WAGGA WAGGA
NSW

TUESDAY 16 & WEDNESDAY 17
FEBRUARY 2021

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

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CORPORATION

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GRDC 2021 Grains Research Update Welcome

If you are reading this, then chances are you are sitting in one of the GRDC's first face-to-face events since COVID-19 changed our lives.

Welcome.

We at the GRDC understand how challenging the past year has been for all Australians, but we also appreciate how well positioned agriculture has been to respond to and work through the restrictions that have come with this global pandemic.

Across many areas of Queensland and New South Wales, an improvement in seasonal conditions has also provided a much-needed reprieve for growers, advisers, agronomists, researchers and those associated with the grains industry.

With that positive change in circumstances comes a thirst for the latest information and advice from grains research and development – we trust that these GRDC Grains Research Updates will help guide your on-farm decisions this season and into the future.

While COVID-19 has forced temporary changes to our traditional Update locations and audience numbers, these events still offer the high quality, seasonally relevant research, development and extension information you have come to depend on. This year our Updates will also be live streamed to ensure the information is available to all who need it.

We would like to take this opportunity to thank our many research partners, who, like growers and advisers, have gone over and above to continue to work in situations constricted by COVID-19 regulations.

Challenging times reinforce the importance of rigorous, innovative research that delivers genuine gains on-farm. For more than a quarter of a century the GRDC has been driving grains research capability and capacity with the understanding that high quality, effective RD&E is vital to the continued viability of the industry.

Sharing the results from this research is a key role of the annual Updates, which are the premier event on the northern grains industry calendar and bring together some of Australia's leading grains research scientists and expert consultants.

To ensure this research answers the most pressing profitability and productivity questions from the paddock, it is critical the GRDC is engaged with and listening to growers, agronomists and advisers.

For the past five years we have been doing that from regional offices across the country. Through the northern region offices in Wagga Wagga and Toowoomba and a team of staff committed to connecting with industry, we are now more closely linked to industry than ever.

This year we have less people on the ground – as a result of COVID-19 restrictions – but more than ever we are available to listen and engage with you. So if you have concerns, questions or feedback please contact our team directly (details on the back of these proceedings) or email northern@grdc.com.au.

Regards,
Gillian Meppem
Senior Regional Manager – North

GRDC Grains Research Update
WAGGA WAGGA, Charles Sturt University

Joyes Hall Agenda, Day 1 – Tuesday 16 February

Time	Topic	Speaker (s)
10:00 AM	Welcome	Tony Williams (*CEO, GRDC*)
Varieties and subsoil constraints		
10:20 AM	**Getting phenology right, what's next?** Project learnings from 2017-20, comparing wheat and barley responses and tactical agronomy to increase yield.	Felicity Harris (*NSW DPI*)
10:55 AM	**Amelioration of hostile subsoils to improve crop productivity** • Techniques • Impact on crop water use and yield • Soil water and crop physiological impacts • Financial implications.	Ehsan Tavakkoli (*NSW DPI*) & Peter McInerney (*3D Ag*)
11:30 AM	**Within-paddock variability of subsurface pH in southern NSW** – its relationship to surface soil properties (pH, buffering capacity) and implications for decision making	Eva Moffitt *(EM Ag Consulting)*
12:00 PM	**Lunch**	Q&A with GRDC CEO Tony Williams 12:15 - to 12:30
Canola establishment, rhizobia, Russian wheat aphid and grazing crops		
12:40 PM	**Optimising canola establishment** • Factors affecting establishment • Growing high vigour seed • Optimising P nutrition and placement • Seed testing.	Col McMaster (*NSW DPI*) & Maurie Street (*GOA*)
1:20 PM	**What difference does rhizobia strain make on grain legume nodulation, nitrogen fixation and grain yield?** o Strain performance in acid soils o Herbicide residue impacts.	Belinda Hackney (*NSW DPI*)
1:50 PM	**Russian wheat aphid update** • Thresholds • Yield impact • Decision making.	Maarten van Helden (*SARDI*)
2:15 PM	**Grazing cattle on dual purpose crops** - managing health risks • Adaptation periods for cattle on canola and practices to mitigate risk • Managing rumen pH depression on cereals • Supplements.	Jeff McCormick (*CSU*) & Paul Cusack *(Central Veterinary Services)*
3:00 PM	**Afternoon tea**	
Diseases		
3:30 PM	**Fungicide resistance in cereals** - which pathogens and strategies to deal with it.	Nick Poole (*FAR Australia*)
3:55 PM	**Wheat rust developments** - a new stripe rust pathotype in bread wheat and durum varieties; LR24 virulence in leaf rust.	Robert Park (*University of Sydney*)
4:20 PM	**Cereal pathology update** - survey data; learnings from 2020; planning for 2021.	Andrew Milgate (*NSW DPI*)
4:45 PM	Are there **economic benefits in control of foliar fungal disease in canola crops** in the low to medium rainfall zones of NSW?	Maurie Street (*GOA*)
5:10 PM	**Diseases in pulse's and canola** - what happened where and why in 2020, and what are the implications for 2021?	Kurt Lindbeck (*NSW DPI*)
5:35 PM	**Close**	

Joyes Hall Agenda, Day 2 – Wednesday 17 February

Time	Topic	Speaker (s)
De-risking nitrogen - the case for change!		
8:30 AM	**Nitrogen loss pathways.** How much N is lost when urea is not mechanically incorporated after application?	Graeme Schwenke (*NSW DPI*)
9:00 AM	**Managing water and nitrogen use efficiency across years and crop sequences to drive profit** - crop legacies and learnings from regional farming systems research and longer term farming systems studies.	John Kirkegaard (*CSIRO*)
9:35 AM	**Strategies for longer term management of the soil N bank across the farming system.**	James Hunt (*La Trobe University*) & John Kirkegaard (*CSIRO*)
10:05 AM	**Discussion on de-risking nitrogen.** • Agronomist advice to clients - what needs to change? • Managing risk and N decision making - optimising N decision making for multiple seasonal outcomes	Led by John Kirkegaard (*CSIRO*), James Hunt (*La Trobe University)* and Graeme Schwenke (*NSW DPI*)
10:25 AM	**Morning tea**	
Pulses		
10:55 AM	Developing new **hard seeded self-regenerating legume species for crop and pasture systems** to fix more N for crops and feed livestock in medium and low rainfall zones.	Belinda Hackney (*NSW DPI*)
11:25 AM	**Profitable pulses in lower rainfall farming systems**	Michael Moodie *(Frontier Farming Systems)*
12:00 PM	**Integrating pulses into the farming system** - double breaks, fallow vs pulses and optimising crop sequence - a grower's perspective	John Stevenson *(Grower/ SNSW Manager, Warakirri)*
12:25 PM	Discussion	
12:40 PM	**Lunch**	
Weeds		
1:20 PM	**Ryegrass - blowouts at seeding in 2020 and management for 2021** • Causes of poor results - resistance vs environment/dose rate • Paraquat stewardship • Optimising glyphosate performance (tank mixes, AMS, formulation, resistance, adjuvants, timing, application, stress)	Peter Boutsalis (*Plant Science Consulting*) & John Broster (*CSU*)
1:55 PM	**Seed dormancy and emergence patterns in annual ryegrass populations from cropped fields** - why a big flush was expected in 2020 and what's on the cards for 2021 in SNSW?	Chris Preston (*University of Adelaide*)
2:15 PM	**Challenges in fitting new pre-emergent herbicides into farming systems and managing them for longevity.**	Greg Condon (*Grassroots Agronomy/WeedSmart*), Chris Preston (*University of Adelaide*)
2:55 PM	**Weeds discussion** • Managing ryegrass blowouts • Agronomist advice to clients - what needs to change?	Peter Boutsalis (*Plant Science Consulting*), John Broster (*CSU*), Greg Condon (*Grassroots Agronomy/WeedSmart*), Chris Preston (*University of Adelaide*)
3:20 PM	Close	

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Pulses

Weeds

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Phenology is FUNdamental – applying key project learnings to optimise grain yield

Felicity Harris[1], Hugh Kanaley[1], Rick Graham[1], Stephen Morphett[1], Peter Matthews[1], Peter Roberts[1], David Burch[1], Nick Moody[1], Greg Brooke[1], Hongtao Xing[1] and Michael Mumford[2]

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Keywords

optimal flowering period, frost, heat stress, risk

GRDC code

DAN00213 (Grains Agronomy and Pathology Partnership, GRDC and NSW DPI)

Take home messages

- Aim to target the optimal flowering period (OFP) for your growing environment – know your risk
- Match varietal phenology and sowing time – use the right variety for the right sowing date
- Remain disciplined with sowing dates – don't sow too early!

Background

The 'Optimising yield potential of winter cereals in the Northern Grains Region' project has been a co-investment by GRDC and NSW DPI under the Grains Agronomy and Pathology Partnership (GAPP) in collaboration with QDAF. From 2017-2020, field experiments were sown across ten locations in New South Wales and Queensland where annual rainfall ranged from 184 to 853 mm and grain yields ranged from 0.2-10 t/ha. The project aimed to provide a better understanding of wheat phenology and yield responses across different environments to refine sowing recommendations and improve yield stability and profitability of growers in the northern grains region (NGR).

The consistent messages presented from the project to date have centered around synchronising crop development (phenology) with seasonal conditions to ensure that the optimal flowering period (OFP) is matched to the growing environment. In previous GRDC Update papers, we combined model simulation and field validation to determine OFPs across locations in the NGR, whereby the OFP varied in timing and duration, as well as for different yield levels (Harris *et al.* 2019, 2020). As flowering time is a function of the interaction between variety, management and environment, the two primary management levers growers can pull to ensure flowering occurs at the optimal time and yield is maximised are *time of sowing* and *variety selection*.

Apply these key project findings to reduce risk and optimise grain yield:

Understand differences in phenology of commercial wheat varieties

In wheat, flowering is generally accelerated under long-day photoperiods and varieties can be broadly classified into two main types: *winter* or *spring*, distinguished by their response to vernalisation and their adaptation to different sowing dates. Winter types can be sown early and will remain vegetative for an extended period (e.g. DS Bennett⁽ᴰ⁾, LRPB Kittyhawk⁽ᴰ⁾). This extended vegetative period arises from a genetic requirement of the plant to experience prolonged cold temperatures to trigger flowering (vernalisation). This delays cold-sensitive reproductive stages to ensure flowering coincides with optimal seasonal conditions in spring.

In contrast, spring types generally do not require a period of cold temperature to initiate flowering. However, they can vary in their responses whereby exposure to cold temperatures can hasten their development (e.g. LRPB NighthawkΦ) or have no effect on development (e.g. DartΦ, SunprimeΦ). There are multiple combinations of vernalisation and photoperiod genes which influence phenology responses, as such we have observed significant variation in flowering response among both winter and spring types across environments and in response to sowing time. The figures below present the range in flowering date responses across years and sowing dates for two sites and highlights the risk of precocious flowering in quicker spring types.

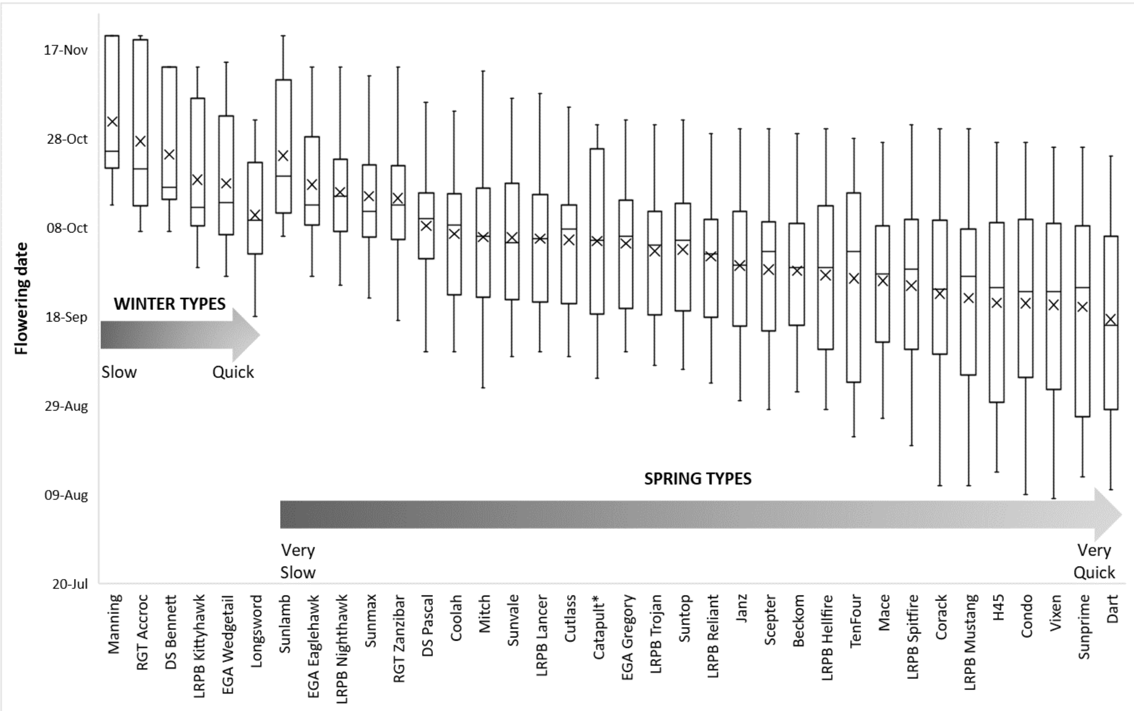

Figure 1. Flowering date responses of genotypes across four sowing dates from early-April to late-May for Wagga Wagga (2018), Marrar (2019) and Harefield (2020) experiments. Asterisk indicates CatapultΦ only evaluated in 2019, 2020 seasons.

(Varieties Manning, Bennett, Kittyhawk, Wedgetail, Longsword, Sunlamb, Nighthawk, Sunmax, Zanzibar, Pascal, Coolah, Mitch, Lancer, Cutlass, Catapult, Gregory, Trojan, Suntop, Reliant, Scepter, Beckom, Hellfire, TenFour, Mace, Spitfire, Corack, Mustang, Condo, Vixen, Sunprime and Dart are varieties protected under the Plant Breeders Rights Act 1994.)

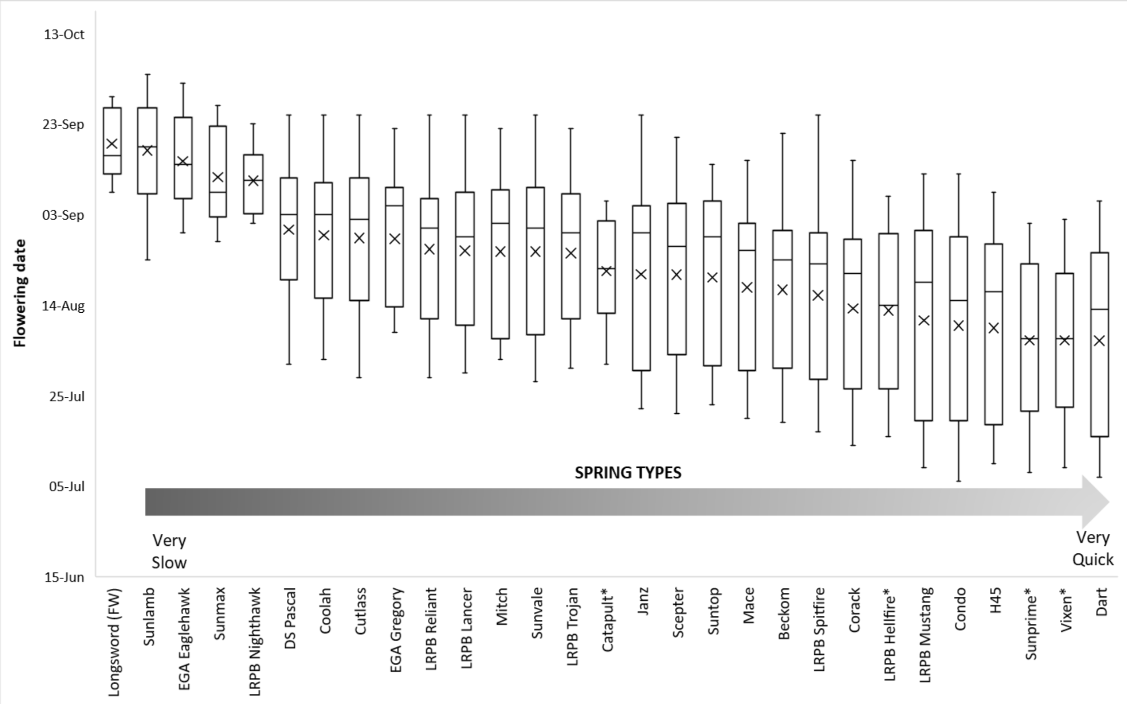

Figure 2. Flowering date responses of genotypes across three sowing dates from mid-April to late-May for Edgeroi (2017) and Narrabri (2019, 2020) experiments. FW – Fast winter type, asterisk indicates genotype only evaluated in two years at Narrabri (2019, 2020).
(Varieties Longsword, Sunlamb, Sunmax, Nighthawk, Pascal, Coolah Cutlass, Gregory, Reliant, Lancer, Mitch, Trojan, Catapult, Scepter, Suntop, Mace, Beckom, Spitfire, Corack, Hellfire, Mustang, Condo, Sunprime, Vixen and Dart are varieties protected under the Plant Breeders Rights Act 1994.)

Need to match varietal phenology and sowing time with environment

Generally, slower developing winter types are more suited to cooler, medium-high rainfall environments in southern NSW which have a longer growing season and increased risk of frost. Winter types when sown early are capable of high water-limited yields, can spread sowing risk and also be a useful frost mitigation tool. However, the vernalisation requirement of these winter types makes them less suited to warmer environments of northern NSW and QLD, where we observed flowering dates later than the OFP and often significant yield penalties in comparison to more adapted mid-quick spring types sown within their recommended window.

In contrast, quicker developing spring types are better adapted to regions with shorter growing seasons, and in environments or later sowing scenarios where frost and heat stress occur in close proximity to each other. Despite the variability across environments and seasons, we were able to identify varieties which were able to maintain relatively stable grain yields across many sowing dates at some sites and which may offer more flexibility to growers.

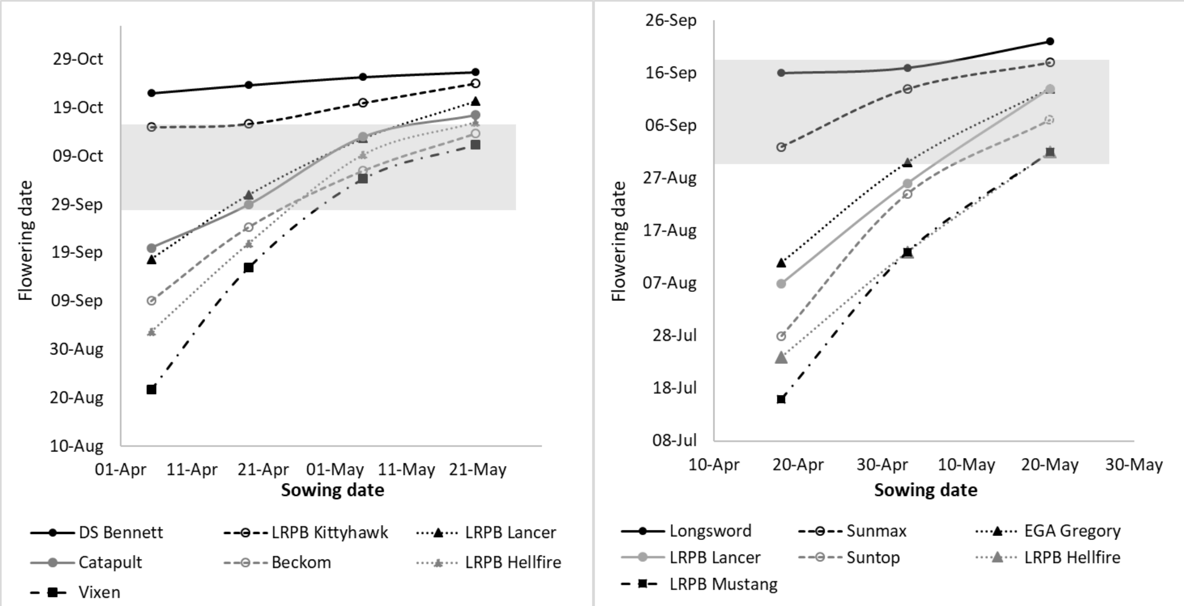

Figure 3. Mean flowering date responses of selected genotypes at a) Wagga Wagga (2018), Marrar (2019) and Harefield (2020) and b) Edgeroi (2017) and Narrabri (2019, 2020) across sowing dates. Shaded box indicates optimal flowering period for each location.

(All the varieties mentioned in the figure above are varieties protected under the Plant Breeders Rights Act 1994.)

Know the risk of getting it wrong - #SowSlowEarly

Winter types – we have observed a yield penalty in many mid-fast winter types when sown prior to early April. This is often due to difficulties establishing crops when soil temperatures are high and there is rapid drying of the seed bed following a rain event. The vernalisation response of some winter varieties has also been observed to be less stable when sown very early, which can result in stem elongation occurring earlier and an increased risk of frost damage. Unless grazing is the primary purpose, sowing prior to early April can increase crop water use under warm temperatures. This can lead to increased likelihood of excessive vegetative growth, taller crop heights and lodging, as well as increased disease pressure.

Spring types – although we have observed significant variation in phenology responses to sowing date amongst spring types, when sown early (when temperatures are warmer and days longer) flowering behaviour is unpredictable and varies substantially across seasons (Figure 1, Figure 2). As such there is increased risk of spring types flowering earlier than the OFP and grain yield penalties due to frost damage or insufficient accumulation of biomass when sown earlier than their recommended windows.

Key recommendation is to remain disciplined with sowing dates – don't sow too early!

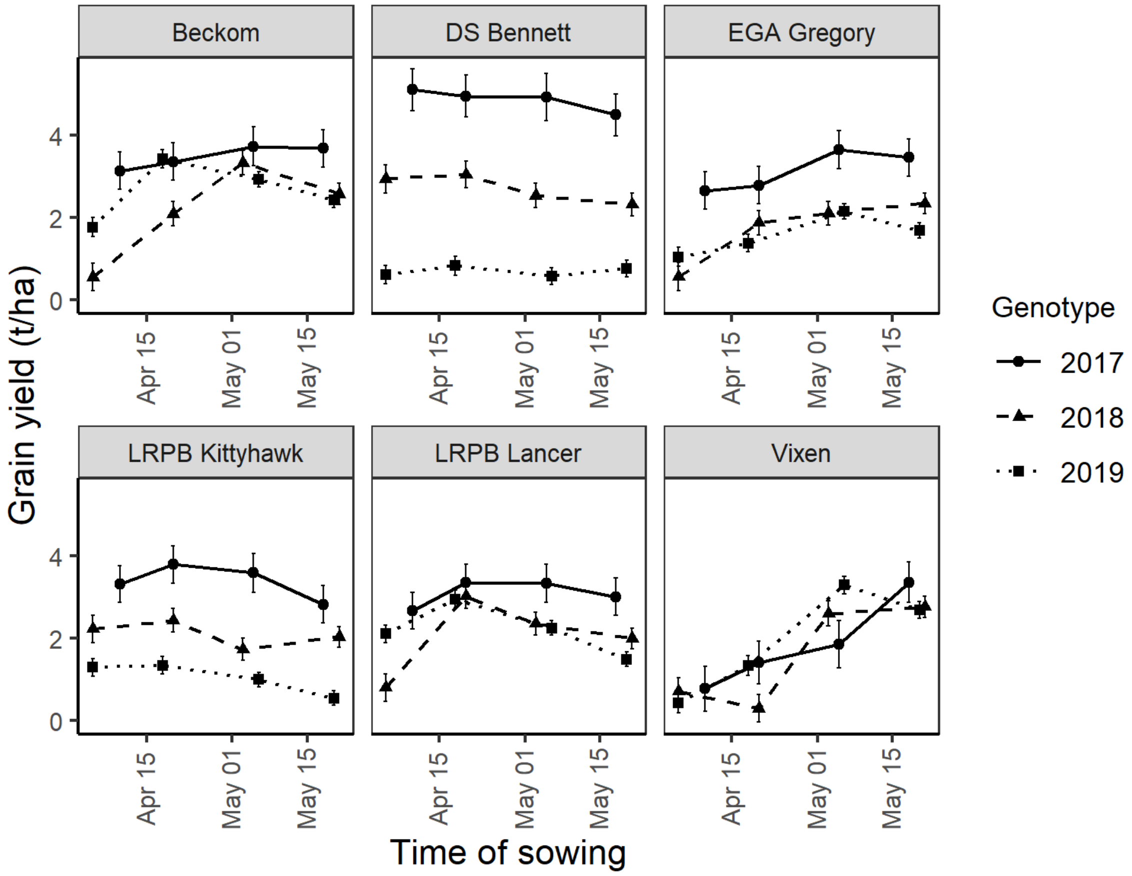

Figure 4. Yield response to sowing time predictions (BLUPs) for a subset of six genotypes for Wagga Wagga in 2017 and 2018 and Marrar in 2019. Vertical error bars denote the 95% confidence interval.
(All the varieties mentioned in the figure above are varieties protected under the Plant Breeders Rights Act 1994.)

Comparing wheat and barley - watch this space...

Compared to wheat, barley is considered to be more widely adapted, have superior frost tolerance and offer higher yield potential across environments in southern Australia. A comparative analysis of the best performing barley and wheat genotypes (defined as the highest yielding treatment) where experiments were co-located across production environments at eight sites in NSW from 2015-2020 is presented in Figure 5. The OFP where yield was maximised for barley was found to be 10-14 days earlier than for wheat, and barley maintained a yield advantage over wheat at yield levels ranging from 1.5-9.6 t/ha. Our understanding of the specific interactions between phenology and environment in barley and the differences in yield physiology between the cereals species is limited. In 2020, a new project was initiated to quantify the flowering time, yield and quality responses of barley, relative to wheat across a range of sowing times. *Preliminary data from 2020 will be presented at the updates.*

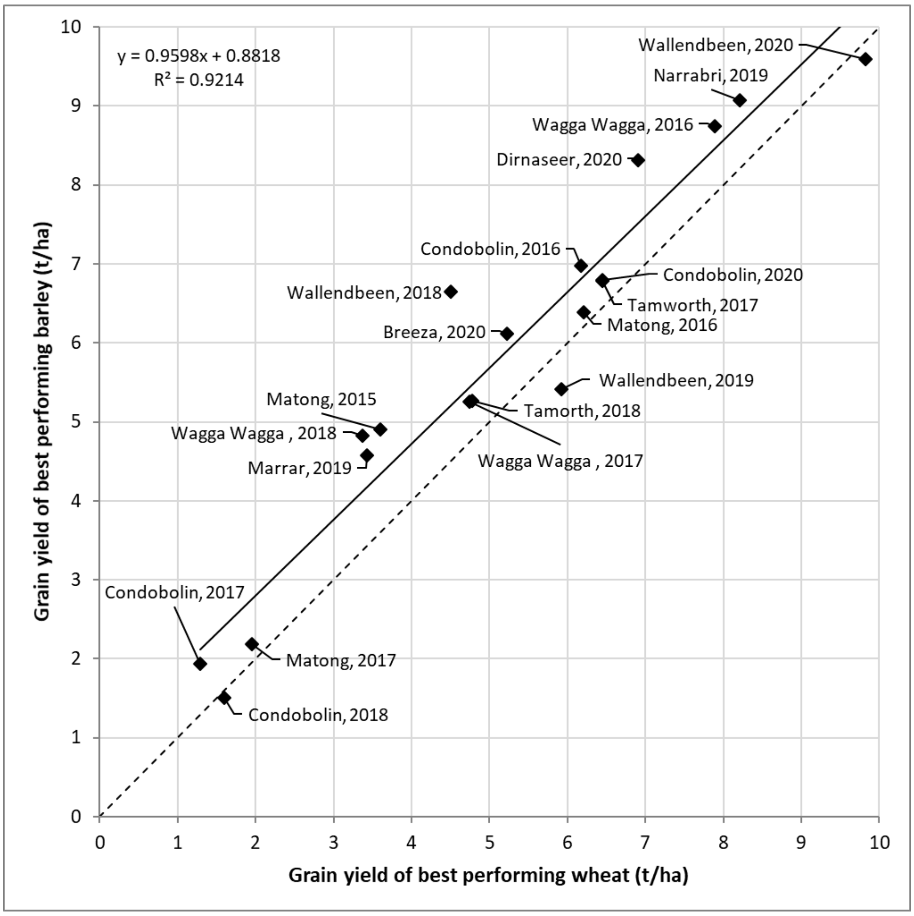

Figure 5. The relationship between the best performing wheat and barley genotypes (sown at optimal time for each environment from mid-April to late-May) at nine sites in NSW from 2015-20. Dotted line indicates 1:1 relationship.

References

Harris, F, Xing, H, Brooke, G, Aisthorpe, D, Matthews, P, Graham, R (2020) Yield stability across sowing dates: how to pick a winner in variable seasons? Proceedings of the GRDC Grains Research Updates, presented at Wagga Wagga, Corowa, Dubbo, Nyngan, Goondiwindi, Barellan and Lake Cargelligo.

Harris, F, Graham, R, Burch, D, Brooke, G, Matthews, P, Xing, H (2019) Hot vs Cold: balancing the risks associated with abiotic stresses in wheat. Proceedings of the GRDC Grains Research Updates, presented at Dubbo and Spring Plains, 2019.

Useful resources

https://grdc.com.au/ten-tips-for-early-sown-wheat

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Amelioration of hostile subsoils via incorporation of organic and inorganic amendments and subsequent changes in soil properties, crop water use and improved yield, in a medium rainfall zone of south-eastern Australia

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Key words

dispersive alkaline subsoils**,** amendments, soil pH, exchangeable sodium percentage, root growth, grain yield

GRDC code

DAV00149 & UA00159

Take home messages

- Deep placement of organic and inorganic amendments increased grain yield in the order of 20 to 50% for four successive years on an alkaline dispersive subsoil at Rand
- Deep placement of organic and inorganic amendments increased root growth, and crop water use from the deeper clay layers during the critical reproductive stages of crop development
- Improvements in grain yield with deep placement of organic and inorganic amendments were associated with a reduction in subsoil pH and improvement in soil aggregation
- Genotypic variability in grain yield response of wheat cultivars grown on alkaline dispersive subsoils has identified varieties and associated traits for enhanced performance and future breeding.

Background

Sodicity, salinity and acidity are significant surface and subsoil constraints that reduce crop productivity throughout the cropping regions of Australia (Sale et al., 2021). The majority of cropping soils contain at minimum one, but more multiple constraints (McDonald et al., 2013). The economic impact to Australian agriculture, expressed by the 'yield gap' between actual and potential yield, attributable to subsoil constraints was estimated to be more than A$1.3 billion annually by Rengasamy (2002), and as much A$2.8 billion by Hajkowicz and Young (2005). Of the 'three', sodicity is thought to be the most detrimental to productivity, resulting in the greatest yield gap. In Australian wheat-cropping regions alone, this 'gap' was estimated to be worth A$1.3 billion per annum in lost income (Orton et al., 2018), while close to 20% of Australia's land area is thought to be sodic.

Sodic soils, which are characterised by an excess of sodium (Na^+) ions, and classified as those with an exchangeable sodium percentage (ESP) greater than 6% (Northcote and Skene, 1972), are often poorly structured, have a high clay content, high bulk density, and are dispersive. These factors result in poor subsoil structure that can impede drainage, promote waterlogging (low water infiltration), and increase de-nitrification (nutrient imbalance), and soil strength (Orton et al., 2018). These properties also impede the infiltration of water into and within the soil, reduce water and nutrient storage capacity, and ultimately the plant available water (PAW) content of the soil. Subsequently, root growth and rooting depth are impeded, as is crop ability to access and extract deeper stored water and nutrients (Passioura and Angus, 2010). Thisis particularly problematic in environments characterised by a dry spring, where the reproductive phase often coincides with periods of water stress, and when the conversion of water to grain has the greatest effect both on yield (Kirkegaard et al., 2007), and the likelihood and magnitude of a yield gap (Adcock et al., 2007).

In southern NSW, winter crops commonly have sufficient water supply either from stored soil water or rainfall during the early growth stages. However, the reproductive phase is often affected by water stress or terminal drought and this is thought to be the major cause of variable grain yield (Farooq et al., 2014). The effect of water stress in the reproductive phase is further impacted by shallow root depth induced by subsoil sodicity. Under such conditions, a key to improving crop productivity is to improve root growth in and through sodic subsoils to enable use of deep subsoil water later in the growing season. Water use at this late stage has a 2 to 3 fold greater conversion efficiency into grain yield (Kirkegaard et al., 2007) than seasonal average based conversions efficiencies (e.g. 20 – 25 kg/mm verses 50 – 60 kg/mm).

While there are large advantages to be gained by improving the soil environment of sodic subsoils, the various amelioration approaches (deep ripping, subsoil manuring, applying gypsum, improved nutrition and use of ‘primer-crops’) have produced variable results (Adcock et al., 2007; Gill et al., 2008). Furthermore the use of subsoil organic material is also impacted by limited local availability, the high cost of suitable organic ameliorants delivered in-paddock, the sometimes large quantities required, the lack of suitable commercial-scale machinery and the poor predictability of when and where the amelioration will benefit crop productivity (Gill et al., 2008; Sale et al., 2019).

Gypsum application has been the most widespread traditional approach used to correct subsoil sodicity. However, problems have included; surface application when the problem is evident in the subsoil, the large quantities of gypsum required to displace significant amounts of sodium and the somewhat low solubility of gypsum.

Genetic improvement is also frequently advocated as an avenue for improving crop productivity and adaptation under different hostile soil conditions (McDonald et al., 2012; Nuttall et al., 2010). Little is known about genetic variation for tolerance of subsoil constraints and how they relate to different plant traits such as elemental toxicity tolerance, canopy cover, rooting depth and harvest index and the integration of these factors in yield response of different genotypes. This limited knowledge is also due to the practical difficulties in measuring dynamic and variable soil constraints under field conditions.

This paper reports on the performance of a barley-wheat-canola-wheat rotation on a Sodosol (Isbell, 2002) soil at a site in the Riverina town of Rand in southern New South Wales in the four years immediately following incorporation of a range of subsoil amendments, and the residual effects of ‘subsoil manuring’ on crop performance, soil physical properties, and access to PAW stored in the soil profile over subsequent seasons. A range of treatments comprising deep-ripping and subsoil incorporation of organic and inorganic amendments at a depth of 20–40cm were compared to, and contrasted with, surface applications, ripping-only and untreated controls. Amendments that could be easily procured or produced as part of a farming system were used in the trial. It is hypothesised that subsoil incorporation of organic or inorganic amendments will provide significant improvements in grain yield, which are associated with changes in the physical properties of the subsoil that result in improved root growth, and access to, and use of, deep soil water.

Method

Rand amendment site

The trial site was located at Rand, in the Riverina region of southern New South Wales in a paddock that had been under a continuous cropping (cereal-canola) for more than 50 years. The soil was a Sodosol with a texture-contrast profile increasing in clay content at depth, and with physical and chemical properties (Table 1.) unfavourable for root growth, including a high bulk density and low hydraulic conductivity.

Table 1. Chemical and physical properties of the soils at different depths at the trial site.

Depth (cm)	pH (H_20)	EC (1:5) (μS/cm)	Nitrate N (mg/kg)	Exchangeable cations (cmol/kg)	Exchangeable sodium percentage (%)	Bulk density (g/cm^3)	Volumetric water content (θv)
0–10	6.6	132.1	20.6	16.1	3.8	1.40	0.120
10–20	7.8	104.0	5.8	22.6	7.3	1.52	0.163
20–40	9.0	201.5	4.1	26.7	12.5	1.50	0.196
40–50	9.4	300.5	3.0	27.5	18.1	1.48	0.232
50–60	9.5	401.3	3.0	28.8	21.8	1.53	0.237
60–100	9.4	645.0	2.9	29.7	26.4	1.55	0.218

The trial was established in February 2017 as a randomized complete block with 13 treatments (Table 2) and four replicates. Experimental plots were arranged in two blocks (ranges) of 26 plots, separated by a 36m cropped buffer. Individual plots within each block were 2.5m wide (South-North) × 20m long (East-West), separated on their long sides by 2m buffers of uncultivated ground. Plots were ripped to a depth of 40cm, and amendments incorporated into the soil via a custom built 3-D ripping machine (NSW DPI), comprising a "Jack" GM77-04 5-tyne ripper (Grizzly Engineering Pty Ltd, Swan Hill, VIC, Australia), configured to 500mm tyne spacings, and topped with a custom designed frame supporting two purpose built discharge hoppers (bins) and a 300L liquid cartage tank. The larger, ~1.6 cubic meter-capacity hopper was designed to deliver organic materials, and can accommodate approximately 1000 kg of material, roughly equivalent to a standard 'spout top, spout bottom' bulk bag. The organic amendments were obtained in pellet form for ease of application and consisted of dried pea straw pellets (1.13% N, 0.05% P, 1.34% K; extrusion diam. 7–10mm, length 6–35mm), wheat stubble pellets (0.34% N, 0.15% P, 1.59% K; diam. 7–10mm, length 6–35mm), and dried poultry manure pellets marketed as Dynamic Lifter® (3% N, 2% P, 1.7% K; diam. 7–10mm, length 6–35mm). The amendments were applied three months prior to sowing the first season.

In 2017, experimental plots were sown to Barley (cv. LaTrobe⊕) on the 11th of May at a seeding rate of 70 kg/ha (target plant density 100 plants/m^2). Monoammonium phosphate (MAP) was applied at 80 kg/ha as a starter fertiliser at sowing. The crop was sown after spraying with Boxer Gold® (800 g/L prosulfocarb + 120 g/L S-metolachlor), Spray.Seed® (135 g/L paraquat dichloride + 115 g/L diquat dibromide) and Treflan® (480 g/L trifluralin). The crop was harvested on the 21st of November.

In 2018, Wheat (cv. Lancer⊕) was sown on the 15th of May at a seeding rate of 80 kg/ha (target plant density 150 plants/m^2). MAP was applied at 80 kg/ha as a starter fertiliser at the time of sowing. The crop was sown after spraying with Spray.Seed, Sakura® (850 g/kg pyroxasulfone), Logran® (750 g/kg triasulfuron) and Treflan. Urea (46% N) at 110 kg/ha (50.6 kg/ha N) was applied at 106 DAS. The crop was harvested on the 6th of December.

In 2019, Canola (Pioneer® 45Y92CL) was sown on the 10th of April at a seeding rate of 4.4kg/ha (target plant density 40 plants/m^2). MAP was applied at 90 kg/ha (9 kg/ha N, 19.8 kg/ha P) as a starter fertiliser at the time of sowing. The crop was sown after spraying with a knockdown mixture of herbicides. Urea at 220 kg/ha (101.2 kg/ha N) was applied as a top-dressing at 119 DAS, and Prosaro® (210 g/L prothioconazole + 210 g/L tebuconazole) at 50% bloom as a preventative for Sclerotinia stem rot (132 DAS). The crop was harvested on the 30th of October.

In 2020, wheat (cv. Scepter⦶) was sown on the 16th of May at a seeding rate of 63 kg/ha (target plant density of 120 plants/m^2). Diammonium phosphate (DAP) was applied at 78 kg/ha as a starter fertiliser at the time of sowing. The crop was sown after spraying with Spray.Seed, Roundup, Sakura and Treflan. Urea at 150 kg/ha (69 kg/ha N) was applied as a top-dressing 7 DAS prior to rain. The crop was harvested on the 7th of December.

The long-term average annual rainfall at the site is 553mm with a reasonably uniform average monthly rainfall. In 2017, in-season rainfall (April-November) totalled 329mm, while 244mm and 242mm, respectively, were recorded for the same period in 2018 and 2019. Rainfall in both 2018 and 2019 was approximately 25% less than that recorded for 2017, and approximately 65% of the long-term average seasonal rainfall. The long-term average monthly rainfall, and average monthly maximum and minimum temperatures, daily (bars) rainfall events and monthly rainfall at the Rand experimental site for the period 2017–2020 (Figure 1).

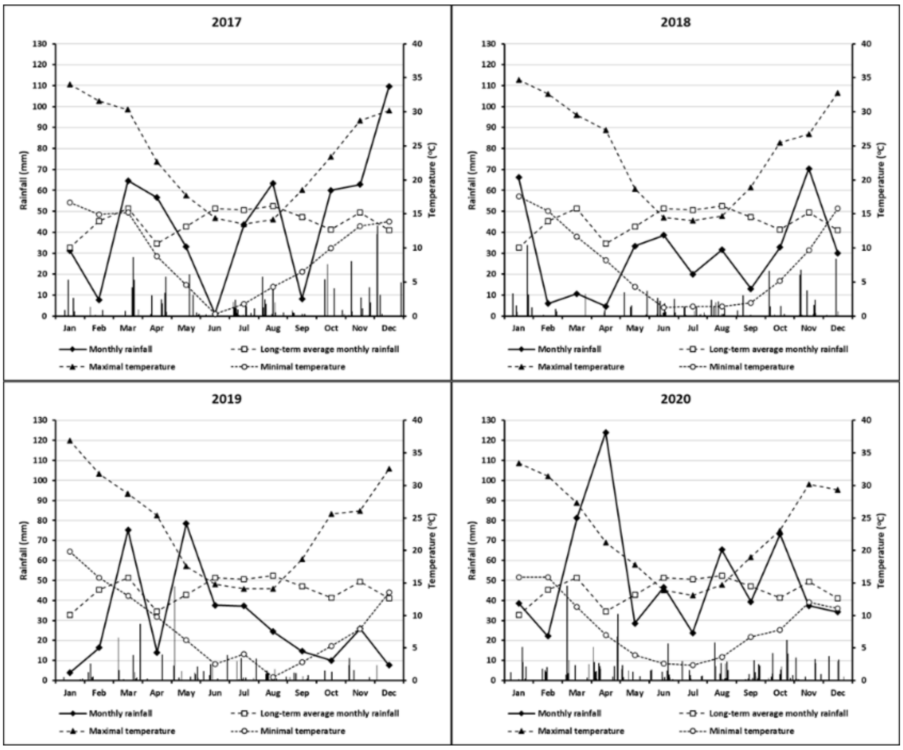

Figure 1. Long-term average monthly rainfall, and average monthly maximum and minimum temperatures, daily (bars) rainfall events and monthly rainfall at the Rand experimental site located at Urangeline East, NSW.

Table 2. Description of the treatments and organic and inorganic amendments used in the trial.

Treatment	Description	Amount of amendment added
1	Control	Direct sowing
2	Deep gypsum	5 t/ha, incorporated to depth of 20-40 cm
3	Deep liquid NPK	Incorporated to depth of 20-40 cm, N to match chicken manure
4	Deep chicken manure	8 t/ha, incorporated to depth of 20-40 cm
5	Deep pea straw	15 t/ha, incorporated to depth of 20-40 cm
6	Deep pea straw +gypsum+NPK	12 t/ha, 2.5 t/ha, incorporated to depth of 20-40 cm,
7	Deep pea straw+NPK	15 t/ha, incorporated to depth of 20-40 cm
8	Deep wheat stubble	15 t/ha, incorporated to depth of 20-40 cm
9	Deep wheat stubble +NPK	15 t/ha, incorporated to depth of 20-40 cm
10	Ripping only	To depth of 40cm
11	Surface gypsum	5 t/ha, applied at soil surface
12	Surface chicken manure	8 t/ha, applied at soil surface
13	Surface pea straw	15 t/ha, applied at soil surface

At late flowering soil coring was completed using a tractor-mounted hydraulic soil-coring rig and 45 mm diameter soil cores. The break core method was used to estimate rooting depth and exposed roots were recorded at the following depths 0 - 10, 10 - 20, 20 - 40, 40 - 60, and 60 – 100 cm. Quadrat samples of $2m^2$ were taken at physiological maturity to measure plant biomass and grain yield.

Grogan genotypes screening experiment

In 2019 an experiment was conducted near the township of Grogan in southern NSW, which included 17 commercial wheat genotypes in a row column design with four replicates. The soil profile was slightly acidic in the top 10cm ($pH_{1:5\ water}$ 5.9) and pH dramatically increases with depth (Table 1). The changes in soil sodicity (exchangeable sodium percentage, ESP) followed a similar trend of soil pH with ESP at 10.5% in the topsoil and increasing up to 40% in the subsoil (Table 1).

Table 3. Site characterisation for the Grogan experimental site. Values are means (n=5).

Soil depths (cm)	EC (µs/cm)	pH (1:5 water)	Colwell-P (µg/g)	CEC (cmol(+)/kg)	Exchangeable sodium percentage
0-10	309.40	5.87	58.80	16.66	10.53
10-20	133.00	7.65	7.40	22.06	11.97
20-30	136.90	8.76	2.62	24.53	15.94
30-40	207.66	9.12	2.50	25.55	20.12
40-60	338.94	9.60	1.34	27.17	26.27
60-80	530.40	9.53	1.00	31.63	36.68
80-100	897.20	9.43	1.48	34.07	40.25
100-120	1148.20	9.38	1.50	35.28	40.35

The experiment was sown on 17 May 2019 using a direct sown drill with DBS tynes spaced at 25cm. At sowing 90 kg MAP (20kg P/ha and 9kg N/ha) was drilled in all plots and 75 kg N/ha was surface applied just prior to stem elongation. Mean plant density as measured by seedling counts at four weeks after sowing was 116 ± 1.6 (mean ± SE of 68 plots) plants m^{-2}. At different growth stages multispectral images (MicaSense RedEdge-MX) were collected using drone technology to determine different vegetation indices such as normalised differences in vegetation index (NDVI) and leaf chlorophyll index (LCI) as a surrogate of canopy attributes and plant physiological processes (Liu et al., 2019; Satir and Berberoglu, 2016; Zhang et al., 2019). Quadrat samples of $1m^2$ area were taken at physiological maturity to measure plant biomass and grain yield. Harvest index was calculated as grain yield divided by biomass.

Results

Rand amendment trial

The one-off application of various amendments (Table 2) significantly affected the crop grain yield over 4 consecutive years. For example, in 2020, wheat grain yield (relative to control) increased following the deep placement of wheat stubble, wheat stubble + nutrient and gypsum by 21%, 20 and 18% respectively ($P < 0.001$) (Figure 2). The variations in yield in response to surface application of amendments or ripping only was not significantly different from the control. A multi-year cumulative analysis of grain yield response (2017-2020) indicated that deep placement of plant-based stubble, gypsum and their combination resulted in significant and consistent improvements in crop yield (Table 4). A preliminary cumulative gross return is also presented in Table 4.

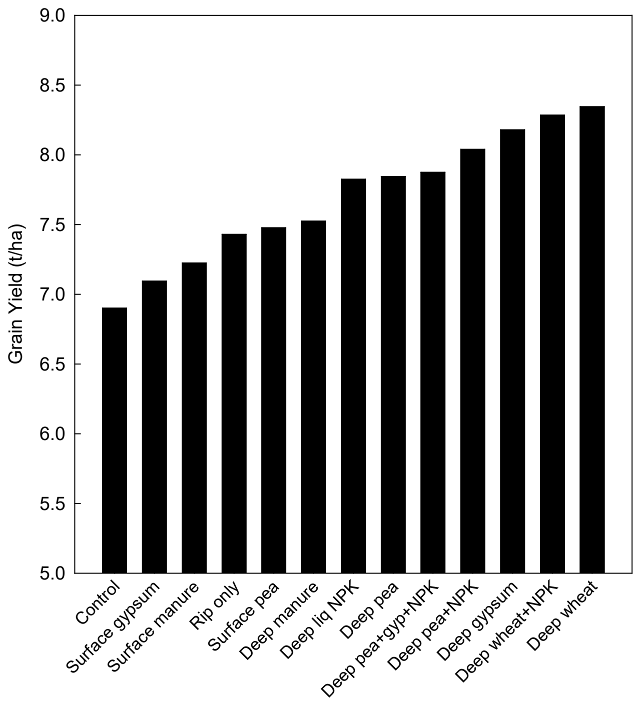

Figure 2. The mean effect of surface or deep-placed amendments on grain yield of wheat (cv. Scepter⦶) grown in an alkaline dispersive subsoil in Rand, SNSW in 2020. Values are mean (n=4). $LSD_{0.05}$ = 0.67.

Table 4. Cumulative grain yield (2017-2020) and cumulative gross return ($) for barley (2017; $220/t), wheat (2018; $250/t), canola (2019; $600/t) and wheat (2020; $250/t) at Rand.

Treat	Yield (t/ha)		$	
Control	15.3	a	4517	a
Surface gypsum	15.5	a	4576	a
Rip only	15.9	ab	4737	ab
Surface pea	16.00	ab	4817	ab
Deep liq NPK	17.1	bc	4847	ab
Surface manure	17.1	bc	5104	bc
Deep wheat	18.2	cd	5388	cd
Deep manure	18.3	cd	5428	cd
Deep pea+NPK	18.4	cd	5557	d
Deep wheat+NPK	18.5	d	5383	cd
Deep pea	18.7	d	5507	d
Deep gypsum	18.9	d	5684	d
Deep pea+gyp+NPK	19.4	d	5699	d

Over the course of this study several key measurements of soil and crop parameters were made to investigate the impact of various amendments on soil:plant interactions.

The number of visible roots in the amended subsoil layer (20 – 40cm depth) were significantly ($P < 0.05$) affected by different amendments (Figure 3). Deep placement of both manure and pea hay increased the number of visible roots by more than 3-fold. Neutron probe readings taken in September also indicate that the highest root counts were associated with the driest soil water profile (Figure 4). Variation in soil pH measured at the amended layer is shown in Table 5. Compared to the control, deep placement of gypsum reduced the soil pH by 0.86 units (8.99 to 8.13) at 20 – 40cm depth. However, pH was not affected by other treatments.

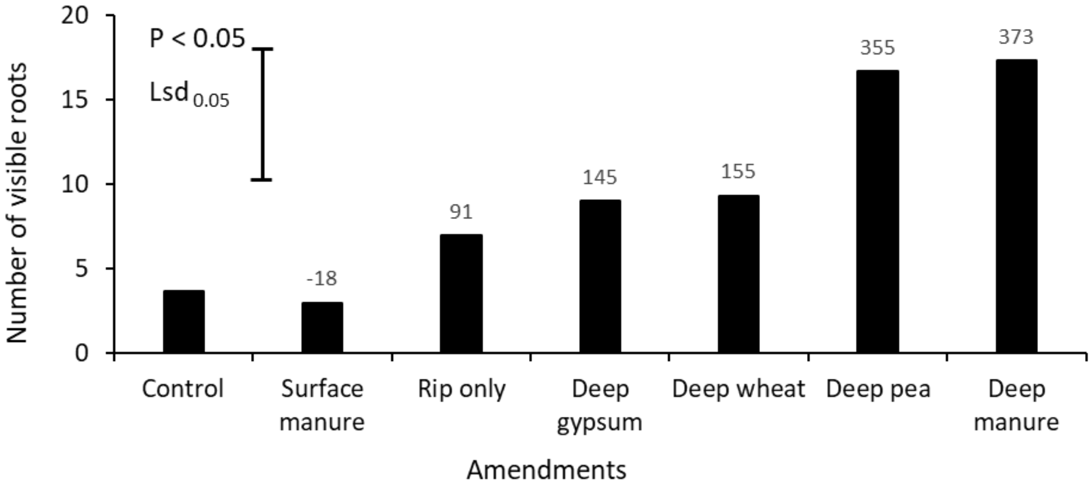

Figure 3. The mean effect of surface or deep-placed amendments on the number of visible roots at 30cm at late flowering of canola (cv. Pioneer® 45Y91CL) grown in alkaline dispersive subsoil in Rand, SNSW in 2019. Values on the top of each bar is representing percent change of visible roots compared to control.

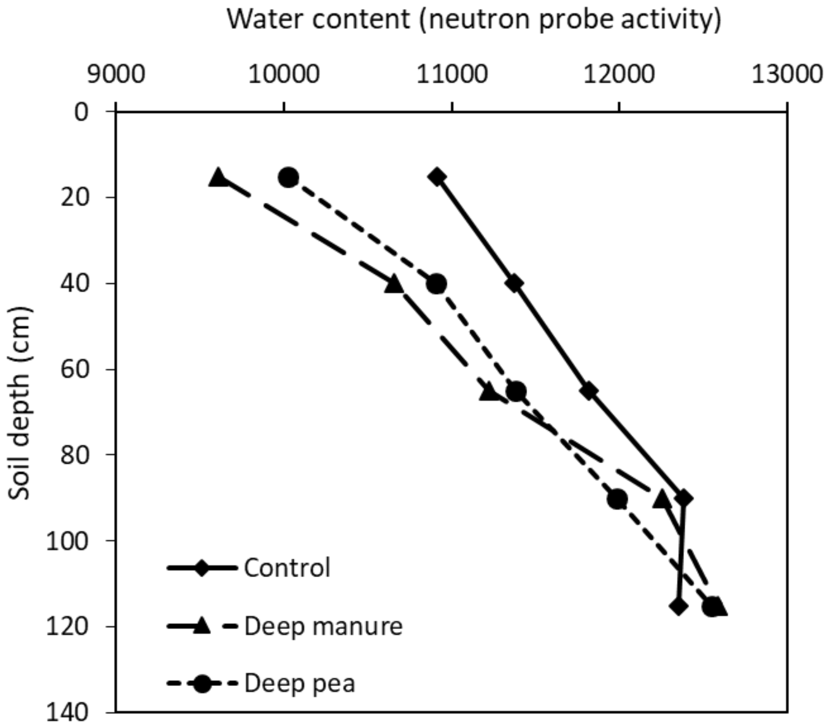

Figure 4. Neutron probe readings taken in September at the Rand amendment site for contrasting treatment comparisons. Results are based on the neutron activity (raw data) where higher values represent higher water content in the soil profile. Values are averages (n = 4).

Table 5. The changes in soil pH (20-40 cm) in selected treatments at the Rand site. Samples were collected in May 2020. $LSD_{0.05}$ = 0.27.

Amendment	Predicted mean	Group
Control	8.99	a
Deep liq NPK	8.96	a
Rip only	8.94	a
Deep wheat+NPK	8.93	ab
Surface gypsum	8.92	ab
Deep pea	8.87	ab
Deep wheat	8.83	ab
Deep manure	8.60	bc
Deep pea+gyp+NPK	8.52	c
Deep gypsum	8.13	d

Grogan genotypes screening trial

Significant ($P < 0.001$) genotypic variation occurred in grain yield among the genotypes and ranged from only 0.57 t/ha (Gregory⦇) to 2.0 t/ha (Scepter⦇, Emu Rock⦇ and Mace⦇; Figure 5). Biomass at final harvest did not significantly differ among the genotypes (data not shown; $P = 0.11$) and there was no significant ($P = 0.09$) correlation between grain yield and biomass at final harvest (Figure 6).

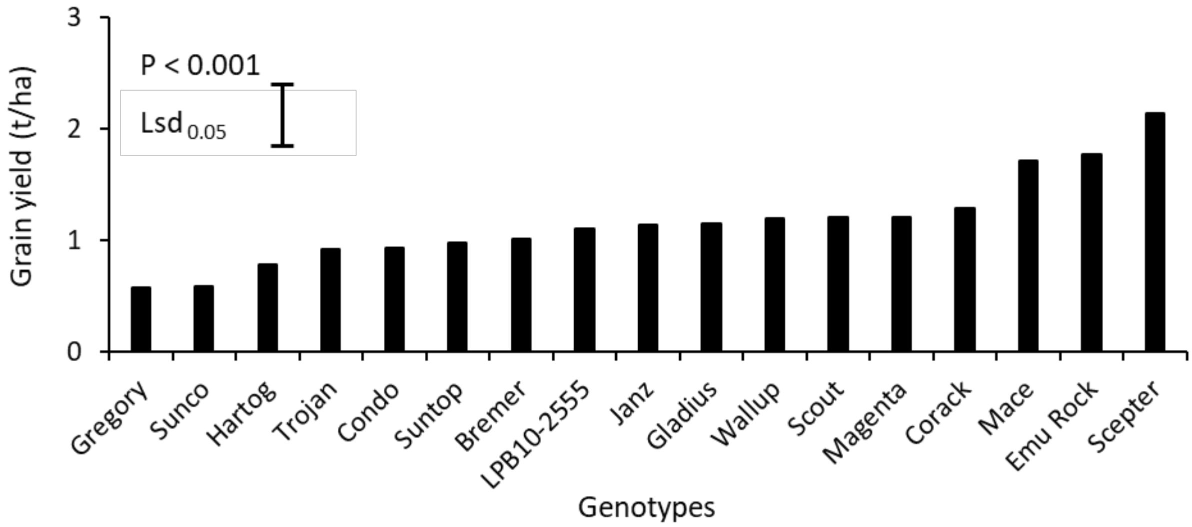

Figure 5. Variations in grain yield of 17 wheat genotypes grown in alkaline sodic dispersive subsoil in Grogan, SNSW in 2019. Each data point is mean values of n = 4.
(Varieties Gregory, Trojan, Condo, Suntop, Bremer, Gladius, Wallup, Scout, Magenta, Corack, Mace, Emu Rock and Scepter are protected under the Plant Breeders Rights Act 1994)

Significant variation was observed in harvest index (data not shown; $P < 0.001$), which ranged from 0.08 (Gregory⦇) to 0.26 (Scepter⦇). A significant ($P < 0.001$) and positive correlation between harvest index and grain yield is observed among the studied genotypes (Figure 6).

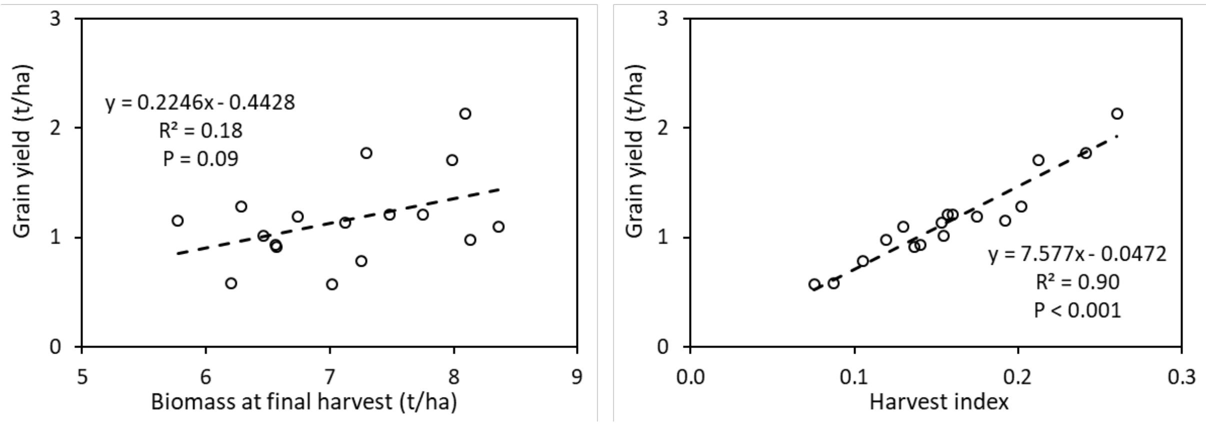

Figure 6. Linear regressions between grain yield and biomass at final harvest (left) and harvest index (right) of 17 wheat genotypes grown in alkaline sodic dispersive subsoil at Grogan, SNSW in 2019.

All the non-destructive vegetation indices, i.e. NDVI ($P < 0.01$), NDRE ($P < 0.001$) and LCI ($P < 0.001$) measured at stem elongation showed significant and positive correlation with biomass at anthesis (Figure 7).

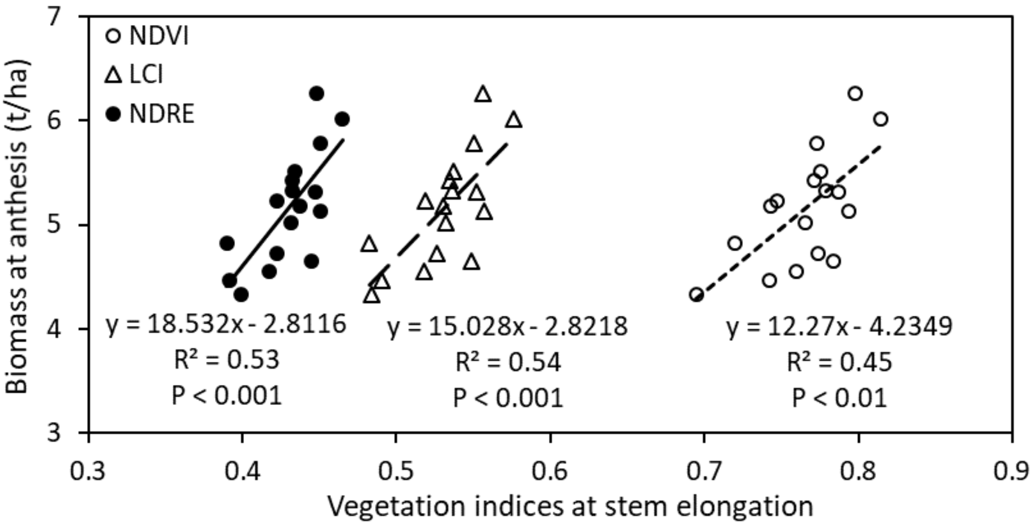

Figure 7. Linear regressions between vegetation indices (measured at stem-elongation) and anthesis biomass of 17 wheat genotypes grown in alkaline sodic dispersive subsoil at Grogan, SNSW in 2019. NDVI = normalised differences in vegetation index; LCI = Leaf chlorophyll index; NDRE = Normalised difference red edge.

Discussion

In Alkaline dispersive soils, several properties of subsoils including, high pH, high levels of soluble carbonate species, poorly structured dense clay, and dispersion together with overall poor chemical fertility, represent a hostile environment for crop roots. Here we demonstrate the impact of various amendments on these properties and the potential to re-engineer these hostile subsoils for improved crop performance.

Barley, wheat, canola and wheat were grown in 2017–2020, respectively, under increasingly dry conditions. Growing season rainfall (April to November total) was average in 2017 (decile 5), and declined in 2018 (decile 1.5), with still drier conditions in 2019 (decile 1.0), when only 45 mm of rain (decile 0) fell during the spring months from September to November. This improved in 2020 where the trial received 401 mm during growing the season. The amendments that consistently resulted in significant yield increases above the control, were the deep-placed combination of pea straw pellets, gypsum and liquid fertilizer nutrients, and the deep-placed gypsum and deep placed pea straw (Table 4). Improvements in subsoil structure were measured in the winter of 2019. The deep crop residue amendments significantly increased macro aggregation, as measured on the rip-line at a depth of 20-40 cm. Similarly, deep gypsum and the deep gypsum/pea straw/nutrient combination markedly increased water infiltration into the soil profile, with higher saturated hydraulic conductivities measured on the rip-line. Our results to date indicate that independent modes of action of various amendments (e.g. crop residue vs gypsum) are required in the amendment mix, in order to ameliorate these subsoils. For example, adding gypsum reduced pH in the amended subsoil to below 8.5 (Table 5). This indicates that significant changes in soil pH can occur with realistic application rates of gypsum in subsoil. Given high alkalinity also increases negative charges on the surfaces of clay particles (Rengasamy et al., 2016), which increases clay dispersion, a reduction in pH following gypsum application also resulted in significant improvement (reduction) in soil dispersion (Tavakkoli et al., 2015). In alkaline sodic soils, high ESP and high pH are always linked together and it is difficult to apportion their effects on the resulting poor soil physicochemical conditions and consequently on crop growth.

The addition of pea straw and nutrients provides substrate for enhanced biological activity resulting in increased macro aggregation and improved subsoil structure. When combined together, organic and inorganic amendments may result in additive effects to improve soil physical and chemical properties (Fang et al., 2020a; Fang et al., 2020b).

In a year of intensive drought like 2019, the grain yield improvements at Rand may be attributed to the additional root growth in the amended subsoil layer (Figure 3), which facilitated the use of extra subsoil water (Tavakkoli et al., 2019 and Figure 4). Under dryland conditions, water captured by roots in the subsoil layer is extremely valuable as its availability coincides with the grain filling period and has a very high conversion efficiency into grain yield (Kirkegaard et al., 2007; Wasson et al., 2012). A major focus of this current research is to understand the amelioration processes of the subsoil application of organic and inorganic amendments. A tentative, but promising, finding from our field and controlled environment trials, is that farm grown products like wheat and pea stubbles when mixed with nutrients improve soil aggregation, root growth, water extraction and grain yield and these treatments are comparable to animal manures and gypsum. If confirmed, this means that grain growers have a potentially large supply of relatively inexpensive organic ameliorants already available in their paddocks, which will increase the application options and viability of correcting subsoil sodicity.

Despite, demonstrating significant improvement in grain yield with subsoil incorporation of organic and inorganic amendments, the widespread adoption of these practices are still limited by their cost effectiveness. Identifying traits associated with the superior tolerance to different soil constraints may be a low cost technique to tackle this issue (McDonald et al., 2012). Given the intensive drought condition in the study year, considerable genotypic variation was observed with some varieties having 3- fold higher grain yield than other varieties. Based on controlled-environment studies, the high yielding varieties at Grogan, 'Mace⦶ and Emu Rock⦶,' are moderately tolerant to tolerant to high pH and have roots that can grow relatively well through soils of high bulk density, whereas low yielding varieties such as Gregory⦶, Hartog and Sunco, are more sensitive to one or both of these stresses. The very low harvest index in the trial suggests that there was severe stress around flowering to reduce grain set, as well as during grain filling. Results suggest that the ability to maintain root growth hay have helped to alleviate stress in varieties like Emu Rock⦶ and Mace⦶. Furthermore, different traits associated with this greater yield performance of wheat genotypes are crucial aspects of future breeding programs.

Conclusions

The findings from the current field studies demonstrate initial but promising results of ameliorating alkaline dispersive subsoils in medium and high rainfall zones of southern NSW. Deep placement of organic and inorganic amendments resulted in significant yield improvement in four successive years at Rand where subsoil water was present. This yield improvement was facilitated by a reduction in soil pH and ESP% and increased microbial activity that can lead to improved soil aggregation. Furthermore, deep placement of organic and inorganic amendments increased root growth, which in turn increased soil water use from the deeper clay layers during the critical reproductive stages of crop development, thereby increasing grain yield. In addition to soil management, genotypic variability in grain yield of wheat cultivars observed and their associated traits identified in the current study can be used for improving wheat germplasm through future breeding programs.

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On farm financial implications of research into varieties and deep soil amelioration

Peter and Hazel McInerney, 3D-Ag, Wagga Wagga

Key words

cost benefit, varieties, deep-soil-amelioration

Take home messages

- Know what is happening to depth, in the soil under your feet
- Grow varieties adapted to the soil type and landscape
- Deep placement of ameliorants has good potential to significantly improve yield and therefore revenue in tough seasons
- Deep placement of ameliorants is very likely to be commercially viable on responsive soils.

Introduction

This paper should be read in conjunction with the research papers produced from GRDC projects DAV00149 & UA00159.

The purpose of this paper is to examine those results for the financial implications to the farmer of two aspects of the above projects, with reference to the farm at Rand hosting the trial site regarding: 1 varietal choice specific to soil type; 2 the potential of deep soil amendment.

With the ever-present cost price squeeze and land prices increasing rapidly, all things that might improve productivity and returns need to be examined carefully in terms of a specific farm and circumstances. Any activity that improves soil condition and resilience can help mitigate production and therefore business risk, leading to more capacity to deal with seasonal volatility. For example; being able to sustain profit even in tough years is a measure of a sustainable farm business.

Varietal screening trial results are a readily available means for farmers to help identify potentially superior varieties to test on their own farms against currently used varieties. Buying the most appropriate variety is a very low cost means of improving potential outcomes.

Deep placement of ameliorants is an emerging technology where the financial implications could have great relevance to farm businesses going forward.

These aspects are ultimately reviewed from the broader farm perspective.

Background

From 2015 to 2017 Dr Tavakkoli and associates conducted a variety screening trial (GRDC project UA00159) at Rand. From 2017 to 2020 this same site hosted the deep soil amelioration experiments (GRDC project DAV00149). Data from these trials is reviewed below and examined in terms of the financial implications to the farmer regarding variety choice and the potential of deep soil amelioration.

On the farm where the trial site is located, the farmer/co-operator has invested in understanding his soil by having the entire property zoned and soil sampled to depth to identify areas most in need of remediation. The soil is sodic with dispersion issues from the surface to depth. In the past, gypsum, lime and animal manures have been applied to improve surface conditions.

Until recently little could be done to address issues deeper (>15cm) in the soil, however this research and the construction of a machine capable of the deep placement of ameliorants will see the research tested at paddock scale in 2021.

Discussion

1. Varietal choice

Variety screening for acid soil tolerance has been routine for over 40 years with the very successful variety Dollarbird, followed by Diamond bird released in the 1980's, with other varieties since. No such program existed for sodic or alkaline subsoils, which occupy a large area of the southern wheat belt. McDonald (2012) was among those suggesting that some varieties might possess genetic traits that were more tolerant of hostile subsoil. In 2015 Project UA00159 began with a site at Rand, NSW, and others subsequently.

The trial at Rand showed spectacular results, with the variety Mace averaging 5.5 t/ha over the three years, almost 0.75 t/ha more than any other variety (Tavakkoli E., pers.comm.). In 2018 AGT donated 1.0 tonne of Scepter (variety A in Figure 1), a new variety of a genetically similar line to Mace for the farmer to try as a commercial comparison. One tonne of Beckom (variety B in Figure 1) was purchased to include in the comparison.

Both varieties performed well and were incorporated in the farm program in 2019. Figure 1 shows the results achieved in 2019 and 2020. In the very dry 2019 season Scepter was harvested, while the Beckom was 'salvaged' as silage and hay. Given the season, both varieties were successful in producing revenue for the business. In 2020 both varieties again did well, although Scepter is clearly well ahead and much more profitable at the Rand site. While Scepter out-performed Beckom *at this site,* Beckom is still an excellent variety.

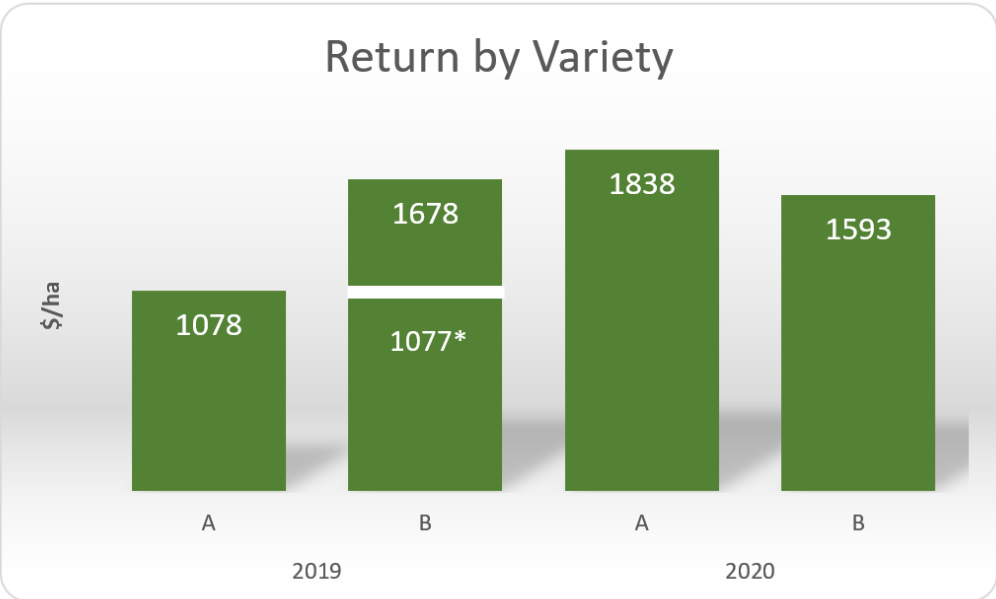

Figure 1. Return by variety 2019-20 (Variety A = Scepter, Variety B = Beckom)

**Note: The return of Variety B in 2019 after deduction of contracting costs for silage and hay making and the estimated loss of nutrients by product removal is reduced from $1678 to $1077/ha.*

Making the most of available information, plus small scale on farm comparative trials to identify superior varieties is an obvious and low cost means of optimising productive potential and profit.

2. Deep soil amendments

Out of twelve different amendments, both surface and deep applied, from the Rand trial, five deep treatments are reviewed below, namely

- *Treatment 1* - Deep pea straw + gypsum + [Nitrogen - Phosphorus – Potassium] (NPK)
- *Treatment 2* - Deep ripping
- *Treatment 3* - Deep placement of pelletised wheat straw
- *Treatment 4* - Deep gypsum and
- *Treatment 5* - Deep placement of pea straw.

In viewing the data, consideration needs to be given to crop type and seasonal conditions. In terms of rainfall, 2017 was a decile 5 or median year, 2018 and 2019 were both decile 1 years (i.e., in the lowest 10% of annual rainfall records for Walbundrie since 1880), while 2020 was a decile 7.

Figure 2 shows the percentage yield change from the control treatment in 2017 through to 2020 and Figure 3 shows the $/ha impact over the same sequence of years and crops. The prices used are the actual price the farmer received in the year concerned.

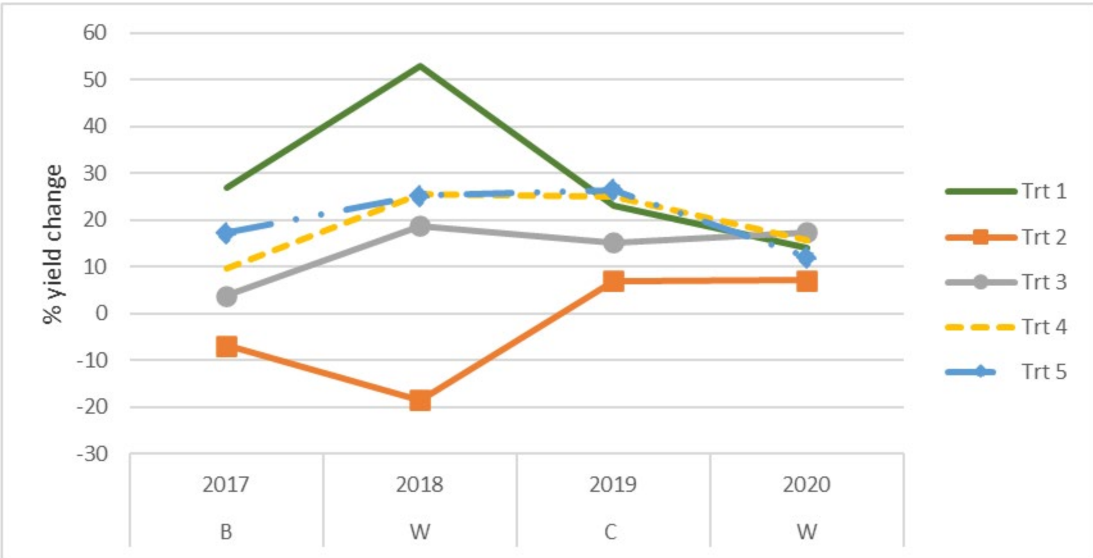

Figure 2. % yield change of each treatment

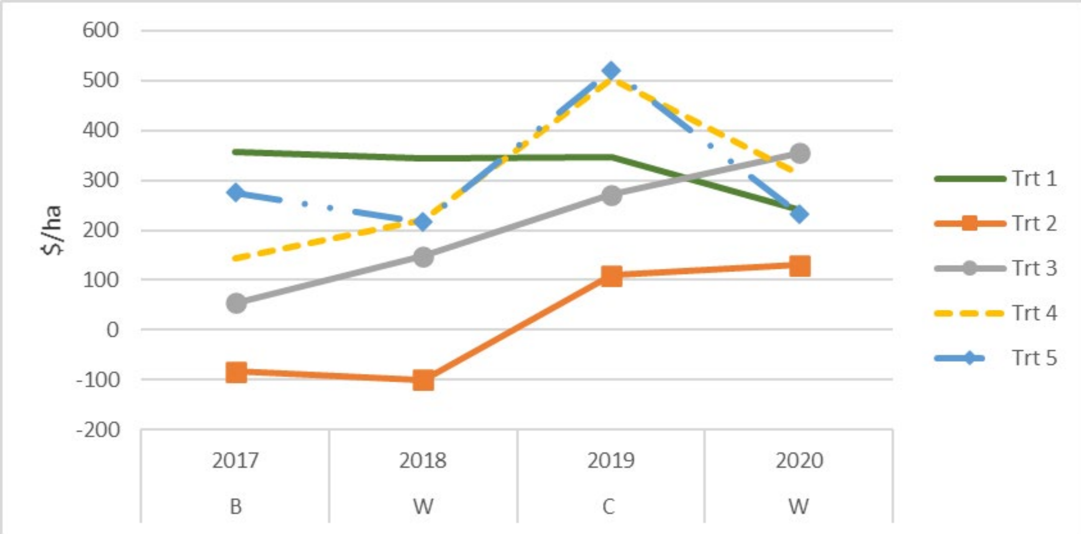

Figure 3. The financial impact of each treatment

Results

From the research outcomes, of note is some strong positive responses in the decile 1 seasons (2018 and 2019) which ultimately translates to an enormous financial benefit to a farm business' bottom line. Specifically;

Treatment 1

Deep pea straw + gypsum + NPK - showed outstanding results in the first three years of the trial and a solid performance in the high yielding decile 7 year of 2020. Although this treatment ranked best on a dollar basis, out all the treatments (not just the deep treatments) it may not be easy to replicate on a commercial basis.

Treatment 2

Deep ripping is included because it is still practiced at an industry level, although most evidence points to it being ineffective in sodic soils. It does however still have a place in removing compaction. This highlights the need to ensure a thorough understanding of the physical and chemical properties of a soil to depth *before* deciding on a course of remediation.

At the sodic Rand site, deep ripping shows a negative response in the first two seasons and every dollar lost hurts the bottom line, particularly in a tough decile 1 season such as 2018. Ranked last of the five deep treatments reviewed.

Treatment 3

Deep placement of pelletised wheat straw. Pelletising this resource for use on farm for deep amelioration has potential. In Figure 3 this treatment shows the $/ha trend line increasing in each of the four seasons of data available, however is overall ranked 4th of the five treatments reviewed.

Treatment 4

Deep gypsum is included as it is commercially available and is used successfully in surface amelioration, in appropriate soil types.

At the Rand site the deep gypsum seems to be producing good yield increases at least initially. Ranked 3/5.

Treatment 5

Deep placement of pea straw - while peas will not be grown on all farms, other pulse crop residue may be able to be substituted, for example in the case of the farmer/co-operator the pulse residue is likely to be faba bean stubble. Pellets of pulse, as with cereal stubble is promising by virtue of its availability and relative simplicity to prepare and use. Ranked 2/5

To draw out the financial impacts for the farmer, the following discussion will be about *money*, not economic theory. In economics, the utility value of a dollar, is almost always a dollar. In farming, the dollar that helps the business scrape into profit in a tough year assumes near magical properties.

Remembering profitability on farm is largely driven by YIELD x PRICE and the factor that the farmer has the greatest capacity to manipulate is yield potential. This means that every opportunity to increase yield, cost effectively, should be examined and the cost:benefit tested on farm.

Table 1 below contains four years of yield data from the trial, derived by averaging the results of the four replicates. The financial outcomes (price per tonne) are based on the grain price achieved by the co-operating farmer for the year concerned.

Table 1. Yield and grain prices over the four years of the trial

Year	2017	**2018**	2019	2020
Crop	Barley	**Wheat**	Canola	Wheat
Yield of control t/ha	4.89	**1.6**	2.38	6.9
Yield of Trt 1	6.21	**2.46**	2.92	7.88
Price $/t	$270	**$385**	$605	$245

Calculations based on this information show that in the Decile 1 season of 2018 Treatment 1 yielded 53% higher than the control treatment. In dollars this means the control treatment generated $640/ha while Treatment 1 generated $948/ha. For such a severe drought year many would consider $640/ha to be a good result, however $948/ha is a profit worthy of any year.

Resilience to drought is something that good farmers are always trying to achieve, and this work shows some very promising results. While the revenue increases look promising, the cost of achieving them can be significant and every farmer should do some on farm investigation and trial work before committing their whole program.

The costs associated with implementing Treatment 1 for example: The machine developed by the co-operating farmer and his engineer colleague, for the deep placement of ameliorants will cost around $200/ha to use. The pelletised straw, for example costs approximately $50 /t to produce and at a rate of 10 t/ha the cost is about $700/ha of upfront investment. Added to this is the cost of the NPK and gypsum if used, approximately another $200/ha.

Regarding the opportunity cost of materials, it is my view that, if the pelletised material is harvest residue from the same paddock, or the same farm, then all that is happening is that the residue is being used in a more effective way and the opportunity cost is zero.

At farm scale

Extrapolating from the research data to what might happen at farm scale - the paddock adjacent to the trial site is used to model two treatments from the trial i.e., Treatments 1 and 5 using the farmer's actual rotation. The farmer's actual yields for the paddock are considered as the 'control, then using the percent increase achieved by the respective treatment and relevant year in the trial, the 'new' yield potential is generated. The grain prices used are the actual prices achieved by the farmer.

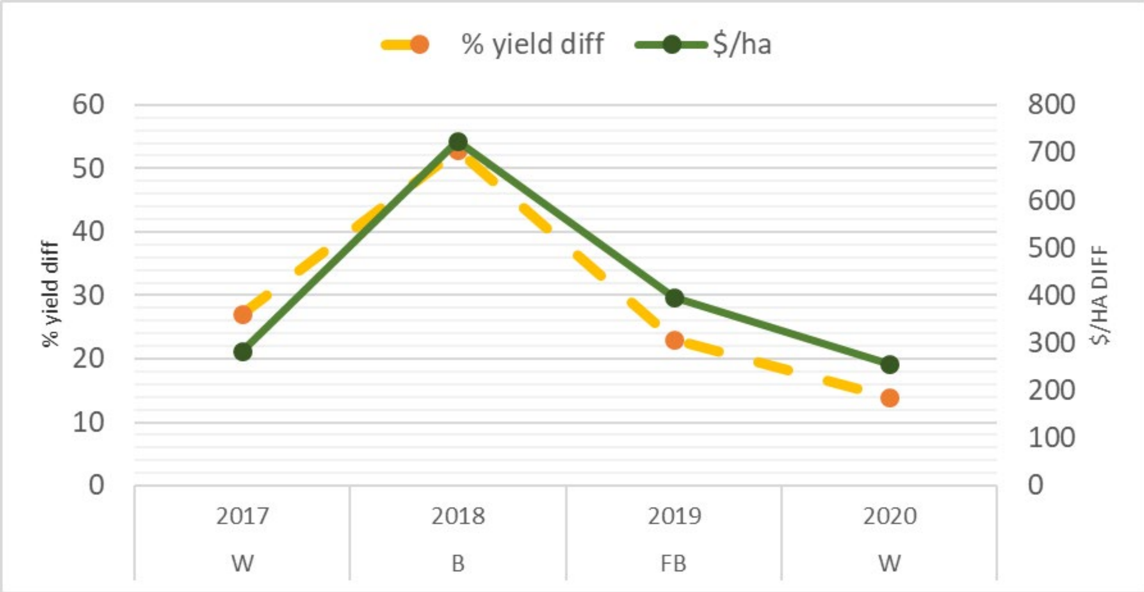

Figure 4. Estimated impact of using Trt 1 (deep placement of pea straw + gypsum + NPK) as the % change in yield and gross margin ($/ha) when compared to grower standard practice

Benefit: The modelled revenue outcome shows a positive return to the farmer and a cumulative additional revenue stream of $1663 over the four years, with outstanding results in 2018 and 2019, which were the toughest years.

Cost: Blending and applying pea straw, gypsum and NPK, would cost approximately $900/ha producing a net benefit of $773 over the four years. It is unclear however how easily this treatment could be done on farm and additional equipment and/or time might add to the cost.

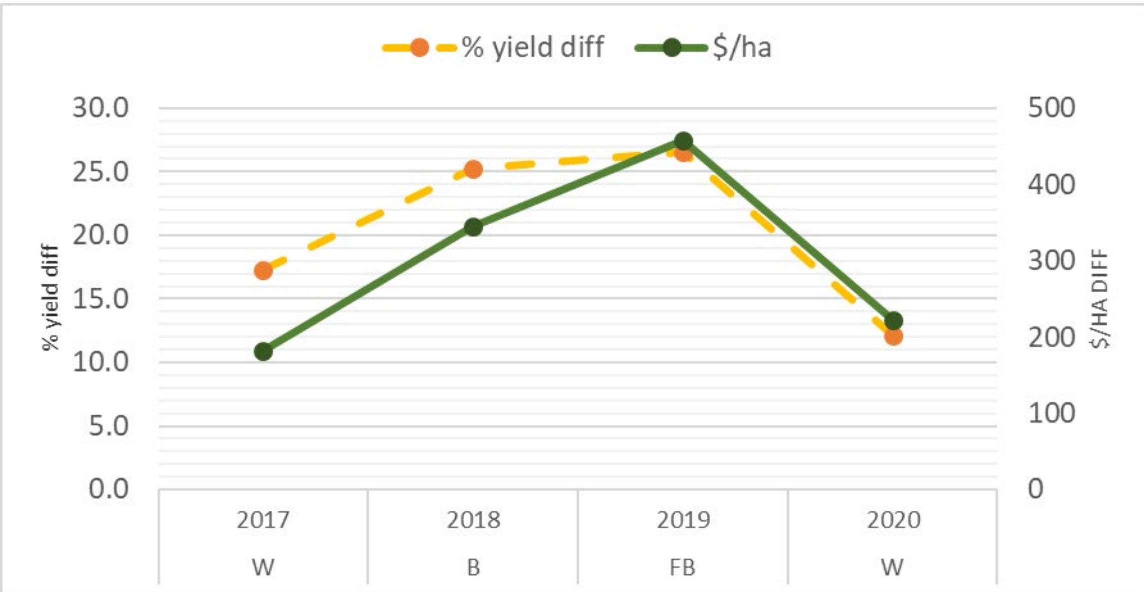

Figure 5. Estimated impact of using Trt 5 (deep placement of pea straw) as the % change in yield and gross margin ($/ha) when compared to grower standard practice

Figure 5 models pelletised pulse straw alone which should be easier for most farmers to make.

Benefit: A cumulative benefit of $1207 over the four years.

Cost: Projected as approximately $700/ha producing a gross surplus of $507/ha.

While only four years of trial data have been collected, we expect yield benefits to continue for several years into the future, making deep soil amelioration financially viable on responsive soils.

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

Within-paddock variability of subsurface pH in southern NSW – its relationship to surface soil properties (pH, buffering capacity) and implications for decision making

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Key words

subsurface acidity, pH stratification, pH variability, precision agriculture, variable rate, liming

Take home messages

- Within-paddock soil pH varied substantially across both surface and subsurface layers however the spatial patterns of 0-10 cm and 10-15 cm pH variability did not necessarily correlate well, particularly where lime was surface applied and not incorporated
- 0-10 cm Cation Exchange Capacity (CEC) correlated more strongly with subsurface (10-15 cm) pH across the whole dataset and in more individual paddocks than 0-10 cm pH, 0-10 cm texture or EM38
- Regardless of surface soil (0-10 cm) pH:
  - Paddocks or soil zones with 0-10 cm CEC values less than ~10-12 cmol/kg (i.e., sands, loamy sands, loams) generally possessed acidic subsurface layers of varying severity unless consistent liming AND incorporation had occurred
  - Paddocks or soil zones with 0-10 cm CEC values greater than ~12-14 cmol/kg (i.e. clays, clay loams, some silty loams) generally did not have severe or yield constraining subsurface acidity
- Liming recommendations should not be made using 0-10 cm data alone. Deeper, segmented soil testing (e.g. 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm) should be used to assess subsurface pH and pH stratification levels. These samples should be strategically located to cover the major 'soil type' zones present within a paddock. 0-10 cm grid pH/CEC mapping is one tool which can be used to map surface soil pH patterns and concurrently develop such 'soil type' zones
- In many paddocks, high rate 'catch up' lime applications will be required to provide enough alkalinity to ameliorate both the surface and subsurface layers. It is critical that these applications are incorporated to bring lime into physical contact with acidic soils.

Background

A recent focus on the prevalence and severity of subsurface acidity in southern NSW has highlighted that current minimum tillage practices including lime top-dressing without incorporation are failing to prevent soil acidification occurring throughout the profile, particularly at 5-15 cm. These results have also highlighted the potential masking effect of traditional 0-10 cm and 10-20 cm soil sampling practices. To negate this effect, it is now recommended that pH sampling be undertaken in finer segmented intervals, such as 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm (Scott et al., 2017; Burns and Norton, 2018; Condon et al., 2020).

Also, within the past few years, a growing understanding of the level of within-paddock pH variability common to our region has led to the increasing uptake of site-specific (variable rate) liming practices. While a number of methods have been utilised, 0-10 cm grid soil mapping has emerged as the most readily implementable, commercially scalable method to capture the combined effect of both inherent (natural) soil type variability and the influences of historical management on surface pH. While automated soil sampling equipment has made this approach feasible in a single depth interval (e.g. 0-10 cm), the current lack of such a solution for segmented soil sampling renders this approach cost-inhibitive for finer interval sampling.

This presents a considerable problem for growers and advisors as they attempt to accurately measure soil pH variability within their paddocks in both a lateral and vertical sense to devise targeted, effective lime application maps. To overcome this problem, substantially more knowledge is required regarding the level of spatial variability of pH in the subsurface and factors driving such variability. If these factors can be understood, they may be utilised to guide the strategic placement of segmented soil tests and/or to create proxy maps of subsurface pH.

Methodology

Eighteen growers in southern NSW each selected approximately 150 ha of broadacre cropping and/or pasture area to be included in the survey, constituting 42 individual paddocks and a total area of 2,692 ha (Figure 1). There was no emphasis on selecting paddocks at a particular stage of the liming rotation or paddocks considered to be acidic. Paddocks spanned the numerous soil types present within the region and across medium to high rainfall zones. The majority of paddocks had received reasonable historic lime inputs in line with industry recommendations, with most recent applications (after 2000) being top-dressed only (not incorporated). No paddocks had been limed in the past two years or undergone variable rate liming, however many paddocks were comprised of amalgamated former paddocks that had been limed separately in the past.

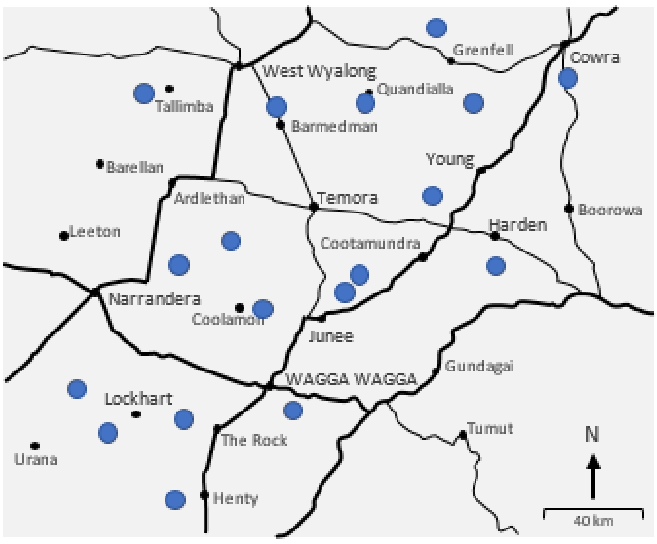

Figure 1. Location of the 18 grower participants and 42 paddocks included in the survey.

Data collection was undertaken during the summer of 2019/20 in two rounds. The first round consisted of apparent Electrical Conductivity (ECa; via EM38) and elevation surveying, followed by surface soil (0-10 cm) pH ($CaCl_2$), Cation Exchange Capacity (CEC) and MIR texture grid mapping at 2 ha resolution. Approximately 20 locations per grower site were selected from the grid soil mapping sampling points for follow up strategic soil sampling at 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm intervals. Locations were chosen to span the range of ECa, pH, CEC and MIR texture values within each paddock. A total of 360 segmented soil samples were collected across the 42 paddocks and analysed for pH ($CaCl_2$), CEC, exchangeable aluminium and acidity, organic carbon and MIR particle size analysis (sand/silt/clay percentages).

Results and discussion

Description of dataset

Across all paddocks, the average grid mapped 0-10 cm pH_{Ca} was 5.16, with individual paddock averages ranging from 4.60 to 6.48. Eighteen paddocks (43%) had an average pH_{Ca} of ≥ 5.2 at 0-10 cm, half (21 paddocks) averaged between 4.8 – 5.2 while three paddocks (7%) averaged < 4.8.

The average within-paddock pH range was similar at both 0-10 cm and 10-15 cm depths (1.23 pH units and 1.28 pH units respectively), suggesting the magnitude of lateral spatial pH variability within the surface and subsurface layers is comparable.

Substantial pH stratification and subsurface acidity was observed across many sites when sampled in 5 cm intervals (Figure 2). As a whole dataset, the most alkaline layer was at 0-5 cm (average 5.38 pH_{Ca}), dropping to 4.87 pH_{Ca} at 5-10 cm. pH levels were most acidic at 10-15 cm (average 4.83 pH_{Ca}), where 33% of samples were < 4.5 pH_{Ca} and 29% of samples had > 5% exchangeable aluminium. Almost three-quarters of samples (73%) were more acidic at 10-15 cm than their corresponding 0-10 cm grid sample. The majority of samples (87%) increased in pH from 10-15 cm to 15-20 cm depth, where the average pH_{Ca} was 5.19.

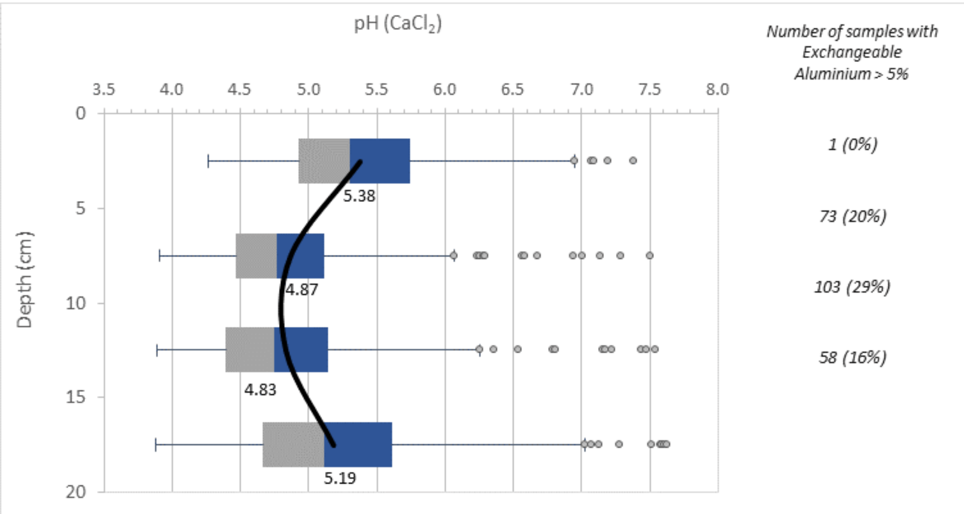

Figure 2. Box and whisker plot for all strategic segmented sampling results (0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm; n = 359). Boxed area represents the middle 50% of data (interquartile range). Heavy black line and data labels are averages at each depth. Dots are outliers beyond 1.5x IQR.

While there was considerable variation within paddocks, examining results grouped by individual growers revealed a number of trends related to historic management (Figure 3). The largest cohort of similar results consisted of paddocks that have had moderate to high, predominantly unincorporated, lime inputs. These sites (e.g., Wagga Wagga, Marrar, Henty) typically displayed a sharp decline in pH between the 0-5 cm to 5-10 cm layers and moderate to high levels of subsurface acidity. For example, Figure 3a located at Marrar (loam; av. 0-10 cm CEC 7.0 cmol/kg) has a total lime history of 6.7 t/ha from 1991-2014 with no physical incorporation. Average pH_{Ca} levels at this site were 5.81 (0-5 cm), 4.57 (5-10 cm), 4.29 (10-15 cm) and 4.61 (15-20 cm). It is worth noting that the average 0-10 cm grid pH_{Ca} at this site was 5.35, highlighting the masking effect of traditional 0-10 cm sampling.

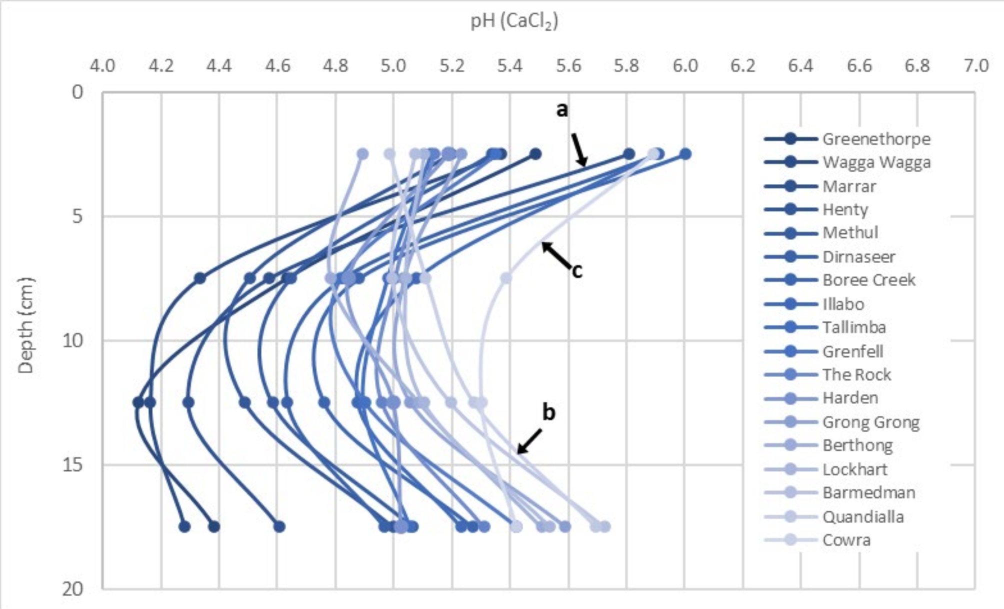

Figure 3. pH profiles to 20 cm depth for each of the 18 growers included in the survey (coded by location of grower). Profiles are averages of all strategic samples taken at each site (n = 17 – 23). Legend is in order of increasing pH at 10-15 cm, where dark = most acidic and light = most alkaline. Arrows point to a) Marrar, b) Quandialla and c) Cowra sites.

A second cohort of results came from sites located on more clay-rich, naturally alkaline soils (e.g., Quandialla, Barmedman, Lockhart) which had mostly received no or low lime inputs owing to their higher starting pH levels (i.e., being on soil types not typically considered acidic). These paddocks generally had lower than average pH levels at 0-5 cm however were consistently more neutral to alkaline in the subsurface layers. For example, at the Quandialla site (Figure 3b; av. 0-10 cm CEC 15.2 cmol/kg), average pH_{Ca} values were 4.99 (0-5 cm), 5.11 (5-10 cm), 5.27 (10-15 cm) and 5.70 (15-20 cm).

Paddocks not fitting into either of the above groups consisted of sites where growers had implemented some form of liming plus incorporation within the past decade. Here, results were highly variable depending on the commencement date, rates and regularity of liming. Of these paddocks, the Cowra site (silty loam/loamy sand; av. 0-10 cm CEC 7.8 cmol/kg) had the most robust liming and incorporation history (between 5 to 7.7 t/ha total since 1994, incorporated to 10 cm depth). This was reflected in the results through much less severe pH stratification and subsurface acidity when compared to most other sites (average pH_{Ca} = 5.89 at 0-5 cm, 5.39 at 5-10 cm, 5.30 at 10-15 cm and 5.42 at 15-20 cm; Figure 3c).

Relationship between surface and subsurface layers

Across the whole dataset, a weak correlation was found between surface (0-10 cm) and subsurface (10-15 cm) soil pH (r^2 = 0.18). Of particular note, results demonstrated that highly acidic (< 4.5) pH_{Ca} levels and elevated exchangeable aluminium percentages can still be present in subsurface layers where the corresponding 0-10 cm sample is neutral or alkaline (i.e., > 5.5 pH_{Ca}; Figure 4a, 4c).

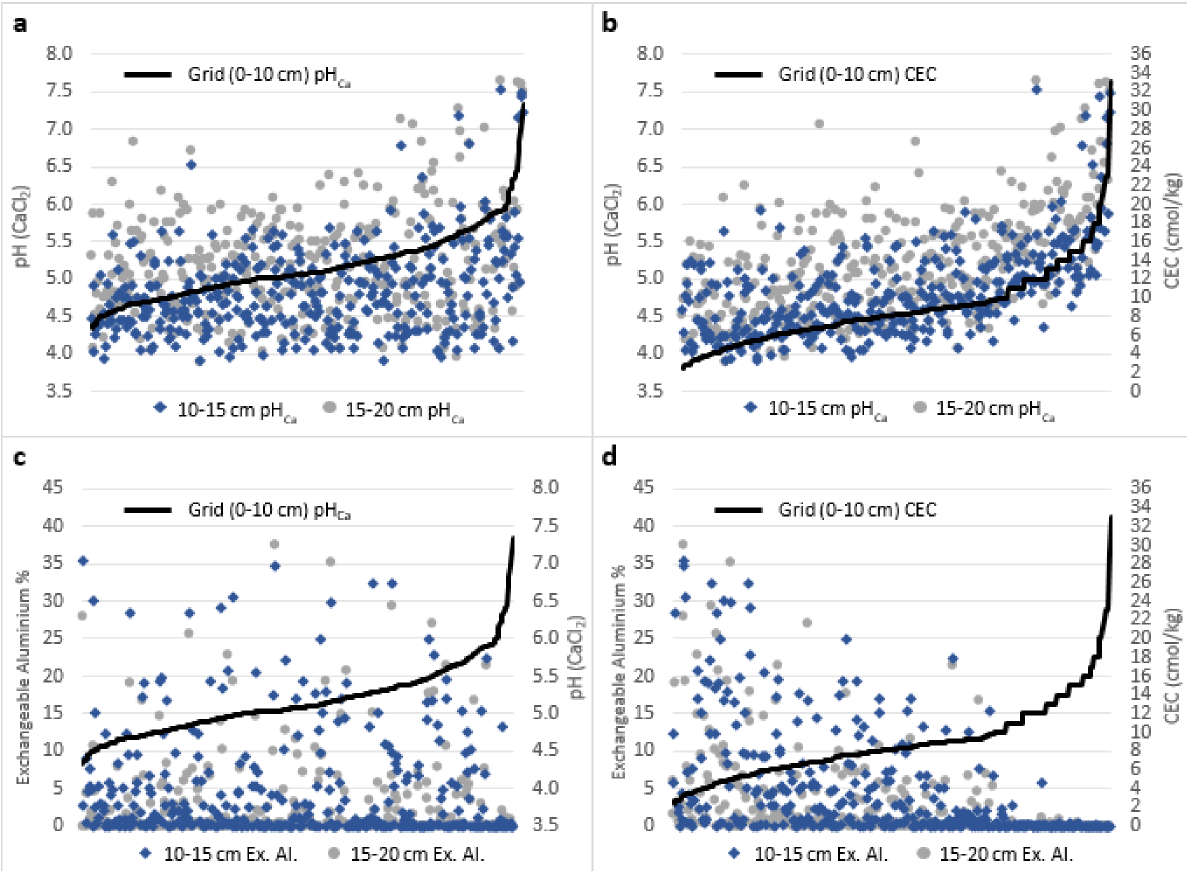

Figure 4. 10-15 cm (◆) and 15-20 cm (●) pH (top) and Exchangeable Aluminium percentages (bottom) plotted against their corresponding 0-10 cm pH_{Ca} (left) and Cation Exchange Capacity (right) as collected by grid soil mapping. Data has been arranged in order of increasing 0-10 cm pH (a,c) and CEC (b,d).

The poor nature of this relationship appears to be strongly driven by the shallow surface layer (0-5 cm pH vs. 10-15 cm pH r^2 = 0.06) rather than the 5-10 cm segment, which correlated strongly with 10-15 cm pH (r^2 = 0.75). This supports the notion that surface applied, unincorporated lime applications are having very little influence on soil pH below 5 cm depth.

Of the various other data layers examined (0-10 cm grid CEC, 0-10 cm texture, EM38); subsurface (10-15 cm) pH correlated most strongly with 0-10 cm grid CEC (r^2 = 0.47). Figure 4b and 4d show:

- For soils or soil zones with 0-10 cm CEC levels less than ~10-12 cmol/kg (i.e. sands, loamy sands, loams), subsurface pH levels ranged from neutral to highly acidic. Individual results appear to be related to liming and incorporation histories
- For soils or soil zones with 0-10 cm CEC levels greater than ~12-14 cmol/kg (i.e. clays, clay loams), no severe acidity or elevated exchangeable aluminium levels were observed in the subsurface layers. This observation can be explained by the longer period of time required to acidify soils of higher buffering capacities given the same management, therefore it is expected that this 'threshold' CEC value will increase over time.

These trends are also reflected when strategic soil sampling data is grouped according to surface soil CEC and soil textural classes (Figure 5). Although substantial variability due to contrasting management histories is encompassed within the dataset, there is a reasonably consistent trend below 5 cm depth of decreasing pH (more severe acidity) with lower CEC and clay concentrations.

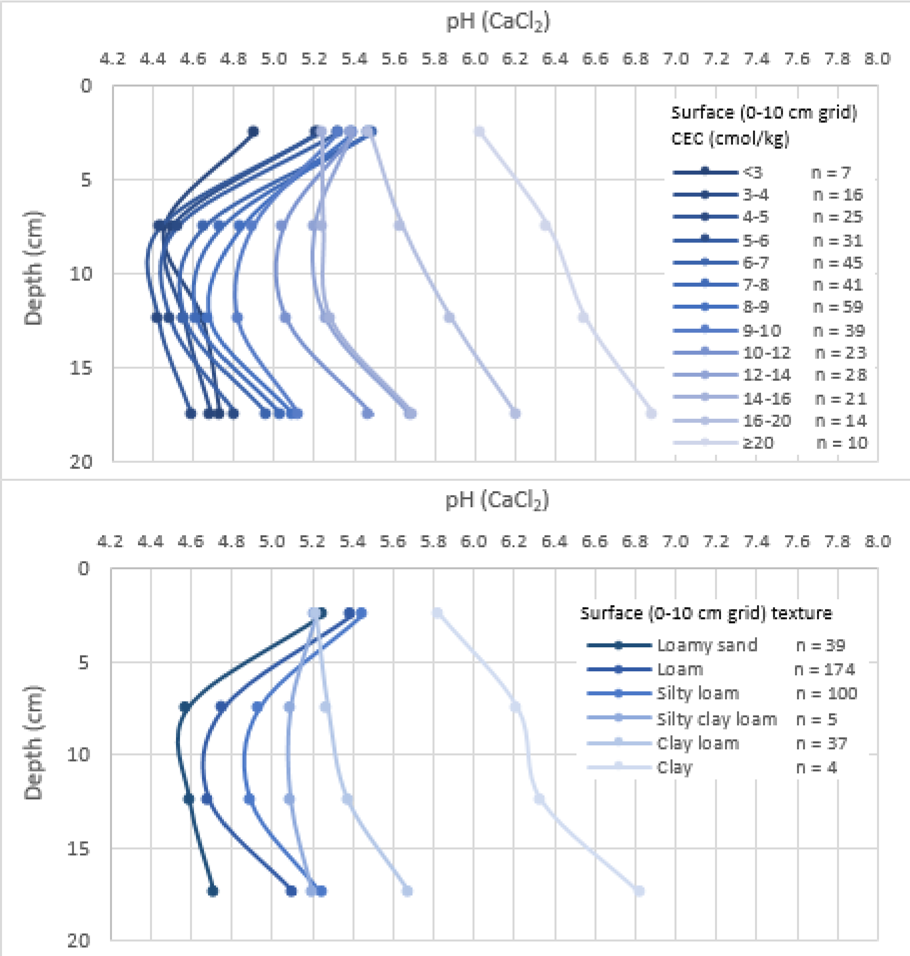

Figure 5. Average pH profiles to 20 cm depth for strategic samples (n = 359) of varying 0-10 cm Cation Exchange Capacity (top) and soil texture (bottom; as per Australian Soil Classification system from MIR Particle Size Analysis data). Note: Averages for samples < 4 cmol/kg were heavily influenced by one location where incorporated lime applications appear to have increased the subsurface pH.

On an individual paddock level, 0-10 cm grid CEC also correlated most strongly with subsurface (10-15 cm) pH for the largest number of paddocks compared to any other layer (followed by grid pH, grid clay%, grid sand%, ECa 0.5 m and ECa 1.0 m).

Correlations between surface pH (0-10 cm grid) and subsurface pH (10-15 cm) were substantially stronger in paddocks with nil or low lime histories (e.g., Case Study 1 (Figure 6)), compared to paddocks where lime had been surface applied without incorporation (particularly within the past five years; e.g., Case Study 2 (Figure 7)).

Correlations between subsurface pH and all 0-10 cm layers were also generally strongest in paddocks with higher degrees of inherent ('natural') soil type variability, such as those with surface (0-10 cm) CEC values spanning a range of greater than 5 cmol/kg. Paddocks with more consistent soil types (particularly those on lower CEC soils) could still possess quite variable subsurface pH levels, however their spatial patterns were often erratic and difficult to predict.

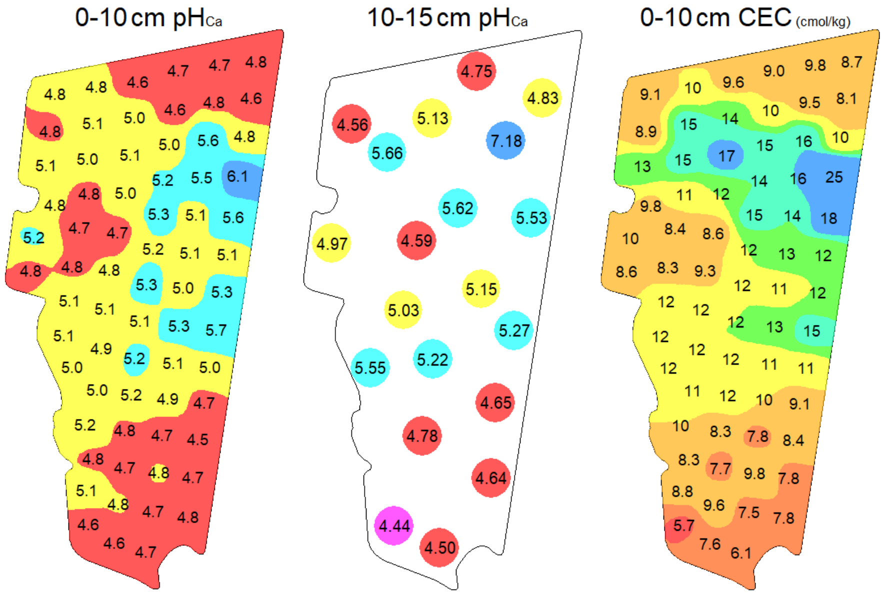

Figure 6 (Case Study 1). 'Lockhart' paddock (143 ha) has a high degree of natural variability in CEC and soil texture (red loam to grey clay). The paddock has never been limed owing to a relatively high starting pH typical of the area. Subsurface acidity (10-15 cm pH) correlates reasonably well with both surface CEC (r^2 = 0.62) and pH (r^2 = 0.56) as mapped by 0-10 cm grid sampling. A zone-based VR strategy could be considered to raise the subsurface pH_{Ca} to 5.2 in areas where the 0-10 cm CEC is less than ~10-12 cmol/kg. This would be applied in addition to the lime required to raise the topsoil pH_{Ca} to 5.5, which would need to be incorporated to be effective.

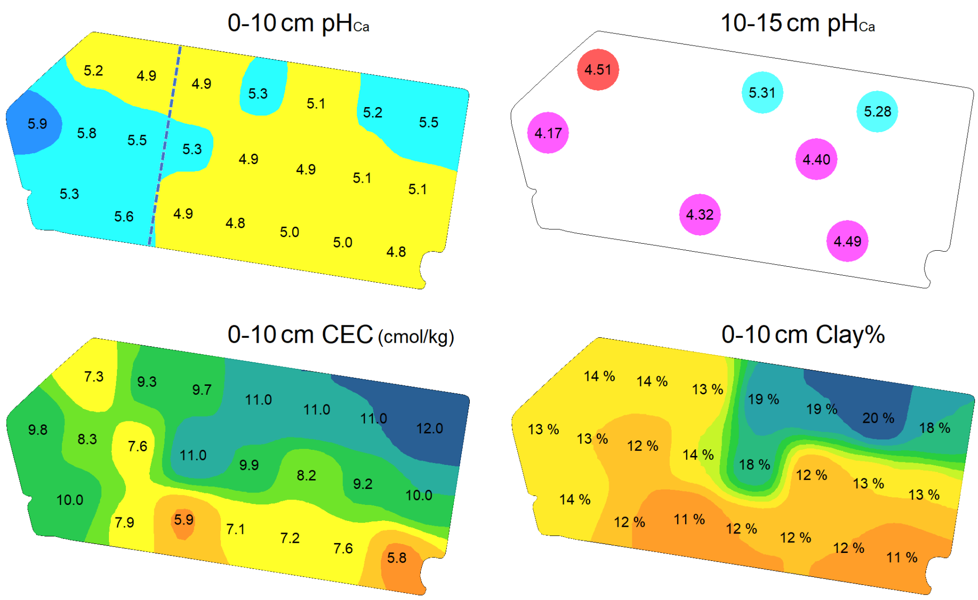

Figure 7 (Case Study 2). 'Henty 3' paddock (48 ha) consists of two former paddocks (dashed line) where the western (left) side received 2.9 t/ha lime in 2017 versus 1.2 t/ha on the eastern (right) side (neither incorporated). Subsurface (10-15 cm) pH correlates well with 0-10 cm CEC (r^2 = 0.50) and clay% (r^2 = 0.88) however there is no correlation whatsoever with 0-10 cm pH (r^2 < 0.01). The higher clay zone in the north-eastern corner has a relatively high subsurface pH compared to the remainder of the paddock, despite contrasting surface soil pH trends driven by recent liming, which has not moved beyond 5 cm depth. This example highlights the potential danger of using 0-10 cm data in isolation to develop site-specific liming plans.

Management implications

The results of this survey strongly echo other recent studies which have highlighted that standard 0-10 cm sampling is not identifying the widespread pH stratification and acidification of subsurface layers in our region. The level and extent of acidification identified at 5-10 cm and 10-15 cm in the present study suggests that significant 'catch-up' lime rates above traditional rates combined with incorporation are now required in many paddocks.

The poor correlation observed between surface (0-10 cm) and subsurface (10-15 cm) pH appears to be the result of contrasting key influencers on soil pH at different depths in minimum tillage systems. In particular, top-dressed lime applications have the potential to greatly alter surface pH patterns, such as in paddocks with varying soil buffering capacities or where historic lime inputs have not been consistent (e.g., across old fencelines). With poor penetration of alkalinity past the top few centimetres of soil, it follows that subsurface pH patterns may more closely align with soil buffering capacity than surface pH patterns.

These findings demonstrate that surface pH patterns (e.g. 0-10 cm grid or zoned sampling) cannot be used in isolation to manage soil acidification throughout the full profile (except perhaps on consistently high CEC soils). Rather, it is suggested that targeted segmented sampling (e.g., 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm) be used to examine the major 'soil type' zones within a paddock. This could be achieved using 0-10 cm grid soil pH/CEC mapping as an initial round of data collection to concurrently map surface pH and develop such 'soil type' zones. Liming rates could then be formulated using a number of approaches; each requiring the lime to be well incorporated into the soil profile:

- Calculate lime rates for 0-10 cm targeting a pH_{Ca} of 5.5, plus add additional requirements for the 10-20 cm layer. If subsurface pH varied in a predictable manner corresponding with CEC/soil type zones, 10-20 cm lime inputs could be adjusted accordingly. This approach is likely most suitable for paddocks possessing a higher level of natural variability (i.e., 0-10 cm CEC levels varying by > 5 cmol/kg). If subsurface pH patterns do not vary in a predictable manner, blanket lime rates to ameliorate the 10-20 cm layer would be more appropriate.
- Alternatively, a simpler approach of targeting a higher 0-10 cm pH_{Ca} (e.g. 5.8 – 6.0) may be suitable in certain situations, however segmented soil sampling to 20 cm should still be undertaken to gain a complete picture of the soil pH profile.

While the resultant lime rates for either approach are likely to be much higher than traditional maintenance rates, it is important that additional product is added on top of that which will be 'used up' neutralising the surface soil. Given the expense of cultivation and preference for minimum tillage management, it is also logical to use higher rates to prolong the period between strategic tillage events.

Concluding comment

The overall findings of this survey have demonstrated that there is currently no single 'one size fits all' solution to accurately measuring and managing vertical and lateral within-paddock pH variability. Rather, a high level of skilled advisor and/or grower input is required for best outcomes, taking into consideration the unique soil type and management history factors of each paddock. This is an area that would greatly benefit from an engineering/technology solution that integrated cost-effective three-dimensional data collection and interpretation methods.

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Optimising canola establishment and performance by phosphorus fertiliser placement

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Key words

Phosphorus, canola, fertiliser, placement, establishment

GRDC code

GOA00002

Take home message

- Traditional methods of applying phosphorus-based starter fertilisers with the seed is often reducing canola establishment, in some cases, by well over 50%
- This is costing growers through the need to increase seeding rates to compensate for losses, reduced yields through low populations or, in extreme cases, the need to resow crops
- Placing fertiliser away from the seed, either below or broadcast on the soil surface either before or after sowing largely eliminated the negative impacts on crop establishment
- These alternate application placement options produced similar yield responses as the traditional option of putting the fertiliser with the seed
- Applying phosphorus fertilisers by these alternate methods may also offer some logistical advantage in timing of operations
- Dry soil conditions may hinder access to applied phosphorus in the surface applied options, but in these trials, there was limited occurrences at commercial rates of phosphorus.

Background

Phosphorus (P) is an important nutrient to optimise canola production. Traditionally, P fertiliser has been applied at planting, banded near the seed. This approach is likely to be based on the premise that P is relatively immobile in the soil and needs to be placed close to the developing root systems of crops to be readily accessible early in the crop cycle.

However, damage to establishing crops by placing fertiliser close to seed has long been accepted. Trials in 2013, by Jenkins and Brill from the Department of Primary Industries demonstrated significant reductions in canola establishment with increasing rates of P (up to 20 kg/ha) applied at seeding. However, yields still increased with increasing rates of P despite the suppression in emergence, demonstrating the ability of canola to compensate for lower plant populations in the circumstances tested.

So, if the crop can compensate and maintain yield despite lower establishment, what is the problem?

Firstly, seed costs for growing canola can be high. When only a fraction of the seed purchased results in an established plant, this inefficiency represents a significant cost, particularly where seed can cost more than $80/ha. Secondly, the impacts on plant establishment can be variable and un-predictable which has resulted in growers increasing seeding rates to cover the possibility of decreased establishments. Thirdly, in extreme cases crop establishment impacts may be so severe, that yields are impacted, or crops need resowing.

Recent changes to farming systems may further increase risk of damage. The adoption of wider row spacings and sowing with knife points or disc seeders all have the effect of increasing fertiliser concentration within the drill line, thus increasing potential for damage. Furthermore, the move to earlier sowing, into warmer and potentially more rapidly drying soils could only be thought to further exacerbate the risks of variable crop establishment.

A field survey undertaken in 2017 (McMaster, C. 2019) assessed canola establishment across 95 commercial crops in the central west of NSW. This survey showed that crop establishments ranged from as low as 17% up to 86% with an average of 48%. Whilst the report suggested that seed size had the greatest influence over establishment it also mentioned several other factors also correlated well, including stubble loads, sowing speed, seeding depth and starter fertiliser and its proximity to the seed.

So how do we apply enough P to optimise yields, without a negative impact on establishment while maintaining or even improving P fertiliser efficiencies? Could altering our way of applying P fertilisers to canola crops also improve the reliability of crop establishment which is a key deterrent to many growers from growing canola (GRDC Grower Network, 2020)?

Trial work undertaken by GOA under the Grower Solutions Group Project since 2015 has been investigating alternate options for applying conventional P fertilisers in canola to address these key questions.

This paper details the outcomes from this series of trials and proposes alternate ways to apply P in winter grown canola crops.

Methodology

The hypothesis was 'can we apply P fertiliser in an alternate manner to the standard approach of banding it with the seed, that minimises the impact on crop establishment whilst maintaining the fertiliser response in crop performance (yield)?'.

A series of 15 trials have been run since 2015 investigating alternate methods of P starter fertiliser placement as detailed below-

- With seed (with)- fertiliser applied through the same seed boot as the seed is delivered
- Below seed (below)- delivered though a second boot set to deliver the fertiliser below the seed with at least 2-3 cm separation from the seed position
- Incorporate by sowing (IBS)- fertiliser was broadcast just prior to sowing and incorporated by the seeder (knife point and press wheel- 27cm row spacing)
- Top-dressed- fertiliser was broadcast just after seeding to the soil surface with no incorporation.

Initially the P fertiliser used was Trifos (triple super) because of the absence of N in its makeup. However, this product is now largely unavailable, and many growers were simply using ammonium phosphate fertilisers such as DAP or MAP as their P source and as such MAP, was used in more recent trials. Details of the fertiliser type, rates tested, and the range of placements is detailed in Table 1 below. Although this report does report the treatments in terms of the rate of P applied, it should be considered that with P supplied as MAP there is an associated amount of N delivered with that rate of P. This Nitrogen may be also contributing to damage but as most starter fertilisers contain both these elements, apportioning the blame to P or N is difficult but also somewhat academic.

However, in trials where MAP was used, the differing nitrogen levels applied were balanced out with urea across all rates to ensure any yield responses were not influenced by differences in N rates applied.

Table 1. Details of trial site and treatments

Year	Location	Site Colwell P (0-10cm)	Fertiliser tested	P rates applied kg P/ha	Fertiliser placement treatments
2015	Wellington	21 ppm	Trifos	0, 10, 20	With, below, IBS
2015	Gilgandra	12 ppm	Trifos	0, 10, 20	With, below, IBS
2016	Gilgandra	18 ppm	Trifos	0, 15, 30, 45	With, below, IBS, top-dressed
2016	Alectown	10 ppm	Trifos	0, 15, 30, 45	With, below, IBS, top-dressed
2017	Nyngan	33 ppm	Trifos	0, 15, 30, 45	With, below, IBS, top-dressed
2017	Jemalong	19 ppm	Trifos	0, 15, 30, 45	With, below, IBS, top-dressed
2017	Gilgandra	21 ppm	Trifos	0, 15, 30, 45	With, below, IBS, top-dressed
2017	Geurie	<5 ppm	Trifos	0, 15, 30, 45	With, below, IBS, top-dressed
2018	Wellington	20 ppm	Trifos	0, 10, 20, 40	With, below, IBS, top-dressed
2018	Canowindra	36 ppm	Trifos	0, 10, 20, 40	With, below, IBS, top-dressed
2019	Gilgandra	23 ppm	MAP	0, 10, 20, 40	With, below, IBS, top-dressed
2020	Gilgandra	39 ppm	MAP	0, 10, 20, 40	With, below, IBS, top-dressed
2020	Gollan	23 ppm	MAP	0, 10, 20, 40	With, below, IBS, top-dressed
2020	Wongarbon	32 ppm	MAP	0, 10, 20, 40	With, below, IBS, top-dressed

Results

Table 2 summarises the statistically analysed responses on two main measures- plant population and yield response to P rate and placement. As the traditional method of P placement is 'with' this is a common comparison made. Further detail on individual trial reports can be found at www.grainorana.com.au.

The '>' indicate the yields from the aforementioned treatment exceeds the following treatment, '&' between two treatments indicates there was no difference between those treatments. Alternate placement methods in **bold** highlight only cases where yields are lower than the traditional 'with' placement.

Table 2 also details the rainfall received for the 60 days following seeding for each site/year, as this is thought to influence nutrient access for some of the placement methods. The yield range of the site is also included for the reader to consider the nutrient requirement for the crop as a pseudo indicator of crop growing conditions throughout the year.

Table 2. Trial results from 15 trials on P rate and placement in canola, summarising the impact on plant population and yield when P fertiliser was applied 'with seed', 'below seed', top-dressed or incorporated by sowing (IBS).

Site/year	Impact on plant populations	Impact on yields	Rainfall 60 days post planting ^	Yield range t/ha
Wellington 2015	P rate applied or placement had no impact	P rate applied or placement had no impact	118 mm	1.4- 1.9
Gilgandra 2015	20 kg/ha P 'with seed' resulted in lower populations than 10 kg/ha. 'Below seed' & IBS had no impact on populations regardless of P rate	Site was rate responsive when P was applied 'with seed' 10 & 20 kg/ha > Nil P At 10 kg/ha P- No impact of placement At 20 kg/ha P- 'with seed' & 'below seed' > **IBS**	159 mm	1.3 – 2.1
Gilgandra 2016	All rates of P applied 'with seed' resulted in lower plant populations by around 30%, compared to 'below seed', IBS & top-dressed in all but one case.	Site was rate responsive when P was applied 'with seed' 30kg/ha > 15 & 45kg/ha > Nil P At 15kg/ha P- No impact of placement At 30kg/ha P- No impact of placement At 45 kg/ha P- IBS, top-dressed & 'below seed > 'with seed'	256 mm	1.8- 2.7
Alectown 2016	At 30 & 45 kg/ha of P 'with seed' resulted in up 40% lower plant populations than 'below seed, IBS or top-dressed which were not different to one another At 15 kg/ha P 'with seed' was lower than IBS & 'below seed' but not different to top-dressed	Site was rate responsive when P was applied 'with seed' 30 kg/ha > 45, 15 kg/ha & Nil At 15kg/ha P- no impact of placement At 30kg/ha P- No impact of placement At 45 kg/ha- IBS & top-dressed > 'with seed & 'below seed'	172 mm	2.3 – 3.4
Nyngan 2017	At 45kg/ha of P 'with seed' or 'below seed' plant populations were reduced by 65% and 40% respectively compared to the best treatment, top-	Site was rate responsive when P was applied 'with seed' 15, 30 & 45 kg/ha > Nil At 15 kg/ha P- no impact of placement At 30 kg/ha- 'below seed' > IBS, top-dressed & 'with seed'	27 mm	0.3 – 0.5

Site/year	Impact on plant populations	Impact on yields	Rainfall 60 days post planting ^	Yield range t/ha
	dressed. At 15kg/ha & 30 kg/ha of P 'with seed' there was no impact by placement.	At 45 kg/ha- 'with seed' & top-dressed > **IBS** & '**below seed'**		
Jemalong 2017-	P rate applied, or placement had no impact	P rate applied or placement had no impact	13 mm	0.3 – 0.9
Gilgandra 2017-	P rate applied, or placement had no impact	Site was rate responsive when P was applied 'with seed' 45 kg/ha & 30 kg/ha >15kg/ha > Nil At 15 kg/ha P- No impact of placement At 30 kg/ha- 'below seed', 'with seed' & top-dressed > **IBS** 45 kg/ha- 'below seed' > 'with seed', IBS and top-dressed	11.6 mm	0.9 – 1.4
Geurie 2017-	P rate applied, or placement had no impact	Site was rate responsive when P was applied 'with seed' 45 kg/ha, 30 kg/ha > 15 kg/ha > Nil At 15 kg/ha P- 'below seed' > 'with seed' & top-dressed > **IBS** At 30 kg/ha P- 'below seed' & 'with seed' > **top-dressed** & **IBS** 45 kg/ha P- 'below seed' & 'with seed' > **IBS** & **top-dressed**	47 mm	0.2 – 1.2
Wellington 2018	At 45 kg/ha P applied 'with seed' resulted in a lower plant population (~37%) than when applied 'below seed', IBS or top-dressed At 10 or 20 kg/ha there was no impact of placement.	Site was not rate responsive when P was applied 'with seed' At 10 kg/ha P- no impact of placement At 20 kg/ha P- 'with seed', 'below seed' & top-dressed > **IBS** At 40 kg/ha P- no impact of placement	37 mm	1.0 – 1.4
Canowindra 2018	At 40 kg/ha P 'with seed' resulted in lower plant populations than top-dressed and IBS	Site was rate responsive when P was applied 'with seed' 40 & 20 kg/ha > 10 kg/ha & Nil At 10 kg/ha P- below> 'with seed', top-	31.5 mm	0.4 – 0.5

Site/year	Impact on plant populations	Impact on yields	Rainfall 60 days post planting ^	Yield range t/ha
	At 20 kg/ha there was no impact of P placement. At 10 kg/ha 'with seed' & 'below seed' resulted in lower plant populations.	dressed & IBS At 20 kg/ha P- top-dressed & 'below seed' > 'with seed' & IBS At 40 kg/ha P- 'below seed' & 'with seed'> **top-dressed** and **IBS**		
Gilgandra 2019	At all rates of P applied 'with seed' resulted in the lower plant populations than IBS, top-dressed & 'below seed' except at 10 kg/ha P where 'below seed' only was no different to 'with seed'.	Site was rate responsive when P was applied 'with seed' 40 kg/ha >10, 20 kg/ha & Nil At 10 kg/ha P- no impact of placement At 20 kg/ha P- top-dressed & 'below seed' > 'with seed' & IBS At 40 kg/ha P- 'below seed' &, top-dressed > IBS & 'with seed'	18.6 mm	0.6 – 0.9
Gilgandra 2020	At any rate of P applied 'with seed' resulted in the lowest plant population. At 40 kg/ha placed 'with seed' the seed reduced establishment by 81% compared to top dressed	There was an inverse response to P rate when applied 'with seed' # No impact when applied by the alternate placements. At 10 kg/ha P- no impact of placement At 20 kg/ha P- top dressed, IBS & 'below seed' > 'with seed' At 40 kg/ha P- IBS, top-dressed & 'below seed' > 'with seed'	52 mm	1.7 – 2.4* *Site was hail damaged prior to harvest-treat results with caution*
Gollan 2020	At any rate of P, establishment was lowest when applied 'with seed'. At 40 kg/ha establishment was reduced by ~58% compared with IBS, top-dressed & 'below seed'. At both 20 & 40 kg/ha there was no difference between IBS and top-dressed but better than 'with seed'	Site was P rate responsive when applied 'with seed' 40 kg/ha >20 kg/ha>10 kg/ha > Nil At 10 kg/ha P- no impact of placement At 20 kg/ha P- no impact of placement At 40 kg/ha P- no impact of placement	58 mm	2.2 – 3.7

Site/year	Impact on plant populations	Impact on yields	Rainfall 60 days post planting ^	Yield range t/ha
Wongarbon 2020	At 10 kg/ha ‘with seed’, ‘below seed’ & top-dressed had lower plant populations than IBS, at 20 & 40 kg/ha ‘with seed’ was lower than IBS and top-dressed all which were no different	Site was P rate responsive when applied ‘with seed’- 40, 20 & 10 kg/ha > nil At 10 kg/ha P- no impact of placement At 20 kg/ha P- no impact of placement At 40 kg/ha P- ‘with seed’, IBS and top-dressed > ‘below seed’	93.6 mm	3.7 – 4.1

*- *Site was hail damaged prior to harvest- treat results with caution*

#- *Increasing P applied ‘with’ the seed reduced yields suggested to be because of very significant reductions in plant populations.*

^- *rainfall data from the nearest BOM or other automatic weather stations*

Summation of trial outcomes

As evidenced above, the P placement and rate can impact on plant populations (crop establishment), and it can be variable. In 11 out of 15 trials, plant populations were lower when P fertiliser was placed ‘with the seed’ when compared with alternate placements tested, in some cases by up to 80%. In general, the negative impact on plant populations increased as the P rate increased, but in some cases as little as 10 kg/ha of P was sufficient to reduce plant establishment.

Three trials in 2017 showed no impact of P rate or placement on plant populations, but all sites experienced very dry soil conditions just after planting. The only other site to show no impact of P on plant population was Wellington in 2015. This site was also not yield responsive to P rate or placement.

In contrast, where fertiliser was placed away from the seed using either IBS or top-dressed, there was no reduction in plant populations. In all cases, plant populations were comparable to where nil fertiliser was applied (data not shown), suggesting that any impact of P fertiliser on plant population had been negated by changing its position relative to the seed.

Placing P fertiliser below the seed did sometimes, but not always avoid impacts on plant populations.

In eight out of the 15 sites the yields of the alternate placements matched the performance of the traditional ‘with seed’ placement and in a small number of cases yields were improved.

Three sites, Gilgandra 2015 & 2017 and Wellington in 2018 had instances where only the IBS option had lower yields than the ‘with seed’ treatment. At Gilgandra in 2017, only the 30 kg/ha of P IBS treatment had lower yields. At all other rates (15 & 45 kg/ha) ‘with seed’ performed equally or worse than the alternates. At Gilgandra 2015 and Wellington 2018 the difference in the IBS treatment was only apparent at 20 kg/ha of P. At all other rates there no difference between placements.

Two sites had instances where the IBS and top-dressed had lower yields than the ‘with seed’ treatment, although only at the higher rates of 30 & 40 kg/ha , but not at the lower, ‘more commercial’ rates tested. It should be noted that most of these cases where differences occurred were in the drier years of 2017 and 2018.

The remaining two sites were non-responsive to both placement and rate for yield and establishment (Wellington 2015 and Jemalong 2017).

This body of work demonstrates that if P fertiliser is placed away from the seed, either IBS or top-dressed and to a lesser extent below the seed, this avoids the negative impacts on plant populations. It has also shown that in most cases, the yield response to the applied rate of P, matched the response where the P was applied ‘with’ the seed.

The placement ‘below seed’ resulted in only two cases where the yield was lower than the ‘with seed’ treatment, though this effect was only evident at the highest rate (45kg/ha) of P, rates that may be considered experimental rather than commercial. This however is not unexpected given the fertiliser was directly under the seed separated by only 2-3 cm where roots would naturally extend through this fertiliser band. However, placement of P ‘below seed’ did not always avoid reduction in plant populations as did IBS or top-dressed.

Interestingly, in most cases both the IBS and top-dressed treatments recorded a yield response even though the resting position of the fertiliser would have been above and or to the side of the seed. Large proliferations of surface roots were commonly observed in these trials, and it is assumed that these facilitated crop P uptake in sufficient quantity and time frame so as not to penalise crop performance.

The notable exception was the drier years, primarily 2017 where the rainfall received in the 60 days post planting was very low and may have limited the development and ability of surface roots to access fertiliser. It these years, in some cases, the ‘with seed’ or ‘below seed’ treatments did outperform the IBS and top-dressed options, but only at the higher rates tested of 30-45 kg/ha. At the more commercially relevant rate of 15 kg/ha, there was no impact of P placement. In a stark contrast, in many other trials applying such high rates of P with the seed was highly detrimental to plant populations and in some cases yields.

Given that not all farmers have the option to apply fertiliser below the seed and there may be some cases, in dry years when IBS and top-dressing may risk underperforming, another option may be to ‘split’ the starter fertiliser application. That is, apply a proportion of the P fertiliser at sowing, say 5-10 kg P/ha, with the seed and apply the balance IBS or top-dressed. In this scenario smaller amounts of P applied with the seed may be sufficient to meet crop requirements in a dry period/season, while reducing the impact on establishment. The remainder of the fertiliser applied IBS or top-dressed, becoming available if wetter (and higher yielding) conditions prevail.

This ‘split’ approach has been tested on a limited basis in the past few years, but further work is needed before this can be recommended.

What does this mean to canola growers?

Clearly placing fertiliser away from seed improving the rate and reliability of establishment of canola crops is a key advantage of this alternate approach. However, there may be further advantages.

In the case of surface applications growers may be able to apply most of their canola P fertiliser requirements ahead of seasonal breaks or the busy sowing periods and this will have significant logistic advantages. The low sowing rates of canola combined with reduced rates (if split) or nil P fertiliser will greatly increase the area that can be sown in any given period, as the number of seeder refills could be greatly reduced.

For growers that have very low seed bed utilisation (wider row spacing, knife points or disc openers), this approach may be the most practical option to apply higher rates of P fertiliser to canola crops without the associated risks and downsides. An alternative that is often considered is applying higher rates in the previous crop. However, this may increase the risk of nutrient tie up and it will extend the time until cash invested in fertiliser is recouped.

Conclusions

The traditional placement of P fertilisers such as MAP/ DAP or other high analysis starter fertilisers can reduce crop establishment by 50% or more. Factoring in these typical losses combined with the need for increased seed rates could potentially be costing growers more than $45/ha. In extreme cases the costs could be greater where yields are impacted or resowing is required. The impact of P fertilisers with seed is also likely to be contributing to the variable establishments growers often experience.

Over five years and 15 trials GOA has looked at alternate placements of P to avoid this issue. This work has shown that reductions in plant populations can be avoided by moving P away from intimate contact with the seed. This work has also shown that in most cases fertiliser efficiency has been maintained and in some cases of high rates of P, improved.

Placing the fertiliser below the seed maybe preferred if growers have suitable machinery. However, for growers who do not have this option, simply broadcasting the fertiliser and incorporating it by sowing (IBS), or even top-dressing post sowing has proven to be similarly effective.

The risk for the latter two approaches is likely to occur when dry soil conditions occur post sowing, which limit the crops ability to forage for that fertiliser, as was experienced in the drought year of 2017. However, in those years, crop fertiliser requirement was less, and yield differences were not apparent at commercial rates of 15 kg/ha. These alternate surface application approaches will have logistical advantages by offsetting some of the fertilising task from away sowing, which alone may be a key attraction.

GOA is planning to fine tune an approach of splitting the P fertiliser application, i.e. small basal amount with the seed and the balance applied to the soil surface. It is hypothesised that this approach may deliver the following advantages: minimise crop establishment impacts, reduce risks in dry conditions whilst maintaining fertiliser responses and improve sowing efficiencies (logistics).

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What difference does rhizobia strain make on grain legume nodulation, nitrogen fixation and grain yield?

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rhizobia, nodulation, cross-compatibility, manufacturability

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Take home messages

- Two rhizobia strains (WSM4643 and WSM1483) continue to out-perform the current Group E (SU303) and Group F (WSM1455) strains in acidic soils of NSW giving rise to increases in host plant nodulation
- Herbicides residues have differing impacts on pulse nodulation which is likely linked to differences in soil, climate, host plant and rhizobia factors.

Summary

Field evaluation over two years has found that the rhizobia strains WSM4643 and WSM1483 produce significant increases in nodulation of the Group E/F host range compared to the current commercial strains, particularly on acidic soils (pH_{Ca} 4.6-5.3). Increasing the interval between inoculation and sowing time from 1 to 48 hours where soil moisture conditions are adequate, also showed these strains were superior to other strains evaluated. Herbicide residues continue to be perplexing in terms of predicting their likely impact on legume nodulation which is likely related to the interaction of soil, climatic, host plant and rhizobia factors.

Introduction

Pulses are an important crop for Australian farming systems as they have the capacity to contribute to building soil nitrogen (N). However, it is not a given that growing pulses will give rise to a net increase in soil N. While pulses are capable of fixing 20-30 kg N/t shoot dry matter, achievement of this is predicated on the formation and maintenance of an effective symbiosis between the host legume and its rhizobia. Many factors such as soil physiochemical conditions and management influences such as the use of herbicides in-crop and in preceding crops can impact the host plant, the rhizobia and/or the symbiosis. Current rhizobia strains for field pea, lentil, vetch and faba bean were isolated from soils where pH_{Ca}>7.0. Recent surveys have shown much of the pulse-growing area of central and southern NSW have soil pH well below this threshold (Hackney et al. 2020a). It is known that the current Group E (SU303) and Group F (WSM1455) strains rapidly lose effectiveness where soil pH_{Ca}<5.5 (Drew et al. 2014). Current investment by the GRDC and research partners in the Northern, Western and Southern regions are evaluating the potential of recently isolated strains where soil pH is more typical of those encountered in each of the growing regions (i.e. pHCa<5.5). Additionally, studies are investigating the response of these strains to aridity via evaluation across soils with varying texture and/or climatic conditions. Further, the impact of herbicides on legume nodulation is also being evaluated. The remainder of this paper reports on some of the results of the first two years of the project in the Northern region.

Strain impact on nodulation

First year results have been previously reported for three sites; Griffith, Condobolin and Canowindra (Hackney et al. 2020b). Briefly, first year results found the strains WSM1483 and WSM4643 were generally superior to the current Group E/F strains and exhibited excellent cross-compatibility across all Group E/F hosts. In 2020, new sites were established at Griffith (pH_{Ca} 4.6) and Condobolin (pH_{Ca} 4.8) with an additional site at Tamworth (pH_{Ca} >6.0). At these sites, the current commercial Group F (WSM1455) and two experimental strains (SRDI969 and WSM4643) were used to inoculate field pea and lentil (all sites) and vetch (Griffith and Condobolin only). An uninoculated control was included for all hosts at all sites.

At the most acidic site (Griffith), WSM4643 produced significantly higher nodulation in all hosts compared to all other strains (Figure 1). WSM4643 produced significantly higher nodulation in field pea and lentil at Condobolin and lentil at Tamworth (Figure 1). SRDI969 was superior to all other strains for field pea at the least acidic site (Tamworth; Figure 1).

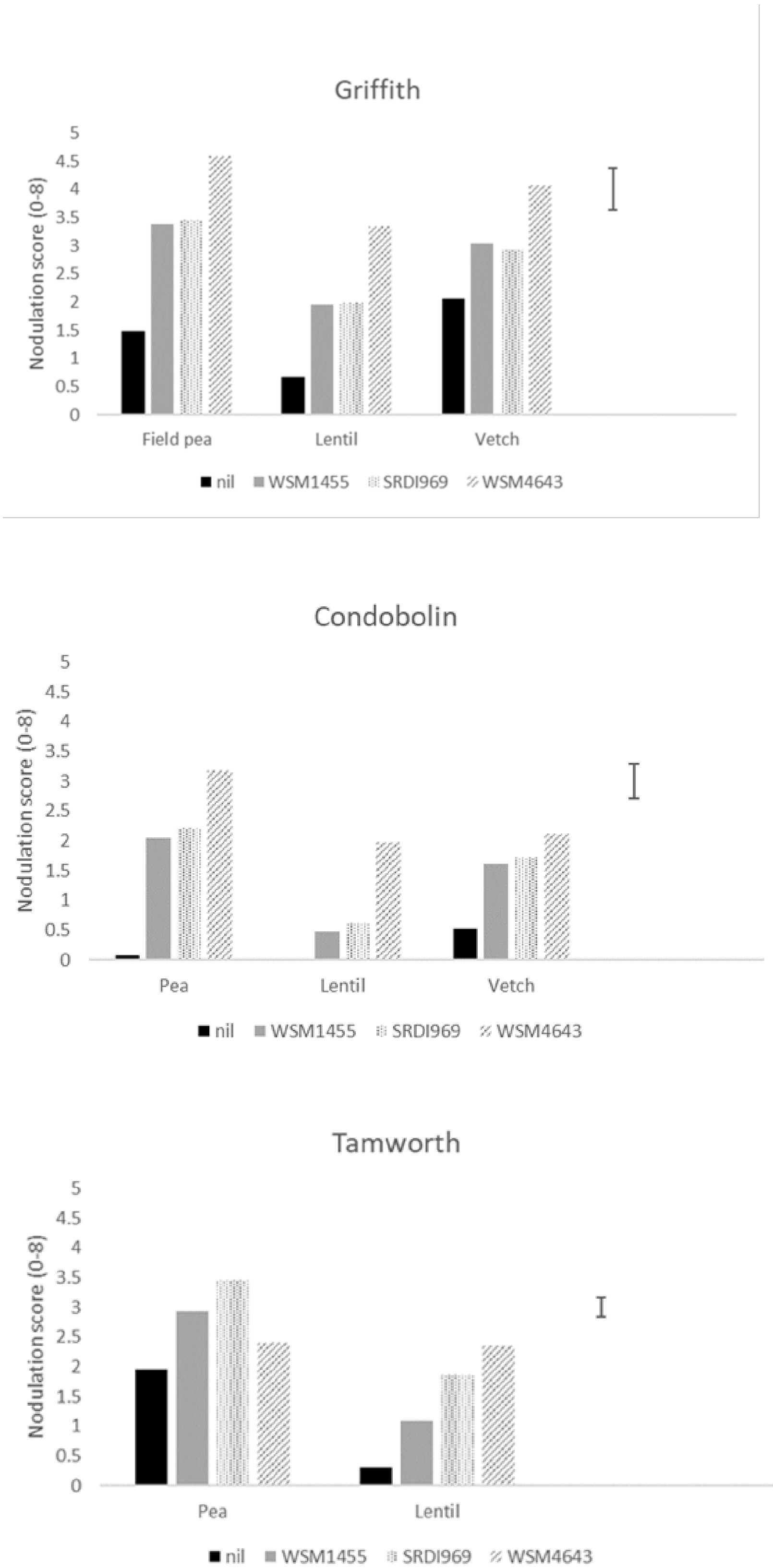

Figure 1. The nodulation score (0-8; adequate =4) for field pea, lentil and vetch at Griffith, and Condobolin and field pea and lentil at Tamworth in 2020 when inoculated prior to sowing with the current Group F (WSM1455) or one of two experimental rhizobia strains. A nil inoculated control was included at all sites. Nodulation assessment was made using the method of Yates et al. (2016).

Time delay between inoculation and sowing

Wet inoculant delivery systems such as peat treated seed or liquid injection deliver high numbers of rhizobia to the soil. However, mortality rates for rhizobia can be very high if soil moisture conditions are inadequate. A row trial was undertaken at Condobolin to determine the impact of time delay since inoculation on nodulation of the host plant (in this case, vetch). Planting of peat treated seed was delayed for 1, 12, 24 or 48 hours following inoculation. Due to seasonal conditions, soil moisture levels were good at the time of planting.

There was no effect of time delay on nodulation of vetch for individual strains (Figure 2) which is not surprising given the good soil moisture conditions. However, there was an effect of strain alone on the nodulation achieved. Overall, WSM1483 achieved significantly higher nodulation than all other strains while WSM4643 was significantly higher than all remaining strains. These results again continue to build evidence of both WSM1483 and WSM4643 as being strains that can improve nodulation compared to the current Group F (WSM1455) strain in acidic soils.

Given the high soil moisture conditions in the field trials which favoured survival of all strains in 2020, laboratory analysis are underway to determine the impact of time delay on rhizobia survival when applied to glass beads. These data will provide useful information on strain behaviour under conditions that favour desiccation.

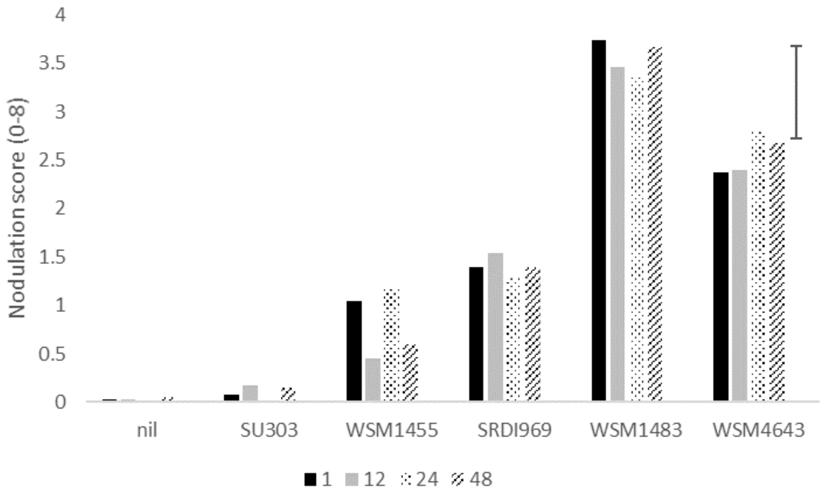

Figure 2. The effect of delaying sowing by 1, 12, 24 or 48 hours following inoculation with a range of rhizobia strains for vetch compared to an uninoculated (nil) control at Condobolin in 2020.

Manufacturability

A key consideration in selecting a possible elite strain for commercial release is capacity to manufacture the strain effectively and have it survive in high numbers until required for use. The current Group E (SU303) strain is difficult to manufacture and thus it is Group F (WSM1455) that is currently used across the Group E/F host plant range. Fortunately, WSM1455 has good cross-compatibility for the Group E/F host range.

A key role of the Australian Inoculant Research Group (AIRG) has been investigation of the manufacturability of the elite strains compared to current Group F strain. To do this, the AIRG group are periodically sampling peat inoculants containing each respective strain over a period of 30 months after manufacture. At four months post manufacture, all strains tested met or exceeded industry standards ($\geq 10^9$ CFU/g). The 12-month sampling count is about to occur. Ultimately, the information obtained from this study will provide confidence around shelf life when the peats are stored under refrigerated conditions.

Herbicide residue impacts on nodulation

Two sites were established in 2019, at Griffith and Canowindra, to determine the impact of herbicide residues on subsequent pulse crop nodulation. Soils differed between the sites. At Griffith, the soil was a light sandy loam with a pH_{Ca} of 4.8 (0-10 cm). At Canowindra, the soil was a Dermosol with a pH_{Ca} of 5.3 (0-10 cm). In winter 2019 (or post-harvest 2019/20 for summer treatments), the herbicides of interest were applied at typical label rates. Lentil and vetch treated with the current Group F (WSM1455) were sown in May 2020. For all winter-applied treatments, the specific plant-back periods (time and/or moisture requirements) as specified on the product labels were met. The summer application of metsulfuron-methyl would not have met the plant-back period for planting of pulses. However, it was included as recent surveys (Hackney et al. 2021) has found almost 60% of growers were including metsulfuron-methyl in fallow sprays. Therefore, it is important to consider the effect that such usage may have on subsequent pulse nodulation.

The effect of herbicides differed with host plant and site (Figure 3). Generally, lentil achieved a lower nodulation score than vetch and all lentil treatments had a nodulation score well below that considered adequate (≥ 4; Yates et al. 2016). Within lentil, there was little difference between herbicides in terms of damage with the exception of imazamox + imazapyr which was particularly damaging at Canowindra and clopyralid which was more damaging at Griffith.

For vetch, 2,4-D, dicamba + MCPA and diflufenican + MCPA appeared to cause no damage at Canowindra where nodulation scores approaching four were recorded. However, these herbicides were significantly more damaging at Griffith. Metsulfuron-methyl, pyroxsulam + halauxifen, imazamox + imazapyr and clopyralid were all significantly more damaging than the best performing treatments within sites. Clopyralid was especially damaging at Canowindra.

There is a complex interaction between herbicide, soil, rainfall, host plant and rhizobia in terms of the impact of herbicide residues on nodulation. These results are preliminary screenings. Further trials were established in 2020 at Griffith and Condobolin with pulses to be sown into these residues in 2021. More research is required in this area particularly with new mode of action herbicides emerging in the marketplace.

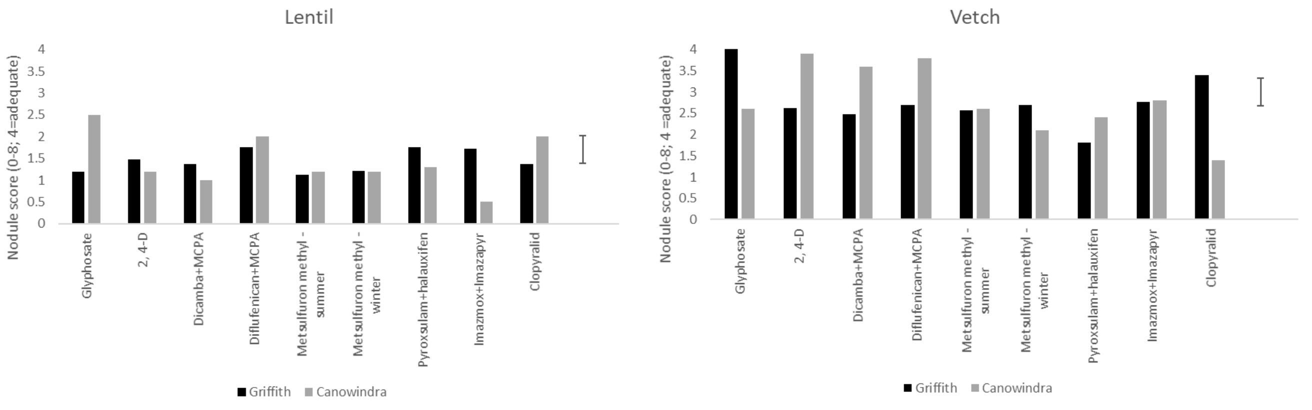

Figure 3. The effect of a range of herbicides applied in 2019 to the nodulation score (based on the system of Yates et al. 2016) of lentil and vetch sown in 2020 at Griffith and Canowindra. (Note: while the nodulation scoring system used covers the range 0-8, a score of 4 is considered adequate. Fixing nitrogen is an energy expensive process and therefore very high scores are not frequently encountered in the field.)

Impact of rhizobia strains on grain yield

Processing is continuing to determine pulse grain yield from the 2020 harvest. Results from 2019 showed little difference in grain yield of the pulses as a consequence of inoculation with different rhizobia strains. However, drought may have impacted those results. Subsequently, wheat was sown over the 2019 trial sites in 2020. Wheat yields at Griffith did not differ between treatments and samples are undergoing processing from the Condobolin site.

Impact of rhizobia strains on nitrogen fixation

Due to COVID-19, there has been a considerable delay in processing of samples to determine nitrogen fixation. We are expecting these results to be available in late January or early February 2021.

Conclusions

After two years of field trials in this project, it appears that the rhizobia strains WSM4643 and WSM1483 are well adapted to acidic soil conditions in NSW. Both appear to have strong cross compatibility with the entire Group E/F host range and have increased nodulation compared to the current Group E (SU3030) and Group F (WSM1455) strains and have thus far performed adequately in terms of manufacturability. Herbicides and their residues continue to have perplexing impacts on legume nodulation with differences between sites and hosts. The impact of herbicides and their residues on pulse nodulation and nitrogen fixation requires significantly more investigation.

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Russian wheat aphid thresholds - Insect density, yield impact and control decision making

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Keywords

Russian wheat aphid, yield loss, action threshold

GRDC code

UOA1805-018RTX: Russian wheat aphid risk assessment and regional thresholds

Take home messages

- Russian wheat aphid (RWA) risk from 'natural invasion' (as opposed to inoculated insect pressure) was nonsignificant in all 28 trials in 2018 and 2019
- RWA yield impact is 0.28 % yield loss per percent of tillers with RWA (%TwRWA)
- After GS30 (start of stem elongation), the number of tillers with RWA doubles about every 35 days, thus doubling %TwRWA'
- The RWA action threshold calculator is now available on-line and supports adoption of an IPM approach.

Background

This project studied the risk of infestation by the Russian Wheat Aphid (RWA, *Diuraphis noxia* Kurdjimov) and its effect on yield to develop best management practices in an Australian context of winter cropping of short cycle cereals (e.g. spring wheat). Risk of yield loss depends on aphid invasion, subsequent pest development and sensitivity of the crop to the pest.

Previously, there were no data available for quantitative and qualitative yield effects of RWA and the development of intervention thresholds in Australian cereal growing conditions. Overseas data, from North America and South Africa, where RWA has been present for many decades (Archer and Bynum 1992; Du Toit and Walters 1984; Du Toit 1986; Bennett 1990a,b; Kieckhefer and Gellner 1992; Girma et al 1990, 1993, Mirik et al 2009, Legg and Archer 1998, Chander et al 2006), report a wide range of potential damage levels (yield loss and qualitative losses) and derived economic injury levels. Losses of around 0.5% of yield loss per percentage of RWA infested tillers during stem elongation and grain filling are most frequently reported (Archer and Bynum 1992).

These knowledge gaps were addressed through

1. 28 natural RWA infestation field trials in 2018 (15) and 2019 (13) in South Australia, Victoria, New South Wales and Tasmania (Table 1)
2. 15 RWA inoculated field trials in 2018 (5) and 2019 (10) where 50 RWA/m^2 (500,000 RWA/ha) were applied at GS15-20 (2-4 leaf stage, Table 1)
3. Green Bridge sampling of grasses during the non-cropping period in both years in all states and extensive continuous sampling of grasses in SA over 26 months (March 2018-May 2020).

Table 1. Location of trial sites in 2018 and 2019

Site Name	State	Lat	Long	Inoculation	Irrigation
		2018			
Birchip	VIC	-35.9666	142.8242	Y	N
Cummins	SA	-34.3050	135.7189	N	N
Griffith	NSW	-34.1902	146.0920	Y	N
Hillston	NSW	-33.5482	145.4408	N	Y
Inverleigh	VIC	-38.1805	144.0390	N	N
Keith	SA	-36.1299	140.3233	Y	N
Lockhart	NSW	-35.0837	147.3280	N	N
Longerenong	VIC	-36.7432	142.1135	N	N
Loxton	SA	-34.4871	140.5891	Y	N
Minnipa	SA	-32.8398	135.1642	N	N
Nile DRY	TAS	-41.6759	147.3140	N	N
Nile IRR	TAS	-41.6759	147.3140	N	Y
Piangil	SA	-35.0519	143.2758	N	N
Riverton	SA	-34.2193	138.7350	Y	N
Yarrawonga	NSW	-36.0484	145.9833	N	N
		2019			
Birchip	VIC	-35.9666	142.8242	Y	N
Bundella	NSW	-31.5851	149.9064	N	N
Cressy	TAS	-41.7854	147.1134	Y	N
Eugowra	NSW	-33.4944	148.3192	N	N
Griffith	NSW	-34.1902	146.0920	Y	N
Horsham	VIC	-36.7432	142.1135	Y	N
Inverleigh	VIC	-38.0497	144.0104	Y	N
Loxton	SA	-34.4871	140.5891	Y	N
Minnipa	SA	-32.8398	135.1642	Y	N
Mildura	VIC	-34.2627	141.8535	Y	N
Pt Broughton	SA	-33.5757	137.9987	Y	N
Thule	NSW	-35.6491	144.3914	Y	N
Yarrawonga	NSW	-36.0484	145.9833	N	N

Outcomes

Risk of RWA invasion of crops: Overall RWA risk was very low during these two (very dry) years with no significant RWA infestation occurring in any of the non-inoculated field trials. This shows that the largely adopted use of prophylactic seed treatments against RWA was not justified.

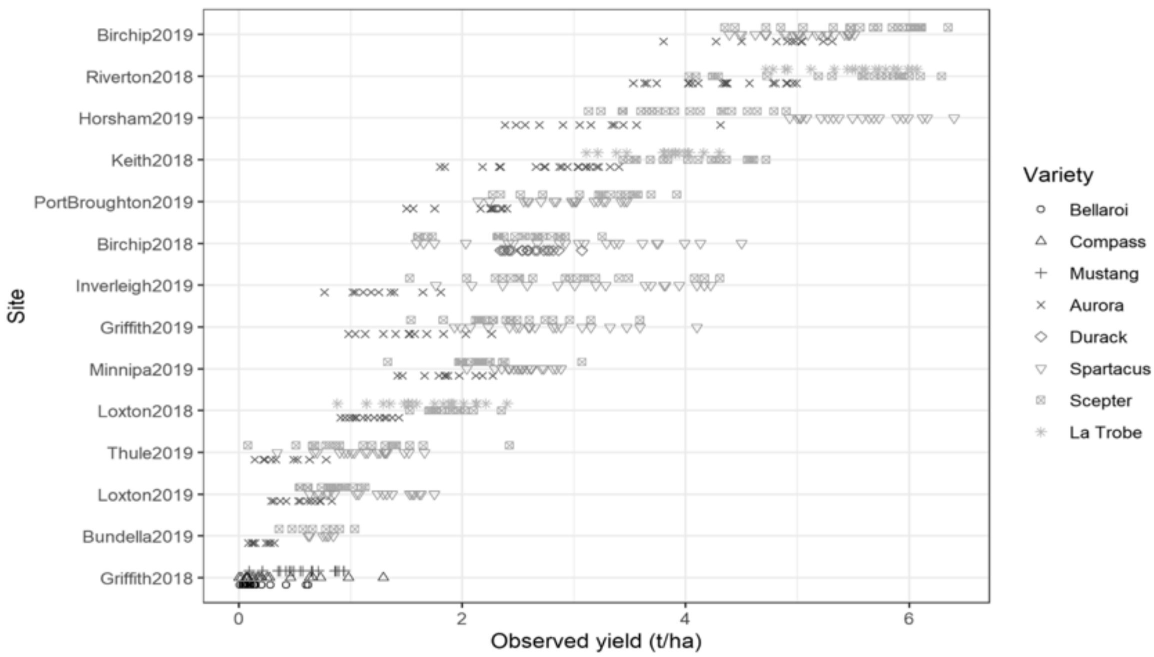

Figure 1. Yield across all trial sites and years with different cereal type/variety denoted by different markers. Varieties used: Barley: Compass⫽; Spartacus CL⫽, La Trobe⫽; Durum wheat: EGA Bellaroi⫽, DBA Aurora⫽; Wheat: Scepter⫽, Mustang ⫽; Oat: Durack⫽.

Yield loss in inoculated trials: Regional and varietal differences were large (Figure 1). In some, but not all, of the inoculated field trials RWA populations reached population levels (maximum observed between GS40 and 50) resulting in yield loss. The best predictor of yield loss of various aphid pressure metrics was the maximum percentage of tillers with RWA present (%TwRWA) and a percentage of the potential yield loss with a 0.28% yield loss observed for every %TwRWA. This simple relationship applied to all the different cereal types (wheat, barley, durum wheat), years and regions (through the adjustment of potential yield), oat did not allow RWA development. This yield impact is significantly lower than described for the USA (0.46-0.48% for every %TwRWA, Archer and Bynum 1992).

From this equation, the economic threshold (the break-even point of yield loss and control measures) can be calculated depending on the costs of control (pesticide, applications costs), the expected yield (region and year dependant) and the farm-gate price of the crop as parameters (Figure 3).

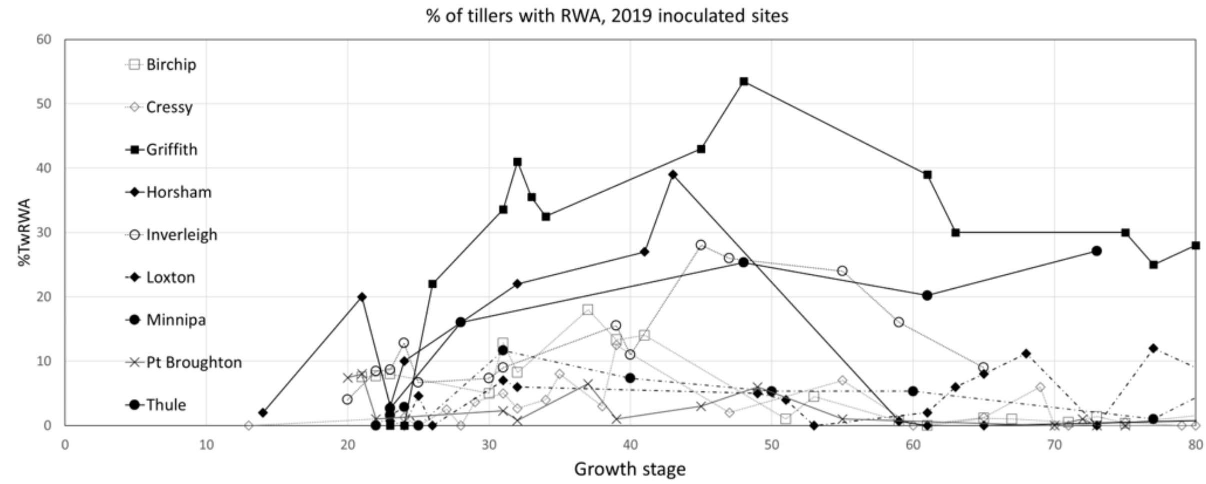

Figure 2. Percentage of tillers with RWA **(**%TwRWA) against growth stage for the RWA inoculated untreated control plots (AI-UTC) in all inoculated trial sites in 2019.

RWA population development: After inoculation with RWA, the highest RWA populations developed in drier regions, through a combination of increased RWA establishment during inoculation and increased rates of subsequent population increase. Less tillering in dry areas also contributed to a higher %TwRWA. The maximum population of RWA and the maximum %TwRWA was reached between GS40 and 50 (Figure 2) followed by a decrease. Between the end of tillering (GS30) and GS50 an increase in the %TwRWA of 0.021%/%/day was observed. This would result in a doubling of the %TwRWA every 35 days.

Action threshold calculator: Based on these observations and equations, we propose a decision rule (action threshold, Figure 3) for RWA management using an observation of the percentage of tillers with symptoms and the %TwRWA at GS30. This observation and the expected increase in %TwRWA (based on the expected time to ear emergence GS50), inform the need for management action, which can (if needed) be combined with existing treatments at GS32-35, thus reducing application costs. Growers and advisers are directed to the GRDC calculator (see additional resources) to calculate thresholds for their growing conditions"

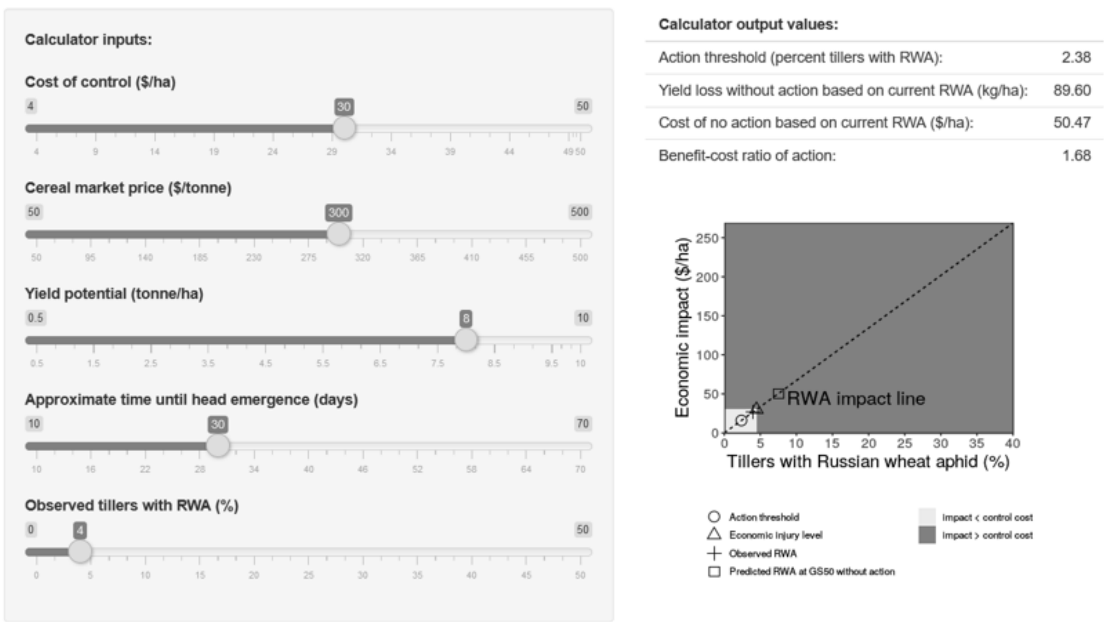

Figure 3. RWA action threshold calculator (example)

Green bridge risk: The environmental conditions over summer that form a 'green bridge' of suitable (grass) habitat between winter crops were expected to determine the risk of early colonisation events.

Field surveys during the spring to autumn periods demonstrated RWA detections being particularly common and with high populations during spring in the warm dry grain growing regions of northern Victoria, southern New South Wales and South Australia. During the summer, growing crops and green vegetation for most grass species disappeared and RWA populations declined (Figure 4). Apart from volunteer cereals (wheat and barley), the majority of RWA detections were on five grass genera (barley grass, *Bromus* sp., phalaris, ryegrass and wild oat.

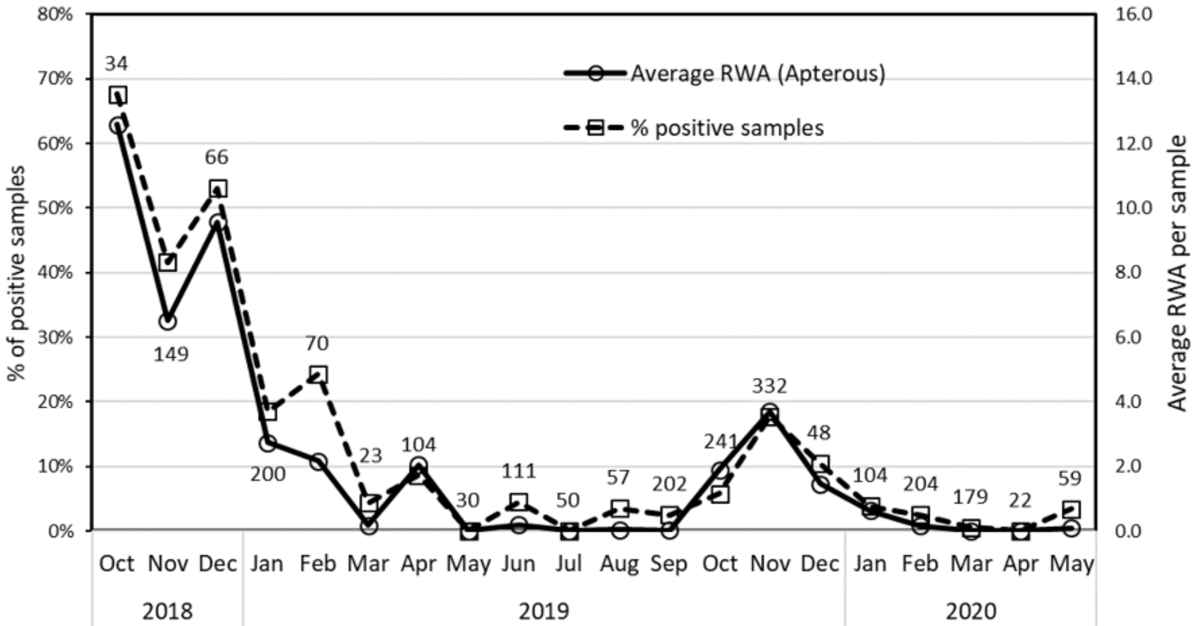

Figure 4. Dynamics of the percentage of positive samples (dotted line, left axis) and average RWA per sample (Solid line, right axis) over time in SA. Samples were 2 litres of grass extracted in a Berlese funnel. Numbers above markers show number of samples taken per month. n = 2285

Barley grass (*Hordeum leporinum*) and (to a lesser extent) Brome grasses (*Bromus* sp.) were the host plants that showed the highest combination of abundance, positive RWA detection frequency and aphid numbers. These introduced species are not summer active in low rainfall areas. In low rainfall areas, the native *Enneapogon nigricans* (bottle-brush) is the most important summer refuge because of its widespread distribution (207 samples collected from 135 sites) and summer growth pattern. Grazing and water availability (irrigation) can make some host grass populations, including prairie grass, couch grass, ryegrass and volunteer cereals, persist in summer. The presence of irrigated crops increased the likelihood of RWA detections 1.6-fold over the green bridge.

Early rainfall in late summer/autumn, 2-3 months before sowing, could cause RWA population to build up on grasses and cereal regrowth, potentially exacerbating early crop invasions. A 250 mm high rainfall event in the Birchip area (Vic) in December 2018 did cause significant development of a green bridge, but did not seem to result in increased RWA risk. Reports in 2020 from the Port Augusta area (SA), where a significant summer rain occurred on February 1st, suggested an increase in RWA pressure. This shows that observations, especially in early break years and better understanding of aphid population dynamics and migration on the green bridge before and after sowing, are needed to obtain more precision on the impact of the green bridge and the risk and timing of crop invasion.

A ‘wetter’ year with a higher green bridge, or if immigration of aphids occurs at a higher level for some other reason, might increase aphid colonisation, but will not automatically result in higher impact of RWA. Wetter and colder conditions are less favourable for RWA development in the crop (as can be seen from the Tasmanian trials), through a combination of slowing down population development, improving the crop development which will better resist RWA, and more tillering (diluting the aphid numbers over a lower % of tillers. The two experimental years experienced generally low levels of growing season rainfall, so RWA development in the crop (after inoculation) was probably maximal on these often drought stressed crops.

Crop sensitivity: Similar yield impact and aphid population *development* was observed for all crops tested, except for oats which is known not to be an RWA host. However, crop and varietal differences in RWA *establishment* are likely to exist and have been reported. Also, the crop condition (growth stage, level of tillering, drought stress, nutritional stage) will play a role in RWA *development* and could change the probability of reaching above threshold populations.

Conclusions

RWA ecology and yield impact in Australia are now somewhat better understood. This allows growers and agronomists to manage RWA more sustainably and economically. Management based on observations and regionally adapted decision rules, rather than an over-reliance on prophylactic seed treatments, will increase profitability, minimise chemical inputs and reduce off-target risks and resistance development.

The two years during which this study was done were very dry, with hot summers and growing seasons, and were generally unfavourable for RWA survival over summer, but favourable for the development of RWA in the inoculated trials (Baugh and Phillips 1991, De Farias et al. 1995). Some anecdotal observations in 2020, and in the few years that RWA is known to be present (since 2016, Ward et al 2020, Yazdani et al 2018), do suggest that the population levels will be very different (but not necessarily more damaging) with different rainfall patterns. More experience and research are needed to better understand RWA ecology and would enable further improvement to management guidelines.

The geographical distribution of RWA is expected to increase further into northern NSW and Queensland (Avila et al. 2019), and RWA was detected in Western Australia in 2020. Different growing conditions (temperature, drought) and presence of other cereal crops, including summer cereals (rice, corn, sorghum, millet), and other grass hosts could alter the risk of RWA in those regions.

Acknowledgements

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Additional resources

https://grdc.com.au/resources-and-publications/resources/russian-wheat-aphid

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

Grazing cattle on dual purpose crops - managing health risks

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Key words

ruminal acidosis, bloat, polioencephalomalacia, buffers, fibre

Take home message

- Cattle grazing dual purpose crops can be a highly profitable option
- Cattle are more susceptible than sheep to livestock forage disorders, including; nitrate toxicity, acidosis, bloat and polioencephalomalcia (induced thiamine deficiency)
- Cattle grazing dual purpose wheat should be supplemented with minerals
- Cattle grazing dual purpose canola should be adapted onto the crop to ensure that rumen adaptation occurs.

Opportunities for cattle on dual purpose crops

The use of dual purpose crops has been well established across the mixed farming zone for more than a decade. Commonly, grazing has occurred with sheep enterprises and has dramatically changed the feed budget on mixed farms, significantly reducing the winter feed gap. Research and uptake of dual purpose crops has occurred primarily with sheep. In the mixed farming zone, sheep are the dominant livestock enterprise. Greater use of dual purpose crops on farms by sheep is unlikely and therefore growers are missing out on utilising the potential of large amounts of forage production. This is because at the time of grazing (May-July) it is common that ewes are pregnant or have recently lambed. There is limited market for young sheep for a grower to expand and respond to large amounts of feed that might be available. In comparison, at that time of year there are often a significant number of young cattle requiring feed either in the saleyards or being hand fed on grazing properties. Research conducted on dual purpose crops with cattle grazing has demonstrated high cattle liveweight gains, with the practice generally safe to livestock. Commercially, cattle have been grazed on wheat and canola dual purpose crops, but there have been some examples of poor cattle health outcomes.

Cattle production from dual-purpose crops

The potential for producing very large amounts of forage from dual purpose crops is high due to the large area for producing these crops. Currently within the mixed farming zone in southern Australia only 10-20% of crop land is utilised as dual purpose. If this area was increased by another 10% in the wheat sheep zone and 50% in the high rainfall zone then approximately 2.2 M head of cattle could be grazed across southern Australia.

Available feed is the driving force behind cattle production on dual purpose crops. Experiments conducted with yearling cattle grazing wheat and canola dual purpose crops have regularly exceeded growth rates of 2 kg/hd/day (McCormick et al., 2020). There is an opportunity to produce large amounts of forage during winter by increasing the area of dual purpose crops sown on a mixed farm leading to an opportunity to either agist or trade in cattle. Calculating a simple gross margin for trading young cattle that includes costs such as transport, agent fees and death rates, indicates that a gross margin per hectare could be \$342-\$945/ha with a buy/sell price of 350 c/kg liveweight just for the cattle enterprise.

Dual purpose crop agronomy for forage and grain production

Achieving high forage production in dual purpose crops relies on good agronomic planning and management including:

- Paddock selection. Select paddocks with low weed pressure as weeds in dual purpose crops can be difficult to manage.
- Control summer weeds. Maintain weed free fallows over summer which will conserve soil water and nitrogen and enable early sowing.
- Select appropriate cultivars. Early sowing of dual purpose crops requires the selection of cultivars with true winter requirement.
- Sow early. Sowing of dual purpose canola can commence from February whereas wheat can start from March depending on soil moisture. Need to be ready to sow when the opportunity is available. Increase sowing rate to ensure good density of plants (>150 plants/m^2 for wheat and >40 plants/m^2 canola)
- Fertiliser use. Dual purpose crops require nitrogen to produce forage. Total nitrogen supply available at sowing for dual purpose wheat and canola should be 100-150 kgN/ha.
- Starting grazing. Grazing can be initiated when the crops will not be pulled from the ground by the cattle commonly this is when wheat has 4-5 leaves and canola has 6-8 leaves. This can occur anywhere from March to June depending on the season with canola commonly grazed before wheat.
- Finishing grazing. The completion of grazing depends on crop growth stage (up to commencement of stem elongation) and is affected by location and cultivar. Winter canola types tend to elongate the stem from mid-late July, while winter wheats tend to elongate during August. Crops can be grazed for longer periods but the residual crop after grazing needs to keep increasing the later the grazing period.
- Stocking rate. Young cattle (approx. 200kg/head) can be grazed at 2-3 head/hectare depending on forage availability. This means that crops could be grazed from 60-90 days with 2-3 young cattle (120-270 cattle grazing days per hectare).
- Nitrogen top-dressing. It is beneficial to top-dress nitrogen after the grazing period to aid in crop recovery and grain yield. Top-dressing before or during grazing is not recommended due to nitrate toxicity.

Risks for cattle on dual purpose crops

Some cattle have died from a range of livestock diseases as a result of feeding on dual purpose crops. Cattle are more susceptible than sheep to many forage induced diseases, so it is critical that the grower understands and manages the risks associated with grazing dual purpose crops.

Nitrate toxicity

Nitrate toxicity can occur in ruminants when cattle consume plants that have accumulated nitrate. Within the rumen, nitrate is converted to nitrite and then to ammonia. High nitrate levels in the plant lead to a high conversion of nitrite, which results in it being directly absorbed into the bloodstream. Here it binds with haemoglobin preventing oxygen from binding and being transported around the body which in turn starves the animal of oxygen.

Within the plant, nitrate is transported within the vascular network and is converted to amino acids in the plant cells. Nitrate can start to accumulate to high levels within the vascular network when the conversion from nitrate to amino acids slows. Nitrate toxicity can be a particular concern in broadleaf leaf crops like dual purpose canola. It has been demonstrated that the stem and petiole have much higher levels of nitrate than the leaf lamina. McCormick et al., (2020) measured nitrate levels of 4465 and 13847 mg/kg in the stem and petiole respectively, compared to 1155 mg/kg in the leaf lamina. A critical value for nitrate where the risk of nitrate toxicity greatly increases has been determined at 5000 mg/kg dry matter (Hibbard et al., 1998).

The use of high levels of nitrogen fertiliser can exacerbate nitrate accumulation as can climate conditions that limit photosynthesis, such as drought stress, cloudy days or cold temperatures. In these situations, nitrate accumulates in the plants vascular network which can lead to higher levels of nitrate intake by livestock. Practices that reduce the risk of nitrate toxicity include not applying high levels of nitrogen fertiliser and delaying grazing until the plant is more mature, as nitrate tends to dilute in plants as they develop. Undertaking a period of adaptation reduces cattle's sensitivity to nitrate levels. In canola crops, having high forage availability and a lower stocking rate will enable livestock to select the leaf lamina and therefore reduce the risk of nitrate toxicity.

Acidosis

Acidosis is a cause of major health problems and production losses that occur in ruminants grazing cereals or canola. It is related to rumen pH depression. The rumen is a large microbial fermentation vat which produces a range of volatile fatty acids (VFA). VFAs are absorbed through the rumen wall and are the main source of energy for cattle. The rumen microbial population is sensitive to pH. Changes in pH result in changes to the VFA profile. Ruminal acidosis can occur with any dietary intake high in rapidly fermentable carbohydrate and low in fibre. Forage with high crude protein concentrations, which result in high rumen ammonia concentrations, can prevent the pH depression that would otherwise occur with a poorly buffered, low fibre intake that is high in water soluble carbohydrates. However, feed with lots of rapidly fermentable carbohydrate that lack sufficient roughage to generate a substantial flow of salivary bicarbonate, can overwhelm the alkalinising effect of the elevated rumen ammonia, leading to acidification. This combination of forage characteristics is a potent stimulant for lactic acidosis. Sub-acute ruminal acidosis can occur simply due to the rapid production of volatile fatty acids (VFA) in excess of rumen absorptive capacity, particularly in cattle newly introduced to a greater availability of lush forage. There is a strong inverse relationship between VFA concentration and rumen pH (Figure 1) – i.e. as rumen pH decreases, total rumen VFA concentration increases.

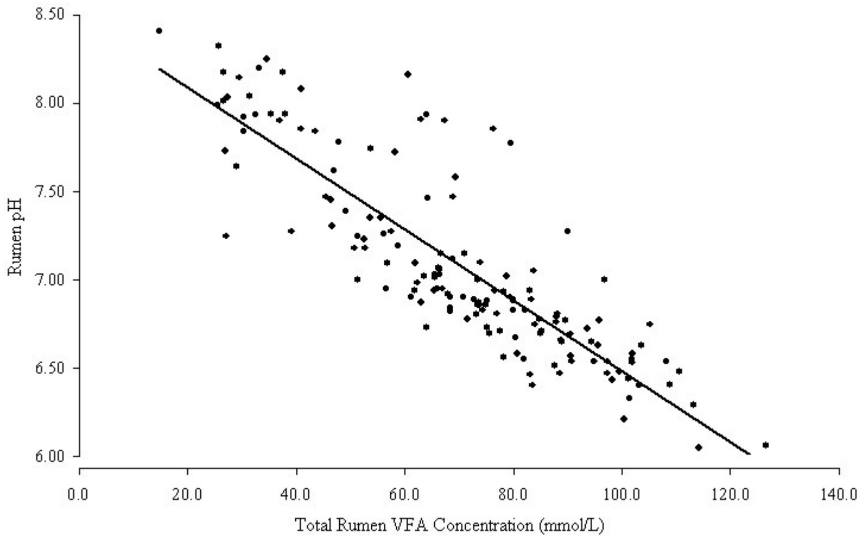

Figure 1. Relationship between total concentration of rumen VFA and rumen pH ($r^2 = 0.742$, $P<0.001$; Packer 2010).

Further research is required with cattle, but growth rate has been increased in lambs grazing cereals that were supplemented with a rumen buffer and an alkalinising agent (MgO and $CaCO_3$; Grain and Graze projects, Dove and Kelman 2015). This suggests that rumen pH might drop sufficiently in forage ruminal acidosis to reduce fermentation efficiency i.e. below 5.6 where the molar proportion of propionate starts to decline (Figure 2). The use of therapeutic agents, such as the ionophores (monensin, salinomycin or lasalocid), that select against lactate producers. If we can reduce this pH drop without significantly diluting dietary nutrient density, we might achieve cost effective increases in growth rate with cattle, as was observed with lambs.

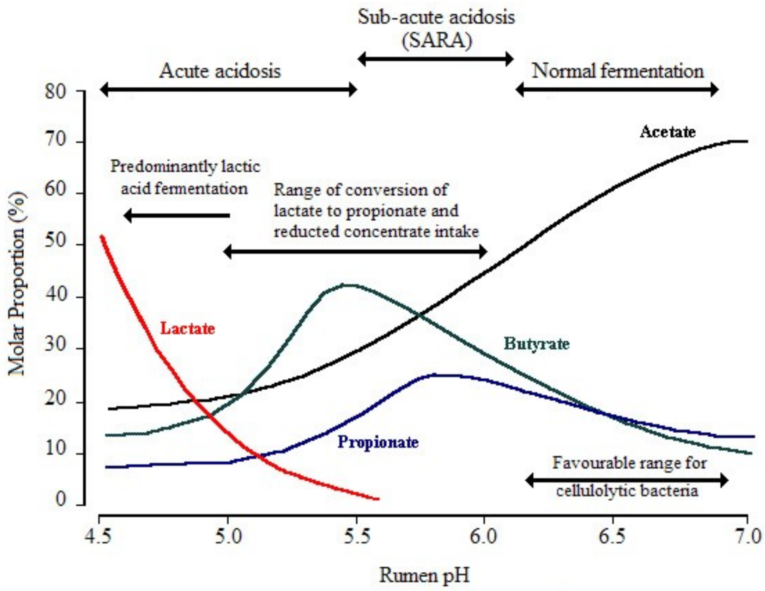

Figure 2. Changes in molar proportions of VFA at with changing pH as presented by Packer (2010) BVSc honours thesis.

Rumen pH depression not only results in direct mortalities and sub-clinical reduction in growth rate and feed efficiency, but it also predisposes ruminants grazing lush forages to bloat and polioencephalomalcia (PEM).

Bloat

The bloat seen when grazing dual purpose canola and cereal crops differs from bloat seen when grazing legumes. The bloat that occurs when grazing dual purpose canola and cereals, does not involve the specific chloroplast proteins that contribute to the formation of a stable foam in legume bloat, although intake of a legume (with these proteins), in addition to the lush forage of a canola/cereal crop could exacerbate the condition. Bloat on lush canola/cereal forages occurs as a result of the rumen contents being more viscous at lower pH, and the contribution of the slimy capsule of *Streptococcus bovis* to the formation of a stable foam. *Streptococcus bovis* overgrows at the expense of its neighbours in the rumen microbial ecosystem when rumen pH is low enough (< 5.6) for long enough, and it produces lactic acid, which is a 10 x stronger acid than the VFA's.

Polioencephalomalacia

Polioencephalomalacia (PEM) occurs due to an induced thiamine (vitamin B1) deficiency. A healthy rumen microbial ecosystem provides the ruminant's requirements for thiamine. However, when there is a high dietary intake of sulphur and when rumen pH is depressed, the rate at which thiamine is destroyed can exceed production and lead to a deficiency in thiamine and PEM. PEM can cause symptoms such as blindness, seizures or holding their head in an unusual position (stargazing). An acidic rumen increases the likelihood of PEM by increasing the release of a thiaminase exoenzyme through acid shocking of certain species of rumen bacteria. An acidic rumen also increases the rate of thiamine destruction by sulphite which is produced from the bacterial reduction of sulphate. Rumen bacteria also reduce sulphate to sulphite, therefore high dietary intakes of sulphate (e.g. from grazing brassicas) can have thiamine-antagonistic activities. Canola crops are often fertilised with sulphur. It is likely that this could increase the risk of PEM as the plants would have higher sulphur levels, although this has not been demonstrated with research.

Management practices to reduce forage disorders

Managing cattle grazing dual purpose crops requires an understanding of the animal health risks and regular observations to ensure a successful outcome. General rules regarding the introduction of a new feed source to cattle should always ensure that the cattle are always full. Hungry cattle are highly susceptible to changes in diet and gorging themselves on unfamiliar forage. One way to enable this is to introduce the livestock to a new forage mid-morning. Cattle will tend to eat a large proportion of their daily intake early in the morning. Care should be taken if cattle are grazing very short pastures prior to introduction as they are likely to still be hungry. The supplementation of hay will enable this transition. There is no requirement to adapt cattle to dual purpose wheat over time. In comparison it is still recommended to adapt cattle to canola over a period of at least 4-6 days. This is because cattle have been known to avoid canola initially leading to hungry cattle. When they finally do start to eat the crop they are likely to gorge themselves leading to health problems. To adapt cattle onto canola it is worth introducing them initially for 2-3 hours and increase the time by 2-3 hours each day. It is critical to observe that the cattle are eating significant amounts of canola before allowing them to be on the crop full time.

Mineral supplementation in wheat

Supplementation of sheep on dual purpose wheat is standard practice. Wheat is deficient in sodium (Na) and magnesium (Mg) for ruminant livestock production. Lime has also showed benefit through supplying calcium (Ca) to the livestock. While there are only limited studies in beef cattle, McCormick et al., (2021) demonstrated a cattle response to mineral supplementation in two out of three experiments, with liveweight gains of up to 27%. The supplement cost 4.5c/hd/day for a cattle liveweight increase of 0.5 kg/hd/day. It is recommended that cattle grazing wheat should be supplied with a loose-lick mineral supplement consisting of salt (NaCl), Causmag® (MgO) and lime ($CaCO_3$) (1:1:1 by weight, as-fed), offered *ad libitum* (at all times). Mineral supplementation with cattle grazing canola has not been tested, but previous research in sheep demonstrated a decrease in liveweight gain.

Liveweight lag period in canola

It has been identified that both sheep and cattle undergo a lag phase of liveweight gain for 1-2 weeks after introduction to dual purpose canola (McCormick et al., 2021). This can occur from cattle avoiding the canola crop, as many cattle in Australian grazing systems are not familiar with brassica grazing crops, or due to rumen adjustment. If cattle avoid eating the crop, this can increase the risk of other conditions such as bloat, as they are not adapted to the crop. The lag phase occurs even when cattle are adapted to the crop over a period of time. Practically this means that cattle should be grazed on canola for at least a month to enable weight gain to catch up.

Use of roughage

The use of roughage is a common risk management strategy to avoid animal health problems in cattle. No research has been conducted on the requirement of roughage when cattle graze dual purpose crops. From experience, there is generally no need to add roughage to cattle grazing dual purpose cereal crops. Due to the higher risk of forage disorders in cattle grazing canola, roughage has generally been recommended as a risk management strategy. Growers should be aware that a potential outcome of using roughage during grazing is that liveweight gains can be reduced. This is due to the reduced forage crop intake as the roughage can part fill the rumen. This effectively dilutes the nutrient intake of the livestock.

Best management practice for cattle on dual purpose crops

To minimise the risk of cattle health problems grazing dual purpose crops it is suggested to:

- Ensure stock are not introduced to a new paddock when hungry. Fill them with a fibre source before introduction – we seek a compromise between quality and fibre, therefore good quality cereal hay is recommended
- Introducing cattle to the crop mid-late morning during the adaptation period will reduce the risk of cattle gorging themselves
- Cattle should be adapted onto dual purpose canola to ensure they are eating the crop and to allow time for rumen adjustment
- Supply mineral supplements for cattle grazing dual purpose wheat
- Reduce pre-sowing sulphur fertilisers for dual purpose canola to reduce the risk of PEM
- Research has found low nitrate levels in the canola leaf, so ensuring that that there are high forage levels available will allow animals to select the leaf and reduce the risk of nitrate toxicity
- Provide hay in the paddock for dual purpose canola to allow cattle to select different forage. This will enable cattle to substitute hay for canola in the diet and increase dietary fibre levels. Be aware that this may result in nutrient dilution
- During the adjustment period the cattle need to eat the crop. If they are grazing fence lines or any other non-crop areas during the adjustment period, it is unlikely the animals have been adjusted
- Supplementation with palatable buffers, alkalinising agents or therapeutic agents can be used to reduce acidosis although limited research has occurred with cattle on dual purpose crops

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Fungicide resistance in cereals – problem pathogens and strategies to deal with them

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Key words

disease management strategies, integrated disease management (IDM), fungicide resistance, septoria tritici blotch (STB), net form of net blotch (NFNB), Group 11 quinone outside inhibitors - QoI (strobilurins) and Group 7 succinate dehydrogenase inhibitors (SDHIs), fungicide resistance

GRDC codes

FAR2004-002SAX, FAR00003, AFREN project (Australian Fungicide Resistance Extension Network) CUR1905-001SAX

Take home messages

- In seasons that favour higher yield potential, one of the most important components in growing high yielding cereal crops is disease management
- Where genetic resistance in a wheat cultivar is not sufficient to delay fungicide decisions until flag leaf emergence (GS37-39), look to target the following three key timings for fungicide intervention; first node GS31, flag leaf emergence GS39 with an optional third application at head emergence GS59
- In barley two timings are essential in order to maximise returns with an option for seed treatment in high disease pressure scenarios. These timings were identified as GS31 and awn tipping (GS49)
- Avoid repeated use of the same fungicide active ingredients, and in the case of the newer Group 11 QoI (strobilurins) and Group 7 SDHIs, where possible restrict strategies to just one application per season in order to slow down and help prevent the selection of resistant strains.

Hyper Yielding Crops research – the importance of disease management

Led by Field Applied Research (FAR) Australia, the Hyper Yielding Crops (HYC) project is a Grains Research and Development Corporation (GRDC) national investment (commenced 1 April 2020) which aims to push the economically attainable yield boundaries of wheat, barley and canola in those regions with higher yield potential. HYC builds on the success of the GRDC's four-year Hyper Yielding Cereals project in Tasmania, which demonstrated that it is possible to significantly increase yields through sowing the right cultivars and effective implementation of appropriately tailored management strategies. Whilst the project team is clearly aware that Tasmania is not mainland Australia, they believe there are some common threads to the research that could benefit this mainland HYC initiative.

The first is the ability to operate a research centre that can look at all the latest developments in germplasm and agronomy in one location. Five HYC research sites across the higher yielding regions of southern Australia (NSW, WA, SA, VIC and TAS) have been established to engage with growers and advisers. With the 25 focus farms and the newly introduced HYC awards, these have been targeted to scale up the results and create a community network aimed at lifting productivity.

Results from the first year of HYC research trials are currently being harvested and processed at the time of writing, however there are some early learnings and results from the previous Hyper Yielding Cereals project in Tasmania that illustrate the importance of disease management when yield potential is higher. The introduction of new fungicide technology over the last five years has increased our ability to secure a greater proportion of our yield potential in more disease prone seasons. The more extensive armoury of fungicides comes with an increased responsibility to protect our fungicides from the development of fungicide resistance and reduced sensitivity. One of the key measures we can adopt to slow down the development of fungicide resistance is to use fewer fungicides. In order to do this the industry needs the evidence that germplasm and other integrated disease management (IDM) measures can be adopted with equal profitability as multiple fungicide applications. With some growers and advisers using up to five fungicides in the 2020 season, HYC research has set out to maximise yield with the use of fewer fungicides, focusing on regions where yield potential is inherently higher.

Critical role of disease management in protecting higher yield potential in better seasons

Disease management is one of the most important components of growing high yielding cereal crops in seasons with higher yield potential or in high rainfall zone (HRZ) regions that inherently have higher yield potential. This is primarily a result of the growing season being longer, wetter and more conducive to disease development In previous Hyper Yielding Cereals research work in Tasmania, in wheat it was found that three key timings for fungicide intervention were essential to protect the upper leaves of the canopy, capture the highest yields and provide the highest economic returns; these were first node growth stage (GS) 31, flag leaf emergence (GS39) and head emergence (GS59). In barley two timings were essential; GS31 and awn tipping (GS49). In HYC 2020 research trials our objective has been to examine whether newer cultivars suitable for high yielding regions (correct phenology and standability) might allow us to delay fungicide intervention and therefore use fewer fungicide applications. If a cultivar has sufficient genetic resistance to prevent disease development, it may be possible to delay fungicide application until flag leaf emergence or at least later into stem elongation (GS33-37). This has two primary benefits; firstly, it allows a much better appraisal of whether the seasonal conditions have the potential to support fungicide expenditure and secondly it means that a fungicide can be applied to more of or all of the upper canopy leaves at the same time. In those seasons where the spring progressively cuts out it means the flag leaf spray expenditure could be cut back or removed altogether. However, the industry needs good genetic resistance in our high yielding cultivars to make this a reality.

Results processed so far in HYC research in southern NSW (Table 2) and southern Victoria (Table 3) show not only the significant influence of disease management but also the large differences in genetic resistance to disease. In a season with higher yield potential and higher disease pressure (primarily Stripe rust (pt. 198 E16 A+ J+ T+ 17+), Septoria tritici blotch and lower levels of leaf rusts at both locations), all wheat cultivars gave a significant yield response to fungicide application, but where cultivars had greater genetic resistance there was no statistical yield difference between a single unit of fungicide (where the flag leaf spray was based on a full rate azoxystrobin/epoxiconazole mixture (Radial® 840 mL/ha) compared to where plots were kept free of disease.

Table 1. Treatment and management applied to 2020 trials.

Plant pop'n:		**180 seeds/m^2 (150 plants/m^2 target) - all three managements**		
	Timing	**Untreated**	**1 fungicide unit**	**4 fungicide units**
Seed treatment:		Vibrance®/Gaucho®	Vibrance/Gaucho	As per 1 F unit + Systiva®
Basal Fertiliser:	21 April	120kg MAP (12 Kg N)	120kg MAP (12 Kg N/ha)	120kg MAP (12 Kg N/ha)
Nitrogen:	18 June	40kg N/ha	40kg N/ha	40kg N/ha
	29 July	70kg N/ha	70kg N/ha	70kg N/ha
Total N Applied:		122kg N/ha	122kg N/ha	122kg N/ha
Fungicide:	GS31	---	---	Prosaro® 300 mL/ha
	GS39	---	Amistar Xtra® 800 mL/ha	Amistar Xtra 800 mL/ha
	GS59-61	---	---	Opus® 125 500 mL/ha

Table 2. Influence of fungicide strategy and cultivar on wheat grain yield (t/ha) – HYC Wallendbeen, NSW. (S.trt = seed treatment)

	Varietal yield under different levels of disease management					
	Untreated		**1 fungicide unit** (GS39)		**4 fungicide units** (S.trt, GS31,39, 61)	
Cultivar	**Yield (t/ha)**		**Yield (t/ha)**		**Yield (t/ha)**	
Trojanɸ (spring)	2.28	n	7.55	hij	8.13	efg
Scepterɸ (spring)*	7.07	kl	8.60	d	8.55	de
Nighthawkɸ (facultative)	7.98	gh	8.47	def	8.54	de
Annapurna (winter)	9.69	c	10.22	b	10.46	ab
RGT Accroc (winter)	9.72	c	10.86	a	10.83	a
Beckomɸ (spring)	7.75	ghi	8.46	def	8.66	d
Catapultɸ (spring)	6.06	m	7.84	ghi	8.46	def
EGA Gregoryɸ (spring)	6.75	l	7.15	jkl	7.40	ijk
Coolahɸ (spring)	7.26	jk	8.07	fg	8.75	d
DS Bennettɸ (winter)	5.68	m	8.75	d	9.48	c
LSD Cultivar x Man. p=0.05	0.45 t/ha		P val		<0.001	

** Scepter was unaffected by wheat powdery mildew at this site.*
Winter = winter wheat, spring = spring wheat, Facultative – can be grown as winter or spring wheat (depending on sowing date).
Yield figures followed by the same letter are not considered to be statistically different (p=0.05).

Table 3. Influence of fungicide strategy and cultivar on wheat grain yield (t/ha) – HYC Gnarwarre, VIC (Results with the same letter after them do not significantly differ. S.trt = Seed treatment)

	Varietal yield under different levels of disease management					
	Untreated		1 Fungicide unit (GS39)		4 Fungicide units (S.trt, GS31,39, 61)	
Cultivar	**Yield t/ha**		**Yield t/ha**		**Yield t/ha**	
Trojan⏀ (spring)	2.14	p	2.90	o	8.97	d-g
Scepter⏀ (spring)	5.82	n	7.87	jkl	8.78	efg
Nighthawk⏀ (facultative)	7.21	m	7.60	lm	8.11	jk
Annapurna (winter)	8.30	hij	8.97	d-g	9.23	b-e
RGT Accroc (winter)	7.85	jkl	9.13	c-f	9.58	abc
RGT Calabro (winter)	7.67	klm	8.63	gh	8.95	efg
SFR 86-090 (winter)	5.94	n	9.15	c-f	9.82	a
Tabasco (winter)	7.67	klm	7.81	kl	8.11	ijk
SF Adagio (winter)	8.71	fgh	9.67	ab	9.44	a-d
SQP Revenue⏀ (winter)	5.71	n	7.92	jkl	8.58	ghi
LSD Cultivar x Man. p=0.05	0.47 t/ha		P val		>0.001	

Winter = winter wheat, spring = spring wheat, Facultative – can be grown as winter or spring wheat (depending on sowing date).
Yield figures followed by the same letter are not considered to be statistically different (p=0.05).

Plot yields: To compensate for edge effect in the outside rows of the plot, yields are calculated on plot area that is larger than the area occupied by the plot itself (approximately half the plot gap either side (0.225m) is added to the plot width (1.575m) giving a total width of 2.025m. . All provisional results have been analysed through ARM software with further analysis when the final results are released.

2020 was a high disease pressure year. The yield data was reflective of the level of disease, diseases present, and variety interactions experienced. Disease data was not available at the time of developing the paper and it will be discussed in the Update presentation and added to this paper online after the Update. The online paper will be available at https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2021/02/fungicide-resistance-in-cereals-problem-pathogens-and-strategies-to-deal-with-them.

So how can we maximise productivity and minimise fungicide resistance development in seasons of high disease pressure?

Firstly, we need to know which are the most problematic pathogens for resistance development. While it's advisable to adopt integrated disease management (IDM) principles for all diseases, some pathogens are more problematic than others. In Australia, the more problematic pathogens for resistance are powdery mildew in wheat (WPM) and barley (BPM), net blotches in barley (both spot and net form) and Septoria tritici blotch (STB) in wheat (Table 4). In addition, the risk of resistance development in these pathogens varies with fungicide mode of action.

- Group 11 QoIs (strobilurins) are at the highest risk of pathogen resistance development, particularly the pathogens responsible for Septoria tritici blotch (STB) in wheat and powdery mildew. Note at present in Australia it's the wheat powdery mildew pathogen that is affected; globally both WPM and STB pathogens have resistance affecting QoI performance.
- Group 7 SDHIs are at moderate to high risk of resistance development in the pathogen with evidence in New Zealand and Europe of pathogen shifts in sensitivity to Ramularia leaf spot in barley and net blotch and STB in Europe. Net blotch pathogens are currently our biggest issue in Australia.
- Group 3 DMIs Demethylase Inhibitors (DMIs – triazoles) are generally considered at low to moderate risk, however recent developments in WA in the net blotch pathogen have challenged this view.

Table 4. Fungicide resistance and reduced sensitivity cases identified in Australian broad acre grains crops.

Disease	Pathogen	Fungicide group	Compounds affected	Region	Industry implications
Barley powdery mildew	*Blumeria graminis* f.sp. *hordei*	3 (DMI)	Tebuconazole, propiconazole, flutriafol	Qld, NSW, Vic, Tas, WA	Field resistance to some Group 3 DMI fungicides
Wheat powdery mildew	*Blumeria graminis* f.sp. *tritici*	3 (DMI)	None	NSW, Vic, Tas	This is a gateway mutation. It does not reduce the efficacy of the fungicide but is the first step towards resistance evolving.
		11 (QoI)	All group 11	Vic, Tas, SA	Field resistance to all Group 11 fungicides
Barley net-form of net blotch	*Pyrenophora teres* f.sp. *teres*	3 (DMI)	Tebuconazole, propiconazole, prothioconazole	WA	Reduced sensitivity that does not cause field failure
		7 (SDHI)	Fluxapyroxad, bixafen	SA (Yorke Peninsula)	Reduced sensitivity or resistance depending on the frequency population.
Barley spot-form of net blotch	*Pyrenophora teres* f.sp. *maculata*	3 (DMI)	Tebuconazole, epoxiconazole, propiconazole	WA	Field resistance to old generation Group 3 fungicides
		7 (SDHI)	Fluxapyroxad, bixafen	WA (Cunderdin region)	Reduced sensitivity identified in 2020
Wheat septoria leaf blotch	*Zymoseptoria tritici*	3 (DMI)	Tebuconazole, flutriafol, propiconazole, cyproconazole, triadimenol	NSW, Vic, SA, Tas	Reduced sensitivity that does not cause complete field failure

Table 3 definitions

Reduced sensitivity: Fungi are considered as having reduced sensitivity to a fungicide when a fungicide application does not work optimally but does not completely fail. In most cases, this would be related to small reductions in product performance which may not be noticeable at the field level. In some cases, growers may find that they need to use increased rates of the fungicide to obtain the previous level of control. Reduced sensitivity needs to be confirmed through specialised laboratory testing.

Resistant: Resistance occurs when the fungicide fails to provide an acceptable level of control of the target pathogen in the field at full label rates. Resistance needs to be confirmed with laboratory testing and be clearly linked with an unacceptable loss of disease control when using the fungicide in the field at full label rates.

Where the cultivar's susceptibility to disease prevents delaying fungicide application until flag leaf (or later in stem elongation) and earlier fungicide intervention is needed (e.g. GS31) to secure the higher yield potential, it's important that we adhere to sound anti resistance measures. These include avoiding repeated use of the same active ingredients/products and in the case of the newer Group 11 QoI (strobilurins) and Group 7 SDHIs, also avoid repeating the same mode of action. This is frequently easier said than done in longer season scenarios, since many of the fungicides with better efficacy are also important co-formulation partners in fungicide mixtures carrying two modes of action. However, focussing on the key physiological timings that protect the upper canopy leaves will ensure that the number of applications is not excessive, usually no more than two applications or three at most is sufficient with the most susceptible scenarios.

Anti-resistance measures when using fungicides as part of an integrated disease management (IDM) strategy

- With wheat and barley crops where two to three applications of fungicide are applied, avoid repeat applications of the same product/active ingredient and where possible also avoid the same mode of action in the same crop. This is particularly important when using Group 11 QoI (strobilurins) and Group 7 SDHIs, which preferably would only be used once in a growing season
- Avoid using the seed treatment fluxapyroxad (Systiva®) in successive years in barley and rotate with foliar fungicides of a different mode of action during the season
- Avoid applying the same DMI (triazole) Group 3 fungicide twice in a row, irrespective of whether the DMI is applied alone or as a mixture with another mode of action
- Avoid the use of tebuconazole alone and flutriafol for STB pathogen control, as these Group 3 DMIs are more affected by reduced sensitivity strains than other DMIs
- Group 3 DMIs (for example; triazoles e.g. epoxiconazole (Opus®) or triazole mixtures (e.g. prothioconazole and tebuconazole (Prosaro®)) used alone are best reserved for less important spray timings, or in situations where disease pressure is low in higher yielding scenarios
- With SDHI seed treatments such as fluxapyroxad (Systiva®) or QoI fungicides used in-furrow such as Uniform® containing azoxystrobin, consider foliar fungicide follow ups which have a different mode of action, and therefore, avoiding if possible, a second application of SDHI or QoI fungicides.

Influence of fungicide rate

Growers and agronomists frequently ask the question whether dose rates have an impact on how likely fungicide resistance is to evolve. Resistance comes in many forms and trying to manipulate rates with fungicides should not be seen as the core resistance management strategy. The reality is that using the most appropriate rate for effective disease control is the best strategy for managing resistance. Label rates have been developed to provide robust and reliable control of the target disease.

In many cases the full label rate is the most appropriate rate for control. However, for some diseases, the lower rate from the label range of a fungicide can be used in conjunction with a crop variety that has a good disease resistance rating because disease pressure will be lower. Contrary to what happens with herbicides, there is evidence that by using a higher rate than necessary increases the risk of resistance, as removing more sensitive individuals from the population provides more opportunity for resistant individuals to dominate the population and hence be the main strain that colonises the plant. This is particularly the case with Group 11 QoIs and Group 7 SDHIs fungicides.

Clearly, the best way to avoid fungicide resistance is not to use fungicides! However, in high disease pressure regions, this would be an unprofitable decision. When a cultivar's genetic resistance breaks down or is incomplete, it is imperative that growers and advisers have access to a diverse range of effective fungicides (in terms of mode of action) for controlling the disease. Hence, we need to protect their longevity. In order to protect them, one of the most effective measures is to minimise the number of fungicide applications applied during the season. Therefore, consider all aspects of an Integrated Disease Management (IDM) strategy including selection of crop varieties with higher levels of genetic resistance to key diseases when putting your cropping plans together at the start of the season.

Principle components of IDM

Rotations – where possible avoid high risk rotations for disease, for example, barley on barley or wheat on wheat.

Seed hygiene – minimise the use of seed from paddocks where there were high levels of disease that could be seedborne (e.g. Ramularia, net form net blotch).

Use cultivars with higher resistance ratings particularly when sowing early. Where this is not possible delay the sowing of the most susceptible cultivars to reduce disease pressure where the phenology of the cultivar is adapted to the later development window.

Cultural control such as stubble management, where disease risks are high and the penalties for stubble removal are not as high.

Grazing early sown cereal crops up to GS30 to reduce disease pressure.

AFREN (Australian Fungicide Resistance Extension Network)

The Australian Fungicide Resistance Extension Network (AFREN) was established to develop and deliver fungicide resistance resources for grains growers and advisers across the country. It brings together regional plant pathologists, fungicide resistance experts and communications and extension specialists.

AFREN wants to equip growers with the knowledge and understanding that they need to reduce the development and manage the impacts of fungicide resistance in Australian grains crops.

As members of AFREN, the authors of this paper are keen to hear if you believe you are encountering reduced sensitivity or resistance in your broad acre crops.

Investment acknowledgement

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Collaborating partners acknowledgement

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We would also like to acknowledge the work of our co-workers and collaborators in AFREN, in particular Dr Kylie Ireland and Dr Fran Lopez from the Centre for Crop and Disease Management (CCDM).

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Wheat rust developments - new stripe rust pathotypes with implications for wheat (common and durum) and triticale; pathotypes of leaf rust and virulence for resistance gene Lr24

Professor Robert F. Park, University of Sydney, Plant Breeding Institute

Key words

rust, common wheat, durum wheat, barley, triticale

GRDC codes

9175448; 9175952; 9176057

Take home messages

- The structure of stripe rust populations in eastern Australia has become more complex in recent years, particularly as a consequence of two further exotic rust incursions. This has had important implications for varietal response to stripe rust, not only in common wheat but also in durum wheat and triticale
- There have now been four documented incursions of stripe rust since it was first detected in Australia in 1979. Three of these originated from Europe (1979, 2017 and 2018) and one from North America (2002). This continues the trend that has emerged over the past 100 years of increasing frequency of exotic incursions, presumably associated with increased international movement of people and inadvertent transport of rust spores on contaminated clothing
- Exotic wheat rust incursions have cost the industry hundreds of millions of dollars. The critical importance of thoroughly laundering clothing and personal effects after interstate or overseas travel cannot be emphasised enough
- Stripe rust in particular is likely to be important during 2021 especially where summer rain supports inoculum carry over. Monitor for the presence of the green bridge, and if present, make sure it is destroyed at least 4 weeks before crops are sown, either by heavy grazing or herbicides
- The variability of rusts and their rapid spread across the Australian continent reinforces the importance of regular and nationally coordinated monitoring of these pathogens. As always, growers and other stakeholders are encouraged to monitor crops closely for rust over the break and in the 2021 season, and to forward freshly collected samples wrapped in paper only, to the Australian Cereal Rust Survey, at University of Sydney, Australian Rust Survey, Reply Paid 88076, Narellan NSW 2567.

Background

Developing new high yielding wheat varieties with in-built genetic resistance to rust diseases has been estimated to save the Australian grains industry some $1.1 billion per year. The resistance of varieties can, however, change due to the occurrence of a new pathotype (aka strain/race).

An important part of keeping one step ahead of the ever-changing fungal rust pathogens has been to monitor the pathotypes that occur in Australia, and to determine their impact on current and yet to be released varieties. This work has been conducted at the University of Sydney for the past 100 years, currently as a core component of the Australian Cereal Rust Control Program (ACRCP). It has been particularly successful in minimising the impact of new rust pathotypes that arise locally, via for example random mutation. In contrast, periodic incursions of wheat rust isolates from outside Australia have made resistance breeding more challenging.

While stem rust and leaf rust of wheat have been present in Australia since at least the first attempts to grow wheat, stripe rust was not detected until 1979 when it is believed it was inadvertently brought here from Europe on contaminated clothing or the like. A second stripe rust incursion was detected in 2002, into WA. In this case, the presumed origin of the new 'WA' ('134') pathotype group was North America.

Rust pathotypes and varietal resistance

Rust pathotypes are variants within a rust pathogen species that differ in ability to infect wheat varieties. They are similar to strains of viruses that infect people, except that differences in the animal and plant immune systems mean that they interact with their hosts differently:

- A person that is susceptible to a new virus strain **can** develop resistance
- A plant that is susceptible to a new rust pathotype **cannot** develop resistance

Our long-term monitoring of wheat rust populations in Australia have shown clearly that new pathotypes arise either via mutation (most commonly), exotic incursion (infrequent), or asexual hybridisation (rare).

Rust pathotypes are identified by applying rust from a field-collected sample to a set of indicator lines carrying different resistance genes. While this basic approach has not changed much in 100 years, rust pathotype identification has improved dramatically as our understanding of the genetic basis of resistance to these pathogens has improved. A landmark in this change was the publication in 1995 of a comprehensive atlas of rust resistance genes in wheat, by Professors McIntosh, Park, and Wellings, with support from the Australian Centre for International Agricultural Research. The book has become an international standard for wheat rust pathogen and rust resistance gene identification and was recently made freely available for download by funds provided by the Bill and Melinda Gates Foundation (see useful resources).

Wheat stripe rust

Wheat stripe rust pt. 239 E237 A- 17+ 33+

This stripe rust pathotype was first detected in rust samples collected from Victoria in November 2017. Although it was not detected in 2018 and only a single isolate was identified in 2019 (from Victoria), 15 isolates were recovered in the 2020 season from widespread locations throughout NSW.

Using DNA sequencing, we were able to determine that this pathotype belongs to a family of stripe rust pathotypes known as the PstS10 group. This is the most common group of wheat stripe rust pathotypes in Europe at present, strongly implicating this region as the origin of this pathotype.

Impact

The main varieties that have increased vulnerability to this pathotype include Coolah⏀, LRPB Flanker⏀, Axe⏀, B53⏀, Buchanan⏀, Cobalt⏀, EGA Gregory⏀, Forrest⏀, Gauntlet⏀, Grenade CL Plus⏀, Mitch⏀, Steel, Trojan⏀, Viking⏀ and Zen⏀.

Wheat stripe rust pt. 198 E16 A+ J+ T+ 17+

This stripe rust pathotype was first detected near Wagga Wagga in late-August 2018 and was subsequently isolated from Victoria and Tasmania that year. In 2019, it was isolated from throughout eastern Australia, where it was the most common pathotype of the wheat stripe rust pathogen. In 2020 it was once again the dominant stripe rust pathotype in eastern Australia (67% of all isolates processed), being isolated from all eastern mainland states.

DNA sequencing has identified that this pathotype belongs to the PstS13 group. Like the PstS10 group, the PstS13 group is also common in Europe at present where it is principally associated with triticale. It has caused total crop failure in organically grown triticale there and was responsible for severe stripe rust epidemics on durum and bread wheat in Italy in 2017. Significantly, this pathotype was introduced into South America around 2016, where it caused severe stripe rust epidemics on over 3 million hectares of wheat in Argentina in the 2016/17 and 2017/18 cropping seasons. Many growers there applied fungicides but were unable to control the disease and suffered significant economic losses. Yield losses of between 53 and 70% were recorded in the seven most susceptible varieties being grown.

Impact

Common wheat: Unlike pathotypes within the 'WA' ('134') group, pt. 198 E16 A+J+ T+ 17+ cannot overcome the resistance gene *Yr25*. Detailed comparative tests have shown the likely occurrence of this resistance gene in the Australian wheat cultivars Cosmick, Derrimut, DS Pascal, Hydra, LRPB Flanker, LRPB Spitfire, Sunprime, and Wallup. These results show that fortunately, some of the wheat varieties currently grown in Australia are more resistant to the 198 pathotype than they are to the older '134' group pathotypes. The results also account for associations between specific wheat varieties and either the '134' group of pathotypes or pathotype 198 E16 A+ J+ T+ 17+ that have emerged in processing stripe rust samples submitted for pathotype analysis in 2020. We are continuing genetic analyses to locate the specific rust resistance gene(s) involved.

Data collected from the field during 2019 by NSW DPI, AgVic and the University of Sydney indicate that pathotype "198" poses an increased threat to several wheat varieties (e.g. DS Bennett and LPB Trojan and to a lesser extent Devil, Illabo, DS Darwin, Emu Rock and Hatchet CL Plus).

Durum wheat: As reported in our Cereal Rust Update Volume 17 Issue 2, several durum varieties (e.g. DBA Artemis, DBA Bindaroi, DBA Lillaroi, DBA Spes, DBA Vittaroi and EGA Bellaroi) are more susceptible to pathotype 198 E16 A+ J+ T+ 17+. While our initial tests implicated the resistance of the foreign wheat variety Suwon92/Omar in this, further testing suggests that pathotype 198 E16 A+ J+ T+ 17+ likely overcomes an as yet uncharacterised seedling resistance gene in these durum wheat cultivars. Further genetic studies are underway to characterize the resistance that has been rendered ineffective in these durums by the 198 pathotype.

Triticale*:* One of the intriguing features of evolution in the wheat stripe rust pathogen in eastern Australia over the past 18 years or so has been the acquisition of virulence for several resistance genes in triticale. Pathotypes within the '134' group have virulence for three stripe rust resistance genes that occur in triticale, all of which are on the rye genome: *Yr9*, *YrJackie*, *YrTobruk*. While virulence for *Yr9* existed in the pathotype that entered Australia in 2002 (i.e. pt. 134 E16 A+), local mutations gave rise to virulence for *YrJackie* (first detected in 2007) and *YrTobruk* (first detected in 2010). This adaptation to triticale was a significant contributing factor in the damaging stripe rust epidemics experienced in eastern Australia from 2008 through 2011, as it allowed very early epidemic onset due to stripe rust build up in early sown triticale crops and later movement into main season wheat crops.

Coincidentally, pathotype 198 E16 A+ J+ T+ 17+ is also virulent for these three resistance genes in triticale. Detailed seedling tests in our greenhouse system have indicated that this pathotype is also virulent for a fourth stripe rust resistance in triticale, which is carried by the varieties Astute, Berkshire, Bison, and Joey. Consequently, these four varieties are now more vulnerable to stripe rust infection.

Barley: Pathotype 198 E16 A+ J+ T+ 17+ differs from the '134' group of pathotypes in being virulent for one or more major (seedling) genes conferring stripe rust resistance in barley. Varieties that carry the resistance overcome by pathotype '198' include: Brindabella, Clipper, Ketch, Maritime, Prior, RGT Planet⊕, Shepherd⊕, and Tantangara. Despite this, we found no evidence of pt. 198 E 16 A+ J+ T+ 17+ on barley crops in eastern Australia in 2020, so it would appear that all current barley varieties have very good levels of resistance to this pathotype and that it poses no threat at this stage to the barley industry.

Several samples of stripe rust from barley crops were received in 2020; all were immediately genotyped using diagnostic SSR markers upon receipt and pathogenicity tested in the greenhouse, and all proved to be the Barley Grass Stripe Rust (BGYR) pathogen. There is circumstantial evidence that the BGYR pathogen may now have increased virulence on barley grass, and that its more common occurrence in barley crops in 2020 is a function of increased inoculum load. We are conducting tests at present to try to verify this.

Wheat leaf rust

Crop losses due to leaf rust of wheat tend to be lower than those caused by stem rust and stripe rust, but it is considered by many to be the most damaging wheat rust disease on a world-wide basis because it can develop under a broader range of environmental conditions and hence is more common and has a larger geographical footprint. As has been documented for stripe rust of wheat, there have been two incursions of exotic leaf rust isolates in recent years.

Wheat leaf rust pt. 104-1,3,4,6,7,8,10,12 +Lr37

This was first detected in August 2014 at Glenroy South Australia and is regarded as having an exotic origin. Significantly, it was shown to be virulent for the resistance genes *Lr27*+*Lr31*, rendering the cultivars Axe⊕, Corack⊕, Emu Rock⊕, Grenade⊕, Mace⊕, SQP Revenue⊕, Wallup⊕ and Wyalkatchem⊕ more susceptible to leaf rust.

This new '2014' rust took only 13 months to spread to all Australian wheat growing states. By the end of 2014, it represented half of the wheat leaf rust isolates identified nationally, and while it was again the dominant pathotype isolated in 2015 (54%) and 2016 (60%), it then declined in frequency due to the rapid increase and spread of yet another new pathotype (pt. 104-1,3,4,5,7,9,10,12 +Lr37), first detected in June 2016 in a sample collected from a crop of Mace⊕ at Port Neill South Australia. Like the '2014' pathotype, this pathotype is now present in all Australian wheat growing states, and it has been the most common pathotype in all regions. Varietal response to leaf rust has not changed due to this pathotype, but its rapid increase in frequency across all wheat growing regions suggests that it is more aggressive and as such may have greater epidemic potential.

The origin of the '2016' pathotype is not clear, but it appears likely to have arisen locally – possibly via asexual hybridisation. If this proves to be the case, it will be only the second documented example in the world, of a new pathotype of the wheat leaf rust pathogen arising in this way.

Wheat leaf rust pt. 93-3,4,7,10,12

This pathotype was first detected on Illabo⊕ wheat from Tootool in southern NSW in October 2020. It was subsequently isolated from several other locations in NSW. It is very similar to, and clearly related to, an existing one that was first detected in 2005, but differs from it in being unable to overcome the resistance genes *Lr2a* and *Lr20*. It is considered to be of exotic origin; an identical one was identified in New Zealand in 2014-15.

Based on the virulence/avirulence of the new pathotype, it is not expected to pose any additional threat to current wheat varieties. Having said that, it is not possible to assess the full risk of the new pathotype to the wheat industry until detailed comparative greenhouse and field tests are conducted. We plan to undertake these in the 2021 field cycle at the Plant Breeding Institute at Cobbitty.

Virulence for the resistance gene Lr24

The leaf rust resistance gene *Lr24* has been used extensively in Australia. It was first deployed in 1983 in the cultivar Torres, and since then more than 60 wheat cultivars have been released with this gene (e.g. Chief CL Plus⊕, LRPB Gazelle⊕, Sunguard⊕, and Supreme⊕).

The first detection of virulence for *Lr24* was in 2000, 17 years after it was first deployed. Virulence for *Lr24* only occurs in eastern Australia. However, unlike virulence for the stripe rust resistance gene *Yr17*, virulence for *Lr24* has not become dominant in eastern Australia. It was nonetheless detected in nine samples of leaf rust collected from wheat crops in NSW from Forbes, Grafton, Narrabri, and Wongarbon in 2020. This means that in many situations, varieties with the resistance gene *Lr24* should remain resistant, unless the pathotypes virulent for this gene increase in frequency. Keeping a watching brief on where *Lr24* virulent pathotypes occur, and their frequency, is important to ensure growers of varieties with this gene minimise their risk of losses due to leaf rust.

An added bonus of growing varieties with the resistance gene *Lr24* is that they also carry the stem rust gene *Sr24* – the two genes are genetically linked. Gene *Sr24* remains completely effective in protecting against stem rust in Australia, despite pathotypes with virulence being detected elsewhere (e.g. USA, South Africa, Kenya, Ethiopia).

Concluding comments

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

Stripe rust was very common in wheat crops in eastern Australia during the 2020 season, and there were many situations in which fungicides were used to control the disease. This was principally due to the occurrence of pathotype 198 E16 A+ J+ T+ 17+. The amount of stripe rust that developed was, however, nowhere near that caused by the same pathotype in Argentina in 2016/17 and 2017/18. The value of existing stripe rust resistance in Australian wheat varieties in minimizing yield losses due to this pathotype in particular is even more apparent when one considers just how favourable the 2020 cropping season was for stripe rust. The much lower impact of pathotype 198 in Australia compared to its impact in Argentina and Europe is a clear endorsement of the value of genetic resistance in controlling rust diseases in cereals, and of the efforts of all stakeholders in using genetics as the foundation of rust control here in Australia.

The latest responses of Australian wheat and triticale cultivars to the pathotypes reported here, based on detailed greenhouse and field testing, are provided in our Cereal Rust Report (Volume 17 Issue 3), which can be downloaded from our website. Updated refined responses will also be provided in early 2021 based on results from the National Variety Trials 2020 cycle.

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The national rust pathotype surveillance program involves active participation by many people including state-based regional cereal pathologists, scientists in Universities and in the private sector, grain growers, and their important contribution is gratefully acknowledged.

Useful resources

Current Cereal Disease Guides, for example:

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

Cereal seed treatment guide, 2020:

https://www.pir.sa.gov.au/__data/assets/pdf_file/0005/237920/Cereal_Seed_Treatments_2021.pdf

University of Sydney Cereal Rust Reports and mapping of rust pathotype distribution:

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

McIntosh RA, Wellings CR, Park RF (1995). Wheat Rusts: An Atlas of Resistance Genes. (https://www.globalrust.org/sites/default/files/wheat_rust_atlas_full.pdf).

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Cereal pathology update - learnings from 2020, planning for 2021

Andrew Milgate, Brad Baxter, Michael McCaig, Tony Goldthorpe, Merrin Spackman and Ben Ovenden, NSW DPI

Key words

disease survey, rotation, take-all, Fusarium crown rot, stripe rust

GRDC codes

DAN00213: Grains Agronomy & Pathology Partnership - *A strategic partnership between GRDC and NSWDPI.* Project BLG207

DAN1907 NVT pathology services NSW

Take home messages

- Ensure you are using the latest variety disease ratings for wheat stripe rust which incorporate changes that have occurred in 2020
- Inoculum of many cereal pathogens will be higher in 2021 hence plans need to account for higher disease risks
- Reduce the risk of rust epidemics in 2021 by controlling cereal volunteers during February
- Use break crops to improve root health and reduce soil-borne disease risks.

Introduction

The favourable 2020 season across southern NSW resulted in high yields for many growers but also favoured development of many cereal diseases. Some diseases such as stripe rust were managed effectively through application of fungicides, while others such as take-all, which cannot be controlled in-crop, caused significant losses in individual paddocks. In this paper we discuss preliminary results from the southern NSW 2020 survey of 32 barley and 54 wheat paddocks which are part of the northern region Grains Agronomy & Pathology Partnership (GAPP) disease investment. This is the second year of the survey and we can start to see trends emerging from the data which can help inform agronomists and growers to improve their rotation decisions to reduce disease risk.

What we did

In 2020, NSW DPI undertook an extensive random survey of winter cereal crops in the northern region to determine disease levels as part of GAPP. In collaboration with locally based agronomists, in southern NSW, 86 winter cereal crops were surveyed between the start and end of grain filling (Zadok stages 71 and 91). The GPS location and background information for each paddock were recorded, but to maintain confidentiality, data is presented here based on broad boundaries and distribution maps (Figure 1). Central NSW sites were situated between Dubbo and West Wyalong, and southern NSW sites were south of West Wyalong. East and west locations were defined by the Newell Highway.

Within each crop, a diagonal transect (~500 m) was created starting at least 50 m in from a road or fence line and avoiding obvious barriers such as trees or dams. Five consecutive whole plants (roots with adhering soil, stems and heads) were collected along the planting row from ten separate sampling points across the diagonal transect (i.e. total of 50 plants/crop). Samples were transported to Wagga Wagga and stored at 4°C before processing. 100 random tillers (i.e. two/plant) were assessed for incidence of basal browning (crown rot), leaf diseases (e.g. yellow spot or net blotch) and head infections (e.g. bunt, smut or Fusarium head blight (FHB)).

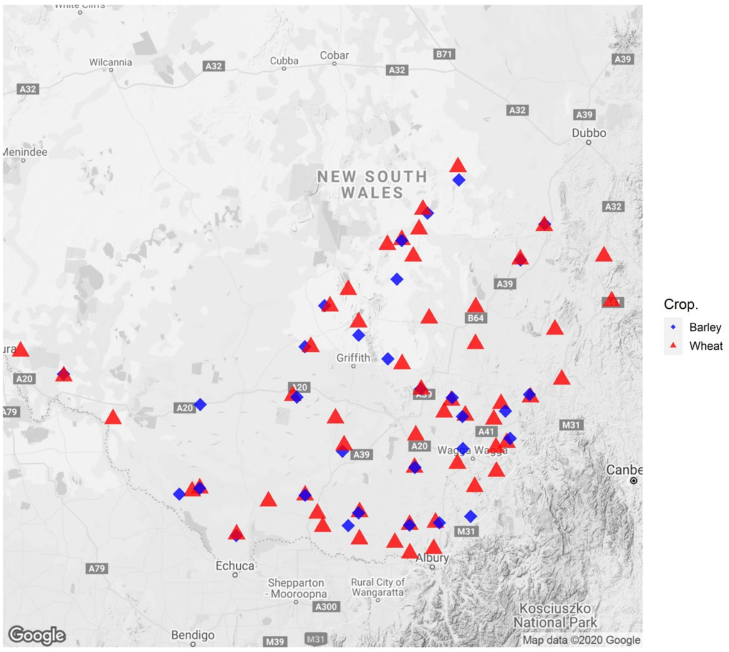

Figure 1. Location of barley (blue diamonds) and wheat (red triangles) paddocks sampled across southern NSW in 2020.

Rotation impacts

In south/central NSW during 2020, 74% of barley crops were sown into the stubble of a previous barley, oat or wheat cereal crop (Table 1). This position in the cropping sequence potentially exposes barley to high root disease pressure. In 2020, barley paddocks suffered higher levels of root disease than in 2019. This was most likely due to build-up of pathogen populations in the 2019 wheat crops (Table 2). Barley is seen as the preferred cereal option to follow wheat when there is a risk of crown rot because of its disease tolerance/late season stress escape with earlier maturity. In addition to this barley is also sown targeting lower protein and higher yield potential. While considered to be lower risk, there can still be yield losses from root diseases in barley crops. If growers wish to maximise yield potential and profitability, then selecting paddocks with lower disease burden would result in higher returns from barley.

Compared to barley, only 36% of wheat crops in 2020 were following another cereal, which was mainly wheat in 30% of the surveyed paddocks. In these wheat-on-wheat paddocks, 62% (10) had moderate to high root disease scores. Whereas wheat following canola in 2020, 60% (9) of paddocks had nil to low root disease scores (data not shown). This highlights the benefits of having non-host disease breaks in the rotation for the control of cereal root diseases. In general, the 2020 season had improved root health in the south-east and south-west regions, while the central regions (based on data collated to date) appear to have experienced similar levels of root disease to 2019.

Table 1. Percent frequency of previous crop in rotation sequence with barley and wheat crops sown in 2020 for southern and central NSW. Numbers in brackets are actual number of paddocks surveyed.

	2020 crop	
Previous crop (2019)	**Barley**	**Wheat**
Barley	6 (2)	4 (2)
Canola	6 (2)	28 (15)
Chickpeas	0 (0)	6 (3)
Cotton	6 (2)	0 (0)
Failed wheat	3 (1)	2 (1)
Fallow	3 (1)	7 (4)
Lentils	0 (0)	2 (1)
Lupins	0 (0)	6 (3)
Oats	12 (4)	2 (1)
Pasture	3 (1)	4 (2)
Peas	0 (0)	4 (2)
Vetch	0 (0)	2 (1)
Wheat	53 (17)	30 (16)
Unknown[#]	6 (2)	6 (3)
Total	***100 (32)***	***100 (54)***

[#]At the time of writing there were 12 paddocks with an unknown previous crop. These are being followed up to complete the dataset.

Table 2. Percent incidence of root diseases in randomly surveyed barley and wheat crops in southern and central NSW in 2019 and 2020. Root disease incidence records the visual presence of crown rot, take-all, Rhizoctonia, common root rot and Pythium. Root disease scores range from 0 (no visual incidence of disease) to 10 (100% of tillers inspected have a root disease). 100 tillers in total from 10 locations within each paddock were assessed. Numbers in brackets are actual number of paddocks surveyed.

Barley	**CE NSW**		**CW NSW**		**SE NSW**		**SW NSW**	
Root disease score	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Nil (0)	12 (1)	0 (0)	36 (8)	0 (0)	0 (0)	0 (0)	25 (1)	0 (0)
Low (0.1-3)	75 (6)	0 (0)	59 (13)	33 (2)	7 (1)	17 (2)	25 (1)	17 (2)
Moderate (4-6)	12 (1)	0 (0)	5 (1)	17 (1)	0 (0)	25 (3)	0 (0)	8 (1)
High (7-10)	0 (0)	100 (2)	0 (0)	50 (3)	93 (13)	58 (7)	50 (2)	75 (9)
Total	***100 (8)***	***100 (2)***	***100 (22)***	***100 (6)***	***100 (14)***	***100 (12)***	***100 (4)***	***100 (12)***
Wheat	**CE NSW**		**CW NSW**		**SE NSW**		**SW NSW**	
Root disease score	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Nil (0)	53 (9)	60 (3)	19 (10)	40 (4)	0 (0)	5 (1)	0 (0)	12 (2)
Low (0.1-3)	35 (6)	20 (1)	65 (34)	30 (3)	0 (0)	36 (8)	33 (2)	24 (4)
Moderate (4-6)	12 (2)	0 (0)	13 (7)	10 (1)	8 (2)	14 (3)	0 (0)	18 (3)
High (7-10)	0 (0)	20 (1)	2 (1)	20 (2)	92 (24)	45 (10)	67 (4)	47 (8)
Total	***100 (17)***	***100 (5)***	***100 (52)***	***100 (10)***	***100 (26)***	***100 (22)***	***100 (6)***	***100 (17)***

Take–all (*Gaeumannomyces graminis* var. *tritici*)

The 2020 season was ideal for the development of take-all to levels not seen for many years. The results of the 2019 GAPP survey showed that the incidence of take-all was common across southern NSW but only at low levels. The conducive conditions of above average rainfall for the months of August - October allowed the pathogen to multiply rapidly and cause yield loss. The reported areas affected, and yield loss varied from small patches, less than 1-3% of paddock area, with 100% loss, to entire paddocks suffering up to an estimated 40-50% yield loss. Compounding the suitable environment for the development of take-all in 2020 was a reduction in the use of flutriafol applied to fertiliser (information provided by agronomists) allowing early infection to occur. This culminated in some paddocks not performing to expected yield potential.

The build-up of take-all inoculum in cereal crops in 2020 will need to be considered when planning 2021 crop choices. This random crop survey highlights that a high proportion of paddocks are sown with a double cereal rotation of wheat and barley. To reduce risk of further losses in those paddocks that showed take-all this year, growers are advised to sow a non-host species such as canola or one of the pulses in 2021. Where a non-host cannot be chosen, growers should consider the use of a fungicide known to provide suppression of early season infections such as flutriafol or fluquinconazole. If the predicted above average summer rainfall occurs, this will also help to reduce take-all inoculum levels over summer as long as grass weeds and cereal volunteers are controlled during this fallow period.

Fusarium crown rot (*Fusarium pseudograminearum*)

The incidence of Fusarium crown rot (FCR) was high in survey paddocks across central and southern NSW in 2019 and again in 2020. This is not surprising given the high frequency of cereal-on-cereal rotations (Table 1) across the region and the prevalence of conservation cropping practices. FCR was often found in association with take-all in 2020 cereal crops.

There are widespread reports of wheat grain yields being lower and grain screening levels higher than expected across many areas of southern and central NSW in 2020, which has often been simply dismissed as frost damage. Frost damage did occur in some more frost prone areas of paddocks or regions in 2020 but underlying levels of FCR and/or take-all appear to have also been potentially involved. Correct diagnosis is important when planning rotations and management for 2021.

Given the extensive area of cereals grown in 2020, to restore ground cover after a run of drier seasons, there is likely to be significant areas of cereal-on-cereal again in 2021. Knowing risk levels prior to sowing is the first step in successfully managing FCR and take-all in 2021. PREDICTA® B testing remains the 'gold standard' for quantification of inoculum and hence risk levels. NSW DPI, Tamworth are also offering a free cereal stubble testing service prior to sowing in 2021. From the 19-cereal stubble samples processed from southern and central NSW so far, Fusarium levels range from 0 to 82% (average 39%). This preliminary testing highlights that FCR risk is very high in the majority of paddocks tested thus far. This is more alarming as FCR inoculum load is a function of infection levels in previous cereal crop and actual amount of stubble present, which is elevated given the seasonal conditions in 2020. However, disease risk can vary dramatically between paddocks with 3 of the 19 tested so far having low to no FCR infection in 2020.

If interested in having paddocks tested using PREDICTA B then refer to the PREDICTA B sampling protocol (https://pir.sa.gov.au/__data/assets/pdf_file/0007/291247/Sampling_protocol_PreDicta_B_Northern_regions.pdf) or with a free NSW DPI cereal stubble test then text Steven Simpfendorfer (0439 581 672) for details.

Wheat stripe rust (*Puccinia striiformis*)

There was an early start to the stripe rust epidemic in 2020, which was detected in early sown crops of DS Bennet⊕ across a very wide area of NSW in late June. A detailed report on the origin of this pathotype and others currently detected across Australia is provided in a 2020 cereal rust report (Volume 17 Issue 4). At the end of the 2020 season there were five pathotypes detected by the Sydney University cereal rust survey in NSW; 198 E16 A+ J+ T+ 17+, 239 E237 A- 17+ 33+, 134E16A+17+, 134E16A+17+ 27+ and 64E0A-, these are likely to be present in 2021 . Growers are advised to be alert for the potential of these pathotypes to cause susceptible reactions in some varieties. The NVT stripe rust nurseries at Wagga Wagga and Tamworth provided excellent data to identify varieties with changes in their resistance reactions. These ratings will be published on the NVT online website and in the NSW DPI 2021 sowing guide. Growers should ensure they are using the latest stripe rust ratings when considering variety choice and appropriate management in 2021.

Growers should routinely check their varieties for changes in resistance ratings as pathotypes change over time. Varieties identified for changes in 2021 include; Catapult⊕, RockStar⊕, Joey⊕, Borlaug 100⊕, Corack⊕, Devil⊕, DS Darwin⊕, Emu Rock⊕, Hatchet CL Plus⊕, LRPB Cobra⊕, LRPB Trojan⊕, SEA Condamine⊕, Sheriff CL Plus⊕, Vixen⊕, Wallup⊕, Sting⊕, Suncentral⊕ and Denison⊕.

The NSW DPI sowing guide and NVT online will show a rating that has a '/' such as MRMS/S. The first position indicates the rating for the most common pathotypes received by the Australian cereal rust survey in 2020 which were 198 E16 A+ J+ T+ 17+, 239 E237 A- 17+ 33+, 134E16A+17+, and 134E16A+17+ 27+. The second rating after the '/' indicates that the variety showed a distinct difference in reaction to the less common 64E0A- pathotype. Which pathotype will be dominant in

NSW during 2021 is not possible to predict. The 198 E16 A+ J+ T+ 17+ became dominant in less than 12 months after only being detected in a few crops during 2019. This highlights the dynamic nature of stripe rust and its ability to travel long distances and develop quickly on susceptible varieties.

The control of cereal volunteers to prevent a 'green bridge' for cereal rusts will be important for reducing the chance of early disease development in 2021. Rusts require a living host to survive, so by controlling volunteers over summer or at least for the month of February before the new crop is sown, reduces disease risk across the region. Being wind borne, rusts are social diseases and require an industry wide effort to help everyone to reduce the risk of community transmission (in Covid speak).

Other diseases

Several other diseases occurred during the 2020 season which are worthy of mention to consider in plans for paddock monitoring and control strategies, should they be found in crops during 2021.

Rusts in oats*;* Stem and leaf rust was observed in oat crops from October to November across central and southern NSW. There is an increased chance for this pathogen to survive on oat volunteers and wild oat populations this summer. Early infections of stem rust can cause high yield losses and be difficult to control with fungicides. Early detection and control are important to prevent losses.

Scald in barley was observed in many crops in southern NSW. Given that most barley was sown following wheat suggests the infections may have been from seed transmission. A spore type which is capable of being wind borne and allows long distance dispersal has not been described for scald, although it may exist. The reduction in use of in-furrow or seed applied fungicides may have also contributed to the increased prevalence of scald during 2020.

Powdery mildew (PM) in both wheat and barley was a feature of 2020. The occurrence of PM in barley is not uncommon in the central region of NSW but the season enabled the spread of the disease into the south-east and south-west barley crops. There are pathotypes of PM that render popular varieties such as La Trobe⚐ and Hindmarsh⚐ susceptible. For wheat, PM has historically not been a major concern in NSW except in highly susceptible varieties. As with other foliar diseases early detection and action is the best approach. Further information on the fungicide resistance status of NSW wheat PM isolates collected during 2020 will be made available once testing is complete.

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Resources

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

NSW cereal diagnostics and enquiries – the 2020 winner is……?

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Key words

correct diagnosis, leaf diseases, soil-borne diseases, wheat, barley

GRDC code

DAN00213: Grains Agronomy & Pathology Partnership (GAPP) - A strategic partnership between GRDC and NSW DPI. Projects BLG208 and BLG207.

Take home messages

- Cereal diseases were prevalent in 2020 with favourable climatic conditions. Hence, in combination with increased cereal stubble loads, pathogen levels are likely to be elevated in 2021
- However, steps can be taken to minimise impacts which include:
  - Remember the basics of disease management – think disease triangle!
  - Know before you sow (e.g. PREDICTA®B or stubble tests) – inoculum levels
  - Varietal resistance – reduce host susceptibility
  - Manipulate canopy microclimate or stress during grain filling – environmental conditions
- NSW DPI plant pathologists can help with correct diagnosis and management options.

Introduction

A 'no-additional charge' cereal diagnostic service is provided to NSW cereal growers and their advisers under projects BLG207 and BLG208 as part of the GAPP co-investment. Evidence based methods are used to confirm diagnosis which include a combination of visual symptoms, crop management history, distribution in paddock and recovery/identification of the causal pathogens (microscopy, humid chamber or plating). Any suspect virus samples are confirmed using ELISA antibody testing at NSW DPI Elizabeth Macarthur Agricultural Institute at Menangle.

Wheat, barley and oat rust samples (stripe, leaf and stem) are sent to the Australia Cereal Rust Control Program (ACRCP). The submission of samples to ACRCP facilitates the tracking of pathotype populations and distribution across the cropping belt of NSW and Australia. This includes a new interactive map (Australian Cereal Rust Survey 2020 Sample Map - Google My Maps) regularly updated throughout the growing season by the ACRCP. Growers can access this resource to see which pathotypes dominate in their region. This can be very important to guide in-crop management decisions given five different stripe rust pathotypes were present at varying levels across NSW in 2020. Individual wheat varieties can have vastly different reactions to these pathotypes, so knowing which ones are dominant, where and when, can guide appropriate seasonal in-crop management.

The projects also record disease enquiries received and resulting management advice provided to growers and advisers throughout each season. These project activities support NSW cereal producers in correct diagnosis of diseases during the season with resulting independent advice on appropriate management strategies to limit economic impacts. This is assisting to limit the unnecessary application of in-crop fungicides by growers.

Which diseases dominated in 2019 and 2020?

Collation of this data across NSW provides an annual 'snapshot' of the key biotic and abiotic constraints to cereal production (Table 1).

Table 1. Cereal diagnostics and enquiries processed across NSW in 2019 and 2020. Disease/issues are ranked in order of frequency in 2020

Disease/issue	**2020**	**2019**
Stripe rust (wheat)	194	13
Spot form of net blotch	65	32
Physiological/melanism	65	10
Scald	65	4
Fusarium crown rot	61	14
Wheat powdery mildew	53	1
Frost damage	45	4
Leaf rust (wheat)	35	2
Other non-disease (e.g. soil constraint, leaf blotching)	34	24
Bacterial blight (other cereals)	30	0
Rusts crown and stem (oats)	29	4
Herbicide	28	6
Net form of net blotch	23	0
Bacterial blight (oats)	22	3
Barley grass stripe rust	20	1
Barley yellow dwarf virus	19	1
Septoria tritici blotch	17	13
Nutrition	16	2
Take-all	16	1
Rhizoctonia	12	7
Barley powdery mildew	12	0
Yellow leaf spot	10	4
Fusarium head blight	10	0
Loose smut	9	1
Seedling root disease complex (Pythium, crown rot, Rhizo,Take-all)	8	2
Septoria oats	3	2
Wheat streak mosaic virus	3	1
Common root rot	2	3
Rye grass rust	2	0
Ergot	1	0
Red leather leaf	1	7
Sclerotium rolfsii	1	2
Spot blotch	1	0
Ring spot	0	1
Total	**912**	**165**

Not surprisingly, individual seasons have a strong influence on the level of cereal diagnostic support provided to NSW growers/advisers, with over five-times the number of activities in the wetter 2020 season compared with much drier conditions experienced in 2019 (Table 1). This increase was primarily due to more conducive conditions for the development of a range of cereal leaf diseases (e.g. rusts, scald, net-blotches, Septoria) in 2020 (537 samples) compared with 2019 (77 samples).

The four main cereal diseases in 2020 were wheat stripe rust (widespread distribution of newer Yr198 pathotype), spot form of net blotch in barley, scald in barley and Fusarium crown rot in different winter cereal crops. In comparison, the four main cereal diseases in 2019 were spot form of net blotch, Fusarium crown rot, wheat stripe rust and Septoria tritici blotch (Table 1).

Interestingly, the levels of yellow leaf spot (*Pyrenophora tritici-repentis*) diagnosed in both seasons were relatively low. However, wheat samples with leaf blotches or mottling were submitted each year, suspected to be caused by yellow leaf spot. There is an ongoing difficulty with correct diagnosis of this particular leaf disease by growers and their advisers, often confused with Septoria tritici blotch (*Zymoseptoria tritici*), Septoria nodorum blotch (*Stagonospora nodorum*) and physiological responses to abiotic stress (e.g. frost yellowing, N mobilisation, herbicide damage).

The 2020 season also highlighted that root diseases like take-all, which have not been seen at damaging levels for many years can quickly re-emerge at significant levels when conducive conditions occur. Conversely, Fusarium crown rot remains a significant issue across seasons.

The number of rust and powdery mildew samples received from susceptible wheat varieties in 2020 highlights the importance of genetic resistance as a component of integrated disease management systems. Susceptible varieties are more reliant on fungicide applications to limit disease levels and associated yield loss, which can increase the risk of fungicide resistance developing. The resistance selected may not necessarily be in the main pathogen targeted by the fungicide applications. For example, reliance on fungicide applications in stripe rust susceptible varieties could inadvertently select for fungicide resistance in wheat powdery mildew populations when they co-infect plants. Preliminary research conducted in collaboration with Curtin University's Centre for Crop Disease Management (CCDM) in 2020, unfortunately indicates issues with reduced sensitivity to azoles (DMIs, Group 3) and resistance to strobilurin (QoIs, Group 11) fungicides are already widespread in wheat powdery mildew populations in NSW and Victoria.

Are you getting a correct diagnosis?

Importantly, 21% of activities in 2020 and 28% in 2019 were not related to disease. These samples were either diagnosed as being plant physiological responses to stress, frost damage, herbicide injury, related to crop nutritional issues or other non-disease issues. All of these samples were submitted as suspected of having disease issues. This highlights the ongoing importance of the diagnostic service provided by these projects to NSW growers and their advisers to support correct identification and implementation of appropriate management strategies. Never be afraid to get a second opinion from a plant pathologist, we are here to help (see contact details).

Management in 2021 – remember the basics!

Showing our ages here by referring back to the good old 'disease triangle', my mentors would be proud! Disease levels in 2021 will still be based around the disease triangle, which requires a combination of pathogen inoculum, susceptible host and environmental conditions conducive to disease development. Given the elevated incidence of a wide range of cereal diseases across NSW in 2020 (Table 1), inoculum levels of a range of cereal pathogens and hence disease risk in 2021 will be higher than previous seasons. Each of the three components of the disease triangle should be considered when implementing management strategies to minimise losses and determine if fungicide application is warranted in 2021.

1. *Inoculum levels*

The first step is 'know before you sow'. PREDICTA®B testing remains the gold standard for a quantitative assessment of a wide range of cereal pathogens and associated risk of both soil-borne and leaf diseases. Refer to the PREDICTA B sampling protocol (https://pir.sa.gov.au/__data/assets/pdf_file/0007/291247/Sampling_protocol_PreDicta_B_Northern_regions.pdf) . NSW DPI is alternatively offering a free cereal stubble testing service prior to sowing in 2021 (Jan-Apr) aimed primarily at determining Fusarium crown rot risk levels in cereal-on-cereal situations (contact Steven Simpfendorfer for details).

The disease risk associated with inoculum levels can be quite different with various pathogens depending on their capacity for wind dispersal. For example, stubble and soil borne pathogens which cause Fusarium crown rot, take-all and Rhizoctonia root rot are not dispersed by wind, hence risk from inoculum is confined to an individual paddock. Consequently, crop rotation to a non-host pulse or oilseed crop breaks the disease triangle. Stubble borne leaf pathogens, which cause net blotch or scald in barley, yellow spot or Septoria tritici blotch in wheat or powdery mildew, have limited wind dispersal (i.e. metres), so again crop rotation largely reduces disease risk and especially at early growth stages. Conversely, rusts are airborne (i.e. kilometres) so crop rotation is irrelevant to disease risk.

Seed borne infection should also be considered with some pathogens such as bacterial blights, scald, net-form of net blotch, smuts and bunts. Sourcing clean seed for sowing in 2021, that is, not from crops infected in 2020, is important to reduce risk of these diseases.

With stripe rust, reducing or delaying the onset of an epidemic significantly reduces disease pressure. Rust spores are readily wind borne and are commonly referred to as 'social diseases' (i.e. 'we are all in this together'). Hence, co-ordinated management across a region can have real benefits for all. Controlling volunteer wheat plants at least three weeks prior to first planting of crops limits the 'green bridge' survival and delays epidemic onset. In-furrow (e.g. flutriafol) and seed treatments (e.g. fluquinconazole) fungicides provide extended protection from stripe rust early in the season delaying epidemic onset. This can be particularly important when early sowing susceptible long season wheat varieties (e.g. DS Bennett⦶), which can place early disease pressure on later sown susceptible main season varieties.

Growers should also be aware that stubble management practices can also influence inoculum dispersal. For example, inter-row sowing between intact standing cereal stubble reduces the level of Fusarium crown rot infection. However, cultivating or mulching infected cereal stubble prior to sowing can spread Fusarium inoculum more evenly across a paddock and potentially into the surface layers of the soil where plant infection primarily occurs. Volunteer cereal plants and grass weeds over the summer fallow period can also be a major source of increased inoculum of Fusarium crown rot, take-all and Rhizoctonia leading into sowing in 2021.

2. *Host susceptibility*

Relatively self-explanatory? If you do not want cereal disease issues, then sow a non-host pulse or oilseed break crop. However, if considering cereal-on-cereal, key points are:

1. Make sure you are using the latest varietal resistance ratings especially to newer pathotypes of stripe rust. Many growers got caught out on this with durum wheats and DS Bennett in 2020. Improved levels of resistance to leaf diseases reduces reliance on foliar fungicides
2. If multiple pathogen risks then hedge towards improved resistance to the more yield limiting, harder to control and/or historically bigger issue in your area. This could be quite different between rainfall zones or dryland vs irrigated situations

3. Barley, bread wheat, durum, oats and triticale are NOT break crops for each other! They all host Fusarium crown rot, take-all and Rhizoctonia. Barley tends to be more susceptible to Rhizoctonia root rot, but its earlier maturity can provide an escape from late season stress which reduces yield loss to Fusarium crown rot
4. Rusts and necrotrophic leaf diseases (net blotches, yellow spot, Septoria) tend to be crop specific. However, note that in wetter seasonal finishes it appears that some of these necrotrophic leaf pathogens have the potential to saprophytically colonise other cereal species.

3. Environmental conditions

Largely in the ‘lap of the gods’? Certainly more limited options here but growers should be aware that subtle microclimate differences within cereal canopies can have a large influence on cycling of leaf diseases. Crash grazing of dual purpose wheat varieties not only reduces any early stripe rust inoculum, but also opens the canopy to reduce the duration of leaf wetness and lowers humidity. This reduces conduciveness to leaf diseases. Higher nitrogen levels can also exacerbate rusts and powdery mildew through thicker canopies creating a more favourable microclimate for these pathogens. However, leaf nitrate also serves as a food source for these biotrophic leaf pathogens.

Yield loss from Fusarium crown rot infection, largely through the expression of the disease as whiteheads, is strongly related to moisture and temperature stress during grain filling. Although growers cannot control rainfall during this period, there is the potential to limit the probability of stress through earlier sowing (matched to varietal maturity and frost risk), maximising soil water storage during fallow periods (stubble cover + weed control), addressing other biotic (e.g. nematodes, Rhizoctonia) or abiotic (e.g. acidity, nutrition, residual herbicides etc.) constraints to root development and canopy management. Recent (last two weeks) and predicted weather conditions (next 2-4 weeks) should also be considered with in-crop leaf disease management decisions in susceptible varieties around key growth stages for fungicide application of GS30-32 (1^{st} node), GS39 (flag leaf emergence) and GS61 (flowering).

Conclusions

Overall the 2020 season was fairly good across a large proportion of NSW with cereal diseases present at higher frequencies than recent seasons. Hopefully 2021 provides another favourable year for cereal production. Cereal disease risk is likely to be higher due to pathogen build-up in 2020 and the likely increased area of cereal-on-cereal in 2021. Calm considered and well planned management strategies in 2021 can minimise disease levels. NSW DPI is here to support correct diagnosis and discuss management options prior to sowing and as required throughout the season. Let’s get back to cereal disease management basics in 2021 and leave any lingering ‘pandemic panic’ from 2020 behind.

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Was canola fungicide investment justified in low and medium rainfall environments in 2020?

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Key words

canola, fungicide, Sclerotinia, upper canopy blackleg, Alternaria black spot, powdery mildew

GRDC codes

GOA2006-001RTX

Take home messages

- Return on investment was strong in only two of five trials, with both these trials being in the south and having higher levels of upper canopy blackleg (branch infection) as well as some Sclerotinia. Best return was from a single fungicide spray at 30% bloom stage
- Application at the recommended timings (30% and 50% bloom) were more likely to result in a yield benefit than an early application (10% bloom)
- Reduction in disease infection did not necessarily result in a positive grain yield response, similarly a positive grain yield response did not always increase profitability
- Overall, with modest yield responses in a high production year, money may be better invested in inputs with a more reliable return on investment.

Introduction

Application of fungicide to manage disease in canola, especially Sclerotinia and upper canopy blackleg (UCB) is a common practice in the higher rainfall, eastern and southern areas of the GRDC Northern Region, but there is little data on the cost-effectiveness in low and medium rainfall zones. In mid to late winter 2020 canola crops had high yield potential across much of the GRDC Northern Region. With forecasts for further rainfall for the spring period, many growers and advisors were considering the need for fungicide in areas where application is not common.

In response Grain Orana Alliance (GOA) and Brill Ag established five canola fungicide response trials through southern and central NSW to determine the response to fungicide in low and medium rainfall environments in a high yield potential season. The trials tested several fungicide products and their timing. The trials were assessed for the common diseases Sclerotinia and UCB as well as the less common diseases Alternaria black spot and powdery mildew that were also present at most sites. This paper outlines the key findings on the effectiveness of fungicide to control each disease as well as the grain yield response from fungicide control and the economics of their application.

Methodology

Trial sites were geographically spread to represent a range of climates and farming systems (Table 1). Trials were a randomised complete block design with four replicates for each treatment. Each trial was sprayed with a ute-mounted boom spray onto existing commercially grown and managed crops to ensure that the canopy remained intact, minimising open space for air to circulate which may have suppressed disease development. The sprayed plots were usually 40-50 m² in size with a smaller area of approximately 15-20 m² harvested with a small plot harvester when the crop was ripe (direct head) to minimise any potential influence from neighbouring treatments. All other crop husbandry prior to applications were completed by the grower.

Table 1. Site description for five canola fungicide response trials conducted in NSW, 2020.

Location	Region	Average annual rainfall	Average growing season rainfall	Variety
Ganmain	Eastern Riverina	475 mm	280 mm	HyTTec® Trophy
Kamarah	Northern Riverina	440 mm	220 mm	Pioneer® 44Y90 CL
Temora	South-west slopes	520 mm	310 mm	Pioneer® 45Y91 CL
Warren	Central-west plains	510 mm	210 mm	HyTTec® Trophy
Wellington	Central-west slopes	580 mm	300 mm	Victory® V75-03CL

Four products were used with multiple combinations of timings and rates (Table 2).

Table 2. Description of fungicide products used in five canola fungicide response trials conducted in NSW, 2020.

Trade Name	Active Ingredient 1	Group	Active Ingredient 2	Group
Aviator Xpro®	Prothioconazole	3	Bixafen	7
Miravis® Star**	Pydiflumetofen	7	Fludioxonil	12
Prosaro®	Prothioconazole	3	Tebuconazole	3
Veritas®	Tebuconazole	3	Azoxystrobin	11

***Miravis Star was applied under a research permit . It is currently under evaluation with APVMA.*

There were three application timings targeted at 10, 30 and 50% bloom (30 and 50% bloom only at Kamarah and Warren). The 30 and 50% timings are commonly suggested timings, with the 10% bloom timing added to reflect grower practice at those sites. Treatments at individual sites are shown in Tables 4-8 later in the paper. These spray timings are overlaid on daily rainfall in Figure 1. After good rains in early to mid-August at all sites, rainfall during the late winter/early spring period was generally below average.

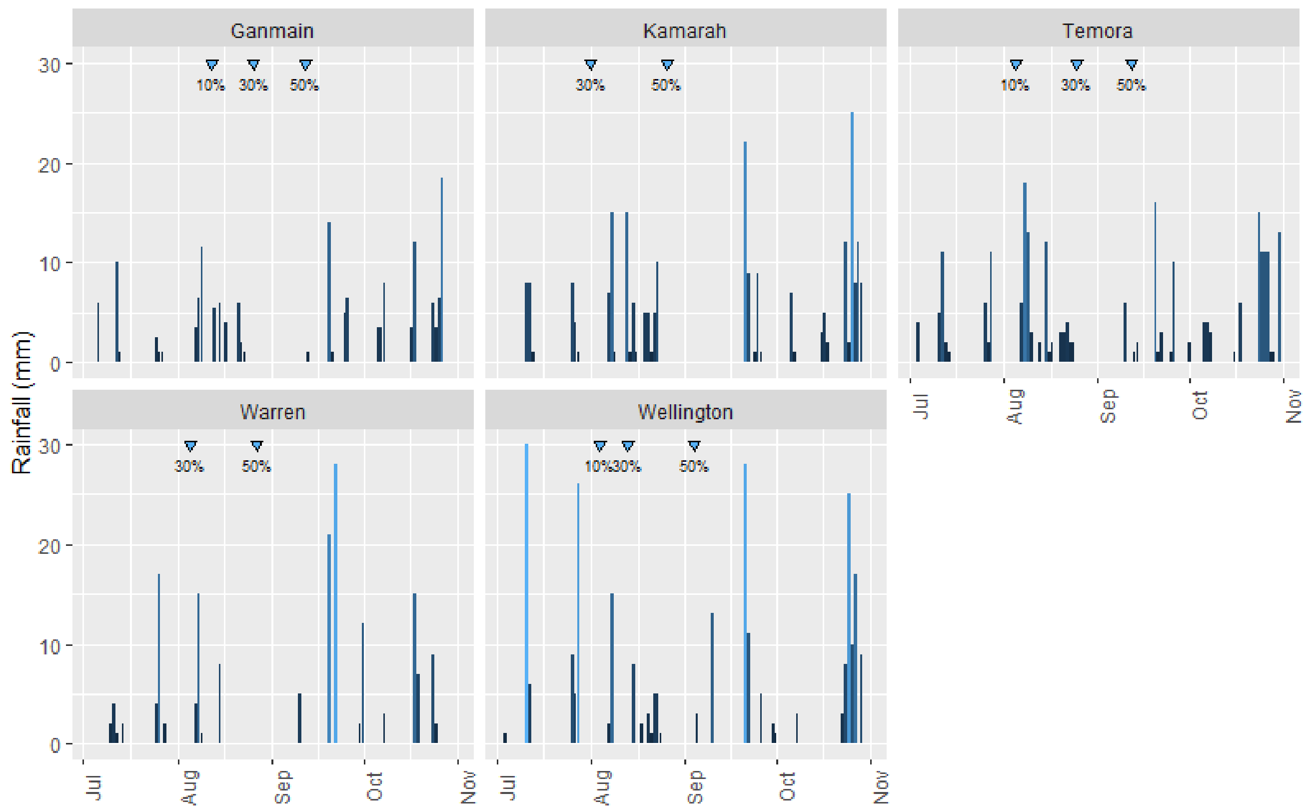

Figure 1. Daily rainfall received (vertical columns) and spray timings (inverted triangles) for five canola fungicide response trials conducted in NSW, 2020. Timings are bloom stage timing, e.g., 10% is 10% bloom stage.

Disease assessment

Diseases prevalence was assessed at one timing, targeted around 60-80 seed colour change (windrowing stage) with the methodologies detailed below.

Sclerotinia – two random sample areas of 1 m^2 were assessed in each plot, with the number of plants with Sclerotinia (basal, main stem and branch) counted along with the total number of plants in the assessment area to determine infection rates.

Upper canopy blackleg – a 0-4 score was allocated for the same two locations that were assessed for Sclerotinia:

- 0 = no infection observed
- 0.5 = at least one lesion found
- 1 = lesions present
- 2 = lesions common
- 3 = lesions common causing damage
- 4 = lesions common causing branch death

Alternaria black spot – the upper canopy blackleg scoring system was adapted for Alternaria with some minor tweaks:

- 0 = no infection observed
- 0.5 = at least one lesion found
- 1 = lesions present
- 2 = lesions common with 1-5% of pod/stem area infected

- 3 = lesions common with 5-15% of pod/stem area infected and low-level early pod senescence.
- 4 = lesions common with >15% of pod/stem area infected and high level of early pod senescence.

Powdery mildew – an assessment was made of the proportion of stem area infected with powdery mildew (two locations per plot as per Sclerotinia).

The trial results were analysed by ANOVA with 95% confidence level. Results are detailed in Tables four to eight below.

Results

Sclerotinia petal testing

Petal samples from 12 flowers from untreated areas were sent to the CCDM for determining the level of Sclerotinia present at each site. Sclerotinia was confirmed as present on petals at each of the five sites, with 100% of petals infected at Ganmain and Temora and down to 55% of petals infected at Wellington.

Table 3. Canola Sclerotinia petal infection rates at from five canola fungicide response trials conducted in NSW 2020.

Site	Petals infected (%)
Ganmain	100
Kamarah	78
Temora	100
Warren	87
Wellington	55

Geographic disease distribution

The highest levels of Sclerotinia infections were at the most south-eastern site Temora, where canola intensity and canopy moisture levels favoured disease development (Figure 2). There was no broader Sclerotinia infection of plants at Warren, despite petal tests confirming Sclerotinia as present at the site. Upper canopy blackleg (UCB) on branches ranged from only trace levels at the north-western site at Warren, to high levels of infection likely causing yield loss at the southern sites at Kamarah and Temora. Powdery mildew and Alternaria black spot (on pods) was most severe in the northern trials.

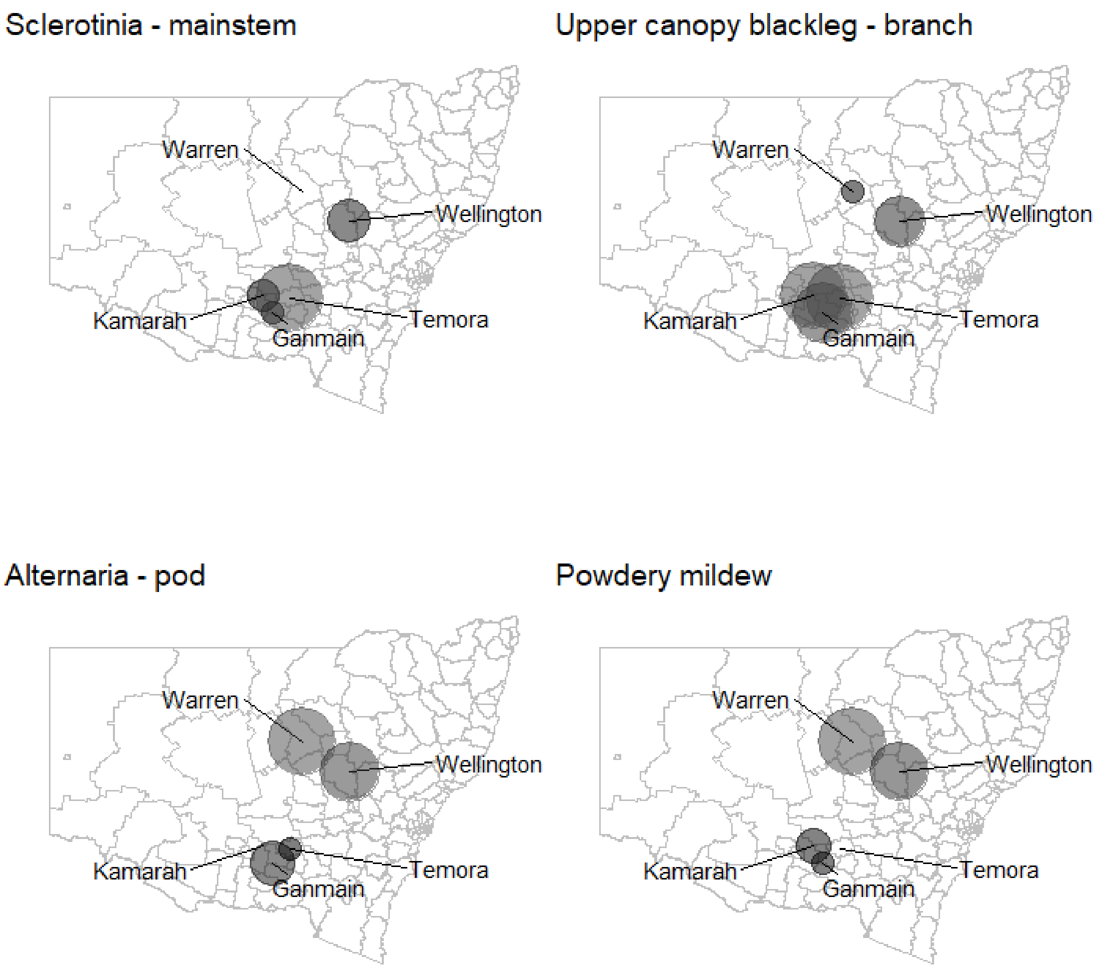

Figure 2. Severity of the diseases Sclerotinia stem rot (main stem), upper canopy blackleg (branch), Alternaria (pod) and powdery mildew across five canola fungicide response trials in NSW in 2020. Larger circles represent greater infection levels (data presented from untreated control). Data presented is dimensionless and no comparison can be made across diseases.

Ganmain

There was no grain yield response to the various fungicide treatments tested at Ganmain.

There was some reduction in Sclerotinia, UCB (branch), powdery mildew and Alternaria incidence, but disease levels were generally low. All fungicide treatments at the 30 and 50% bloom stage reduced Sclerotinia incidence compared to the untreated, but the 10% bloom fungicide treatment (Aviator Xpro only) did not reduce incidence. UCB (branch) was present but not at levels that would impact grain yield (rating of less than 2). Some reduction in incidence was achieved with single applications at 10 and 30% bloom applications of Aviator Xpro, second applications did not reduce incidence further than single spray treatments. A single application of Miravis Star at 30% also reduced incidence. Alternaria on pods was also common but not consequential, with incidence reduced by 50% bloom applications of Aviator Xpro. Powdery mildew was present at low levels, but disease incidence reduced further wherever Prosaro was applied at 50% bloom.

The Ganmain crop was HyTTec Trophy which has effective major gene (Group ABD) resistance to blackleg which may have reduced the severity of UCB infection. Although incidence on branches was easy to find, it was generally not at levels that would impact grain yield. There was only low level of blackleg on pods (data not shown). A further factor that reduced infection risk of this crop was that it flowered the latest of all the crops, with most (30-50% bloom) of the flowering period coinciding with a dry four-week period in late winter/early spring. For the period 1 July to 31 October, Ganmain had the least rainfall (160 mm) of the five sites.

Table 4. Canola grain yield, quality and disease response to fungicide in a crop of HyTTec Trophy at Ganmain 2020.

Fungicide treatment and timing (% bloom)*	Yield (t/ha)	Oil (%)	Sclero MS (%)	Sclero Br. (%)	UC BL Br.	Alt. pod	PM (%)
Aviator Xpro 650 mL/ha 10%	2.47	44.2	5.7	0.6	1.4	2.5	10
Aviator Xpro 650 mL/ha 30%	2.59	43.5	0.3	0	1.4	2.1	5.4
Prosaro 450 mL/ha 30%	2.56	42.9	0.3	0	1.7	2.5	2.9
Miravis Star 30%	2.61	43.9	0.5	0	1.4	2	5
Aviator Xpro 650 mL/ha 10% + Prosaro 450 mL/ha 50%	2.48	44	0.8	0	1.7	2.4	2.7
Aviator Xpro 650 mL/ha 30% + Prosaro 450 mL/ha 50%	2.56	43.5	0.6	0	1.4	2.4	1.2
Prosaro 375 mL/ha 30% + Prosaro 375 mL/ha 50%	2.61	43.4	0	0	1.9	2.2	1.5
Aviator Xpro 550 mL/ha 30% + Aviator 550 mL/ha 50%	2.52	43.6	0	0	1.4	1.5	5.6
Aviator Xpro 650 mL/ha 50%	2.53	43.9	0.6	0.3	1.7	1.9	4.5
Prosaro 450 mL/ha 50%	2.47	43.8	0.3	0	2.1	2.8	1.6
Untreated	2.49	42.9	3.3	1.8	2.2	2.8	9.1
l.s.d. (*p<0.05*)	n.s.	1	1.2	0.5	0.8	0.5	3.2

** Product recommendations for timing of application in canola vary. Not all products have claims at the 10% timing used in these trials or for all diseases evaluated (no products have claims for control of Alternaria or powdery mildew in canola). Check product labels for details.*

Sclero MS = Proportion of plants with Sclerotinia infection on the main stem. Sclero Br. = proportion of plants with Sclerotinia infection on a branch. UC BL Br = Upper canopy blackleg branch infection with protocol outlined in methodology. Alt. pod = Alternaria pod infection score with protocol outlined in methodology. PM (%) is proportion of stem are infected with powdery mildew. Shaded cells indicate results are significantly better than untreated i.e., less disease or more yield/oil.

Kamarah

There was a positive grain yield response (up to 0.4 t/ha) to all single-spray treatments at Kamarah except Prosaro at 50% bloom. There was no additional benefit of two-spray strategies over one fungicide spray.

Sclerotinia (main stem) infection was low, but all treatments reduced the incidence of the disease except the single applications of Prosaro (both 30 and 50% bloom) or Aviator Xpro at 50% bloom. Fungicide application at 30% bloom (except Veritas) reduced UCB (branch) infection, from levels that would likely reduce yield in the untreated control. All fungicide treatments provided some (but not complete) reduction in the incidence of powdery mildew.

The period between 30 and 50% bloom was relatively wet at Kamarah which may have partly contributed to higher branch blackleg infection than Ganmain. A further contributing factor is that the cultivar 44Y90 CL, despite having effective crown canker resistance, does not have effective major gene resistance.

Table 5. Canola grain yield, quality, and disease response to fungicide in a crop of 44Y90 CL at Kamarah 2020.

Fungicide treatment and timing (% bloom)*	Yield (t/ha)	Oil (%)	Sclero MS (%)	Sclero Br. (%)	UCI Br.	Alt. pod	PM (%)
Aviator Xpro 650 mL/ha 30%	2.87	42.7	0	0	1.9		4.1
Prosaro 450 mL/ha 30%	2.89	43.3	0	0	2.2		5
Veritas 1 L/ha 30%	2.71	42.3	0.5	0	3.1		8.6
Miravis Star 30%	2.70	42.7	0	0	1.9		4.9
Aviator Xpro 650 mL/ha 30% + Prosaro 450 mL/ha 50%	2.78	42.5	0	0	1.5		3.2
Prosaro 375 mL/ha 30% + Prosaro 375 mL/ha 50%	2.70	43.1	0	0	2		4.9
Aviator Xpro 550 mL/ha 30% + Aviator 550 mL/ha 50%	2.75	42.7	0	0	1.6		3.4
Aviator Xpro 650 mL/ha 50%	2.74	42.6	4.4	0.6	2.8		7.5
Prosaro 450 mL/ha 50%	2.67	42.6	3.4	0	2.6		7.4
Untreated	2.49	42.7	2.8	0	3.4		15
l.s.d. (*p<0.05*)	0.20	1	1.1	0.5	0.6		4.2

** Product recommendations for timing of application in canola vary. Not all products have claims at the 10% timing used in these trials or for all diseases evaluated (no products have claims for control of Alternaria or powdery mildew in canola). Check product labels for details.*

Sclero MS = Proportion of plants with Sclerotinia infection on the main stem. Sclero Br. = proportion of plants with Sclerotinia infection on a branch. UC BL Br = Upper canopy blackleg branch infection with protocol outlined in methodology. Alt. pod = Alternaria pod infection score with protocol outlined in methodology. PM (%) is proportion of stem are infected with powdery mildew Shaded cells indicate results are significantly better than untreated i.e., less disease or more yield/oil.

Temora

There was a positive grain yield response of up to 0.6 t/ha at Temora. Aviator at 10 and 30% bloom but not 50% bloom improved yields as did Miravis Star at 30% bloom. Prosaro at 30% did not increase yield but did at 50% bloom. Most (but not all) two-spray treatments improved yield.

Sclerotinia infection was highest of all five sites at Temora, but still only a moderate infection level of 12.2% of main stems infected where no fungicide was applied. Aviator Xpro at 10 and 50% bloom, and Veritas at 30% bloom did not reduce Sclerotinia incidence. Aviator Xpro at 10% followed by Prosaro at 50% bloom did not improve yield. Application of Aviator Xpro at 10 and 30%, Miravis Star at 30% bloom and all the two spray strategies reduced UCB (branch), but the best treatment still only reduced the score to a range from 1.5 to 2.1. Application of Prosaro and Veritas at 30% bloom and Prosaro and Aviator Xpro at 50% bloom did not reduce branch blackleg. Miravis Star at 30%, Aviator Xpro followed by Aviator Xpro (30 and 50% bloom) or Prosaro or Aviator Xpro at 50% bloom reduced Alternaria incidence on the pods but did not give full control.

A two-spray strategy generally provided good reductions of both Sclerotinia and blackleg, but no two-spray treatment resulted in higher grain yield than a single application of Aviator Xpro at 30% bloom.

Table 6. Canola grain yield, quality, and disease response to fungicide in a crop of 45Y91 CL at Temora 2020.

Fungicide treatment and timing (% bloom)*	Yield (t/ha)	Oil (%)	Sclero MS (%)	Sclero Br. (%)	UCI Br.	Alt. pod	PM (%)
Aviator Xpro 650mL/ha 10%	3.50	43.2	13.8	1.5	1.5	2	*Nil*
Aviator Xpro 650 mL/ha 30%	3.73	43.5	3.1	1.5	2.1	1.9	*Nil*
Prosaro 450 mL/ha 30%	3.37	43.6	2.6	0.3	2.9	2.1	*Nil*
Veritas 1 L/ha 30%	3.45	42.9	9.9	2	2.9	2.1	*Nil*
Miravis Star 30%	3.58	43.2	2.3	0	2.1	1.4	*Nil*
Aviator Xpro 650 mL/ha 10% + Prosaro 450 mL/ha 50%	3.73	42.6	6.1	0.3	1.7	1.9	*Nil*
Aviator Xpro 650 mL/ha 30% + Prosaro 450 mL/ha 50%	3.46	43.1	1	0	1.9	1.6	*Nil*
Prosaro 375 mL/ha 30% + Prosaro 375 mL/ha 50%	3.70	43.5	1	0	2.1	1.8	*Nil*
Aviator Xpro 550 mL/ha 30% + Aviator 550 mL/ha 50%	3.71	43	1.3	0.3	2	1.6	*Nil*
Aviator Xpro 650 mL/ha 50%	3.45	43.1	7.4	0.8	2.6	1.2	*Nil*
Prosaro 450 mL/ha 50%	3.62	43.6	4.6	0.8	3.3	2.1	*Nil*
Untreated	3.07	43.7	12.2	3.6	3.1	2.4	*Nil*
l.s.d. (*p<0.05*)	0.44	0.8	6.3	1.7	0.7	0.7	n.s.

** Product recommendations for timing of application in canola vary. Not all products have claims at the 10% timing used in these trials or for all diseases evaluated (no products have claims for control of Alternaria or powdery mildew in canola). Check product labels for details.*

Sclero MS = Proportion of plants with Sclerotinia infection on the main stem. Sclero Br. = proportion of plants with Sclerotinia infection on a branch. UC BL Br = Upper canopy blackleg branch infection with protocol outlined in methodology. Alt. pod = Alternaria pod infection score with protocol outlined in methodology. PM (%) is proportion of stem are infected with powdery mildew. Shaded cells indicate results are significantly better than untreated i.e., less disease or more yield/oil.

Warren

No fungicide treatments resulted in a significant increase in grain yield.

There was no Sclerotinia infection at Warren and low (inconsequential) levels of upper canopy blackleg. The main diseases apparent were powdery mildew and Alternaria infection on pods and stems. Powdery mildew infection was the highest of all five sites, with 67% of stem/branch area infected with powdery mildew by crop maturity (windrow timing) in the untreated control. Fungicide treatments with Prosaro applied at 50% bloom reduced powdery mildew incidence to close to very low levels with no benefit to yields (Prosaro does not claim control of powdery mildew in canola on its label). Alternaria infection on pods was high with only two-spray fungicide treatments providing a small level of control. The Warren site also had high levels of Alternaria on stems/branches, with all fungicide treatments giving some reduction in incidence (data not shown). Unlike branch blackleg observed at other sites, Alternaria did not manifest into cankers that eventually resulted in branch death but were usually superficial. It is difficult to ascertain if Alternaria infection on pods had any effect on grain yield, as no fungicide treatment resulted in clean pods. It is likely that fungicide would need to be applied when all pods are formed (e.g., end of flowering) to achieve good control of Alternaria, but all fungicide products need to be applied by the 50% bloom stage.

Table 7. Canola grain yield, quality, and disease response to fungicide in a crop of HyTTec Trophy at Warren 2020.

Fungicide treatment and timing (% bloom)*	Yield (t/ha)	Oil (%)	Sclero MS (%)	Sclero Br. (%)	UCI Br.	Alt. pod	PM (%)
Aviator Xpro 650 mL/ha 30%	3.72	41.3			0	3.6	19.5
Aviator Xpro 800 mL/ha 30%	3.60	41.1			0	3.6	17.1
Prosaro 450 mL/ha 30%	3.52	41			0	4	17.7
Veritas 1 L/ha 30%	3.39	40.2			0	3.6	20.6
Miravis Star 30%	3.56	40			0	4	43.1
Aviator Xpro 650 mL/ha 30% + Prosaro 450 mL/ha 50%	3.70	39.6	*Nil*	*Nil*	0	3	2.5
Prosaro 375 mL/ha 30% + Prosaro 375 mL/ha 50%	3.75	40.6			0	4	5.3
Aviator Xpro 650 mL/ha 50%	3.43	40.9			0.2	3.2	16.9
Prosaro 450 mL/ha 50%	3.47	40.5			0.2	3.6	5.8
Untreated	3.43	40.5			0.2	4	67.4
l.s.d. (*p<0.05*)	0.35	1.6	*n.s.*	*n.s.*	*0.1*	0.4	14.8

** Product recommendations for timing of application in canola vary. Not all products have claims at the 10% timing used in these trials or for all diseases evaluated (no products have claims for control of Alternaria or powdery mildew in canola). Check product labels for details.*

Sclero MS = Proportion of plants with Sclerotinia infection on the main stem. Sclero Br. = proportion of plants with Sclerotinia infection on a branch. UC BL Br = Upper Canopy Blackleg Branch infection with protocol outlined in methodology. Alt. pod = Alternaria pod infection score with protocol outlined in methodology. PM (%) is proportion of stem are infected with powdery mildew. Shaded cells indicate results are significantly better than untreated i.e., less disease or more yield/oil.

Wellington

There was a positive (0.2-0.3 t/ha) grain yield response for two of two-spray fungicide treatments, but no single-spray treatments increased yield. Sclerotinia infection levels were low and upper canopy blackleg infection levels were moderate at Wellington. All fungicide treatments except Prosaro and Veritas at 30% bloom provided control of Sclerotinia and upper canopy blackleg branch incidence. Powdery mildew incidence was moderate with best control where Prosaro was applied at the 50% bloom stage. Alternaria infection levels in the untreated control were high on pods (score of 3.9) and stems (score of 4, data not shown for stems) with best reductions from the single Aviator Xpro 50% bloom application (score of 1.4). Fungicide application did a better job of reducing Alternaria on the stems than on pods, again due to the inability to spray fungicide beyond 50% bloom stage to protect all pods. The large differences between Alternaria scores on the stems did not manifest into major differences in grain yield, indicating that Alternaria may have only been superficial.

Table 8. Canola grain yield, quality and disease response to fungicide in a crop of Victory V75-03CL at Wellington 2020.

Fungicide treatment and timing (% bloom)*	Yield (t/ha)	Oil (%)	Sclero MS (%)	Sclero Br. (%)	UCI Br.	Alt. pod	PM (%)
Aviator Xpro 650mL/ha 10%	3.78	43.1	1.1	0	0.7	3.4	24.4
Aviator Xpro 650 mL/ha 30%	3.71	42.9	0.6	0	0.7	3.5	21
Aviator Xpro 800 mL/ha 30%	3.75	43.4	0.4	0.4	0.9	3.1	15.9
Prosaro 450 mL/ha 30%	3.51	43	5.8	0.3	1.9	3.6	15.2
Veritas 1 L/ha 30%	3.62	43.1	3.5	3.3	1.4	3.6	18.2
Aviator Xpro 650 mL/ha 10% + Prosaro 450 mL/ha 50%	3.90	43.3	0	0	0.4	3.3	4.4
Aviator Xpro 650 mL/ha 30% + Prosaro 450 mL/ha 50%	3.77	42.7	0.5	0	0.7	3.4	8.2
Prosaro 375 mL/ha 30% + Prosaro 375 mL/ha 50%	3.81	43.2	0.8	0.3	0.7	3.2	5.2
Aviator Xpro 650 mL/ha 50%	3.76	43.7	1.1	0	1.1	2.1	12.5
Prosaro 450 mL/ha 50%	3.77	42.5	0.9	0.4	0.8	3	6.1
Untreated	3.64	43	4	1.7	1.9	3.9	18.8
l.s.d. (*$p<0.05$*)	0.17	0.9	2	2.2	0.6	0.6	8.7

** Product recommendations for timing of application in canola vary. Not all products have claims at the 10% timing used in these trials or for all diseases evaluated (no products have claims for control of Alternaria or powdery mildew in canola). Check product labels for details.*

Sclero MS = Proportion of plants with Sclerotinia infection on the main stem. Sclero Br. = proportion of plants with Sclerotinia infection on a branch. UC BL Br = Upper Canopy Blackleg Branch infection with protocol outlined in methodology. Alt. pod = Alternaria pod infection score with protocol outlined in methodology. PM (%) is proportion of stem are infected with powdery mildew. Shaded cells indicate results are significantly better than untreated i.e., less disease or more yield/oil.

Fungicide economics

To determine the economic benefit of the fungicide treatments, grain yield was multiplied by price (allowing for oil increments) and costs of fungicide product and application costs were subtracted. This partial gross margin was then analysed as a variate in the same way that grain yield was analysed (Miravis Star was not included in the economic analysis as it has not yet commercially available).

We assumed a price of:

- $550/tonne for canola (+/- 1.5% for each 1% oil above or below 42%)
- $54.50/L Aviator Xpro
- $74.50/L Prosaro
- $21/L Veritas
- $13/ha application cost

At Ganmain there was no (statistical) difference in the partial gross margin (gross income less treatment and application costs) of any treatment compared to the untreated control. There was a higher partial gross margin at Kamarah only from the application of both Aviator Xpro and Prosaro at 30% bloom. At Temora, the highest partial gross margin was from a single spray of Aviator Xpro at 30% bloom. At both Warren and Wellington, there was no economic benefit of any fungicide treatment compared to the untreated control.

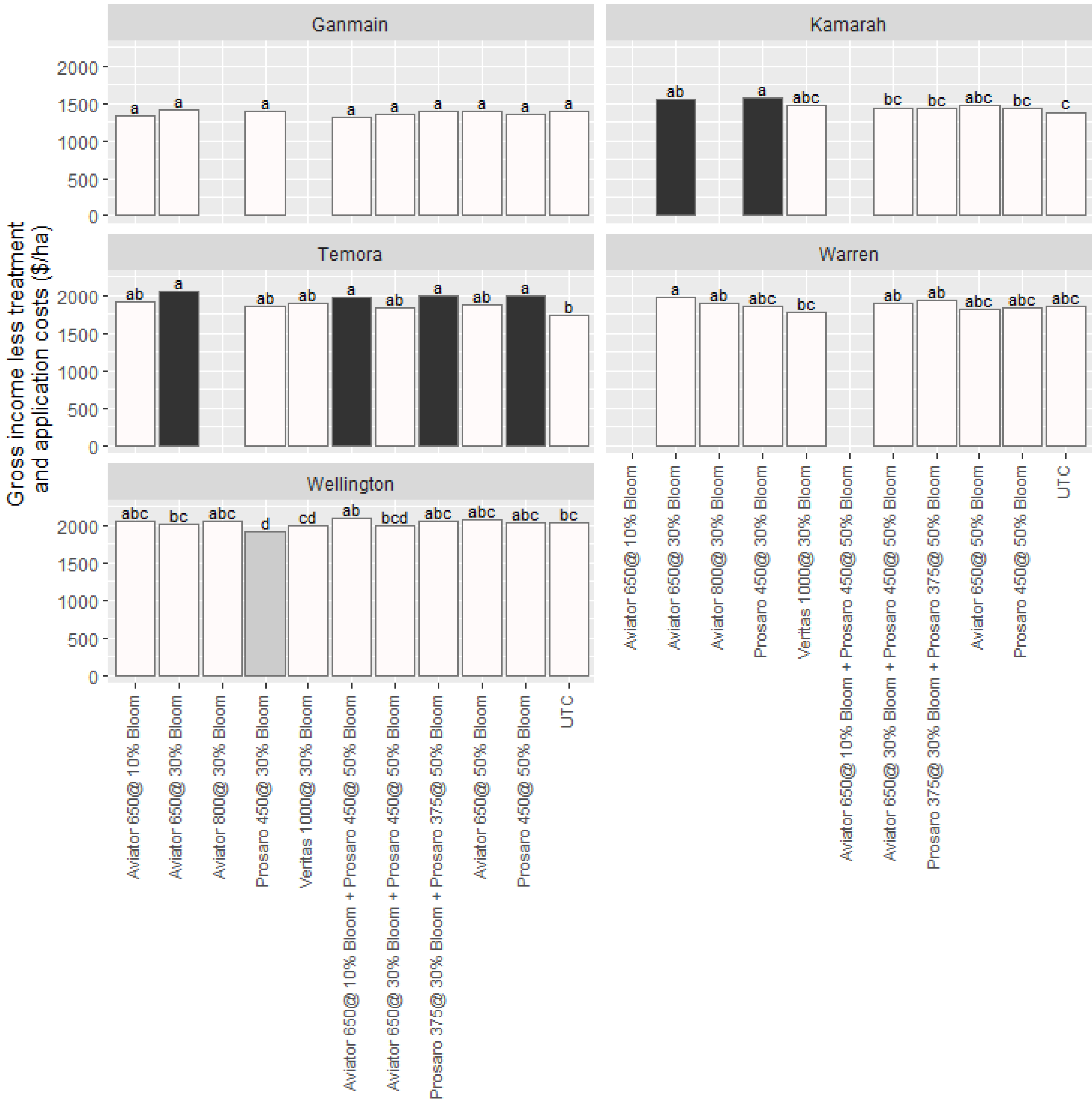

Figure 3. Partial gross margin (gross income less fungicide product and application costs) of fungicide treatments across five sites in NSW in 2020. Treatments with the same letter are not significantly different at p=0.05. Treatments in black are significantly higher than untreated control (UTC) and treatments in grey are significantly lower than UTC.

Discussion and conclusion

Many southern and central NSW canola crops in low-medium rainfall zones had a foliar fungicide applied to them in 2020. The primary driver was protection from Sclerotinia stem rot predicted by a wet first half to the cropping year leading to higher yield potential and medium-term forecasts predicting above average rain through spring. The secondary concern was UCB, especially in southern regions. The presence of Sclerotinia spores was confirmed by petal testing at all trial sites and blackleg was observed at all sites. Despite presence of these diseases at all sites, improvements in grain yield were not common or consistent and economic benefits from fungicide were evident at only two sites.

Petal testing indicated that Sclerotinia inoculum was present at all sites. That visual inspections at Warren and Wellington did not find any apothecia would tend to indicate that infections may have come from neighbouring paddocks. On the other hand, the presence of inoculum was not a good predictor of the ensuing levels of infection.

At all sites, a period of dry weather was experienced through late August and early September which may have limited the development of Sclerotinia in the canopy, however, all sites received good rainfall thorough the early flowering period and again during the late flowering period at most sites.

However, Sclerotinia and blackleg were not the only diseases present in these trials and, although separate assessments were made on the impact of fungicide treatment on the multiple diseases present, it is impossible to attribute yield response (where observed) to any one disease. Yield responses may have been due to reduction in infection of one or more diseases.

Sclerotinia and blackleg were at low levels in the two northern trials (Warren and Wellington) whereas powdery mildew and Alternaria infection were relatively high but spraying fungicide did not provide an economic benefit at these two sites. (None of the products tested have label claims for these two diseases in canola).

Some reduction in Alternaria was achieved with fungicides but it was difficult to ascertain the level of yield loss as even a two-spray strategy was not enough to fully protect pods. The latest spray timing on label is 50% bloom and at this stage only 20-30% of pods have formed. Powdery mildew was a talking point at windrowing time in many crops in the central-west. We found good reductions in in symptoms where Prosaro was applied at 50% bloom yet there did not appear to be significant yield losses even at high levels of infection. Prosaro does not have a label claim for control of powdery mildew in canola.

There was a more compelling case for the economic benefit of fungicides in two of the three southern sites, but not with all treatments. Both responsive sites (Kamarah and Temora) were in cultivars without effective major gene resistance to blackleg, so yield response may have been due to upper canopy blackleg (branch) infection as well as Sclerotinia (especially at Temora). A single spray of Aviator Xpro at 30% bloom provided the most consistent economic benefit in the two responsive southern sites, at Temora returning a net $323/ha net advantage over the untreated.

Overall, despite the presence of several diseases including Sclerotinia and UCB and high yield potential, positive responses to fungicide applications were not universal across sites. In hindsight the dryer conditions in late Autumn to early Spring may have limited disease progression and hence reduced the necessity for fungicides. However, as fungicides are prophylactic, growers and advisors can only work with the information they had at the time.

Many growers and advisors saw the application of fungicide as an insurance policy rather than as an investment and were comfortable knowing they had some of the best crops they had ever grown protected from the potential negative yield effects of key fungal diseases. There are several other 'investments' that could be made into a canola crop where returns are more predictable (such as nitrogen) and ideally the investments that give a reliable return should be addressed before spending more money on 'insurance'.

However, given that 2020 was such a good season with very high yield potential, and that economic benefits were not always present, should give growers the confidence that in seasons with only 'average' grain yield potential, expenditure on fungicide may not be justified and money may be better invested elsewhere.

Management factors that growers can implement in 2021 to reduce fungicide requirement during the flowering period include:

- Select cultivars with effective major gene blackleg resistance. Monitor updates to the GRDC Blackleg Management Guide to guide decision making

- Match phenology and sowing date so that crops do not flower too early. Early flowering will usually result in greater exposure to disease - especially upper canopy blackleg
- Closely monitor short-term forecasts as diseases require moisture for infection
- Consider using some of the decision support tools that may quantify the risks of canola diseases and the need for fungicide applications.
  - One example promoted by Bayer can be found at- https://www.crop.bayer.com.au/-/media/bcs-inter/ws_australia/use-our-products/product-resources/prosaro/prosaro_420_sc-factsheet-sclerotinia_control.pdf
  - Download the SclerotiniaCM and BlacklegCM decision support Apps for your tablet or iPad device
- Avoid sowing canola in or near paddocks that have had high levels of disease infection recently
- When a fungicide is required, apply at the correct time (~30% bloom) and with good coverage to avoid needing a second fungicide.

By reducing the need for fungicide, growers may be able to invest in other inputs where higher returns are guaranteed.

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Diseases in pulses and canola – the watchouts and implications for 2021

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GRDC code

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Take home messages

- Changes in farming practice in the last 15 years have increased disease pressure on cropping rotations in southern NSW
- In 2020, exceptional conditions for crop production also increased the incidence and severity of disease in broadleaf crops in the region. This will have implications for disease management in crops in 2021
- Annual crop surveys are an important means of monitoring disease incidence and severity between districts and between years. Surveys enable the identification of emerging disease issues and forewarning of potential problems
- Sclerotinia diseases were widespread in broadleaf crops across the region in 2020, especially narrowleaf lupin and canola. This will have implications in 2021 and beyond
- Blackleg was observed in every canola crop assessed as part of the IDM crop survey
- Canola sown into a double break scenario will potentially require pre-emptive management to minimise disease risk
- The decision to use fungicides is not always clear and should be assessed every year, depending on the disease risk profile of your crop
- Other significant diseases this season included virus diseases and Botrytis grey mould (especially in narrowleaf lupin).

Introduction

In the last 20 years, grains production in southern NSW has changed significantly. Many landholders have moved entirely into grain production enterprises, removing livestock and pastures from their farming system. Agronomic practices have changed including stubble retention, minimum tillage and crop sequences. These changes have increased the disease burden across the farming system. Management of disease in the cropping system is now an important and annual consideration for many grain producers in southern NSW.

In 2020, sowing conditions were considered ideal across many districts, and crops were sown on time. Rainfall patterns and mild temperatures across the south provided ideal conditions for developing crops and resulted in some of the best crop yields seen for many years. These ideal conditions also allowed development of root and foliar diseases in broadleaf crops across the region. In many instances, even low levels of pathogens were able to develop into epidemic levels, despite the dry conditions in 2018 and 2019. In general, disease management practices across the region were very good, but there will be disease implications to consider moving into 2021.

Crop surveys have been undertaken for several years in southern NSW to monitor changes in disease prevalence, distribution and impact across farming systems and districts. Surveys are a valuable tool in the identification of emerging disease threats, monitoring IDM strategies, guide priorities for future research effort, and provide a mechanism for industry awareness and preparedness.

This paper discusses the priority diseases identified in 2020 crop surveys and implications for grains producers in 2021.

Methodology

With the assistance of local agribusiness, 45 pulse crops and 30 canola crops were sampled in 2020 at the early flowering to early pod filling stage (early August to late September). Crops details were collected including GPS location, previous cropping history and herbicide use. Crop locations were restricted to the southern half of NSW, that is south of Dubbo to the Victorian border.

Six pulse crop species were surveyed (albus lupin, narrowleaf (NL) lupin, faba bean, field pea, lentil and chickpea) and one oilseed crop (canola). There were no targets set for each species, but rather the number of crops sampled reflected the frequency of crops across the region.

At each crop a diagonal transect was followed starting at least 25m into the crop from the edge, to avoid any double sown areas, roadsides, dam or trees. At 10 locations at least 25 m apart along the transect, a row of 10 random plants was assessed for symptoms of foliar disease and any other abiotic issues present. At five locations (every second assessment point), five random whole plants along a row were collected for detailed assessment of disease and root health. The samples were prepared for assessment of fungal DNA concentrations at SARDI.

Table 1. The breakdown of commercial crops assessed and sampled as part of the 2020 IDM crop survey.

Region	NL lupin	Albus lupin	Chickpea	Field pea	Faba bean	Lentil	Canola	Total
Riverina	6	2	4	5	4	2	9	32
SW Slopes	8	3	2	2	3	2	16	36
CW Slopes and Plains	2						6	8
Total	***16***	***5***	***6***	***7***	***7***	***4***	***31***	***76***

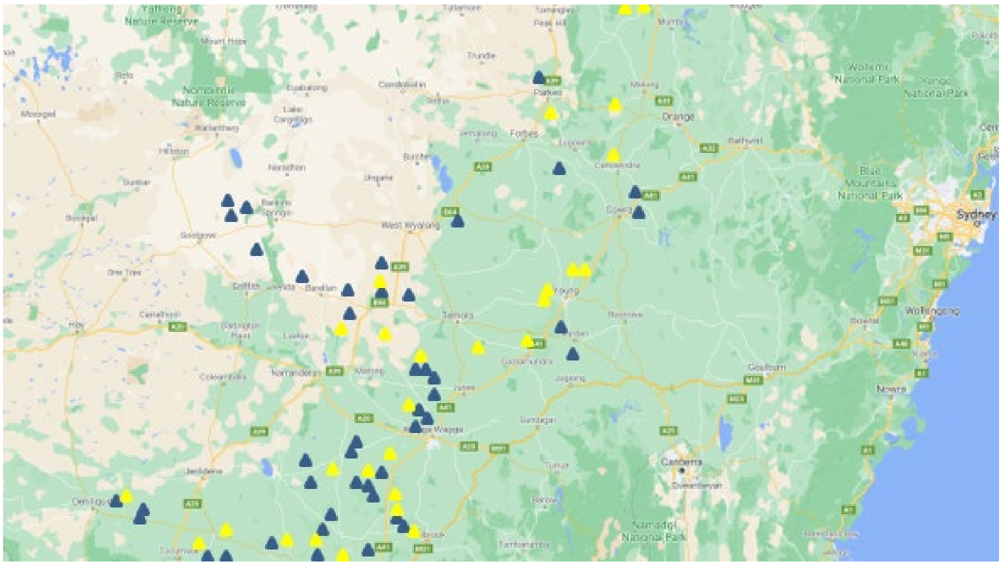

Figure 1. Distribution of pulse and canola paddocks assessed as part of the 2020 IDM crop survey. 45 pulse crops (blue triangles) and 30 canola crops (yellow triangles) were sampled for the presence of foliar and root disease.

What did the survey find?

Sclerotinia (all pulses)

Sclerotinia diseases (stem rot and white mould) were the most prevalent diseases found across all pulses in this season's survey. A combination of exceptional crop growth and frequent rain periods during late winter and spring provided ideal conditions for this pathogen to develop across a wide region of southern NSW and range of broadleaf crops in the rotation.

Symptoms of the disease included basal infections, stem lesions and pod infections. Basal infections are the result of direct infection of plants by mycelium from germinating sclerotia. As sclerotia in the soil soften in winter from wet soil conditions, mycelium is produced that grows along or just under the soil surface. Once this mycelium encounters a plant stem, direct infection occurs that can kill the plant completely. Symptoms appear as a fluffy white collar that occurs around the stem base at soil level (often referred to as collar rot). Newly formed sclerotia will also be produced in this tissue. Stem and pod lesions are the result of infection via ascospores, in a similar way to the infection process in canola. Apothecia (flattened golf tee like fruiting structures of the Sclerotinia fungus) germinate from sclerotia in the soil. The apothecia produce and release airborne ascospores that land on and infect suitable plant tissues, often old senescent leaf and flower tissue or pods. Symptoms appear as fluffy white mycelium on the outside of stems and on pods (particularly lupin), often killing the plant above the lesion. Newly formed sclerotia often develop either within infected stems or on the outside, if conditions are favourable.

Table 2. Proportion of pulse crops inspected and found to have Sclerotinia spp. present as part of the 2020 IDM crop survey.

	NL Lupin	Albus lupin	Chickpea	Field pea	Faba bean	Lentil
No. of crops sampled	16	5	6	7	7	4
No. of crops with Sclerotinia	13	3	3	3	5	1
% of crops infected	81%	60%	50%	43%	71%	25%

Implications for 2021: Sclerotia produced by infected crops in 2020 pose a significant disease threat in 2021 and beyond. Many of the crops detected with the disease in 2020 had been sown to successive cereal crops in 2018 and 2019, meaning the sclerotia responsible for the disease in 2020 were most likely formed prior to these cereal crops, therefore in 2017 or 2016. It is well known that sclerotia are long lived. The majority of sclerotia can survive for up to 5 years in the top five centimetres of soil, however this can increase up to 10 years if buried deeper and not exposed to microbial activity. Growers, agronomists and advisers should pay attention to crop choice and management for the next few seasons, especially those growers following 'double break' cropping systems. Sowing canola or pulses into paddocks known to have outbreaks of Sclerotinia in 2020 face a significant disease risk, especially in medium to high rainfall districts.

Blackleg (canola)

Blackleg, caused by the fungus *Leptosphaeria maculans*, was the most common disease observed in canola in the 2020 crop survey. Each of the 31 crops inspected had symptoms of the disease present at varying levels of severity. Symptoms ranged from leaf infection to stem cankered plants.

The high incidence of blackleg in commercial canola crops is not surprising in 2020 given the conducive conditions for the disease to develop this year. Differences in severity could be attributed to crop variety, fungicide use and proximity to old canola stubble. Frequent wet days throughout winter and spring provided multiple leaf wetness periods for infections to occur and proliferate. At the time of observation (mid-August to early September), those leaf infections that had developed towards the top of the crop canopy had potential to develop into upper canopy infection (UCI).

Implications for 2021: The large area sown to canola in central and southern NSW means there will be large areas of canola stubble in 2021 producing blackleg inoculum. Disease management in canola changes seasonally depending on the variety, seasonal conditions and frequency of canola in the rotation.

Consideration also must be given to disease risk factors impacting on the new season crop; is seedling protection important, do I need to apply fungicides for UCI, or are there diseases other than blackleg to consider? Often these risk factors cannot be addressed at the start of the season and require on-going crop monitoring and scouting for disease symptoms to make decisions that are cost effective. Scouting for symptoms is a powerful way to keep abreast of blackleg development within crops and make decisions around fungicide applications. Scouting is particularly important in the management of UCI.

More than ever, blackleg management in medium to high rainfall zones relies on fungicides as cultural practices become difficult to implement. With a suite of new fungicides and fungicide actives on the market, it is strongly recommended to rotate actives where possible to avoid the development of resistance in the pathogen population. CropLife Australia has on-line resources available for rotating fungicides in canola:
(https://www.croplife.org.au/resources/programs/resistance-management/canola-blackleg/)

Another useful resource is the BlacklegCM app. Prior to sowing, use the BlacklegCM decision support tool to identify high risk paddocks and explore management strategies to reduce yield loss due to disease.

Botrytis grey mould (narrowleaf lupin)

Botrytis grey mould (BGM), caused by the fungus *Botrytis cinerea*, is a disease normally associated with lentil, chickpea, vetch and faba bean production. Crop surveys in 2020 also observed this disease in narrowleaf lupin crops, with 43% of crops infected. Outbreaks of BGM are initiated on senescent plant tissues, such as old leaves and flower parts before developing into larger, more damaging lesions. The large, dense crop canopies produced by narrowleaf lupin crops in 2020 favoured the development of senescent tissue following canopy closure and when light penetration into the canopy was hindered.

Symptoms of the disease included stem and leaf infections, and infections of old flower parts and pods. Whilst the disease can be confused with Sclerotinia white mould, the fluffy mycelium produced by the fungus is grey rather than white and no sclerotia are produced. Outbreaks of BGM are considered rare in narrowleaf lupin, but the causal fungus is ubiquitous. Extraordinary seasonal conditions in 2020 favoured development of this disease.

Implications for 2021: Old lupin stubbles affected by BGM present a significant inoculum source in 2021. The BGM fungus can infect other pulses including chickpea, lentil and faba bean. Spores of the BGM pathogen are airborne and will form readily on old infected stubble and be blown into surrounding crops. Care should be taken to avoid growing pulse crops (especially chickpea, lentil and faba bean) adjacent to old narrowleaf lupin stubbles in 2021. If this cannot be avoided, the crop should be managed as a medium to high disease risk and considerations made for foliar fungicide use where economically justified.

Virus (all pulses)

Virus diseases were evident in many pulse crops across central and southern NSW in 2020. All major pulse viruses require an aphid vector to infect host plants and the severity of virus diseases depends on the movement of aphids through a crop. Aphids require a living host plant to survive crop-free periods ('green bridge'). For the 2020 season, good summer and autumn rainfall, and mild winter temperatures allowed for the build-up and maintenance of aphid activity across the region. This resulted in the appearance of virus symptoms in many pulse crops by late winter and early spring. Within the survey, virus symptoms were most noticeable in narrowleaf lupin and lentil crops.

Symptoms in narrowleaf lupin ranged from plants with shortened internodes and bunchy tops (typical for cucumber mosaic virus, CMV), to plants with a withered top, bright yellow leaves and premature death (typical for bean yellow mosaic virus, BYMV). Lentil crops featured shortened plants, bunchy growth and premature yellowing. Virus diseases in southern NSW during 2020 were not as severe as in northern NSW, where BYMV resulted in serious yield losses in a large number of faba bean crops. A number of narrow-leafed lupin crops in central NSW also suffered severe yield losses caused by CMV and Alfalfa mosaic virus (AMV).

Yield loss due to virus is not always easy to estimate compared to a fungal disease. Early virus infections tend to result in greater yield loss and subsequent plant death compared to infections later in the season when plants are more developed.

Implications for 2021: The occurrence of virus in pulse crops in 2020 demonstrated how dynamic virus diseases can be within the cropping system, and the influence of environmental conditions on the build-up and movement of virus vectors. The use of virus-free seed is of particular importance for narrow-leafed lupins, as CMV can be transmitted at high levels in narrow-leafed lupins. Sowing crops with virus infected seed can result in poor establishment and seedling vigour, in addition to becoming a source of virus infection throughout the crop. Following the agronomic recommendations of sowing into cereal stubble and sowing at the recommended sowing rate to avoid having thin or poorly established crops can also discourage aphid landings within crops and slow down virus spread.

Department of Primary Industries and Rural Development (DPIRD) in Western Australia offer commercial tesing of pulse seed for virus, for more details on the diagnostic services provided contact DDLS Specimen Reception +61 (0)8 9368 3351 or DDLS@dpird.wa.gov.au for .

Other diseases

Ascochyta blight: The most serious disease of chickpea in Australia was recorded in 30% of chickpea crops surveyed in 2020, however, reports of damaging levels of the disease in southern NSW were minimal. Strategic use of fungicides is highly effective at managing the disease which is spread through rain splash of spores. Be aware of the significant inoculum sources in 2021, as the pathogen survives on old infected chickpea stubble and seed.

Blackspot: The most common disease of field pea in Australia and most damaging in paddocks with a high frequency of field pea production. Spores of the fungus survive on old field pea stubble and in soil. Whilst blackspot was observed in 71% of field pea crops surveyed, only a single crop developed the disease at a damaging level. Avoid sowing next season's crop adjacent to last year's stubble and observe a four-year break between field pea crops in the same paddock.

Chocolate spot: Potentially the most damaging disease of faba bean and responsible for the nickname 'failure beans' in the 1990's. The 2020 crop survey observed the disease in 43% of crops at low to moderate levels. Improvements in variety resistance and the range of foliar fungicide options available have significantly improved disease management and reduced potential for yield loss.

Bacterial blight: Mild winter conditions and few damaging frost events resulted in limited outbreaks of this disease compared to 2018 and 2019. Bacterial blight was observed in 28% of field pea crops inspected in the survey. The disease generally appears in low lying areas of field pea crops, which are most prone to frost and freezing injury. The disease is challenging and relies on pre-emptive disease management strategies such as maintaining at least a 3-year rotation between field pea crops and sowing disease-free seed. There are no post emergent disease management options. The bacterial pathogens survive on old field pea stubble and seed.

Phomopsis stem blight: Whilst this disease does not cause significant yield loss, presence of the disease within lupin crops poses a significant risk to livestock health. The causal fungus, *Diaporthe toxica*, produces a toxin as it grows within lupins that can kill grazing livestock, especially young sheep. Care should be taken when grazing lupin stubbles following harvest and especially following summer rain which stimulates growth of the fungus within stubble. It is rare to observe the disease whilst lupin plants are still green, but a single narrowleaf and a single albus lupin crop were observed with the disease during the survey. Typically, growth of the fungus becomes most apparent following harvest and after rain when fruiting structures of the fungus develop on lupin stubbles.

Conclusions

The results from the survey this year demonstrate the ability of pathogens to persist between years, even when conditions are unfavourable. Environmental conditions in 2020 allowed what were considered to be low levels of disease to build up quickly and becoming potentially damaging in broadleaf crops across the region. No new emerging disease threats were identified in 2020 from surveys, but several common diseases occurred at significant levels that will potentially impact for the next few seasons including Sclerotinia stem rot, blackleg and Botrytis grey mould.

Where possible an integrated approach should be used to manage disease in grains crops. More than ever we are becoming reliant on fungicides to maintain tight cropping rotations and high yields. The loss of fungicides from the system due to the development of resistance or detection of residues in end products will quickly remove these valuable tools from the system.

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Day 2 – Wednesday 17 February 2021

De-risking nitrogen - the case for change!

Nitrogen loss pathways. How much N is lost when urea is not mechanically incorporated after application?

Graeme Schwenke, NSW DPI

Key words

volatilisation, ammonia, broadcasting, urea, nitrogen loss, nitrogen cycle

Take home messages

- If surface-applied urea is not incorporated into the soil, some of the nitrogen (N) may be lost via volatilisation of ammonia (NH_3) gas from the soil to the atmosphere. Runoff of dissolved urea soon after fertiliser application can also occur if intense rainfall exceeds infiltration
- Volatilisation of broadcast urea from Australian cropping soils average 11.7% of applied N (range: 5.4–27%) from fallow soils, and 8.1% (range: 0–29%) in-crop. Field measurements of volatilised N in the grains industry have been sparse and sporadic. Globally, urea volatilisation loss averages 14.5% of applied N (includes crop, pasture, forest). Losses of up to 64% of applied N have been reported
- Loss of N via volatilisation is driven by soil properties, weather conditions, and stubble/crop cover. A simple on-line model is available to estimate NH_3 volatilisation from urea applied to moist soils. Inputs required are soil pH, clay%, fertiliser rate/placement, rainfall, and crop growth stage. More field measurements are required to better validate its use across the many soils of the Australian grains industry under various soil moisture, crop/stubble cover and weather conditions
- Ammonia volatilisation loss will be low when urea is broadcast onto dry, clay soil under non-humid, non-windy conditions followed within a few days of application by sufficient rainfall to move the urea/ammonium into the soil. In contrast, NH_3 loss will be higher when urea is applied to wet soil followed by dry, windy conditions with little or no follow-up rainfall.

Nitrogen pathways

The nitrogen (N) cycle in the soil, water and air is complex (Figure 1). There are many solid, solution and gaseous forms of N that are interconnected by a variety of processes—some biologically-driven others purely chemical. What diagrams like Figure 1 do not show, are the relative amounts of N present in the different forms and the different rates of change from one form to another. In many situations, only some of these pathways are relevant, with the actual conditions dictating which will dominate. For example, N loss to the air via denitrification can be a major pathway for loss of nitrate-N in clay soils if they become anaerobic due to waterlogging, but denitrification is typically minimal otherwise. Likewise, soil erosion can lead to catastrophic losses of both organic and inorganic N forms in extreme situations, but should be minor under more normal weather conditions and well-managed (minimised) surface water flow.

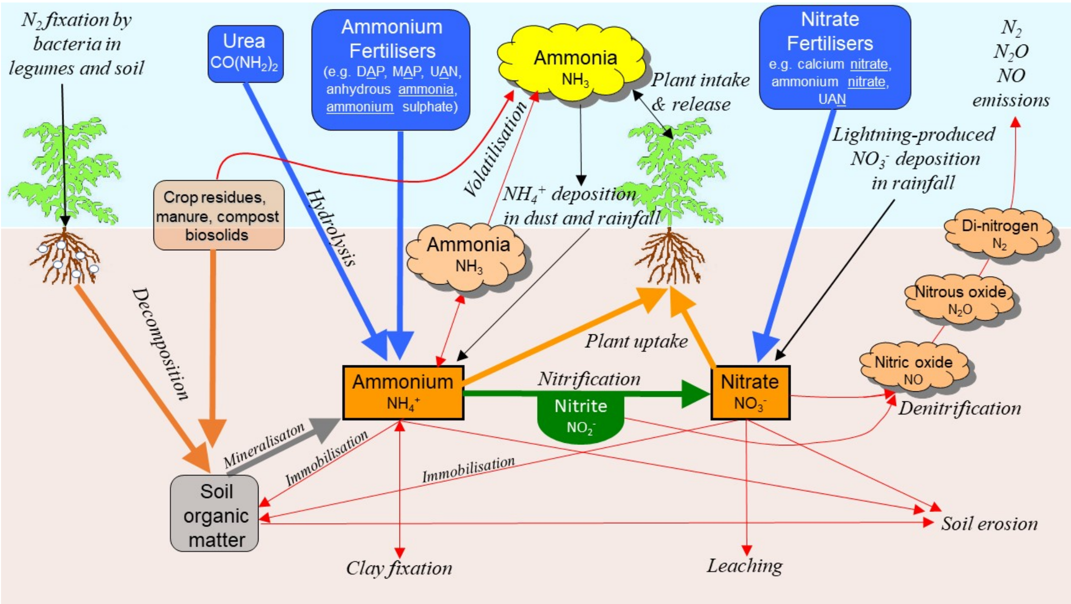

Figure 1. Major pathways and forms in the nitrogen cycle in soil, water and air.

The specific situation considered here is the fate of urea fertiliser applied to the soil surface but not mechanically incorporated. What happens next depends on the soil properties, the weather, stubble/crop cover and the soil surface condition.

Urea dissolves

Urea is highly soluble (1079 g/L at 20°C) so broadcast granules dissolve on contact with dew, rain, wet soil, wet plant/crop residue surfaces or even a humid atmosphere. Urea is hygroscopic, meaning it will absorb moisture from the air depending on the ambient relative humidity and air temperature. If the critical relative humidity is exceeded, urea will quickly dissolve. As temperature increases from 5 to 35°C, the critical relative humidity required for urea to dissolve decreases from 83.9% to 72.6%. Humidity within furrows, surface soil cracks and indentations, stubble cover and crop canopies may be greater than in the bulk atmosphere and therefore dissolve urea falling into these microsites. In contrast, urea scattered on bare, flat soil surfaces during cold, low-humidity conditions may remain undissolved for up to several weeks (Schwenke et al., 2014).

One possible scenario where broadcasting urea may lead to immediate N loss from the target paddock is where the urea is applied to a soil profile that is already at field capacity and is then immediately followed by high-intensity rainfall. If the rainfall intensity exceeds the rate of water infiltration into the soil, the dissolved urea may be carried off the target field in surface water flow, or at least be concentrated into the furrows and downslope paddock areas.

Within the soil, dissolved urea moves easily via diffusion and mass flow as it has no ionic charge. Therefore, the best chance to move applied urea-N into the soil via rainfall or irrigation is as soon as possible after broadcasting while it is still in the urea form. In irrigated cropping, urea is commonly broadcast directly ahead of irrigation or water-run in irrigation water (fertigation).

Urea hydrolysis

Once dissolved, urea chemically decomposes via hydrolysis (Figure 2). Hydrolysis is a chemical process in which a molecule of water ruptures another chemical bond—in this case the two carbon-nitrogen bonds in a urea molecule. Urea hydrolysis is accelerated (catalysed) by urease, an enzyme naturally found in numerous bacteria, fungi, algae, plants, some invertebrates and in bulk soils. The activity of urease tends to decrease with soil depth as does biological activity. If the enzyme were not present, the reaction would take years rather than minutes/hours, but ureases are ubiquitous in agricultural landscapes. In a warm, moist soil urea hydrolysis normally takes 3–7 days. Volatilisation of N does not occur until urea is hydrolysed so slowing or inhibiting the process allows more time for rainfall to move urea into the soil before ammonium is produced.

During hydrolysis, dissolved urea reacts with water (H_2O) and consumes H^+ ions from the soil solution to form bicarbonate (HCO_3^-) and ammonium (NH_4^+) ions (Figure 2). The HCO_3^- then consumes more H^+ ions from the soil to form carbon dioxide (CO_2) and H_2O. Where the urea is placed at the soil surface, the CO_2 gas readily escapes and the HCO_3^- continues to be lost.

The consumption of H^+ ions from the soil in both the hydrolysis and the HCO_3^- breakdown reactions causes an increase in pH (more alkaline) at the reaction sites—how much of an increase depends on the soil's pH and its pH-buffering capacity. Soils with a low buffering capacity will show a greater pH increase during urea hydrolysis than soils with a high capacity. Soil pH buffering capacity is mainly determined by its clay minerals (type and amount) and organic matter content.

When the pH in the hydrolysis reaction zone exceeds 8.2, the breakdown of HCO_3^- may instead produce carbonate (CO_3^{2-}) ions which slows the net increase in pH. The final pH reached has a major influence on the subsequent loss of NH_3 gas via volatilisation (see next section).

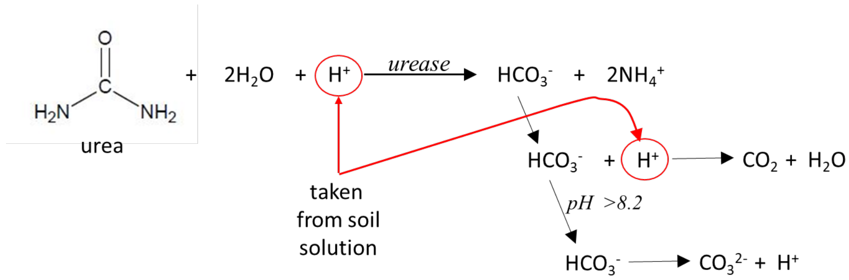

Figure 2. The urea hydrolysis process (Kissel and Cabrera, 2005).

How and where the urea is applied will also influence the scale of the pH changes associated with hydrolysis. When urea is applied upon or within the soil, there will be a strong gradient from a very high pH at the hydrolysis reaction site, to the bulk soil pH, with an intermediate zone where pH is mediated to some degree by the interaction with the soil. This gradient occurs over millimetres in the soil. Sherlock et al. (1986) showed that soil pH around a surface-applied urea granule ranged from 9 (at the edge of the granule) to 6 (bulk soil) over a distance of just 14 mm.

Application of urea in bands means that the pH change due to hydrolysis will impact on a smaller volume of soil and therefore lead to a greater, more prolonged increase in pH at the reaction zone. A laboratory study using an acidic clay loam soil in Canada by Rochette et al. (2009), found greater NH_3 volatilisation associated with shallow (3–5 cm) banding than from surface broadcasting—due to greater pH change during hydrolysis in the banded treatments.

Applying urea at higher rates will also lead to greater pH increases in this zone. Where broadcast urea is incorporated, the change in pH at the reaction zones is likely to be less as the urea is in contact with a greater volume of soil and its concentration in the reaction zone is much less.

The rate of urea hydrolysis in soils is affected by (a) concentration/activity of urease, (b) temperature, (c) water content and (d) pH. After surface spreading urea, there is typically a 'lag' in the onset of hydrolysis of up to several days after urea has dissolved. This lag is thought to be due to the time it takes for the dissolved urea to diffuse down into the soil and contact the urease catalyst. Therefore, hydrolysis is quicker if the urea is applied directly as a solution instead of granules. While urease enzymes are found in almost all soil/plant/stubble environments, rates of hydrolysis can be affected by the actual amount of urease present. Urease catalysis can be inhibited by very high concentrations of dissolved urea, which can be of benefit as it gives more time for rainfall to occur and move the dissolved urea lower into the soil.

Warmer temperatures increase the rate of hydrolysis—a 4-fold increase between 5°C and 25°C. Hydrolysis at 27°C will be 90% complete after 3 days but will take 9 days at 2°C. Since hydrolysis requires available water, the hydrolysis reaction slows down in dry soil conditions (below plant wilting point) and stops altogether when soils are air-dry. It is also more rapid when the urea is incorporated, as soil moisture is typically greater with increasing soil depth from the surface. Hydrolysis is typically optimised in a pH range from 8–9, but optimum pH effects vary between soil types.

Ammonium pathways

Once urea has been hydrolysed to form ammonium (NH_4^+) in the soil solution, it follows one or more competing pathways, each with specific rate-determining factors (Figure 3). Only in very dry soils will NH_4^+ persist unchanged. Nitrification, plant uptake and microbial immobilisation generally remove most of the NH_4^+ over time, with rates depending primarily on soil moisture and plant growth demand. Most plant species prefer to take up nitrogen in the nitrate form, but plants also take up NH_4^+ for growth.

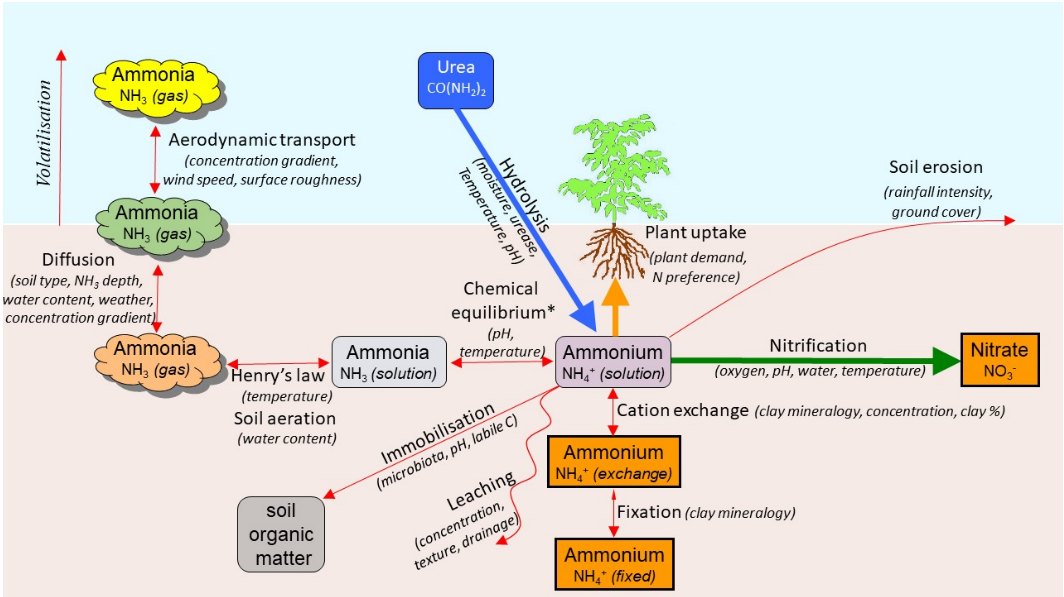

Figure 3. Pathways and rate-determining factors for the transformation of ammonium N formed from urea hydrolysis in the soil (adapted from Cichota and Snow (2012)).

Ammonium adsorption on the soil's cation exchange sites greatly reduces the amount of NH_4^+ in the soil solution. This is why many researchers have found that soils with a CEC >25–30 cmol+/kg have vastly reduced losses via NH_3 volatilisation. Soil CEC is closely related to soil clay content although there is some variation between different clay minerals.

Ammonium can be rendered unavailable to uptake/nitrification by;

(a) fixation within clay minerals—especially illite, vermiculite and to a lesser extent montmorillonite, or

(b) microbial immobilisation during the decomposition of organic materials with high C/N ratios, such as cereal crop roots, straw or stubble.

Both fixation and immobilisation can be regarded as temporary losses, as the captured NH_4^+ is released back into the soil solution over time.

Ammonium is rarely observed to leach in soils as its positive charge bonds it to cation exchange surfaces on clay minerals and organic matter. However, where concentrations of NH_4^+ are very high, such as under urine patches or in high N-rate fertiliser bands, or if applied to sandy soils, the soil's exchange capacity may be exceeded and downward movement with water can occur.

Ammonium in surface soil can also be lost via episodic wind and water erosion events.

Ammonia volatilisation

When ammonium is present in the soil solution, a series of chemical reactions and soil physical properties can lead to it being volatilised as NH_3 (Figure 3). Principal among this chain of processes is the equilibrium between NH_4^+ and NH_3 in solution (Figure 4).

$$NH_4^+ \leftrightarrow NH_3 + H^+$$

Figure 4. The equilibrium between ammonium (NH_4^+) and ammonia (NH_3)

This equilibrium is strongly governed by pH and temperature (Figure 5). This is where the changes in pH generated by hydrolysis become important to determining the amount of N loss.

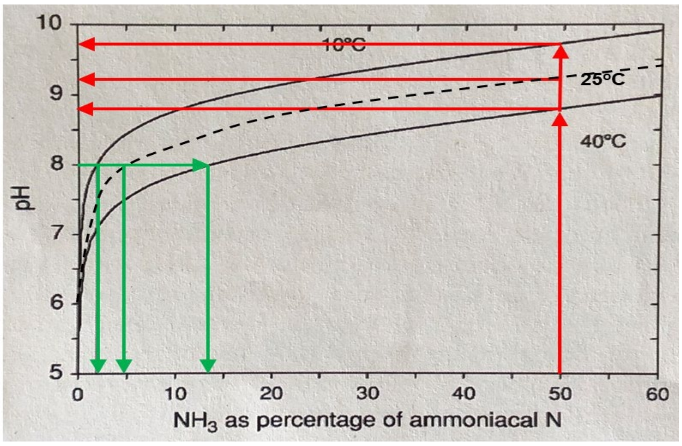

Figure 5. The percentage of total ammoniacal N (sum of NH_4^+ and NH_3) made up by NH_3, as affected by solution pH and temperature (Kissel and Cabrera, 2005). Green arrows show difference in percentages according to temperature at pH = 8. Red arrows show pH required at different temperatures for NH_3 to be 50% of total ammoniacal N

As pH increases (i.e. becomes more alkaline), more of the total ammoniacal N (sum of NH_4^+ and NH_3) will be present as NH_3. For example, at a pH of 8, the proportion present as NH_3 will be 2% at 10°C, 5% at 25°C and 13% at 40°C (follow the green arrows on Figure 5). The pH where the proportions of NH_4^+ and NH_3 are equal (known as the pK_a value) will be 9.75 at 10°C, 9.25 at 25°C and 8.8 at 40°C (follow the red arrows on Figure 5). These high pHs can occur naturally in highly alkaline soils but will also develop in the urea hydrolysis reaction zone of acidic-neutral soils. When NH_3 is produced from NH_4^+, a H^+ ion is produced (Figure 4). In alkaline soils, this H^+ can be neutralised (buffered) by carbonate ions (CO_3^{2-}) in the soil solution and the reaction can continue. However, in acidic or poorly buffered soils, the additional H^+ will cause pH to decrease and the equilibrium between ammonium and ammonia will favour ammonium, and reduce the potential for volatilisation loss.

Ammonium and ammonia in solution can move within the soil as water moves either;

(a) upwards via capillary rise and evaporation, or

(b) downwards in percolating rainfall or irrigation water.

Ammonia/ammonium also diffuse outwards from concentrated sources such as granules or bands.

The partitioning between NH_3 present in solution and NH_3 present in air contacting that solution is described by an equilibrium constant for NH_3 in Henry's law (at a constant temperature, the amount of a gas that dissolves in a liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid). Then, as temperature increases, more of the NH_3 will be present as a gas because the soil solution can hold less NH_3 gas than in colder solutions. At 40^oC the soil air will hold three times as much NH_3 gas than at 10^oC. This equilibrium is also affected by the soil's aeration which will limit the contact of the solution with the air in the soil.

The next phase within the volatilisation process is the movement of gaseous NH_3 from the soil to the bulk atmosphere. For the NH_3 gas to escape, it must first move via diffusion or evaporation through soil pores to the surface. Soil structure and texture will influence the porosity-driven pathway to the surface. Along the way, contact of NH_3 gas with soil moisture that is low in NH_3 will cause it to go from gas form back into solution. Ammonia gas moving to areas of lower pH will also affect the NH_3/NH_4^+ equilibrium and thus potentially move back to the NH_4^+ form where it can be held on the soil's cation exchange surfaces. Ammonia gas can also be directly adsorbed to dry soil mineral and organic matter surfaces, so soils with greater surface area (finer texture = higher clay content) will adsorb more. These are all reasons why banding or incorporation broadcast urea into the soil typically reduce volatilisation losses, particularly in acidic soils.

Ammonia gas produced at or near the soil surface is said to have volatilised once it has been transported into the bulk atmosphere. This process is driven by the concentration gradient between the NH_3 gas in the soil and in the air directly above the soil (boundary layer). Where the concentration of NH_3 in the soil air is greater than the concentration in the boundary layer air, the NH_3 gas will move out of the soil and volatilise. This is why the rate of NH_3 volatilisation is often linked to wind speed, surface roughness and air turbulence. These factors regulate the removal of NH_3-rich air away from the boundary layer at the soil surface, replacing it with 'fresh' air of lower NH_3 concentration (creating a higher concentration difference compared to that emitted from the soil). The presence of a crop can greatly reduce the wind speed at the soil surface and therefore markedly reduce volatilisation losses.

Ammonia transport and deposition

In a cropping scenario, some of the NH_3 volatilised from the soil surface may be absorbed directly into or onto plant leaves before it escapes above the canopy. How much is absorbed by the crop depends on the difference in concentration of NH_3 in the air compared to that in the plant's sub-stomatal cavities. Field measurements of NH_3 volatilisation are typically done above the plant canopy and so represent the net loss after the crop has absorbed what it can.

Depending on wind and air currents, volatilised NH_3 can be transported just meters away, or up to a hundred kilometres away from the source. However, NH_3 is readily absorbed onto dust particles and raindrops resulting in it commonly being deposited back to earth relatively close to the source (Figure 1). Ammonia in the air can also react with acidic air-borne chemicals to form extremely small particulates ($P_{2.5}$ = <2.5 µm diameter) that can persist in the air for weeks and contribute to atmospheric haze and aggravate health issues in humans. Transport of these NH_4^+-based particulates can occur over much larger distances, up to and exceeding 1000 kilometres. Deposition will be determined by ecosystem type and weather conditions.

Field measurements of ammonia volatilisation losses from Australian cropping soils

Measuring NH3 volatilisation in field situations is best done in open-air plots that do not restrict the wind flow across the treated area. The treated area, commonly a large circular plot, must be spatially separated from other treated areas to prevent confounding concentration gradient effects. Normal agronomy-trial plots or small chambers are generally not suitable. Ammonia volatilisation from broadcast urea typically begins within a day or two of spreading, peaks during the next few days, then gradually diminishes over the following 1–2 weeks as the available NH3 in the soil is either lost or depleted via other NH4+ pathways. Measurements continue for up to 1 month after fertiliser application to capture all NH3 emitted and cover all variations in weather conditions. Indirect measurements of inorganic N concentrations in soil over time are unreliable as they do not account for plant uptake, soil microbial immobilisation or other N losses such as leaching or denitrification.

Field-measured volatilisation losses from urea applied to Australian cropping soils averaged 11.7% of applied N (range: 5.4–27%) from fallow soils, and 8.1% (range: 0–29%) of N applied in-crop. Globally, NH_3 volatilisation losses from urea use average 14.5% of the N applied (includes pastures, horticulture, forestry and irrigated cropping in all climatic zones), with losses of up to 64% reported (Ma et al., 2020). Australian measurements were made in north-west NSW (Schwenke et al., 2014), southern NSW (Griffith) (Bacon and Freney, 1989), western Victoria (Wimmera) (Turner et al., 2010; Turner et al., 2012) and Western Australia (Merredin, Regans Ford) (Fillery and Khimashia, 2016). Clearly, field measurements across the Australian grains industry have been sparse and sporadic.

Ammonia volatilisation has also been measured for other N-fertilisers and manures, and in other Australian industries, including pastures and sugarcane. In the northern NSW study, losses from broadcast urea averaged 27% when applied to two grass pastures as much of the urea was held up by the thatch and did not contact the soil—a situation that may be similar to thick stubble cover. Nitrogen losses from ammonium sulfate were less than half the losses from urea at 2 pasture sites and 5 of 8 fallow paddocks on non-calcareous soils but were higher than urea (19–34% N loss) from fallowed soils naturally containing more than 10% calcium carbonate (Schwenke 2014). This is because of a specific chemical reaction between ammonium sulfate and calcium carbonate that drives the formation of unstable ammonium carbonate. Urea is not affected in the same way.

Crop residue effects on NH_3 volatilisation have had little attention in Australian research, but in general terms the trend from global research is for the presence of residues to increase NH_3 emissions compared to bare soil (Ma et al., 2020). This could be due to increased urease activity, greater NH_4^+ availability from decomposition, greater localised humidity, and even preventing urea granules reaching the soil surface. In one of the paddocks measured by Bacon and Freney (1989), high NH_3 volatilisation from urea spread at sowing was explained by a thick surface covering of highly alkaline ash (pH = 9.5) from burnt rice stubble. In addition to the high pH, the ash would have also saturated the cation exchange sites with basic cations preventing adsorption of NH_4^+. Delaying N application till later in the growing season considerably reduced this loss.

Urea can be coated with a urease inhibitor to delay the hydrolysis process and allow more time for rainfall to occur and move the more mobile urea into the soil. While there are many compounds that can inhibit the urease enzyme, the main one available for use in Australian is NBPT [N-(n-butyl) thiophosphoric triamide]. Globally, urea coated with NBPT has been shown to reduce NH_3 volatilisation losses by around half, on average, when compared to uncoated urea (Ma *et al.* 2020).

A model for estimating urea losses via ammonia volatilisation

With so many processes and rate-determining factors affecting the volatilisation loss of NH3, it should be clear that the actual amount of N lost will depend on soil properties (especially clay type and clay%, pH, texture, structure), the soil moisture content and humidity when the urea was applied, and the weather conditions (temperature, rainfall, wind) experienced for the following days–weeks after applying it. Biophysical (mechanistic) models using detailed understanding of the physical and chemical processes in soil described in the previous sections have been developed, but these require many details and specific soil properties that are not routinely available. Models based on observed relationships between measured NH3 volatilisation and major influencing factors are more suitable for use by growers, advisors and most researchers.

Fillery and Khimashia (2015) published a simple model to predict NH_3 volatilisation losses from fertiliser applied to moist soils. Their model starts with a maximum potential loss figure (65%) which is then 'discounted' according to the effects of input factors including clay content, soil pH, fertiliser rate, rainfall in the week after application, presence and growth stage of a crop canopy, and the placement of the fertiliser. The starting figure and discount factor algorithms were not derived from Australian research, but the model did a reasonable job of predicting the losses measured in the previous Australian studies (and some Chinese and American ones). The model is not suitable for soils that are very dry at the time of application as this delays the soil processes involved. Further validation is needed using field measurements on a greater range of Australian soil types and soil moisture contents at spreading. The impacts of crop residues (amount and orientation), timing of N application throughout the year, application methods/rates and subsequent weather conditions all need further research.

This model can be used via an online calculator on the BackPaddock Website: https://downloads.backpaddock.com.au/tools/Fillery_Volatweb032017/Fillery_Volatweb032017.htm

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Managing water and N across years and crop sequences to drive profit

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Take home messages

- Matching N supply to water limited yield targets annually is an ongoing challenge. But with legacies of carry-over N and water, how do these decisions play out over a crop sequence?
- Our system experiments investigate interactions of crop sequence and early sowing systems (+/- grazing) with two N fertiliser strategies (decile 2 (low); 7 (high)) on WUE, production and profit
- In the consecutive dry seasons of 2018/2019, grain yield did not respond to the higher N fertiliser strategy, but grazed forage and hay yields were increased by applied and carry-over N. In the wet 2020 season, responses to N fertiliser were strongly influenced by crop sequence – less response to N in more intense sequences, and in sequences with legumes
- As for the dry 2018-19 seasons, there were legume options as profitable as wheat and canola in 2020 despite higher disease management costs, although canola was the most profitable option at the higher rainfall Greenethorpe site where subsurface acidity may impact some legumes
- Overall average annual earnings before interest and taxes (EBIT) over 3 years were higher for early-sown, grazed systems ($600-$1400/ha) than for timely-sown, un-grazed systems ($200 - $800/ha). Grazed systems responded profitably to higher N, while the profitability of ungrazed systems depended on the crop intensity and the N strategy.

Background – changing the water and N-use paradigm from crop to crop sequence

Australian farmers have been enthusiastic adopters of crop benchmarking tools (e.g. French and Schultz or Yield Prophet®) to compare the performance of **individual crops** to water-limited potential. However, in dryland farming systems, it makes sense to consider the efficiency of water use **across the crop sequence**, to account for the inevitable legacy effects of one crop to the next (i.e. carry over effects on water, N, weeds and disease).

In southern NSW, significant improvements in the water-use efficiency and profitability of crops have been achieved in recent years with improved crop sequences, better fallow management and new earlier sowing systems with suitable varieties (including grazed crops). Diversifying the crop sequence to maintain profit and manage biotic constraints can increase the average profitability across 3-4-yr crop sequences by $150 to $200/ha compared with common sequences, even when individual crops were well managed. Earlier sowing systems are also proving efficient and profitable for individual wheat and canola crops (including grazed crops), but the legacy of dry or low-N soils left by these higher-yielding crops may affect following crops. Our experiments and simulation studies suggest earlier sowing strategies can provide benefits across the crop sequence, but this is influenced by rainfall, crop sequence and **modified by N management**.

Our farming systems project is unique in exploring these interactions to develop strategies to convert annual rainfall into more profit across a crop sequence while managing costs, risk, soil fertility, weeds and diseases. Here we provide a brief overview of the overall project, and the focus of this paper is on understanding how nitrogen strategies play out in terms of productivity and profitability across a range of different systems involving different sequence, sowing time and grazing choices.

The Southern Farming Systems Project – a brief description

To cover the range of soils and climates in southern NSW, sites were established at Wagga Wagga (core site), Greenethorpe (higher rainfall), Condobolin (lower rainfall) and Urana (different soil type). A range of different sequences were established to compare with the common baseline of canola-wheat-wheat sequences typical of the area (Table 1). These included more intensive cereal sequences (wheat and barley), a range of high value (lentil, chickpea) and low-value (lupin, faba) legume options and a forage option (high density legume, mainly vetch) grazed and/or cut for hay. The treatments generated different water and N-use patterns as well as weed, disease and cover legacies monitored by the team. For some sequences, we included interactions of early sowing (March-early April) and timely sowing (mid-April-mid May) of the wheat and canola options. The early-sown options at Wagga and Greenethorpe were grazed by sheep in winter, a recent and profitable management choice on mixed farms with significant implications for water and N use.

Together with the experimental measurements at the 4 sites, we are validating and running APSIM simulations to extrapolate the results across more seasons and explore the data more fully.

N strategies

The N management strategies compared across some systems were based on either a conservative (decile 2) outlook, or a more optimistic (decile 7) outlook for spring in each season. For each non-legume crop in each year of the sequences, the soil N was measured pre-sowing and a potential yield estimate was made in winter based on the starting soil water and N and the seasonal conditions up to that time. Nitrogen was then top-dressed as urea assuming either a decile 2 or a decile 7 finish to the season. Assuming an average season is decile 5, this means that often the decile 2 N strategy would be too low, and the decile 7 treatment too high for the yield potential in any year. Using this approach, the legacies of carry-over N from either legumes or unused fertiliser N would be accounted for in the pre-sowing tests, and less N required accordingly. This approach (compared to set N rates) better mimics farmer practice, and also allows consideration of the risk and reward for conservative or robust N strategies. In the following sections we will focus on selected results that explore the consequences of these strategies in terms of productivity, efficiency and risk in the different systems outlined in Table 1.

Table 1. Selected treatments common to most sites including crop sequence, time of sowing and N strategies. Early-sown treatments included winter grazing of the crops at Wagga and Greenethorpe.

Treatment description	Sequence	Sowing time	N strategy (decile 2 or 7)	Grazing
Baseline	Canola-wheat-barley	Timely	2, 7	
Intense baseline	Canola-wheat	Early, timely	2, 7	Yes
Diverse high value 1	Lentil-canola-wheat	Early, timely	2, 7	
Diverse high value 2	Chickpea-wheat	Timely	2	
Diverse low value	(Faba/lupin)-canola-wheat	Timely	2	
Diverse (mix)	HDL*-canola-wheat	Early, timely	2, 7	Yes
Continuous wheat	Wheat-wheat-wheat	Timely	2, 7	
Fallow	Fallow-canola-wheat	Early, timely	7	

* HDL = high density legume dominated by vetch

A brief recap on the dry 2018-2019 seasons

The 2018 and 2019 seasons were consecutive decile 1 seasons across the sites, while 2020 was decile 7-9 across the sites (Table 2).

Table 2. Annual rainfall (irrigation in brackets) at the experiment sites in 2018 and 2019 and the long-term median rainfall.

Site	2018	2019	2020	LTM
Greenethorpe	359	353	726	579
Wagga Wagga	403	320	557	526
Urana	276	222	488	449
Condobolin	218 (120)	162 (118)	685	434

As would be expected, the productivity and profitability of the individual crop options differed significantly between the decile 1 conditions in 2018 and 2019, and the wetter conditions in 2020. A detailed consideration of the productivity and profitability of the different crops and systems under the dry conditions in 2018 and 2019 was provided in two previous papers (see reference section at the end of this paper).

As a brief summary of the results, despite the decile 1 conditions, the annual earnings before interest and taxes (EBITs) for different crop options varied from -$500 to $1700/ha in 2018, and -$500 to $1200/ha in 2019, with the 2 year average annual EBITs varying from $-50 to $1000/ha across the sites.

Early-sown grazed crops were highly profitable (double to triple non-grazed equivalents) even without grain harvests, while many grain-only crops were low yielding or cut for hay. Both barley grain and hay were profitable options in the dry years, and there was a noticeable effect of the amount of stubble cover remaining over summer (range 0.9 to 9 t/ha depending on crop and sequence).

Legumes and N fertiliser in the dry years

Grain legume crops, and diverse sequences including legume options outperformed baseline canola-wheat sequences at all sites during the dry 2018-2019 seasons. This resulted from both the profitability of the legumes in their own right, and the legacy of water (20-60 mm) and N (50-100 kg/ha) that influenced subsequent crops in the sequence.

The higher N strategy (decile 7) generally provided increased biomass for grazing crops or hay cuts but had either no effect or a negative effect on grain yield and profit in the dry years. However, the N carried over from one season to the next to influence biomass (positively) and yield (variable effects) in subsequent years.

At the completion of the first two years of the project there were systems at all sites achieving annual average EBITs across the 2 dry years **$200 - $600/ha above the Baseline C-W-W system**.

The 2020 season – major crop responses observed

At the time of writing, the 2020 data set for Wagga and Greenethorpe had been finalised so examples for those sites are included. Data for the other sites will be available for the presentation. The high rainfall in 2020 shifted the agronomic management focus from water management and decisions on graze-out and hay cutting in spring, to a focus on higher N fertiliser requirements and disease management.

Overall yield and profit levels were high in 2020, but some observations were consistent

The excellent seasonal conditions meant that both the yield and EBIT of the individual crop options across the sites were generally higher in 2020 than in the previous seasons (Table 3). The ranges in yield and profit for the crops shown in Table 3 are driven by effects of different crop sequence and N strategy which will be discussed further in following sections.

Table 3. Summary of overall yield and EBIT range for different crops in 2020. Highest yields did not correspond to highest profit at either sites for the different crop types. (compare grey squares).

Crop	Sowing (date)	Graze	Variety	Grazing (dse.d/ha)	Yield range (t/ha)	EBIT range ($/ha)
Wagga Wagga						
Canola	E (10/3)	G	Hyola® 970CL	730 - 1780	2.1-3.6	$1220 - $1630
Canola	E (31/3)	NG	Hyola 970CL	-	3.6-3.9	$1290 - $1500
Canola	T (23/4)	NG	43Y92	-	3.5-4.3	$1202 - $1590
Wheat	E (10/3)	G	Bennett⏀	1360 - 2070	5.3-6.1	$1250 - $1370
Wheat	E (31/3)	NG	Bennett⏀	-	5.4-6.1	$455 - $657
Wheat	T (12/5)	NG	Beckom⏀	-	5.2-7.5	$645 - $1120
Barley	T (12/5)	NG	LaTrobe⏀	-	7.5-8.0	$720 - $780
Chickpea	T (12/5)	NG	Captain⏀	-	3.3	$988
Lentil	T (12/5)	NG	HallmarkXT⏀	-	4.2-4.4	$1708 - $1851
Lupin	T (12/5)	NG	Bateman⏀	-	4.8	$1453
HDL vetch	E (10/3)	G	Timok⏀	1200	-	$1260
Greenethorpe						
Canola	Early	G	Hyola970CL	2690 - 3600	3.2 - 3.9	$2700 - $2800
Canola	Early	NG	Hyola970CL	-	2.9 - 3.1	$1,100
Canola	Timely	NG	HyTTec® Trophy	-	4.4 – 4.9	$2000 - $2200
Wheat	Early	G	Bennett⏀	1600 - 2150	3.7-6.2	$1,100 - 1700
Wheat	Early	NG	Kittyhawk⏀	-	8.0-8.3	$1400 - $1500
Wheat	Timely	NG	Coolah⏀	-	6.8-8.7	$1080 - $1550
Chickpea	Timely	NG	Captain⏀	-	4.1	$1331
Lentil	Timely	NG	HallmarkXT⏀	-	3.1	$1100
Faba	Timely	NG	Samira⏀	-	5.3	$652
HDL vetch	Early	G	Morava	1480	4.4 (hay)	$1468
HDL vetch	Timely	NG	Morava		4.9 (hay)	1,050

HDL=High Density Legume dominated by vetch, E=early sowing, T=timely sowing, G=grazed, NG = ungrazed and dse.d/ha = dry sheep equivalents per day per hectare.

Some consistencies in crop performance in 2020 with 2018 and 2019 include:

- Overall yield and profit levels are higher at Greenethorpe than Wagga reflecting the higher rainfall and longer growing season. However, yields and profit levels of some crops (e.g. lentils) were superior at Wagga
- Early sown grazed crops were among the most profitable at both sites and outperformed early-sown grain-only options in most circumstances. Grain-only crops of wheat at the Wagga site had

similar yields to grazed crops, while the same comparison for canola yield at Wagga showed grazing reduced grain yield. At Greenethorpe the results differed with grazing canola producing higher yield than un-grazed crops of the same variety
- Timely-sown grain legume options at Wagga matched or exceeded the profit generated by un-grazed timely canola and wheat, while at Greenethorpe grain legumes matched the cereals, but not canola, which was the most profitable option (by ~$500/ha). Lentils were the most profitable at Wagga, while the chickpea and vetch did best at Greenethorpe
- The top barley yield was higher than that of wheat at Wagga however the profit was higher for the wheat.

Responses to crop sequence and N fertiliser strategies in 2020

Early-sown grazed crops

The early-sown wheat and canola crops both responded significantly and similarly to crop sequence and N fertiliser at Greenethorpe and Wagga in 2020. Table 4 summarises the key responses using the data from Greenethorpe. In the canola-wheat-canola sequence, the additional N (in soil and applied) in the decile 7 strategy (~extra 100 kg N /ha) increased canola grazing and yield by 765 dry sheep equivalent (dse) days/ha and 0.2 t/ha respectively, and wheat grazing and yield by 515 dse days/ha and 2.5 t/ha. This generated an increase in EBIT of $103/ha for canola and $598/ha for wheat.

Diversifying the sequence with a high density legume (HDL) (with decile 2 N strategy) compared to the canola-wheat-canola strategy with decile 2, increased the grazing of canola by 906 dse days/ha but reduced canola grain yield by 0.5 t/ha so that the EBIT was similar. In contrast in the grazed wheat, the diversified sequence had an increase in grazing (387 dse d/ha), yield (0.6 t/ha) and EBIT ($278/ha) but did not match the EBIT of the decile 7 N treatment, predominately due to the higher grain yield.

The N legacy of the HDL measured at sowing was 34 kg N/ha in the canola and 67 kg N/ha in the wheat, and it is likely to provide further benefits from greater in-season mineralisation.

Table 4. Response to crop sequence and N strategy in early-sown grazed canola and wheat crops at Greenethorpe in 2020. Data for soil N at sowing (0-2m) and applied fertiliser N are shown.

Sequence 18-19-20	Crop variety	N strategy	Graze (dse.d/ha)	Yield (t/ha)	EBIT ($/ha)	Nitrogen supply (kg/ha)		
						Soil	Applied	TOTAL
Canola								
C-W-**C**	C = Hyola 970	D2	2689	3.7	$2708	210	100	310
C-W-**C**	C = Hyola 970	D7	3454	3.9	$2839	167	259	426
W-HDL-**C**	C = Hyola 970	D2	3595	3.2	$2774	244	65	309
Wheat								
W-C-**W**	W = Bennett⦸	D2	1631	3.7	$1137	227	15	242
W-C-**W**	W = Bennett⦸	D7	2146	6.2	$1735	196	137	333
HDL-C-**W**	W = Bennett⦸	D2	2018	4.3	$1414	294	15	309

W-Wheat, C=Canola, HDL=high density legume, D2= nitrogen treatment for a decile 2 rainfall projected from mid-winter and D7 = nitrogen treatment for a decile 7 rainfall projected from mid-winter.

Timely sown un-grazed crops

The timely-sown wheat and canola crops also responded significantly to crop sequence and N fertiliser at the sites in 2020, demonstrated here in data from Wagga Wagga (Table 5).

In the canola, a positive yield response to N was only observed in the canola-cereal systems but no yield response in sequences that included legumes. The lowest canola profit ($1232/ha) was generated by the intense baseline low N system, while the equal highest profit occurred in the baseline with decile 7 N ($1578/ha) and the diverse HDL with decile 2 N ($1590/ha). In this case, the diverse treatment profit was generated at lower total cost ($650/ha *vs* $700/ha) reducing production risk.

Table 5. Effect of previous sequence and N strategy on the yield and profit of timely sown canola (upper Table) and wheat crops (lower Table) at Wagga Wagga in 2020. Diverse sequences that include a legume are shown in grey. Total Min N at sowing (0-1.4m) and top-dressed N are shown.

System	Sequence 18-19-20	N strategy	Yield (t/ha)	Crop intensity	EBIT ($/ha)	Nitrogen supply (kg/ha)		
						Soil	Applied	TOTAL
Timely canola (43Y92) sown 23 April								
Baseline	W-B-**C**	D2	3.7	1 in 3	$1355	86	80	166
Baseline	W-B-**C**	D7	**4.3**	1 in 3	**$1578**	123	170	293
Intensive baseline	C-W-**C**	D2	3.5	1 in 2	$1232	79	106	185
Intensive baseline	C-W-**C**	D7	**4.0**	1 in 2	**$1440**	150	138	288
DivHV1	W-Le-**C**	D2	3.8	1 in 3	$1383	111	106	217
DivHV1	W-Le-**C**	D7	3.6	1 in 3	$1202	105	178	283
DivMix	W-HDL-**C**	D2	4.1	1 in 3	$1590	124	53	177
DivMix	W-HDL-**C**	D7	4.2	1 in 3	$1356	99	188	287
DivLV	W-Lu-**C**	D2	4.0	1 in 3	$1475	67	106	173
Timely wheat (Beckom⁽ᵇ⁾) sown 12 May								
Baseline	B-C-W	D2	7.3	1 in 3	$1095	51	101	152
Baseline	B-C-W	D7	7.0	1 in 3	$1013	111	101	212
Intensive baseline	W-C-W	D2	6.9	1 in 2	$960	52	101	153
Intensive baseline	W-C-W	D7	6.9	1 in 2	$917	61	147	208
ContW	W-W-W	D2	5.2	1 in 1	$645	111	41	152
DivHV1	Le-C-W	D2	7.0	1 in 3	$1014	57	87	144
DivHV1	Le-C-W	D7	7.4	1 in 3	$1079	81	129	210
DivMix	HDL-C-W	D2	7.0	1 in 3	$1007	73	78	151
DivMix	HDL-C-W	D7	7.5	1 in 3	$1114	79	129	208
DivLV	Lu-C-W	D2	7.0	1 in 3	$1049	89	60	149
DivHV2	W-Ch-W	D2	6.4	1 in 2	$901	88	60	148

W-Wheat, C=Canola, B=Barley, Le=lentil, Lu=Lupin, HDL=high density legume, D2= nitrogen treatment for a decile 2 rainfall projected from mid-winter and D7 = nitrogen treatment for a decile 7 rainfall projected from mid-winter. Soil nitrogen is measured pre-sowing and applied nitrogen is spread as urea. DivHV1 = Diverse high value 1, DivMix = Diverse (mix), DivLV = Diverse low value, DivHV2 = Diverse high value 2.

In contrast to the canola, the timely wheat only responded to higher N in the diverse sequences and not in the canola-wheat sequences, and it appears sequence and crop intensity had a much more significant overriding effect on wheat yield than nitrogen. For example, the yield of the continuous wheat (1 in 1 intensity, decile 2) was only 5.2 t/ha, the yields in the sequences that were 1 in 2 intensity and with decile 2 nitrogen were 6.4 to 6.9 t/ha, while the yields in sequences that were 1 in 3 and D2 nitrogen were 7.0 to 7.5 t/ha. The highest yields of 7.4 to 7.5 t/ha were in diverse sequences with decile 7 N. In most cases the extra cost of N was not reflected in higher profit, while the effects of crop intensity on profit were clear.

System performance across the 3-year sequence

Overall average annual EBITs across the 3 years were higher at Greenethorpe (Figure 1) than at Wagga Wagga (Figure 2) as would be expected by the higher rainfall and yield potential at the site.

Grazed crops remain the most profitable option at both Greenethorpe and Wagga Wagga (see green (lighter) bars) at both sites across the 3-year period and were also the most profitable in individual years (not shown). The grazing income was significant in all years, including the drought years and more than offsets any impact on grain yield. The profits from grazed crops were also responsive to fertiliser N in both the intense C-W sequence and in the diverse sequence with the HDL, however the return on investment and on N was generally improved in the diverse sequence with decile 2 N strategy at both sites.

The 3-year average annual EBITs among the un-grazed treatments were relatively consistent except for the early-sown un-grazed sequence at Greenethorpe and the early-sown fallow and ley-phase at Wagga Wagga. These treatments suffered as a result of the poor performance of the early-sown winter wheat and canola which generally flowered too late and suffered badly in the drought, and to income forgone in fallow and ley phase.

Of the other ungrazed treatments, there were several at both sites with EBITs that exceeded the baseline system (black in Figures 1 and 2) and these included diverse options with decile 2 N strategy at both sites. In the diverse systems at both sites, the decile 2 N strategy has been more profitable than the decile 7 N strategy. The same trend is also the case for the intense baseline and baseline systems at Greenethorpe, while at Wagga the decile 7 N strategy has been marginally more profitable, suggesting a greater responsiveness to N at that site. The decile 2 N strategy generally has a marginally better return on investment overall, but a much higher return on N investment. The response to nitrogen should be considered in the context of two decile 1-2 seasons and one decile 5-6 season.

The continuous wheat system (timely wheat with decile 2 N) has performed well at Greenethorpe though not as well at Wagga Wagga, and this is presumably due to the lack of significant disease pressure during and after the consecutive droughts in 2018-2019, and lack of significant weed pressure. Fungicides were cost effective in controlling disease in the wheat year and high stubble loads retained water in the dry seasons.

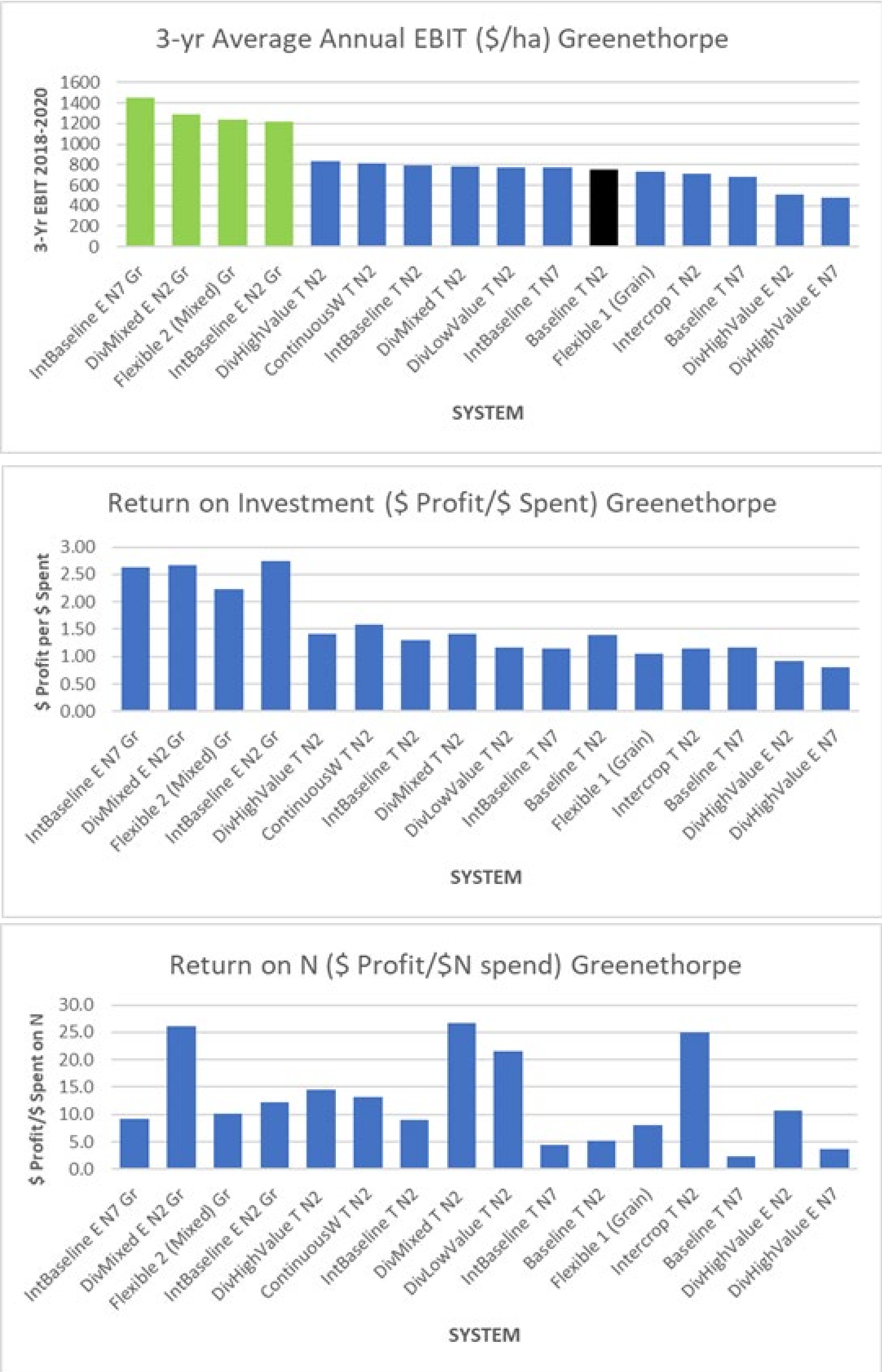

Figure 1. Average annual EBIT (top), return on investment (centre) and return per $ spent on N fertiliser across 3 years (2018-2020) for a range of systems at Greenethorpe. Systems are arranged in order of highest to lowest annual average EBIT in all panels. (green=grazed; black=baseline)

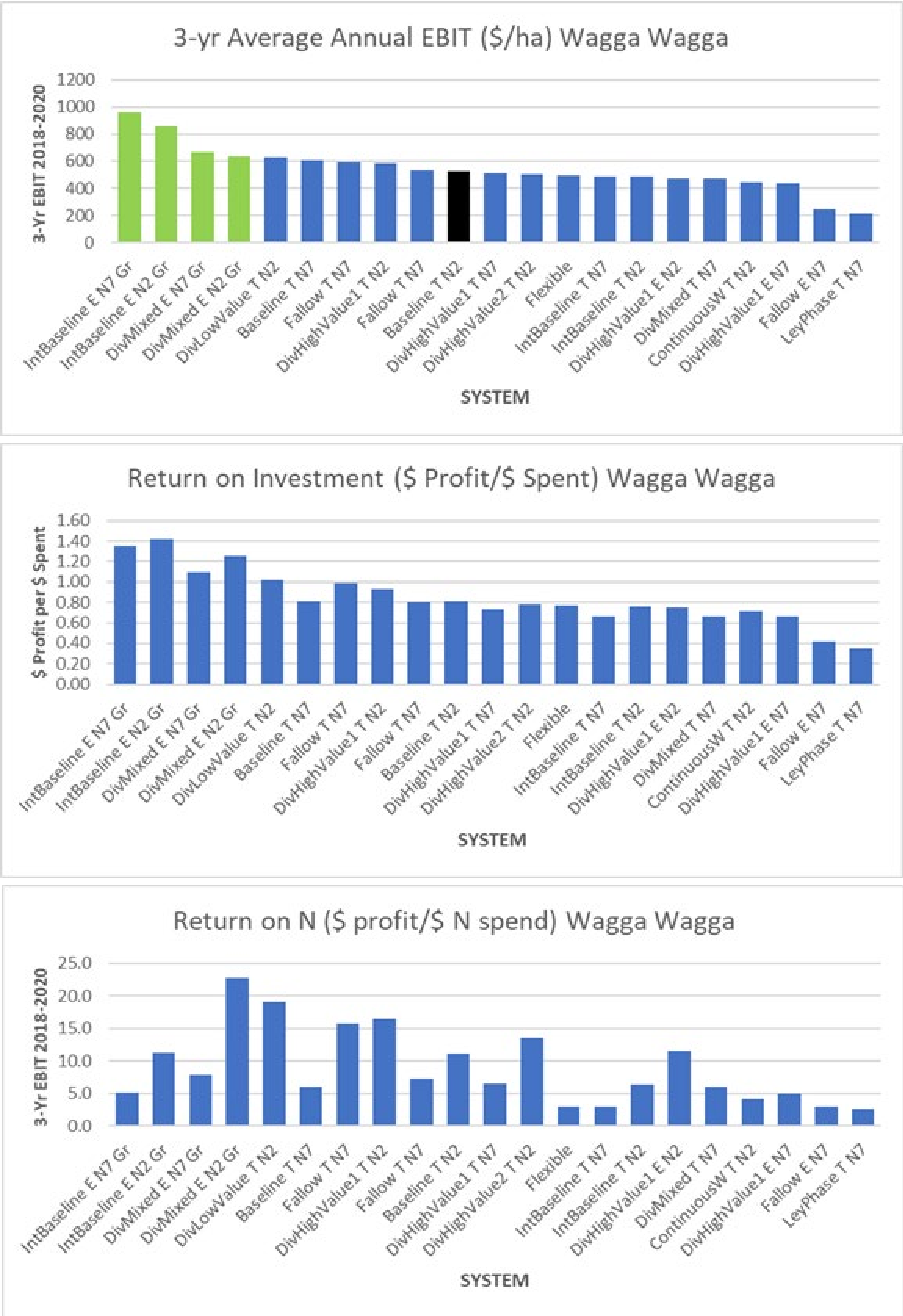

Figure 2. Average annual EBIT (top), return on investment (centre) and return per $ spent on N fertiliser across 3 years (2018-2020) for a range of systems at Wagga Wagga. Systems are arranged in order of highest to lowest annual average EBIT in all panels. (green=grazed; black=baseline)

Conclusions

The results of these system experiments show that both sequence and N strategies have significant effects on crop productivity, profitability and risk in individual years, and these effects can differ depending on individual seasonal conditions. However, the significant legacy effects of crop sequence (crop intensity and legume inclusion) and N strategy across seasons mean that the profitability of the systems over 3 years can play out differently to responses observed in a single season. Further analysis and simulation of this data set will explore this in more detail.

The current area sown to wheat in cropping systems of NSW varies between 55 and 60% which approximates one wheat year every two growing seasons. Years like 2020 represent opportunities to maximise farming systems profits. Results from this farming systems research indicate that on-farm income could be increased if the wheat area were reduced to 30% or approximately one wheat year in every three growing seasons. Profit in this sequence (1:3) are maximised for wheat where more aggressive nitrogen strategies are pursued.

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 especially thank Mr Rod Kershaw at "Landra" Greenethorpe and Warakirri Cropping "Karoola Park" Urana for the use of land for experimental purpose and for management advice at the sites. We also thank Peter Watt (Elders), Tim Condon (DeltaAg), Greg Condon (Grassroots Agronomy) and Chris Baker (BakerAg) for the many useful discussions in their role on the Project Advisory Committee.

Further reading

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Appendix 1: Determining earnings before interest and tax (EBIT)

To calculate the annual EBIT for all treatments, we have initially used the following assumptions/prices.

A. Expenditure

1. All herbicides/fungicides/insecticides, seed dressings, fertilisers, GRDC levies and crop insurance costs were obtained from the annual NSW winter cropping guide or the annual SAGIT farm gross margin and enterprise planning guides with links at:
   i. https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/weed-control-winter-crops
   ii. https://grdc.com.au/resources-and-publications/all-publications/publications/2019/farm-gross-margin-and-enterprise-planning-guide
2. All seed was priced according to purchasing as pure treated seed from seed companies. i.e. In 2019, prices used were wheat seed at $1/kg, faba bean seed at $1.20/kg, chickpea seed at $1.80/kg and canola seed ranging between $23-30/kg
3. All operations costs (sowing, spraying, spreading, haymaking, harvest) were based on the principal that a contractor performed the task. These costs were extracted from the yearly SAGIT Farm gross margin and enterprise planning guides. i.e. In 2019 prices used included sowing at $50/ha, ground spraying at $10/ha, cereal harvest at $70-85/ha, cut/rake/bale hay at $115/ha, with links at: https://grdc.com.au/resources-and-publications/all-publications/publications/2019/farm-gross-margin-and-enterprise-planning-guide
4. All variety levies for all crops and varieties were determined from the variety central website at: (e.g. for pulses) http://www.varietycentral.com.au/varieties-and-rates/201920-harvest/pulse/

B. Income

1. Wheat, barley and canola grain prices were obtained on the day of harvest from the AWB daily contract sheet for specific regions relating to trial location at: https://www.awb.com.au/daily-grain-prices
2. Pulse grain prices were obtained on the day of harvest from Del AGT Horsham and confirmed with local seed merchants.
3. Hay prices were obtained in the week of baling from a combination of sources including The Land newspaper and local sellers.

Appendix 2: Determining grazing value

To determine the estimated value of grazing the early sown crops, we have used the following formulae:

Winter grazing value ($/ha) = Plant dry matter (kg) removed x Liveweight dressed weight (c/kg) x Feed conversion efficiency (0.12) x Dressing % (lambs) x Feed utilisation efficiency (0.75)

Dressed weight and value:

- Lambs = 22.9kg (3 year average of light, heavy and trade lambs)
- Dressed weight = $6.25/kg (3 year average NSW)
- Dressing percentage = 50%

An example of 45kg lambs grazing winter Hyola 970 canola:

3800kg plant DM removed x $6.25 x 0.12 x 50% x 0.75 = $1069/ha

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Strategies for long term management of N across farming systems

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Key words

nitrogen, yield gap, Yield Prophet®, N bank, nitrogen deficiency

Take home message

- Maintain a neutral to slightly positive long-term N balance (as much N inputs from legumes and fertiliser as is removed in grain) to maximise profit and slow soil organic matter decline
- 'N bank' targets, Yield Prophet® and WUE tools and are all valid ways to manage N fertiliser and achieve potential yield without total soil N run-down
- Don't fear occasional overapplication of N - on most soils in southern NSW unused N carries over and is available to subsequent crops and to help maintain soil organic matter.

Background

Modelled data suggests Australian wheat yields are only half what they could be for the rainfall received (Hochman et al., 2017). Nitrogen (N) deficiency is the single biggest factor contributing to this yield gap (Collis, 2018; Hochman and Horan, 2018). This is also likely to be true for other non-legume crops (barley, canola and oats) which reduces farm profitability and global food security. Alleviating N deficiency economically could increase national wheat yields by 40 per cent (Hochman and Horan, 2018), and substantially improve farm profit.

On farms with no legume pastures, and with low levels of soil organic matter (SOM), most of the crop N supply must come from fertiliser. Grain legumes do not provide enough N to support yield of subsequent crops at the intensity (and targeted yield levels) at which they are currently grown. N fertiliser is a costly input and use of it increases cost of production and value-at-risk for growers. Growers fear that over-fertilisation will result in 'haying off', which reduces both yield and quality. There is also the concern that overapplied fertiliser that is not used by crops is lost to the environment by leaching, volatilisation and denitrification. Consequently, efforts continue to be made to match N fertiliser inputs to predicted seasonal yield potential. This is difficult in southern Australia due to the lack of accurate seasonal forecasts for rainfall.

The difficulty in matching N supply to crop demand and a tendency for growers to be conservative in their N inputs is responsible for a large proportion of the yield gap that can be explained by N deficiency. Chronic N deficiency has also caused soil organic matter to decline (Angus and Grace, 2017) and has driven a rise in the proportion of low protein grain produced in Australia (GrainCorp, 2016), which has eroded our standing as a producer of quality wheat in export markets.

What can we do about it?

We propose that the yield gaps due to N deficiency could be reduced if a longer-term approach to N management within farming systems is taken. This means recognising that on most soil types in southern NSW, environmental losses (volatilisation, denitrification, leaching, run-off/lateral flow) of N are low and episodic (Smith et al., 2019). The majority of fertiliser N that is applied in one season and not taken up by the crop is stored in the soil either in mineral or organic form and carries over for use by subsequent crops. This means N fertiliser applied that is surplus to crop requirements is not a lost cost but will be recouped in subsequent seasons and in fact can play a vital role replenishing soil organic N (Alvarez, 2005; Ladha et al., 2011).

How do we implement this?

The first step is using a valid method to ensure that enough fertiliser N is being applied to meet seasonal crop demand. The two key types of tools to do this are:

1. Those that try and match N inputs to seasonal demand such as WUE tools (e.g. Yield Prophet® Lite), Yield Prophet® and;
2. 'N bank' targets which maintain a base level of fertility.

Both are valid ways to calculate N supply to meet crop demand.

Yield Prophet® is still a highly effective tool to match N supply to seasonal demand. The downside of Yield Prophet® is that it is 'data-hungry' and requires experience to get it right. Yield Prophet Lite® and this simple spreadsheet tool (available here; https://www.bcg.org.au/understanding-crop-potential-and-calculating-nitrogen-to-improve-crop-biomass-workshop-recording/) requires less data but doesn't give probabilistic output or include seasonal forecasts.

'N banks' (Meier et al., 2021) are a strategy to manage N in crop production areas with low environmental losses (leaching, denitrification, volatilisation). Most of southern NSW has soils which are free-draining and hold a reasonable amount of water, receive low to medium rainfall and are generally acidic in the surface. Therefore, environmental losses of N are low, and N banks are likely to be an effective strategy to manage N in most of the region. Exceptions are areas prone to waterlogging or that have very sandy soils where leaching may occur. The advantages of N banks are that they are simple to calculate, crops are rarely N deficient, and if set at an appropriate level for the environment, the soil organic N is not mined but maintained. They also shift the cost of N fertiliser into years following a season of high production (when income is high), rather than within the current season of **possible** high production. Possible disadvantages include higher chance of N losses if the N is not used or immobilised, and haying-off (low yield, high protein) in low rainfall seasons. The risk of these are being experimentally evaluated at a BCG-La Trobe long term field experiment in the southern Mallee.

N banks require growers to set a locally relevant target for crop N supply (soil mineral N plus fertiliser N) that is enough to maximise yield in most seasons. Soil mineral N is then measured early in the growing season, and if less than the target N bank, is topped up to the target value with fertiliser N. A more detailed description of N banks and a long-term experiment investigating their effectiveness can be found here:
http://www.ausgrain.com.au/Back%20Issues/301mjgrn20/Grower%20group%20focus.pdf

The problem with Yield Prophet® and WUE tools is they require a forecast of the future (i.e. how much rain is going to fall between now and the end of the season). The N bank management strategy that is currently being developed does not even attempt to match crop N supply to seasonal demand, it simply makes sure that the crop has enough N supply (soil mineral N measured early in the season + fertiliser) to achieve water limited potential yield in most seasons. We do this by selecting an N bank yield target appropriate for the environment and apply N accordingly. A target of 125kg/ha N is proving most profitable in the southern Mallee (average wheat yield ~3.0 t/ha), but it is likely to be more like ~200 kg/ha N (average wheat yield >5 t/ha) at higher rainfall locations in south eastern NSW (Smith et al., 2019). We then use soil mineral N measurements from soil cores to work out how much mineral N the crop has available and top up the balance with fertiliser. For example:

Soil mineral N measured in soil cores (0-1 m) = 75kg/ha N

N bank target = 200kg/ha N

Fertiliser required to meet N bank target = 200 – 75 = 125kg/ha N (271kg/ha urea)

This system relies on having well drained loams or clay soils with low risks of leaching or denitrification losses associated with waterlogging, so that most surplus N applied carries over to the next season. Less N is needed following a low yielding year when a lot of mineral N is not used by the crop and carried over, and more N is required to be applied following a high yielding year when lots of N has been taken up by the crop and removed in grain.

How do the two different approaches stack up?

Three years of results from a BCG-La Trobe University long term experiment at Curyo indicate that an environmentally appropriate N bank strategy and Yield Prophet® (matching N to seasonal yield potential) use similar amounts of N and are equally profitable (Figure 1), and this is confirmed by simulation studies over many seasons (Meier et al., 2021). Modelling also suggests the strategy works in southern NSW across a rainfall gradient from Griffith to Young in free draining soils with at least 147 mm plant available water capacity (Smith et al., 2019).

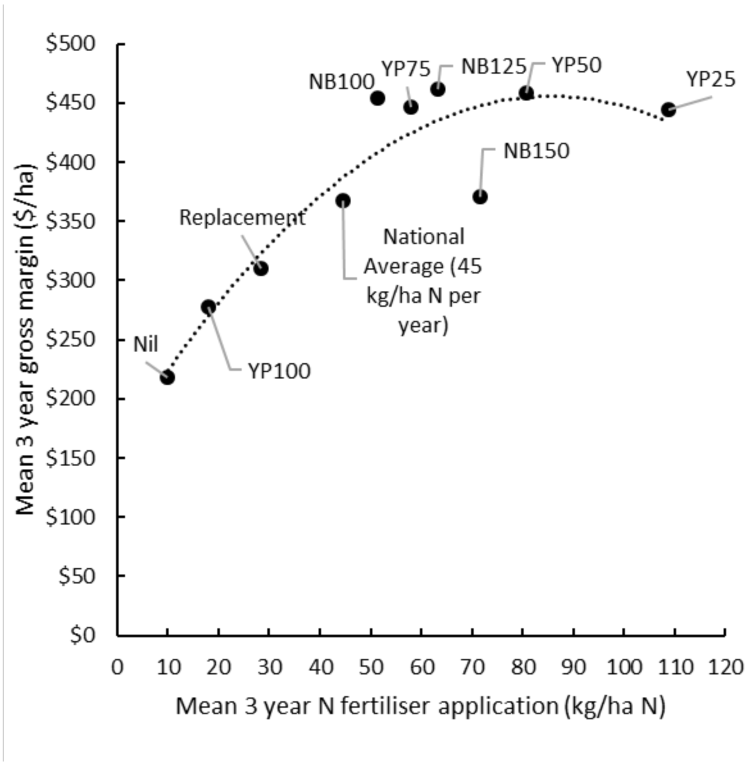

Figure 1. Mean fertiliser application and mean gross margin (2018-2020) for the BCG-La Trobe University long-term N management experiment at Curyo. For details of the experiment see http://www.ausgrain.com.au/Back%20Issues/301mjgrn20/Grower%20group%20focus.pdf. The number following 'N bank' treatments, is the N bank target in kg/ha. YP=Yield Prophet treatments at different levels of probability (YP100% targets yield assuming the worst season finish on record, YP50% targets yield assuming a median finish etc.).

Soil testing is essential

WUE tools, Yield Prophet® and the 'N bank' management system all rely on growers knowing how much mineral N (nitrate and ammonium) they have available to a crop early in the growing season. In all these tools it is best not to include in-season mineralisation in the calculations, because mineralisation is cancelled out by immobilisation in systems where soil organic matter is being maintained (i.e. stubble retained systems with neutral to positive N balance). Consequently, for any rational decision to be made on N management, it is critical that paddocks are soil tested to measure mineral N at the start of the season. Assessment of the soil N bank is achieved by testing for nitrate and ammonium. This can be done any time from March through to June, but if done following sowing it is essential that samples are taken from the inter-row to avoid sampling any fertiliser N applied at sowing. Soil cores should be taken to at least 0.6m (ideally >1.0m) and segmented into different depths (e.g., 0-0.1 m, 0.1-0.3 m, 0.3-0.6 m). At least six cores need to be taken per paddock or production zone within a paddock, and bulked samples carefully mixed. Samples should be kept cool and sent to the laboratory as soon as possible after sampling. A good soil sampling contractor will do all these things for you!

Managing spatial variability

Soil mineral N varies a lot spatially, and this makes soil sampling difficult and prone to error. It can be beneficial to soil sample high and low yielding zones of paddocks independently to get a better picture of what is happening across the paddock. Some growers are making variable rate N applications based on protein maps from previous crops and are reporting a high level of success at achieving higher yield and protein in high performing areas of paddocks and avoiding chronic over-fertilisation in low yielding areas. Whilst protein maps are an effective way of informing how N is best allocated across a paddock, they can't help with estimating the base rate, with soil testing and the management systems described above necessary to achieve this.

Reviewing performance

N management performance should be reviewed over the longer term (>3 years), and there are two effective ways to do this and make sure growers are achieving your production goals. The first is by reviewing wheat grain protein. If growers are producing wheat with less than 10.5% protein (ASW), then yields are highly likely to be N limited, and profits will almost certainly be increased by increasing N application rates. If protein is between 10.5% and 11.5% (APW), yields are likely to be N limited and profits improved by increasing N application. If protein is between 11.5% and 13% (H2) yield is likely maximised and there will be no benefit from further N application. If protein is over 13% (APH) it is extremely unlikely that yields are N limited, and growers may be over applying N at the expense of some yield and perhaps profit, depending on whether they are attracting price premiums for high protein grain.

The second way to review N management is to calculate a long-term N balance for individual paddocks. N balance is the sum of N inputs from fertiliser and legumes minus the amount of N that has been exported in grain (a simple spreadsheet to calculate N balances is available here; https://www.bcg.org.au/understanding-crop-potential-and-calculating-nitrogen-to-improve-crop-biomass-workshop-recording/. N balance is a good indicator of levels of soil organic N mining. Paddocks with a neutral to positive N balance are unlikely to be mining soil organic N, and soil organic matter under cropping should be maintained. Paddocks with a negative N balance are mining soil organic N and soil organic matter will be declining. A very positive N balance indicates chronic over application, and whilst this might be building soil organic matter in stubble retained systems (soil organic matter contains C and N as well as P and S in constant ratios), profits might be increased by reducing N applications.

The BCG-La Trobe field experiment (Figure 2) and simulation studies (Meier et al., 2021; Smith et al., 2019) both indicate that profit is maximised at neutral to slightly positive N balances.

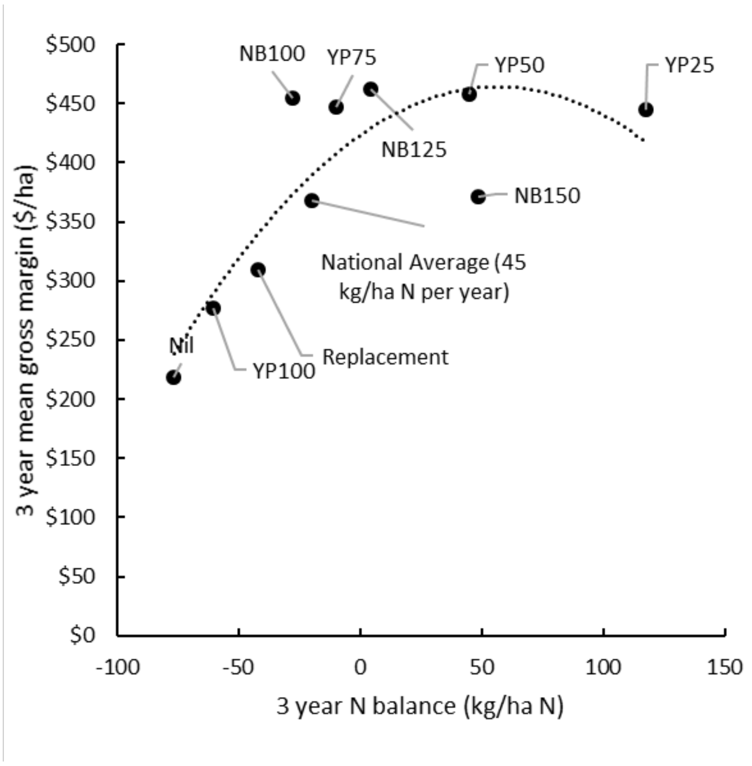

Figure 2. The BCG-La Trobe University long-term N management experiment at Curyo is showing that N management strategies that over-apply (i.e., have a neutral to positive N balance) are more profitable. These strategies will also reduce likelihood of mining soil mineral N and thus running down soil organic matter. For details of the experiment see: http://www.ausgrain.com.au/Back%20Issues/301mjgrn20/Grower%20group%20focus.pdf The number following 'N bank' treatments is the N bank target in kg/ha. YP=Yield Prophet treatments at different levels of probability (YP100% targets yield assuming the worst seasonal finish on record, YP50% targets yield assuming a median finish, etc.).

Recent farming systems experiments in southern NSW demonstrate the concept

GRDC funded farming systems experiments in southern NSW over the last 3 years have used different crop sequences and N strategies that exemplify the concept of taking a longer view with N management. The experiments included two N targets for topdressing decisions – one targeting Decile 2 conditions (conservative) and one targeting Decile 7 conditions (more akin to N-bank). The results during the two consecutive Decile 1 years of 2018 and 2019 tended to demonstrate that Decile 7 approach was less profitable in those years, however the record season of 2020 revealed significant responses to carry-over N that had been applied in previous years. At the time of writing the data for the full 3 years N balance was being reviewed and will be presented at the Update.

Conclusion

Nitrogen deficiency is the single biggest cause of the Australian wheat yield gap. Growers can easily reduce this yield gap, increase profit, and stop mining soil organic matter by taking a longer-term view of N management. Soil testing is essential to do this. N banks, Yield Prophet® or WUE tools are all equally effective at reducing N limitation and increasing profit. N management performance can be reviewed using wheat grain protein and calculating N balances for individual paddocks to make sure yields and profit are maximised and organic N is not being mined.

Acknowledgements

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Useful resources

http://www.ausgrain.com.au/Back%20Issues/301mjgrn20/Grower%20group%20focus.pdf

https://www.bcg.org.au/managing-n-fertiliser-to-profitably-close-yield-gaps/

https://grdc.com.au/resources-and-publications/all-publications/publications/2020/a-nitrogen-reference-manual-for-the-southern-cropping-region

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Developing pasture-crop rotation systems with hard seeded self-regenerating legume species to fix more N for crops and feed livestock in medium and low rainfall zones

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Key words

hardseeded, summer sowing, nitrogen fixation

GRDC code

917595

Take home messages

- Hardseeded pasture legumes have produced significantly more herbage, supplied more nitrogen and have capacity to support increased livestock production compared to traditional legumes over the past decade across regions of NSW under variable growing conditions
- Summer sowing has proven to be significantly more effective as an establishment method for hardseeded legumes than conventional sowing
- Hardseeded legumes can provide more flexible pasture-crop rotation systems than afforded by traditional legumes.

Summary

Over the past decade, hardseeded annual legumes including arrowleaf clover, biserrula, bladder clover, gland clover and serradella (French and yellow) have proven to be more productive than traditional legumes with greater capacity to supply nitrogen for following crops and provide high quality feed for livestock. The capacity to harvest seed on farm and employ alternative establishment methods such as summer sowing has been a particularly effective strategy across regions of NSW under a range of growing conditions including extreme drought. Hardseeded pasture legumes offer capacity to develop very flexible crop-pasture rotation systems that exploit the hard seed characteristics of these legumes.

Introduction

Pastures used in rotation with crops in eastern Australia have traditionally relied on subterranean clover, annual medics and the perennial legume, lucerne. The traditional annual legumes rely on sowing after the danger of a false break has past due to their relatively shallow root system and poor capacity to control moisture loss through transpiration which can give rise to high seedling mortality. When used in the mixed farming zone, traditional annual legumes are frequently sown after the main winter cropping program has been completed. Consequently, sowing may occur in late autumn or even early winter. While pasture legumes are capable of germinating at lower temperatures of late autumn and early winter, the time for emergence is greatly increased in these circumstances. Thus, poor herbage production can be a feature of late sown conventional annual legume-based pastures. Further, plants established on late sowing are frequently small coming into spring. Small plants with poorly developed root systems are more prone to spring moisture stress and the strongly determinate nature of subterranean clover and annual medics mean that such conditions can result in low levels of seed production that compromises future regeneration capacity. Poor growth also means reduced capacity to build soil nitrogen via biological nitrogen fixation. Lucerne, while more hardy in terms of establishment as a consequence of a vigorous root system, has adaptation limitations, particularly with respect to tolerance of soil acidity and the often associated aluminium and/or manganese toxicities which limits its production, persistence and capacity to build soil nitrogen. Growers also frequently report high levels of bare ground in lucerne stands and seek companion plants to fill these gaps. This can be difficult to achieve as lucerne is very effective in drying the soil and reducing opportunity for germination of companion annual species in established stands. In eastern Australia, regardless of whether pastures used are based on traditional annual legumes or lucerne, they tend to be grown in phase systems with crops, with the pastures sown after each cropping phase. These systems can be considered relatively inflexible in terms of achieving rapid change in crop to pasture ratios on farm. In turn, capacity to change the ratio of crop to livestock in the farming system is constrained. High returns from livestock systems is seeing increasing interest in including pastures in rotations, while there is also increasing appreciation amongst growers of the capacity of pasture legumes to contribute to building soil nitrogen for following crops. In recent decades, a range of annual legumes have been developed which have proven to be well adapted to the soil and climatic challenges frequently encountered in the medium and low rainfall cropping regions of eastern Australia. These legumes produce their seed aerially which means they can be harvested using cereal headers and enabling on-farm seed production. When harvested in this manner, a high hard seed content is retained. This opens the opportunity for alternative pasture establishment options. Summer sowing (Nutt et al. 2021) was developed to exploit the opportunity of being able to header harvest pasture legume seed easily on farm and then successfully establish pasture without needing to further process the seed. Over the last decade, this technique has proven to be highly successful in establishing pastures in eastern Australia across a range of soil and climatic conditions. Hardseeded legumes are contributing significantly higher quantities of nitrogen to future crops compared to traditional legumes. Additionally, replicated trial and grower experience is showing these legumes are regenerating strongly following cropping phases of variable length without the need for resowing. Feed quality of hardseeded legumes has been found to be equivalent to or higher than traditional legumes at the same stage of growth. But higher herbage biomass means livestock production per hectare is significantly higher, with capacity to utilise herbage directly or conserve as silage or hay. Hardseeded legumes including arrowleaf clover, biserrula, bladder clover, French serradella, gland clover and yellow serradella, provide rotation options to complement those provided by traditional legume species. The remainder of this paper will provide snapshots of research undertaken involving hardseeded legumes over the last decade in NSW.

Getting started with hardseeded legumes

Because seed of many of the hardseeded annual legumes can be harvested with a standard header, there does not need to be a large on-going investment after the initial purchase of seed. Purchase seed to grow a nursery paddock, harvest it and then utilise that seed to commence a summer sowing program. The seed you initially purchase for your nursery paddocks, if coming from a reseller, will have been scarified so that there is a high percentage (usually > 90%) that will germinate soon after sowing. For that reason, sow your nursery paddock as you would a traditional legume such as subterranean clover or annual medic; that is, from mid-autumn onwards. Seed sowing rates for hardseeded annual legumes in nursery paddocks range from 5-10 kg/ha depending on species, regional climatic conditions and machinery spacing.

From our work with growers over the last decade, the quantity of seed of annual legume species harvested with a header are shown below. The range in seed yield achieved reflects differences between regions (i.e. low vs medium rainfall) and seasonal conditions:

Arrowleaf clover – 300-800 kg/ha. Most growers windrow arrowleaf clover for harvesting as the cultivars are relatively long-season and this prevents green stalks blocking the header.

Biserrula – 100-350 kg/ha. Biserrula has a very papery pod. To achieve higher yields, biserrula is best harvested under hot, dry conditions. Raking into windrows generally results in higher yields. (Note: total seed available for harvest typically ranges from 500-1000 kg/ha but as the pod is papery, a lot will pass through the header and will contribute to regeneration in subsequent years.)

Bladder clover – 300-1200 kg/ha. Bladder clover is a prolific seeder and is relatively easy to harvest. It generally harvests well via direct heading.

Gland clover – 250-600 kg/ha. Gland clover has a very high harvest index. It harvests very well via direct heading.

French serradella – 300-1000 kg pod segments/ha. French serradella harvests well via direct heading.

Yellow serradella – 200-500 kg pod segment/ha. Yellow serradella cultivars can vary in ease of harvest. Some of the old cultivars have quite hooked pods that can become entangled in the box and therefore growers often recommend only partially filling the box (one-third to one-half) to prevent difficulty in augering out the pods.

While these seed yields may appear low compared to yields achieved by winter crops, it needs to be remembered in using this harvested seed in summer sowing, sowing rates will be 10-12 kg/ha for bare seed and 20-30 kg/ha for the in-pod serradella. Therefore, a small nursery paddock can yield sufficient seed for subsequent sowing of very large areas. The advantage of using nursery paddocks, is that a range of species can be evaluated for their suitability on your farm and you can then harvest those that you think are most suitable. Over the last decade, we have worked with many growers who typically start with nursery paddocks of 40-80 ha where they might evaluate 4-5 species/cultivars in 5-20 ha blocks.

(Important note: Some cultivars of hardseeded legumes are protected by Plant Breeders Rights. Growers are able to harvest seed of these cultivars for their own use, but it is illegal to sell them)

Summer sowing in a nutshell

Summer sowing relies on having a ready source of pasture legume seed that has been minimally processed and therefore retains a very high proportion of hard seed. Seed of these legumes is then sown in mid to late summer with a robust legume inoculant capable of supporting rhizobial survival until opening autumn rains are received. Seed then softens due to fluctuation in temperature and moisture. Pasture sowing is therefore completed prior to the commencement of the winter cropping program and the pasture can get up and away while temperatures are warm and conducive to supporting growth.

Over the last decade across environments receiving long term average rainfall of 350-650 mm, summer sowing has, across all 14 replicated field sites for all hardseeded legumes, resulted in significant increases in herbage production compared to when the same species is conventionally sown using scarified seed (Figure 1). Moreover, summer sowing of any of the hardseeded species has given significantly higher herbage production than conventional sowing of subterranean clover or annual medics.

If we divide the data for the 14 sites up for seasonal conditions, we see the same trends emerging for severe drought (2019) and average years (Figure 1). Only in the wet year (2016), did conventional sowing for some species equal or exceed that achieved by the summer sowing. Interestingly, in 2020, herbage yields for summer sowing was significantly higher than for conventional sowing (data not shown). In summary, summer sowing has proved to be a robust method for the establishment of pasture giving significantly higher herbage production than where legumes are conventionally sown in late autumn.

Not all cultivars of all hardseeded legumes are suitable for summer sowing. In Western Australia, where the summer sowing technique was pioneered, hardseeded French serradella (cv. Margurita and Frano) and bladder clover (cv. Bartolo) can be successfully used in summer sowing. In NSW however, in addition to these species and cultivars, arrowleaf clover (cv. Cefalu), biserrula (cv. Casbah), gland clover (cv. Prima) and yellow serradella (cv. Avila and acc. 87GEH72.1a) have been successfully used in summer sowing. Differences between WA and NSW in species and cultivar suitability for summer sowing appears to be a consequence of differences in summer moisture regimes (Howieson et al. 2021). Bottom line: it is important to consider which cultivars of certain species are suitable for summer sowing. Some just do not break down sufficiently for use in summer sowing.

Nitrogen fixation

Across sites, biological nitrogen fixation for all hardseeded and traditional legumes has ranged from 18-33 kg N/t shoot DM with an average of 23 kg N/ t DM. Average biomass production for most species when summer sown across 14 sites and six years is around 4 t DM/ha indicating close to 100 kg N/ha is being fixed on average (Figure 1). Interestingly, the summer sown hardseeded legumes, based on this average would have contributed similar quantities of nitrogen in drought and average years (Figure 1). In comparison, most conventionally sown legumes have contributed < 50 kg N/ha except in 2016. Summer sown arrowleaf clover has, from our results, tremendous capacity for nitrogen fixation exceeding 150 kg N/ha averaged across all 14 sites, under severe drought (2019) and in average years and >200 kg N/ha in 2016.

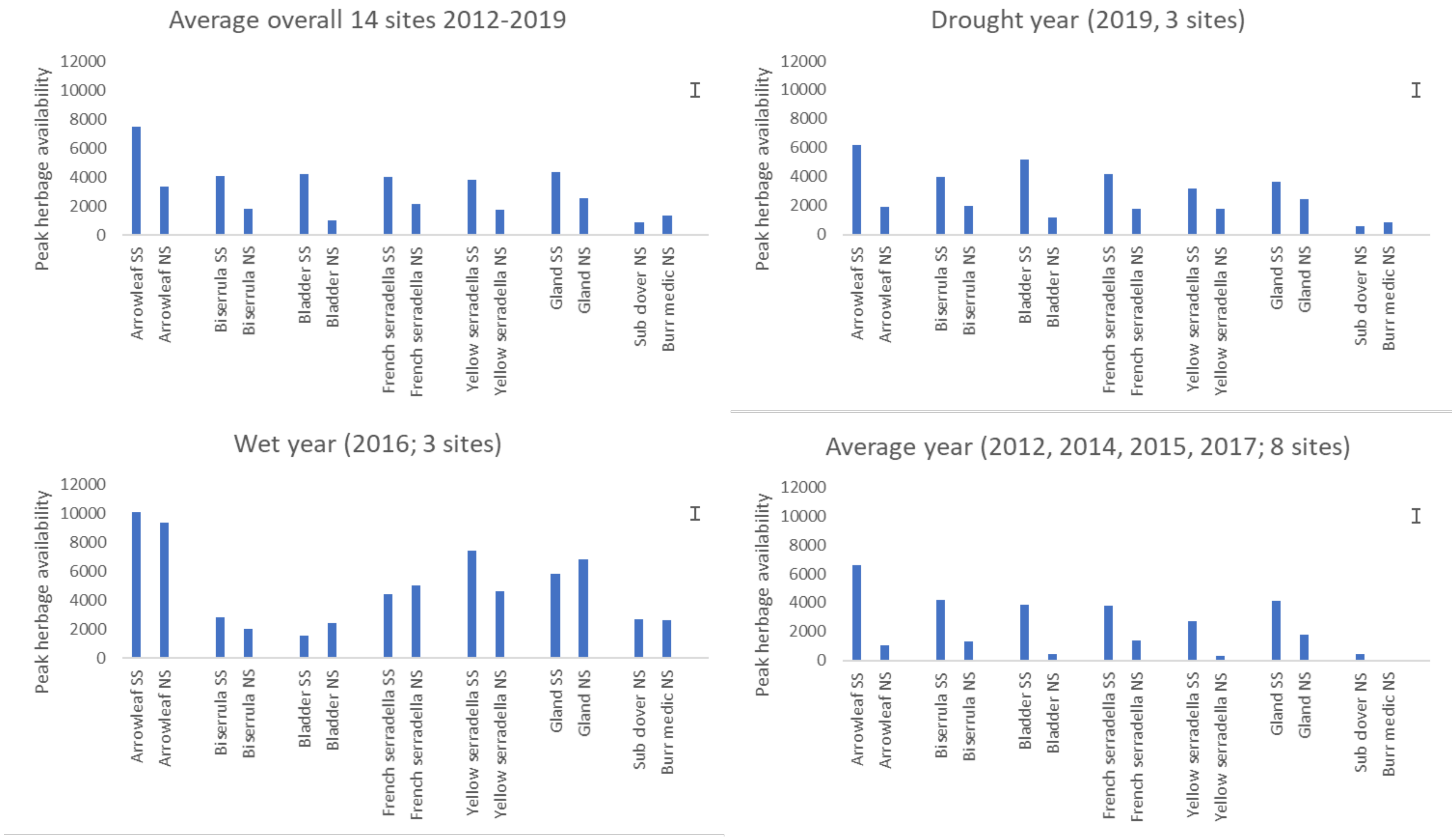

Figure 1. Peak biomass (herbage) production (kg DM/ha) for a range of annual legumes sown either as unscarified/in-pod seed in mid to late summer (SS) or as scarified seed in May (NS) averaged across 14 sites from 2012-2019. The data is then divided into peak biomass production in drought, wet and average rainfall years

Seed yield

As with herbage production, seed yields achieved from summer sowing of hardseeded legumes has been significantly higher than that achieved by conventional sowing. For traditional species such as subterranean clover and annual medics, the aim would be to achieve a minimum seed set of 150 kg seed/ha to have reasonable capacity for subsequent regeneration (Dear et al. 2008). Using that benchmark (Figure 2), it can be seen that summer sowing averaged across all sites and all years for each hardseeded legume achieved or exceeded this benchmark whereas conventional sowing of the same species was less consistent. Interestingly, subterranean clover and burr medic did not achieve this benchmark. Even under severe drought conditions, all hardseeded legumes that were summer sown achieved this benchmark with the exception of gland clover.

Herbage quality and livestock production potential

The results presented above indicate significant increases in capacity of hardseeded legumes to increase feed supply for livestock compared to conventional sowing. While feed supply is one component impacting potential livestock production, herbage quality (digestibility and crude protein) also needs to be considered.

During 2019, herbage quality assessments were undertaken throughout the growing season. These results were then used to predict liveweight gain in merino lambs (25 kg liveweight) using Grazfeed. Liveweight gain per head ranged from 340-430 g/hd/d for hardseeded legumes sown in summer (Figure 3). Some of the conventionally sown legumes were predicted to provide <100 g/hd/d gain, a consequence of low herbage availability. Given feed was very scarce in 2019 and if feed available had been utilised to support weaner lambs, then weight gains of 470-1440 kg/ha (average 870 kg/ha) were predicted from summer sowing, depending on legume species. This compared to 35-460 kg/ha (average 145 kg/ha) for conventionally sown legumes.

Weeds

While summer sowing can produce dense, vigorously growing stands that compete well with weeds, it does not compensate for a lack of site preparation prior to sowing of pastures. As with conventionally sown pastures, it is advisable to have a minimum of two and preferably three years of sound weed control prior to sowing of pastures. Unlike conventional sowing where there is opportunity for a final knockdown of weeds after opening autumn rains, this opportunity is foregone for summer sowing. Research is ongoing in terms of selective herbicide options for use in alternative legumes.

In terms of alternative weed control strategies, species such as biserrula give some opportunity for non-herbicide options. Biserrula is not a highly palatable legume and sheep will tend to graze other pasture components initially. In replicated field trials we have measured significant reductions in density of ryegrass (plants and inflorescences) following grazing by sheep (Howieson and Hackney 2018). Further, growers have reported success with control not only of annual ryegrass but also capeweed and other problem broadleaves using sheep. Again, this is a complementary strategy in weed control and is not a substitute for weed control prior to pasture establishment.

There is often concern expressed by growers and advisors that the legumes themselves may become weeds in following crops. Knockdown herbicides used prior to sowing crops control any summer germinating legumes. Crops compete very strongly against germinating legumes post-sowing and the hardseeded legumes are highly susceptible to many of the common selective broadleaf sprays used in-crop.

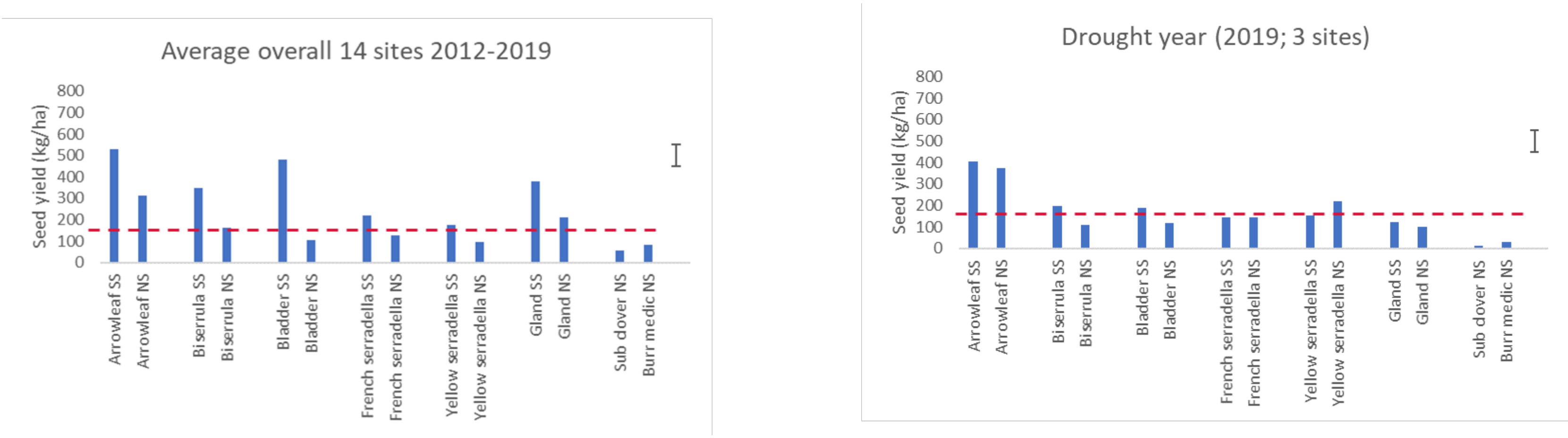

Figure 2. Seed yield (kg/ha) for a range of annual legumes sown either as unscarified/in-pod seed in mid to late summer (SS) or as scarified seed in May (NS) averaged across 14 sites from 2012-2019. The seed yield under severe drought (2019) conditions is also shown. Red dotted line = minimum seed set of subterranean clover and annual medics of 150 kg seed/ha

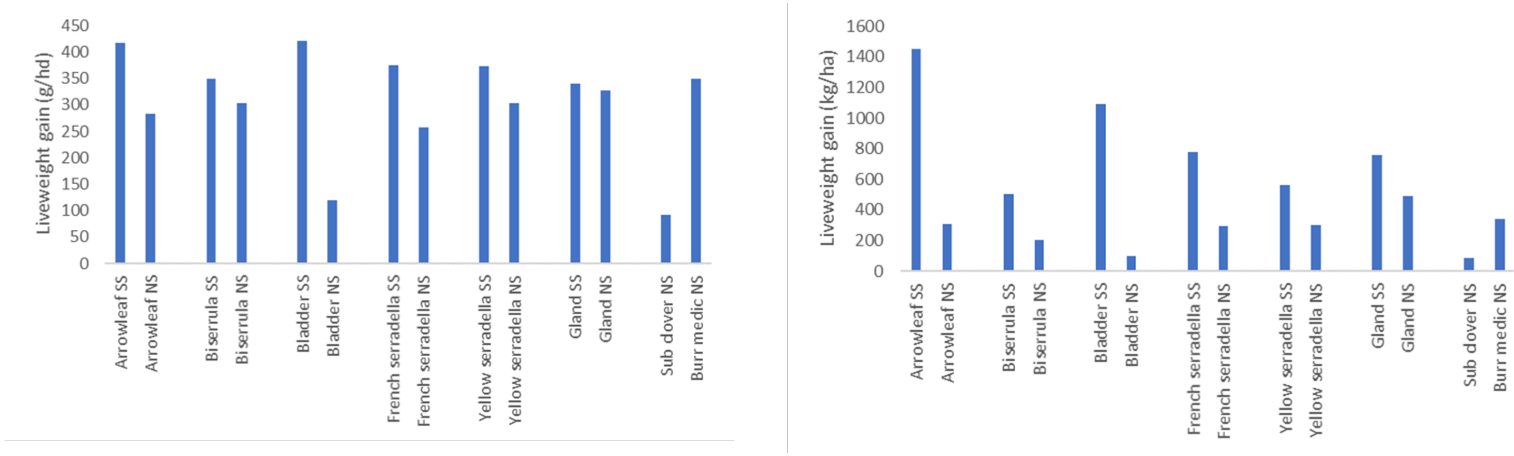

Figure 3. Predicted liveweight gain (g/hd/d) from Grazfeed for a range of pasture legumes established via summer sowing (SS) or conventional sowing in May (NS) based on feed quality (digestibility and crude protein), herbage biomass and the calculated weight gain (kg/ha) based on herbage biomass at the time of sampling for three sites in 2019.

Using hardseeded legumes in rotations

Once a seedbank of hardseeded legumes is established, they can be cropped and have the capacity to regenerate following the cropping phase without the need for resowing. The length of the cropping phase that can be employed without risking seedbank exhaustion varies with species and cultivar. For example, biserrula and some cultivars of yellow serradella have very high levels of hard seed (>90%) and can persist in the seedbank for many years. These species can survive longer cropping phases. Species such as arrowleaf clover, bladder clover and gland clover tend to have hard seed levels in the autumn following seed set of 50-60% depending on environmental conditions. As a result, shorter cropping phases are preferred to facilitate seed bank replenishment. Ultimately, the decision on cropping phase length will include consideration of utilisation of fixed nitrogen.

Growers using hardseeded legumes report running cropping phases of 2-4 years over areas with established legume seedbanks, and shorter phases (2 years) for hardseeded clovers, while legumes with higher hard seed content are used in both short and longer term rotations. We are currently evaluating the effect of rotation systems on regenerative capacity of these legumes.

Conclusions

Hardseeded annual legumes have been proven over many years and across regions to have significant potential to contribute to increased farm productivity through capacity to fix nitrogen for following crops and provide high quality feed for livestock. Such legumes provide flexibility and risk reduction options in terms of alternative methods for pasture establishment and development of more flexible crop-pasture rotation systems.

Acknowledgements

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

Profitable pulses in lower rainfall farming systems

Michael Moodie, Frontier Farming Systems

Key words

break effect, risk, pulses, low rainfall zone, nitrogen, fixation, herbicide residues, time of sowing, soil constraints

GRDC codes

Profitable crop sequences in the low rainfall regions of south eastern Australia (DAS00119), Increasing the effectiveness of nitrogen fixation in pulse crops through extension and communication of improved inoculation and crop management practices in the southern region (9176601), Understanding the implications of new traits on the adaption, crop physiology and management of pulses in the southern region (DAV00150).

Take home messages

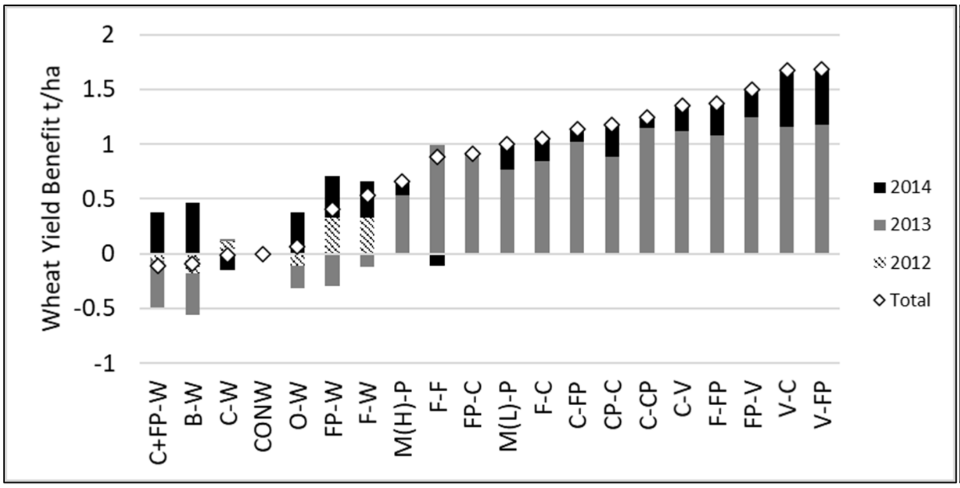
- Pulse crops contribute to increased productivity and profitability of low rainfall crop sequences by reducing constraints to subsequent crops. This benefit is commonly 0.5-1.5 t/ha depending on the level of constraints
- Over the long term it is predicted that lentils are likely to be the most profitable and lowest risk break crop in the low rainfall zone, however all crop sequences need diversity to counter seasonal climate and price risks
- Sowing pulse crops in late April – mid May has typically provided the best balance of optimising biomass accumulation and reducing frost risk to maximise grain yields
- Pulse crops typically contribute ~50 kg N/ha through net fixed nitrogen inputs to low rainfall farming systems
- Addressing local soil constraints has demonstrated large increases in the productivity of pulses, for example deep ripping Mallee sands increased chickpea yields from 0.5 t/ha to 2 t/ha.

Pulse crops contribute to the profitability of low rainfall farming systems by two mechanisms:

1. Improved profitability of the crop sequence through providing break crop effects
2. As a profitable enterprise in their own right.

Break crop effects

Pulse crops contribute the productivity and profitability of the cropping sequence by reducing the impact of agronomic constraints on subsequent crops. They provide multiple pathways to control grass weeds, contribute biologically fixed N, can reduce soil borne disease and, in some cases, provide a positive water balance. A long term rotation trial conduced at near Mildura from 2011-2014 demonstrated the production and profitability benefits of addressing agronomic constraints with the use of break crops, including pulses. In this trial the inclusion of a a double break phase in 2011 and 2012 resulted in increased wheat production of between 0.6 – 1.6 t/ha in 2013 and 2014 (Figure 1). This is despite relatively low yields of the continuous wheat treatments of less than 1.4 t/ha. The choice of break phase appered to have little effect on the break effect as it sucesfully addressed the biological constraints present. At Mildura, the top five rotations increased gross margin by an average of $320/ha over the four years or approximately $80/ha/year. Key attributes of the most profitable crop sequences were having at least one profitable break crop and that the break phase delivered large yield benefits to subsequent wheat crops.



4 Year Rotation	Ident
canola-chickpea-w-w	C-CP
canola-field pea-w-w	C-FP
canola-[bm]vetch-w-w	C-V
chickpea-canola-w-w	CP-C
fallow-canola-w-w	F-C
fallow-fallow-w-w	F-F
fallow-field pea-w-w	F-FP
[a,g]medic-[g]pasture-w-w	M(H)-P
[b,g]medic-[g]pasture-w-w	M(L)-P
field pea-canola-w-w	FP-C
field pea-[bm]vetch-w-w	FP-V
[bm]vetch-canola-w-w	V-C
[bm]vetch-field pea-w-w	V-FP
barley-wheat-w-w	B-W
canola-w-w-w	C-W
canola+field pea-w-w-w	C+FP-W
[h]oat-w-w-w	O-W
field pea-w-w-w	FP-W
fallow-w-w-w	F-W
w-w-w-w	CONW

Figure 1. Wheat yield benefit (treatment wheat yield – continuous wheat yield) achieved at the Mildura site following one and two year break phase. Yields of the continuous wheat treatment (CONW) were 0.93, 1.42 and 1.31 t/ha in 2012, 2013 and 2014 respectively.

Comparative pulse crop productivity and profitability

To understand the financial risk of growing pulse crops in the longer term, a gross margin analysis was undertaken using Monte Carlo simulation with the Microsoft Excel add-in @Risk. Data was combined from several Mallee sites with mean annual rainfall of less than 330 mm where all pulse crops had been grown on a sandy loam soil type over the eight seasons (2013 – 2020). This data was then analysed to generate a long-term yield probability using a gamma distribution. A long-term grain price distribution (log logistic) was also developed for each crop using long-term (2003 – 2020) average January grain price from the Farm gross margin and enterprise planning guide (Rural Solutions). A gross margin analysis was then repeated 5000 times for each crop, drawing a new random yield by price combination each time from the distributions described above to generate a new gross margin distribution. Each yield output for the sandy loam soil type was moderated by 30% to account for typical within paddock variability where both heavier and lighter soil types are less favourable for pulse production. The outcome of this analysis is shown in Table 1.

This analysis shows than lentils are predicted to be both the most profitable and least risky pulse crop grown in the long term. The average long term gross margin for lentils is predicted as $365, however importantly a negative gross margin is expected only 15% of the time. Conversely lentils also have a strong possibility of achieving a high gross margin with a gross margin of more than $500/ha probable 28% of the time.

Vetch was the next most profitable break crop with an average gross margin of $255/ha (Table 1). However, vetch as grain is predominantly sold for seed to plant fodder and hay crops. While there have been some high prices received for vetch, 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 a mean long-term gross margin of about $200/ha (Table 1). Both crops also had similar risk of not achieving a break-even gross margin (25%) while both crops had an 15% 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 pea which flowers and matures earlier tended to perform well in frost-free situations with terminal drought and/or high levels of heat in spring. Conversely, chickpea which flowers and matures later, performed well at sites which were frosted in early spring or in situations where soil moisture was available late in the season.

Lupin and faba bean had lowest simulated long-term gross margins of $65/ha (Table 1). Faba bean were also the riskiest crop and are expected to not break even in 49% of seasons. Lupin 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.

Table 1. Mean gross margins for pulse crops and the probability of gross margin which are less than $0/ha or greater than $500/ha generated from Mallee sites with less than 330 mm annual rainfall.

Crop	Mean ($/ha)	Probability gross margin <$0/ha	Probability gross margin $0 - $500/ha	Probability gross margin >$500/ha
Lentil	365	15%	57%	28%
Vetch	255	23%	60%	15%
Chickpea	220	24%	60%	15%
Field Pea	174	27%	62%	10%
Faba Bean	65	49%	46%	5%
Lupin	65	40%	58%	2%

Agronomic options to improve pulse profitability

Sowing time

Sowing pulse crops in late April to mid-May has frequently delivered a yield advantage over sowing pulse crops in the later part of May or early June. This yield benefit is particularly pronounced in seasons with limited spring rainfall. However, when spring is favourable, the effect of sowing time on grain yield is often negated. Time of sowing of pulses in the low rainfall zone is often a compromise between sowing early enough to accumulate adequate biomass and delaying sowing to avoid frost. Figure 2 presents data from Loxton in 2019 where lentil yields were maximised from early sowing despite higher levels of frost damage (percentage of frosted pods). In this example early sowing lead to higher biomass and harvest index (due to terminal spring drought). Sowing on the 26 April (time of sowing (TOS) 2) provided the maximum combination of grain yield, biomass production, harvest index and frost damage, although there was no significant difference for yield, biomass or harvest index between TOS 1 and 2, despite more frost damage in TOS 1.

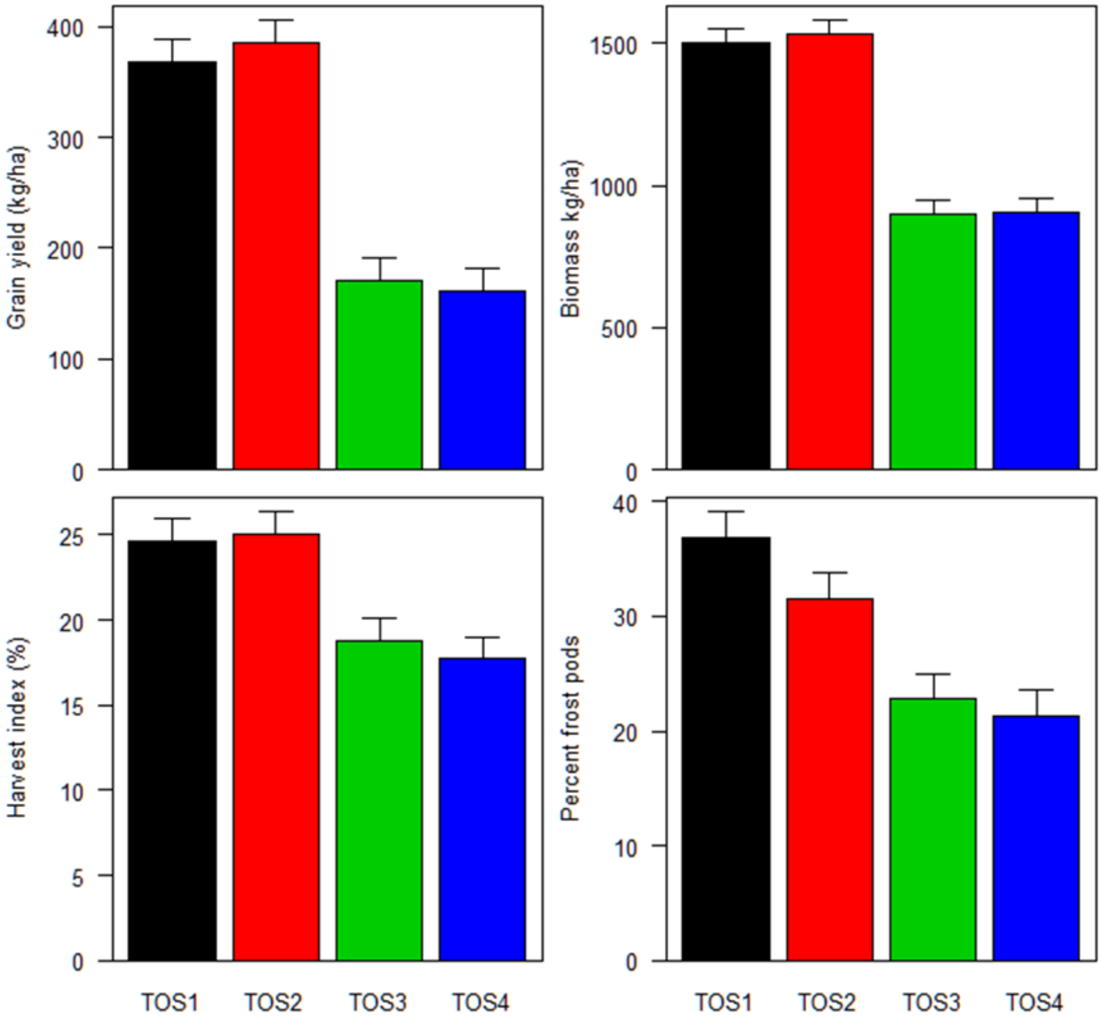


Figure 2. Effect of sowing date on the grain yield, biomass, harvest index and frost damage of lentils at Loxton (SA) in 2019. The sowing dates were time of sowing (TOS) 1: 17 April; TOS 2: 26 April; TOS 3: 6 May; TOS 4; 13 May. Data is averaged across 6 varieties: PBA Hurricane XT⦶, PBA Jumbo2⦶, PBA Bolt⦶, PBA HighlandXT⦶, PBA Ace⦶ and PBA HallmarkXT⦶.

Managing herbicide residues

Herbicide residues are an important constraint to the integration of pulse crops into low rainfall farming systems. Soils within the low rainfall zone often are low in organic carbon and the topsoil can remain dry for prolonged periods. These conditions do not favour microbial breakdown of herbicides and residues of some herbicides may persist in the soil for several seasons post application. Leading pulse growers undertake careful planning of their crop sequences several seasons before they intend to grow a pulse crop, and many have even excluded the use of the highest risk residual herbicides such as sulfonylureas and clopyralid.

Several pulse crops now have commercial varieties with herbicide tolerant (HT) traits which can assist in establishing crops into soils containing herbicide residues. Currently available varieties are tolerant to Group B imidazolinone herbicides, however breeding programs are developing pulse crops and varieties with tolerances to Group I (e.g. clopyralid) and Group C (e.g. metribuzin) herbicides.

The tolerance of crops and varieties to Group B herbicide residues were evaluated at Pinnaroo (SA) in 2019. Four varieties of lentils and field pea and two varieties of faba beans were included in the trial (Table 2).

Table 2. Conventional and herbicide tolerant lentil, field pea and faba bean varieties included in the Group B herbicide residue trial at Pinnaroo (SA) in 2019.

Crop	Conventional		Herbicide tolerant		
Lentil	PBA Jumbo2⊕		PBA Hurricane XT⊕	PBA Hallmark XT⊕	GIA Leader⊕
Field pea	PBA Wharton⊕	PBA Oura⊕	GIA Kastar⊕	GIA Ourstar⊕	
Faba bean	PBA Samira⊕		PBA Bendoc⊕		

Approximately one month prior to sowing, herbicides were applied to the soil surface to simulate residue treatments and the impact of the simulated residues on pulse grain yield (Figure 3). It should be noted that this application timing is generally well within labelled plantback periods for conventional varieties, and therefore 'off-label'. There is currently no published plantback periods for the HT varieties to these herbicides. This trial methodology is likely to provide a worst-case scenario for herbicide residues to affect establishment, however may not fully replicate historical field applications. Group B herbicides do not bind strongly to organic matter or soil binding sites and are highly water-soluble. As such, they are prone to leaching down the profile over time. Commercial applications made in previous season crops are likely to be distributed to greater depths within a soil profile than has occurred within this simulation trial where treatments were applied one month prior to sowing.

As would be expected, the grain yield of the conventional lentil variety PBA Jumbo2⊕ was significantly reduced by the presence of both imidazolinone and sulfonylurea herbicides (Figure 3). In contrast the three HT lentil lines-maintained yield potential in the presence of group B residues. Although there appeared to be a slight reduction in grain yield from sulfonylurea residues, this was not statistically significant.

For field peas, the HT variety GIA Ourstar⊕ demonstrated a high level of tolerance to all simulated group B residues while GIA Kastar⊕ maintained grain yield only in the presence of imidazolinone residues. Both conventional lines (PBA Wharton⊕ and PBA Oura⊕) demonstrated some inherent tolerance to imidazolinone residues.

The grain yield of the HT faba bean variety PBA Bendoc⊕ was not significantly affected by any of the simulated group B residues. The conventional variety PBA Samira⊕ withstood low levels of imidazolinone residues (12.4gai/ha imazamox + 5.6gai/ha imazapyr), however significant grain yield reductions were evident where the high rates were simulated or where metsulfuron-methyl was applied. Chlorsulfuron residues resulted in near crop failure of PBA Samira⊕.

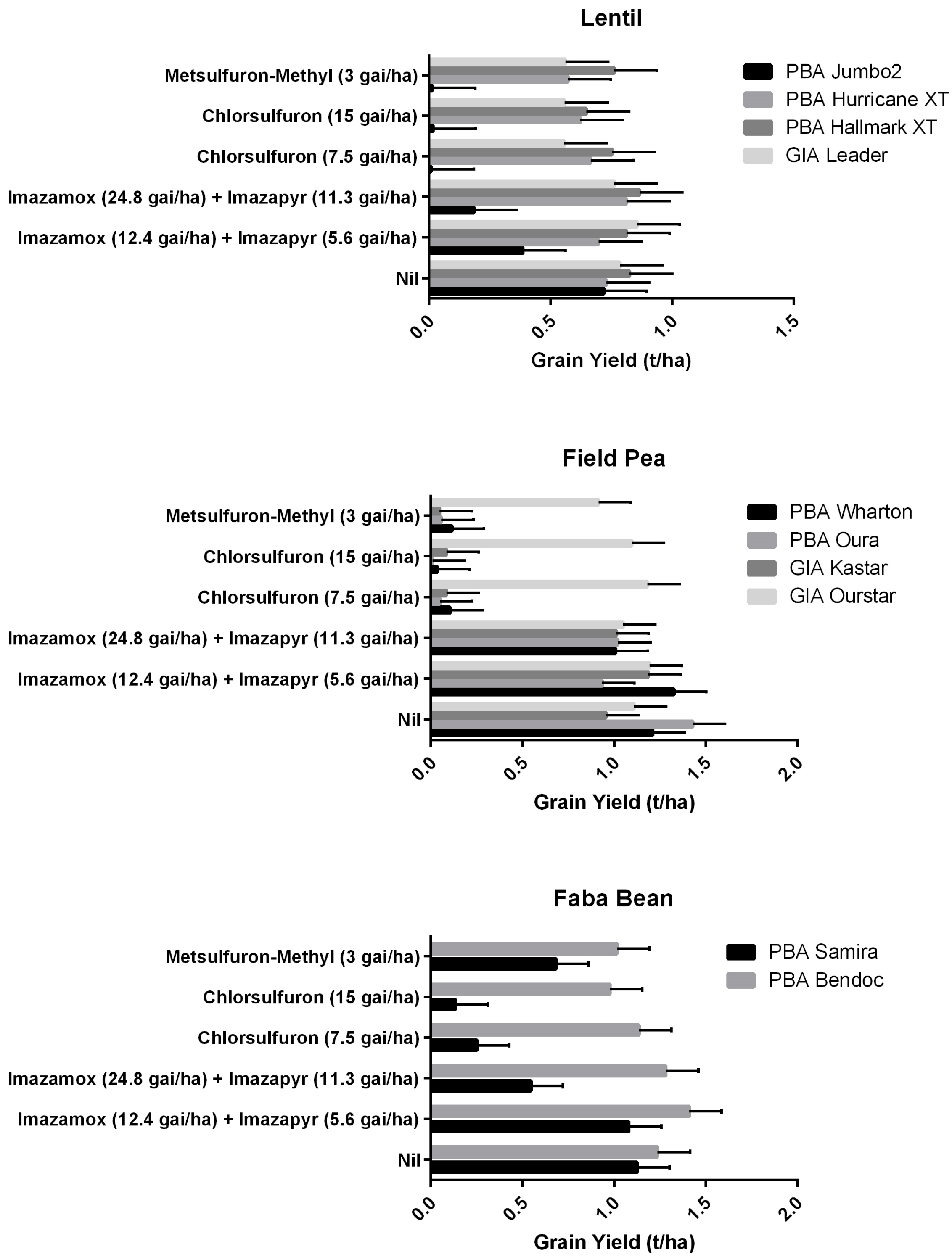


Figure 3. Effect of simulated Group B herbicide residues on the grain yield of lentil, field pea and faba bean varieties at Pinnaroo (SA) in 2019. Error bars represent the LSD (P<0.05).

Nitrogen fixation and inoculation

Pulse crops can contribute significant fixed nitrogen inputs to low rainfall farming systems with the net input being a function of the amount of nitrogen fixed by the pulse crop and the level of export from the paddock through products such as grain and hay. Over three seasons (2013-2015) break crop comparison trials were sampled to measure dry matter (DM) production and symbiotic N_2 fixation of chickpea, field pea, lentil, lupin, faba bean and vetch crops grown in the Victorian and South Australian Mallee. After taking account of the amount of nitrogen removed in harvested grain across the three seasons and including estimates of the likely contributions of fixed nitrogen associated with the nodulated roots, all except three of the 15 legume treatments were calculated to have provided agronomically significant (> 10 kg N/ha) net inputs of fixed nitrogen for the potential benefit of following crops (Figure 4). The average net input of fixed nitrogen across all legume crops and seasons was ~50 kg N/ha; however, the average for all crops varied between 17 and 103 kg N/ha between seasons. Based on an average cereal yield of 1.6 t/ha and nitrogen removal of 32 kg N/ha per year during the cereal phase, soil nitrogen reserves could perhaps be maintained if one to two cereal crops were grown for every grain legume phase in this environment. Such intensity would present challenges both for farm business risk and profitability in the low rainfall zone and could also lead to agronomic issues such as legume disease build up and broadleaf weed problems arising from such frequent phases of legume crops in paddocks. Therefore, farmers need to consider a wider range of options than pulse crops alone to maintain the nitrogen balance and soil fertility in the low rainfall regions. Such options could include legume pastures, legume crops sown for forage or manuring and supplementary nitrogen fertiliser strategies.

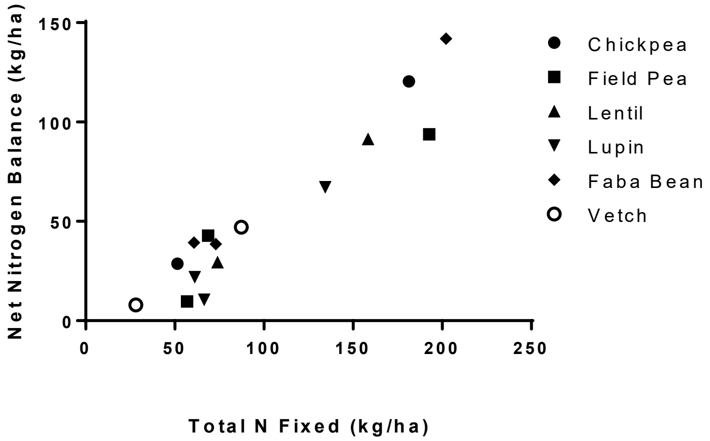


Figure 4. Relationship between total nitrogen (N) fixed (shoot + root) and net inputs of fixed N following grain harvest for various legume crops grown in the low rainfall zone at Mildura (Victoria) in 2013 and 2014 and Loxton (South Australia) in 2015.

Nitrogen fixation by pulse crops requires adequate nodulation of the legume plants roots. This requires an appropriate background population of rhizobia, or for the correct rhizobia to be introduced through inoculation of pulse seed at sowing time. In the low rainfall farming systems, slurry inoculation with peat inoculants can be problematic, especially when farmers have large seeding programs or are sowing into dry soil conditions. In 2020 a trial was undertaken at Kooloonong to evaluate inoculation strategies for Mallee sandy soils. Prior to sowing the background soil rhizobium level was measured and it showed that levels were adequate for lentils and vetch (group E/F), however chickpea (group N) and lupin (group G) were likely to be responsive. These four crops were subsequently sown without inoculant; or with peat slurry (Nodulaid®); or in furrow granule (TagTeam ®granular) treatments. Subsequent assessments showed a significant response in the number of nodules per plant in chickpea and lupin with inoculants but not vetch or lentils (Figure 5) which confirmed the predictions of the pre sowing soil test. Another important result of the trial was the generally equivalent performance of the granule product relative to the peat slurry (Figure 5). In chickpea we often see that granules promote more nodules per plant than peat-based inoculants, however nodules are smaller and therefore the nodule weight per plant is often similar. Although there is additional cost for granule products relative to peat slurry inoculation, the granule products provide a useful option in dry sowing conditions where rhizobia survival in a peat slurry may be compromised. Another potential use for granulated products is to boost the rhizobium levels of certain high risk soil types within the paddock using variable rate technology.

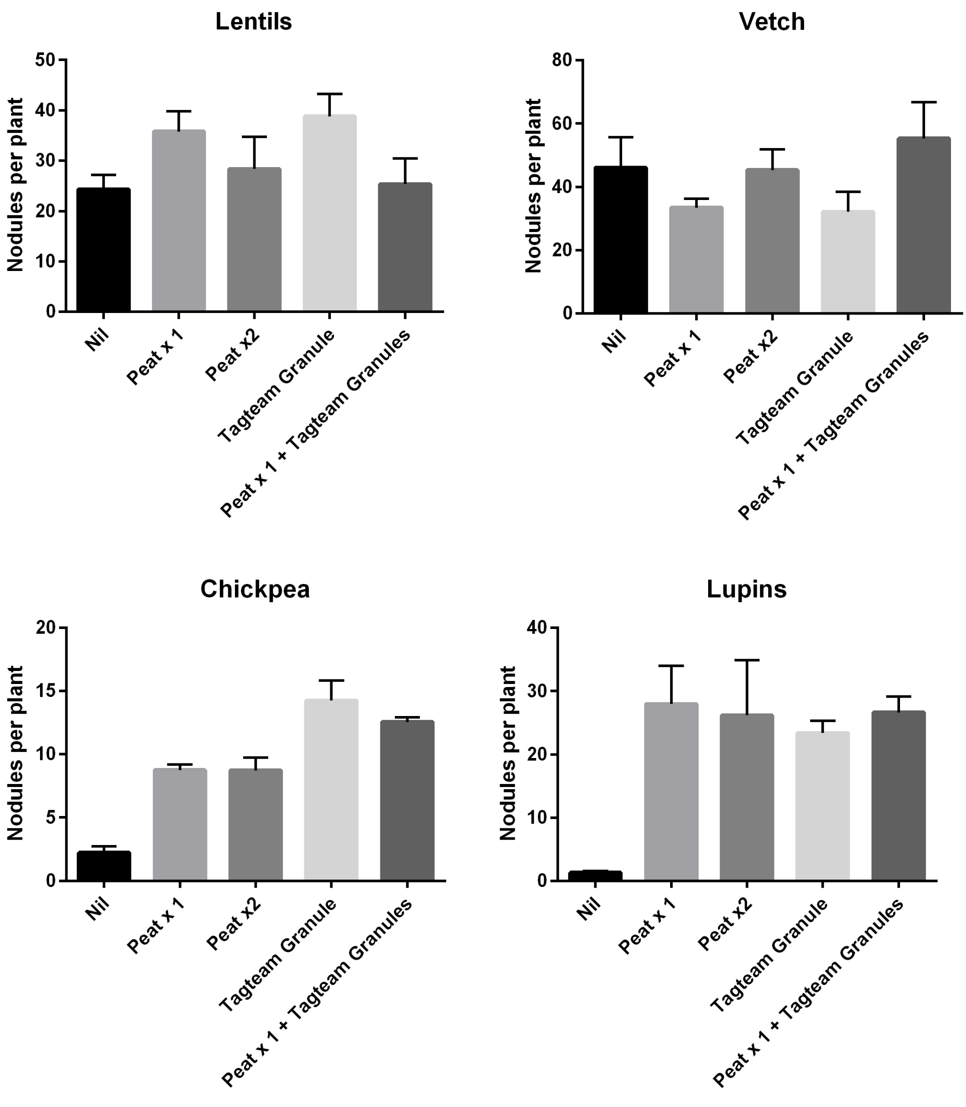


Figure 5. Effect of inoculant treatment on the number of nodules per plant for lentil, vetch, chickpea, and lupin grown on a deep ripped sand at Kooloonong in 2020. Error bars are standard error's

Soil constraints

Pulse crops can be extremely sensitive to soil constraints such as saline and waterlogged soils. In the low rainfall Mallee region, the deep sandy soils which comprise 20-30% of most paddocks have been a major constraint to pulse production. Recent research has highlighted that reducing soil penetration resistance though practices such as deep ripping has led to substantial productivity gains of pulses on these deep sands. For example, chickpea grain yield on an un-ripped deep sand at Kooloonong in 2020 was about one third of the yield achieved on the sandy clay loam (flat) soil nearby within the same paddock (Figure 6). When deep ripping to 50 cm prior to sowing, chickpea grain yield on the ripped sand was improved by over 1.5 t/ha and was equal to or better than what was achieved on the flat (Figure 6). This example highlights the potential benefit from careful investigation of soil constraints and strategies to address these to improve pulse production in the low rainfall zone.

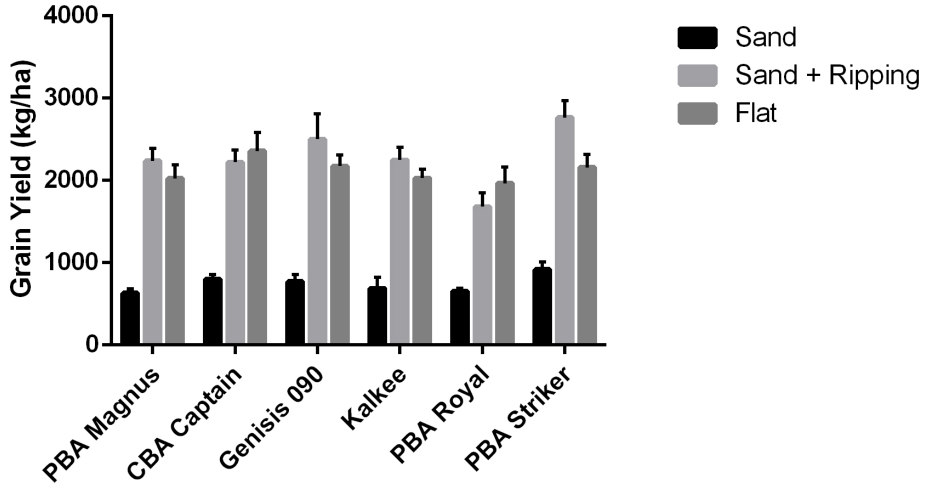


Figure 6. Effect of soil type and deep ripping sandy soils on the grain yield of chickpea varieties at Kooloonong in 2020.

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- MSF 218: Investigating frost susceptibility on Clearfield® varieties treated with imidazolinone herbicide
- MSF 115: Adopting profitable crop sequences in the South Australian Mallee

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Integrating pulses into the farming system - double breaks, fallow vs pulses and optimising crop sequence - a grower's perspective

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Notes:

Causes of poor ryegrass results & paraquat & glyphosate resistance - 2020 season

Peter Boutsalis[1,2], John Broster[3] & Christopher Preston[1]

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Key words

multiple tactics, pre-emergence, glyphosate and paraquat resistance, annual ryegrass, optimising control, testing, random weed survey, double knock, high rainfall

GRDC code

UCS00020

Take home messages

- Ryegrass blowouts are a result of large seedbanks, insufficient weed control strategies and herbicide resistance
- Pre-emergence herbicides offer alternative modes of action to control multiple resistant ryegrass and extend the duration of activity
- Glyphosate resistance in annual ryegrass continues to increase whereas resistance to paraquat remains very low
- Improving herbicide efficacy by good application can reduce selection for herbicide resistance.

Ryegrass blowouts in 2020

The 2020 season saw the return of good rainfall across a large part of the NSW cropping zone. Ryegrass seed can survive in the seedbank for up to three years and longer if dry seasons prevail as occurred in the past few years in this region. Over the past few decades, controlling ryegrass with a single management practice is becoming increasingly difficult as the germination window of ryegrass has increased. Use of a single tactic can cause serious blowouts. Multiple tactics are often required to manage ryegrass particularly during a long season as in 2020 in NSW. Practices such as one or more double-knocks, a robust pre-emergence herbicide or herbicide mixture (Figure 1), in-crop effective post-emergent herbicides (if resistance testing has indicated susceptibility or low resistance), crop-topping if in a suitable crop and harvest weed seed control are necessary to combat ryegrass germinating during the growing season. A greater diversity of pre-emergence herbicides are becoming available with multiple modes of action providing greater benefits including duration of activity and control of multiple resistant ryegrass. It is important to introduce herbicides with alternative modes of action into cropping rotations to reduce herbicide resistance. Ultro® (Group E) and Overwatch® (Group Q) have been registered for the 2021 cropping season for use in pulses and wheat, barley and canola, respectively.

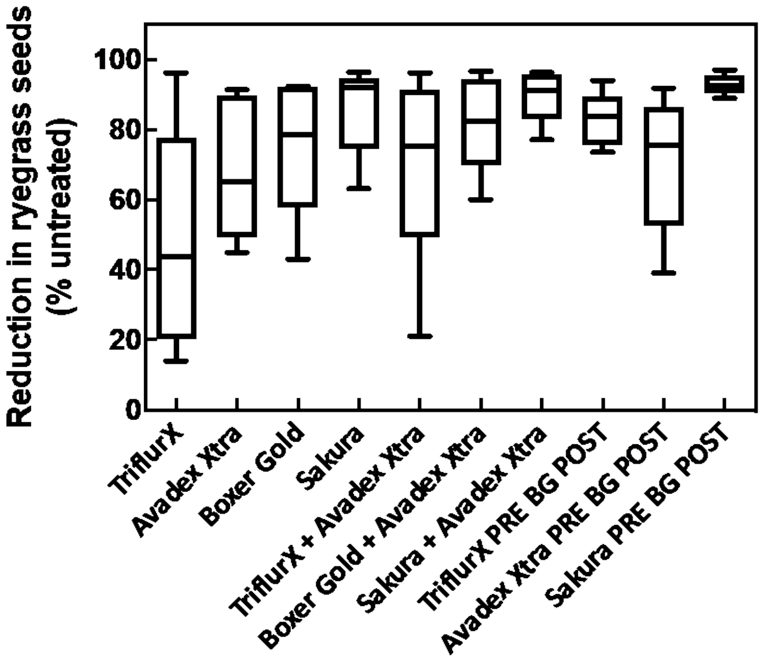


Figure 1. Averaged data showing efficacy of pre-emergence herbicide combinations from field trials in SA, Vic and NSW. As a standalone, Sakura® provided the best control. Tank-mixing or sequential applications improved control (Project code UA00113).

In addition to herbicide choice, there are several other factors such as using full label rates, good application techniques and spraying under ideal conditions that are required to optimise weed control. These are discussed for glyphosate below but are valid for most other herbicides. For pre-emergence herbicides specifically, the stubble load and rainfall prior and after sowing are two additional critical factors. Herbicides must wash off stubble and come into contact with the seed or in close proximity to be active. The germination phase of a seed is important for some herbicides. The mode of action of trifluralin is to prevent the first stage of germination with control reduced on seeds that have already started germinating (Figure 2) with Sakura and Boxer® Gold effective if sufficient moisture distributes the herbicide in close proximity to the seedling.

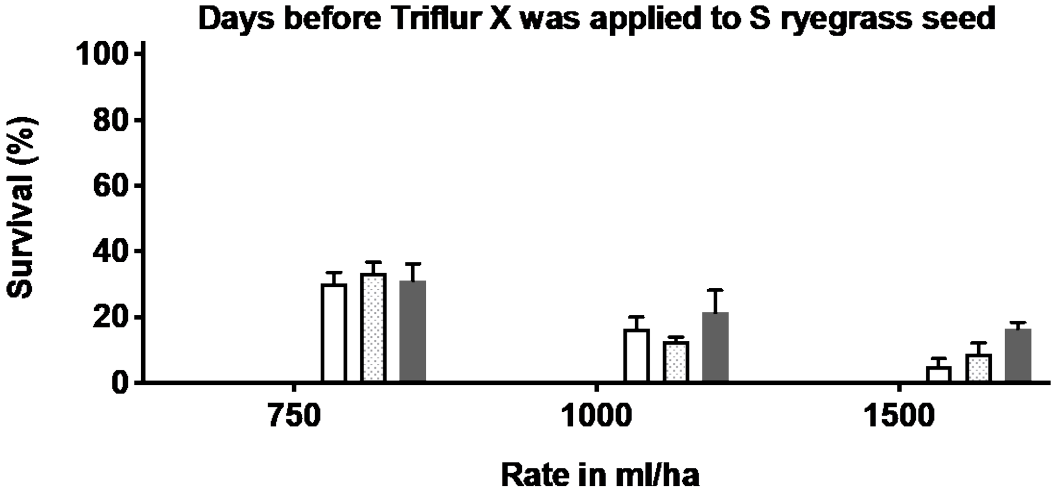


Figure 2. Percent survival of a herbicide susceptible ryegrass biotype measured 4 weeks after treatment. Three rates of Triflur X, Boxer Gold and Sakura were applied in pots. Product rates (mL/ha) are shown in the x-axis. Herbicides were applied on 13 July 2015 to seed that had been exposed to moisture 0, 3, 5, 7, 10, 12 and 14 days prior. Error bars indicate standard error of the means. No plots shown for Sakura and Boxer Gold as no survival was observed even at the lowest rate. As product is applied direct to seed, rates applied are lower or at the low end of label rates as this equates to robust field rates.

A long season can result in ryegrass germinating over an extended period. Whilst the competitive effects of later germinating ryegrass can be minimal on crop yield, the additional contribution of seed into the seedbank from these late germinators can be important for the following seasons. The presence of herbicide resistance can restrict the herbicide options available. Resistance testing can help in identifying herbicides to avoid if no longer effective.

Incidence of resistance in NSW

The GRDC continues to fund random weed surveys in cropping regions to monitor for changes in resistance levels in key weed species. The methodology involves collecting weed seeds from paddocks chosen randomly at pre-determined distances. Plants are tested in outdoor pot trials during the growing season. The majority of annual ryegrass populations in NSW are resistant to Group A 'fop' and Group B herbicides with some variability between the surveyed sub-regions (Table 1). No populations have been found that are resistant to the newer pre-emergent herbicides although this has been reported in other states. Of particular concern is the amount of populations resistant to glyphosate in some of the sub-regions.

Table 1. Extent (percentage) of herbicide resistance in annual ryegrass populations collected in NSW random surveys (resistance defined as populations with >20% survival)

	NSW (2015 - 2019)	2019 eastern NSW	2015 western NSW	2016 NSW northern	2016 NSW plains	2017 southern NSW	2018 NSW slopes
diclofop	59	92	16	32	65	84	77
clethodim	2	12	1	1	1	3	0
sulfometuron	50	82	30	22	35	74	70
imazamox/imazapyr	47	83	8	22	39	75	76
trifluralin	1	2	2	0	0	1	1
prosulfocarb + S-metolachlor	0	0	0	0	0	0	0
pyroxasulfone	0	0	0	0	0	0	0
glyphosate	5	14	6	5	0	7	3
Samples	608	53	117	94	111	128	105

Among the other species, resistance was much lower. 29% of wild oat populations across NSW were resistant to Group A ‘fop’ herbicides (Table 2). Group B ‘SU’ resistance was common for sow thistle (43%) and Indian hedge mustard (27%) across the state, with this rising to 75% of sow thistle populations in eastern NSW resistant (data not shown). Three populations (1%) of sow thistle from northern NSW were resistant to glyphosate. Of the wild radish populations surveyed, 38% were resistant to diflufenican and 23% to 2,4-D amine (Table 2)

Table 2. Extent (percentage) of herbicide resistance in populations of the other species collected in NSW random surveys (resistance >20% survival, * herbicide not tested or not applicable for species)

Herbicide group	Wild oats	Barley grass	Brome grass	Sow thistle	Wild radish	Indian hedge mustard
diclofop	29	0	0	*	*	*
clethodim	1	0	0	*	*	*
sulfometuron	4	1	7	43	4	27
imazamox/ imazapyr	*	*	2	*	0	8
atrazine	*	*	*	*	4	0
diflufenican	*	*	*	*	38	4
2,4-D Amine	*	*	*	1	23	2
triallate	0	*	*	*	*	*
paraquat	*	3	*	*	*	*
glyphosate	0	*	0	1	0	0
Samples	511	133	110	202	28	71

Incidence of paraquat resistance

Resistance to paraquat has been detected in a few ryegrass populations from WA, SA, Vic. They have typically originated along fencelines, non-cropped farm areas, lucerne/clover seed production paddocks and vineyards (Figure 3). Detection has been via random weed surveys or samples sent to Plant Science Consulting and Charles Sturt University following reduced control in the field. While the number remains low it is important to use paraquat according to label recommendations with emphasis on rate, growth stage and population size. The first case of paraquat resistance in ryegrass detected globally was in South African orchards after decades of use on advanced growth stages resulting in sub-lethal effects (Yu *et. al.* 2004). More locally, a sample of perennial ryegrass was confirmed highly resistant to paraquat from a vineyard in the Adelaide Hills in 2019 following application of sublethal rates of paraquat for many years to keep the ryegrass suppressed but maintain ground cover (P. Boutsalis). This sample was also highly resistant to glyphosate.

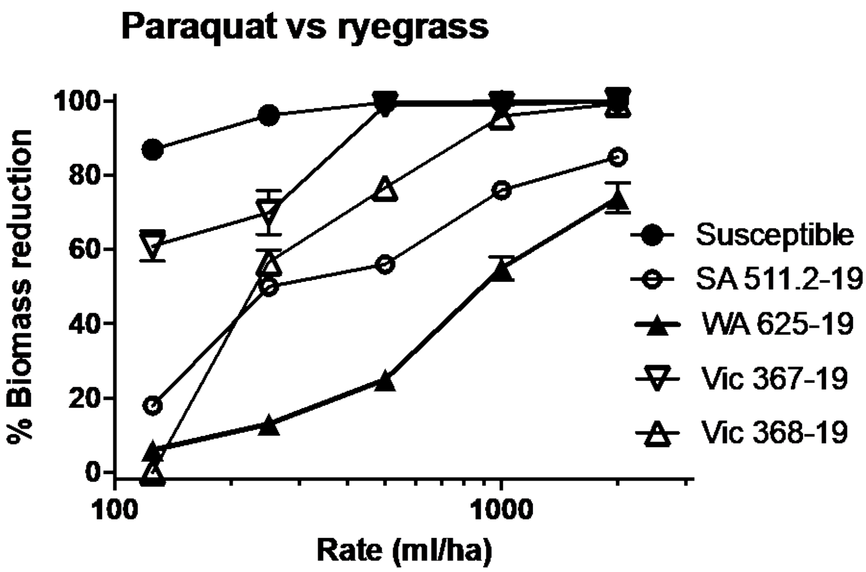
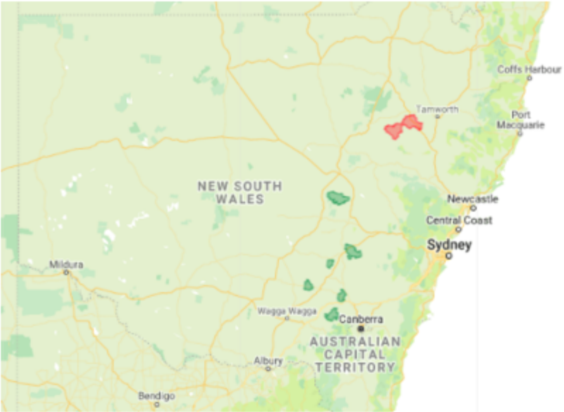
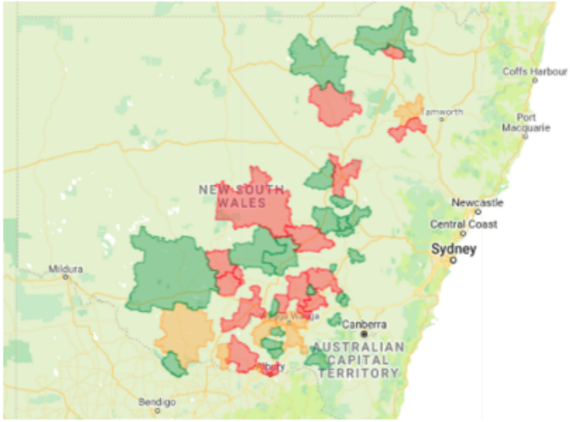


Figure 3. Efficacy of the first confirmed cases of paraquat resistance in annual ryegrass from SA, Vic and WA. Error bars indicate variation. Study conducted by Plant Science Consulting.

Additionally, two populations of barley grass resistant to paraquat and one developing resistance (10-20% survival) have been collected during the NSW random surveys.

Incidence of glyphosate resistance in NSW

Bayer CropScience provides free access to the Resistance Tracker website consisting of thousands of weed samples from resistance testing across Australia (https://www.crop.bayer.com.au/tools/mix-it-up/resistance-tracker). This website enables the searching of resistance according to weed species, mode of action herbicide, postcode and closest town with data presented from 2003 (Figure 4).

2003	2009
	

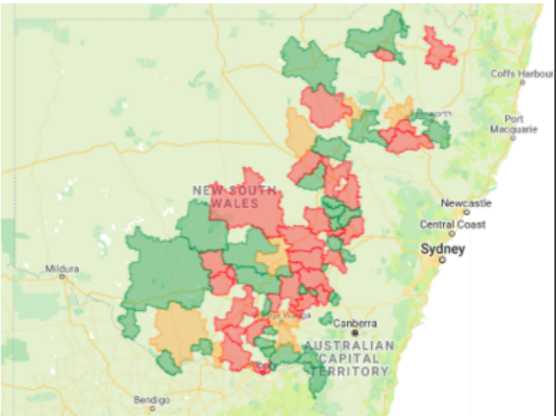
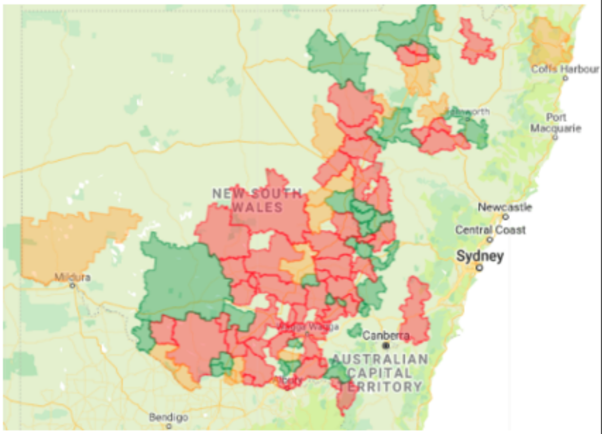
2015	2020
	

Figure 4. Occurrence of glyphosate resistance in annual ryegrass in NSW in 2003, 2009, 2015 and 2020. **Dark green shading** = postcode regions where testing has not detected glyphosate resistance in ryegrass, **orange shading** = postcodes where glyphosate resistance is developing and **red shading** = postcodes where resistance has been detected.

2020 season: The early break in 2020 across most southern cropping regions resulted in an opportunity for knockdown weed control. Multiple applications of glyphosate and paraquat were possibly targeting multiple flushes of weeds, in particular ryegrass from early autumn prior to sowing. Plants surviving glyphosate from WA, SA, Vic and NSW were sent to Plant Science Consulting for testing using the Quick-Test method to verify whether herbicide resistance had contributed to survival in the field. The data presented in Figure 5 indicates that 43%, 70% and 78% of ryegrass samples sent from SA, Vic and NSW in 2020 respectively, were confirmed resistant to glyphosate. This highlights that in a majority of cases, glyphosate resistance has contributed to reduced control in the paddock.

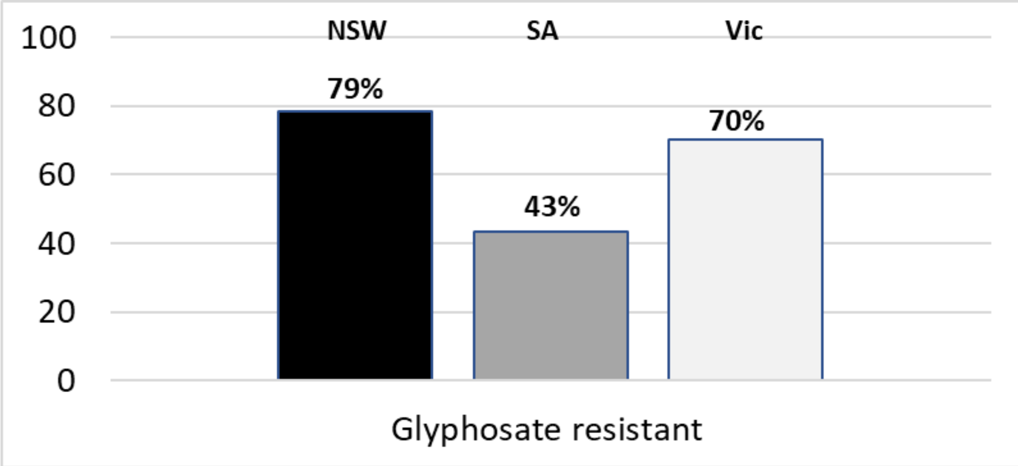


Figure 5. Percent (%) resistance to glyphosate confirmed in farmer ryegrass samples originating from 83 NSW, 37 SA and 74 Vic cropping paddocks treated with glyphosate in autumn 2020. Testing conducted by Plant Science Consulting using the Quick-Test.

Discrepancy between resistance testing and paddock failures to glyphosate

In some cases, plants that survived glyphosate in the paddock are not resistant. Reasons for the discrepancy between the paddock and a resistance test can include poor application or application onto stressed plants, incorrect timing, sampling plants that were not exposed to glyphosate, antagonistic tank mixes, inferior glyphosate formulation, poor water quality, incorrect adjuvants, or a combination of the above.

Evolution of glyphosate resistance

Glyphosate was first registered in the 1970s and rapidly became the benchmark herbicide for non-selective weed control. Resistance was not detected until 1996 in annual ryegrass in an orchard in southern NSW (Powles et. al. 1998). Only a few cases of resistance were detected in the following decade (refer to Bayer Resistance Tracker). The fact that it required decades of repeated use before resistance was confirmed indicated that the natural frequency of glyphosate resistance was extremely low.

There are several contributing factors for the increasing resistance in ryegrass to glyphosate with generally more than one factor responsible. Reducing rates can increase the development of resistance particularly in an obligate outcrossing species such as ryegrass, resulting in the accumulation of weak resistance mechanisms to generate individuals capable of surviving higher rates. This has been confirmed by Dr Chris Preston where ryegrass hybrids possessing multiple resistance mechanisms were generated by crossing parent plants with different resistance mechanisms. Other factors that can select for glyphosate resistance by reducing efficacy include:

1. Using low quality glyphosate products and surfactants
2. Mixing glyphosate with too many other active ingredients resulting in antagonism, particularly in low water volumes
3. Using low quality water, particularly hard water. Glyphosate is a weak acid and binds to positive cations (i.e. magnesium, calcium and bicarbonate) that are in high concentration in hard water (i.e. >200 ppm)
4. Applying glyphosate during periods of high temperature and low humidity, resulting in the rapid loss of glyphosate from solution on leaf surfaces thereby reducing absorption
5. Translocation of glyphosate in stressed plants can be reduced. Optimising glyphosate performance requires the translocation to the root and shoot tips. While this can occur readily in

small seedlings, in larger plants, glyphosate is required to translocate further to the root and shoot tips to maximise control

6. Shading effects reducing leaf coverage resulting in sub-lethal effects
7. Applying glyphosate onto plants covered with dust can result in reduced available product for absorption as glyphosate strongly binds to soil particles
8. Application factors such as speed and nozzle selection, boom height can reduce the amount of glyphosate coverage
9. A combination of the above factors can reduce control and increase selection for resistance.

Optimising glyphosate performance

The selection of glyphosate resistance can be minimised by considering the points above. A number of important pathways to improve glyphosate performance include:

Avoid applying glyphosate under hot conditions.

A trial spraying ryegrass during the end of a hot period and a following cool change was conducted in October 2019. Ryegrass growing in pots were sprayed at 8am, 1pm and 8pm with temperature and Delta T recorded prior to each application. Control of well hydrated plants ranged between 0% and 40% when glyphosate was applied during hot weather (30 to 32.5°C) and high Delta T (14 to 16.7) with the lowest control when glyphosate was applied at midday (Figure 6). In contrast, glyphosate applied under cool conditions just after a hot spell resulted in significantly greater control (65%-80%), indicating that plants can rapidly recover from temperature stress provided moisture is not limiting.

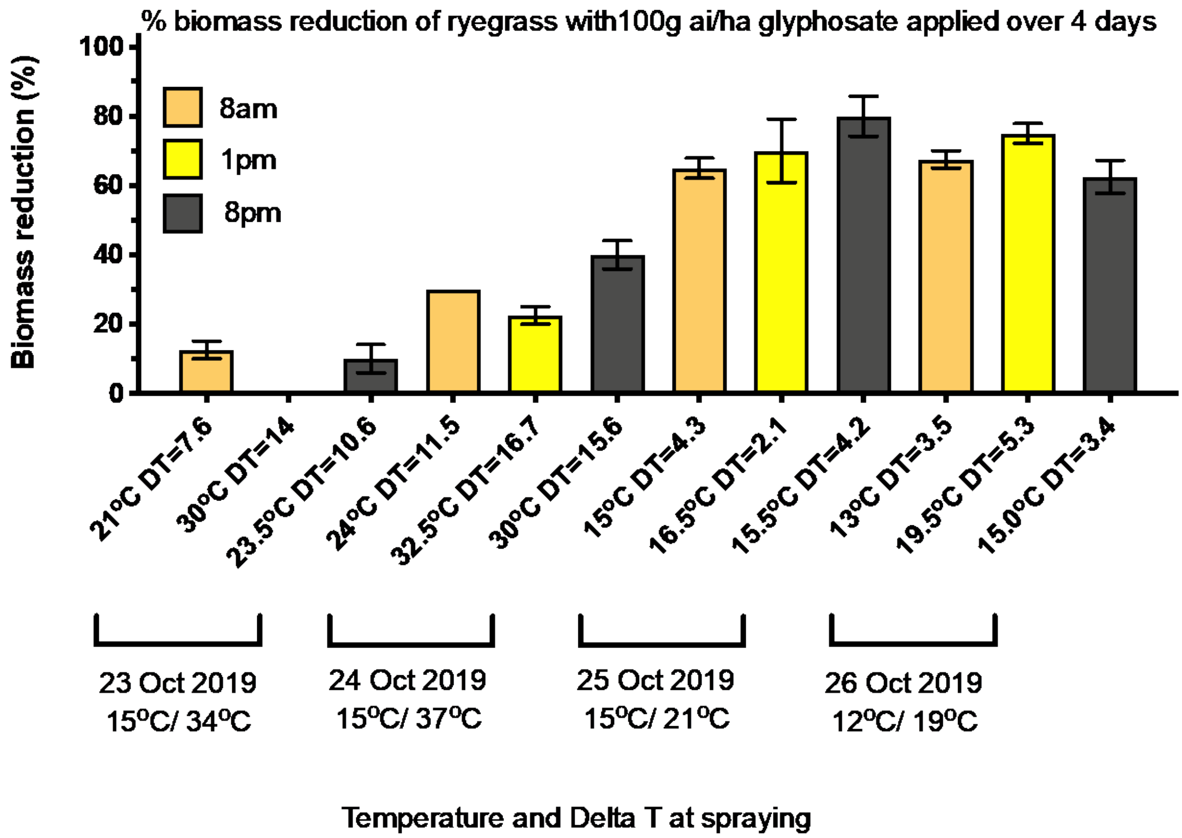


Figure 6. Effect of temperature & Delta T on glyphosate for ryegrass control

Improving water quality and glyphosate activity by using ammonium sulfate (AMS)

The addition of AMS has several functions. One is to soften water by combining to positively charged ions such as magnesium and calcium common in hard water. The negative charged sulfate ions combine with the positive cations preventing them from interacting with glyphosate and reducing glyphosate solubility and leaf penetration. Additionally, AMS has been shown to independently improve glyphosate performance, as the ammonium ions can work with glyphosate to assist cell entry, increasing uptake and activity. In a pot trial conducted with soft water, ammonium sulfate was shown to significantly improve control of ryegrass with 222mL/ha (100g ai/ha) of glyphosate 450 (Figure 7). As a general rule, growers using rainwater (soft) should consider 1% AMS, if using hardwater (i.e. bore, dam) 2% AMS is recommended. The addition of a wetter resulted in a further improvement of herbicide efficacy.

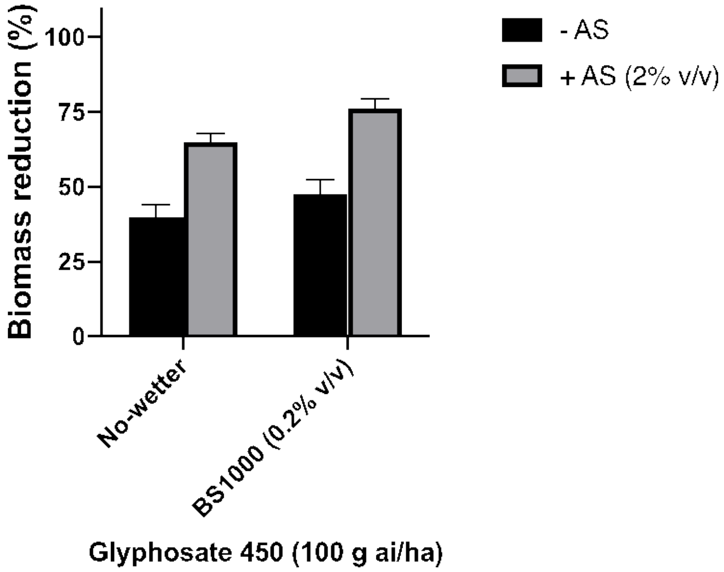


Figure 7. Effect of ammonium sulfate and wetter on glyphosate for ryegrass control

Herbicide activity can vary at different growth stages

In a pot trial investigating the effect of glyphosate at 4 ryegrass growth stages (1-leaf to 4-tiller), good control was achieved at the 3 older growth stages but not on small 1-leaf ryegrass (Figure 8). Most glyphosate labels do not recommend application of glyphosate on 1-leaf ryegrass seedlings. Very small seedlings (i.e. 1-leaf) are still growing on seed reserves and have not yet commenced sugar production via photosynthesis. As a consequence, little glyphosate is translocated downwards with the sugars to the growing point (meristem) of shoots and roots, thus reducing efficacy.

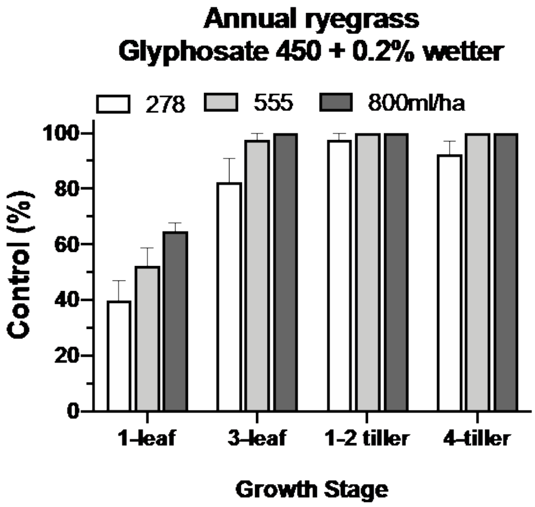


Figure 8. Effect of ryegrass growth stage on glyphosate activity

Double knock

A double knock strategy is defined as the sequential application of two weed control tactics directed at the same weed cohort (germination). The most common double knock strategy is glyphosate followed by paraquat. This has been widely adopted to prevent or combat glyphosate resistance in several weed species, including ryegrass. The first 'knock' with glyphosate controls the majority of the population, with the second 'knock' (paraquat) intended to kill any individuals that have survived glyphosate. Trial work conducted by Dr Christopher Preston (Figure 9) showed that control was optimised when the paraquat was applied 1-5 days after the glyphosate for two glyphosate resistant ryegrass populations. However optimal timing depends on weed size and growing conditions, with at least 3-5 days often being required for full glyphosate uptake and translocation, especially in larger plants. In this study, when the glyphosate resistant plants were left for 7 days before the paraquat application they can stress, resulting in the absorption of less paraquat, reducing control with the second tactic. If growing conditions are poor or plants large, the stress imposed by glyphosate maybe further delayed.

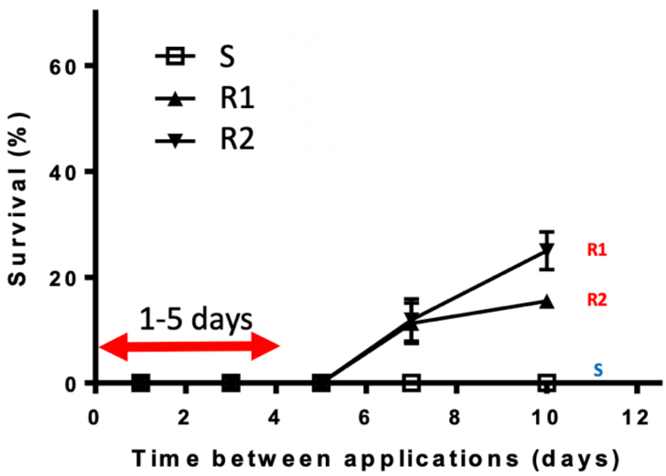


Figure 9. Double knock timing. Glyphosate applied onto a susceptible (S) and two glyphosate resistant ryegrass biotypes (R1 & R2) followed by paraquat 1, 3, 5, 7 and 10 DAA. Trial work conducted by Dr Christopher Preston (The University of Adelaide).

Summary

Ryegrass blowouts in 2020 were a result of large seedbanks, reduced weed control tactics and herbicide resistance. Using multiple tactics including new mode of action herbicides can improve ryegrass control. While paraquat resistance remains very low, glyphosate resistance in ryegrass is increasing at a rapid rate. The early break in autumn 2020 resulted in the testing of about 200 ryegrass populations prior to sowing with over half confirmed resistant to glyphosate. Decades of strong selection pressure resulting from repeated use coupled with application under suboptimum conditions has played a major role. More efficient use of glyphosate combined with effective IWM strategies is required to reduce further increases in resistance.

Acknowledgements

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Seed dormancy and emergence patterns in annual ryegrass populations from cropped fields - why a big flush was expected in 2020 and what is on the cards for 2021 in SNSW

Christopher Preston, Zarka Ramiz and Gurjeet Gill, School of Agriculture, Food & Wine, University of Adelaide

Key words

seed dormancy, glyphosate resistance, weed seed bank

GRDC codes

UOA1803-008RTX, UCS00020

Take home message

- Continuous cropping leads to annual ryegrass populations with higher dormancy
- Early annual ryegrass emergence occurs often after a drought break
- Glyphosate resistance is present at low frequencies in many crop fields
- Annual ryegrass emergence in 2021 will be 'more normal'.

Seed dormancy changes in annual grass

Annual ryegrass has high genetic diversity. This has allowed it to become widely adapted across southern Australia, but also allows it to adapt to changes in the environment. One of the most obvious adaptive traits of annual ryegrass is the widespread evolution of herbicide resistance. However, this is not the only way annual ryegrass populations evolve. In the 1970s, studies of annual ryegrass emergence found 95 % of the population emerged in two flushes shortly after the autumn break of the season. By the 2000s, studies were finding higher levels of seed dormancy and carryover between seasons for annual ryegrass.

There is considerable variability in emergence patterns of annual ryegrass between weed populations. Figure 1 shows the germination of four populations of annual ryegrass from different farms across the mid-North of South Australia under ideal conditions. The population 'Middle top' germinates rapidly within 24 days from sowing. This population has low levels of primary seed dormancy. The other three populations all show delayed germination, taking at least twice as long to reach 50 % germination.

These changes in germination pattern are not just due to environmental conditions. Figure 2 shows the germination patterns of 3 populations of annual ryegrass from fields on the University of Adelaide's Roseworthy farm in the mid-north of South Australia. Even with the same environment, there are differences in emergence pattern for the different fields. The Roseworthy farm is operated as a mixed farming enterprise. Buckby is located at the extreme northern end of the farm and has been continuously cropped for more than 20 years. The other two fields have also been cropped for much of that time, but lucerne and pasture have also been grown in those fields.

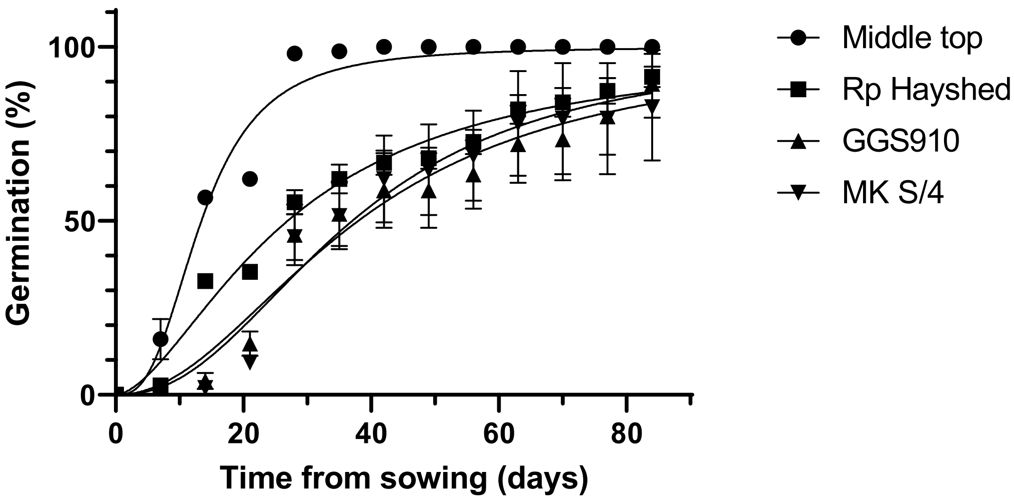

Figure 1. Germination pattern of four populations of annual ryegrass from fields in South Australia tested under ideal conditions.

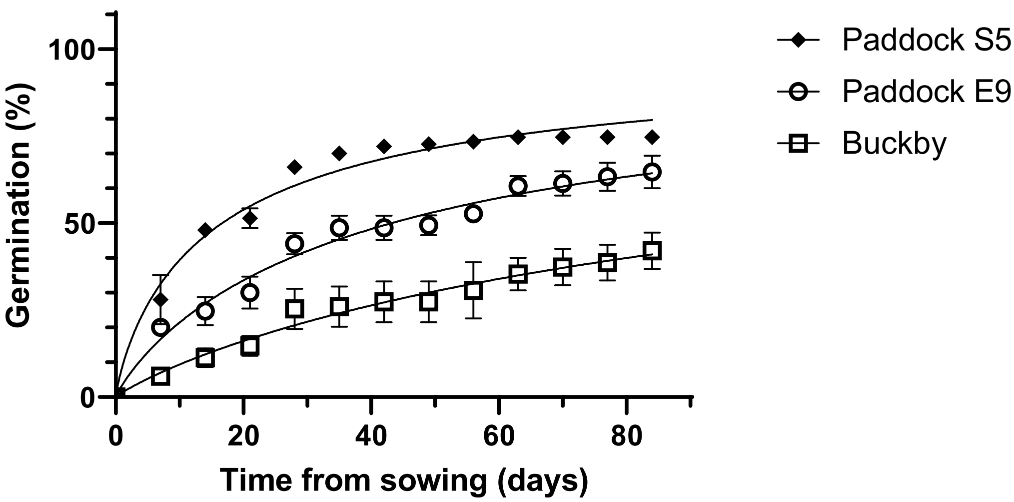

Figure 2. Germination pattern of three populations of annual ryegrass from fields on the Roseworthy farm in South Australia tested under ideal conditions.

Early and late germination is heritable

It is possible to select for higher dormancy in annual ryegrass populations by crossing later germinating individuals among themselves (Figure 3). Likewise, by selecting the early germinating individuals, a low dormancy population can be selected.

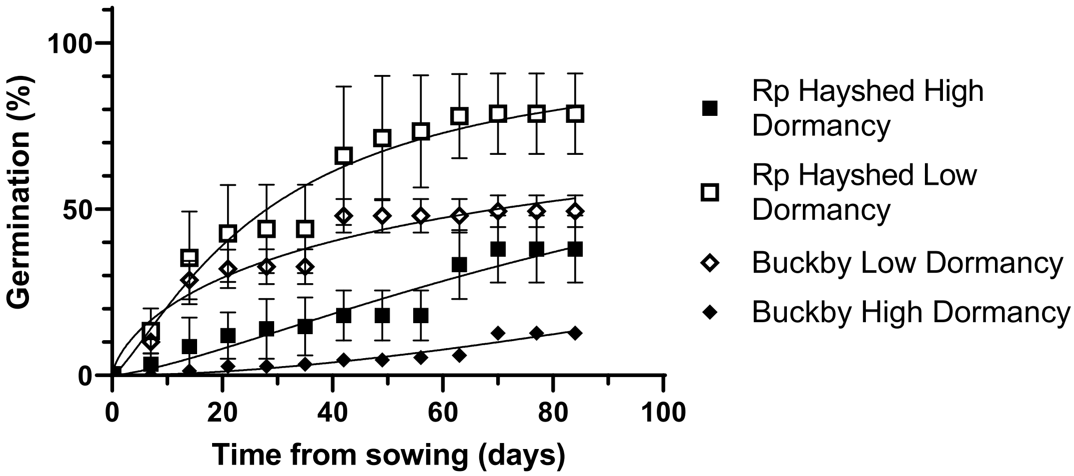

Figure 3. Germination of high and low dormancy sub-populations of annual ryegrass from two populations created by selecting early and late emerging individuals from each population.

As has been observed with brome grass and barley grass populations, it is evident that annual ryegrass populations are evolving in response to continuous cropping by developing more dormant populations. These can escape knockdown herbicide control and emerge once pre-emergent herbicides have declined in concentration. Our previous work looking at early versus delayed sowing in continuously cropped fields found that annual ryegrass numbers in crop were not different with sowing at the start of May compared to the start of June, despite an extra knockdown herbicide application. The selection for increased dormancy in annual ryegrass will be slower than in barley grass and brome grass, due to annual ryegrass being an obligate outcrossing species.

High emergence of annual ryegrass was seen in 2020 – Was this predictable?

The short answer to this question is “Yes”. To understand why, we need to go back to 2016. In 2016, there was an extended wet spring (Figure 4). While this was good for grain yield, it was also good for annual ryegrass seed set. The wet spring also made it hard to get crop-topping applications right and more ryegrass seed was shed before harvest. In addition, cool wet spring periods result in seed with greater dormancy than in years with dry springs.

Emergence of annual ryegrass from the soil seed bank requires sufficient moisture, primarily in autumn and winter when the soil temperature has fallen, and the loss of primary dormancy of seed in the seed bank. Shallow seed burial can encourage emergence; however, deeper burial discourages emergence and induces secondary dormancy, extending the life of the seed bank. However, 2017 had a slightly drier than normal autumn and spring period. By 2018, much of the 2016 seed bank would be ready to germinate, but a drier than average autumn and winter discouraged emergence. Spring was dry, meaning that any new seed produced tended to have low primary dormancy. Similar conditions occurred in 2019, only with even less rainfall.

These conditions created a situation in 2020 where nearly all the annual ryegrass seed in the seed bank had lost primary dormancy and was ready to germinate, provided sufficient rainfall occurred. There were large rainfall events from early in autumn 2020 that allowed this annual ryegrass seed to germinate and establish.

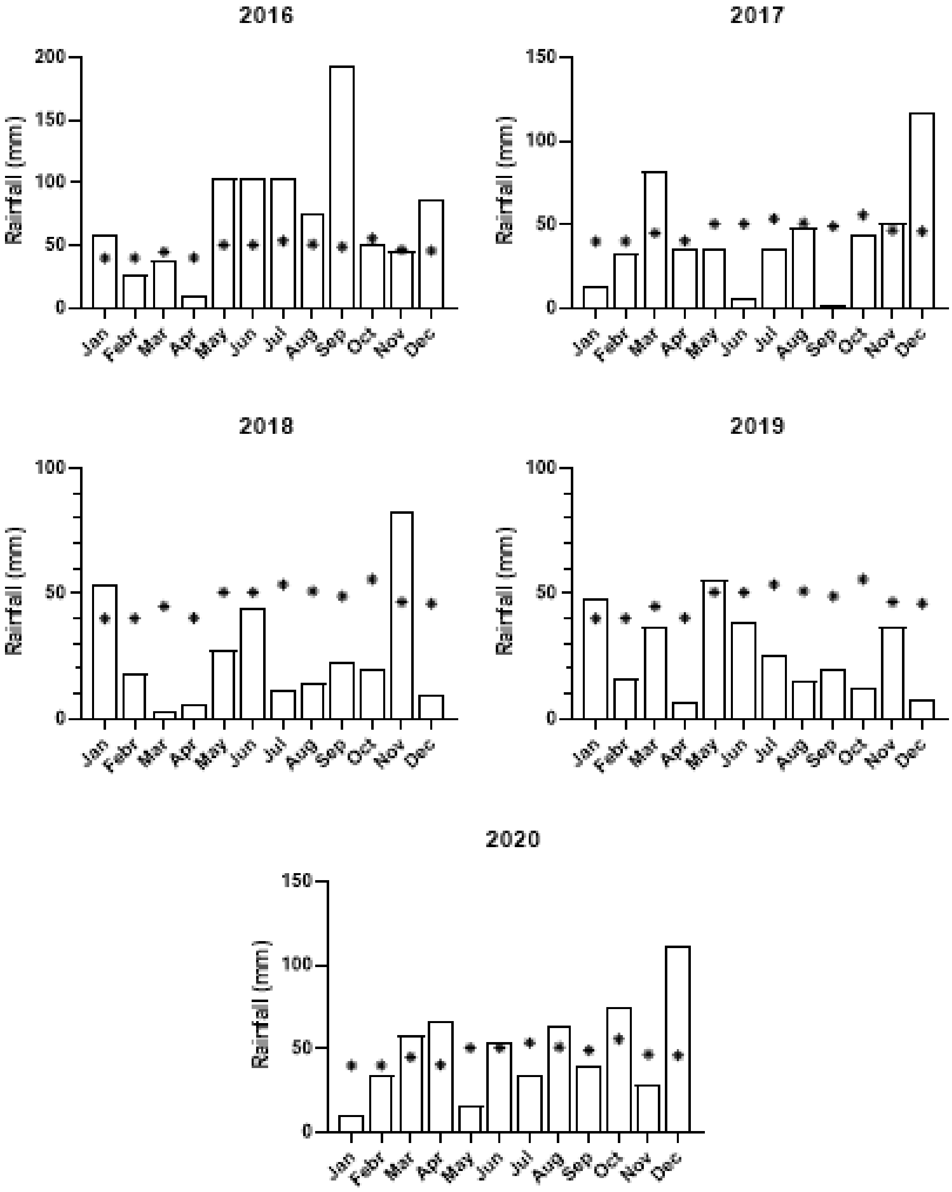

Figure 4. Monthly rainfall at Old Junee, NSW from 2016 to 2020. Asterisks indicate the mean monthly rainfall.

Early annual ryegrass emergence made glyphosate resistance obvious

One consequence of the rainfall patterns was glyphosate resistant annual ryegrass was particularly obvious in 2020. The early autumn rains resulted in the emergence of a lot of weeds well in front of sowing. The longer than normal time between when glyphosate was applied in 2020 and sowing commenced made glyphosate resistant annual ryegrass easy to observe. Reduced glyphosate availability exacerbated the problem. Growers likely used products they were less familiar with and trimmed rates to stretch the product available across the farm. Resistance surveys have shown that glyphosate resistant annual ryegrass is present in low frequencies across the cropping region. Mostly this is not noticed, because the crop is sown shortly after the knockdown applications and other practices tend to keep the low numbers under control.

What to expect for 2021

Most of the residual seed bank of annual ryegrass from previous years has been exhausted. This means most of the seed in the seed bank now will be from 2020, which had a more normal rainfall pattern compared to 2018 and 2019 (Figure 4). This means annual ryegrass seed will have its normal level of seed dormancy. The size of the annual ryegrass flush will depend on how much and how early rain falls in autumn, but it should be smaller than in 2020.

Are there any management practices that can change ryegrass emergence patterns?

It has long been known that light burial, an autumn tickle, can encourage annual ryegrass to germinate. However, doing this will have less impact on the dormant part of the annual ryegrass population and will severely compromise pre-emergent herbicide efficacy. Introducing pasture into the cropping system will select for earlier emerging annual ryegrass and shift the population towards lower dormancy. The most practical management change can come from understanding what to do after a drought. This is when there is likely to be a large autumn flush of annual ryegrass, as there will be little dormant seed left in the seed bank. This is the best time to employ a double knock prior to sowing. It is also the time when more effective pre-emergent herbicide strategies should be employed to help deal with the expected large emergence.

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Fitting new pre-emergent chemistries in the farming system and managing them for longevity

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pre-emergent herbicide, annual ryegrass, herbicide resistance, WeedSmart, Big Six

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Take home message

- New pre-emergent herbicides are becoming available; however, it is vital that these are used appropriately to get the best results
- Choice of herbicide should consider soil type, seeding system, soil organic matter and likely rainfall after application
- Non-chemical tools such as crop competition, hay and harvest weed seed control are vital to protect the longevity of new and existing chemistry
- Ryegrass blowouts in 2020 will drive the adoption of WeedSmart Big 6 tactics to manage seedbanks over the medium to longer term.

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. Resistance to trifluralin is now common across many cropping regions of South Australia and Victoria, and is increasing in NSW. Worryingly, resistance to the Group J and K pre-emergent herbicides can also be detected in random weed surveys. In some parts of South Australia and Victoria, resistance to triallate is becoming common. It is likely resistance will further increase, making it more difficult to control annual ryegrass with the current suite of herbicides available. New pre-emergent herbicides offer an opportunity to expand the suite of products that can be rotated. However, it is important that these are used well to optimise performance while also maintaining their longevity.

New pre-emergent grass herbicides

Several new pre-emergent herbicides have recently been released or will be released in the next few years for grass weed control. The main characteristics of these herbicides are provided in Table 1. As with previous 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. Characteristics of new pre-emergent herbicides for grass weed control

Herbicide	Devrinol®-C	Luximax®	Overwatch®	Ultro®	Mateno® Complete[a]
Active ingredient	Napropamide	Cinmethylin	Bixlozone	Carbetamide	Aclonifen + pyroxasulfone + diflufenican
Mode of Action	K	T	Q	E	New + K + F
Solubility ($mg\ L^{-1}$)	74	63	42	3270	1.4 (aclonifen) 3.5 (pyroxasulfone) 0.1 (diflufenican)
Binding K_{OC} ($mL\ g^{-1}$)	839	6850	~400	89	7126 (aclonifen) 223 (pyroxasulfone) 5504 (diflufenican)
Crops	Canola	Wheat (not durum wheat)	Wheat Barley Canola	Pulses	Wheat

[a]Registration of Mateno Complete is expected in 2023

Devrinol-C is a Group K herbicide from UPL registered in 2019 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 it much safer under adverse conditions. Devrinol-C offers an alternative pre-emergent herbicide to propyzamide or trifluralin for canola.

Luximax is registered 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®. It has moderate water solubility and higher binding to organic matter in soils. It will move readily into the soil with rainfall events, but will be held up in soils with high organic matter. Persistence of Luximax is generally good, but it degrades sufficiently quickly that plant backs are 3 to 9 months. 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 is the only safe seeding system and the crop seed needs to be sown 3 cm 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 from FMC is a Group Q herbicide that should 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 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. 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 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. Chickpeas are the least tolerant pulse and rates are lower. 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. Knife-points and press-wheels are the preferred seeding system for IBS applications.

Mateno Complete from Bayer is likely to be available for 2023. It contains three modes of action including a new mode of action aclonifen. For ryegrass control, it will be similar to Sakura; however, it will provide more control of wild oats and brome grass and some broadleaf weed activity. It is planned to be registered for both IBS and early post-emergent use in wheat. 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.

New pre-emergent broadleaf weed herbicides

In addition to pre-emergent herbicides for grasses, there are also new pre-emergent herbicides for broadleaf weeds. The main characteristics of these herbicides are provided in Table 2.

Table 2. Characteristics of new pre-emergent herbicides for broadleaf weed control

Herbicide	Callisto®	Reflex®[a]	Voraxor®
Active ingredient	Mesotrione	Fomesafen	Trifludimoxazin + saflufenacil
Mode of Action	H	G	G
Solubility (mg L^{-1})	1500	50	1.8 (trifludimoxazin) 2100 (saflufenacil)
Binding K_{OC} (mL g^{-1})	122	50	~570 (trifludimoxazin) ~30 (saflufenacil)
Crops	Wheat Barley	Pulses	Wheat Barley

[a]Registration of Reflex is expected in 2021

Callisto is a pre-emergent Group H herbicide from Syngenta. It is registered in wheat and barley for use in IBS, knife-point press wheel seeding systems. It has strong activity on 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 9 months, provided 250 mm of rainfall has occurred. Callisto offers an alternative to post-emergent Group H herbicide mixtures, where early weed control is important.

Reflex is a Group G herbicide from Syngenta with expected registration in 2021. It will be registered pre-emergent and 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. Lentils are the most sensitive pulse crop and separation of herbicide from the seed is important, particularly on light soils with low organic matter.

Voraxor, from BASF, contains the active ingredients trifludimoxazin and saflufenacil, which are both Group G herbicides. Voraxor provides broadleaf weed control and some annual ryegrass control as a pre-emergent herbicide in wheat, durum and barley. 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. The mobility of the herbicide means crop damage may occur with heavy rainfall after application. This damage can be exacerbated if some grass pre-emergent herbicides are applied as a tank mix.

Mix and rotate in diverse farming systems

An expanded range of herbicides creates opportunities for the rotation of herbicide modes of action and the ability to mix with existing chemistry. Research by Pat Tranel from the University of Illinois, USA found that resistance can be mitigated by mixing herbicides at full rates. Pat is quoted saying ”rotating buys you time, mixing buys you shots”. Peter Newman from WeedSmart expanded on the concept to recommend that we mix herbicides and rotate modes of action so that we can ”buy time and shots”.

Research by Roberto Busi from AHRI found that rotating groups alone may not substantially delay resistance occuring. However *mixing* herbicide groups can be a highly effective tactic, even on resistant populations. Rygegrass from 140 fields across 58 farms in WA were tested for susceptibility to a range of pre- and post-emergent herbicides. The testing showed that a number of ryegrass populations were resistant to individual herbicides, for example 34% of the ryegrass populations were developing resistance to trifluralin and 11% developing resistance to triallate. Yet when these two herbicides were combined in a mix, full control was achieved.

For the other pre- and post-emergent mixtures that were tested: prosulfocarb + trifluralin, pyroxasulfone + trifluralin, triallate + trifluralin, prosulfocarb + trialliate, prosulfocarb + pyroxasulfone, triallate + pyroxasulfone and butroxydim + clethodim; there was consistently less resistance to the mixture, compared to the resistance levels of the individual herbicides when applied alone.

The mix and rotate strategy will not only provide improved weed control but more importantly aids in resistance management where unpredictable patterns of cross-resistance are evolving. Even the best pre-emergent herbicides can be broken by resistance if not managed wisely.

Populations of ryegrass from the Eyre Peninsula in South Australia have recently been confirmed as resistant to all of the pre-emergent herbicides – triallate (Avadex®), prosulfocarb (Arcade®), trifluralin, propyzamide and pyroxasulfone (Sakura). These findings by the University of Adelaide have huge implications for an industry now heavily dependent on pre-emergent herbicides in no-till systems, showing they can quickly break down in the face of metabolic cross-resistance.

Repeated applications of the same herbicides in simple canola-wheat rotations has allowed ryegrass to develop metabolic cross resistance. This is in the absence of alternative tactics such as croptopping, hay, harvest weed seed control or diverse rotations which create opportunities to run down the weed seedbank.

A heavy reliance on Groups J & K (eg Avadex®, Boxer Gold, Sakura) in no-till systems can be alleviated with the introduction of herbicides from Groups E, T and Q (eg Ultro, Luximax and Overwatch). The new chemistry used alone or in mixtures creates opportunities for targeting resistant weeds or managing resistance through alterntive use patterns.

The new Group E product Ultro (carbetamide) provides an alternative to trilflualin or propyzamide for pre-emergent grass weed control in pulses. Ultro will also reduce the heavy selection pressure on post emergent grass herbicides such as clethodim or clethodim + butroxydim (Factor) mixtures.

Crop rotation allows greater diversity with some of the new herbicide choices available. For example the new Group G product Reflex (fomesafen) has shown good control of broadleaf weeds such as sowthistle and prickly lettuce which are problematic in pulses. A heavy reliance on Imi chemistry in Clearfield® tolerant pulse crops has seen the development of resistance in brassica and thistle species. This new Group G product allows growers to relieve pressure on the Imi chemistry and strengthen the value of older herbicides such as simazine when used in a mixture.

Resistance stewardship – WeedSmart Big 6

As new chemistry becomes available it is crucial for all involved to protect the longevity of any new products and minimise the risk of resistance. The WeedSmart Big 6 brings together weed research data with grower experiences to create a set of practical guidelines focused on minimising the weed seedbank without compromising profit.

The WeedSmart Big 6:

1. rotate crops and pastures
2. double knock – to preserve glyphosate
3. test, mix and rotate herbicides
4. stop weed seed set
5. increase crop competition
6. adopt harvest weed seed control

Best practice agronomy is a key component of the Big 6 and pulls together all the aspects of profitable no-till cropping such as precision seeding, timely sowing, targeted nutrition, soil amelioration and crop competition so that crops have the edge over weeds. Tactics such as harvest weed seed control, cutting hay and diverse rotations are also essential to complement herbicide use including the mix and rotation of herbicides, double or triple knock and late season crop-topping.

Site specific applications such as shielded sprayers or optical spray technology are also effective at reducing herbicide inputs and introducing diverse chemistry. Application technology is now emerging as realistic option for controlling weeds and managing resistance. Optical spray technology is being developed for green on green scenarios where sensors detect weeds and activate the spraying of weeds only. Artificial intelligence and associated machine learning systems will reduce overall herbicide usage but also open up potential opportunities for high value chemistry or alternative site specific tools such as lasers.

Grower success in reducing weed seedbanks but staying profitable has been achieved through stacking Big 6 tactics over an extended period of time. For example, a diverse rotation with pulses, competitive barley and early sown hybrid canola combined with pre-emergent herbicides, opportunistic double knocks, croptopping and chaff decks has all the Big 6 tactics stacked together.

Harvest weed seed control – the mills are here

In 2020 the industry observed a surge in the adoption of weed seed impact mills for harvest weed seed control. Given a favourable season in the eastern states and moderate weed pressure, an increasing number of growers made the decision to invest between $60,000-$120,000 in one of the four impact mills available. These include the: Seed Terminator, iHSD – Harrington Seed Destructor, Redekop Seed Control Unit and Techfarm WeedHOG. With approximately 500 units now in use across Australia, growers are beginning to understand the strengths and weaknesses associated with the technology.

The objective of an impact mill is to grind, shear and crush the weed seeds contained in the chaff fraction of harvest residue. The objective is to get as many weed seeds into the header in order for the mill to destroy the viability of seed and reduce the seedbank. On average, a harvester cutting low can capture 70% of the seeds prior to shedding or lodging and then destroy 98-99% of these weed seeds that enter the header. Overall the feedback has been positive especially those committed to making the system work over the long term, but a number of growers expressed concern with several issues. This included exorbitant running costs, mill wear, belt alignment and excessive heating, fuel use and loss of capacity. In a big season such as 2020 where crop yields were generally above average, the power requirements to harvest the crop are already significant, and a mill then adds more load on the machine. This in turn reduced operator output and subsequently increased costs which was frustrating during a wet harvest.

Not every harvest will be as slow and challenging as 2020 and all impact mill owners are encouraged to assess the true cost of the machine over a number of seasons. All systems involve compromise and the processing of weed seeds with an impact mill is no different. Working with the mill manufacturer and local dealer to review the strengths and weaknesses of the unit, and then following up in the paddock to see how well the machine worked is vital. Harvest weed seed control is a part of a long term commitment to controlling weeds. Like herbicides it requires ongoing learning and attention to detail to achieve success.

Summary

New chemistry is providing opportuntites for growers to manage resistant weeds using a broad range of herbicides. In order to protect these new products, the industry needs to continue working together to ensure farming practices include both chemical and cultural weed control options to keep seedbanks low and minimise the risk of resistance.

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