect of establishment date and plant density on crop canopy structure and yield components of faba bean grown at Tarrington, Victoria in 2019.

	Crop est. (plants/m^2)		Crop height (cm)		Height to first pod (cm)		Grain-filled pods per tiller		Grain biomass (g) per tiller	
Emergence date (E)										
20-May-19	31.1	-	111.0	a	27.4	-	9.6	-	14.6	-
4-Jun-19	30.8	-	101.6	b	27.5	-	9.4	-	13.8	-
Lsd (P<0.05)	2.3	3.3	ns	ns	ns					
P-value (E)	0.777		<0.001		0.901		0.353		0.056	
Target plant density (D)										
5 plants/m^2	9.6	e	88.6	e	20.1	e	12.7	a	18.4	a
15 plants/m^2	19.0	d	100.6	d	24.0	d	10.5	b	15.3	b
25 plants/m^2	32.1	c	107.1	c	26.9	c	9.4	c	14.1	b
35 plants/m^2	42.9	b	115.3	b	30.8	b	8.0	d	12.0	c
45 plants/m^2	51.1	a	119.6	a	35.3	a	7.2	d	11.0	c
Lsd (P<0.05)	3.9	3.8	2.8	ns	ns					
P-value (D)	<0.001		<0.001		<0.001		0.353		0.056	
Emergence date x Density (ExD)										
20 May 5 pl/m^2	9.2	-	89.1	f	19.6	-	12.4	-	18.6	-
15 pl/m^2	18.3	-	103.9	d	22.5	-	10.5	-	15.4	-
25 pl/m^2	34.7	-	113.1	c	28.0	-	9.4	-	14.5	-
35 pl/m^2	41.8	-	120.8	b	30.3	-	8.3	-	12.3	-
45 pl/m^2	51.5	-	127.9	a	36.4	-	7.7	-	12.0	-
4 June 5 pl/m^2	10	-	88.1	f	20.6	-	13.0	-	18.3	-
15 pl/m^2	19.7	-	97.3	e	25.6	-	10.5	-	15.2	-
25 pl/m^2	29.4	-	101.1	de	25.9	-	9.3	-	13.7	-
35 pl/m^2	44.1	-	109.9	c	31.4	-	7.8	-	11.7	-
45 pl/m^2	50.8	-	111.3	c	34.1	-	6.7	-	10.1	-
Lsd (P<0.05)	ns		5.4		ns		ns		ns	
P-value (ExD)	0.322		0.002		0.267		0.473		0.680	

Even though treatments with lower plant numbers had greater grain biomass per tiller, plant density increased yield from 5 to 45 plants/m^2 (Figure 1). This suggests that plant density has a greater effect on yield than the ability of faba bean (cv. PBA Samira$^{(b)}$) to adjust pod number and grain biomass per plant. This was true in 2019 for both emergence dates.

It is possible that in a different season with earlier emergence dates, the gains to yield from higher plant density would be overshadowed by the yield penalty from fungal disease, especially in very early-emerging crops. Therefore, these results should not be taken to mean that very high plant densities are recommended in all situations. Rather, these results demonstrate that with reasonable genetic resistance to fungal disease, alongside an adequate fungicide program, the yield potential of faba bean is much greater than what can be achieved with a standard sowing rate. In the situation where the autumn break is delayed, the sowing rate can be increased substantially and managed accordingly. It should be noted that these trials were sown at 20cm row spacing after burning stubble residues and this may affect extrapolation to specific on-farm situations.

Figure 2 illustrates that while yield increased from 5 to 45 plants/m^2, gross margin (GM) did not. Rather, for both emergence dates, the GM increased up to 35 plants/m2 and then remained constant. In this trial the same fungicide program was applied to all plant densities, maintaining the cost of fungicide between treatments. Change in GM in this case is being driven by the extra cost of seed at sowing ($1.70/kg seed) and the extra yield ($500/t) gained from higher plant densities. While the increase in yield from 35 to 45 plants/m^2 was significant, it did not outweigh the extra cost in seed, resulting in comparable gross margins. Therefore, the economic threshold for target plant density was lower than the

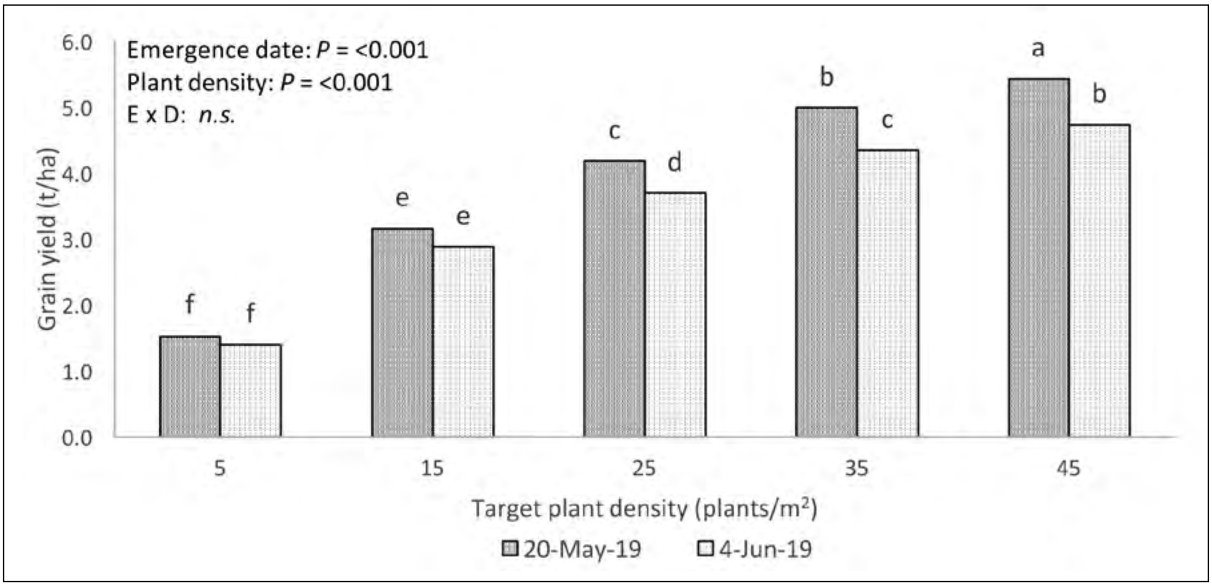

Figure 1. Effect of emergence date and plant density on faba bean yield at Tarrington, Victoria. Different letters indicate the difference between means is greater than the ExD Lsd value (P<0.05).

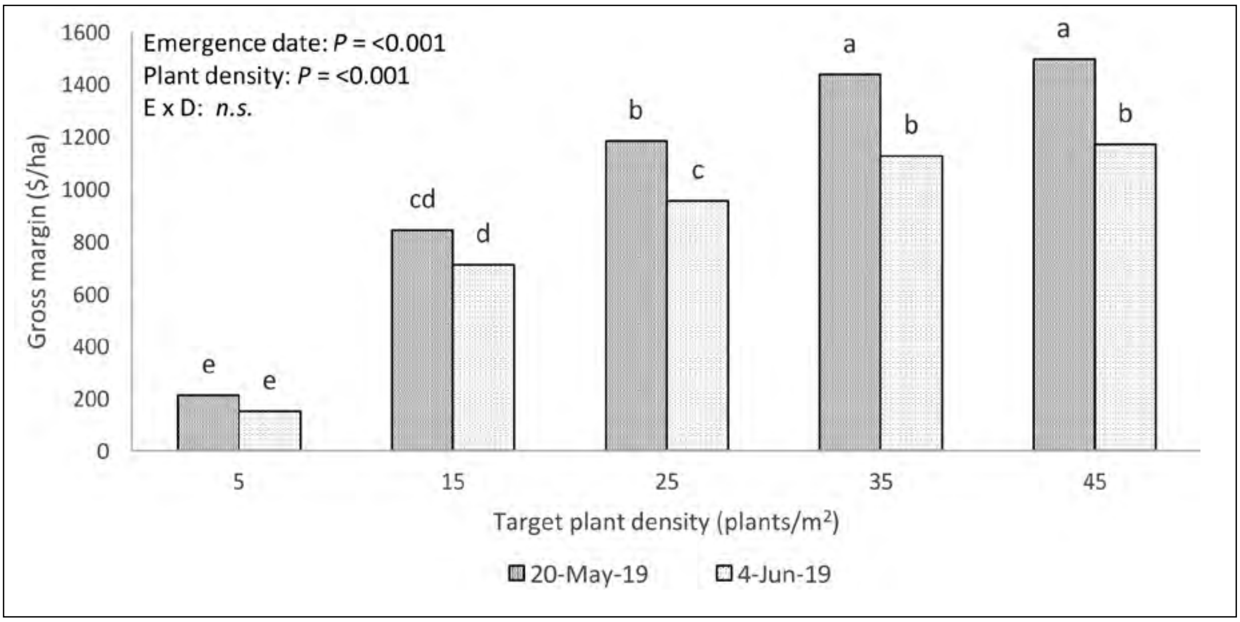

Figure 2. Effect of emergence date and plant density on faba bean gross margin at Tarrington, VIC (sowing seed cost: $1.70/kg; grain price: $500/t). Different letters indicate the difference between means is greater than the ExD Lsd value (P<0.05).

yield threshold but is still much greater than typical target plant densities of 15 plants/m^2. To summarise, if there is a late break, and a variety with genetic resistance comparable to PBA Samira⁽ᵈ⁾ is used with adequate fungicide control, sowing rates can be increased substantially from a GM point of view. Conclusions were not sensitive to sowing seed cost ($0.90/kg vs. $1.70/kg) or grain price ($400/t vs $500/t vs $600/t), however may be sensitive to changes in fungicide costs, which was not explored.

Higher sowing rates also involve higher risk, one source being the greater upfront cost of sowing seed. The breakeven yield, or yield required to cover variable costs, is presented in Table 9 for four grain prices. The long-term average grain price for faba bean is $500/t, and at this price the breakeven yield ranges from 1.1 t/ha to 2.4 t/ha for crop densities of 5 to 45 plants/m^2. Therefore, the higher the sowing rate, the more dependent enterprise becomes on favourable environmental conditions.

Table 9. Breakeven yield (t/ha, yield required to cover variable costs) of faba bean grown at five plant densities at Tarrington, VIC in 2019 (sowing seed cost; $1.70/kg).

	Breakeven yield (t/ha)			
Grain price ($/t)	300	400	500	600
5 plants/m^2	1.8	1.4	1.1	0.9
15 plants/m^2	2.5	1.8	1.5	1.2
25 plants/m^2	3.0	2.2	1.8	1.5
35 plants/m^2	3.5	2.6	2.1	1.8
45 plants/m^2	4.0	3.0	2.4	2.0

Disease risk is another source of increased risk with high plant densities. 2019 was a high disease-pressure year at the Tarrington research site, however the fungicide program used in the plant density trial minimised foliar fungal disease (Table 3). The role of disease control in this season was explored a neighbouring trial testing varieties and fungicide programs for disease control and yield.

Effect of variety and fungicide program on foliar fungal disease and yield

At Tarrington in 2019, variety and fungicide program affected chocolate spot incidence and yield (Table 10). The effect of fungicide on chocolate spot differed by variety (VxF P = <0.001), but the effect of fungicide on yield was consistent across varieties (VxF P = 0.623). This indicates that yield was less correlated to disease control than chocolate spot symptoms.

Three applications of mancozeb had the most severe disease symptoms among the treatments tested and this older chemistry should not be relied upon to control chocolate spot. Adding carbendazim or chlorothalonil to mancozeb, 'district practice', significantly increased fungal disease control.

Interestingly, a single application of Aviator Xpro® at early flowering ('Early flower only' treatment) significantly reduced chocolate spot incidence compared to three applications of Mancozeb ('Old chemistry' treatment). This suggests that the early flowering spray timing was an important application in this season. Although it received an extra application compared to 'Old chemistry', the large reduction in chocolate spot symptoms by 'District practice' suggests that the other active ingredients in this program are providing most of the benefit.

The Complete control treatment, which used multiple fungicide applications to achieve the greatest extent of disease control in the experiment, increased yield by 1 t/ha compared to the least effective program, 'Early flower spray only'. Furthermore, the importance of disease control to yield in 2019 is underscored by the fact that the ranking of fungicide programs by yield is the reverse order to the ranking of treatments by chocolate spot incidence.

The contribution of genetic resistance to chocolate spot was also demonstrated in this experiment. Ranking varieties by chocolate spot incidence matches their resistance ranking (compare Tables 4 and 10). Yield was again inversely related to chocolate spot incidence for these treatments as well.

The significant interaction of varieties and fungicide programs (VxF P = <0.001) for chocolate spot control shows the interplay of these factors. Varieties with high genetic resistance, such as PBA Amberley⁽ᵖ⁾, responded to increased fungicide intensity but to a lesser degree than a more susceptible variety such as PBA Marne⁽ᵖ⁾. The incidence of chocolate spot in PBA Amberley⁽ᵖ⁾ with an 'early flower only' spray was 6% of plot leaf area, decreasing to 4% under the Complete Control program. In comparison, PBA Marne⁽ᵖ⁾ changed from 35 to 25% for the same fungicide treatments. Genetic resistance reduced, but did not negate, the reliance of the crop on fungicides to control chocolate spot. PBA Amberley⁽ᵖ⁾ is more resistant to chocolate spot than PBA Samira⁽ᵖ⁾ or PBA Zahra⁽ᵖ⁾, but it still benefitted from chemical disease control.

By contrast, there was no interaction between fungicide program and variety for yield. Every variety increased in yield by about 1t/ha, from the worst fungicide program (old chemistry only) to the best fungicide program (Complete Control program). This shows that a range of genetic and environmental factors were affecting yield other than disease control. These factors lie outside the scope of this experiment.

Table 10. Effect of variety and fungicide program on chocolate spot incidence and grain yield of faba beans grown at Tarrington, VIC in 2019.

		Chocolate spot (late spring) (% of plot leaf area affected)		Grain yield (t/ha)	
Variety (V)					
PBA Amberleyⓓ		6	e	4.6	a
PBA Zahraⓓ		13	d	4.4	a
PBA Samiraⓓ		12	d	3.5	b
PBA Ranaⓓ		27	c	3.4	b
PBA Marneⓓ		34	b	2.5	c
PBA Bendocⓓ		38	a	2.4	c
Lsd (P<0.05)		3	0.2		
P-value (V)		<0.001	<0.001		
Fungicide program (F)					
Complete control		15	c	4.0	a
District practice		18	bc	3.6	b
Early flower spray only		23	b	3.0	c
Old chemistry only		34	a	3.0	c
Lsd (P<0.05)		7	0.3		
P-value (F)		<0.001		<0.001	
Variety x Fungicide (VxF)					
Amberleyⓓ	Complete control	4	k	5.0	-
	District	4	jk	4.6	-
	Early flower x1	6	ijk	4.2	-
	Old chemistry	11	hi	4.1	-
Zahraⓓ	Complete control	8	ijk	5.1	-
	District	13	hi	4.5	-
	Early flower x1	11	hij	3.7	-
	Old chemistry	21	fg	3.9	-
Samiraⓓ	Complete control	9	ijk	4.1	-
	District	11	hi	3.4	-
	Early flower x1	13	hi	3.0	-
	Old chemistry	20	fg	3.2	-
Ranaⓓ	Complete control	16	gh	3.9	-
	District	21	fg	3.6	-
	Early flower x1	31	cd	3.1	-
	Old chemistry	40	b	2.9	-
Marneⓓ	Complete control	25	def	2.8	-
	District	25	def	2.7	-
	Early flower x1	35	bc	2.2	-
	Old chemistry	58	a	2.3	-
Bendocⓓ	Complete control	29	cde	2.9	-
	District	34	bc	2.5	-
	Early flower x1	40	b	2.1	-
	Old chemistry	55	a	1.9	-
Lsd (P<0.05)		6		ns	
P-value (VxF)		<0.001		0.623	

Conclusion

A robust fungicide program can significantly reduce foliar fungal disease in faba bean but a variety with a resistance rating of at least MS was required to maintain chocolate spot disease at low levels (<10% leaf area) in 2019. The greatest level of disease control was achieved with PBA Amberley⍉ (MR) under fungicide programs that were as intense, or more intense, than a standard fungicide program in the region. Yields responded consistently to both variety and fungicide program, led by PBA Amberley⍉, PBA Zahra⍉ and PBA Samira⍉.

Plant densities of 5 to 45 plants/m^2 in PBA Samira⍉ that emerged on 20 May or 4 June increased yield with each increase in plant density, however gross margin only increased up to 35 plants/m^2. The fungicide program in this experiment was comparable to the most effective programs in the disease trial mentioned above. The experiments were on the same research site, suggesting that fungicides played an important role in maintaining the yield potential of these higher plant densities. High sowing rates are associated with a greater financial risk due to greater up-front costs in sowing seed and a higher agronomic risk of disease. In a situation where the autumn break is late, using a variety with a resistance rating of at least MS for chocolate spot and application of an adequate fungicide program, it may be economical to increase plant densities well above the typical 15-20 plants/m^2 to maximise the yield potential. This will depend on the level of risk the business is comfortable with.

Finally, new acid-tolerant rhizobia strains were demonstrated to increase faba bean nodulation compared to a commercially available strain on acid soils (pH $CaCl_2$<5.0) with low background rhizobia. However, they did not increase nodulation to the optimal level of 50 nodules/plant by themselves. Proactive liming programs and high inoculant rates remain important ways to achieve sufficient nodulation in faba bean on acid soils.

Acknowledgements

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Useful resources

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Deep ripping - where it will work (and where it won't)

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GRDC project codes: DAV00149; VGIP2A

Keywords

- physicochemical constraints, amelioration, deep ripping, spatial variability, 3D mapping.

Take home messages

- Deep ripping is most likely to improve grain yields on sandy soils where upper parts of the soil profile have been compacted by machinery traffic.
- Deep ripping is less effective on heavy clay soils which appears related to subsoil constraints.
- On clay soils with subsoil constraints, the application of ameliorants such as gypsum and organic matter in combination with deep ripping can often result in yield improvements.
- Post-ripping traffic management is critical for maintaining benefits, as is implement design and soil moisture conditions when conducting the operation.
- A thorough testing program is recommended to diagnose soil constraints to depth before undertaking any amelioration practices
- Soil type can vary markedly across a paddock, and the use of 3D spatial mapping to target where to treat specific soil constraints and minimise costs is currently being investigated.

Background

There has been recent interest in the potential benefits of deep ripping in the Australian grain industry. In Western Australia (WA), a range of GRDC investment projects (DAW00242; DAW00243; DAW00244) led by Steve Davies and colleagues have conclusively demonstrated the benefits of ameliorating sandy duplex soils using a range of soil inversion, mixing or loosening techniques such as ploughing, spading and deep ripping. On heavier textured soils however, these approaches have been much less successful and often create issues such as bringing large clods to the surface, which are then difficult to manage (Davies et al. 2019).

The Sandy Soils project (CSP00203) focuses on constraints to root growth and water uptake on sandy soils predominantly in the low rainfall zone (LRZ) but also includes some medium rainfall sites across the Southern Region. Results indicate physical compaction is a common constraint on sandy soils and average yield responses to deep ripping of about 0.5t/ha have been widely measured (refer to paper by Moodie et al. 2020 within this publication). Although these yield gains may be short lived (e.g. 2-3 years), further increases are believed to be possible via optimising crop nutrition where seasonal rainfall is favourable.

A deep ripping field day was held in March 2019 at Ouyen Victoria as part of the Sandy Soils project with a machinery and soil focus. This attracted over 200 participants indicating the large interest in deep ripping in the Southern Region. The findings from this project has led to the impression amongst some growers that deep ripping shows great promise and is certainly worth trying on other soil types; but is this so? We argue that it is wise to consider a significant body of soil research conducted over the past two to three decades. This and recent experience indicate that crop responses to deep ripping is highly contingent on several factors, principally soil type (texture) and the presence of physicochemical constraints, but also soil water and machinery type.

Table 1, which was compiled by John Kirkegaard in 2009, is based on research and expert opinions of a range of scientists and advisers working on soil constraints in the Australian grains industry at the time and summarises the likely effectiveness of deep ripping. The major conclusions arising from this summary are:

(i) the effectiveness of ripping decreases as the clay content of the soil increases,

(ii) ripping effectiveness depends on the presence of physicochemical constraints (e.g. acidity or other constraints may restrict root growth even if compaction is overcome).

(iii) in duplex type soils, depth to the clay layer is important.

The benefits of deep ripping on sandy soils appears to be a function of both the removal of tillage induced compaction as well as overcoming natural 'cementing' (alluviation) processes (L McDonald, pers comm.). At the other end of the soil texture spectrum, many high clay soils (e.g. black Vertosols and Kandosols) rarely respond to ripping as they are naturally 'self-repairing' over one or two wetting and drying cycles.

More than 85% of soils used for cropping in Victoria have sodic subsoils (Ford et al. 1993), with a naturally poor structure as a result of excess sodium, in addition to other chemically induced constraints. These soils are also prone to temporary water logging. Deep ripping of these soils often results in little yield response (or possibly a yield depression), especially if the highly sodic subsoil is lifted to the surface which subsequently reduces

Table 1. Summary of deep ripping responses by grain crops (Source: GRDC FactSheet 2009 'Deep Ripping' complied by J Kirkegaard)

RELIABLE RESPONSES >>>			VARIABLE RESPONSES >>>			FEW RESPONSES	
SOIL TYPE	DEEP SANDS	MALLEE SANDS	SODIC CLAY	DUPLEX-DEEP	DUPLEX-SHALLOW	RED EARTH	BLACK VERTOSOLS
CULTIVATED ZONE (0–10)			Waterlogging	Waterlogging	Waterlogging		Self mulching
COMPACT LAYER	Strength >1.5-2.0 MPa; Distorted roots						
ASSOCIATED SUBSOIL PROBLEMS (25–200cm)	Acid Layer High density Porous Low water and N holding N leaching	Low nutrient availability Salinity Boron	Waterlogging Sodic Clay Anaerobic High density Poor structure Salinity	Waterlogging Sodic Clay Anaerobic High density Poor structure Salinity	Waterlogging Sodic Clay Anaerobic High density Poor structure	Acid Layer High density Well structured	Salinity (Cl^-)
MEAN CROP RESPONSE RANGE (Wheat)	WA 20-37%	VIC/SA	NSW 0-500% WA 47% VIC 44-50%	WA 22% NSW 0-20%	4%	Few	Few
BEST BET MANAGEMENT	Rip with lime if acid Claying	Rip with nutrition	Rip with Gypsum Avoid re-compaction	Rip if clay >30cm Gypsum/Lime?	Do not rip	Few responses	Few responses Self repairing
REFERENCES	Jarvis (2000) Davies et al (2006) Hall (W'shop) Hamza (W'shop)	Sadras (200?) Wilhelm (W'shop) Unpub Armstrong	Chan et al (2003) Hamza (W'shop) Armstrong	Crabtree (1989) Davies (2006) Jarvis (Various) Ellington (Unpub) Kirkegaard (W'shop) Angus	Crabtree (1989) Davies et al (2006)	Angus (Unpub) Fettell (Unpub)	Dalal et al (Unpub?)

crop establishment. Duplex soils with a deep sandy topsoil (>30cm) can respond to ripping, but care should be taken to avoid hostile subsoils, especially is the top soil is shallow. A thorough soil sampling and analysis program to depth is recommended to diagnose these constraints before undertaking any amelioration practices.

On hostile soils, constraints other than compaction should generally be ameliorated to ensure yield benefits from ripping, and for this benefit to last more than one cropping cycle. For example, research conducted within GRDC investment project DAV00149, which focuses on soil amelioration in poorly structured clay soils in the medium and high rainfall zones of south-east Australia, found that deep ripping has consistently produced negative yield responses compared to the non-ripped control in the first one to two years following ripping. These negative yield responses are partly explained by the difficulties in establishing a uniform plant stand in poor seedbed conditions. Critically, yield responses to ripping were only achieved when a suitable ameliorant was also applied to the subsoil. For example, at Rand in southern NSW, deep ripping alone resulted in no benefit, but the application of gypsum in deep ripping slots produced a 0.55t/ha yield increase and deep ripping + organic matter + nutrients produced a yield benefit of 0.86 t/ha (Figure 1).

Other considerations

For a given soil type, the effectiveness of ripping depends on several key factors. Critically, ripping will provide little long-term benefit to subsequent crops if the soil is recompacted by machinery traffic. Ideally ripping should be used in conjunction within a controlled traffic farming (CTF) system. Not only will CTF help maintain the improvements in soil structure, but it can also provide a range of other agronomic (e.g. improved trafficability), economic (e.g. reduced fuel costs) and environmental (e.g. reduced soil erosion) benefits to the cropping system (Mitchell et al. 2019). In some cases, it may pay to delay ripping until a plan to implement CTF has been developed. Importantly, 'prevention is better than cure', especially in terms of avoiding compaction.

The effectiveness of the ripping operation itself is also highly influenced by soil moisture, depth and machinery (implement) design and operation. Most ripping is conducted in late summer or autumn after rain. If soil moisture is greater than the 'plastic limit' of the soil, mechanical disturbance, including deep ripping and machinery traffic, must be avoided. The plastic limit is the soil moisture content at which soil begins to behave as a plastic material, above which mechanical forces can smear the soil and markedly reduce its physical structure. Conversely, if the soil

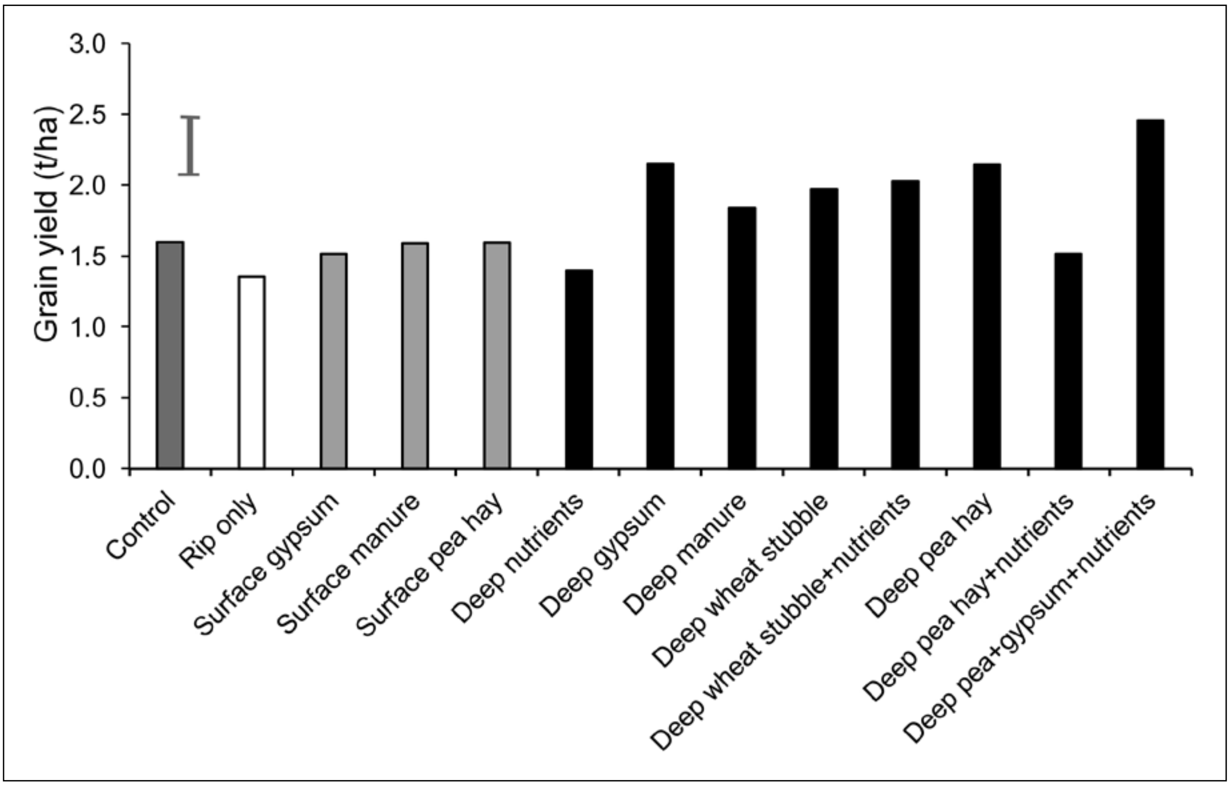

Figure 1. Grain yield of wheat in response to a range of soil amelioration treatments applied to either the soil surface or subsoil (ca. 30-40cm) at Rand (NSW) in 2018. Vertical bar is l.s.d. (P = 0.05).

is too dry, machinery drafting requirements and fuel usage will be high and the soil loosening outcome will be suboptimal (Ucgul et al. 2019). It is important to know the depth of compacted layers and then to rip to just below this layer (e.g. 10cm deeper).

If compaction is the only constraint, then the use of appropriate 'loosening shanks' and points is important i.e. avoid shallow forward leaning, wide shanks which are designed to delve lower soil layers and bring them to the soil surface. This will help maintain the structure of the soil above the compacted layer and also minimise bringing the subsoil, potentially with its severe physicochemical constraints, to the surface. The use of shallow leading tines can reduce draft significantly depending on tine arrangement and soil type (Davies et al. 2019).

Inclusion plates fitted behind ripper tines were initially developed in WA to keep the rip line open for longer, and encourage some of the top soil to fall into the bottom of the rip before it closes. This can benefit root growth especially if a recently limed topsoil, rich in organic matter, occurs over an acid layer in the subsurface. The optimisation of the inclusion process and other tillage operations is currently being investigated in the southern region (Ucgul et al. 2019). The speed of operation is also important, particularly for the effectiveness of inclusion plates, with less back fill at faster speeds.

Beware when ripping sandy soils that these may be very soft, creating problems for sowing and crop establishment. Make sure the seeder is set up appropriately for ripped areas and depth of seeding is not excessive. Also note that ripped sandy soils are highly prone to wind erosion, especially if small amounts of crop stubble are left between the rip lines.

Future opportunities

The time requirements and costs of deep ripping paddocks can be prohibitive, so it is important to avoid deep ripping parts of the paddock where compaction is not a problem. Soil types can vary markedly within a paddock (Figure 2), and even within paddock with a uniform soil type, the depth at which subsoil constraints can begin to limit crop performance may vary. These constraint variations

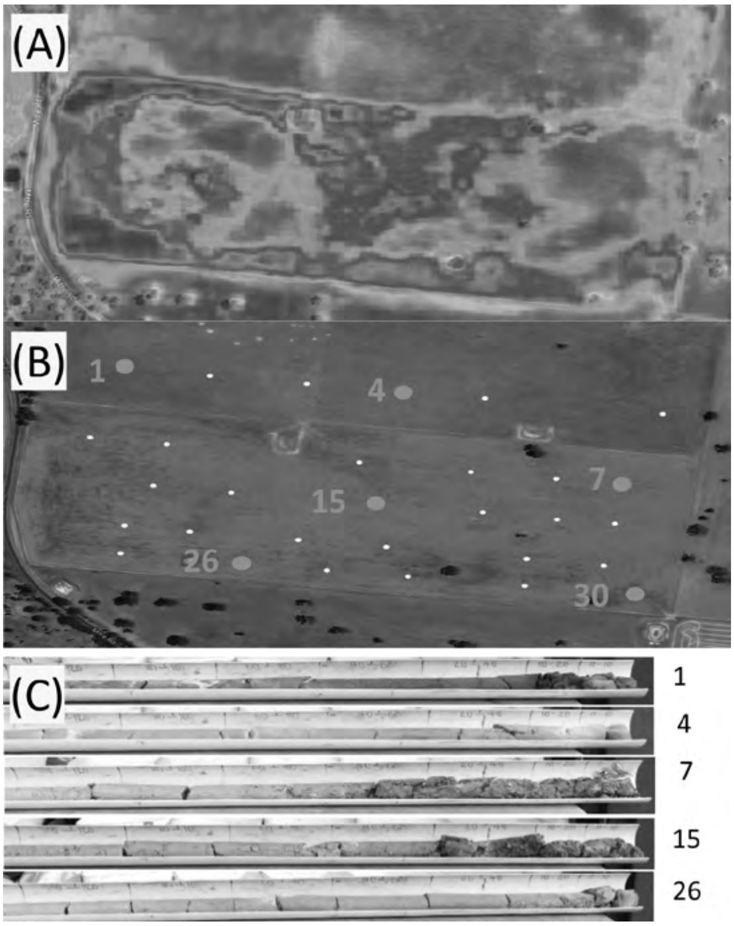

Figure 2. Variation in crop productivity across a paddock near Warracknabeal as indicated by normalised difference vegetation index (NDVI) satellite imagery (A); Soil type using colour imagery (B); and Variation in soil properties such as texture down the profile at six sampling points within this paddock (C).

are strongly linked to crop productivity and NDVI maps. Agriculture Victoria is currently examining the potential of NDVI maps and different soil sensing procedures such as EM38, Ground Penetrating Radar and Gamma Radiometric analysis to rapidly identify where soil constraints occur within a paddock at a 3D scale and then correlating this with the production response after imposing appropriate soil management treatments (e.g. deep ripping or the application of gypsum for sodicity).

Conclusions

Potential yield benefits arising from deep ripping are strongly soil type specific and the longevity of benefits is influenced by post-ripping management. Although major yield responses to deep ripping have been recorded on sandy soils in the Southern Region, few benefits or yield depressions are likely on clay soils or shallow duplex soils with physicochemical constraints in the subsoil. A thorough soil sampling and analysis program is recommended to diagnose these constraints. If deep ripping is undertaken, a range of logistical factors need to be considered including soil moisture, depth of ripping, implement design and speed of operations to maximise yield benefits and reduce costs.

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The health report - 2019 pulse disease seasonal update and NVT disease ratings

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Keywords

- pulses, disease resistance, lentil, faba bean, chickpea, field pea, fungicides, resistance changes, national variety trials (NVT).

Take home messages

- Consult a current pulse disease guide for the latest pulse disease ratings and up to date disease management information.
- A new national pulse disease rating system has been implemented, which will ensure a consistent and independent disease rating system for pulses.
- In lentils, there are now two pathotypes of Ascochyta blight (AB) present in the southern region. In Victoria, the AB rating for PBA Hurricane XT⁽ᵇ⁾ has not been downgraded, as it has in South Australia (SA). Growers are advised to closely monitor both PBA Hurricane XT⁽ᵇ⁾ and PBA Hallmark XT⁽ᵇ⁾ varieties for infection, and manage as a potentially higher risk of AB.
- In faba beans, there are currently two pathotypes of AB which are widespread across the southern region. It is assumed reports of higher incidences of AB on PBA Samira⁽ᵇ⁾ is due to on-farm retained seed which had outcrossed with more susceptible varieties. Ensure seed is isolated from other varieties by a minimum of 200m to minimise the risk of cross-pollination.
- Following the first signs of AB infection in chickpea, a fungicide application of a premium product has resulted in grain yield and AB infection comparable to the multiple preventative application of fungicides. Research is continuing to ensure a similar result is observed across seasons.

2019 pulse disease seasonal review

Widespread disease development occurred in pulse crops, in Victoria, during winter 2019. The dry conditions during spring slowed further disease development, however Agriculture Victoria field experiments measured yield losses up to 95% when susceptible chickpea varieties were not protected with fungicides. This highlighted the benefits of proactive disease control, even in a season with a dry finish. Bacterial blight was a significant issue in field peas during 2019, with several reports of total crop loss. Unfortunately, there are no in-crop management options available for bacterial blight.

New varieties and their disease resistance

The recent release of several new pulse varieties is, in many cases, providing improvements in resistance to diseases of importance in Victoria. Implementation of a nationally standardised approach to pulse disease resistance ratings may have resulted in some minor changes to resistance classifications. With the changes in diseases over time, it is always recommended to consult a current disease guide.

Chickpea

PBA Royal⑴ is a new kabuli chickpea variety with comparable Ascochyta blight (AB) resistance to GenesisTM090.

Experiments conducted during 2018 and 2019 compared AB severity and grain yield across varieties, in the presence of AB, at both Curyo and Horsham. These experiments had three treatments:

- Full control/minimal disease – multiple fungicides applied to achieve no disease. No infested stubble applied.
- Bixafen (45gai/ha) and prothioconazole (90gai/ha), applied at 4-node and flowering growth stages. Plots were inoculated with AB infested stubble at the 4-node growth stage.
- Diseased plots where no fungicides were applied. Plots were inoculated with AB infested stubble at the 4-node growth stage.

During 2019, high levels of disease was observed in the experiments at both sites, particularly where no fungicide was applied. At Curyo, GenesisTM090 and PBA Royal⑴ showed equivalent yield loss due to AB. This was less than in most other lines evaluated in the experiment, showing the benefit of partial resistance in newer varieties (Table 1). At Horsham, PBA Royal⑴ had less disease than GenesisTM090. At both sites both PBA Royal⑴ and GenesisTM090 had similar grain yields in the reduced fungicide treatment (Bixafen + Prothioconazole), compared with the 'full control' treatment.

Faba bean

PBA Amberley⑴ has improved chocolate spot resistance compared to the other commercial varieties. Preliminary field data is showing minimal yield losses due to chocolate spot, although currently there are few experiments with good levels of infection. Glasshouse results are also showing good resistance to AB pathotypes 1 and 2.

Lentil

PBA Highland XT⑴ has improved resistance to AB, including the isolates in SA that are now compromising the resistance in PBA Hurricane XT⑴ and PBA Hallmark XT⑴.

Table 1. Grain yield (t/ha) of 15 chickpea varieties in the presence and absence of Ascochyta blight (AB), with three different treatments applied at Curyo during 2019.

Variety	Treatment*		
	Full control	Bixafen (45gai/ha) + Prothioconazole (90gai/ha)	
		4-node and flowering	Nil
PBA Striker⑴	1.97	0.93	0.37
Howzat⑴	1.87	1.09	0.53
CICA1521	1.89	1.18	0.61
PBA Monarch⑴	1.94	1.26	0.73
Sonali	2.01	1.42	0.79
CICA1841	1.63	1.27	0.84
CICA1352	1.81	1.71	1.06
PBA Slasher⑴	1.79	1.49	1.10
Almaz⑴	1.83	1.66	1.12
Kalkee	1.41	1.57	1.13
CICA1551	1.88	1.46	1.35
CICA1552	1.69	1.78	1.39
GenesisTM090	1.76	1.72	1.39
PBA Royal⑴	1.67	1.60	1.56
CICA1454	1.94	1.75	1.59
	P value	**Lsd**	
Variety	<.001	0.09	
Treatment	<.001	0.21	
Variety x Treatment	<.001	0.36	

**The three treatments were; full control — no AB stubble was applied and fungicides were applied to ensure no disease; Bixafen + Prothioconazole — applied at 4-node and flowering growth stages and inoculated with AB infested stubble at the 4-node stage; and Nil — where there was no disease control and the plots were inoculated with AB infested stubble.*

Pulse disease National Variety Trials (NVT)

Through an expansion of the GRDC's National Variety Trials (NVT) program, independent disease ratings of pulses are now available. This provides robust disease ratings using processes adapted from those established for wheat and barley. Table 2 lists included crops and diseases.

Definitions for each disease rating category were updated as part of this new project (Table 3). The update changes some pulse disease ratings, with better alignment between crops and diseases nationally.

A total of 49 disease screens are conducted annually, drawing on the extensive plant pathology expertise available across Australia. Disease screens are conducted in field, and/or glasshouse conditions designed to maximise disease expression.

At the end of the season, data collected nationally are collated and disease ratings are assigned by experts. Disease ratings are updated annually and made available in State-based disease guides and on the NVT web site - https://www.nvtonline.com.au/.

Monitoring Ascochyta blight pathogen populations of lentil and faba bean

To monitor shifts in the AB pathogen population of both lentil and faba bean, annual monitoring and pathogenicity testing has been conducted at SARDI since 2015. Each year, in controlled environment conditions, 40 isolates (single disease sample) of *Ascochyta lentis* and *Ascochyta fabae* are tested on a differential host set of lentil and faba bean, respectively. Results from isolates collected from commercial crops and field trials in SA and Victoria during the previous season, are reported in Tables 4 and 5.

Ascochyta blight in lentil

Early and severe *Ascochyta lentis* infection in PBA Hurricane XT$^{\phi}$ crops and volunteer plants were reported during 2019 on the Yorke Peninsula

Table 2. Crops and diseases included in the new National Variety Trials (NVT) 2019 screening and 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

Table 3. Updated pulse disease ratings used in the National Variety Trials (NVT), to 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. 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.

(YP) and in the Mid-North region of South Australia (SA). Indicating that the variety's MRMS rating is under threat. PBA Hurricane XT⁽ᴾ⁾ remains rated MR in Victoria but may change when additional data becomes available.

Annual testing has confirmed two pathotypes of *A. lentis* present in SA; a Nipper-virulent type, and a Hurricane-virulent type. Controlled environment testing was conducted in 2019, of *A. lentis* isolates collected in 2018 (35 from SA, five from Victoria) on a differential host set that includes Nipper⁽ᴾ⁾ and PBA Hurricane XT⁽ᴾ⁾ (Table 4). Of the isolates tested in 2019; 27 out of 40 (67.5%) were capable of infecting PBA Hurricane XT⁽ᴾ⁾, 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⁽ᴾ⁾, 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 for, over time, in intensive cropping systems. Although high levels of AB are not commonly observed in Victoria, the SA isolates may spread, so growers and agronomists are advised to monitor lentil crops for this potential new pathotype.

Table 4. Forty (40) *Ascochyta lentis* isolates collected in 2018 were inoculated onto a lentil host differential set, in controlled environment conditions during 2019 at SARDI. Entries in the table are the number of isolates per category.

Test reaction*	Cumra (susceptible check)	Nipper⁽ᴾ⁾	PBA Hurricane XT⁽ᴾ⁾	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

**R = resistant, MR = moderately resistant, MRMS = moderately resistant-moderately susceptible, MS = moderately susceptible, and S = susceptible.*

In light of the observed reactions on PBA Hurricane XT⁽ᵇ⁾ in SA coupled with the results of the annual pathogenicity testing, growers should regularly inspect both PBA Hurricane XT⁽ᵇ⁾ and PBA Hallmark XT⁽ᵇ⁾ lentil crops to determine if AB infection is severe enough to directly affect yield. PBA Hallmark XT⁽ᵇ⁾ is presumed to have the same source of resistance to AB as PBA Hurricane XT⁽ᵇ⁾. Tests at SARDI have found that PBA Hallmark XT⁽ᵇ⁾ is able to be infected by recently collected Hurricane-virulent isolates at a moderate level.

The newly released lentil variety, PBA Highland XT⁽ᵇ⁾, 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.

Ascochyta blight in faba bean

There were a number of reports of mild AB leaf infection in SA and Victorian faba bean crops in 2019. This did not cause major problems as the cool (5-15°C) and wet conditions did not persist in most growing regions. However, two pathotypes of *A.fabae* are found in all faba bean growing regions in the southern region, with the more aggressive pathotype 2 also present across Victoria. Farah⁽ᵇ⁾ is currently 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 RMR to both pathotypes. Check updated pulse disease guides as ratings may change between years.

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

The annual testing of *A. fabae* 2018 isolates (23 from SA, 17 from VIC) were conducted on a differential faba bean host set, including the commercial varieties PBA Rana⁽ᵇ⁾ and PBA Zahra⁽ᵇ⁾, as well as three Ascochyta resistant (AR) selections; *viz.* Farah AR, Samira AR and Nura AR. The AR selections are 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 which is aggressive on PBA Samira⁽ᵇ⁾. This is demonstrated by four out of 40 (10%) isolates causing a MRMS reaction on Samira AR (Table 5). Continued monitoring will be critical to confirm these shifts in the pathogen population.

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.

Table 5. Forty (40) *Ascochyta fabae* isolates collected in 2018 were inoculated in 2019 onto a faba bean host differential set, in controlled environment conditions at SARDI. 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

**R = resistant, MR = moderately resistant, MRMS = moderately resistant-moderately susceptible, MS = moderately susceptible, and S = susceptible.*

Chickpea Ascochyta blight management

Research to reduce fungicide use in chickpeas is an Agriculture Victoria priority. Experiments continue to investigate the use of post infection sprays of premium fungicides, as opposed to the current practice of multiple preventative fungicide applications. These experiments compared two varieties with different resistance; Genesis™090 and PBA Striker(b), across 10 fungicide treatments (Table 6). During the 2019 experiments at Curyo and Horsham, there was no significant difference in grain yields between the single application of a premium fungicide, once the first signs of AB infection were observed, compared to multiple preventative fungicide applications (Table 7). These results are similar to 2018, however, only two applications of strategic chlorothalonil (1080 gai/ha) were required during 2019 compared to three during 2018 (Brand and Fanning 2019). This indicates a fungicide application of a premium product, following the first signs of AB infection, results in comparable grain yield and AB infection compared to the preventative application of fungicides during 2019.

The application of fungicides following disease infection remains a higher-risk scenario. These field experiments were inoculated with infested stubble however, so it would be expected that results on a paddock scale may vary. This work will continue so we can develop solid messaging around fungicide usage as a curative approach for disease control.

Disease survey of chickpea, faba bean and lentil in Victoria

A survey of 19 chickpea, nine faba bean and 26 lentil crops for the incidence and severity of foliar and soil-borne diseases was conducted between September and October 2019. The results showed that both soilborne and foliar diseases posed important threats to Victorian crops (Figure 1). Among the foliar diseases in pulses, AB was most commonly observed. The soil-borne disease analysis is still ongoing.

Table 6. Fungicide treatments and the number of sprays applied for each treatment to assess control of ascochyta blight (AB) in chickpea at Curyo during 2019.

Seed Treatment[A]	Rate (gai/kg of seed)	In-season Fungicide[A]	Rate (gai/ha)	Timing[B]	Number of Sprays
Thiram Thiabendazole	0.72 0.4	Captan™	1000	Strategically	2
Thiram Thiabendazole	0.72 0.4	Propiconazole[A]	125	Strategically	2
Thiram Thiabendazole	0.72 0.4	Chlorothalonil	1080	Strategically	2
Thiram Thiabendazole	0.72 0.4	Tebuconazole Azoxystrobin	200 120	Strategically	2
Thiram Thiabendazole	0.72 0.4	Bixafen Prothioconazole	45 90	Strategically	2
Thiram Thiabendazole	0.72 0.4	Tebuconazole + Azoxystrobin	200 120	Post Infection	1
Thiram Thiabendazole	0.72 0.4	Bixafen Prothioconazole	45 90	Post Infection	1
Fluxapyroxad[A]	0.5	Bixafen Prothioconazole	45 90	Post Infection	1
Thiram Thiabendazole	0.72 0.4	Full control[C]			

[A] *Some of the fungicides used in this trial have been used in an off-label manner. The 'Off-label' treatments used in these trials are allowable in the state of Victoria ONLY having met the requirements of the state legislation. Their use remains a high risk activity so before using a chemical off-label please consult your agronomist or go to http://agriculture.vic.gov.au/agriculture/farm-management/chemicals*

[B] *Strategic sprays were applied before rainfall events, at key growth stages to maximise foliage protection (4th node and late vegetative / early flowering stage). Post infection sprays were applied when the first AB lesions were observed and at flowering. Trials were inspected at least weekly.*

[C] *The full control treatment is a rotation of fungicides applied to ensure minimal to no disease as a control in the experiment.*

Table 7. Grain yield, percentage plot affected with ascochyta blight (AB) and percentage of pods affected with AB in plots treated with 10 fungicide treatments at Curyo during 2019. Different letters indicate pairwise significance where the variety, treatment or interaction were significant (P<0.05).						
Treatment	Timing[B]	Plot affected (%)		Yield (t/ha)		
		Genesis™090	PBA Striker⁽ᴰ	Genesis™090	PBA Striker⁽ᴰ	Mean
Nil	Nil	21 cde	88 h	1.35	0.56	0.95 a
Thiram + Thiabendazole on seed Captan	Strategically	14 abcd	79 gh	1.36	0.88	1.12 ab
Thiram + Thiabendazole on seed Propiconozole[A]	Strategically	9 abc	69 fg	1.60	0.94	1.27 bcd
Thiram + Thiabendazole on seed Tebuconazole + Azoxystrobin	Strategically	18 bcde	57 f	1.63	1.07	1.35 bcd
Thiram + Thiabendazole on seed Chlorothalonil	Strategically	8 abc	58 f	1.57	1.16	1.37 bcd
Thiram + Thiabendazole on seed Bixafen + Prothioconazole	Strategically	2 ab	26 de	1.65	1.30	1.48 cd
Thiram + Thiabendazole on seed Tebuconazole + Azoxystrobin	Post Infection	5 abc	33 e	1.56	0.94	1.25 bc
Thiram + Thiabendazole on seed Bixafen + Prothioconazole	Post Infection	3 ab	16 abcde	1.76	1.20	1.48 cd
Fluxapyroxad[A] on seed Bixafen + Prothioconazole	Post Infection	2 ab	14 abcd	1.88	1.21	1.54 d
Thiram + Thiabendazole on seed Full Control[C]		0 a	0 a	1.94	1.87	1.9 e
Mean				1.63	1.11	
		P value	**Lsd**	**P value**	**Lsd**	
Variety		<.001	6	<.001	0.06	
Treatment		<.001	12	<.001	0.14	
Variety x Treatment		<.001	17	0.412	ns	

[A] *Some of the fungicides used in this trial have been used in an off-label manner. The 'Off-label' treatments used in these trials are allowable in the state of Victoria ONLY having met the requirements of the state legislation. Their use remains a high risk activity so before using a chemical off-label please consult your agronomist or go to http://agriculture.vic.gov.au/agriculture/farm-management/chemicals*

[B] *Strategic sprays were applied before rainfall events, at key growth stages to maximise foliage protection (4th node and late vegetative / early flowering stage). Post infection sprays were applied when the first AB lesions were observed and at flowering. Trials were inspected at least weekly.*

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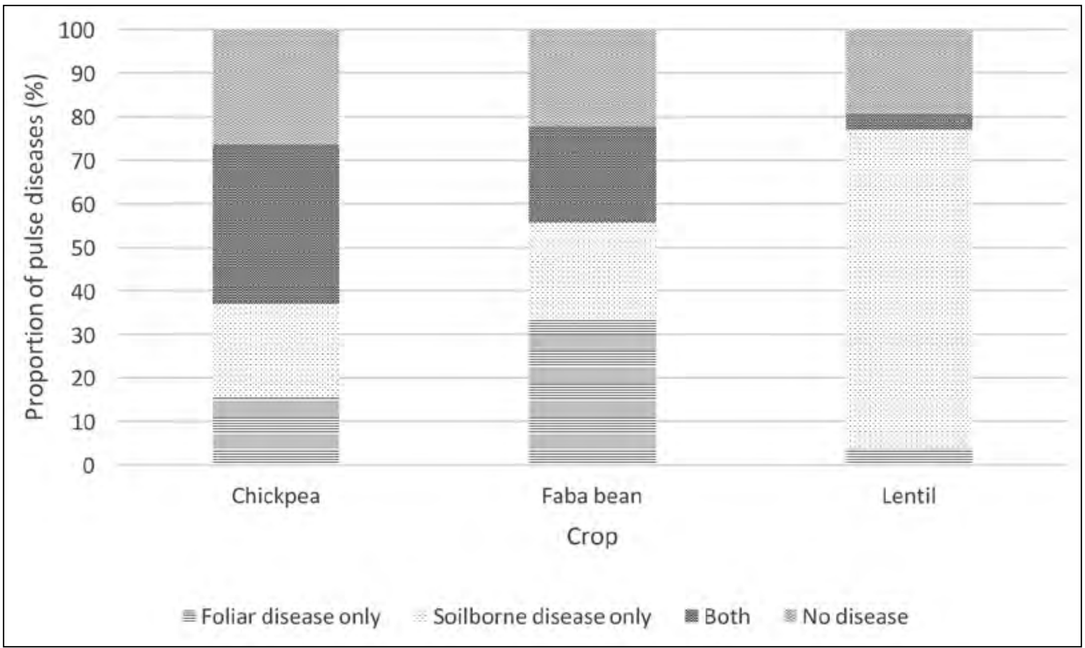

Figure 1. Proportion of pulse diseases in Victoria.

How can you help pulse pathology research?

Samples of pulse crops with the following diseases are being sought:

- Ascochyta blight,
- Botrytis (Botrytis grey mould (BGM) or chocolate spot),
- Sclerotinia; and,
- soil-borne disease.

The latest disease samples ensure researchers are monitoring changes in both the pathogen populations and variety resistance. If you can help, please contact Joshua Fanning (Victoria) for a collection kit, which includes sample envelopes and a return post envelope.

Crop protection products

There are often changes to permits for the use of fungicides in pulse crops. Pulse Australia's website (www.pulseaus.com.au) has current information on Crop Protection Products including Minor Use Permits, as does the Australian Pesticides and Veterinary Medicines Authority (APVMA) website; www.apvma.gov.au.

Off-label chemical use (Victoria ONLY)

The 'Off-label' treatments used in these trials are allowable in the state of Victoria ONLY having met the requirements of the state legislation. Their use remains a high-risk activity.

Any person that uses a chemical off label must accept and manage all risks associated with that use, such as the risk of residues in produce or the environment, occupational health and safety concerns and the efficacy of the chemical. This is particularly important for export commodities. In the past, access to export markets have been disrupted due to unacceptable residues caused by off-label use.

It is critical that people using chemicals off-label under the Victorian legalisation:

- DO NOT use a Schedule 7 Dangerous Poison (e.g. Carbendazim) in an off-label manner without a permit from the Australian Pesticides and Veterinary Medicines Authority (APVMA)
- DO NOT use the chemical at an above label rate
- DO NOT use the chemical more frequently than the label states
- DO NOT use the chemical contrary to any prohibitive label statements e.g. DO NOT statements

For more information on the off-label use of chemical in Victoria; http://agriculture.vic.gov.au/agriculture/farm-management/chemicals/off-label-chemical-use

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Significant contributions have been made by of growers and agronomists through provision of diseased plant materials for the isolate collection, the authors would like to thank them for their continued support. We would also like to thank the large research teams supporting this research at Agriculture Victoria and the South Australian Research and Development Institute (SARDI).

Useful resources

Pulse disease guide http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/plant-diseases/grains-pulses-and-cereals/pulse-disease-guide

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

National Variety Trial (NVT) website https://www.nvtonline.com.au/

Victorian crop sowing guide https://grdc.com.au/2020-victorian-crop-sowing-guide

New pulse variety releases:

PBA Royal⍭ chickpea: https://www.seednet.com.au/product/pba-royal

PBA Highland XT⍭ lentil: https://www.pbseeds.com.au/docs/PBAHIGHLANDXT.pdf

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

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

Gerard McMullen.

Chair National Working Party on Grain Protection (NWPGP).

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

This project is undertaken solely as a GRDC project and is made possible by the significant contribution of growers through the support of the GRDC. The author would like to thank growers and the GRDC for their continued support.

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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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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Plant power - plant-based meat substitutes in the flexitarian age

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Keywords

- meat substitute, meat alternative, plant protein, sustainability, flexitarian, vegetarian, vegan, grain, whole grain, legume.

Take home messages

- This study aimed to provide an overview of currently available plant-based meat substitutes available on Australian supermarket shelves, nutrition composition compared to animal products of comparable culinary use (burgers, sausages and mince) and changes in the make-up of the category from 2015 data.
- Product numbers increased 429% in four years.
- Plant-based options were generally lower in kilojoules, total and saturated fat, higher in carbohydrate, sugars, and dietary fibre compared with meat. Only 4% of products were low in sodium (58–1200mg/100 g).
- The plant protein trend has prompted innovation in meat substitutes, however wide nutrient ranges and higher sodium levels highlights the importance of nutrition guidelines in their development.

Background

Demand for plant-based meat substitutes is growing globally for nutritional and environmental reasons, with Australia the third-fastest growing vegan market worldwide. Food choice is strongly linked with human health and the health of our environment, with excessive meat consumption often viewed as detrimental for both factors (Tillman and Clark, 2014). Globally, agriculture and food production is responsible for more than 25% of all greenhouse gas (GHG) emissions (Tillman and Clark, 2014), with effects widely varied based on food-type. It is well-accepted that animal-based foods have a greater environmental impact than plant-based foods.

Suboptimal diets are responsible for more deaths than any other risk factors globally, including tobacco smoking. Suboptimal diets cause an estimated 11 million deaths and 255 million Disability Adjusted Life Years (GBD 2017 Diet Collaborators, 2019). Worldwide, intake of red meat surpasses what is considered optimal by 18% (led by Australasia, southern, and tropical Latin America) and consumption of processed meat is 90% greater than the optimal amount (led by North America, Asia Pacific, and western Europe) (GBD 2017 Diet Collaborators, 2019). However, compared to other dietary risks, high intake of red and processed meat ranked at the bottom end (at number 13, and 15, respectively) for death and disability. Conversely, high intakes of sodium, and low intakes of whole grains, fruit, vegetables, nuts and seeds all featured in the top five risk factors (GBD 2017 Diet Collaborators, 2019).

The focus on plant-based proteins has created a significant opportunity within the food industry against a backdrop of health and environmental concern. Meat substitutes such as tofu and textured soy protein products have existed in the Western World since at least the 1960s (Elzerman et al. 2013; Mellentin, 2018), however it now appears that the target has moved from niche, to more mainstream, with products designed specifically to appeal to meat-eaters. Products resembling burger patties, mince, sausages, and chicken are displayed alongside meat in the chilled cabinets and many mimic meat products directly, with 'bleeding' burgers and other products designed to exhibit 'meaty' characteristics (Kaczorowskim, 2019).

In light of growing consumer interest in alternatives to traditional animal proteins, this study aimed to provide an overview of currently available plant-based meat substitutes available on Australian supermarket shelves, nutrition composition compared to animal products of comparable culinary use (burgers, sausages, and mince) and changes in the make-up of the category from 2015 data.

Method

A recognised process was used to conduct an audit of plant-based meat substitutes (Grafenauer, 2018) in the four major supermarkets (Aldi, Coles, IGA, and Woolworths) of metropolitan Sydney in June 2019, replicating a process that was conducted on the same category in 2015. These supermarket chains represent more than 80% of the total Australian market share and were chosen in an effort to reflect choices available to the majority of Australian shoppers. Researchers used smartphones to capture all data on food packaging, including ingredients, nutrition information panel (NIP), health and nutrition claims, country of origin, Health Star Rating (HSR), and any additional logos and endorsements.

Following data collection:

1. Products meeting the inclusion criteria were grouped into common categories based on their similarity to meat-based products and dishes, including plant-based burgers, sausages, mince, chicken, seafood, and an additional 'other' category with products that fell outside of these categories. Products excluded were vegetarian foods not specifically created to imitate meat products, such as tofu, tempeh, and falafel.
2. Data from photographs was then transcribed into a Microsoft Excel spreadsheet (Redmond, WA, USA) for analysis.
3. Eligibility for products to make nutrition content claims was assessed in line with Food Standards Australia New Zealand (FSANZ) and the Grains and Legumes Nutrition Council Code of Practice for Whole Grain Ingredient Content Claims (The Code).
4. Health Star Rating (HSR) was calculated for all products that did not display the system on-pack, using the HSR website calculator.
5. The number and type of products collected were compared with data from a 2015 study that followed the same process, to assess changes in numbers and types of products.
6. In order to compare meat substitutes to their equivalent animal-based versions, nutrition composition data was obtained for mince and sausages through FSANZ's Australian Food Composition Database [35]. Information for burgers did not exist within this database, so nutrition data was averaged from ten products found on Coles and Woolworths websites.

Statistic analyses

All data were checked for normality using the Shapiro–Wilk test (IBM SPSS®, version 25.0, IBM Corp., Chicago, IL, USA) and mean and standard deviation were presented in addition to median and range as only energy, protein, fat and dietary fibre were normally distributed. As expected, there were missing values for dietary fibre, sugars, sodium and iron as these would not be presented in the NIP unless specifically added to the products, therefore these nutrients were analysed separately.

Independent sample t-tests (IBM SPSS®, version 25.0, IBM Corp., Chicago, IL, USA) were used to compare differences in nutrients per 100g between meat and plant-based meat substitutes for the burger, sausage, and mince categories with data sourced from FSANZ or online supermarkets as described above.

Results and discussion

Data from 137 plant-based meat substitute products were collected, including 50 burgers, 29 sausages, 10 mince, 24 chicken, 9 seafood, and 15 'other' meat substitutes (including 'vegie roasts,' deli slices such as mock ham and bacon, and tinned nut meat). The number of products overall had increased more than five-fold compared to 2015, with greatest growth seen in burgers (+614%), and seafood emerging as a new category, with no products previously captured from this group (Table 1).

Table 1. Changes in product numbers and type of plant-based meat substitute product between 2015 and 2019 audits.			
Category	2015 Total Products (n=26)	2019 Total Products (n=137)	Increase
Burgers	7	50	614%
Sausages	6	29	383%
Mince	5	10	100%
Chicken	4	24	500%
Seafood	0	9	
Other	4	15	275%
Total	26	137	429%

When considering country of origin, the majority of products (61%) were made in Australia. This was followed by 12% from South Africa, 9% from United Kingdom, and 7% from New Zealand, with USA, Canada, Thailand, Taiwan, and Denmark producing smaller numbers of products.

Data on HSR, a comparison with similar meat-based products, key ingredients and packaging claims are also presented.

Meat consumption is growing globally (Gomez-Luciano, 2019; Wong et al. 2015) alongside recommendations to consume protein from plant sources. Although plant-based foods (both natural and manufactured) have been available for many years, the rapid and recent rise in the availability of new plant-based meat substitutes means that they have not been specifically included or addressed in country specific guidelines (Herforth et al. 2019) or in documents such as EAT Lancet (Willett et al. 2019). Yet, it has been said that moving to a diet based on more whole and plant-based foods could be 'one of the most important dietary strategies at a global level both for the planet and for human health' (Williams, 2019).

Understanding the nutrition implications and the profile of this category of products is important as more people adopt flexitarian, vegetarian and vegan dietary patterns. Also, there appears to be a 'health halo' effect (Sundar and Kardes, 2015) surrounding plant-based meat substitutes, that leads to a healthier perception, which may not be entirely justifiable. This research points to some limitations in the formulation of products, with some being higher than preferred in their sodium level. Importantly, many products fell short in terms of equivalence to similar meat varieties particularly in respect to micronutrients such as iron, zinc and Vitamin B12.

While this research was focused only on supermarket-based products, two known Australian fast food chains are also producing products utilising plant-based meat substitutes. At the fast-food chain; Grill'd, the Beyond Burger™ is used in five meat free options (https://www.grilld.com.au) and through leveraging the established Whopper® brand at Hungry Jacks® a Vegan Cheeseburger is available (https://www.hungryjacks.com.au). It is likely that the opportunity to purchase these products via fast food outlets will help grow consumer acceptance due to a lower level of commitment attached to a fast-food purchase compared with supermarket.

Legumes were found in more than two-thirds of products captured within this audit. This is an important finding as modelling shows Australians need to increase current levels of legume intake by 470% to meet recommended amounts (National Health and Medical Research Council, 2011). Given the known barriers to legume consumption, such as a lack of knowledge in how to prepare them, and time constraints (Figueira et al. 2019), plant-based meat substitutes may offer a convenient and surreptitious way to increase intake, a conclusion supported by others (Figueira et al. 2019; Gilham et al. 2018). Similarly, in this study, 20% of burgers contained >8g/manufacturer serve of whole grain, presenting a distinct opportunity to help consumers reach their 48g Daily Intake Target. Ingredients like brown rice, buckwheat, quinoa and other on-trend grains could be considered when formulating new options. In this respect, plant-based meat substitutes could become a vehicle for increasing whole grain consumption.

In order to attract consumers, front-of-pack claims and labelling systems such as the HSR, may be useful in directing consumers to healthier products within the category. Protein content as a claim was used on 60% of products yet a further 17% of products could be using this claim. The same was true for dietary fibre, where 39% of products display the claim yet an additional 19% of products from this review would be eligible to make a claim.

Conclusion

Plant-based meat substitutes may help disrupt the negativity around reducing meat, however, it is clear that some attention to nutrient composition and equivalence to meat is required from manufacturers to ensure that those with the greatest health literacy do not reject plant-based meat due to the detailed nutrition information on pack. Ethically, it is in the interest of good public health policy to ensure equivalence. There is also a very clear opportunity for grains, particularly whole grains and legumes to be featured in these products.

Full open access paper click here:

https://www.mdpi.com/2072-6643/11/11/2603/htm

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Discussion paper - Busting the big yield constraints – considerations for the future?

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Keywords

- yield, cost of production, sustainable intensification.

Take home messages

- Yield increases are necessary to keep cost of production for Australian growers competitive in international markets.
- Recent yield increases associated with improved genetics and agronomy (25kg/ha/year) are struggling to counteract the yield decline due to climate change (-24 kg/ha/year), and in coming decades it is likely that yield gains need to double to maintain profits.
- Yield increases are rarely the result of a single practice or technology but occur when new and old technologies and practices combine to form improved systems that overcome a constraint to production.
- Removing nitrogen (N) limitation, allowing crop establishment in the absence of breaking rainfall and genetic tolerance to heat/drought or frost are currently major constraints to yield in Australia, and require multidisciplinary systems research to overcome them.

Why increase yield?

Cost of production ($/t) is an important factor influencing the ability of Australian grain growers to compete in export markets. One of the main ways in which Australian grain growers have been able to maintain relatively low costs of production despite declining terms of trade has been by increasing crop yield with relatively small additional overhead and input costs. While ways of reducing overhead, input and transport costs can be found (for example; through economies of scale), yield increases are still an important way in which cost of production will be kept at an internationally competitive value in the future. Yield increases are also necessary to meet the goals of sustainable intensification, whereby the additional food required for a growing global population is produced on the same area of land that is currently farmed, without the further destruction of natural ecosystems. This paper will take a brief look at where historic yield increases in Australian crop (particularly wheat) production have come from, and where we believe future gains can be made. It is based on a chapter written for the book 'Australian Agriculture in 2020', recently published by the Australian Society of Agronomy (Hunt et al. 2019a), details of which can be found in the useful resources section within this paper.

Yield, yield and yield

The concept of potential yield (PY), Figure 1, and yield gaps is crucial when looking at ways to improve yield and we follow the nomenclature of Fischer (2015). The most important definition for dryland crop production in Australia is water limited potential yield (PY_w), defined as the yield of the best cultivar under optimum management with no manageable constraints (for example; nutrient deficiency, weeds, disease) except for water supply (Figure 1). Farm yield (FY) is yield achieved by growers in their fields. The difference between FY and PY_w is termed the yield gap. Economic yield (EY) is the yield attained by growers when economically optimal practices and levels of inputs have been adopted while facing all the vagaries of weather

(Figure 1). Economic or attainable yield is typically 7 5-85 % of PY_w (van Ittersum et al. 2013). The difference between EY and FY is the exploitable yield gap. Hochman et al. (2017) describes the proportion that FY comprises of PY_w as relative yield.

The yield gap of an individual farmer is dependent on management skill and level of investment in inputs, but also incentives and capacity to achieve higher yields. Management skill means the ability of a farmer to use management and inputs to reduce the biotic (weeds, pests and diseases) and abiotic stresses (water, nutrient and temperature stress) placed on crops. The different points in Figure 1 describe different situations under which growers may or may not be achieving potential yield. The first point describes a farmer with a high level of management skill, but who under-invests in inputs and is therefore not achieving economic yield. The second point describes a farmer with a high level of skill and appropriate investment in inputs who is achieving economic yield. This farmer has closed the exploitable yield gap.

The third point describes a farmer with a high level of skill who is over investing in inputs and while exceeding economic yield, is not as profitable (due to higher costs of production) or is more exposed to risk than the second farmer. The fourth point describes a farmer who is investing enough inputs to achieve economic yield, but due to a lack of management skill has an exploitable yield gap. This farmer will obviously not be as profitable as the second farmer. To close yield gaps, the first farmer needs to invest more inputs while maintaining current level of management skill. The fourth farmer needs to improve their management while maintaining current levels of inputs. The third farmer has closed the yield gap but can afford to invest less in inputs while maintaining their management skill, thereby increasing profits.

Where do yield increases come from?

Yield of crops is determined by the interaction between genotype (G = species, cultivar), environment (E = soil and climate) and management (M = rotational position, fallow management, tillage system, sowing date, fertiliser, control of weeds, pests and disease etc.) which is referred to as G x E x M. The case of wheat (and likely other grain crops) in Australia makes an interesting case study, because the climate has deteriorated (rainfall decreased and temperature increased) and reduced water limited potential yield by 27% during the period 1990 to 2015 (Hochman et al. 2017), which is equivalent to 24kg/ha/year (Ababaei and Chenu 2020). However, growers have maintained yields by adopting improved genotypes and management practices and increased farm yield relative to water limited potential yield (closed the yield gap) at a rate of 25kg/ha/year (Hochman et al. 2017). In other words, climate change has effectively robbed the industry of the yield gains it needs to stay competitive. Of course, national averages can be deceptive; many leading growers have increased yields despite climate change by increasing water-use efficiency, and therefore, remain globally competitive. For others, there is some room to

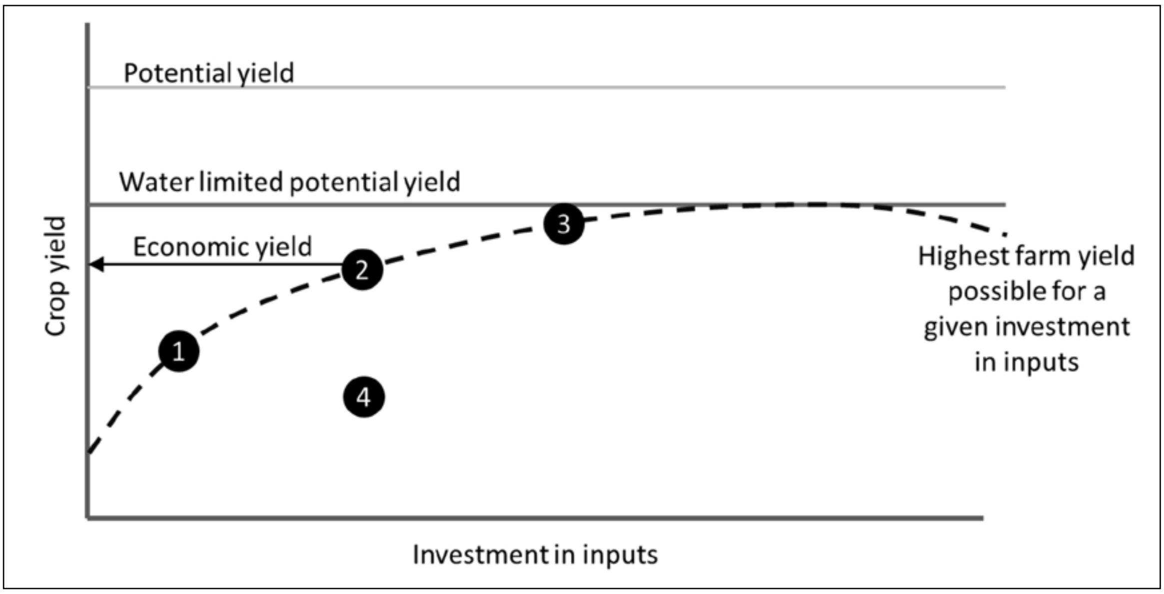

Figure 1. A graphical representation of potential yield, water limited potential yield, attainable yield and farm yield. The numbered dots represent growers with different yield gaps and different reasons for those yield gaps.

move in terms of yield gap closure. Australian wheat growers are currently achieving 55% of water limited potential yield (Hochman et al. 2017), meaning that for many growers there still exists a substantial yield gap, and yield could be further increased through adoption of best practice. Leading growers have closed the exploitable yield gap, and increased yield requires an increase in water limited potential yield (van Rees et al. 2014).

Past yield increases

Throughout history, increases in crop water productivity have rarely been attributable to an individual innovation in technology or farming practice. Increases have occurred when new and old technologies and practices combine to form improved systems that overcome a constraint to production (Kirkegaard 2019). In the example of Australian wheat production, the yield gap closure of the last 30 years has been due to many disparate technologies combining to form improved systems. The advent of non-selective knockdown herbicides (mainly glyphosate) and grass selectives drove the rapid adoption of no-till (Llewellyn et al. 2012) which improved soil water conservation and allowed earlier sowing (Stephens and Lyons 1998; Flohr et al. 2018c). Wheat was increasingly grown in rotation with broadleaf break crops (canola and pulses) rather than other cereals or weedy pastures which enhanced disease and weed management, and in the case of cereals following pulses, reduced fertiliser N requirements. Summer fallow weed control further increased soil water conservation, N accumulation and reduced root disease burdens (Hunt et al. 2013). Meanwhile breeders consistently achieved genetic yield progress of 0.5% per annum (Siddique et al. 1990; Sadras and Lawson 2011; Fischer et al. 2014; Kitonyo et al. 2017; Flohr et al. 2018b) and overcame significant biotic and abiotic constraints to production which interact with management (cereal cyst nematode, stripe rust, acidity, salinity, boron). Early sown, disease free crops responded profitably to increasing N fertiliser, applications of which tripled over the last 30 years (Angus and Grace 2017).

Future yield increases

Yield increases comparable to or exceeding those of the last 30 years are necessary to keep Australian growers competitive and to meet the goals of sustainable intensification. Fischer and Connor (2018) estimate that crop yields must increase at around 1.1% per year globally to ensure adequate food supply. While Australian growers have been able to close the yield gap by 25kg/ha/year (equivalent to 1.2% per year increase in relative yield, Hochman et al. 2017), declining rainfall and increasing temperatures have reduced water limited potential yield.

Significant yield gains in the coming decades requires a transformational change in the way we do research, development and extension. We argue that focussing research effort on developing synergistic systems that overcome current and future production constraints, combined with effective extension and adoption, will accelerate increases in yield. This will require a coordinated effort from multi-disciplinary teams, and in Hunt et al. (2019a), we describe a process of 'transformational agronomy' to achieve this. Briefly, agronomic researchers must work closely with growers and advisers to accurately define and quantify constraints to production. Solutions can then be sought and evaluated from diverse sources. Multidisciplinary teams with leadership from agronomists and close cooperation with growers and advisers will be required to achieve this. Once solutions have been evaluated and tested using a combination of crop simulation, small plot experiments and paddock-scale experiments in growers' fields, research teams need to work closely with growers and advisers to build and integrate improved, robust and adoptable farming systems that overcome the intended constraint.

Three constraints follow that we believe could be overcome with the multi-disciplinary research approach that is embodied in transformational agronomy. Indeed, if these could be achieved, we believe it would lead to transformational changes in production and profit for Australian growers. These are complex problems and will not be overcome cheaply or easily, but the pay-off from doing so would justify the investment.

Removal of N limitation

Nitrogen deficiency remains the single biggest factor contributing to the sizeable exploitable yield gap in Australian wheat production (Hochman and Horan 2018) and likely other non-legume crops (barley, oats, canola) as well. Even leading growers struggle with N management in favourable seasons (van Rees et al. 2014). At first this appears somewhat paradoxical; N management in grain crops should be extremely simple – crop requirement is well related to yield as described by the simple rule of thumb taught to all budding agronomists: 40kg/ha N per tonne of anticipated wheat yield. The supplies of N to the crop are also readily quantified – mineral N in the soil prior to sowing can be cheaply and easily measured from intact soil cores. Mineralisation is more difficult to estimate but it is possible and is self-correcting in that spring rain which leads to higher yield potential, also promotes more N mineralisation. The complexity comes in reliably estimating anticipated yields. This requires no less capability than the accurate prediction of weather several months in advance. But the difficulty arises from Australia's extremely variable rainfall. For instance, in southern NSW when growers need to make decisions regarding post-emergent N applications (typically in July-August), possible yields range from 0t/ha to 7t/ha in seasons with no stored soil water prior to sowing, and yield and N demand all depend on September and October rainfall. In addition, over-fertilisation with N can reduce both yield and grain quality through haying-off (van Herwaarden et al. 1998). N fertiliser is also a costly input and, mindful of environmental losses (Turner et al. 2012; Schwenke et al. 2014), many growers tend to err on the conservative side in their applications.

There have been consistent attempts to improve prediction of yields and to make N management more precise. This has included the use of forecast systems (Asseng et al. 2012) and decision support systems that integrate soil resources and management variables, and present likely response to N inputs in probabilistic terms (Hochman et al. 2009). While seasonal forecasts are likely to improve, they will never be perfect. Given the substantial nature of the problem, a fresh approach is required. One such solution that may work in environments with low N losses (for example; low rainfall areas with high soil water holding capacity) is the use of N fertiliser to maintain a base level of soil fertility ('N bank') sufficient to achieve water limited potential yields in the majority of growing seasons (as is currently done for phosphorus). Implementation of this strategy would need to consider the amount of mineral N in the soil profile and to adjust inputs for carry-over of previously applied N fertiliser not used by the crop. If applied appropriately at the time of rapid crop uptake, environmental losses from the 'N bank' would be low in farming systems where stubble is retained, and the majority of applied N is either taken up by the crop or immobilised into organic forms. Losses could be further reduced through use of higher efficiency N application strategies (e.g. deep and mid-row banding). Once the N banks are built, the cost of N fertiliser for growers is deferred into the season following rather with the season of high yields; this could have substantial economic value through improved cash flow and tax benefits. It may also reverse the mining of soil N that has occurred under Australian crop production since the decline in area of legume-based pastures (Angus and Grace 2017).

A multidisciplinary team is essential to test this potential solution. It requires accurate measurement of N losses and N cycling within the soil, and this requires discipline-specific expertise from within the field of soil science. In addition, economic assessment will be critical, and an investigation of management techniques to minimise possible negative effects on yield and quality from high levels of soil mineral N is required. Pre- and post-experimental crop simulation would be essential to test assumptions, identify locations and treatments that would be promising to test in the field, and extend field results over multiple sites and seasons. If found to be successful, geographic information system tools (e.g. yield and protein mapping) would allow even greater efficiencies through mapping of N removal in grain.

The 'N bank' concept has been tested using simulations at different rainfall locations in southern NSW, and were found to increase yields with minimal environmental impact (Smith et al. 2019). The first field experiment designed to test this was funded by La Trobe University and established by BCG at Curyo in 2018. The first two years of results indicate that 'N bank' strategies are equally profitable as attempting to match N inputs to seasonal yield potential using Yield Prophet® (Figure 2). More research is required to evaluate the approach across environments and to closely measure N losses.

Crop establishment in the absence of autumn rainfall

From the early breeding work of Farrer, much of the agricultural research conducted in Australia has aimed to coincide critical periods of yield determination in crops with climatically optimal conditions for growth. The cool, wet winters during which crops are grown in Southern and Western Australia often transition rapidly into hot, dry conditions with supra-optimal temperatures and limited soil water. When combined with spring frosts, this creates a reasonably narrow period during which crops must undergo their critical development phases (e.g. flowering) for yields to be maximised (Dreccer et al. 2018). While the concept of the optimum flowering window has long been known (Anderson et al. 1996), it has been the advent of computer simulation that has allowed them to be quantified for multiple locations across

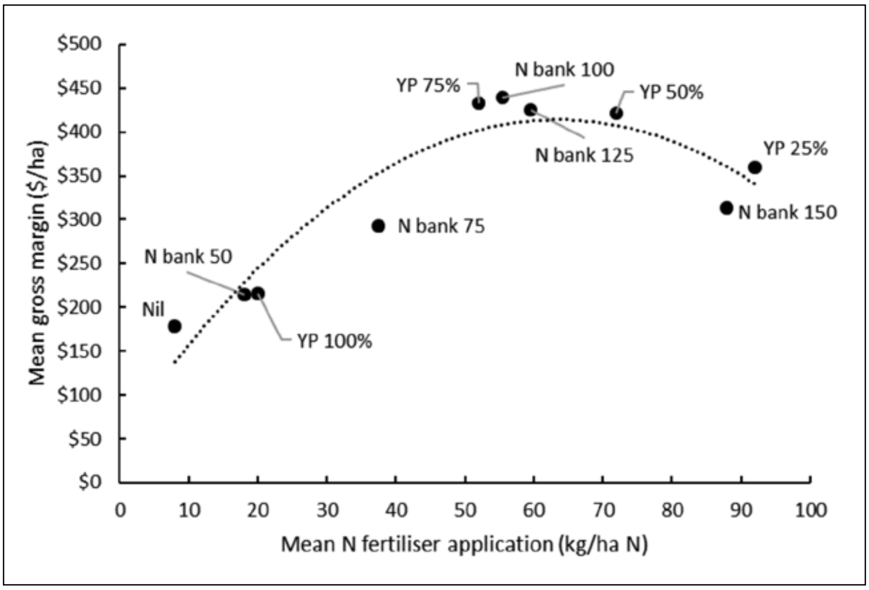

Figure 2. Mean annual N fertiliser application and mean annual gross margin 2018-2019 for different N management systems (N bank vs. Yield Prophet®) being tested in an experiment at Curyo in north west Victoria. The number following the Yield Prophet® (YP) treatments is the probability of different yield outcomes occurring at time of top-dressing in July (e.g. YP 75% targets each year the yield at which there is a 75% chance of exceeding). The numbers in the N banks treatments represent the total N supply (soil mineral N + fertiliser) that each treatment is topped-up to with N fertiliser (e.g. in the N bank 125 treatment, if 75kg/ha of soil mineral N is measured prior to sowing, it is topped up to 125kg/ha total N supply with 50kg/ha fertiliser N).

many seasons, for wheat (Flohr et al. 2017) and canola (Lilley et al. 2019) and barley (Liu et al. 2020). Shifting crop development closer toward optimal flowering periods has been the major mechanism behind many of the transformational changes in Australian crop production. This includes iconic advances such as the release of Federation wheat with its faster development pattern (Pugsley 1983), the rise of no-till which allowed much earlier sowing (Stephens and Lyons 1998), and more recent shifts to dry and early sowing (Fletcher et al. 2016; Hunt et al. 2019b).

Recent quantification of optimal flowering periods has revealed that leading growers are now coinciding critical periods with seasonal optima (Flohr et al. 2018c). The only times they do not achieve timely flowering is when they have been unable to do so due following dry autumns with insufficient soil moisture to allow seeds to germinate and emerge. Somewhat ironically, this new understanding of optimal sowing times has coincided with declining autumn rainfall (Pook et al. 2009; Cai et al. 2012) making it harder than ever for growers to achieve optimal flowering periods. This defines our second opportunity to overcome a major constraint to crop production – achieving crop establishment in the absence of favourable autumn rain. Once again, an integrated solution to this constraint demands multidisciplinary expertise led by a generalist with appreciation of the G x E x M context. Input is required from disciplines of agricultural engineering, plant physiology, genetics and soil physics.

Knowledge of the regulation of seed germination has developed greatly in recent times, yet our understanding of the mechanisms causing variation of plant establishment in the field remains limited. This is probably because most seed biology experiments are performed in laboratories under optimal conditions, whereas seeds in the field are subject to a complicated soil matrix where they experience a variety of different stresses (Finch-Savage and Bassel 2015). Domestication and breeding have provided incremental improvements in the ability of crops to germinate and emerge under sub-optimal conditions, but here we discuss ways in which agronomically directed research could be applied to transform seed performance when surface soil is dry.

Soil water potential is a major factor in determining seed germination and plant establishment. Many species can germinate at soil water potentials well below those that maximise plant growth (Wuest and Lutcher 2013). Distinguishing between adequate and marginal water to enable germination can be difficult for growers – there are no well-defined criteria for determining if a soil contains a high enough water content to germinate different crop species. At water potentials above -1.1MPa, germination rates are rapid (Wuest and Lutcher 2013). Water potentials below this slow the speed of germination, and below -1.6MPa, germination ceases. Pawloski and Shaykewich (1972) showed that these effects were similar between soils, even when soils differ in hydraulic conductivity.

Crop establishment could be enhanced by the ability of seeds to germinate at lower water potentials. This could be achieved by genetic or other means. Singh et al. (2013) found differences between wheat cultivars in the ability to germinate at low water potentials. Genetic variation for rates of seed water uptake (which initiates germination and is the first stage in the malting process) exists in barley, and it has been suggested that this could be exploited by breeders for the benefit of the malting and brewing industries (Cu et al. 2016). The same principles and expertise could be applied to field germination at low water potential. An obvious trade-off that may arise with the genetic ability to germinate at low water potentials is susceptibility to pre-harvest sprouting (Rodríguez et al. 2015). Expertise from plant physiologists concerned with the regulation of dormancy would be essential to harness this opportunity.

Beyond genetic means, strategies for manipulating germination processes used in horticulture crops and rice could be evaluated. Seed priming techniques limit the availability of water to the seed so that imbibition and seed metabolism commences, but germination is not completed (Halmer 2004). Seed priming has potential to reduce the lag time between imbibition and emergence, and to synchronise seedling emergence. It can improve emergence of wheat under low temperatures (Farooq et al. 2008), but not necessarily under low water potentials (Giri and Schillinger 2003). The inclusion of plant growth regulators, hormones or micronutrients during priming can also improve germination and emergence (Jisha et al. 2013; Ali et al. 2018). It is clear from the literature there are many potential solutions that could improve seed germination and establishment at low water potentials. Extensive field appraisal of these techniques is required.

Inadequate moisture at the ideal sowing depth has led to growers sowing deeper to seek moist soil and to make use of residual moisture stored from summer rains or the previous growing season. Their ability to do this is currently restricted by the availability of sowing equipment capable of placing seeds into moist soil at depth, and the ability of plants to emerge from depth. Coleoptile length is an important trait determining the success of emergence from depth, but there are also other genetic factors involved (Mohan et al. 2013). Modern Australian semi-dwarf wheat and barley cultivars show poor emergence when sown deep (greater than 8cm) due to short coleoptiles (Rebetzke et al. 2007). Warmer soils in the future may further exacerbate poor establishment and especially with deep sowing.

Pre-experimental modelling indicates substantial benefits for crop yield in southern Australia if machinery and genotypes could be developed that allowed placement and emergence of seed at depth (Kirkegaard and Hunt 2010; Flohr et al. 2018a). Establishment of crops in this way is routine in the drylands of the Pacific North West USA, where annual rainfall in some regions is as low as 160mm. Seeds of winter wheat and other crops are sown deep using deep furrow drills into moisture remaining from 13-month fallow periods and can emerge with 10cm to 15cm of soil covering them (Schillinger and Papendick 2008). Rebetzke et al. (2016) have argued the case for Australian breeders to use novel dwarfing genes that do not suppress coleoptile length. Larger seed size is also known to improve deep-sown crop establishment. Large-seeded canola improved the timeliness of establishment and subsequent grain yield when rainfall for crop establishment was marginal but there was moisture available deeper in the seedbed (Brill et al. 2016).

Frost, drought and heat

While optimisation of flowering times allows the combined stresses of drought, frost and heat to be minimised, these abiotic stresses still take a large toll on crops every year, and will continue to do so even if establishment in the absence of autumn rain could be achieved (see preceding discussion within this paper). Most avenues minimising the risks of frost, drought and heat have been explored, the only remaining means to increase yields in the face of these cardinal abiotic stresses is through crop tolerance. It is our opinion that this will most likely be achieved via genetic solutions, but these must be considered in an appropriate G x E x M context.

Frost, drought and heat risks are inextricably linked. Frost risk declines as flowering is deayed later into the spring, while the risk of drought and heat increases. This means that tolerances to all three stresses are not necessary to improve yields, and if tolerance can be found to either frost on the one hand, or drought and heat on the other, then the optimal flowering period will shift accordingly to reduce the likelihood of occurrence of the opposing stress. That is, if we can minimise frost stress then we can reduce the effects of drought and heat stress by flowering earlier, and vice versa. The value of this approach has been demonstrated by economic analyses of potential frost tolerance, where the benefit of shifting flowering time earlier to avoid drought and heat has also been quantified (An-Vo et al. 2018). Therefore, the important question is which of these stresses will be cheapest and easiest to solve?

Drought and heat are perhaps easier targets compared with frost in that they are reasonably easy to screen for within a breeding program, and some genetic regions associated with combined drought and heat tolerance have been identified (Tricker et al. 2018). Conversely, frost is virtually impossible to recreate under controlled conditions and tolerance is extremely difficult to identify. Heat and drought often interact. Heat tolerance in the absence of drought is associated with stomatal opening and rapid water-use that depresses canopy temperatures relative to the atmosphere (Reynolds et al. 1994). For heat tolerance to be useful in the Australian context, it must be effective under limited water supply (Hunt et al. 2018; Tricker et al. 2018).

While there may be some promise in selecting morphological traits known to confer both heat and drought tolerance, the greatest and most cost-effective progress may be made by breeders selecting for high yield at late flowering times where crops would be routinely exposed to concurrent drought and heat stress. However, this is where the wider crop physiology and management context becomes important. It would be crucial that late flowering be achieved with slow developing cultivars sown early and thus exploit a full growing season rather than by late sowing of faster developing cultivars where yield potential would be limited by shallow rooting depth and low biomass accumulation (Kirkegaard et al. 2015; Lilley and Kirkegaard 2016).

Conclusion

Yield increases are necessary to keep Australian growers competitive in international markets and to feed a growing population without increasing the area of land devoted to farming. Yield increases can be achieved by closing yield gaps, or increasing water limited potential yield. Climate change has reduced water limited potential yield and the industry needs to increase its efforts if real yield gains are to be realised. Historically this has happened when new and old practices and technologies synergise in improved farming systems. We argue that research should focus on developing new systems to overcome current constraints to production and we identify three opportunities for future yield gains - minimising N limitations, establishment of crops in dry or marginal soil moisture, and combined drought and heat tolerance. To solve these problems will require multi-disciplinary teams working closely with growers and advisers in appropriate farming systems context.

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This GRDC update paper is based on the following book chapter:

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JANUARY 2020

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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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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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Acknowledgements

We would like to thank those who have contributed to the successful staging of the Victorian GRDC Grains Research Update:

- The local GRDC Grains Research Update planning committee including both government and private consultants and GRDC representatives (see page 2 for list of contributors).
- Industry supporters including:

Adama Australia Pty Ltd	GenTech Seeds - Pioneer Seeds
AgVita	Intergrain
Agriculture Victoria	Nufarm/Nuseed Pty Ltd
Australian Grain Technologies (AGT)	Seed Force Pty Ltd
Back Paddock Company	Seednet
BASF Australia Ltd	UPL Australia Limited

GRDC
GRAINS RESEARCH
& DEVELOPMENT
CORPORATION

Networking event supported by

AGT

Barista coffee supported by

ADAMA

Trade display supported by

BASF
We create chemistry

AGVITA
ANALYTICAL

Seed Force
the power to grow

AGRICULTURE VICTORIA

UPL

INTERGRAIN
Growing Together

Seednet

Nufarm
Grow a better tomorrow

BACK PADDOCK
COMPANY

PIONEER®
BRAND · PRODUCTS

ABOUT US

Networking event supported by

Australian Grain Technologies

AGT is Australia's largest plant breeding company, and the market leader in wheat genetics.

Barista coffee supported by

ADAMA Australia

ADAMA Australia is a leading global manufacturer and distributor of crop protection solutions, with a heritage of nearly 70 years.

We understand that farming is complex and full of ever increasing challenges. We recognise that in order to make a genuine difference, we can't do this alone. Neither can farmers. So we work together with our partners in Australia and around the world to find ways to simplify it.

Together, we develop simple, practical and innovative solutions in crop protection and beyond to make the complex job of farming a little easier. www.adama.com/australia

Trade display supported by

AgVita Analytical

AgVita Analytical has all of your analysis requirements covered with rapid, innovative testing suites. We encourage you to visit our booth at the Grains Research Updates to experience our complete analysis capabilities.

We are unique, and our refreshingly simplified approach separates us from other providers. AgVitaAnalytical can provide the best solutions for your agricultural business, guaranteed.

AgVitaAnalytical is an efficient and professional laboratory offering a premium service for soil, plant and water nationally. We've been analysing nutrients since 1984 and use the very latest in technology. Our turn-around time is fast, in fact we are consistently the fastest throughout Australia, we have built our reputation on it. AgVita Analytical does not batch samples –we test every day.

AgVita Analytical is truly independent. We have no affiliation with any consultants or fertiliser companies.

Talk to us today, visit our website www.agvita.com.au or catch us at the 2020 Grains Research Updates, and experience the AgVita difference . . .

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.

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.

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.

Trade display supported by

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.

SOUTHERN/WESTERN REGION*

PREDICTA® B
KNOW BEFORE YOU SOW

*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.

Enquire with your local agronomist or visit
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)

There are PREDICTA® B tests for most of the soil-borne diseases of cereals and some pulse crops:

- 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

Government of South Australia
Primary Industries and Regions SA

SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

GRDC™
GRAINS RESEARCH & DEVELOPMENT CORPORATION

CONTACT:
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russell.burns@sa.gov.au
0401 122 115

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/Bendigo-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 Bendigo 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. A look into the future - capitalising on barley market opportunities: ***Mary Raynes***

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

4. Understanding pre-emergent herbicide availability, selectivity and persistence: ***Mark Congreve***

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. 11.10 am	**Assessing the value in soil and plant testing** *Harm van Rees*	**The risks and rewards of growing pulse crops in the LRZ** *Michael Moodie*	**Improving the outcomes of oaten hay in the rotation** *Courtney Peirce*	**The continuing evolution of HWSC options** *Mike Walsh*	**None**

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

6. 11.50 am	**Better pastures, better crops - best management of pastures in a mixed farming system** *Tim Condon*	**Stubble and nutrient management to build soil carbon - challenges and opportunities** *BP Singh*	**Management tweaks making a difference with canola and lentil establishment success rates** *Glenn McDonald*	**Latest strategies in canola disease control** *Steve Marcroft*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

7. 12.30 pm	**2020 cereal disease update** *Grant Hollaway and Mark McLean*	**Eye on active plant pests** *Rohan Kimber*	**The risks and rewards of growing pulse crops in the LRZ** *Michael Moodie*	**The continuing evolution of HWSC options** *Mike Walsh*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

LUNCH

8. 2.10 pm	**Problem weeds - management to minimise impact** *Gurjeet Gill*	**Improving the outcomes of oaten hay in the rotation** *Courtney Peirce*	**Management tweaks making a difference with canola and lentil establishment success rates** *Glenn McDonald*	**2020 cereal disease update** *Grant Hollaway and Mark McLean*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

9. 2.50 pm	**Latest strategies in canola disease control** *Steve Marcroft*	**Aphid and insecticide resistance management in oilseed and pulse crops** *Marielle Babineau*	**Better pastures, better crops - best management of pastures in a mixed farming system** *Tim Condon*	**Biology of nitrogen release from pulses** *Gupta Vadakkattu*	**None**

Content relevance /10 Presentation quality /10

Have you got any comments on the content or quality of the presentation?

10. 3.30 pm	**Insect pest control - are you advising for today or the future?** *Kelly Angel, Greg Toomey and Craig Drum*	**Problem weeds - management to minimise impact** *Gurjeet Gill*	**Assessing the value in soil and plant testing** *Harm van Rees*	**Latest research for improving management of snails** *Greg Baker*	**None**

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

11. Student session: Developing a nationally validated model to predict flowering time of wheat and barley crop species? *Max Bloomfield*

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

12. Student session: How will rising atmospheric CO_2 concentrations affect the uptake of phosphorus in crop species? *James O'Sullivan*

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

13. Biosecurity status update on the top 5 nasties: *Dale Grey*

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

14. Hitting production targets in the UK amidst a highly regulated environment: *Keith Norman*

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

DAY 2

15. EARLY RISERS: Everything you want to know and ask about crop diseases heading into 2020

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

16. 9.00 am	**Canola roots and water use - big is not always best** *John Kirkegaard*	**Estimating in-crop N mineralisation in current cropping systems** *Katherine Dunsford*	**Spotlight on pulses** *Jason Brand and Garry Rosewarne*	**Soil acidity - sampling and lime incorporation under review** *Lisa Miller*	**None**

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

17. 9.40 am	**Integrating new chemistries in the field** *Chris Preston*	**The hows and whys for deep ripping sandy soils** *Michael Moodie and Chris Saunders*	**Earwigs - an appetite for destruction or are they beneficial?** *Matthew Binns*	**Rapid post-event frost damage assessment - can it be achieved?** *James Nuttall and Eileen Perry*	**None**

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

18. 10.55 am	**High Rainfall Zone research forum:** *Jon Midwood, Keith Norman, James Manson and John Kirkegaard*	**Deep ripping - does it work for all situations?** *Roger Armstrong*	**The health report: pulse disease updatew** *Josh Fanning and Sara Blake*	**Soil acidity - sampling and lime incorporation under review** *Lisa Miller*	**None**

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

19. 11.35 am	**High Rainfall Zone research forum continued: (as previous)**	**Estimating in-crop N mineralisation in current cropping systems** *Katherine Dunsford*	**Integrating new chemistries in the field** *Chris Preston*	**Rapid post-event frost damage assessment - can it be achieved?** *James Nuttall and Eileen Perry*	**None**

Content relevance [ ] /10 Presentation quality [ ] /10

Have you got any comments on the content or quality of the presentation?

20. 12.15 pm	**Use of chemicals and residues arising** *Gerard McMullen*	**Canola roots and water use - big is not always best** *John Kirkegaard*	**The health report: pulse disease update** *Josh Fanning and Sara Blake*	**Spotlight on pulses** *Jason Brand and Garry Rosewarne*	**None**

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

21. Food and diet trends affecting the grains industry: *Sara Grafenauer*

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

22. Breaking through the big yield constraints - where to next? *James Hunt*

Content relevance ☐ /10 Presentation quality ☐ /10

Have you got any comments on the content or quality of the presentation?

Your next steps

23. Please describe at least one new strategy you will undertake as a result of attending this Update event

24. 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

25. This Update has increased my awareness and knowledge of the latest in grains research

Strongly agree	Agree	Neither agree nor Disagree	Disagree	Strongly disagree
❑	❑	❑	❑	❑

26. Do you have any comments or suggestions to improve the GRDC Update events?

27. Are there any subjects you would like covered in the next Update?

Thank you for your feedback.

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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