MULLALEY
NEW SOUTH WALES
JULY 2020

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

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GRDC 2020 Grains Research Update Welcome

If you are reading this, then chances are you have taken time out from an extraordinarily tough season in our very sunburnt country to hear the latest grains research, development and extension (RD&E) information.

Welcome.

We at the GRDC understand how very challenging the current situation is for growers, advisers, agronomists, researchers and those associated with the grains industry across New South Wales and Queensland.

Drought takes an enormous toll financially, emotionally and physically on those working and living through it daily. We trust that these GRDC Grains Research Updates will offer you new research information to help guide your on-farm decisions this season and to be best placed to take advantage of future seasons. We also hope the Updates provide a chance to connect with your peers and temporarily escape work pressures.

We would like to take this opportunity to thank our many research partners, who, like growers and advisers, have gone over and above in recent years to keep trials alive in rain-deprived environments.

Challenging seasons 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 four 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.

Today, GRDC staff and GRDC Northern Panel members are at this Update to listen and engage with you. This is a vital forum for learning, sharing ideas and networking, all of which are critical to effect successful change and progress on-farm.

Regards,
Gillian Meppem
Senior Regional Manager North

P PO Box 5367 Kingston, ACT 2604 Australia
T +61 2 6166 4500 **F** +61 2 6166 4599 **E** grdc@grdc.com.au

GRAINS RESEARCH & DEVELOPMENT CORPORATION ABN 55 611 223 291

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ICAN
Independent Consultants Australia Network

Compiled by Independent Consultants Australia Network (ICAN) Pty Ltd.
PO Box 718, Hornsby NSW 1630
Ph: (02) 9482 4930, Fx: (02) 9482 4931, E-mail: northernupdates@icanrural.com.au
Follow us on twitter @GRDCNorth or Facebook: http://www.facebook.com/icanrural

How has Mullaley's climate changed and what impact has it had on sorghum productivity

Jeremy Whish and Elizabeth Meier, CSIRO

Key words

climate, historic climate, changing yield potential, sorghum

GRDC code

CSP1806-01

Take home messages

- Increasing temperatures and reduced rainfall have lowered the yield potential of sorghum in many areas
- Avoiding high temperatures at flowering and using a conservative sowing trigger (>100mm PAW) can reduce the impact of a changing climate
- There is still room to reduce the yield gap with targeted sowing dates, nitrogen rates and soil water triggers despite a changing climate reducing sorghum yield potential.

Introduction

Australia's climate is warming, including an increase in average temperature, increase in number of days exceeding 35°C and a decrease in rainfall (CSIRO and BOM, 2015).

But what is happening at Mullaley? How will this affect the crops I grow? What can I do to manage this change?

These are some of the questions we have tried to address.

Over the last few years, several suggestions have been made to GRDC that have warranted our examination of sorghum production in response to changing climates. The key concern was that a changing climate had reduced the yield potential of central Queensland crops and would cause the key sorghum production areas to move south to cooler and less variable climates. In this paper we review local annual and growing season climates, sorghum production and compare these results to other sorghum production areas to see how or if things have changed.

Methods

Current climate was compared with historical climate using a climate normal approach to compare overlapping 30-year time periods. This is recognised as the most statistically sound method to determine if a change in climate has occurred (Arguez and Vose, 2011) and is recommended by the World Meteorological Organisation's standard for placing current climate conditions in a historical perspective. A simulation analysis of sorghum production in response to a range of initial soil water and sowing dates was then conducted using APSIM (Holzworth,2014) to identify whether changing these management practices could mitigate the effect of any changes in climate.

How is the Mullaley environment changing?

Rainfall

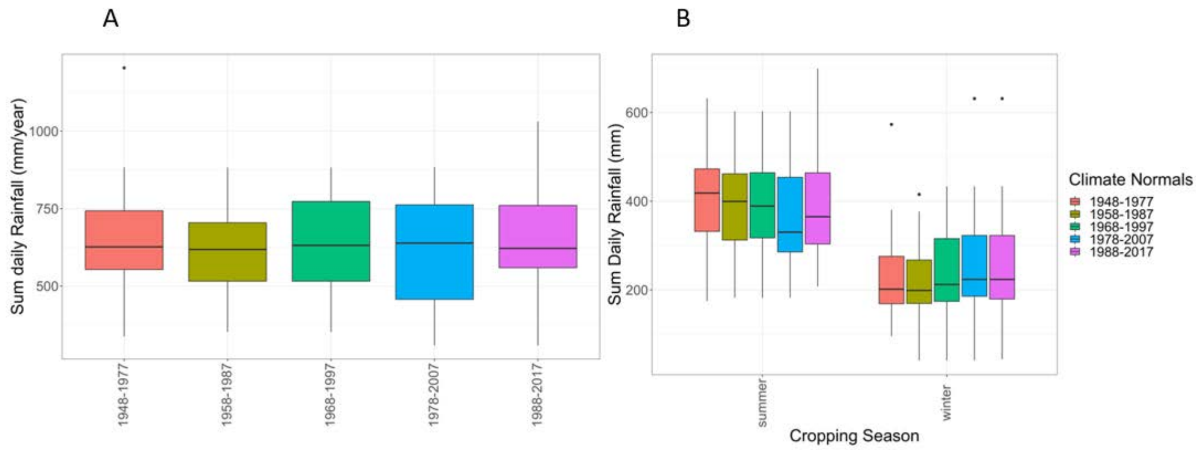

Figure 1. Sum of rainfall for each 30-year climate normal period on an annual (A) and cropping season (B) basis at Mullaley. The results show how rainfall has changed over time. In general, there has been little change in rainfall over the study period. A decline in summer rainfall has been compensated by a slight increase in winter rainfall.

Temperature

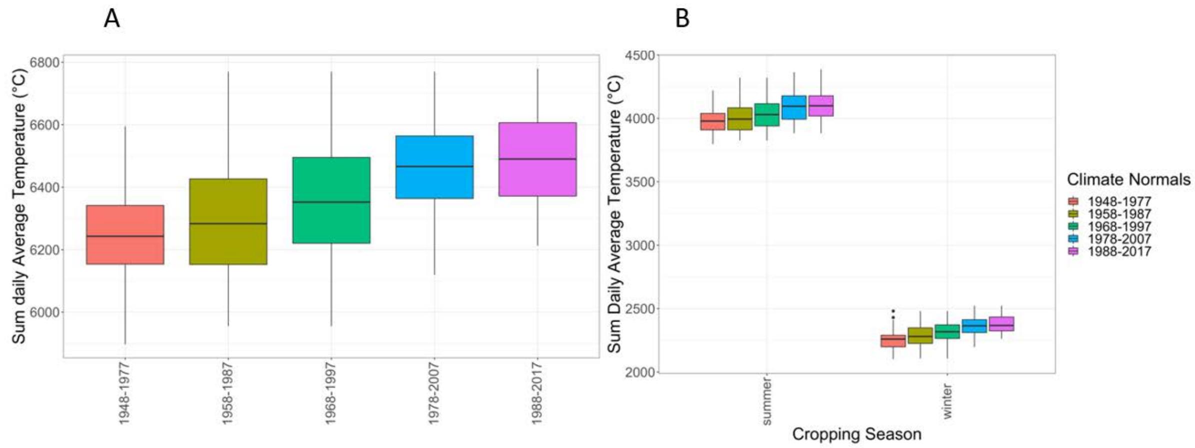

Figure 2. Sum of daily average temperature on an annual (A) and cropping season basis at Mullaley. Average temperature showed a continual increase in heat to the most recent climate normal (1988-2017). The change in accumulation of heat was similar in both summer and winter growing seasons.

Extreme temperatures

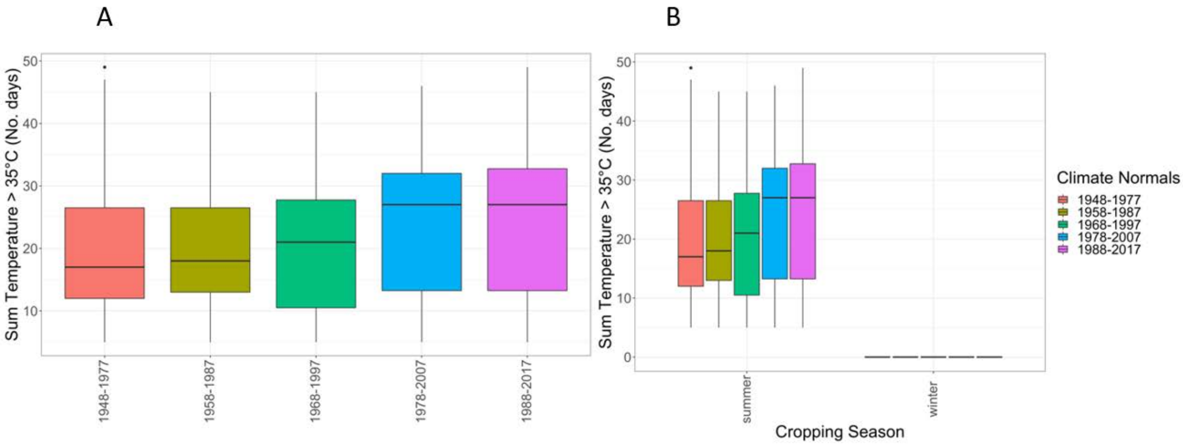

Figure 3. Number of days of extreme temperatures (above 35°C) summed on an annual (A) and growing season (B) basis. The days above 35°C follow a similar pattern to the heat sum on an annual basis increasing to the most recent normal (1988-2017). Extreme temperatures occurred in the summer only.

How will these changes in climate affect sorghum?

Higher temperatures increase the rate of crop development and the amount of water transpired by the crop. If rainfall remains stable or decreases then this will increase the chance of moisture stress occurring in the crop. However, if the growing period of the crop can be matched to the timing of rainfall then it may be possible to maintain or increase crop grain yield despite an annual reduction in rainfall.

To identify whether the yield potential of sorghum crops had changed over the last 60 years a series of simulations were undertaken. The 60-year period from 1958-2017 was used for this analysis and sub-divided into two climate normals – 1958-1987 and 1988-2017 - that could be compared.

Water stored within the soil helps to buffer crops from variability in the climate. In order to understand the effect on yield of changes in the climate, the median yield from a crop sown into a full profile of water was compared across the 60-year period. This approach was expected to demonstrate the least difference between the two climate normal periods, because each site by sowing date combination had optimal soil water at sowing. The study was completed for a selection of locations ('transects') in both the eastern and western parts of the GRDC northern growing region (Figure 4).

Sorghum crop yields sown on a full profile of soil water

For northern sites of the western transect (from Mungindi north) there was little change in yield except for a reduction in yield of around 0.5 t/ha at the extremes of early sowing and late sowing (Figure 4). For the northern sites of the eastern transect there was a clear reduction in yield for sites north of Goondiwindi, especially for sowing dates before November. For the eastern transect there were distinct groupings of change in yield: improved yield between Goondiwindi and Moree for crops sown between November and January, and decline in yield on the Liverpool Plains that worsened with later sowings and culminated around a mid-December plant.

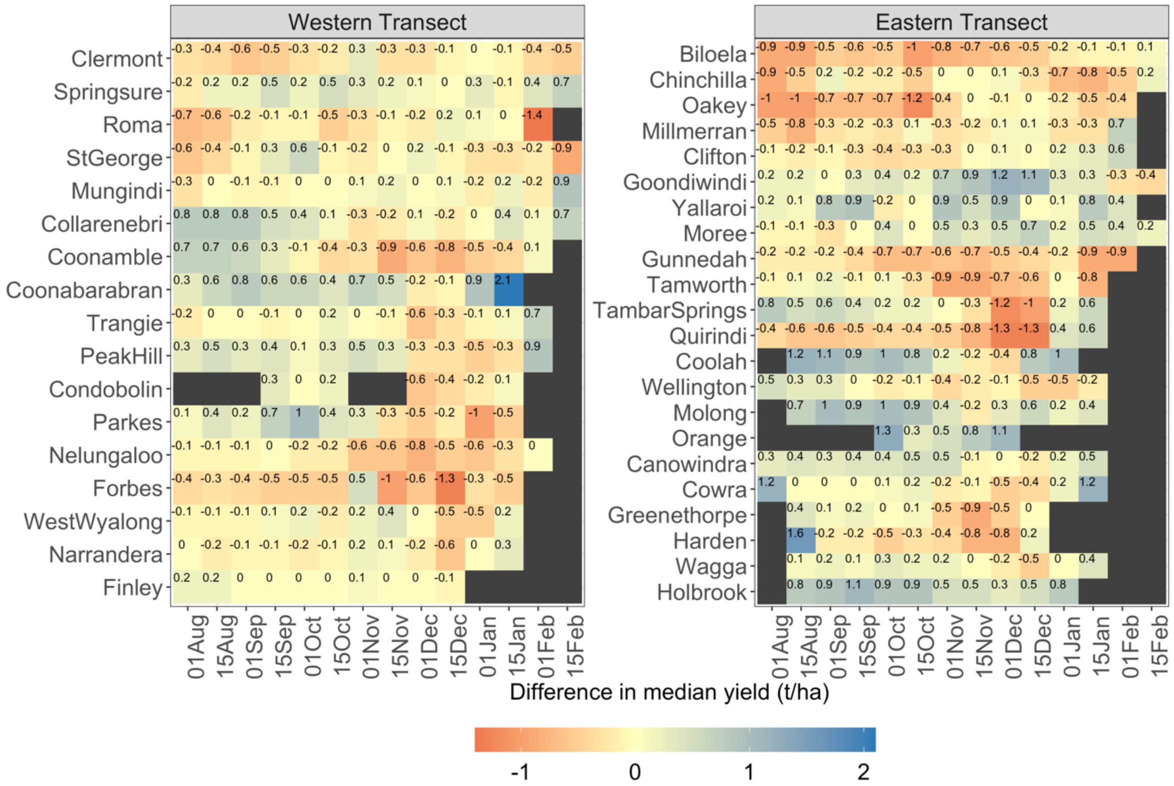

Figure 4. Difference in median yield of sorghum crops between climate normals 1958-1987 and 1988-2017 when sown into a full profile of water, for different sowing dates for locations divided into western and eastern transects. Red shading in cells indicates a decrease in yield, blue indicates an increase, and yellow indicates sowing dates where there was minimal to no difference in crop yield. Only median yields from sowing dates that had fewer than 50% failed crops are included (other location-sowing date combinations were considered unsuitable for crop production and are coloured black). Values within each cell are the difference in yield between the climate normals (t/ha).

What has been the effect of changing climate on yield when there isn't a full profile of soil water at sowing?

The objective of simulating sorghum crop yields in response to a full profile of water in the previous step, was to understand whether the most recent 30-year climate normal period was different to the previous 30-year normal in terms of its effect on crop yield. However, it can be inefficient to wait for a soil profile to fill because producing adequate crops regularly, can more be financially rewarding than waiting for ideal conditions (such as a full soil water profile) to occur. In this section we present results for crops sown into a profile with an initial amount of 100mm of available soil water. This amount is towards the lower end of soil water that would be present when a decision to sow occurs (the general sowing rule for western sites (west of the Newell highway) is commonly, 150mm of plant available water). In the eastern sites with higher rainfall 100 mm is more common. The use of 100mm for both transects is a compromise.

There was an increase in crop failures (cells shaded black) between crops sown on a full profile of soil water (Figure 4) and those sown into a profile containing 100mm (Figure 5). This difference in initial soil water also explains the use of wide row configuration and 150 mm soil water trigger that is used by many grain growers along the western transect. However, despite these differences in yield arising from differences in initial soil water. The general patterns of changes in yield and optimal sowing dates between climate normals were the same. There were minimal differences in yield between climate normals for the north-western sites, but a decrease in yield potential for the eastern sites. The November to mid-January sowing dates between Goondiwindi and Moree continued to demonstrate an increase in yield for the more recent normal, while later sowing in the Liverpool Plains continued to demonstrate a yield reduction.

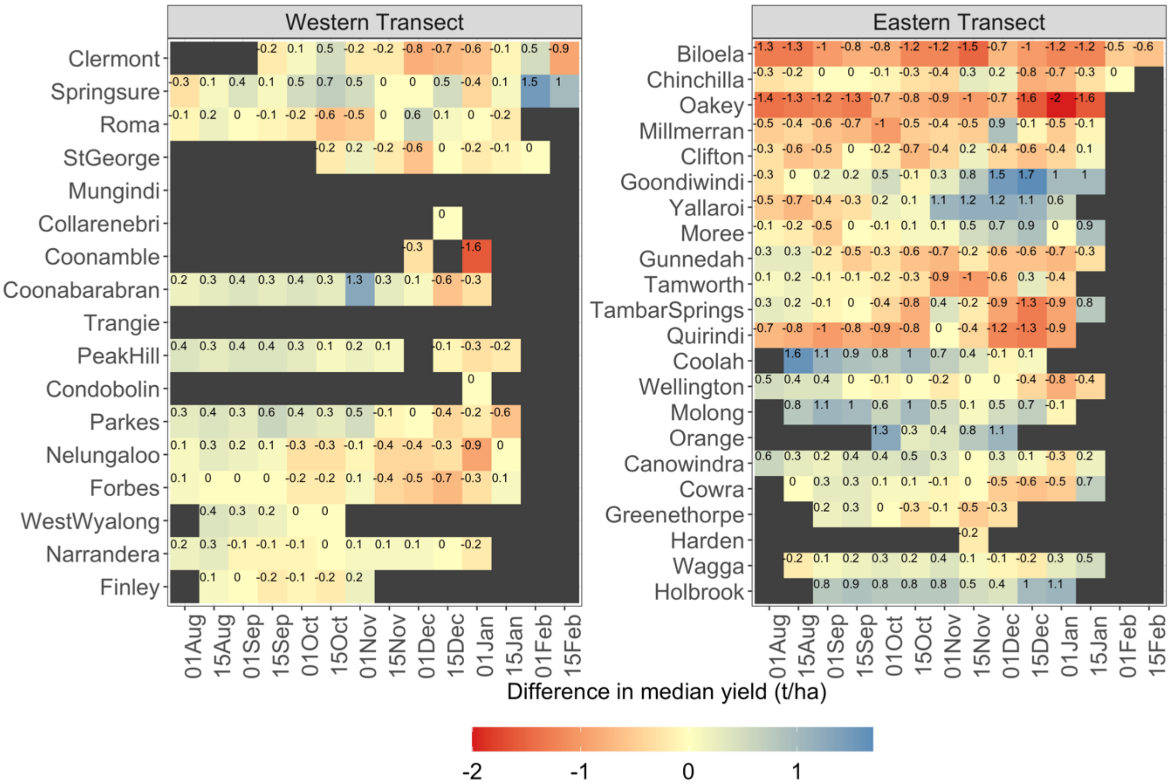

Figure 5. Difference in median yield of sorghum crops between climate normals 1958-1987 and 1988-2017 when sown into a profile of 100mm of water, for different sowing dates for locations divided into western and eastern transects. Red shading indicates a decrease in yield, blue shading indicates an increase in yield, and yellow shading indicates sowing dates for each location with minimal to no difference in yield. Only median yields from sowing dates that had fewer than 50% failed crops are included (other location-sowing date combinations were considered unsuitable for crop production and are coloured black). The values within each cell specifies the magnitude of the difference in yield between the climate normal periods (t/ha).

Why are yields changing?

Rainfall

The availability of water to the crop is the key determinant of yield in Australia. The value of stored soil water is its ability to buffer the demands of the plant in between rainfall events and ensure optimal plant growth. The timing and size of rainfall events are critical to maintaining this buffer as is the specific soil type. In general, the quantity of in-crop rainfall decreased or remained neutral across locations in both eastern and western transects, although there was an increase in in-crop rainfall at a few locations (e.g. Coonabarabran, Goondiwindi and Yallaroi for some times of sowing). These locations are those that showed an increase in water limited yield potential (Figures 4 and 7), and highlight that this increase in rainfall pattern has directly resulted in increased yield.

Mullaley being at a similar latitude to Gunnedah is assumed to behave in a similar way, though being slightly west the magnitude of the differences could be less but not as great as in Coonabarabran.

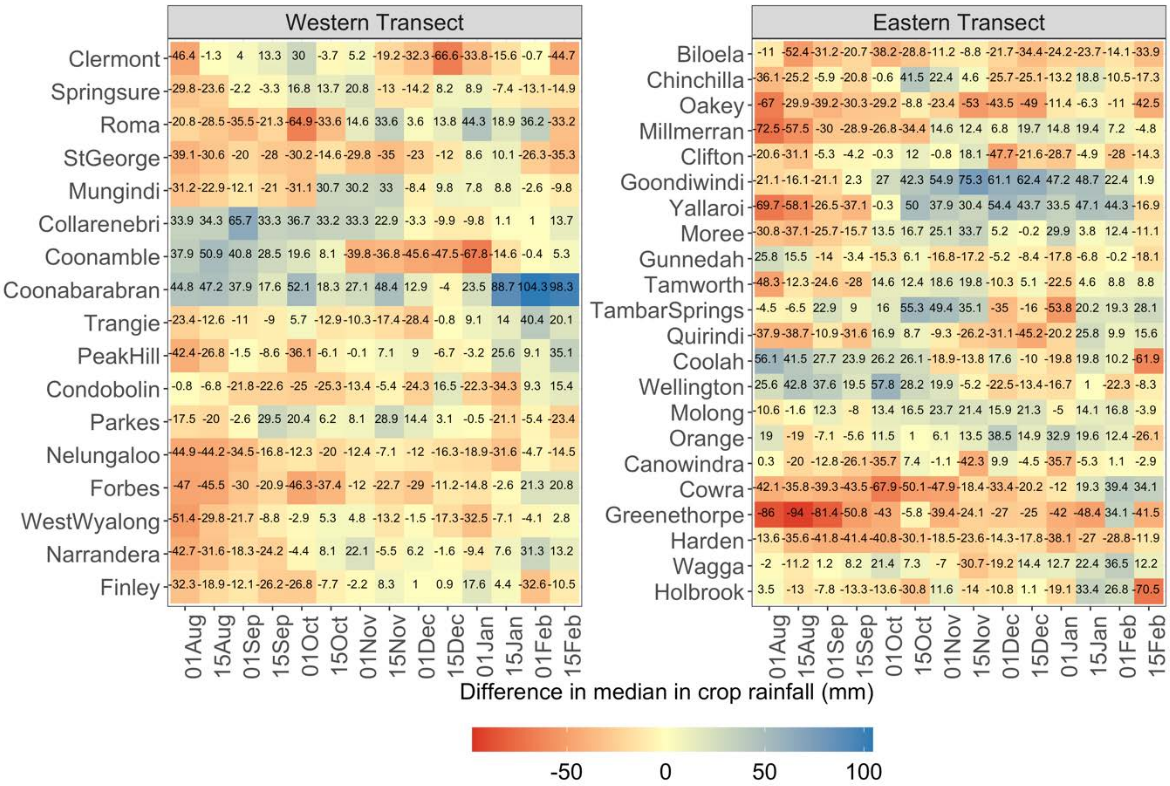

Figure 6. Difference in median in-crop rainfall for the 14 different sowing dates between the two climate periods 1958-1987 and 1988-2017, for locations in western and eastern transects. Red shading indicates a decrease in in-crop rainfall, blue shading indicates an increase in rainfall, and yellow indicates sowing dates with minimal to no difference in rainfall between normals. The values within each cell are the difference in median in in-crop rainfall (mm).

Extreme temperatures

High temperatures around flowering can significantly reduce sorghum grain yield (Lobell et al., 2015; Singh et al., 2017; 2016). The difference in the number of days with temperatures in excess of 35°C increased between the past 30-year climate normal period (1958-1987) and the more recent 30-year normal (1988-2017). The increase in days with extreme temperatures was greater for the western transect, especially for crops sown between October and November. For the eastern transect there was a general increase in the number of days with extreme temperatures for all sowing dates before December. However, a few specific sites experienced a reduction in extreme temperatures; these sites and sowing dates correspond with those that experienced an increase in rainfall and consequently an increase in median yield potential (Figure 7).

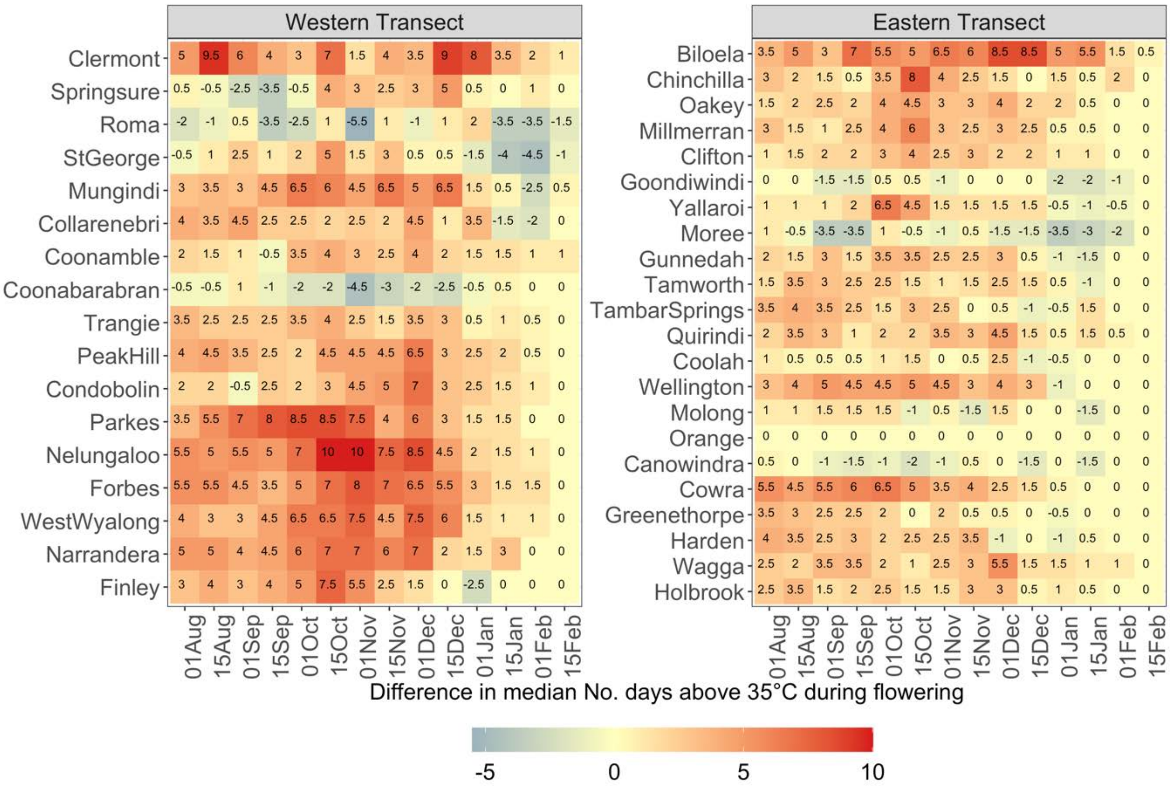

Figure 7. Difference in the median number of days above 35°C during flowering for the 14 different sowing dates between the two time periods of 1958-1987 and 1988-2017, for western and eastern transects within the northern grain zone of eastern Australia. Red indicates an increase in rainfall while blue indicates a decrease, yellow highlights those sowing dates with minimal to no difference. The values within each cell are the difference in median number of days above 35°C during flowering.

So, what does it mean and what can I do?

The climate of Australia's sorghum production area has changed, with increases in the average daily temperature, an increase in the number of days with extreme temperatures during flowering, and a decrease in in-crop rainfall for many locations. These changes have resulted in an overall reduction in crop yield potential. However, despite this decrease the yield potential has not been reduced to a point where it is no longer economical to grow sorghum. Good agronomy and the use of high soil water triggers at sowing will help maintain profitable returns under changing climates. For sites that had an increase in yield for some sowing dates, this could be traced to increased rainfall and a decrease in extreme temperatures during flowering. However, these increases were relative only to the areas historic production and not an increase above traditionally high yield regions. Thus, despite a decrease in the yield potential over the study period for many areas, this decrease was too small to cause a noticeable shift in sorghum production areas, and so NSW is not the new central Queensland for sorghum production.

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Contact details

Jeremy Whish
CSIRO Agriculture and Food
306 Carmody Rd St Lucia Qld 4067
Ph: 07 4571 3215
Email: Jeremy.Whish@csiro.au

Moving summer crop sowing early or late - risks and rewards on the Liverpool Plains

Loretta Serafin and Mark Hellyer, NSW DPI, Tamworth

Key words

sorghum, sunflower, maize

GRDC code

Optimising Sorghum Agronomy project (UOQ 1808-001RTX)
Tactical sorghum and maize agronomy (DAN 00195)

Take home message

- Planting early in August/September has less risk than delaying planting later until February for both sorghum and maize. There is little information to support moving sunflower sowing time earlier than currently established sowing windows
- Risks associated with earlier sowing include variable and low soil temperatures resulting in poor establishment and frost risk for all crops. Also, the risk of winter weed competition with young establishing crops. However, the flowering, grain fill and harvest periods are all brought considerably forward
- Late planting (i.e. early February) was not successful for sorghum or sunflower in the 2019/20 season due to damage from birds in sunflower and a combination of ergot, midge and slow grain ripening being affected by frost in sorghum. Maize had few agronomic issues apart from a longer grain filling period and dry down delaying harvest
- Additional research, particularly in maize and sunflower is required to support the conclusions in this paper before adoption by growers.

Introduction

The Liverpool Plains is the land of opportunity when it comes to selecting a summer crop. It is considered a very reliable region with the ability to grow a wide range of summer crop species namely, sorghum, sunflower, maize, mungbean and cotton.

Climate variability seems to be increasing and over the last decade, fluctuations in rainfall and temperature have brought new challenges to this dynamic cropping system. These include questions over the most reliable and productive way to ensure summer crops remain in the system.

The concept of varying sowing windows to either much earlier or later than “normal” in response to weather patterns expected in individual seasons brings with it risks and opportunities which each need to be evaluated.

The largest influence in all decisions though is water, primarily how much has been stored in the soil profile. Deciding to plant with less than a full profile immediately increases the risk of reduced crop yields or failure and ultimately profitability unless you can be “under the right cloud” during the season.

This paper merges the results from a range of NSW DPI experiments over the last 5 years which relate to optimising the performance of sorghum, sunflower and maize.

Sowing windows - a moving target?

Identifying the recommended sowing window for all summer crops is easy if you stick with traditional guides. Where it becomes more interesting is when you want or need to push the boundaries by planting significantly earlier or later to respond to changing seasonal conditions.

NSW DPI produces the summer crop production guide which has indicative planting times for summer crops on the Liverpool Plains (Table 1). These tables are based largely on the need to meet three criteria:

1. Adequate soil temperatures to enable rapid crop emergence; 12°C for maize and sunflowers and 16-18°C for sorghum
2. To minimise the risk of damaging frosts on young establishing crops in the spring
3. To minimise the risk of frost damage to crops during grain fill if late sown.

Ideal timing for the early plant starts in mid-September for sunflower and maize and the second week of October for sorghum (Table 1). It is recommended to cease sowing maize at the end of October. Sorghum and sunflower have the advantage of a late planting opportunity which starts in early December and ends in mid-January for sorghum and late January for sunflowers.

Table 1. Recommended sowing times for summer crops on the Liverpool Plains (source: an extract from the NSW DPI Summer crop production Guide, 2019)

Liverpool Plains	Early plant										Late plant											
	Aug		Sept				Oct				Nov				Dec				Jan				Feb	
	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2
Sorghum							<	★	★	★	★	★	>		<	★	★	★	★	>				
Sunflower			<	<	★	★	★	★	★	>	>				<	<	★	★	★	★	★	>	>	
Maize			<	<	★	★	★	★	★	★	>	>												

< earlier than ideal but acceptable

★ optimum planting time

> Later than ideal but acceptable

In the last 5 years we have experienced hotter and drier summer conditions which have highlighted the need to avoid crops flowering during peak heat stress conditions, most likely to occur in late December/ early January.

Using CliMate, we can see that in 45% of years (1990 to present) we have received temperatures over 35°C during a 7-day period at Breeza. In the last 5 years this has occurred between 6 and 23 times in the period between 15 December and 31 January which is the traditional flowering period for all three summer crops. These conditions have resulted in reduced seed set, grain yield and quality.

These issues have led us to conduct research on two alternative options for planting:

1. moving the sowing window forward by around 4 weeks from the "ideal" sowing time
2. extending the sowing window later to include the end of January and early February.

This past season, many parts of the Liverpool Plains did not receive enough rain to enable planting prior to mid-January when the sorghum window closes. Following a dry winter, many producers were faced with the prospect of no summer crop or planting outside of the normal sowing window in mid to late January.

Sorghum

Early sowing – risks and rewards

The largest 'early sowing' research effort has been on sorghum in recent years. A series of early sown sorghum trials have been conducted across the northern grain's region stretching from Emerald in central Queensland to the Liverpool Plains, including a site at Breeza.

This research has been evaluating the potential for sowing sorghum into soil temperatures as low as 12°C, which in local terms means planting at the beginning of September on the Liverpool Plains.

Trials which were sown in August or early September; produced better yields than a late October plant in the first two seasons (2017-18 and 2018-19). In this season, the October 29 plant out yielded the September 11 planting, but was not different to planting on October 8. This is probably not surprising considering that late season rainfall amounted to an additional 100mm of in-crop moisture for the late October sown crop.

The primary risks with early planting relate to ensuring crops are sown when soil temperatures are at a minimum of 12°C and rising to allow uniform emergence within 14 days of planting. This relies on good quality seed (germination and vigour) and accurate weather forecasting to predict a warming front for at least 7 days following planting.

The risk of a severe frost in September, which could cause significant early plant death, remains. However, we have not experienced this in the last three seasons. At most we have lost 10% of emerged plants in our earliest sowing time. This equates to 5 dead plants in 10m of plant row. At a population of 50,000 plants/ha, this loss seems acceptable. It is also possible to lose the main stem only from frost and have tillers recover.

Planting early at soil temps of 12°C will result in slower emergence and a longer vegetative period. It will also generally move the flowering period forward towards early December, reducing the risk of heat stress at flowering.

Early planting should also move grain fill, and crop maturity forward allowing an earlier harvest and increased time for fallow refill and consideration of a double crop option in the following winter.

On the downside, there is potential for winter weeds to still germinate and compete with early sown sorghum crops. The main species of concern are grass weeds such as black/wild oats.

Late sowing in 2019-20 - risks and rewards

With little research data to support our decisions to stop planting after mid-January, a late summer species trial was planted at Breeza. The trial was watered up on the 5 February and has since remained dryland. The trial included three hybrids each of sorghum, sunflower and maize.

The main risks associated with planting sorghum in late January into early February is predicting when temperatures fall to a point where pollination will be affected or when a frost will occur. The date of the first frost has often been suggested as Anzac Day based on local memories, or the middle of May based on crop modelling. This season the first frost occurred on the 6 June at Breeza and visible leaf damage was observed in the following days although plant death did not occur.

Other challenges for late planted sorghum include ergot and midge, with both present this season. Even though the midge resistance of hybrids has greatly improved, there was still a requirement to spray this season. However, more damage has resulted from ergot this season caused by fungal infection (*Claviceps africana*) which can produce toxins in the grain. No control options are available for this disease in sorghum.

In the middle of June, the sorghum was looking dismal due to the heavy ergot infection. A combination of poor seed set, ergot infection and honeydew coated seed with a low percentage of coloured grain present, gave little hope of a harvest prior to our next early sowing opportunity.

Our conclusion from this season has been that delaying sorghum planting until early February at Breeza is likely to result in crop failure. There is a slim chance that a successful crop can be produced from sowing this late, the period for grain fill, physiological maturity and crop dry down for harvest would be extremely prolonged.

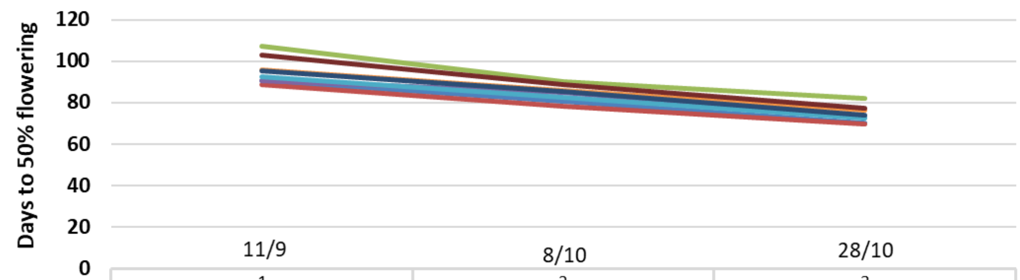
If planting very late, as per our trial this season, the recommendation would be to increase the plant population to reduce tillering and force the hybrids into earlier flowering as well as carefully selecting your hybrid for maturity and midge resistance.

What is the impact on days to flowering in sorghum from varying sowing time?

Early sowing (e.g. 11 September) results in a longer vegetative period compared with a ‘normal’ sowing time of the 28 October (Figure 1). For example, a mid-maturity hybrid such as MR Buster, when sown on the 11 September took 95 days to reach 50% flowering but only 76 days when sown 7 weeks later, on the 28 October.

When sowing on a late plant, it is generally expected that the days to reach flowering will continue to decrease but this can depend on the day degrees and photoperiod response of individual hybrids. In this season, MR Bazley (73 vs 67 days) shortened its days to flowering whilst A66 (70 vs 71 days) was stable when comparing the late October planting date to our 5 February planting date (Figure 1).

The general rule in sorghum is that warmer temperatures during the vegetative stages cause the crop to be quicker to flower. This however is somewhat dependent on the day degrees and photo period requirement of individual hybrids.



	1	2	3
A66	90	81	70
Agitator	89	78	70
Cracka	107	90	82
HGS114	91	85	73
MR Bazley	92	83	73
MR Buster	96	86	76
MR Taurus	95	85	74
Sentinel IG	103	88	77

Figure 1. Days to 50% flowering for eight sorghum hybrids at Breeza in 2019-20

Maize

Early sowing – risks and rewards

Little research has been conducted in maize in northern NSW since the 2017-18 season. Only one season of trials which compared the effects of planting maize earlier than normal was conducted at Breeza.

In 2017-18 early planting in the second week of August into a soil temperature of less than 10°C, lower than the recommended 12°C, did not affect plant establishment at this site in this season. Further research is needed to validate these results and allow for variations in climate in different seasons. In August it is typical to experience frosts at Breeza. The cold soil temperatures slowed emergence in this trial but did not impact establishment. Frosts at the early vegetative stages could burn leaves or kill plants. Similar to sunflower there is no compensatory mechanism of tillering and dryland populations are quite low, around 30,000 plants/ha. Under irrigation, plant populations are much higher, but cold soil temperatures will also be compounded by cold water temperatures if irrigation is required.

The 2017-18 trial included three times of sowing, each with different soil temperatures:

- TOS 1: 9 August 2017 at 9.7 °C soil temperature
- TOS 2: 28 August 2017 at 10.8 °C soil temperature
- TOS 3: 20 September 2017 at 15.8 °C soil temperature

The main effect of sowing in August was that the flowering period was moved considerably earlier, into late November and as a result both maximum and minimum temperatures experienced by the crop were lower compared with the September planting date (Figure 2).

This trial was provided with supplementary irrigation to prevent water stress. Under dryland conditions, the impact of these higher temperatures are likely to be larger, especially if combined with a water deficit.

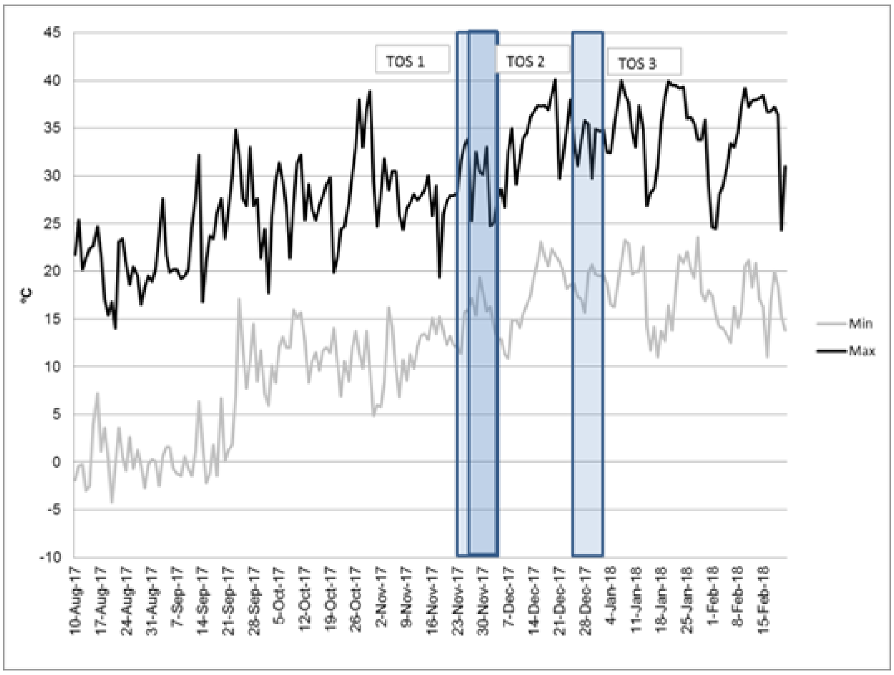


Figure 2. Maximum and minimum temperatures at Breeza 2017-18
Blue rectangles indicate flowering periods associated with the three sowing times

There was no impact on grain yield (site averaged 7.5 t/ha) of varying the sowing time from early August, late August or mid-September (data not shown). There was also no significant difference in grain yield between the three maize hybrids (P1467, P1756 and PAC606IT) included in this experiment (data not shown).

There was a significant impact of sowing time on grain protein, with the protein content declining as the sowing date became earlier. Sowing in September produced significantly higher protein at 11.3% than sowing in early or late August, which produced grain protein levels of 10.7 and 11.0% protein, respectively.

Late sowing in 2019-20 - risks and rewards

Sowing maize late is rarely discussed as an option by growers. This season we included maize in our late sowing trial which was watered up on the 5th February. The maize hybrid Pac606IT was the quickest of all hybrids across species to reach flowering, at just over 60 days (Figure 3). The slow progress towards harvest ripeness is the main concern with maize.

The maize did not have any agronomic issues and only suffered some moderate leaf burn from the first frost of the season on the 6 June. The cobs were well into grain fill and the quickest hybrid was approaching physiological maturity in mid-June. A small amount of leaf rust was noted but not at levels to cause concern.

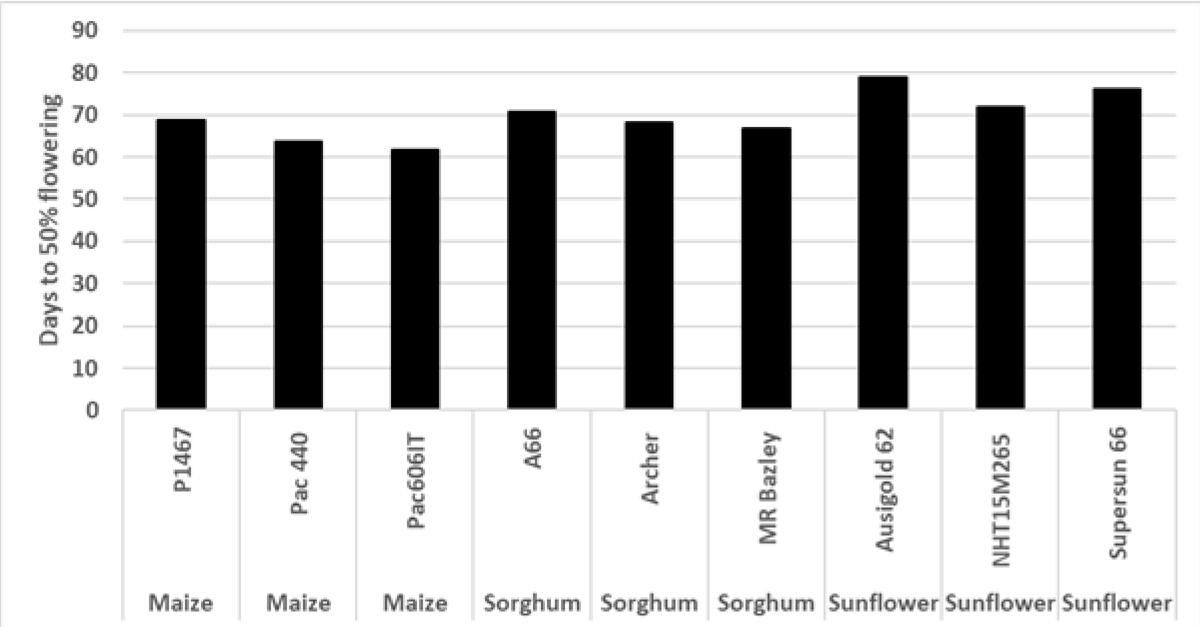


Figure 3. Days to 50% flowering for maize, sorghum and sunflower sown on 5th Feb 2020 at Breeza

What is the impact on days to flowering in maize from varying sowing time?

The 2017-18 maize trial collected data on the impact of sowing time on days to flowering. The number of days taken to reach 50% flowering was recorded for each of the treatments (Table 2). There was a significant reduction in the time taken to reach flowering between TOS 1 and TOS 3 from 117 days to 105 days for P1467 which was the slowest maize hybrid in the trial.

In the late species trial sown on the 5 Feb 2020, the maize hybrids were much quicker, taking only 60-70 days to each flowering with PAC606IT remaining the quickest and P1467 being the slowest (Figure 3).

Like sorghum and sunflower, the super late planting caused a reduction in the days to flower in maize.

Table 2. Days to 50% flowering of maize treatments in 2017-18 at Breeza

TOS	Hybrid	Days to 50% flowering
1 - 9th August	P1467	117
	PAC1756	112
	PAC606IT	109
2 - 28th August	P1467	98
	PAC1756	97
	PAC606IT	95
3 - 20th September	P1467	105
	PAC1756	103
	PAC606IT	99

Sunflower

Early sowing – risks and rewards

The least research has been conducted in sunflower. Spring sown sunflower crops are comfortably planted from the middle of September on the Liverpool Plains. These spring sown crops take longer to move through vegetative growth stages and take longer to reach flowering compared with a summer planted crop. In general, it takes 80-85 days for a spring sunflower crop to reach flowering, whilst a December planted crop takes only 65 days (Table 3).

The longer vegetative period with spring planting typically leads to a larger biomass crop with higher yield potential. They are also generally taller than a summer planted crop. However, the high yields will only occur if the water supply is adequate to realise this increased yield potential.

Sunflowers are reasonably tolerant of frost at certain growth stages. Newly emerged seedlings are frost tolerant up until between the 6–8 leaf stage but are frost sensitive from the 6-leaf stage until the seed ripening stage. For early plant sunflower the largest risk is from plant death as a result of frost, as there is no compensatory mechanism such as with tillering in sorghum and the established plant populations are lower, meaning increased impact of any plant loss on yield.

Unfortunately, to date not trials have been conducted to evaluate early sowing in sunflower.

Late sowing in 2019-20 - risks and rewards

Late plant sunflower is at risk of similar issues to sorghum and maize. Late season flowering and grain fill hold the risk of poor seed set, slow crop maturity and failure to adequately dry down for harvest. This season late season powdery mildew was present due to conducive humid conditions, but infection did not develop to a point that required fungicide application.

Bird damage and the lack of effective control options has been challenging for our trials and commercial crops. Our research plots were decimated by cockatoos even though they were covered with nets.

As temperatures cool in autumn the risk of frost increases. Sunflower buds are susceptible to frost damage but a significant drop in air temperature can also be detrimental to pollen viability at flowering. Frosting during the bud development stage can result in distortion of the bud, failure to set seed and even a complete lack of flower production. Mild frost damage is seen as blackening or purpling around the edges of the head. Temperatures of 2°C can prevent flowers from opening and subsequently reduce seed set, while frosts (0°C) during grain fill can substantially reduce yield.

What is the impact on days to flowering in sunflower from varying sowing time?

Like sorghum, the days taken to reach flowering are longer with a spring planted crop compared with a summer planted crop. Moving planting from mid-September to early December results in a change of around 20 days (Table 3). There was also an impact on the days to flowering associated with plant population, moisture and hybrid (data not shown).

Table 3. Days to flowering in sunflower at Gunnedah

Hybrid	Region	Days to mid flower
Ausigold 62	Gunnedah – spring – early plant	90
	Gunnedah – summer - Dec plant	70
Ausigold 4	Gunnedah – spring – early plant	90
	Gunnedah – summer - Dec plant	67

Source: An extract from the Big Yellow Sunflower Pack

Conclusions

Early or late sowing of summer crops have both associated risks and rewards. The greatest risk of early sowing is the soil and air temperatures which the establishing crop are exposed to. Slow, patchy and reduced establishment can occur if the crop is sown too early, or colder than expected conditions or frosts prevail. There is a greater emphasis on selecting paddocks which do not have a history of winter weeds which may be difficult to control. Early planting can allow the flowering, grain fill and harvest to occur earlier than normal, reducing the risk of high temperatures and heat stress during flowering. An earlier harvest also provides a longer period to refill the soil water profile, increasing the likelihood of a double crop option.

Late sowing seems to bring more theoretical risks than sowing early. Planting is occurring in the heat of summer, so seedbed temperatures will be hotter, possibly impacting establishment, and seedbed moisture will decline faster. Later sown summer crops will grow more rapidly through the vegetative stages and reach flowering in fewer days. There was no risk of heat stress at flowering though.

The late species trial suffered with issues of ergot and midge in the sorghum, bird damage and powdery mildew in the sunflower, with slow grain filling and dry down in all three summer crops, pushing harvest into July. Frosts only commenced in early June in this season, much later than normal. The use of harvest aids, i.e. desiccants may also be needed to assist in bringing the crop into harvest. This is an additional expense rarely needed with an early planted crop. Furthermore, following a late harvest there is minimal opportunity to double crop back into a winter crop.

Frost remains the largest risk for both early and late planting of summer crops.

In addition, waiting for a late plant may mean watching several sowing opportunities pass by over the summer. As such, late planting is most likely to hold merit only in seasons when insufficient summer rain has fallen to allow earlier planting.

The challenge is selecting the right crop to plant at the right time. In all seasons, this decision will be based on gross margins, crop rotation, stored soil moisture over the fallow and of course personal preference. In summary the risks from an earlier planting of summer crops appears much smaller than the potential rewards.

In contrast, late planting is most likely to be the last resort, when cash flow is needed, and other options have past, as the risks are numerous including frost terminating the crop before maturity, slow dry down and delayed harvest as well as clashes with winter crop planting. While crop modelling has suggested the autumn grain fill period as being more favourable due to lower temperatures and an increased likelihood of rain, the logistics often outweigh the risk.

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Contact details

Loretta Serafin
NSW Department of Primary Industries
4 Marsden Park Road, Calala
Mb: 0427 311 819
Email: loretta.serafin@dpi.nsw.gov.au

Summer crops: relative water use efficiencies and legacy impacts in farming systems

Lindsay Bell[1], Brook Anderson[1], Darren Aisthorpe[2], Andrew Verrell[3], Jon Baird[3], Andrew Erbacher[2], Jayne Gentry[2] and David Lawrence[2]

[1] CSIRO Agriculture and Food
[2] Department of Agriculture and Fisheries, Queensland
[3] New South Wales Department of Primary Industries

Key words

sorghum, maize, cotton, mungbean, water-use-efficiency, soil, yield, systems

GRDC codes

CSA00050, DAQ00192

Take home message

- While summer crops offer rotational options in the farming system, choose the correct crop to match your available soil water and crop history
- Sorghum is a reliable performer often exceeding other options in terms of $ returned per mm used
- Cotton and maize require higher water availability and produce less reliable WUE ($/mm). However, cotton has legacy impacts on water availability for subsequent crops that should be considered
- Mungbean can produce higher $/mm in low water availability situations (<200 mm of rain + soil water). Repeated sowings of mungbeans are likely to induce yield reductions due to disease
- Sorghum crops sown with > 150 mm of plant available water will maximise crop WUE and profitability. Every extra mm at sowing could be worth as much as $35-70 extra return/ha
- Higher density sorghum crops may provide greater crop competition against weeds and potential upside yield benefits in good season. We have seen limited legacy benefits (e.g. improved ground cover) or costs (e.g. greater soil water/nutrient extraction) for soil water or nutrient availability.

Introduction

Summer crops are becoming an increasingly important component of cropping systems in the summer-dominant rainfall zone. They are often useful for providing disease or weed management benefits when in rotation with winter crop dominated systems. While it is widely recognised that summer crops are often critical for improving the system sustainability, a key challenge is transitioning between summer and winter crops or phases in the crop sequence. This requires either double cropping or introducing long-fallows (>10 months) during transitions between the summer and winter crop phases. Hence understanding how effectively different summer crop options convert available water into grain yield and ultimately profit is critical to making better decisions about when summer crops may be used in the crop sequence. Further, differences in water extraction, subsequent fallow water and nitrogen accumulation are likely to influence how subsequent crops will perform or the period of fallow time required to reach critical sowing moisture levels. So, it is important to target the right summer crop option to the system.

This paper will report on several comparisons of relative water use efficiency of different summer crops, and effects of summer crop management practices (e.g. soil water at sowing, sorghum configuration and density) and their legacy impacts in the farming system.

Relative WUE ($/mm) of summer crop options

Over the past 4 years of experiments, different summer crop options have been grown in the same season and under common previous fallow length and starting moisture. Using this data, we have calculated for these various comparisons the crop water use efficiency as $ of income generated per mm of crop water use. This was done using long-term median crop prices and inputs for each of the crops, but these relative values would shift if prices for individual crops were more/less favourable compared to others.

Across a range of seasons and growing conditions, sorghum always exceeded mungbeans in terms of $ generated per mm. This was even though on several occasions mungbean crops use less water and often left significantly more residual soil water than the sorghum crops grown in the same conditions. Sorghum was only bettered in terms of crop WUE by a cotton crop at Pampas in summer 18/19 and sunflowers when they were sown as a double crop in 17/18.

Table 1. Crop water use efficiencies ($ gross margin per mm water used) comparisons between summer crops when grown in the same season with similar starting conditions (long fallow – LF, short fallow – SF, double crop – DC).

	Pampas 16/17 (LF)	Pampas 17/18 (DC)	Pampas 17/18 (SF)	Pampas 18/19 (LF)	Pampas 18/19 (SF)	Pampas 19/20 (DC)	Pampas 19/20 (SF)	Billa Billa 16/17 (LF)	Narrabri 18/19 (LF)
Sorghum	12.0	2.82	9.4	10.1	6.1			3.4	0.7
Mungbean	7.0		3.8		5.5	2.0	12.5	1.3	0.4
Cotton	6.4			15.8					
Maize	7.3								
Sunflower		11.4							
French millet						2.7	3.0		

Figure 1 shows the relationships between crop water use and crop income generated for 100 summer crops (sorghum, mungbean, cotton, sunflower and maize) that have been grown in our farming systems research over the past 5 years. This graph demonstrates that:

- In sorghum, a strong relationship was found between crop revenue and crop water use; on average $4.50 of income generated per mm of crop water use above 200mm. That is, 200mm of available water through in-crop rain or soil water at sowing is required before a positive return is generated
- Mungbeans show a higher return per mm at lower crop water use than sorghum, particularly when available crop water is less than 250mm
- Sunflowers produced a similar return per mm to sorghum in the few seasons when they were grown. This outcome would be greatly influenced by the price obtained for sunflowers which can be highly variable
- In maize and cotton, higher variation in returns per mm were observed. In some seasons, this exceeded sorghum but was lower in others.

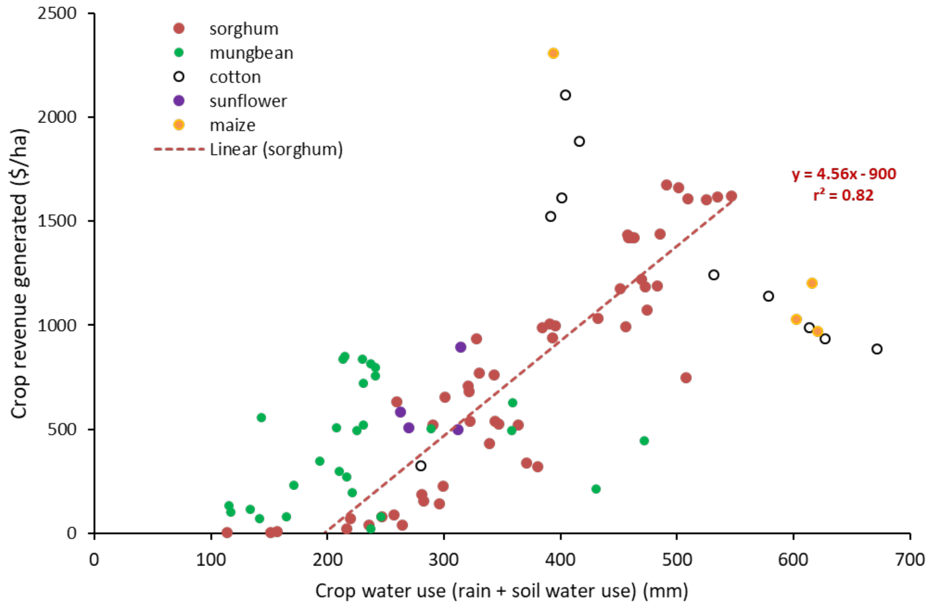

Figure 1. Relationships between crop water use (in-crop rainfall + soil water extraction) and crop revenue generated amongst 100 summer crops grown in farming systems experiments 2015-2019 (sorghum n= 51, mungbean n = 28, cotton n = 10, sunflower n = 4, maize n = 5).

Sowing soil water effects on sorghum crop performance

Soil water at sowing is critical for driving the efficiency of summer crops, especially sorghum. Here we compare the performance of sorghum crops grown in the same season with common nutrient and crop management but with significantly different soil water at sowing (Table 2). As expected, crops with higher soil water at sowing had higher grain yields. But, perhaps something less obvious was that the crops with more staring water regularly converted the available soil water more efficiently into grain and accordingly into profit. This effect was larger in seasons with limited in-crop rain, while the effect was diminished in the wetter growing season (i.e. Pampas 2016/17). This phenomenon occurs because it takes a critical amount of water to grow crop biomass, and hence when there is less available water at sowing there is less water left to efficiently convert any residual water into grain during grain filling. Hence, in wetter seasons this is less pronounced because the crop may still have enough available water to minimise this effect.

Across these studies we calculated the increase in crop return that was obtained for each extra mm of soil water available at sowing. While there was some variation in some seasons, this could be as high as $70 extra return per extra mm at sowing. These effects were largest where crops were sown on marginal soil water (< 100mm) and had limited in-crop rain (e.g. <300mm). These data clearly suggest that for sorghum to maximise its return per mm of water used, higher soil water at sowing is critical. Other analyses by Erbacher et al. (2020 Goondiwindi update paper), suggest plant available soil water at sowing of 150mm was required to optimise sorghum WUE.

Table 2. Starting soil water effects on sorghum crop performance and the marginal water use efficiency i.e. extra $ generated per mm of extra water available at sowing.

Site – year (in crop rain)	PAW prior to sowing	Crop yield (t/ha)	Crop WUE (kg grain/mm)	Crop WUE ($/mm)	Marginal $/mm water at sowing
Billa Billa 16 (118mm)	98	0.88	3.1	2.2	7.5
	194	1.52	4.1	3.6	
Pampas 16 (345mm)	153	6.12	13.4	12.5	7.2
	245	7.42	13.6	12.0	
Pampas 17 (230mm)	108	0.91	3.1	3.0	70.0
	163	4.52	9.4	9.8	
Pampas 18 (277mm)	62	2.70	7.9	6.1	32.4
	120	4.03	10.2	10.1	

Crop WUE and legacy effects of growing higher density sorghum crops

Integrated weed management practices involving greater in-crop competition with summer grass weeds is seeing interest in increasing sorghum density and narrowing row spacing. In addition to this weed benefit this is likely to have impacts on water and nutrient use efficiency of the crop and legacy impacts on subsequent water and nitrogen accumulation in fallows. It was hypothesised that the higher density sorghum would grow additional biomass which may or may not be converted into grain yield depending on the season. However, this greater biomass would contribute to greater and more even ground cover and improved fallow efficiency. Similarly, this may have impacts on nutrient cycling due to increased immobilisation of soil N from the higher residue with a high C:N ratio.

Across the 3 experimental comparisons we have implemented in our farming systems research, we found that consistently the higher density sorghum increased biomass production, but this was only translated into additional yield at Emerald in 17/18 (Table 3). At the other sites there was no significant yield penalty from growing this additional biomass and grain yields were comparable. Soil water extraction and crop water use was the same amongst the high and low density crops.

The higher biomass production in the higher density sorghum crops has required higher soil N extraction without an increase in grain yield and N. Hence, the nutrient use efficiency of these crops is lower. That is, such higher density crops will require a different nutrient strategy to ensure sufficient N in provided to maximise their yield potential.

Finally, while we anticipated there may be some benefits for improved soil water accumulation over the subsequent fallow following the higher density sorghum crops this was not shown resoundingly. In one season (Pampas 17/18) we did observe an extra 33mm was accumulated in the subsequent fallow after the higher density sorghum crop than the standard management. However, this was largely due to a drier soil profile at crop harvest and there was no significant difference in soil water at the end of the subsequent fallow in any of these cases. However, observations suggested there was greater uniformity of the soil water where more evenly distributed cover occurred following the narrower sorghum rows compared to wider row crops.

Table 3. Crop yield and legacy effects of growing higher density grain sorghum (i.e. 30% higher population & 0.5m compared with 1m row spacing) across 3 seasons in farming systems experiments.

Sorghum crop performance		**Emerald 17/18**	**Pampas 17/18**	**Pampas 18/19**
Sorghum grain yield (t/ha)	Standard	5.0	4.7	4.0
	High density	5.9	4.7	3.7
Sorghum biomass (t/ha)	Standard	11.6	14.1	9.1
	High Density	15.6	16.0	10.1
Sorghum WUE (kg grain/mm)	Standard	15.4	9.4	10.2
	High Density	18.4	10.4	9.6
Sorghum NUE (kg grain N/kg N used)	Standard		0.593	1.7
	High Density		0.484	1.1
Following fallow				
Soil water accumulation (mm)	Standard	+97	+63	+85
	High Density	+71	+96	+79
Mineral N accumulation (kg/ha)	Standard		+89	+107
	High Density		+116	+102

Legacy impacts of summer crop choices

Finally, here we make comparisons of the impacts of summer crops on residual soil water, accumulation during the subsequent fallow and effects on subsequent crop productivity in the sequence.

From these comparisons the legacy impacts of cotton in the farming system are clear, with lower soil water available for subsequent crops due to higher extraction and also lower fallow efficiencies (Table 4). This has translated into reductions in yield of 0.5 t/ha in sorghum and 0.3 t/ha in mungbeans when sown following cotton compared to maize.

Comparisons of sorghum with mungbean show little differences in residual soil water or soil water in the following crops. However, mungbean performance was affected by the preceding crop. ‘Mungbean after mungbean’ yield was 0.5 t/ha lower than ‘mungbean after sorghum’, despite starting with similar moisture after a long fallow (17/18). In contrast, mungbean yields were similar following short fallows out of sorghum and mungbean (18/19), even though the sorghum left less residual water. These effects are likely to be related to disease reductions rather than soil water or nutrient impacts.

Finally, a comparison between sorghum and sunflower legacy effects found little or any effects on subsequent fallow water accumulation or crop yields.

Table 4. Comparisons of legacy impacts of different summer crops on soil water accumulation and subsequent crop productivity in the crop sequence.

Crop year	Crop grown	Residual PAW (mm)	Soil water accumulation (mm)	Subsequent crop performance			
				PAW at sowing (mm)	Crop sown	Crop biomass (t/ha)	Grain yield (t/ha)
16/17	Maize	168	-6	162	Sorghum 17/18	14.1	5.37
	Cotton	149	-23	126		12.8	4.85
	Maize	168	-67	101	Mungbean 17/18	5.0	1.06
	Cotton	149	-67	82		3.4	0.75
18/19	Sorghum	2	+91	93	Not sown yet	-	-
	Cotton	-16	+64	48		-	-
17/18	Sorghum	48	+24	72	Mungbean 19/20	4.75	1.62
	Mungbean	30	+58	88		3.59	1.12
18/19	Sorghum	-10	+45	35	Mungbean 19/20	2.33	0.59
	Mungbean	-26	+112	76		2.15	0.61
17/18	Sorghum	38	+29	67	Sorghum 18/19	7.96	2.80
	Sunflower	2	+39	41		7.38	2.94
	Sorghum	41	+42	83	Mungbean 18/19	2.35	0.74
	Sunflower	3	+22	25		2.23	0.75

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Contact details

Lindsay Bell
CSIRO Agriculture and Food
203 Tor St, Toowoomba Qld, 4350
Mb: 0409 881 988
Email: Lindsay.Bell@csiro.au

Nutritional strategies to support productive farming systems

Michael Bell[1], David Lester[2] and Doug Sands[3]

[1] University of Queensland Gatton Campus
[2] Department of Agriculture and Forestry, Toowoomba
[3] Department of Agriculture and Forestry, Emerald

Key words

fertilisers, placement, blends, recovery efficiency, application strategies

GRDC codes

UQ00063, UQ000666, UQ00078, UQ00082

Take home messages

- A critical success factor for cropping systems that rely heavily on stored soil water is co-location of plant nutrients with moist soil and active roots
- Our current fertiliser management practices need refinement, with low efficiency of fertiliser recovery often associated with nutrients and water being in different parts of the soil profile
- There needs to be greater consideration of placement and timing of fertiliser applications to improve fertiliser nutrient recovery
- Declining native fertility reserves means more complex fertilizer combinations will be needed to meet crop demands

Introduction

This paper is based on a series of observations made in recent years from the projects listed above, as well as others made by Richard Daniel and the NGA team in their work on fertiliser N application strategies for winter crops. Collectively, the findings from this research, backed by the underlying regional trends in soil fertility and the drivers for successful rainfed cropping in our region, provide some useful insights into what are likely to be the critical success factors for future fertiliser management programs.

Do we have successful fertility management systems?

To maximise the chance of achieving effective use of available moisture, an effective fertiliser management strategy needs to consider all of the 4R's (right product, in the right place, at the right time and at the right rate – Johnson and Bruulsema 2014). While everyone pays lip service to these 4R's, our real thinking is often driven by considerations about only one – rate. We spend a lot of time agonising over rate, because rate is clearly an important part of the economics of growing the crop. Rate is also an important consideration in terms of soil fertility maintenance (ie. replacing what we remove in grain). In many cases the rate we can afford is not always the rate we need to apply to optimise productivity, much less balance nutrient removal, but we still spend a lot of time thinking about it.

Because of that, we find that the thinking about the other 3R's tends to be much more superficial. Occasionally we might have a try at something a bit different, but in many cases we tend to keep doing what we have always done, and put the same products in the same place at the same time each year. Meanwhile, our background soil fertility reserves have fallen and our crops are becoming increasingly reliant on off-farm sources of fertility (fertilisers, manures etc.) to sustain productivity. It is this increasing reliance on fertilisers, especially N, P and (increasingly) K, that is allowing us to really see the inefficiency in current use practices. The impact of these inefficiencies in terms of lost productivity can often dwarf any of the considerations of rate, and are highlighting challenges for productivity and profitability in the long term.

We will now cover some examples of inefficiencies that are apparent in what has been considered as best practice for both N and P, and how the emergence of K infertility is adding further complexity to fertiliser best practice.

Management of fertiliser N

In the case of N in winter cereals, the recent comprehensive analysis of a series of N experiments from 2014-2017 by Daniel et al. (2018) highlighted the poor winter crop recovery of fertiliser N applied in the traditional application window (the months leading up to sowing, or at sowing itself). Fertiliser N recovered in grain averaged only 15% for applications of 50kg N/ha and 9% for 100kg N/ha. On average, 65% of the applied N was still in the soil as mineral N at the end of the crop season, while an only 15% was in the crop (grain and stubble). The fate of the other 20% of applied N could not be determined. Some of the soil and stubble N will carry over until the next season, but it means that you need last year's residual fertiliser to get you through this year. If you had a big year last year (little residual N) or lost a lot of the N carryover during a wet season, the current crop will suffer.

The poor winter crop recovery of applied N in the year of application mirrored that reported for summer sorghum in the NANORP research program reported by Bell, Schwenke and Lester (2016), with the use of ^{15}N tracers enabling a more precise quantification of the fate of N applied prior to planting. Data from the Queensland sites in commercial fields are shown in Figure 1 for the 40 and 80 kg N rates across three growing seasons. Fertiliser N in grain averaged 27% and 23% of the applied N for the 40 and 80N rates, respectively, while total crop uptake averaged only 37% and 32% for the same N rates. What is noticeable in this figure is the variable N losses (presumably via denitrification) and the residual N in the soil, which may or may not be available for a subsequent crop in the rotation, depending on the fallow conditions. Schwenke and Haig (2019) reported good carryover of fertiliser applied for the 2013/14 sorghum crop for recovery by the 2014/15 season under favourable fallow conditions, while extensive loss of residual soil N after summer crops was experienced over large areas during the wet 2016 winter fallow.

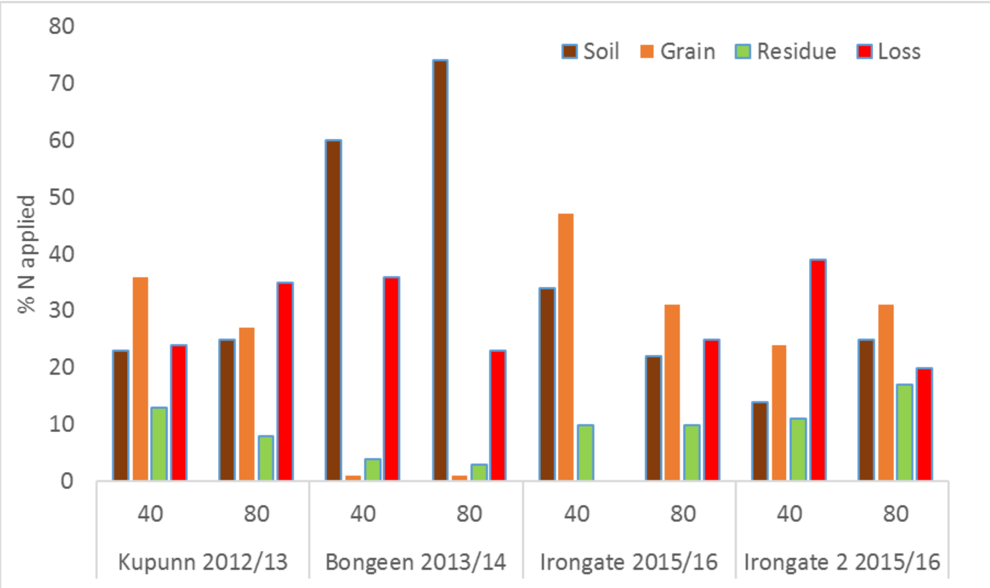


Figure 1. Partitioning of fertiliser N between soil, plant and environmental loss pools for summer sorghum crops grown on the Darling Downs in UQ00066 from 2012-2016

All studies have shown there can be significant amounts of residual N in the soil at the end of the growing season. Large amounts of that N are often found in quite shallow parts of the soil profile (ie. the 0-10cm and possibly 10-20cm layers) and still strongly centred on the fertiliser bands, despite what were often significant falls of rain in-crop (ie. 200-300mm). Even after a subsequent fallow, the Daniel et al. (2018) paper reported that 50-60% of the mineral N residual from fertiliser applied in the previous season was still in the top 45cm, with as much as half of this still in the 0-15cm layer. This largely surface-stratified residual N would have contributed to the quite muted (although still significant) grain yield response to the residual N in those studies.

Interestingly, findings from both the summer sorghum and winter cereal research suggest that crops recover mineral N that is distributed through the soil profile with much greater efficiency than fertiliser applied at or near sowing. In both seasons, 70-80% of the mineral N in the soil profile was recovered in the crop biomass, compared to recoveries of applied fertiliser that were commonly less than half that. The distribution of that N relative to soil water is likely to have played a major role in this greater recovery efficiency.

Management of fertiliser P

The substantial responses to deep P bands across the northern region where subsoil P is low have been detailed in a number of recent publications (Lester et al. 2019b, Sands et al. 2018), with these responses typically additive to any responses to starter P fertiliser (the traditional P fertiliser application method – eg. Figure 2a,b). There has unfortunately been no direct measurement of P unequivocally taken from either deep or starter P bands due to the lack of suitable tracer technology, especially when we consider residual benefits over 4-5 years. However, simple differences in biomass P uptake in a single season suggest that the quantum of P accumulated from deep bands (3-5kg P/ha) is substantially greater than that from starter P alone (1-1.5kg P/ha) in all bar exceptionally dry seasons.

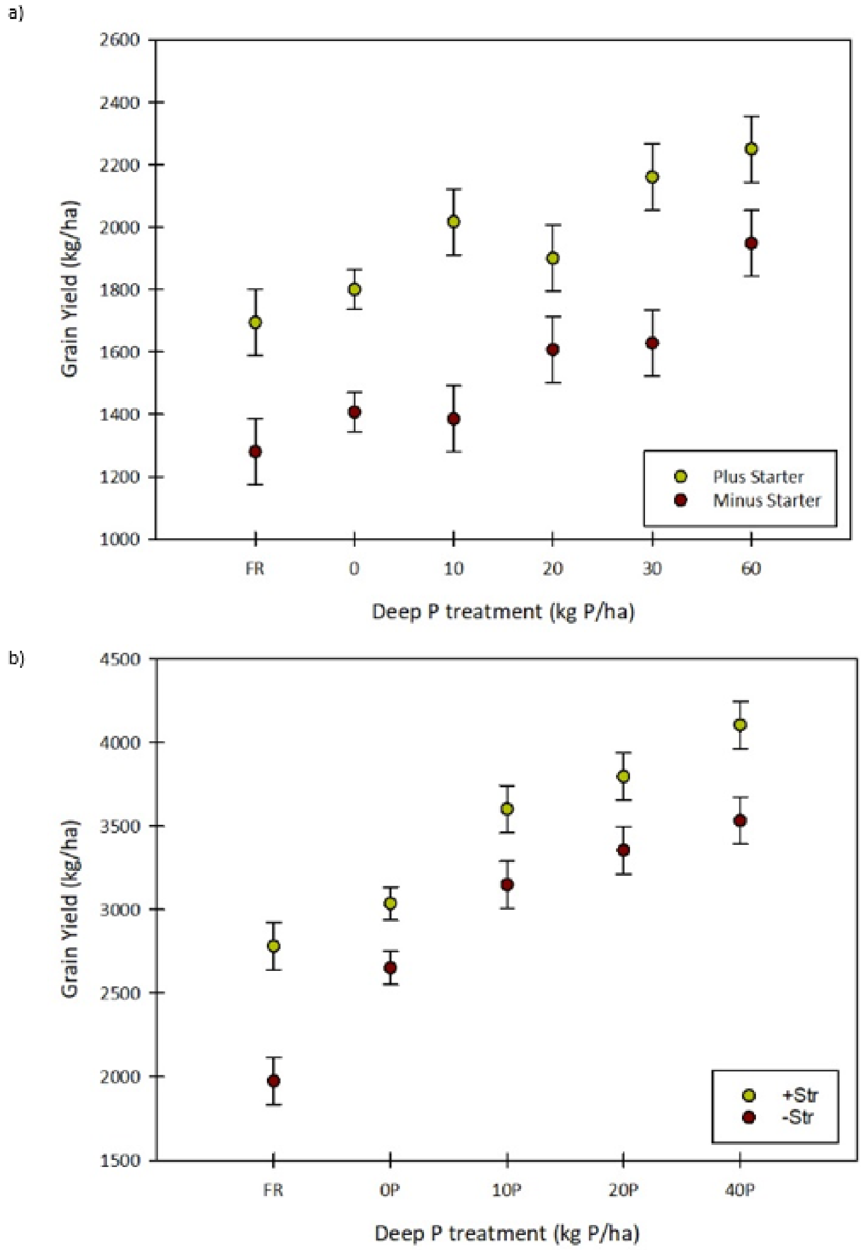


Figure 2. Response to different rates of deep P with and without applications of starter P fertiliser in (a) a wheat crop at Condamine in 2018 wheat, and (b) a sorghum crop at Dysart in 2018/19 grain yield for deep-placed P treatments (kg P/ha) with or without starter application. The vertical bars represent the standard error for each mean. (Lester et al. 2019a)

Perhaps one of the most significant findings from the deep P research has been the relative consistency of P acquisition from deep bands, despite significant variability in seasonal conditions. Research results from sites in Central Qld (CQ) often provide the best examples of this, due to the extremely low subsoil P reserves in some of those situations – if the crop cannot access the deep P bands, there is not much to find anywhere else in the subsoil! Interestingly, this type of profile P distribution is consistent with the lack of grain yield responses to starter P that were recorded over a number of years of trials in CQ and that contributed to reluctance to use starter P in some situations. Early growth responses that were consistent with the crop obtaining an extra 1-1.5kg P/ha from the starter application were observed, but a lack of available profile P to grow biomass and fill grains limited any resulting yield responses.

The inability to acquire P from a depleted subsoil places greater importance on access to P in the topsoil, which means that seasonal rainfall distribution can have a huge impact on crop P status. This is illustrated for a site near Clermont in Figure 3 (a, b), in which the growing season conditions and crop P acquisition by successive crops of sorghum and chickpea are compared. From a yield perspective, deep P increased crop yield by 1100kg and 960kg for the sorghum and chickpea crops, relative to the untreated Farmer Reference treatment, and by 720kg and 970kg/ha for the same crops relative to the 0P treatment that received ripping and other background nutrients. The similar size of yield responses in the two crops represented quite different relative yield increases (40-60% in the sorghum, versus about 300% in the chickpeas), and obviously had hugely different impacts economically, given the price differential between sorghum and chickpea grain. However, from a nutrient use efficiency perspective it is interesting to note that the apparent P acquisition from the deep P bands was similar (3.3kg P/ha in the sorghum and 2.7kg P/ha in the chickpeas - Figure 3b)) despite the vastly different in-season rainfall (Figure 3a).

What is dramatically different, and what is driving the much larger relative yield response in the chickpea crop, was the inability to access P without deep P bands in that growing season. Crop P contents in the Farmer Reference and 0P treatments averaged 2.9kg P/ha in the sorghum crop but only 0.6kg P/ha in the chickpeas. This difference was driven by the combination of deep sowing and extremely dry topsoils encountered in the 2018 winter season. The chickpea crop was planted below the 0-10cm layer, and there was never enough in-season rainfall to encourage later root growth and P recovery from that layer. Despite available moisture in the subsoil, there was not much P available to support growth and yield. In contrast, the sorghum crop was planted into the relatively P-rich top 10cm layer, which was then rewet regularly over a significant proportion of the vegetative phase. This allowed better P acquisition from the background soil, but the deep P bands were still able to supplement this and provide an additional yield benefit.

a)

b)

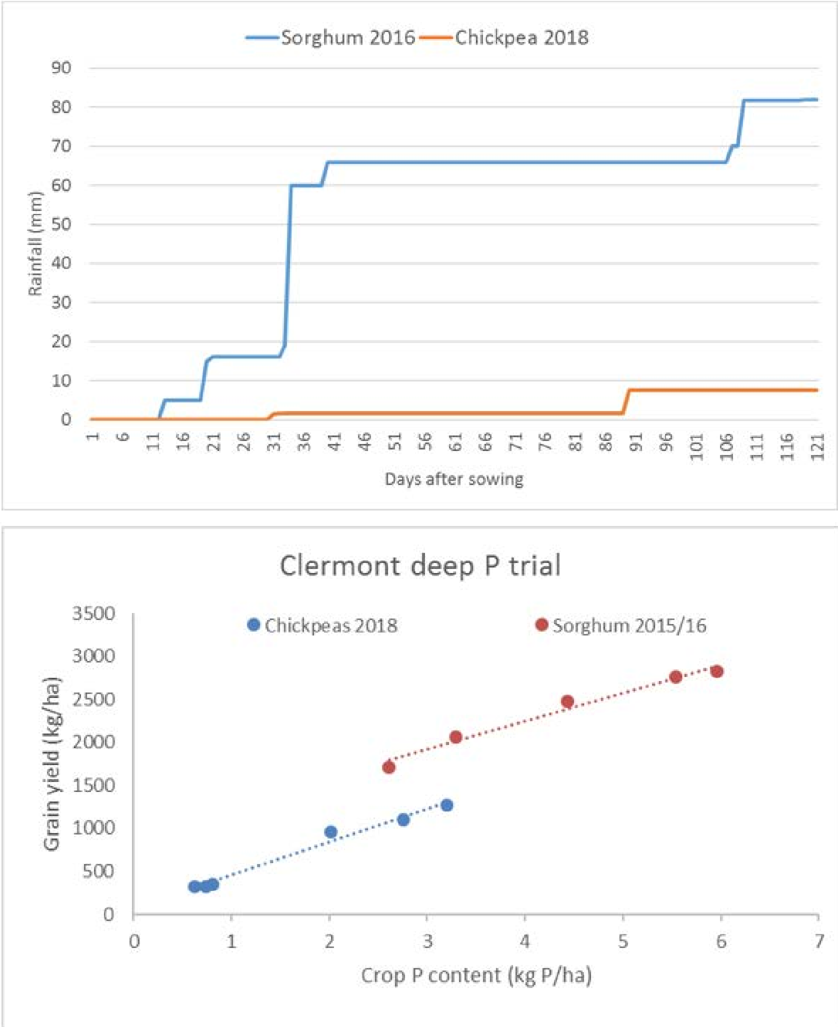


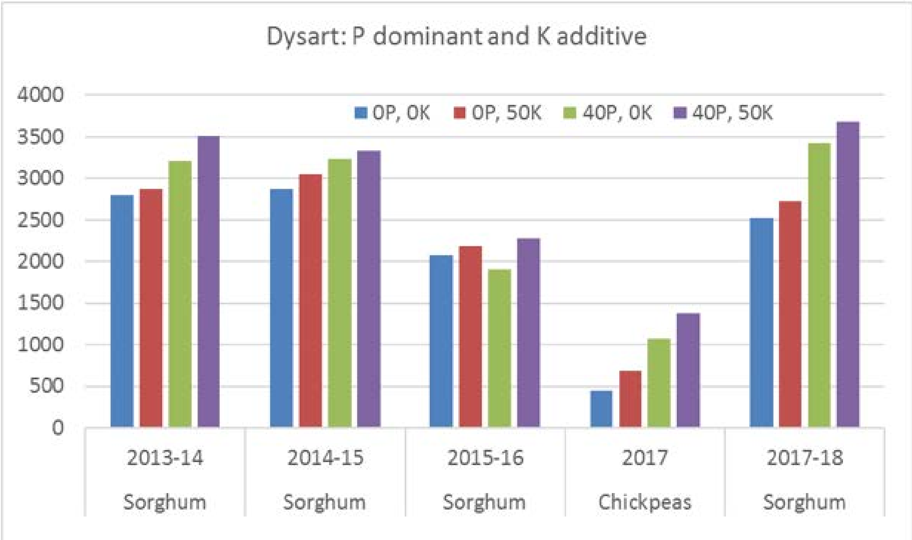
Figure 3. (a) Cumulative in-crop rainfall and (b) the relationship between crop P content and grain yield for consecutive crops of sorghum (2015/16) and chickpea (2018) grown at a site near Clermont, in Central Queensland (Sands et al., 2019)

Choice of product to address multiple nutrient limitations

As native fertility has been eroded by negative nutrient budgets and/or inappropriate placement, there are an increasing number of instances of complex nutrient limitations that require compound fertilisers to address multiple constraints, with the relative severity of each constraint changing from season to season. Perhaps the best example has been the emergence of widespread examples of K deficiency in recent (drier) seasons, but which can ‘disappear’ in more favourable ones. This is an example of the impact of increasingly depleted and more stratified K reserves, and is an issue that adds complexity to fertility management programs. Soil testing benchmarks for subsoil nutrients are improving as a result of current programs, but at best they are only likely to ring alarm bells for the different constraints, rather than predict the relative importance of each in future (uncertain) seasonal conditions. Examples provided in Figure 4, again from sites in CQ, show fields where subsoil P and K would both be considered limiting to productivity, but the responses to deep placed P and K have varied with crop and seasonal conditions. Assuming enough N is applied, the site at Dysart shows a dominant P constraint which is evident in most seasons, and a smaller K limitation that is only visible once the P constraint has been overcome. The Gindie site, on the other hand, has limitations of both P and K, but the relative importance of each constraint seems to depend on the crop choice and/or seasonal conditions. In both cases, the appropriate agronomic response would be to apply both nutrients, but the relative economic returns of adding K to the fertiliser program (as opposed to higher/more frequent P additions) would be different.

The emergence of multiple constraints such as those shown in Figure 4 require a greater understanding of the implications of co-location of different products, especially in concentrated bands applied at high(er) rates, less frequently. There is evidence that effective utilisation of banded K, at least in Vertosols, is dependent on co-location with a nutrient like P to encourage root proliferation around the K source (Figure 5 - Bell et al., 2017). However, there is also evidence that there can be negative interactions between P and K applied together in concentrated bands that can reduce the availability of both nutrients. There is an existing investment (UQ00086) exploring the reactions that occur in bands containing N, P and K, and the implications of changing the products and the in-band concentrations on nutrient availability. Current findings suggest that more acidic the band the more likely there will be reduced P availability, which explains why the response to triple superphosphate has been almost uniformly poor. Use MAP or even DAP in preference, and if in lighter textured, neutral to acidic soils DAP looks to be more beneficial than MAP. Adding K to a band of MAP or DAP will reduce the availability of P to a small extent in a concentrated band, but the effects are far less than those from choosing the wrong form of P fertiliser. Minimise the negative effects of adding K by reducing the in band concentration (ie. band spacing of 50cm and not 100cm) and increasing the soil-fertiliser mixing as much as possible (ie. use tines and not discs).

a)



b)

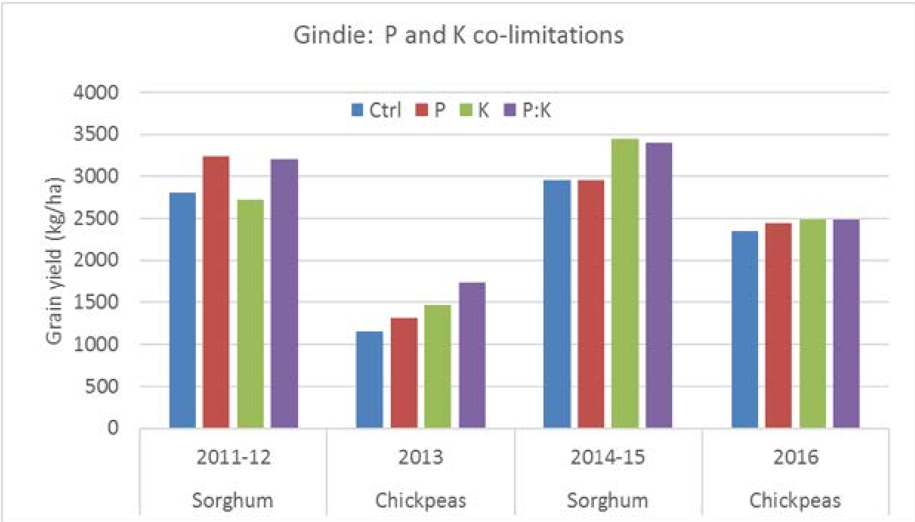


Figure 4. Examples of combinations of P and K limitations to crop performance at (a) Dysart and (b) Gindie, and the response to deep banded applications of those nutrients alone, or in combination

What are the key farming systems characteristics complicating nutrient management?

The changing nutrient demands in dryland grains systems, especially on Vertosols, are driven by the combination of nutrient removal that has not been balanced by nutrient addition (especially in subsoil layers), and the reliance of our cropping systems on stored soil water for long (and in some cases all) of the growing season. Crops need access to adequate supplies of water and nutrients to perform, and while crop roots can acquire water from a soil layer with little to no nutrient, they certainly can't acquire nutrients from soil layers with little or no available moisture. The co-location of water, nutrients and active crop roots enable successful crop production. Historically our cropping systems have been successful because (i) soils originally had moderate or higher reserves of organic and inorganic nutrients; (ii) there were sufficient reserves of those nutrients at depth so the crop could still perform when the topsoil was dry; and (iii) our modern farming systems are now much better at capturing water in the soil profile for later crop use.

Our soils are becoming increasingly characterised by low organic matter, with reserves of P and K that are concentrated in shallow topsoil layers and depleted at depth. Our typical fertiliser management program applies all nutrients into those topsoil layers, with the immobile ones like P and K staying there, and the mobile nutrients like N applied late in the fallow or at planting, when there is no wetting front to move the N deeper into the subsoil layers. Without that wetting front, even mobile nutrients like N are not able to move far enough into the soil profile to match the distribution of water – at least for the targeted crop season. We also grow a very low frequency of legumes in our crop rotation, which increases overall fertiliser demand and produces residues that are slow to decompose and release nutrients during the fallow and for the following crop. This means that nutrients like N are mineralised later in the fallow, again with less chance to move deeper into the soil profile for co-location with stored water.

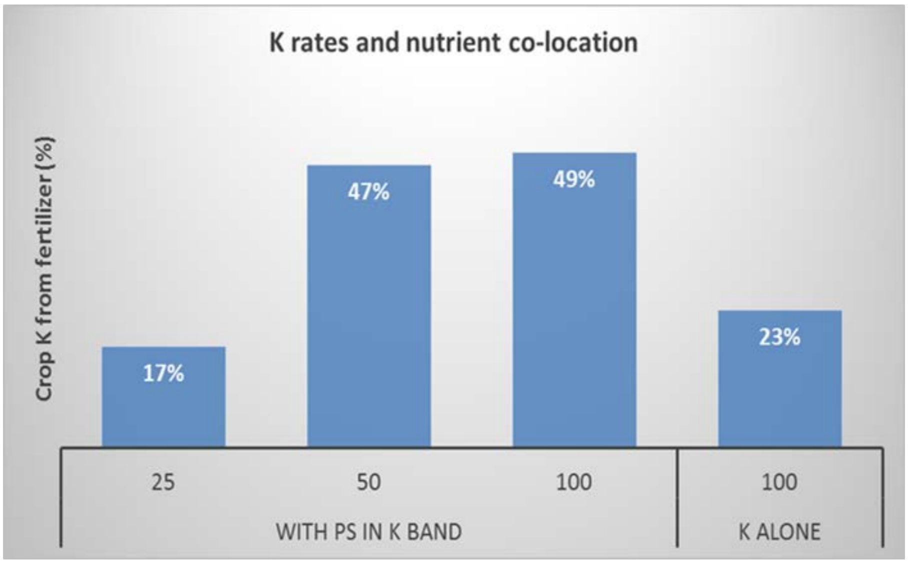


Figure 5. The impact of rate of applied K and co-location of K with other nutrients in a band (in this case P and S) on the proportion of crop K that was derived from applied fertiliser

The net result is an increasing frequency of dislocated reserves of stored soil water and nutrients, with in-crop rainfall at critical stages being a major determinant of whether the crop will be able to acquire the nutrients to achieve the water-limited yield potential. Unless our management systems change to address these issues, there will inevitably be a decline in overall water use efficiency across the cropping system, with an increasing frequency of poor or unprofitable crops. The changes that we think are needed require a stronger focus be placed on the 'forgotten' 3R's – right product (product choice/combination), in the right place, at the right time.

In the concluding section of this paper, we provide a brief outline of what we feel are going to be key strategies that need to be considered in future nutrient management programs. We note that a number of these have not yet been extensively validated, or are simply hypotheses that are worthy of testing. However, they do provide what we think are opportunities to address some of the main nutrient supply issues outlined in the preceding sections of this paper.

Future nutrient management opportunities

In general

- Focus more on feeding the soil to support the farming system, in addition to targeting the next crop in the rotation sequence. This will involve applying nutrients at a time and in a part of the soil profile that maximises the chance of having nutrients co-located with water when future crops need it. Making those decisions once the profile water has largely accumulated and the planting decision is more certain is resulting in frequent spatial dislocation between nutrient and water supply
- Where possible, legume crops should be grown with greater frequency, as they reduce the fertiliser N demand. This will allow diversion of money from the fertiliser budget spent on N into other nutrients that can be exploited across the rotation

- Be adaptive in your fertiliser management program. Respond to the opportunities that are offered to put the right nutrient in the right place at the right time and chose the right combination of products to match the soil nutrient status. This will involve a good understanding of the variation in profile nutrient status from field to field, and also understanding how seasonal conditions may impact on those application decisions.

For specific nutrients

Nitrogen (N)

- Understanding the soil water holding and drainage characteristics is critical, as strategies appropriate for heavy clays will not be suitable for lighter textured soils. For example, in clay soils you should be prepared consider changing the timing of at least some of the fertiliser N input, so it is applied into dry soils at the beginning of a fallow. The Daniel et al. (2018) paper showed nice examples of how early fallow N applications can increase the proportion of fertiliser N that is accumulated in deeper profile layers, potentially ensuring N availability with deep water to enable continued growth when the crop is experiencing dry periods. The greater efficiency of recovery of distributed 'soil' N compared to freshly applied fertiliser may allow possible rate reductions that could help to offset any interest paid on early fertiliser investment
- Be aware when conditions have changed from the 'normal' upon which your current fertiliser strategies have been based. For example, what would differences in (especially shallow) profile moisture status at the beginning of a fallow mean for the denitrification risk to early N applications? How should you respond to an unusually large crop that has depleted the soil N profile and left stubble that is low in N? How would you respond to an unseasonal rainfall event after N applications had been made?
- Legume residues should better synchronise the release of N with the recharge of profile moisture during a fallow. This should result in soil N that is more readily accessible during a following crop, as well as a lower fertiliser N requirement.

Phosphorus (P) and Potassium (K)

- Don't ignore starter fertilisers, but also be aware that they are not an effective solution to meeting crop P demand in most seasons, and adding K to starter blends can impact the 'salt' risk to crop establishment
- While there is no requirement for starter K to meet early growth demands, starter P has an important role to play in early season growth and establishing yield potential, even though the amount of P acquired from the starter P band is quite small. There may be opportunities to reduce the rates of P applied at planting if uniform distribution along the seeding trench can be maintained, where fluid forms of P may possibly having a role. The 'saved' P should be diverted into increased rates or frequencies of deep P application
- Starter P is especially important in very dry seasonal conditions, and can have an unusually large impact on crop P uptake due to restricted access to the rest of the P-rich topsoil. Under these conditions, starter P can also have a large impact on secondary root growth and improved soil P access
- Deep P and K work – use them. Question marks still exist about the length of the residual effect, and some of the risks from co-locating products in a band. Minimise the risk by applying products in more closely spaced bands (i.e. at lower in-band concentrations) more often (i.e. lower application rates)
- Remember that the main subsoil constraint has generally been P, so get the P rate right and complement that with additional K as funds allow
- Don't let subsoil P and K fall too far! Whilst we have got some great responses to deep P (and K) bands, and they are certainly economic, we have not seen evidence that a deep banded

application (of P at least) is sufficient to completely overcome a severe deficiency. The band is a very small proportion of the soil volume, and when roots proliferate around a band, they dry it out. Unless the band area re-wets during the season, allowing roots a second opportunity to access the banded nutrient, the amount of nutrient recovered will be limited. In short, bands provide a useful but not luxury supply. Nutrient concentrations in foliage and grains still show signs of crops that are still P deficient in many situations, and it is obvious that the greater the volume of subsoil that can be fertilised (more bands, more often) the greater the chance we have of meeting crop demand.

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Contact details

Mike Bell
University of Queensland
Gatton Campus
Ph: 0429 600 730
Email: m.bell4@uq.edu.au

5 years of nitrogen research – Have we got the system right?

Richard Daniel, Rachel Norton, Anthony Mitchell, Linda Bailey, Denielle Kilby, Branko Duric and Lawrie Price, Northern Grower Alliance

Key words

nitrogen, efficiency, soil movement, timing

GRDC code

NGA00004

Take home messages

- Over the 14 trials from 2014 to 2017, the efficiency of nitrogen (N) grain recovery from soil N was ~4 times that of fertiliser N that was applied in the year of cropping
- Maintaining high soil N levels is critical for cereal production efficiency due to the poor fertiliser N grain recovery
- Testing of grain, stubble and soil at harvest was able to account for a mean level of ~79% of the applied fertiliser N over 23 comparisons, however in 4 of the 23 comparisons, testing only accounted for 30-50% applied fertiliser N
- The majority of the additional N at harvest was recovered in the soil and averaged ~65% of the applied quantity
- The slow and shallow fertiliser N movement in soil is likely to be impacting on grain recovery efficiency
- Strategies to get fertiliser N deeper, more quickly, may provide useful efficiencies in uptake and reduce potential losses
- Strategies that can improve N contribution from the legume phase will be highly productive
- Fallow N fertiliser applications are likely to provide a benefit over at planting application in years with low in-crop rainfall.

Background

Northern Grower Alliance (NGA) have been heavily involved in nitrogen (N) management trials in wheat since 2012. The focus has always been on methods to improve the efficiency and economics of N nutrition in wheat but the specific focus shifted over time:

1) 2012-2014: Economics and fit of late application
2) 2014-2018: Impact of application method and timing.

In addition to generating answers on the two main themes, a large body of data had been created on N uptake efficiency together with measurements of soil movement and fate of N.

Rather than focusing on individual trial results, this paper focuses on N management 'system implications' and challenges whether we really have got the system right.

Grain nitrogen recovery

Grain N recovery in wheat has been calculated in trials from 14 individual locations conducted during the 2014-2017 seasons. A wide range of production conditions have been experienced with yields ranging from ~1 to 5t/ha. Three steps were taken in calculating the grain N recovery from fertiliser:

1. Grain N recovery for each treatment was calculated as yield (kg/ha) x % protein/100 x 0.175
2. 'Net' grain N recovery was then calculated by deducting the grain N recovery in the untreated (unfertilised treatment)

3. % grain N recovery was calculated by dividing the net recovery by the amount of N applied

Table 1. % grain N recovery from urea applications in 15 trials, 2014-2017

Season	2014		2015		2016		2017	
Method/ timing	All IBS		Drilled in fallow/IBS/ PSPE		Incorporated in fallow/IBS/ PSPE		Spread in fallow x 2/PSPE	
Variety(s)	EGA Gregory⚗		EGA Gregory⚗		Suntop⚗		Lancer⚗, Suntop⚗ & 5 other varieties	
# of trials	4		5		3		3	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Urea 50 kg N/ha	21%	13-34%	30%	<0-45%	23%	16-27%	15%	10-19%
Urea 100 kg N/ha	16%	12-26%	19%	<0-31%	18%	12-23%	9%	7-12%
Urea 200 kg N/ha	9%	5-17%	11%	<0-17%	10%	8-12%	5%	3-6%

NB Data from two trials at Billa Billa 2017 site included. IBS = Incorporated By Sowing, PSPE = Spread Post Sowing Pre Emergent. Recovery data for each urea rate was generated from one application timing in 2014 but 3 timings in all 2015-2017 trials.

Key points

1. As expected, the % grain N recovery reduces as the N application rate increases.
2. Trials were conducted over a range of varieties with no indication of a consistent difference in response to fertiliser N rate between varieties.
3. Most applications were incorporated but some were surface spread and not incorporated.
4. No indication of difference between incorporated versus spread but not incorporated.
5. Recoveries appeared lower in 2017 – low in-crop rain, low yields with reduced N responses.

Grain N recovery from available soil N was also calculated for all trials in 2016 and 2017. Soil N was measured to 120cm at both planting and harvest. (Data from 2014 and 2015 was not included as soil N was only assessed during the fallow for site selection and often to 60cm depth). Two steps were taken in calculating the grain N recovery from soil N:

1. The quantity of soil N 'used' was calculated by the amount in the soil at planting minus the amount at harvest.
2. % grain N recovery was calculated by dividing the untreated grain N recovery by the amount of soil N used.

NB: an estimate of the quantity of N mineralised during the cropping season was not included for any calculation but was assumed to be consistent for all treatments. Inclusion of an estimate of mineralised N would lower the % grain recovery for both soil and fertiliser but is unlikely to change the relative differences.

Table 2. % grain N recovery from soil only, fertiliser only or combined soil and fertiliser application in 6 trials 2016-2017

Season	2016		2017	
Number of trials	3		3	
N 'source'	Mean	Range	Mean	Range
Soil only	98%	73-112%	62%	55-70%
Fertiliser only	23%	16-27%	15%	10-19%
Soil & fertiliser	62%	54-74%	40%	33-46%

NB: The mean and range used for 'fertiliser only' is for the most efficient rate (50 kg N/ha) from Table 1.

Key points

1. The % grain N recovery when calculated on combined soil and fertiliser quantities is in line with industry convention (~40-60% N efficiency depending on year).
2. However, **each kg of soil N was ~4 times more efficient** (range 3-6 times) in producing yield and protein than each kg of fertiliser N – even when fertiliser was applied at the most efficient rate.

Situations of concern

N fertiliser recommendations are generally based on setting a target for yield and protein and then ensuring a quantity of soil and fertiliser N that is generally double that target (i.e. working on a 40-60% grain N recovery efficiency). This approach is generally effective, but on the basis of these results, will struggle when soil N levels become low. Common examples would be:

- Soil N levels are heavily depleted following an unexpectedly very high yielding crop (e.g. in 2012); and
- Following a very dry fallow where mineralisation is greatly reduced.

In these situations, N fertiliser application rates may need to be increased to commercially impractical and uneconomic levels to achieve the expected outcome. In some situations with very low starting N quantities, a change from cereal to a legume may be a much better option.

Why is the fertiliser efficiency so low in the year of cropping?

Movement of N

One possible reason for the low observed efficiency of grain N recovery from fertiliser applied in the year of cropping may be the amount and speed of N movement in soil. During 2015-2017 a primary objective has been to evaluate the impact of N application into a dry soil profile during the fallow. The hypothesis was that the applied N would move further with fallow rain events so that N would be deeper and more uniformly distributed by planting.

Figures 1 and 2 are indicative of the results achieved following N application during the fallow in 2015/16 and 2016/17.

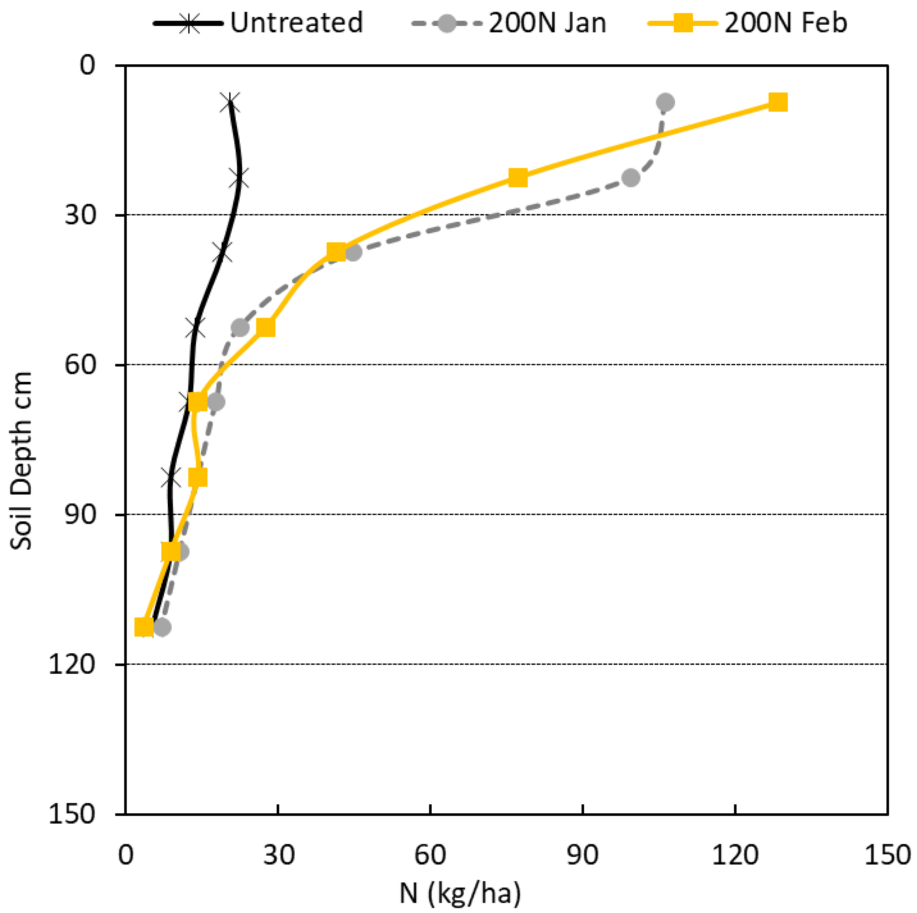


Figure 1. Soil distribution of N at Mullaley at planting (May 2017) following application of urea in January or February 2017. 175mm of rain was recorded between the January application and planting. 140mm of rain was recorded between the February application and planting.
(NB: Both N applications were spread and not incorporated. Sampling method - 6 individual 0-120cm depth cores taken per plot. Samples from each depth were bulked with a single sub sample taken for analysis. Not replicated.)

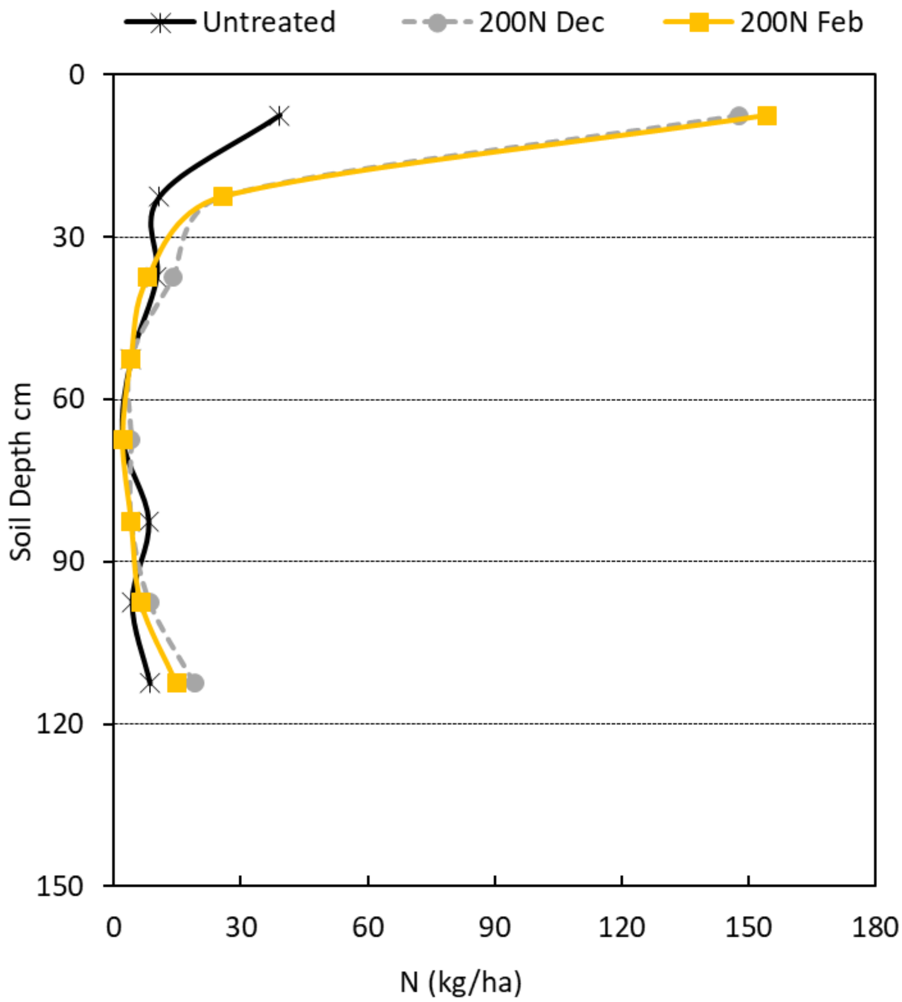


Figure 2. Soil distribution of N at Tulloona at planting (June 2016) following application of urea in December 2015 or February 2016. 225mm of rain was recorded between the December application (spread and incorporated) and planting. 65mm of rain was recorded between the February application (spread and not incorporated) and planting.
(NB: Sampling method - 6 individual 0-120cm depth cores taken per plot. Samples from each depth were bulked with a single sub sample taken for analysis. Not replicated.)

Key points

1. Even in a dry soil profile, the movement of N in these trials (predominantly vertosol soil types) was slower and shallower than expected.
2. The majority of N applied in fallow (either surface spread or incorporated to depths of ~3-5cm) was still in the 0-15cm soil segment at planting.
3. Sampling in smaller increments e.g. 5cm may reveal clearer differences in movement between application timings.

Implications of reduced N movement

The slower observed movement of N in soil may explain why in 10 of the 11 application timing trials there has not been a significant advantage from fallow N application compared to N applied at planting - as long as there were reasonable levels of in-crop rain. The 2017 season was however characterised by useful fallow rains (particularly in March) but with very low levels of in-crop rain (particularly June-September).

Billa Billa 2017

The site at Billa Billa in 2017 was the first to show a significant benefit from both fallow N applications compared to the same quantity applied at planting (or in-crop).

Figure 3 shows the distribution of soil N at planting from fallow application with the majority of N in the 0-15cm depth for both December and March 2017 applications, but with apparent increased movement from the December application. This site had the deepest movement of N recorded in any of the trials in 2016 or 2017.

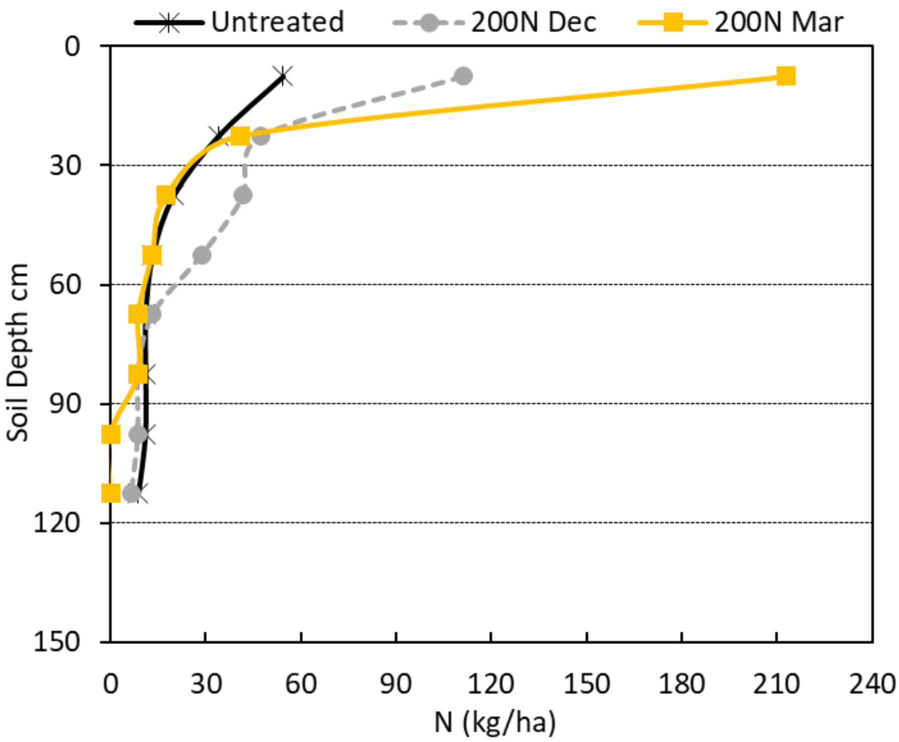


Figure 3. Soil distribution of N at Billa Billa at planting (May 2017) following application of urea in December 2016 or March 2017. 279mm of rain was recorded between the December application and planting. 154mm of rain was recorded between the March application and planting.
(NB: Both applications spread and not incorporated. Sampling method - 6 individual 0-120cm depth cores taken per plot. Samples from each depth were bulked with a single sub sample taken for analysis. Not replicated.)

Figure 4 shows the yield results (variety Lancer⦶) at this site. There was no significant N response from fertiliser applied at planting (or in-crop) at this site, with only 71mm of in-crop rain received between planting and the end of September. However applications in December or March provided a significant increase in both yield and protein (not presented).

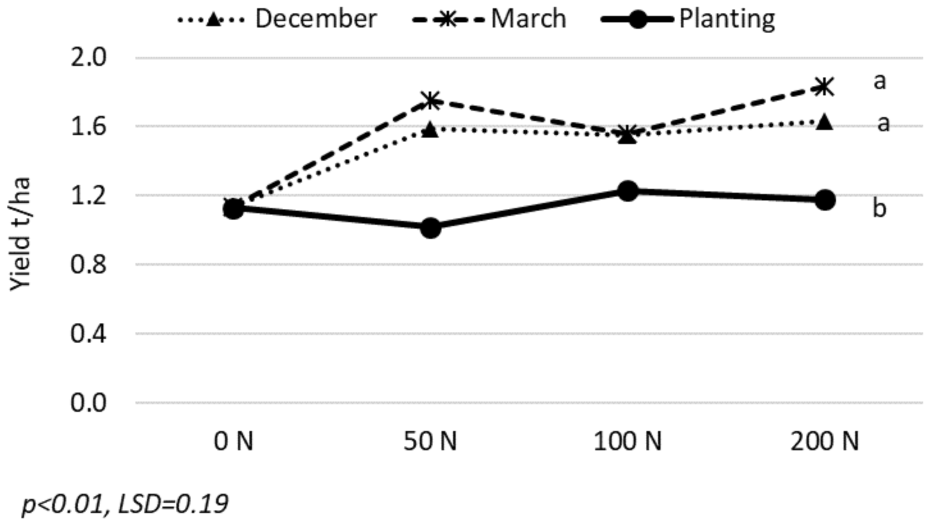


Figure 4. Effect of application timing and N rate on yield, Billa Billa 2017
(Treatments that share the same letter are not significantly different at P=0.05. All N rates were spread only)

Table 3 shows the distribution of N (in excess of untreated levels) by soil depth at harvest and the quantities of rainfall recorded between application and planting or harvest.

Table 3. Depth distribution of soil N at harvest (in excess of untreated levels) from 200 kg N/ha applications, Billa Billa November 2017

	December spread	**March spread**	**Planting PSPE**	**In-crop Spread**
Rainfall - application to planting	279mm	154mm	-	-
Rainfall - application to harvest	465mm	340mm	186mm	160mm
Soil depth	**Additional soil N kg/ha v untreated at harvest**			
0-15cm	32	70	36	82
15-30cm	48	48	4	2
30-45cm	35	11	4	4
45-60cm	20	7	4	4

NB There was no indication of any movement of fertiliser applied N deeper than 60cm. Soil recovery from PSPE application was very low with only 1mm of rain recorded 4 days after application, followed by 9mm at 37-38 days after application.

Key points

1. Although the majority of N from December or March application was still in the 0-15cm zone at planting (Figure 3), the yield and protein results indicate it had moved deep enough to be available to the crop in a season with very low in-crop rainfall.
2. Increased benefit from fallow N application compared to application at planting are likely in situations with good levels of fallow rainfall but followed by low levels of in-crop rainfall.
3. The majority of excess N applied in December was recovered in the top 45cm at harvest after a total of 465mm of rainfall.
4. The majority of N applied in March was recovered in the top 30cm at harvest after a total of 340mm of rainfall.

NB Soil recovery from the PSPE application was very low in this trial with the first useful rainfall (9mm) 37 days after application. Unfortunately soil sampling was not planned/conducted in plots where N was incorporated by sowing for comparison.

How much nitrogen was actually recovered at harvest?

Assessment of the fertiliser N fate (in grain, soil and stubble) was conducted in 2015, 2016 and 2017 but with no attempt to estimate the residual N in the root system. Table 4 shows the mean quantities of N, in excess of the level where no fertiliser N was added. In 2015, results were only assessed for 200 kg N/ha applied and incorporated by sowing. Results in 2016 and 2017 are a mean of 4 application timings. In 2016, 3 of the 4 applications were spread and not incorporated with all applications spread and not incorporated in 2017.

Table 4. Mean levels of N (kg N/ha) in grain, stubble and soil samples at harvest following application of 200 kg N/ha, in excess of untreated levels, 8 trials 2015-2017

Season	2015		2016		2017	
Number of trials	3		3		2	
	Mean	Range	Mean	Range	Mean	Range
Grain	0	-16-21	20	5-39	8	3-13
Stubble	17	6-48	17	3-43	8	1-26
Soil	79	58-102	136	50-221	128	54-234
Total	**96**	**85-134**	**174**	**66-263**	**143**	**60-258**

Key points

1. Over 23 individual application timing comparisons, ~79% of the applied rate was recovered between grain, stubble and soil.
2. On average ~21% of the applied N was not able to be accounted for in grain, stubble or soil.
3. The majority of additional N was recovered in the soil and on average accounted for 65% of the applied N.
4. In 18 of 23 comparisons, testing accounted for more than 60% of the applied N.
5. The lowest recoveries were from 2 sites in 2015 where N was incorporated by sowing – both 40-50%, one site in 2016 from spreading on wet soil at GS30 – 30-40% and one in 2017 from application PSPE – 30-40%.
6. Grain recovery is likely to be the most accurate measure with stubble and soil more variable due to issues such as sampling and uniformity of spreading.

Was nitrogen still available for the following crop?

Two of the trial sites from 2016 (Tulloona and Macalister) were planted to winter crop in 2017 and were monitored for response and benefits in the 'year 2' crop. Table 5 shows the soil test results taken at planting and harvest in year 2.

Table 5. Soil N levels (kg N/ha) at Tulloona and Macalister following application of N at different rates applied at wheat planting in 2016

	Tulloona		Macalister	
N rate at sowing in 2016	April 2017	Oct 2017	Aug 2017	Dec 2017
Untreated	53 b	29 b	78 c	44 b
50 kg N/ha IBS	76 b	32 b	99 bc	46 b
100 kg N/ha IBS	71 b	21 b	131 b	80 b
200 kg N/ha IBS	162 a	122 a	237 a	178 a
P value	*<.01*	*.04*	*<.01*	*<.01*
LSD	*33*	*75*	*39*	*62*

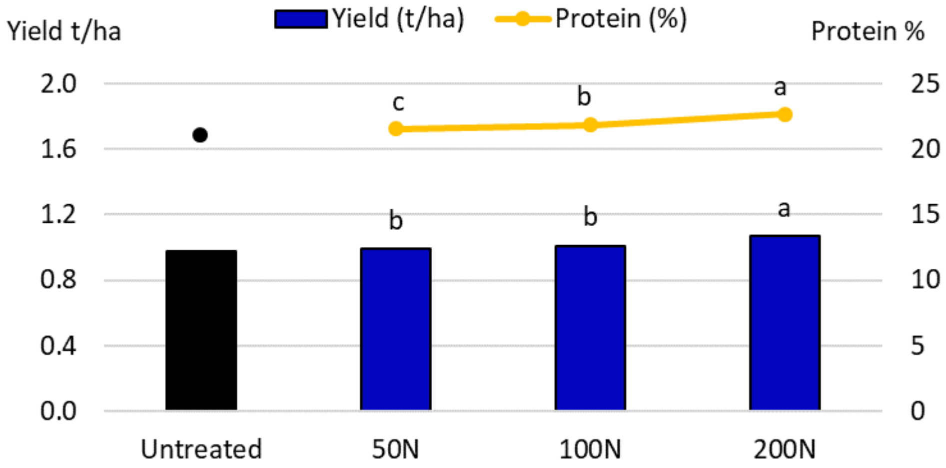
NB Sampling method - 4 individual 0-120cm depth cores taken per plot. Samples were separated into 0-30 and 30-90cm intervals with each depth bulked and a single sub sample taken for analysis. 4 replicates sampled in each treatment

Key points

1. The large LSD figures (least significant differences) highlight the variability that can occur with soil testing and that the number of soil samples collected should have been larger to account for this.
2. While acknowledging the above, soil testing ~12 months after N application (April and August 2017) showed significantly increased soil N levels in the 200 kg N/ha treatments (109-159 kg N/ha additional compared to untreated).
3. Differences were less clear from the 50-100 kg N/ha rates applied in 2016.
4. The lowest soil N levels at planting in 2017 were from the untreated samples.
5. At harvest of the year 2 crops, there was still an additional ~90-130 kg N/ha of soil N in plots that had received 200 kg N/ha in 2016.

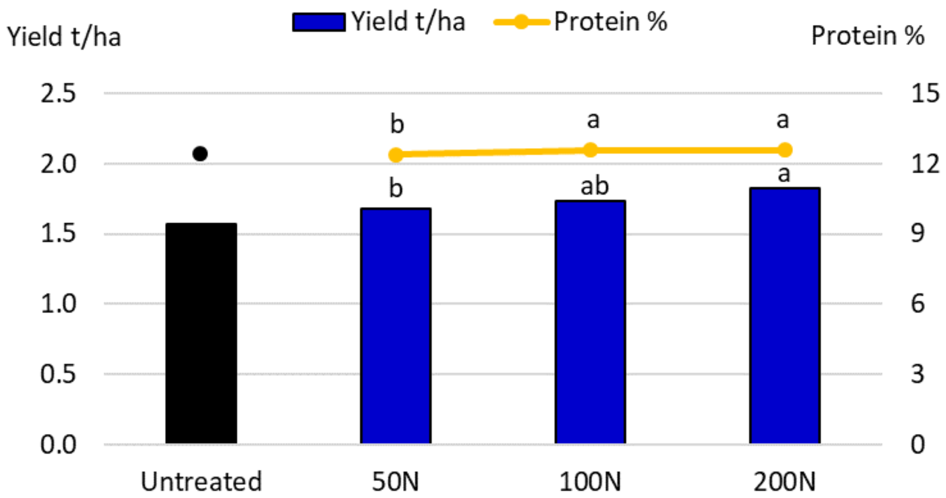
NB At the Tulloona site, ~60 % of the additional soil N was still found in the top 45cm with 45% found between 15 and 45cm. At the Macalister site, ~49 % of the additional soil N was still found in the top 45cm with 31% found between 15 and 45cm.

The Tulloona site was commercially planted to chickpeas and the Macalister site was planted to wheat. At Tulloona, at the end of September it was visually apparent that all plots that had received the 200 kg N/ha rate in year 1 were ‘greener’ than the remaining plots and the trial warranted harvest. Previous wheat results had indicated the most consistent N response was in grain protein, so yield and grain quality were assessed at both sites. Figures 5 and 6 show the yield and protein responses in year 2.



Yield: p=0.02, LSD=0.06 *Protein: p<0.01, LSD=0.29*

Figure 5. 2nd year impact of N rate - chickpeas, Tulloona 2017
(Treatments that share the same letter, within an assessment, are not significantly different at P=0.05. Results for each N rate are from a factorial of 3 timings x 2 varieties. Untreated not analysed and included for comparison only)



Yield: p=0.02, LSD=0.10 *Protein: p<0.01, LSD=0.1*

Figure 6. 2nd year impact of N rate - wheat, Macalister 2017
(Treatments that share the same letter, within an assessment, are not significantly different at P=0.05. Results for each N rate are from a factorial of 3 timings x 2 varieties. Untreated not analysed and included for comparison only)

Key points

1. Significant increases in both yield and grain protein were recorded in year 2 from the 200 kg N/ha rates applied in 2016 compared to the 50 kg N/ha rate at both sites.
2. Although soil testing did not show a significant difference in soil N between the 50 and 100 kg N/ha rates, there was a significant increase in grain protein recorded in both crops from the 100 kg N/ha treatments compared to the 50 kg N/ha rate.

Economic impact

Tulloona

- Wheat 2016: all nitrogen rates achieved at least break even in 2016 due to yield benefits (0.7-1.2t/ha) combined with increased grain quality in a ~4t/ha yielding situation
- Chickpeas 2017: although grain protein was increased by all rates of N applied in 2016, only the 200 kg N/ha rate resulted in a significant yield increase. This equated to an extra $60/ha net benefit
- Soil testing indicates an extra 90 kg N/ha is still available to benefit year 3 cropping from the 200kg N/ha applications.

Macalister

- Wheat 2016: there was no yield impact from applied N but increases in protein of ~2-3%. There was no net benefit with mean yields ~2.0-2.5t/ha
- Wheat 2017: significant yield increases were recorded from all 2016 rates compared to the untreated (0.1-0.25t/ha). Despite significantly increased protein from the 100 and 200 kg N/ha rates, all grain was H2 quality. Net benefits of $32-$73/ha were achieved in year 2
- The 50 kg N/ha rate was the only one to achieve a net benefit over the 2 years of ~$20/ha
- Soil testing indicates an extra 130 kg N/ha is still available to benefit year 3 cropping from the 200 kg N/ha applications.

Conclusions

This series of trials over 4 cropping seasons and 14 trial locations has provided results that question some of our current management practices.

- It has supported the general N grain recovery 'rule' applied in N budgeting of 40-60% of available soil and fertiliser N but highlighted a large difference in efficiency between the two sources
- It has highlighted the poor efficiency of fertiliser N grain recovery in the year of application with mean levels of ~15-20% applied N recovered in grain at common commercial rates (50 -100 kg N/ha)
- The relatively shallow and slow movement of the applied N is likely to be a major cause for this inefficiency
- Consider non-cereal options in paddocks with very low soil N levels
- Testing at harvest of grain, stubble and soil indicated nearly 80% of the applied N could be accounted for, although in a small number of situations this level dropped to as low as 30-50%
- There was no clear pattern of difference between urea surface spread or spread and shallow incorporated in terms of N recovery. They were both equally good (or bad)
- Initial assessment of response in 2nd year crops was encouraging with ~50% of the initial 200 kg N/ha rate still available for crop response in year 3
- At one of the two sites monitored in year 2, all of the net benefit from fertiliser occurred in year 2
- The errors associated with soil testing (e.g. core number, uniformity of sample mixing and sub sampling) make 'precise' recommendations on fertiliser N levels difficult.

Key industry challenges

- Ensure soil N levels do not continue to decline as the required levels of fertiliser N in the year of cropping would rapidly become uneconomic and impractical and cereal production less efficient
- We need to identify methods to get fertiliser N deeper in the profile, more quickly, to improve availability and efficiency

- Identify and if possible, manage the unaccounted losses from fertiliser N application.

Where to next?

The results from this work indicate we still have much to learn, or at least to refine, with the management of our most important and best understood nutrient for cereal production. Any practices that can improve the efficiency of N accumulation from the legume phase are going to be exceedingly valuable, together with methods to increase the efficiency of fertiliser N use in the year of cropping.

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Contact details

Richard Daniel
Northern Grower Alliance
Ph: 07 4639 5344
Email: richard.daniel@nga.org.au

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Using plant available water (PAW) to inform decision-making and crop resourcing: What to do when you do not have a PAWC characterisation on-site

Brett Cocks[1], Uta Stockmann[2], David Deery[2], Jenet Austin[3], Mark Glover[2], Mark Thomas[3], John Gallant[3], Graeme Schwenke[5], William Manning[6] and Kirsten Verburg[2]

[1] CSIRO Agriculture and Food, Toowoomba QLD
[2] CSIRO Agriculture and Food, Canberra ACT
[3] CSIRO Land and Water, Canberra ACT
[4] CSIRO Land and Water, Adelaide SA
[5] Tamworth Agricultural Institute, NSW Department of Primary Industries, Tamworth NSW
[6] NSW Local Land Services, Gunnedah, NSW

Key words

Plant Available Water Capacity (PAWC), soil water, APSoil, eSPADE, soil survey, Crop Lower Limit (CLL), subsoil constraints, soil-landscape, yield forecasting, APSIM

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CSP00210

Take home messages

- Plant available water (PAW) is a key determinant of potential yield in dryland agriculture. Obtaining a measurement or estimate of PAW can, therefore, inform crop management decisions relating to time of sowing, crop type or the level of fertiliser inputs
- Estimating PAW, whether through soil coring, use of a soil water monitoring device or a push probe, requires knowledge of the plant available water capacity (PAWC) of a soil. PAWC characterisations for 26 soils in the Liverpool Plains are publicly available in the APSoil database, which can be viewed in Google Earth and in the 'SoilMapp' application for iPad and Android
- Variation in the observed PAWC is linked to parent material, texture and subsoil constraints. Similarity in soil properties is therefore key, when choosing an appropriate PAWC data for your soil
- Recognising how soils are distributed across the landscape, helped by understanding how the soils have been formed, assists with assessing similarity in soil properties. The nearest characterisation is not necessarily the most appropriate one
- Relationships between soil properties, parent material and position in the landscape are reflected in soil-landscape, soil and land resources and land resource area mapping and described in accompanying reports available online through eSPADE (NSW)
- Digital soil maps (DSMs) provide predictions of soil properties at 90 or 100 m resolution and are available through eSPADE for NSW, and the Soil and Landscape Grid of Australia (SLGA), for all of Australia
- The project is currently testing a 5-step PAWC estimation approach at sites across the Liverpool Plains involving: 1) identification of soil-landscape unit., 2) observations on position within the soil-landscape units, 3) comparison with APSoil PAWC characterisations in the same or similar soil-landscape unit, 4) use of digital soil mapping products to compare properties and identify risk of salinity subsoil constraints, 5) adjustment of PAWC based on local conditions.

The Authors stipulate that the examples below are from currently successfully cropped sites, and any constraints mentioned are just constraints to PAWC and do not necessarily reflect the overall productivity of a paddock.

Plant available water and crop management decisions

A key determinant of potential yield in dryland agriculture is the amount of water available to the crop, either from rainfall or stored soil water. In the GRDC Northern Region the contribution of stored soil water to crop productivity for both winter and summer cropping has long been recognised. The amount of stored soil water influences decisions to plant or wait (for the next opportunity or long fallow), to sow earlier or later (and associated variety choice) and the input level of resources such as nitrogen fertiliser.

The amount of stored soil water available to a crop - Plant Available Water (PAW) – is affected by pre-season and in-season rainfall, infiltration, evaporation and transpiration. It also strongly depends on a soil's Plant Available Water Capacity (PAWC; Figure 1), which is the total amount of water a soil can store and release to different crops. The PAWC, or 'bucket size', depends on the soil's physical and chemical properties as well as the crop being grown.

Over the past 20 years, CSIRO in collaboration with state agencies, catchment management organisations, consultants and farmers has characterised PAWCs for more than 1000 sites around Australia. This data is publicly available in the APSoil database, including via Google Earth and in the 'SoilMapp' application (see Resources section).

But what should be done when you are not in the position to have a local field PAWC characterisation and there is no APSoil PAWC characterisation on-site?

The APSoil database provides geo-referenced data (i.e. data linked with locations on a map). The nearest APSoil PAWC characterisation may, however, not be the most appropriate as its surface and subsoil properties could be quite different. The challenge is, therefore, to find a PAWC characterisation for a soil with similar properties to the one on your site.

The soil properties that affect PAWC (texture, stones and gravel, chemical constraints) change within the landscape as a function of parent material and how the soil formed, or how soil material got there. These aspects are reflected in soil-landscape models that underpin soil survey maps produced by state government departments and other research organisations.

This paper uses examples from the Liverpool Plains to illustrate how you can use the available PAWC data, along with soil-landscape information and local observations to inform estimation of PAWC on your farm.

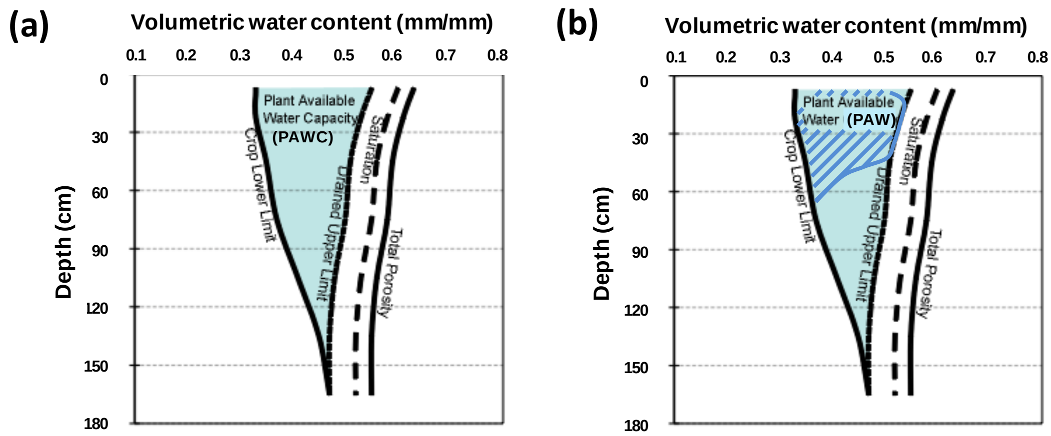


Figure 1. (a) The Plant Available Water Capacity (PAWC) is the total amount of water that each soil type can store and release to different crops and is defined by its Drained Upper Limit (DUL) and its crop specific Crop Lower Limit (CLL); (b) Plant Available Water (PAW) represents the volume of water stored within the soil available to the plant at a point in time. It is defined by the difference between the current volumetric soil water content and the CLL.

Plant Available Water (PAW)

Plant available water is the difference between the CLL and the volumetric soil water content (mm water / mm of soil) (Figure 1b). The latter can be assessed by soil coring (gravimetric moisture which is converted into a volumetric water content using the bulk density of the soil) or the use of soil water monitoring devices (requiring calibration in order to quantitatively report soil water content).

An approximate estimate of PAW can be obtained from knowledge of the PAWC (mm of available water/cm of soil depth down the profile) and the depth of wet soil (push probe or based on a feel of wet and dry limits using an uncalibrated soil water monitoring device).

Field measurement of PAWC

The PAWC can be determined in the field following procedures described in the GRDC PAWC Booklet ‘Estimating plant available water capacity’ (Burk and Dalgliesh, 2013). This method will usually provide the best estimate for a location of interest, although there are some pitfalls and common mischaracterization issues that need to be avoided (Verburg et al., 2017).

Where to find existing information on PAWC for Liverpool Plains soils

Characterisations of PAWC for 26 soils within the Liverpool Plains are among more than 1100 soils across Australia available in the APSoil database. The database software and data can be downloaded from http://www.apsim.info/Products/APSoil.aspx. The characterisations can also be accessed via Google Earth (KML file from APSoil website) and in SoilMapp, an application for iPad and Android devices. The yield forecasting tool Yield Prophet® also draws on this database. See our Update paper from two years ago (Verburg et al. 2018) for instructions how to find the APSoil sites.

Most cropping in the Liverpool Plains is practiced on heavy (high clay content) shrink-swell soils (Vertosols) of the plains and foot slopes. These soils are of basaltic origin, with many having relatively large PAWCs of 200-350mm. There are, however, some subtle differences in response to clay mineralogy (related to parent material composition) and texture (e.g. inclusion of sand or fine gravel), which explain the variation within that range. Larger variation in PAWC within the Liverpool

Plains is, however, caused by subsoil constraints, in particular subsoil salinity. Where present, these constraints can limit root water uptake quite dramatically and reduce PAWC by as much as 50%.

How to find an APSoil that has similar soil properties

Extrapolating from the APSoil PAWC characterisations to predict PAWC at a location of interest is not an easy task. The nearest APSoil PAWC characterisation may not be the most appropriate as its soil properties could be quite different. The presence or level of subsoil constraints may also vary. The challenge is, therefore, to find an APSoil PAWC characterisation for a soil with similar properties.

In many landscapes, including the Liverpool Plains, soil properties are tightly linked to a soil's parent material, development and position in the landscape. These same aspects underpin the many soil and land resource surveys that have been carried out over the years and that are increasingly becoming available on-line. The NSW government manages eSpade, an online portal for soil resource information. The mapping on eSpade divides the landscape into Soil Landscape Units (SLUs) https://www.environment.nsw.gov.au/eSpade2. We can draw on this information to assist with PAWC prediction.

Current evaluation of a five-step PAWC estimation method

Our current GRDC Project 'Methods to predict plant available water capacity (PAWC)' has developed a 5-step approach to estimate PAWC using the available information and is currently testing this for sites within the Liverpool Plains (Table 1). The methodology is currently at proof-of-concept stage, but below we will illustrate its application for selected sites within the Liverpool Plains. We hope this will provide insights into how soil properties change within the landscape and what consequences this has for PAWC.

Soils and landscapes of the Liverpool Plains

The Liverpool Plains are characterised by extensive plains with quaternary alluvial deposits originating from the surrounding hills of different age, origin and composition. All the SLUs considered in this paper are alluvial soil landscapes. These are formed by deposition along rivers and streams. The term 'alluvium' refers to deposits resulting from the action of rivers and streams and an 'alluvial plain' refers to the landform pattern that includes the stream channel (stream bed and bank) and plain. A flood plain is an alluvial plain which is 'frequently active' (meaning that it floods with an interval of 50 years or less). Almost all the cropped soils on The Liverpool Plains are Vertosols characterised by a clay-size-particle content of 30 percent or more. Salinity constraints are the main source of variation in PAWC in the alluvial plains and can have a large effect on PAWC. While Electrical Conductivity (EC) can have confounding effects from carbonates or gypsum, the chemical analyses in this case study and that of the earlier work documented in Verburg et al. (2017) all indicated good correlation between EC and chloride.

Table 1. 5 Step extrapolation process (based on findings from Output 4 of project CSP00210).

Step	Description	Process/Resource
1	Identify the Soil Landscape Unit (SLU) your site of interest belongs to.	Soil and land resource mapping available through eSPADE.
2	Consider the descriptions of your SLU and landscape position to assess whether they match the local situation. Consider slope position in footslope SLUs. Draw on local landscape and soil observations to help with this assessment.	Soil and land resource mapping available through eSPADE.
3	Identify possible APSoil PAWC profiles that fall within the SLU identified. This will give you a starting estimate for PAWC and possible PAWC profiles. Compare site location and local soil information with that available for the APSoil profiles. Future Digital Soil Map (DSM) of PAWC for the whole profile may provide a direct ballpark estimate.	APSoils and SLU rules of thumb in Verburg et al. (2017) (and Stockmann et al.) (unpublished report) APSoil database including via SoilMapp app Future DSM-based PAWC product for the whole profile
4	Use DSM products to assess • Whether chosen APSoil sites are in areas with similar clay % and PAWC prediction as the site of interest • Whether salinity constraints need to be considered that may modify the CLL and reduce the PAWC	Evaluate the soil and Landscape Grid of Australia (SLGA) soil attributes for topsoil and subsoil clay% and sand% and NSW Office of Environment and Heritage (OEH) eSpade for subsoil EC. The SLGA pedotransfer function (PTF) derived PAWC, CLL and DUL predictions overlaid with the SLU linework from Step 1.
5	Adjust the PAWC or APSoil PAWC profile for local conditions based on the assessment in Step 4 and any available local information on soil texture, soil depth or subsoil constraints. Paddock yield history may also provide guidance. Consult local soil measurements e.g. from soil sampling at sowing or obtain informal observations e.g. during the digging of posts. Chloride values exceeding 600 mg/kg are likely to increase CLL and reduce PAWC. Compare the shape of unconstrained and constrained APSoil PAWC profiles.	Based on available data the grower or advisor may have. Seek guidance on likely reductions from subsoil constraints for different size PAWC. If no particle size data is available, consider determining soil texture by hand when conducting soil chloride tests. Compare the PAWC profiles of unconstrained and constrained APSoils or by viewing in APSoil database, Google Earth or SoilMapp.

Table 2. APSoil characterisations by soil landscape unit (SLU) in the Liverpool Plains with PAWC (to 180cm or rooting depth).

APSoil	SLU	PAWC (mm)*	Soil	Soil constraints to PAWC
119	Conadilly	204^{S}, 207^{Co}, 282^{W}	Black Vertosol	
123	Conadilly	165^{M}, 210^{Ch}, 273^{S}, 237^{Co}, 264^{W}	Grey-Black Vertosol	
866	Conadilly	249^{W}	Black Vertosol	Salinity constraints from 90cm
869	Conadilly	245^{W}	Black Vertosol	Salinity constraints from 120cm
1165	Conadilly	135^{Co}-178^{Co}	Grey Vertosol	Constrained, cause unknown
1305	Conadilly	305^{S}	Black Vertosol	(to 150cm depth, DUL may be overestimated)
1309	Conadilly	288^{S}	Vertosol	(to 150cm depth)
912	Yarraman	183^{W}	Vertosol	Constrained, cause unknown
1306	Yarraman	145^{Ch}, 205^{C}, 261^{W}	Vertosol	Salinity constraints from 110cm
1307	Yarraman	64^{Ch}, 116^{C}, 129^{W}	Vertosol	Salinity constraints from 50cm
1308	Yarraman	243^{W}	Vertosol	Salinity constraints from 130cm
1166	Quirindi Creek	215^{Co}-216^{S}	Grey Vertosol	Coarser material at depth
1169	Upper Coxs	221^{S}	Black Vertosol	Constrained below 150cm
1170	Bando	116^{W}-131^{M}	Grey Vertosol	Salinity constraints (variable levels of salinity near site)
1171	Bando/Lesley Rd	245^{W}-253^{W}	Grey Vertosol	
122	Lower Coxs	149^{M}, 200^{Ch}, 248^{W}, 257^{S}, 278^{Co}	Grey-Black Vertosol	
1172	Lower Coxs	246^{S}	Brown Vertosol	Salinity constraints below 150cm
1173	Burburgate	183^{W}	Brown Vertosol	(may be underestimated)
867	Lever Gully	292^{W}	Vertosol	
1167	Lever Gully	252^{S}	Black Vertosol	
1168	Lever Gully	283^{W}	Black Vertosol	
868	Windy Creek	292^{W}	Vertosol	
94	Noojee	254^{S}, 272^{W}, 302^{Co}	Black Vertosol	
127	Noojee	188^{M}, 221^{Ch}, 302^{W}, 329^{S}, 356^{Co}	Grey-Black Vertosol	
128	Noojee	186^{M}, 225^{Ch}, 300^{W}, 324^{S}, 351^{Co}	Grey-Black Vertosol	
1174	Gunnebene	149^{Ch}, 177^{S}, 211^{W}	Grey Vertosol	(to 150cm depth)

*^{W}=wheat, ^{C}=canola, ^{Co}=cotton, ^{S}=sorghum, ^{Ch} = chickpea, ^{M}=mungbean

The Authors stipulate that the examples below are from currently successfully cropped sites, and any constraints mentioned are just constraints to PAWC and <u>do not necessarily reflect the overall productivity of a paddock</u>.

Example 1. Determining the effects of subsoil constraints on PAWC

Step 1. Identify your site located within the Yarraman SLU (Figure 2)

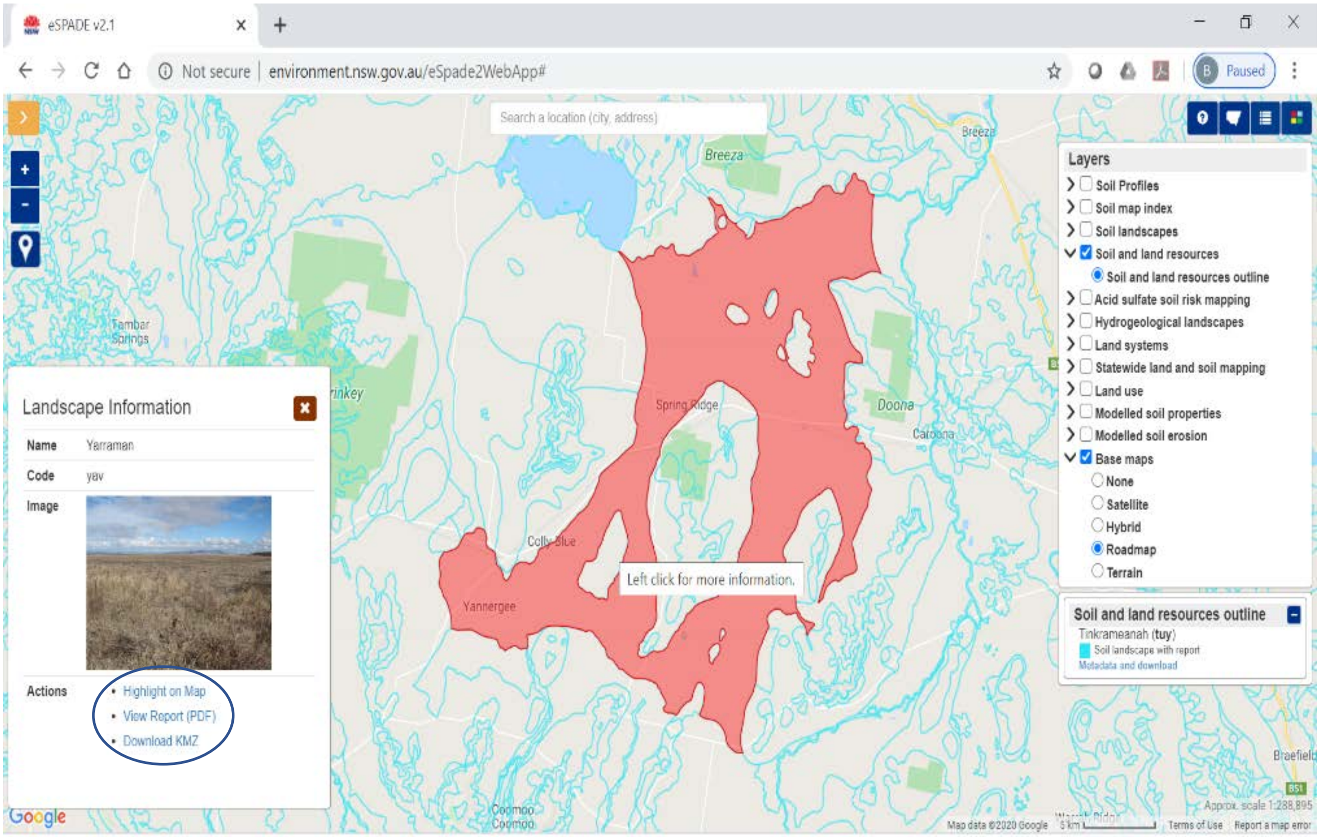


Figure 2. The landscape unit "Yarraman" surrounding Spring Ridge NSW, NSW OEH (2011)

Step 2. Consider the description of your SLU (SLU Report) and the landscape position

The Yarraman LSU report (NSW OEH,2011) describes the soil landscape as follows:

Landscape— Level to gently inclined extensive drainage plains and floodplains on basaltic alluvium in the Goran Basin Plains. Slopes <1%, local relief <9 m, elevation 290-360 m. Closed grassland mostly cleared for agriculture.

Soils— Very deep, poorly drained self-mulching grey vertosols (grey clays) with very deep, poorly drained black vertosols (black earths) in less waterlogged areas.

Qualities and limitations— High soil fertility, widespread foundation hazard, widespread productive arable land, widespread recharge zone, localised discharge zone, widespread salinity hazard, localised wind erosion hazard, localised gully erosion hazard, localised streambank erosion hazard, widespread high run-on, localised poor drainage, localised permanently high watertables, widespread seasonal waterlogging, widespread flood hazard. NSW OEH (2011)

Step 3. Identify possible APSoil sites that fall within you SLU

Overlay the “Yarraman” SLU with the APSoil KMZ file in Google Earth, (Figure 3). This shows the distribution of APSoil sites in the area and in within the Yarraman SLU. Note, that whilst most APSoil sites are geo-referenced, some as in this case are not. APSoil sites 1306, 1307 and 912 are centred on the town of Spring Ridge, however the descriptions state that they belong in the Yarraman SLU (Figure 4).

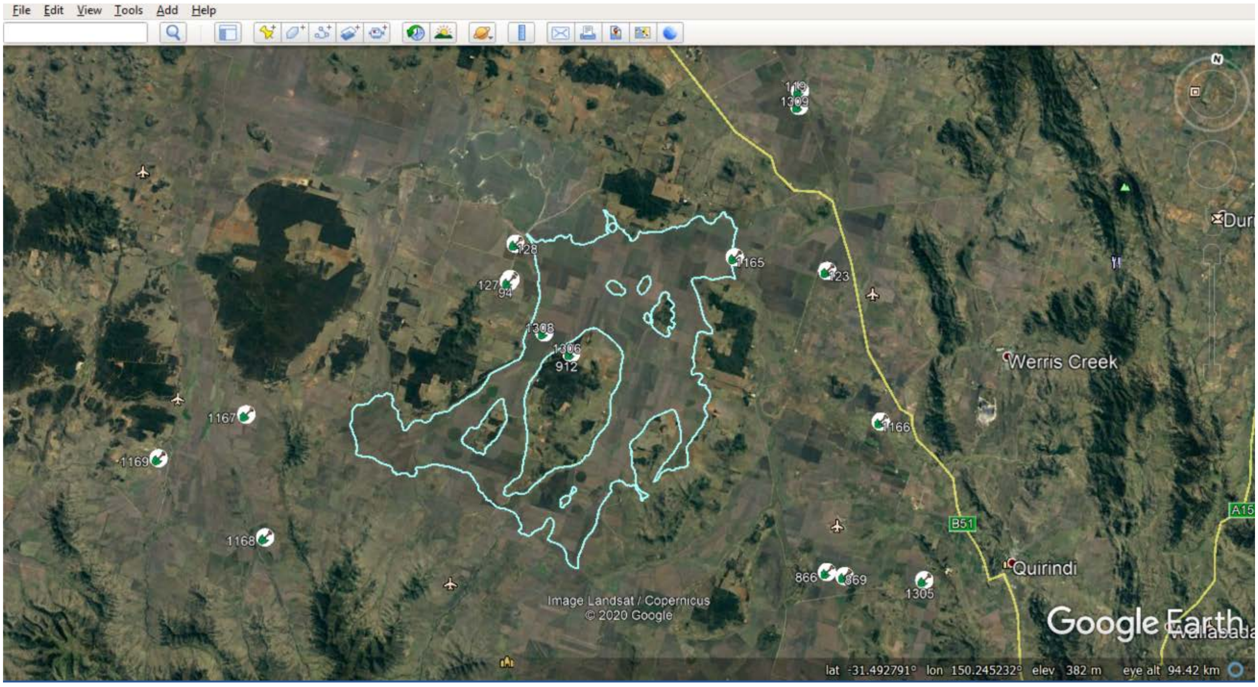


Figure 3. APSoil sites distribution in relation to the Yarraman SLU

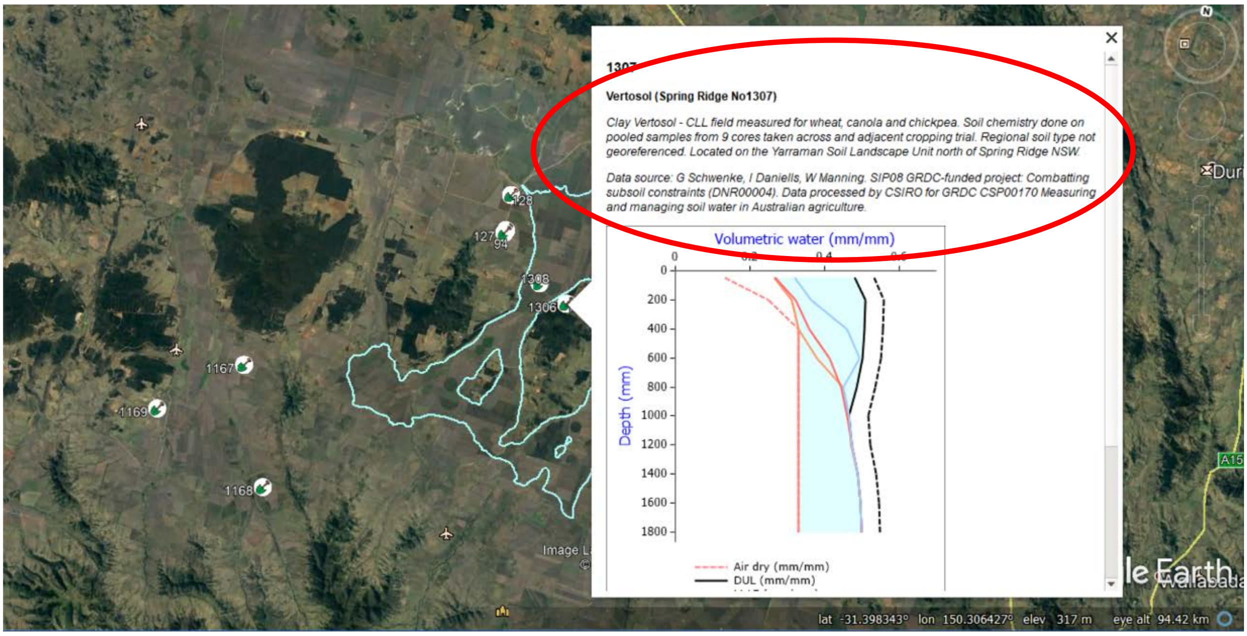


Figure 4. APSoil site 1307 description, which belongs to the Yarraman SLU. However, its location is centred on the town of Spring Ridge.

Step 4. Use soil texture and salinity properties provided for the Yarraman APSoil site as well as DSM products to assess whether your site has similar %clay contents and whether soil salinity constraints need to be considered.

As previously mentioned, salinity constraints are the main source of variation in PAWC in the alluvial plains and can have a large effect on PAWC. Water soluble salts can accumulate in soils. In most cases, these are mainly of sodium, but also of potassium, calcium and magnesium, which then may be chlorides, sulfates or carbonates (Hazelton and Murphy, 2007). While EC can have confounding effects from carbonates or gypsum, the chemical analyses in this case study and that of the earlier APSoil characterisations documented in Verburg et al. (2017) all indicated good correlation between EC and chloride content. To estimate the contribution of chloride to EC1:5 in a 1:5 soil:water suspension, where EC is measured as dS/m, use the following conversion 'EC = 6.64 x %Cl (per weight of soil)'. This assumes that chloride is the dominant ion.

APSoil shows three APSoil sites all of them Grey Vertosol soil types belonging to the Yarraman SLU. These are shown in Figure 5 in a graphical representation of the PAWC. Table 3 shows the distribution of chloride and clay down the profile.

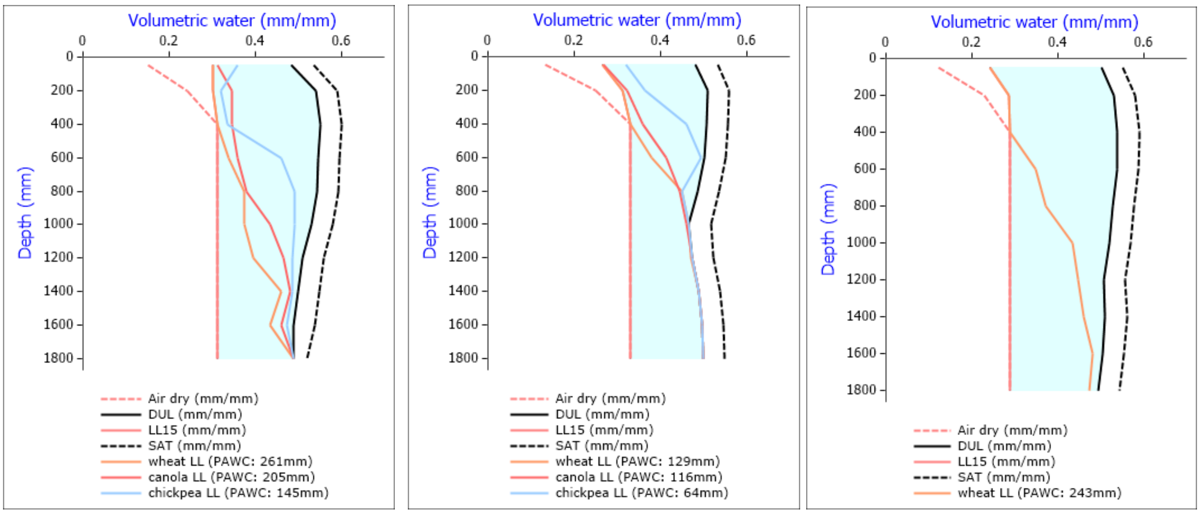


Figure 5. APSoil 1306, APSoil 1307, APSoil 1308 (left to right respectively)

Table 3. Chloride content (mg/kg) and clay content (%) distribution for APSoil sites 1306, 1307 and 1308

	APSoil 1306	**APSoil 1307**	**APSoil 1308**
Soil depth (cm)	Cl (mg/kg)	Cl (mg/kg)	Cl (mg/kg)
0-15	49	65	21
15-30	104	202	3
30-60	187	589	11
60-90	336	1537	30
90-120	482	2555	110
120-150	1108	2797	304
150-180	1206	2919	562
Soil depth (cm)	Clay (%)	Clay (%)	Clay (%)
0-15	69	65	71
15-30	81	74	69
30-60	81	72	73
60-90	77	73	74
90-120	71	78	74

APSoil 1307 shows Cl beginning to inhibit growth at about 60cm and completely inhibiting PAWC at 100cm, resulting in a wheat PAWC of 129mm. APSoil 1306 is showing a Cl inhibition of PAWC at 120cm becoming severe at 140cm resulting in a wheat PAWC of 261mm. APSoil 1308 is essentially unconstrained, however Cl may become an issue for very deep-rooted crops. The wheat PAWC is 243mm.

APSoil 1306 has a higher PAW despite having a subsoil constraint compared to APSoil 1308. This is because of the higher clay content giving a slightly higher total water holding capacity and is most likely due to its position in the landscape. PAWC in footslope positions (upslope) with higher elevations could be considerably reduced due to soil depth restrictions. However, some of the in-situ basalt soils found on the footslopes (Noojee SLU adjacent to the Yarraman SLU) are particularly high in clay content which results in a higher PAWC. These are not alluvials soils; but are basalt soils that have developed insitu.

Using a combination of these measured soils, your known position and some local knowledge like understanding where water accumulates (suggesting possible chloride hotspots), we can choose an APSoil characterisation based on EC and clay content.

Figures 6, 7 and 8 below show the predicted EC (Figure 8) and clay layers (Figure 6) from eSpade. It should be noted that the predictions are for large depth intervals in the topsoil (0-30cm) and subsoil (30-100cm), so any extra data from soil tests etc would be useful to help better inform your decision.

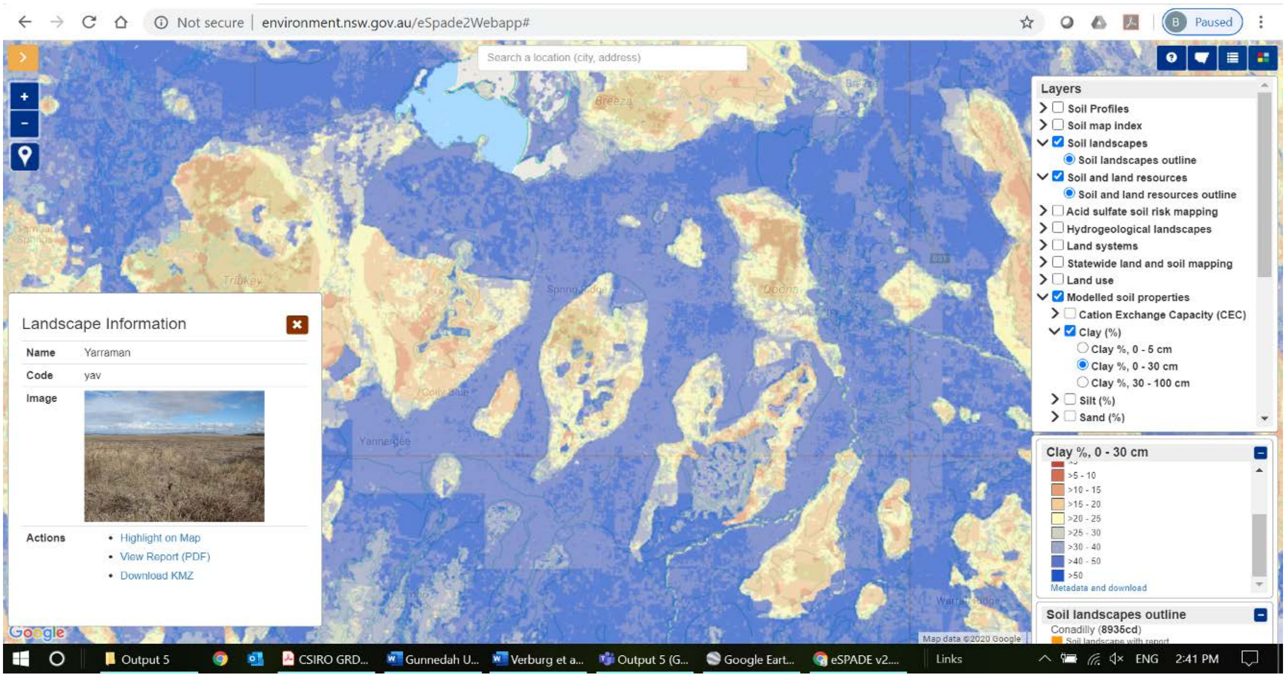


Figure 6. Predicted topsoil clay content at 0-30cm (NSW OEH 2011)

Figure 7. Yarraman SLU distribution (NSW OEH, 2011)

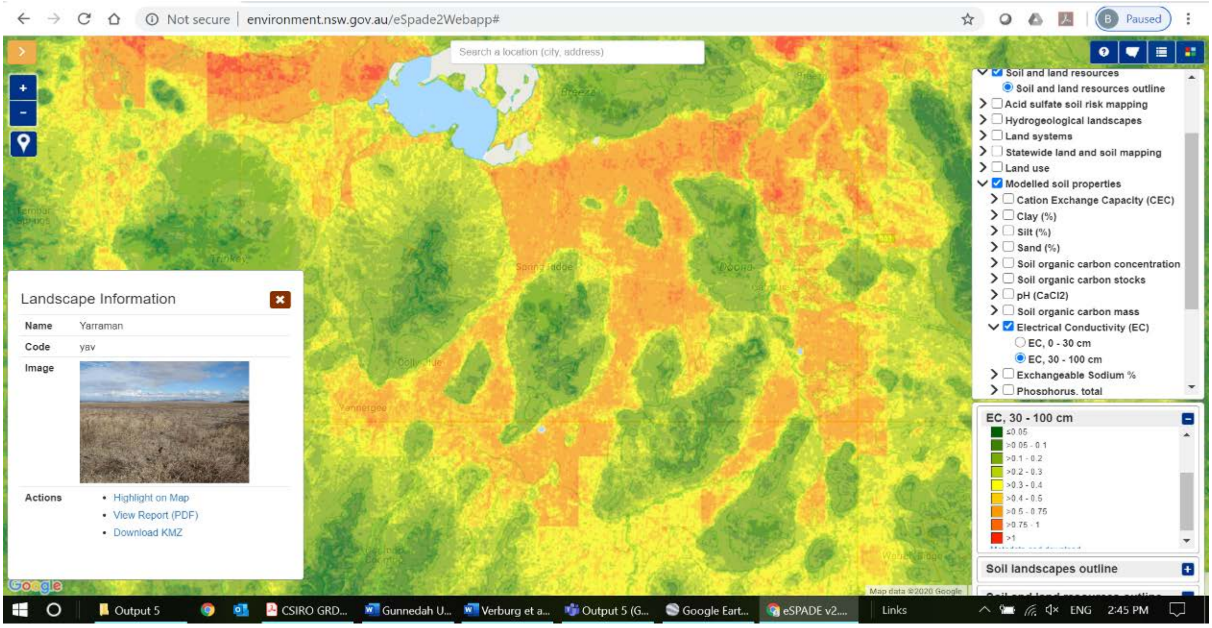


Figure 8. Predicted subsoil EC1:5 (dS/m) at 30-100cm (NSW OEH, 2011)

Example 2 What to do when there is no APSoil characterisations in your SLU?

The following example uses the Leslies Road SLU that does not have an APSoil site characterisation.

Step 1. and 2. Identify your site and consider the description of your SLU (SLU report) and landscape position.

The Leslies Road SLU (Figure 10) is a large and widely dispersed SLU within the Liverpool Plains. The Leslies Road SLU report describes the soil landscape as follows (NSW OEH, 2011):

Landscape— Level to gently inclined lower footslopes, drainage plains, and alluvial fans on Quaternary alluvium derived from Jurassic and minor Tertiary basalts of the Mullaley Hills and Liverpool Plains. Slopes 0 - 2%, local relief <3m, elevation 260 - 380 m. Open woodland and closed grassland, mostly cleared for agriculture.

Soils— Giant, imperfectly drained calcareous self-mulching black vertosols (black earths), with deep, rapidly drained red and brown ferrosols and dermosols (euchrozems) and brown and red vertosols (brown and red clays) on lower footslopes and upper drainage plains and giant, moderately well drained self-mulching brown and black vertosols (brown clays and black earths) on lower drainage plains. Giant, imperfectly drained self-mulching grey vertosols (grey clays) in poorly drained areas, such as lower margins.

Qualities and limitations— high soil fertility, widespread foundation hazard, widespread productive arable land, widespread dieback, localised recharge zone, localised discharge zone, localised salinity hazard, localised streambank erosion hazard, widespread high run-on, localised poor drainage, localised permanently high water tables, localised seasonal waterlogging, localised flood hazard. NSW OEH (2011))

Comparison also shows a good correlation between measured chloride and eSpade predicted EC as demonstrated below.

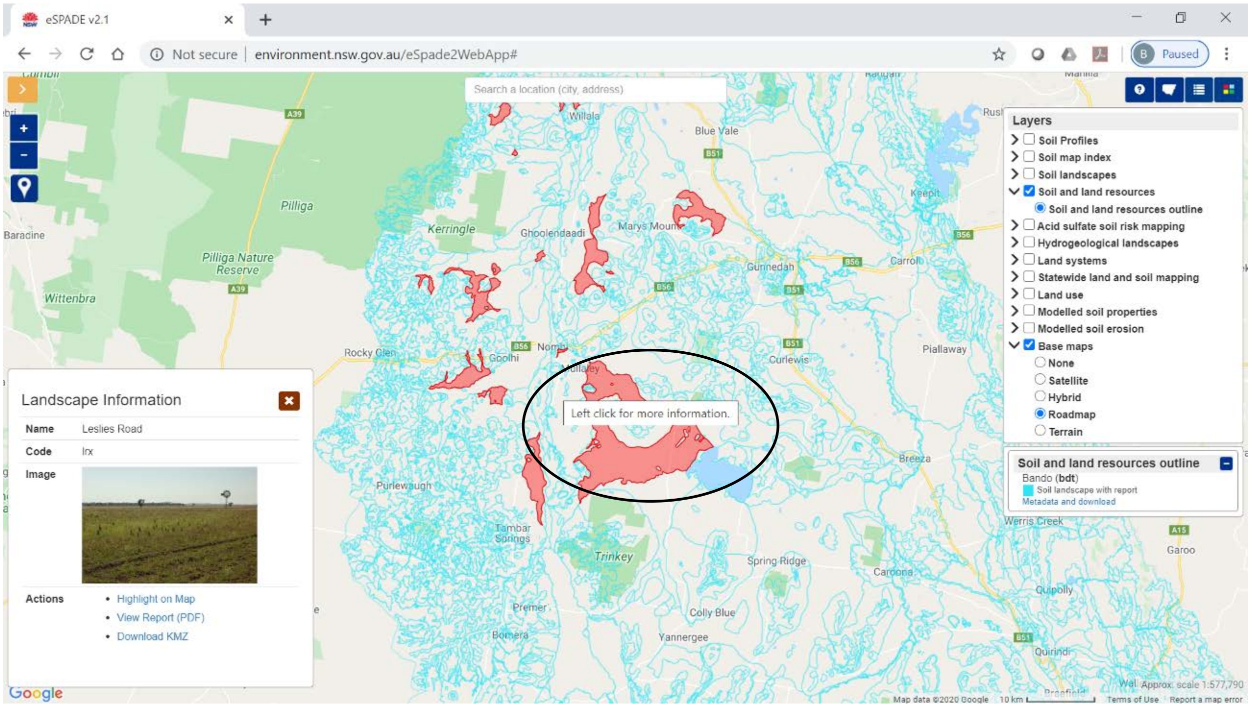


Figure 9. Distribution of the Leslies Road SLU within the Liverpool Plains (NSW OEH, 2011)

Step 3. Identify potential APSoil sites that fall within your SLU

There are APSoil characterisations nearby but none that fall within the Leslies Road SLU boundaries. As suggested in Table 1 Step 3, gather as much local information as you can. In the following, we will demonstrate this for 8 sites that fall within the Leslie Road SLU. Figure 10 shows the SLU boundary overlayed onto Google Earth and the spatial distribution of these sites within one fragment of the Leslie Road SLU. These sites belong to four currently successfully cropped paddocks, with two sites each (a and b) in each paddock. The 'b' site is historically a better yielding area of the paddock and the 'a' site is anecdotally lower yielding.

Table 4 shows the distribution of particle size (sand, silt and clay) and the ECEC and chloride levels for these sites. (ECEC (cation exchange capacity) is an indication of the cation exchange capacity).

Figure 10. Location of sites (a and b) for four paddocks belonging to the Leslie Road SLU

Table 4. Distribution of soil texture and salinity down the profile for 4 successfully cropped paddocks (1 to 4), and 2 soil profile sites (a and b) within these paddocks

LP_No	Soil Depth (cm)	ECEC (meq/100 g)	Clay (%)	MIR 2-20µm Silt (%)	Sand (%)	Australian Soil Texture Classification	Cl (mg/kg)
1a	0-15	88.89					35
1a	15-30	70.76	70.6	20.1	9.3	CLAY	79
1a	30-60		74.6	17.9	7.5	CLAY	269
1a	60-90		75.6	18.1	6.3	CLAY	879
1b	0-15						32
1b	15-30	74.83	60.6	27.0	12.4	SILTY CLAY	31
1b	30-60		78.6	16.5	4.9	CLAY	34
1b	60-90						151
2a	0-15	41.02					10
2a	15-30	45.07	65.6	23.7	10.7	CLAY	13
2a	30-60		76.6	16.5	6.9	CLAY	13
2a	60-90		74.6	18.1	7.3	CLAY	35
2b	0-15						16
2b	15-30	54.51	63.6	19.9	16.5	CLAY	27
2b	30-60		71.6	16.1	12.3	CLAY	42
2b	60-90		80.6	10.6	8.8	CLAY	125
3a	0-15	46.60				**IS**	27
3a	15-30	51.97	62.8	18.0	19.2	CLAY	137
3a	30-60		77.6	9.1	13.3	CLAY	542
3a	60-90					-	1303
3b	0-15						48
3b	15-30	76.48	72.6	15.1	12.3	CLAY	60
3b	30-60		71.6	16.7	11.7	CLAY	218
3b	60-90		75.6	15.1	9.3	CLAY	619
4a	0-15						21
4a	15-30	55.51	63.6	17.8	18.6	CLAY	22
4a	30-60		77.6	12.2	10.2	CLAY	135
4a	60-90		77.6	13.6	8.8	CLAY	572
4b	0-15						26
4b	15-30	62.41	74.6	16.7	8.7	CLAY	18
4b	30-60		71.6	18.1	10.3	CLAY	19
4b	60-90		77.6	16.3	6.1	CLAY	105

Step 4. Use DSM products to assess whether your site has similar %clay contents and whether soil salinity constraints need to be considered

Figure 11 below shows the spatial distribution, the predicted EC and clay contents for the subsoil at 30 to 100cm for the northern most sites LP2a and LP2b. These soils are similar in clay content in the 30 to 100cm layer and so the expectation is that they will hold similar amounts of water if unconstrained. The chloride levels are where the differences in these soils become apparent. This is typical for soils on the Liverpool Plains. LP2b is showing signs of increasing salinity in the deeper layers. Further investigation of chloride at depth is warranted and may result in the PAWC being lower at depth than that of LP2a. This is counter to the evidence that site LP2b is a higher yielding site.

This may be explained by further investigation of the PSA which shows that LP2b has a significantly higher sand content in the top layers, this increases the hydraulic conductivity of the soil, (the rate that water infiltrates the soil), this will allow better infiltration of rain and hence a wetter soil not necessarily a bigger PAWC. Table 1 step 5 addresses this buy suggesting paddock yield history and measurement of soil water at sowing be considered.

In terms of selecting an APSoil PAWC for this site, APSoil 1170 is very close but just outside the boundaries of the Leslies Road SLU in the Bando SLU. This may not be a problem as the SLU boundaries may not be perfect. However as can be seen on the eSpade EC layer prediction (figure 11), it is in an area of potentially high chloride. An adjustment to the crop lower limit to suit a more unconstrained environment could suffice. But, the nearest APSoil may not be the best one, APSoil 1171 further to the west and also in the Bando SLU has a less constrained PAWC of 253mm for wheat as compared to 1170 which has a PAWC for wheat of 116mm and looks to be a more appropriate PAWC characterisation. Refer to Figure 18.

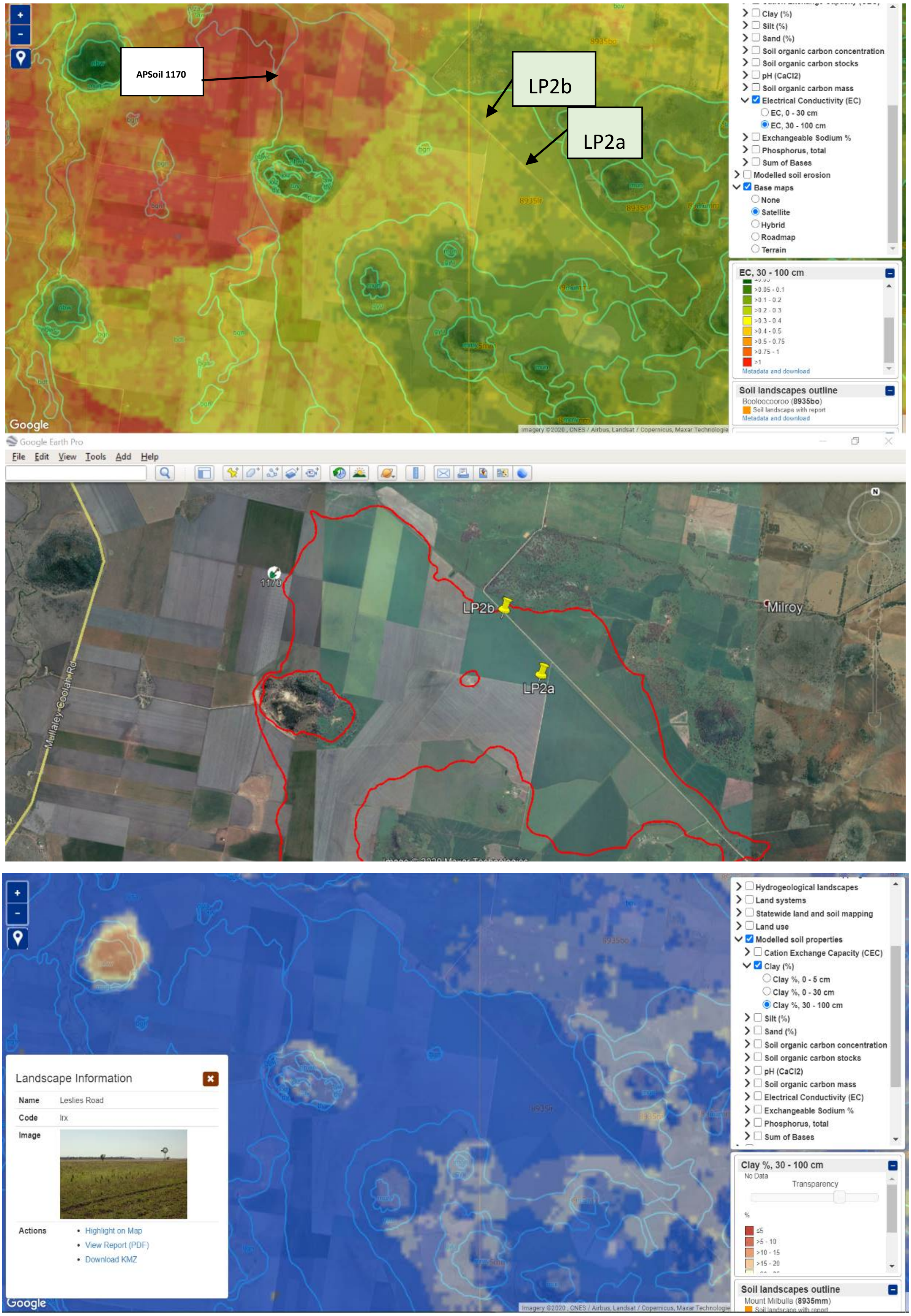


Figure 11. (Predicted EC1:5 (dS/m) (top), and clay content (%) (bottom) for the subsoil at 30-100cm depth for site ‘a’ and ‘b’ of Paddock 2 (LP2a and LP2b) whose locations are also shown (middle) (NSW OEH, 2011).)

The sites LP 1,3 and 4 are in the southern part of the SLU, Figures 13,14 and 15 show the spatial distribution of the sites and the predicted EC and clay contents for the subsoil at 30 to 100cm. These soils are similar in clay content in the 30 to 100cm layer and so the expectation is that unconstrained they will hold similar amounts of water. Some of the sites have lighter textured clays in the surface which will lower the surface PAWC but will not have a great impact on the total profile PAWC. The chloride levels are where the differences in these soils become apparent. This is typical for soils on the Liverpool Plains.

LP1a and LP1b (Figure 14) are comparable to LP2a and LP2b in the north of the SLU fragment. They are similar in clay content and the only difference seems to be chloride at depth (Figure 12), LP1a is showing increasing chloride below 60cm which points to a restriction in PAWC. LP1b also has a lighter textured surface with a higher sand and silt percentage. As discussed previously, this will increase the hydraulic conductivity of the soil allowing better water capture. This coupled with the fact that LP1a may have a PAWC restriction at depth could lead to a better performance of this area of the paddock.

LP3a and LP3b (Figure 13) are similar to the above examples with LP3a showing a chloride constraint to PAWC at depth which is offset by a lighter textured surface. LP3a is a small portion of the paddock showing a restraint to PAWC beginning in the 60 to 90cm layer.

LP4a and LP4b (Figure 13) illustrates one of the issues that can come from this process. Both sites look to be unconstrained and of the same clay content according to the modelling on eSpade (Figure 12, Figure 13). The modelled soil property predictions sourced from eSpade are based on previously collected soil legacy data which is extrapolated to landscape scale and as such will not be able to show some isolated areas of soil constraints. There are some differences in soil properties and chemistry that may affect PAWC evident in the chemistry (Table 4). LP4a has an increasing chloride constraint below one meter as the chemistry though incomplete, shows an upward trend. However, the PSA in the surface shows a lower clay content and hence a higher percentage of silt and sand. This gives this soil a better infiltration rate and it may be more effective in capturing rainfall and can thus fill the bucket more effectively offsetting the increasing chloride levels at depth.

This demonstrates the importance of some corroborating data as outlined in Table 1 Step 5.

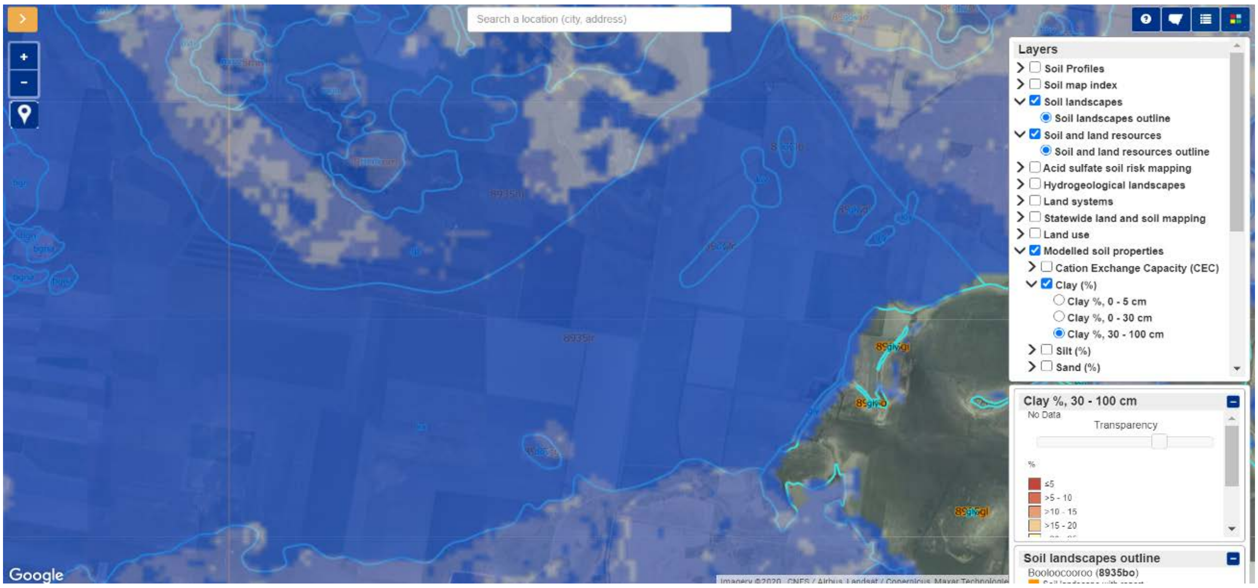


Figure 12. Predicted clay content for the subsoil at 30-100cm, for paddock site LP1 a and b, LP3 a and b, and LP4 a and b (NSW OEH, 2011)

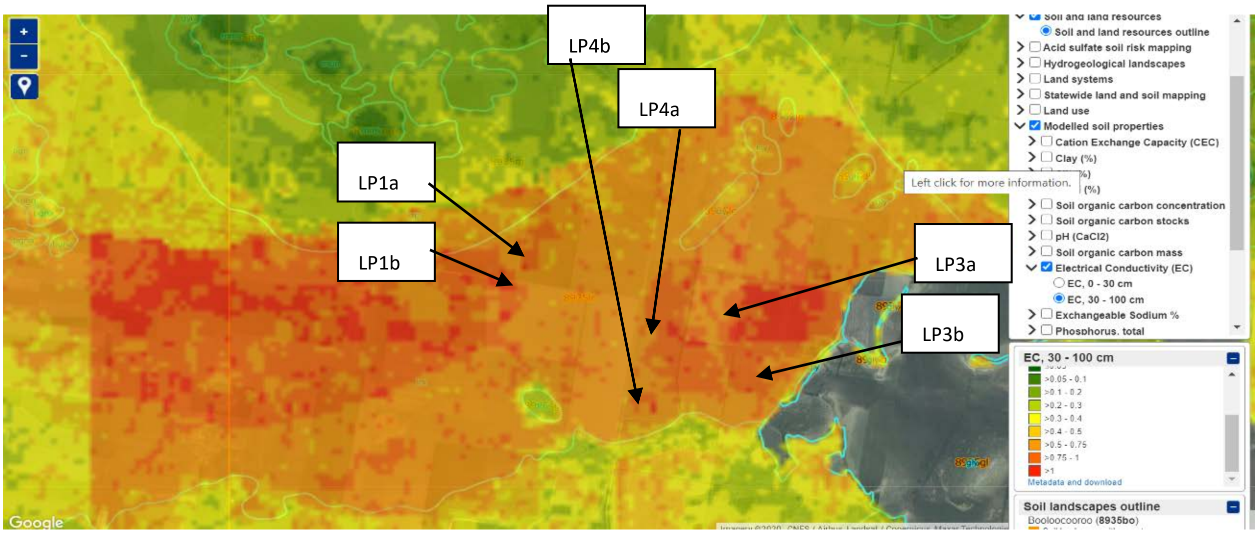


Figure 13. Predicted EC1:5 for the subsoil at 30-100cm, for paddock site LP1 a and b, LP3 a and b, and LP4 a and b (NSW OEH, 2011)

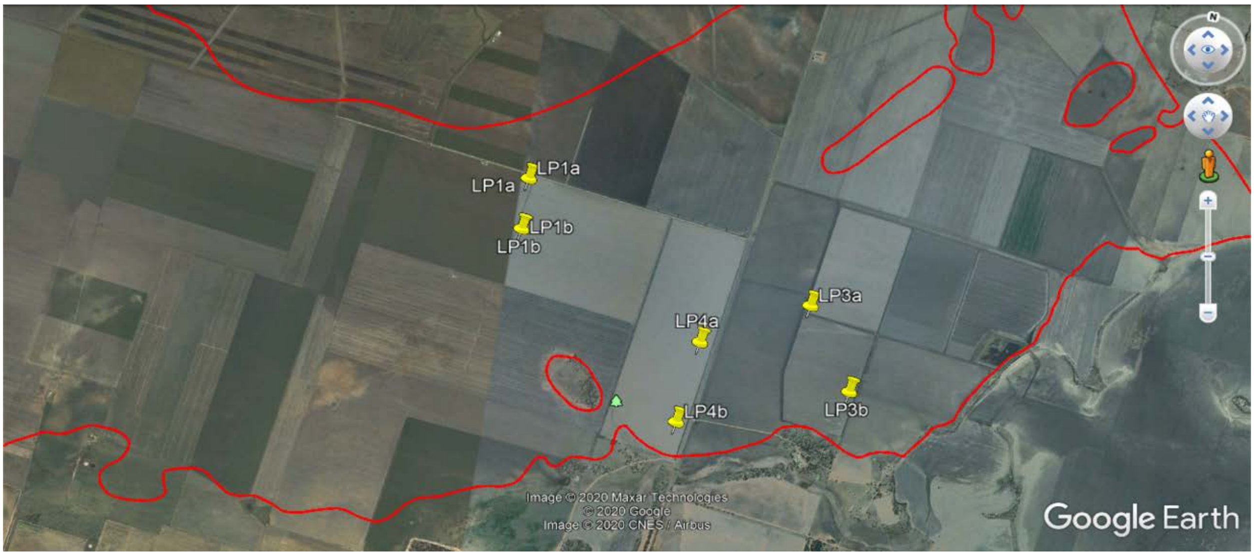


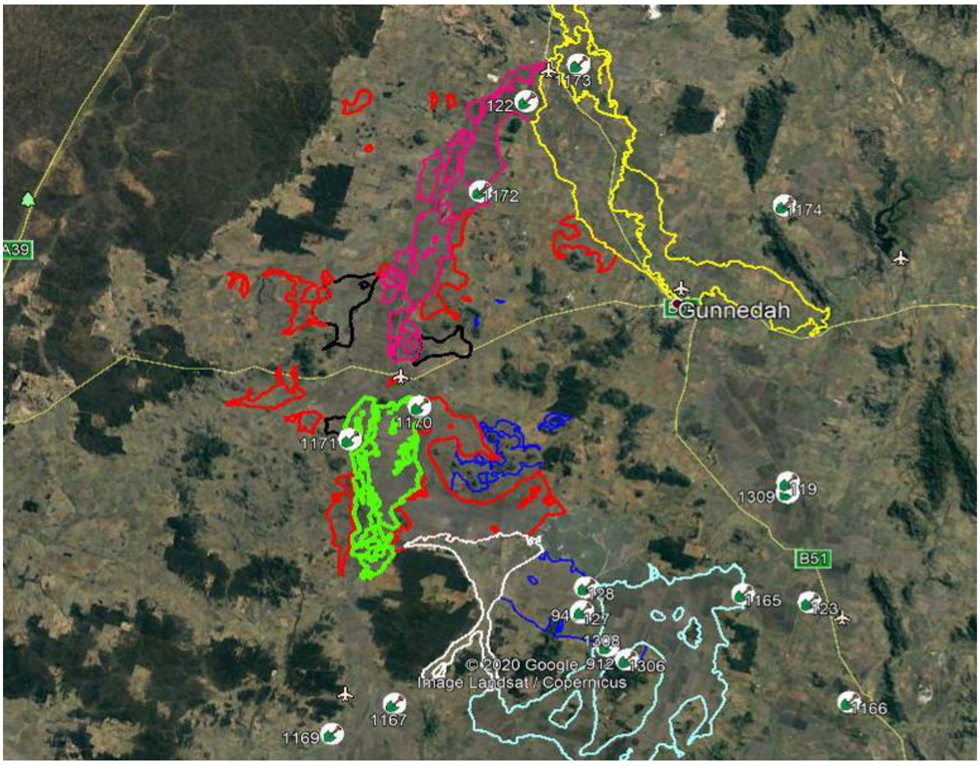
Figure 14. Location of paddock sites LP1 a and b, LP3 a and b, and LP4 a and b within the Leslies Road SLU (NSW OEH, 2011)

Step 5. Selecting APSoil characterisations for the Leslies road SLU

Look for APSoil characterisations firstly close to the site, notably for Leslies Road SLU the Bando SLU, check that they are within the expected PAWC range. Investigate soil elements that effect PAWC like clay content, EC and chloride levels. Consider preplant soil testing for water, and sub-soil constraints.

Look to the SLU report in eSpade and evaluate the 'Soils, Landscape, Qualities and Limitations', headings to help inform your knowledge of the soil provenance and landscape variations (Figure 16).

Because the Leslies Road SLU is fragmented, you could also look for adjacent SLUs of other fragments such as Burburgate, Lower Coxs and Noojee. These SLUs have APSoil characterisations that may be relevant and may only require minor modification. Look for similarities in chloride and clay content (Figure 15).



Leslies Rs SLU RED

Burburgate SLU Yellow

Lower COXS Pink

Noojee Blue

Bando Green

Yarraman SLU Light Blue

Figure 15. Distribution of different SLUs around Leslies Road fragments and possible APSoil characterisations.

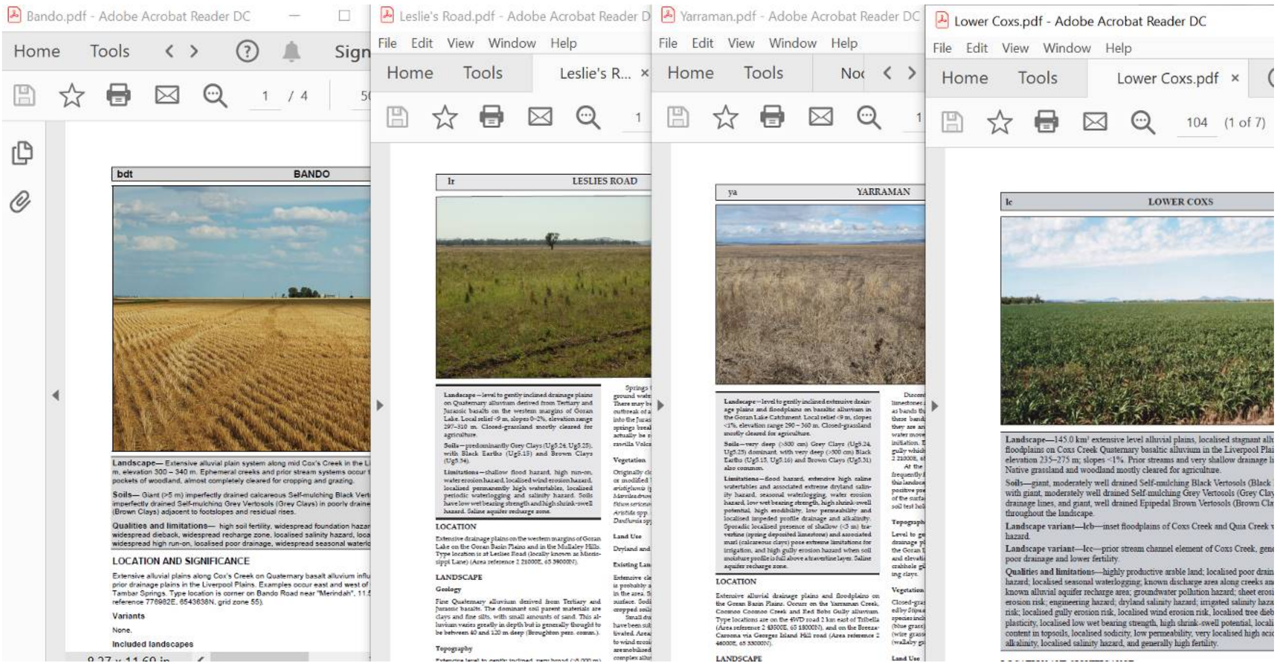


Figure 16. Examples of SLU reports

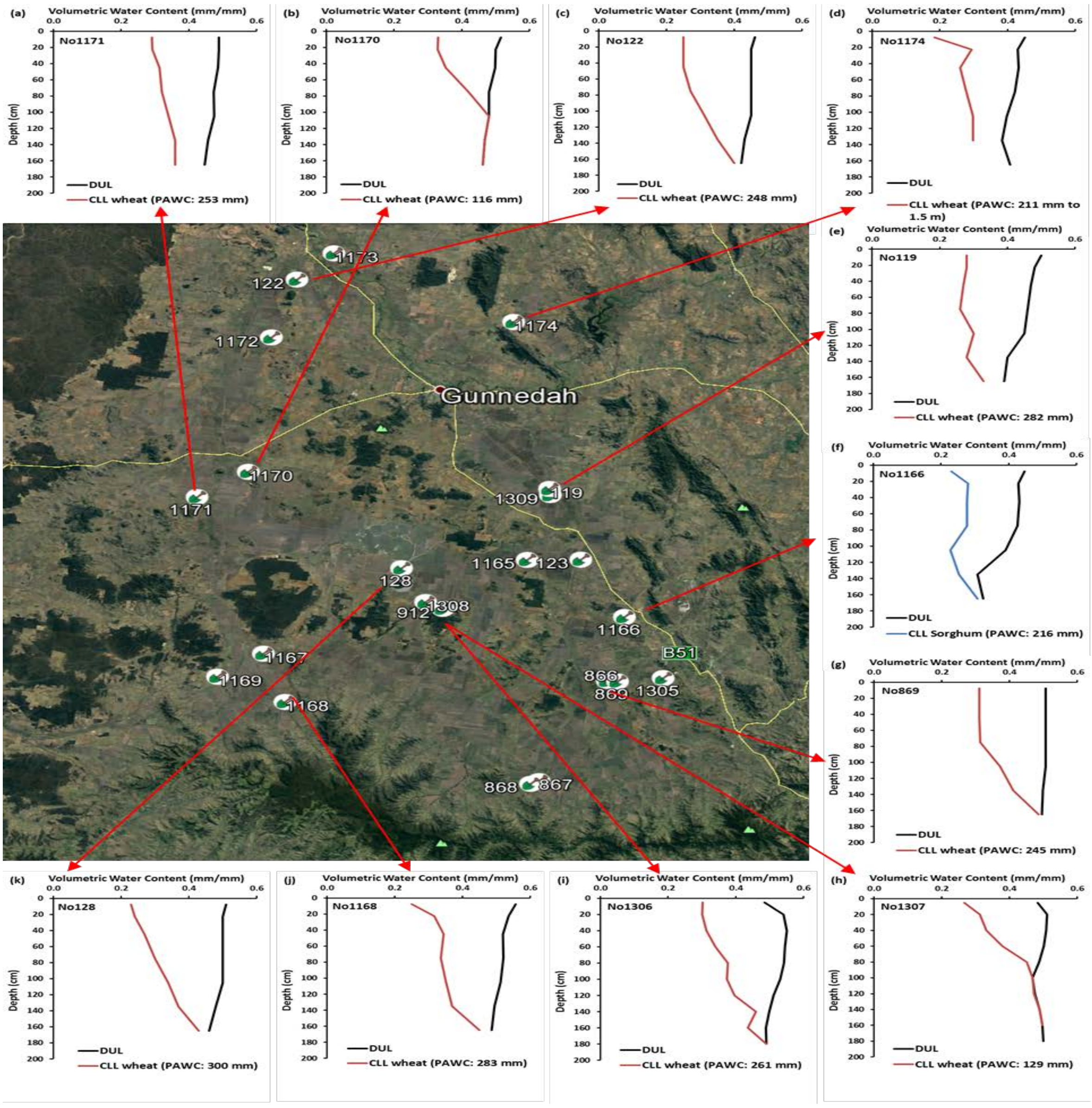


Figure 17. The different PAWCs for APSoil sites found on The Liverpool Plains. (Verburg et al. 2018)

Care must be taken when deciding which nearby PAWC to select, as these can change considerably in relation to constraints which can be seen in Figure 17.

Conclusions

From the preceding examples we can see that it is possible to estimate PAWC with some certainty, provided we use a consistent approach and understand some of the properties and provenance of our soils.

The importance of monitoring soil water over time with coring or water monitoring devices cannot be understated, as it informs a better understanding of PAWC. Soil testing for subsoil constraints is also important to understand the availability of soil water to plants. Testing of subsoil constraints can be done over time and in conjunction with nutrient testing. Gaining an understanding of how soil parent material and landscape position can affect PAWC will assist in choosing a soil characterisation where there are none close by. Digital Soil Maps (DSMs) such as available in eSpade and through the Soil and Landscape Grid of Australia are not generally high resolution, but they are an important tool when trying to understand landscape processes. eSpade also provides access to specific soil landscape reports and modelled soil properties and is an excellent tool for the Liverpool Plains.

Acknowledgements

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Resources

APSoil database: http://www.apsim.info/Products/APSoil.aspx (includes link to Google Earth file)

GRDC PAWC booklet: https://grdc.com.au/resources-and-publications/all-publications/publications/2013/05/grdc-booklet-plantavailablewater

eSPADE v2.1 (soil-landscape and land systems mapping and reports, reports on soil characterisation sites from various surveys): http://www.environment.nsw.gov.au/eSpade2Webapp

Soil and Landscape Grid of Australia: http://www.clw.csiro.au/aclep/soilandlandscapegrid/

Soil Matters book: https://www.apsim.info/wp-content/uploads/2019/10/Soil-matters.pdf

SoilMapp (soil maps, soil characterisation, archive and APSoil sites): Apple iPad and Android app; documentation: https://confluence.csiro.au/display/soilmappdoc/SoilMapp+Home

SoilWaterApp: Apple iPad app for estimating soil water during fallow and crops

Yield Prophet®: http://www.yieldprophet.com.au

Yield Prophet Lite: http://www.yieldprophet.com.au/yplite/

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Contact details

Mr Brett Cocks
CSIRO Agriculture and Food
GPO Box 102, Toowoomba QLD 4350
Ph: 07 45713280
Mob. 0427583756
Email: brett.cocks@csiro.au

Dr Kirsten Verburg
CSIRO Agriculture and Food
GPO Box 1700, Canberra ACT 2601
Ph: 02 6246 5954
Email: kirsten.verburg@csiro.au

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Cereal disease management in 2020 – from famine to moving feast!

Steven Simpfendorfer, NSW DPI, Tamworth

Keywords

correct diagnosis, leaf diseases, stripe rust, net blotch, fungicide strategy, stay up to date, COVID-19

GRDC code

DAN00213: Grains Agronomy & Pathology Partnership - A strategic partnership between GRDC and NSW DPI

Take home messages

- 'We're all in this together'
- Ensure you know the latest resistance ratings of cereal varieties you have sown – they change
- Back to basics – destroy the green bridge – oh well, move on from this in 2020
- Ensure correct diagnosis – not everything is disease and if not fungicides won't help
- Timing is everything – protect the top three leaves. However, with stripe rust 'flattening the curve' helps
- Prophylactic or responsive in 2020 with tight fungicide supply? Is a 2-3 week wait for product in Spring a potential consequence?
- Seek information and advice – NSW DPI pathologists are here to help ('we're all in this together').

Introduction

Gotta love 2020! Prolonged drought, bushfires/dust storms, COVID-19 global pandemic, barley tariff, wet/cold and now early development of leaf diseases (stripe rust in wheat and net blotch in barley) in winter cereal crops.

The other significant issue at play is continued concerns around the availability of fungicides throughout the season. The only thing that is certain in 2020 is that whatever I write here will likely be outdated by August when we do the webinar. Hence, I'll try and stick to the principles of disease management.

1. Know resistance levels in varieties you are sowing – they do change!

At the time of writing continuing reports of stripe rust 'hotspots' in the early sown wheat variety DS Bennett⊕ are occurring. This has been a considerable surprise to some growers and their advisers as they thought this variety was rated R to stripe rust. Well it was in 2018, but with the detection of a new pathotype (198 E16 A+ J+ 17+, '198 pathotype') in Tasmania and Victoria in 2018, the rating of DS Bennett⊕ dropped to MS in 2019 sowing guides. The 198 pathotype was detected at 4 sites in NSW, 2 in Victoria and 1 in QLD in the 2019 season with further evaluation of stripe rust reactions to this pathotype seeing DS Bennett⊕ lowered to an S rating for 2020 variety guides. Ensure you are using the latest variety ratings which are updated annually to reflect the expected reactions to new pathotypes of different pathogens if required (Winter crop variety sowing guide 2020).

The resistance within the varieties does not change, rather it is pathogen which has adapted (mutated) to overcome a resistance gene(s) within a variety. This can therefore lower the resistance rating of varieties which rely on this particular resistance gene. How far the rating drops depends on what other resistance genes are sitting in the background within individual varieties. For example, with the 198 pathotype of stripe rust, DS Bennett⏀ has fallen from R to S, Illabo⏀ has dropped from RMR to MR, whilst LRPB Kittyhawk⏀ remains unchanged at RMR. Some other big changes with varieties to the 198 pathotype are in LRPB Trojan⏀ which drops from MRMS to MSS and some durum varieties such as DBA Lillaroi⏀ and DBA Vittaroi⏀ which drop from RMR to MS. Note there have also been changes in leaf rust resistance ratings in wheat to a new Lr24 pathotype. It pays to stay up to date with the latest resistance ratings.

2. Destroy the green bridge is still important – volunteers are not good!

All rusts are what is termed '*biotrophs'* which simply means they need to host in a living plant to enable them to survive between crops. With wheat rusts, volunteer wheat plants are the green bridge, if they are from a susceptible variety. Removing these volunteers and hence the green bridge, delays the onset of rust epidemics if adopted widely. However, many growers have come off the back of a few tough years and with prolonged drought we all expected to have a reduced risk from green bridge build-up of rusts.

Volunteers which emerged on December/January rains were a valuable source of much needed feed and with great growing conditions there was unfortunately not enough stock to keep on top of the growth in many situations. Unfortunately, it has been reported that the growth was so good that some growers have even attempted to hang onto some of these volunteer crops and take to harvest. This, combined with an early seasonal break in 2020 in many regions of NSW and the widespread sowing of longer season wheat varieties, has resulted in a continuous 'green ramp' since January in many areas. The need to reduce input costs has also seen a reduction in the use of seed and in-furrow fungicide treatments for stripe rust which normally provide early protection and delay the onset of stripe rust in regions when used widely. The levels of stripe rust already present in long season wheat varieties across NSW will place pressure on plantings of susceptible main season varieties (potential 'second wave'?).

Some central NSW growers have also hung onto volunteer barley crops, attempting to take them to harvest. With prolonged wet/cold weather there have been issues with getting the heads to dry down, high levels of either spot or net-form of net blotch and weeds. At least with net blotch these situations are largely confined to the paddock where the problem was created. Hence, lesson learnt for the growers. Unfortunately, this is not the case with rust as the spores from infected crops can blow 100s of kilometres. Yes, 'we're all in this together' (COVID-19 parallel 1).

3. Monitor crops and get correct diagnosis

Do not get the impression from this paper that everything that is happening in cereal crops in 2020 is related to disease. Underlying issues with nutrient, herbicides, frost and other stresses are also causing some yellowing or discolouration of leaves in 2020. Physiological spotting not related to disease occurs especially in barley every year with 2020 being no exception. However, disease has clear patterns of distribution within and between paddocks, plants and even on individual leaves. The key message is testing is available which can be as simple as texting or emailing some good quality photos to NSW DPI pathologists (contact details below). This can be a quick way of ruling disease(s) in (or out), before pulling the sprayer out of the shed. If symptoms appear consistent with disease, we can then confirm this through testing of submitted samples. Testing and correct diagnosis is important (COVID-19 parallel 2). Also remember that all diseases have what's termed a '*latent period.'* Latent periods which vary in length and are basically the delay/number of days from when the fungal pathogen infects the plant and when symptoms (i.e. lesions or pustules) are visible on leaves. Hence, infections you see in your crop now are actually related to infection events that happened in the past. For example, stripe rust has a 10-14 day latent period, so hot spots that growers are seeing in their crops now started from infection events around or more than a fortnight ago (COVID-19 parallel 3).

4. Fungicide management – timing is everything

Fungicide application does not increase yield, rather it protects yield potential. Not all varieties will need extra protection from in-crop fungicide application if they have an adequate level of resistance to the disease of interest. For example, wheat varieties rated MR or better for stripe rust do not require fungicide management even though they may still show some infections at the seedling stage. The only caveat here is that we have seen some varieties (e.g. Suntop⸙ and Lancer⸙) take a bit more stripe rust when under high levels of background nitrogen nutrition which realistically only drops their rating by one category. That is, they DO NOT become 'suckers' under high N.

When it comes to protecting yield potential from development of leaf diseases in cereals it is the top three leaves (flag, flag-1 and flag-2) that need to be kept green for as long as possible. This is because these leaves intercept the most sunlight to drive grain filling and hence yield. In most barley varieties the flag leaf is smaller compared with wheat so the flag-1 is generally a bit more important with barley, but the surface area of the flag leaf sheath is big in barley and as such, is an important solar panel to protect. However, irrespective of exactly which of these three leaves do the heavy lifting, they all need to be protected in susceptible varieties if under disease pressure and weather conditions conducive to disease development are expected.

The flag-2 leaf is fully emerged at GS32 whilst the flag leaf is fully emerged at GS39. This is why a two spray strategy at GS32 followed by GS39 is effective in susceptible wheat varieties. This could equally be an up-front (seed or in-furrow) treatment followed by an in-crop spray at GS39. In barley, a two spray timing would be at ~GS32 and 49, with the latter spray timed to protect the flag leaf sheath. Leaves that are not emerged at the time of fungicide application are not protected as there is no systemic movement of foliar fungicides into new growth. Hence, early in-crop application prior to GS30-32 are questionable especially with 'necrotrophic' leaf diseases (e.g. yellow spot in wheat or net-blotches in barley) as leaves that emerge after foliar fungicide application are unprotected and exposed to continued infection from ongoing ascospore release from wheat or barley stubble, respectively within the paddock. The situation is more complicated with rusts such as stripe rust because, depending on coverage, a foliar fungicide application within an infected crop can eliminate the disease from a paddock. This can be to an extent that a new infection event from outside the paddock or successive cycles of the pathogen are required for the rust to build back up to damaging levels. That is, you have essentially flattened the curve of the stripe rust epidemic (COVID-19 parallel 4).

5. Prophylactic or responsive in 2020?

All fungicides have stronger preventative than curative activity against leaf diseases. This means that they are generally most effective when applied prior to or early in disease development rather than once the disease has established in a crop. Once lesions or pustules have developed on infected leaves and green leaf area has been lost, it cannot be restored by application of a foliar fungicide.

With tight fungicide supplies, prophylactic applications, if not warranted, could potentially leave growers short in spring when protection of key leaves is required and when spraying is most likely to provide maximum economic return. If the season remains wet and temperatures warm, which decreases the latent period for many leaf diseases, a 2-3 week wait for product in late winter - early spring could cause significant angst. Timing is everything with a foliar application at GS39 in late-winter - spring likely to be the best time to 'flatten the curve' on a leaf disease epidemic. If spraying crops prior to GS30, unless justified (i.e. stripe rust evident in MRMS or lower variety), then first consider the potential implications for your ability to hit a well-timed foliar fungicide application around GS39. 'Cheap insurance' in 2020 may be better addressed by keeping product in the shed for a targeted maximum benefit application at around GS39 (or possibly later in barley), rather than by a more questionable earlier prophylactic application. This situation could vary considerably between growers and change during the course of the season. Ensure you are talking with suppliers now before using up what you have on hand.

Conclusions

It is great to be having a relatively wet start to the winter cropping season across much of NSW and hopefully this continues. Consequently, leaf diseases are more likely to be more prevalent in wheat and barley crops than over the past three seasons. This may be the first experience for some newer agronomists in managing leaf diseases whilst the rest of us are drawing on medium-term memory. Be aware that some things have invariably changed during this time. Do not assume that the resistance levels in your wheat varieties are the same as three years ago, as new pathotypes of rust pathogens have developed and potentially distributed widely across NSW. Make sure you are using the latest resistance ratings and manage crops appropriately based on this.

Stay calm. Panicked decisions are not always the best decisions. Remember any disease you are seeing in your crops are from infection events that occurred 1-2 weeks ago so why do you need to spray in the next 5 minutes? Ensure you have the correct diagnosis as using up tight fungicide stocks on physiological, nutritional, environmental or herbicide related symptoms in leaves wastes product and may leave you short for spring when a timely fungicide application is more likely to have maximum economic benefit.

Remember 'we're all in this together' and NSW DPI pathologists are here to help.

Useful resources

Winter crop variety sowing guide 2020. NSW DPI

Agronomists and NSW DPI pathologists but never be shy to get a second opinion.

Useless resources

'Chicken little' old mate down the pub (if allowed) who is a little excited and full of 'information'. Two weeks in isolation suggested.

Glossy product brochures which claim one product is 'significantly' better than another. Yes, some actives have stronger activity than others but don't let it become a distraction. None of them can restore green leaf area if you have to wait 2-3 weeks to get them in the middle of an epidemic. Research shows that if you apply a registered product for the target leaf disease then timing is generally as or more important than product choice.

Tweets from world leaders.

Acknowledgements

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

Contact details

Steven Simpfendorfer
NSW DPI, 4 Marsden Park Rd,
Tamworth, NSW 2340
Mb: 0439581672
Email: steven.simpfendorfer@dpi.nsw.gov.au
Twitter: @s_simpfendorfer, @NSWDPI_AGRONOMY

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How crown rot disease severity affects yield loss in wheat

Philip Davies, University of Sydney

Key words

crown rot, wheat, resistance, tolerance

GRDC code

US00075

Take home message

While seasonal conditions are the strongest factors controlling disease expression and yield loss due to crown rot, host resistance has been shown to mediate the effects of this disease. More recently, the role of tolerance to crown rot has been described, providing growers with additional opportunities to limit the impact of crown rot.

Background

Crown rot of wheat is an insidious disease, caused by the fungus *Fusarium pseudograminearum;* a stubble borne pathogen which causes significant damage in no-till farming systems. The disease is of significant concern where wheat is grown under water limited conditions and can be found in all cropping regions in Australia. The impact of this disease is exacerbated by post anthesis drought, leading to premature ripening of infected tillers and the formation of characteristic whiteheads. These whiteheads can either be completely devoid of grains, or contain shrivelled grains, resulting in an increase in screenings and subsequent yield and quality downgrades. A more diagnostic symptom is the light honey-brown to dark-brown discolouration on the base of infected tillers, extending upwards under more severe infection.

Various strategies have been proposed and implemented for managing crown rot; generally aimed at reducing the incidence of initial infection rather than mitigating the effects of subsequent colonisation. This has been achieved through a reduction in inoculum levels by rotation away from susceptible hosts (Simpfendorfer et al., 2003), or by avoiding inoculum in the field by inter-row sowing, stubble management and other cultural practices (Verrell et al., 2017). While individually and in concert, these approaches can provide some benefit to growers, they alone do not provide complete protection; thus an integrated disease management strategy which includes improved varietal performance is required.

Growing resistant cultivars has long been recognised as an effective strategy for minimising the damage caused by crown rot. Resistance is defined as the ability of a plant to restrict initial infection or supress pathogen spread or multiplication (Bos and Parlevliet, 1995). With respect to crown rot, this is generally measured by the reduction in severity of the characteristic stem browning in infected tillers; a trait that is directly linked with the amount of fungus in the plant.

Resistance ratings are a well-accepted tool for varietal selection by growers. However, this rating system does not consider the impact of tolerance on the performance of a variety under crown rot. Tolerance is the ability of a host to limit the damage or impact of a pathogen, irrespective of the severity (Kause and Ødegård, 2012). This trait has been observed both in un-released breeding material and in a select number of varieties and represents an additional opportunity for growers to limit the impact of crown rot. This paper describes the relationship between resistance, tolerance, disease severity and yield loss due to crown rot.

Yield loss experiments

A series of four crown rot yield loss experiments were conducted over two years in 2017 and 2018. These trials were part of an ongoing pre-breeding program improving resistance and tolerance to crown rot. In these experiments, between 50 and 200 breeding lines and varieties were planted in paired plots with and without inoculum to assess the amount of yield lost due to this disease.

Yield loss was calculated by regressing yield under disease against disease free conditions in each trial. The slope for this regression determines the average yield loss in the trial, and deviation from the average yield loss is reported. By calculating yield loss in this manner, the effect of environment can be factored, allowing for effective comparisons between trials.

In addition, the severity of infection for each genotype was measured by assessing the extent of spread of the characteristic stem browning systems up the tiller. These trials were conducted in Toowoomba and Pampas in 2018, and Narrabri in 2017 and 2018 across a range of seasonal conditions.

Relationship between disease severity and yield loss

Surprisingly, to date there has been little work completed assessing the relationship between disease severity and yield under crown rot (Kelly et al., 2016; Forknall et al., 2019), and in the main, it is left largely as an assumption that a reduction in disease levels in the stem will have a uniformly positive impact on genotype yield. Despite this, resistance ratings are a well-accepted tool for varietal selection by growers (Matthews and McCaffery, 2019).

To establish the relationship between disease severity and yield loss, correlations between these traits were calculated for each trial (Table 1). In all these trials, there was a moderate to strong relationship between disease severity and yield loss. This indicates that with increasing disease severity (measured as extent of stem browning), there is an increase in yield lost due to crown rot. While this result is logical and, in many respects, to be expected, its importance cannot be overstated as it validates the use of resistance as a tool for growers to limit the amount of yield lost due to crown rot. Resistant varieties display reduced disease severity, and therefore by selecting varieties with higher resistance ratings, growers will experience less yield loss in seasons favourable to crown rot expression.

Table 1. Correlation between yield loss and disease severity for each of the crown rot yield loss trials. A value of 1 would indicate that with an increase in disease severity, there would be a direct proportionate increase in yield loss. Conversely, a correlation of 0 would indicate there was no relationship between severity and yield loss.

Trial	Correlation between yield loss and disease severity
2017 Narrabri	0.67
2018 Narrabri	0.83
2018 Pampas	0.32
2018 Toowoomba	0.61

In these trials, while there was a moderate relationship between disease severity and yield loss, the rate of yield loss in any genotype was only partially explained by the extent of stem browning symptoms (severity). Indeed, if the degree of disease severity alone was solely responsible for the yield response to crown rot in the trials reported here, then the genetic correlation between these traits would be expected to be approaching one. Instead, this value ranged from 0.32 to 0.83 under different conditions, suggesting that yield loss can be impacted independently of disease severity. This is an important consideration, as it indicates that traits other than resistance can be used to manage crown rot. Broadly speaking, the genetic traits that mitigate yield loss independently of resistance are described as tolerance.

Tolerance to crown rot

While breeding for tolerance is a relatively new area of research, this trait is already being used by industry for managing crown rot. Wheat breeding companies have anecdotal evidence (Lush and Lu, 2018) from multi-site-season yield loss experiments, that the moderately susceptible to susceptible variety Suntop⒫ had reduced yield loss to crown rot than other cultivars with similar resistance ratings. This echoes the findings of Forknall et al. (2019) (DAW00025) and those from this breeding program that Suntop⒫ was more tolerant than many other cultivars. Similarly, Lancer⒫ and Mace⒫ also lost less yield than expected given their observed disease severity. Given that the option to grow tolerant cultivars is now available, many farm advisers believe that tolerance can be used to minimise the impact of crown rot on yield. However, while variety guides publish resistance ratings for a wide range of diseases, including crown rot (Matthews and McCaffery, 2019), information on the tolerance ratings of individual varieties for crown rot is hard to find.

A methodology developed within the GRDC crown rot pre-breeding program (US00075) (Kelly et al. 2016) allows an estimate of the tolerance of a genotype to be calculated relatively efficiently. This methodology first estimates the average relationship between yield loss and disease severity in a yield loss trial. A variety's tolerance is then estimated based on a deviation from this relationship. Varieties that lose less yield than expected given the amount of stem browning symptoms (disease severity) are considered tolerant, while those that lose more yield than expected given the amount of disease severity are intolerant. These values have been calculated for a select number of varieties as part of the pre-breeding program (Figure 1).

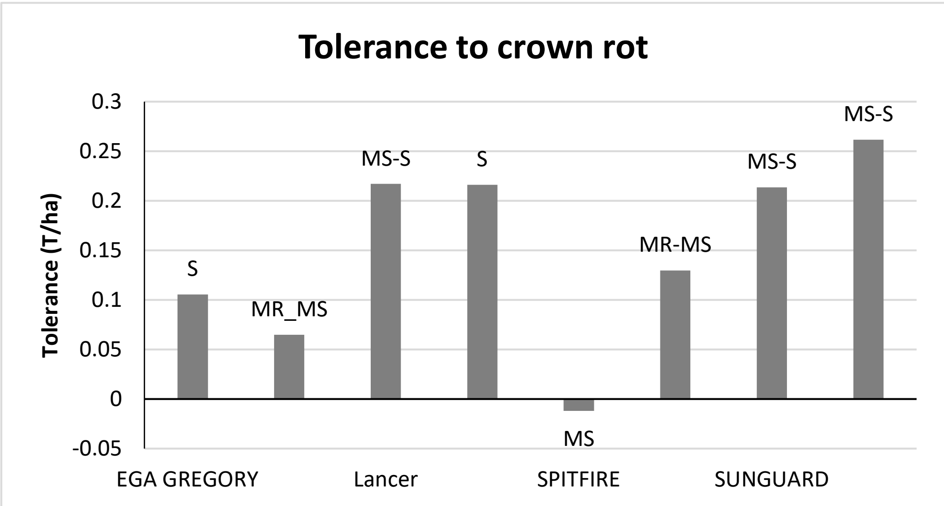

Figure 1. Average tolerance of a select number of varieties across four trials in 2017-2018 (column) and NVT resistance ratings (text above column). Tolerance is measured as the deviation (in t/ha) from the variety's expected yield loss given the amount of disease severity observed. Varieties that have high tolerance values lose less yield than expected given their observed disease severity. Varieties with negative tolerance values lose more yield than expected given the observed disease severity and are intolerant.

While this set of data only represents a small number of varieties relevant to growers and advisors, a larger series of experiments supported by Sydney University is currently underway to estimate the level of tolerance in a wider set of elite northern varieties. Nevertheless, this preliminary data demonstrates that in the trials presented, a yield improvement of as much as 300kg/ha was achieved between two varieties (Suntop⚬ and Spitfire⚬) with similar resistance ratings due to improved tolerance to crown rot (independent of yield potential).

This study also demonstrates the lack of a relationship between resistance and tolerance to crown rot. According to the NVT resistance ratings, the most tolerant varieties in this study were moderately susceptible to susceptible to crown rot, while the most resistant variety (EGA Wylie⚬) displayed only a very low level of tolerance. This highlights the importance of considering both resistance and tolerance ratings separately to provide growers and advisors more information as to the likely response of a variety when grown under crown rot pressure.

The impact of resistance on the rate of inoculum build-up for following seasons however needs to be considered. This relationship is well understood for root lesion nematodes (*Pratylenchus* spp.), where tolerant varieties can provide relief from impact from the disease but still allow multiplication of nematodes, increasing inoculum load for subsequent seasons. Resistant varieties conversely restrict nematode reproduction, reducing impact of this disease in future seasons. It is not clear whether this relationship holds true for crown rot given the ability of the crown rot pathogen to grow saprophytically in senesced plant tissue. However, high inoculum levels are frequently observed following highly susceptible varieties, suggesting that at least in-part resistance plays a role in limiting inoculum build-up.

Of further interest is the relative importance of resistance versus tolerance as genetic tools for managing the impact of crown rot. While the data available is still inconclusive, there appears to be a trend towards a higher correlation between severity and yield loss under conditions less conducive to disease expression, and a lower correlation when post anthesis stresses (drought and heat) enhance crown rot yield loss symptoms. This suggests that in seasons with tougher finishes where crown rot significantly affects yield, varietal tolerance will play a more important role in maintaining yield, compared to resistance. While research in this area is still ongoing, this observation stands to reason, given that tolerances to abiotic stresses are believed to play a major role in reducing the yield loss due to crown rot.

Conclusions

Resistance is an effective tool in reducing disease severity and maintaining yield under crown rot pressure. However, while there are varieties with moderate levels of resistance, most high yielding varieties are still relatively susceptible to crown rot. Tolerance represents an additional genetic tool for mitigating the effects of this disease. Selecting more tolerant varieties and breeding for improved tolerance to crown rot represent both short- and long-term opportunities for managing the impact of this disease.

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Contact details

Philip Davies
The University of Sydney
12656 Newell Hwy, Narrabri, NSW
Mb: 0403 613 974
Email: philip.davies@sydney.edu.au

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Feathertop Rhodes grass ecology and management. What strategies are working best?

Richard Daniel[1], Hanwen Wu[2] and Mark Congreve[3]

[1] Northern Grower Alliance (NGA)
[2] NSW Department of Primary Industries (NSW DPI)
[3] Independent Consultants Australia Network (ICAN)

Key words

feathertop Rhodes grass, *Chloris virgata*, ecology, management

GRDC code

NGA00003 and NGA00004, DAN1912-034RTX, ICN1912-002SAX

Take home message

Feathertop Rhodes grass is well adapted to colonise bare ground (fallows, roadsides)

Commitment to two summers of 100% control of feathertop Rhodes grass should deplete the seed bank in the soil

Control strategies require an integrated approach that includes tillage, crop selection, maximising crop competition, residual herbicides and selective use of double knock applications in fallow.

Feathertop Rhodes grass (*Chloris virgata*) (FTR) continues to be a major problem weed in zero till farming systems in the northern grains region, with populations continuing to expand further south, particularly along road corridors.

Biological factors that influence control strategies

Feathertop Rhodes grass is a prolific seed producer which can produce up to 40 000 seeds per plant under optimal conditions. However, when plants are under moisture stress, they will quickly begin setting viable seed, even when the plant is small/young.

It appears to have a short dormancy period, with poor germination for the first few months after shedding.

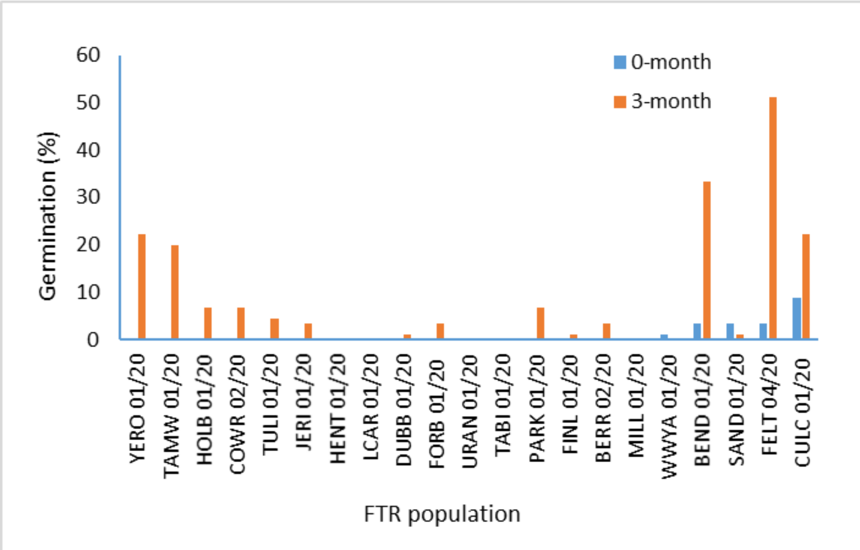

Figure 1. Germination percentage of different FTR collections soon after shedding (Hanwen Wu. NSW DPI)

FTR is often the first weed to establish on bare ground following a rainfall event in spring/summer, although it can germinate at all times of the year (including winter).

Glasshouse studies by Queensland Department of Agriculture and Fisheries (Werth 2017) showed that FTR will emerge following as little as a 10mm simulated rainfall event (Figure 2) however larger rainfall events resulted in increased emergence.

Awnless barnyard grass, common sowthistle and flaxleaf fleabane were also included in this study (data not shown). The rainfall requirement for emergence of FTR was less than for awnless barnyard grass, especially at the lower temperature tested, while rainfall >20mm was required to provide significant emergence of sowthistle and fleabane. This ability for FTR to establish on lower rainfall highlights one of the reasons that FTR is often the first weed to establish following spring rainfall.

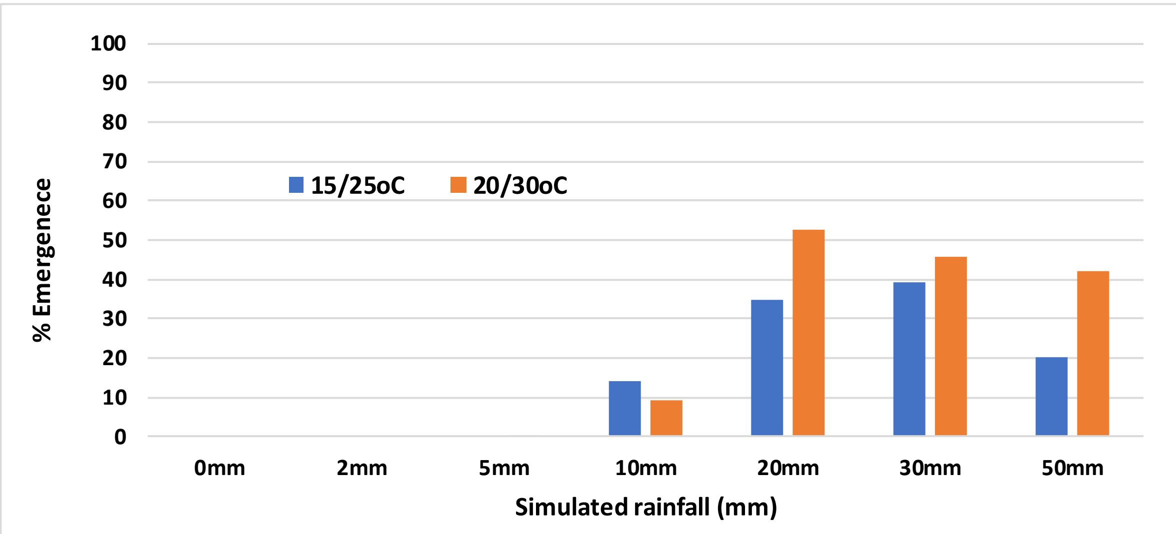

Figure 2. Percentage FTR emergence with respect to temperature and rainfall

In a second trial in the same study, different amounts of rainfall were simulated over consecutive days (Figure 3). Keeping the soil surface moist for a longer period typically increased the percentage emergence compared to a single application of the same total amount of rainfall.

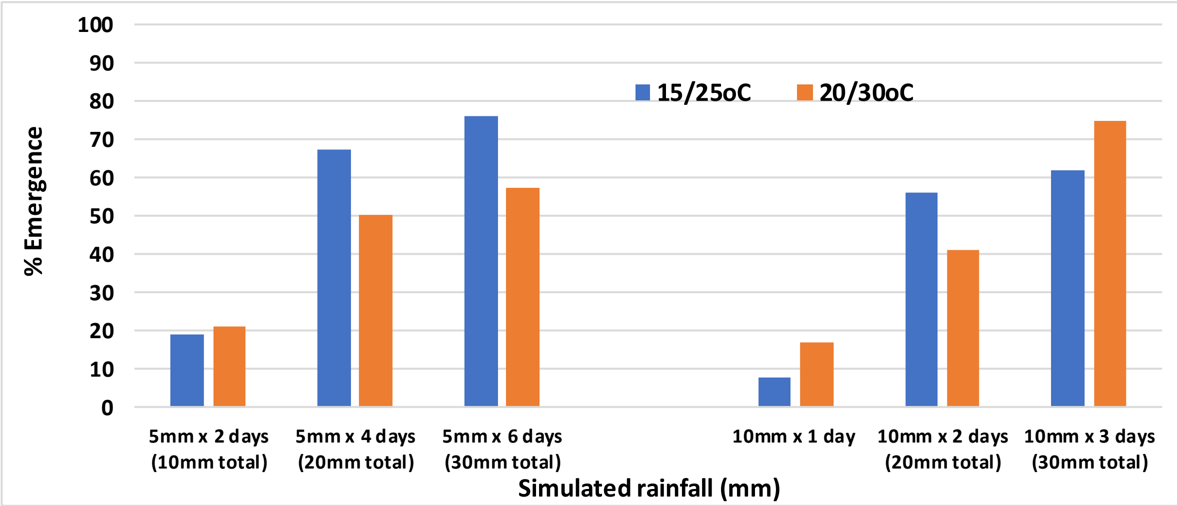

Figure 3. Percentage FTR emergence with multiple rainfall events

Feathertop Rhodes grass is predominantly a surface germinator, with minimal germination occurring from seed below the top 2cm in the soil (Figure 4).

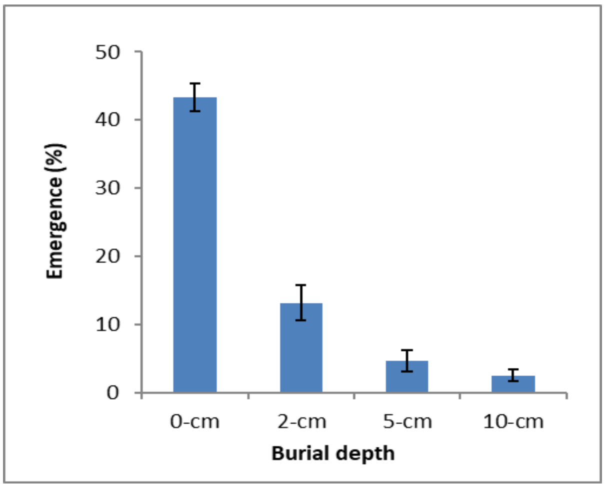

Figure 4. Effect on emergence of FTR seed burial (Hanwen Wu, NSW DPI)
Pot trial -duplex red Kandosol soil, pH 5.4 and organic carbon 0.6%.

The combination of surface germination and germinating on less rainfall than competitor weeds means that FTR is well adapted to zero till fallows and other bare areas (such as roadsides sprayed with glyphosate).

Seed persistence is short. Viability of seed declines rapidly and almost no seed remains viable 12-18 months after shedding (Figure 5). Unlike most other weeds, studies have shown that burying seed does not significantly increase persistence.

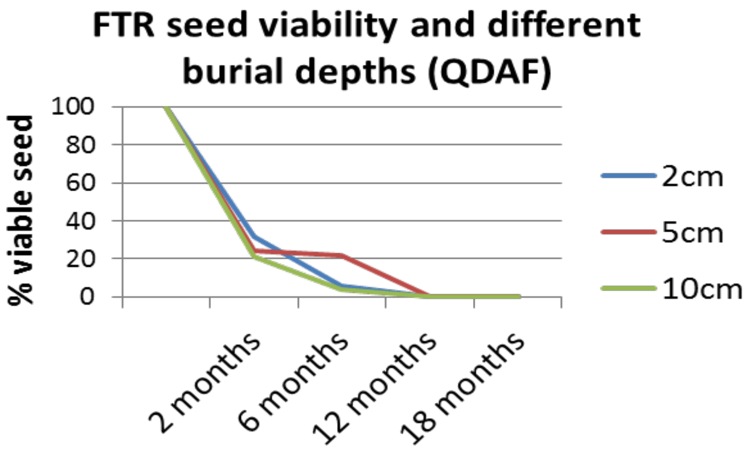

Figure 5. FTR persistence over time
Adapted from QDAF (2014) Integrated weed management of feathertop Rhodes Grass

This lack of seedbank persistence can be utilised as the proverbial boxer's 'glass jaw' in management of FTR – a concerted effort over two consecutive summers to completely stop seed set and any further recruitment into the paddock can see paddocks rapidly go from infested to effectively clear of FTR in a couple of years.

Feathertop Rhodes grass does not compete well with existing crops or pasture. However, it often is the dominant species in any bare areas (eg. roads, fallow) right up against the edge of the crop or pasture paddocks.

These factors see FTR quickly dominate bare earth roadsides or zero till paddocks, especially following wet summers where control programs have not been able to stop seed set and recruitment into the seed bank.

Outside of the cropping paddock, residual control can be achieved by the use of imazapyr based herbicides (e.g. Arsenal®) in non-crop areas. The flumioxazin based herbicides Terrain® and Valor® have recently obtained registrations for residual control along fencelines and irrigation channels respectively.

The first punch – prevention is better than cure

Control of established populations of large FTR is difficult, extremely costly and most likely to be incompatible with zero till farming. Therefore, growers should aim to keep FTR out of farming paddocks wherever possible, and urgently seek to remove individual plants before they have a chance to set seed.

Where glyphosate has been used on roadways and fence lines and FTR has then become established, seed can be blown into adjacent paddocks. Alternatively, seeds may be deposited in the paddock via livestock and kangaroos; from machinery or in flood water.

Typically, a single plant in year 1 will result in a small clump covering maybe 2-3m^2 in year two. Over coming years these patches will continue to expand, potentially seeing the whole paddock infested if nothing is done to stop seed set.

Growers should be continually on the lookout for individual plants and act quickly to manually remove or spot spray these before they are allowed to set seed. Small patches should be chipped, burnt or cultivated to prevent spread. Ideally these should be GPS mapped for future monitoring with a residual herbicide applied prior to the commencement of spring rainfall events.

The second punch – knockdown herbicides

Glyphosate alone is not registered for control of FTR and cannot be expected to achieve control (Widderick 2014, Douglas 2019). Even when using a double knock of glyphosate followed by paraquat under ideal conditions and targeting seedlings before they start tillering, control is variable and rarely provides a commercially acceptable result.

Targeting larger weeds that have commenced tillering, or are under any stress, will typically achieve less than 50% control as a double knock, and often not significantly better than using paraquat alone as a single application.

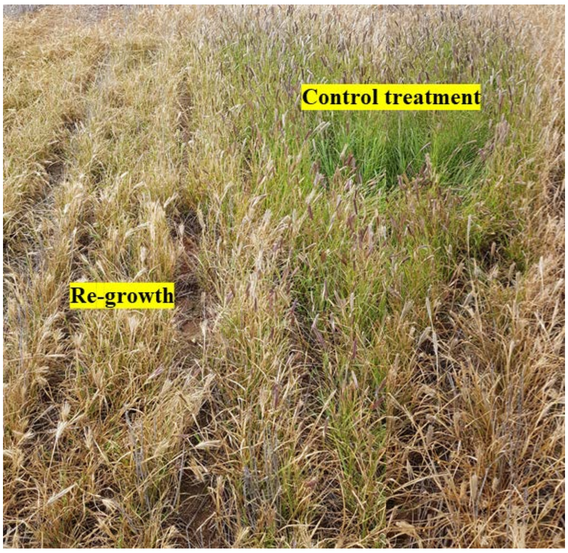

Figure 6. Re-growth (left) with single knock of glyphosate (540g ai/L) at 1.44L/ha (not registered for FTR) (Photo: Hanwen Wu)

Research trials and commercial experience have shown that Group A herbicides can be effective in providing useful control.

Shogun® (propaquizafop) is registered for the control of feathertop Rhodes grass in fallow and in cotton, peanuts and sunflower. In fallow, Shogun must be applied to weeds at the 3-leaf to early tillering growth stage and followed with an application of paraquat within 7-14 days (double knock).

Firepower 900 (haloxyfop) has recently been registered for control of FTR in fallow. (Note: this is the only haloxyfop formulation approved for use on FTR in NSW). Weed size is restricted to 2 leaf to early tillering (Z12 to Z22) and for FTR, this should always be followed by a paraquat double knock.

The APVMA has also recently approved an emergency permit that supports the use of clethodim formulations for control of FTR in fallow (PER89322 – Expires 31 August 2021, for NSW and Queensland only). This must also be followed by a paraquat double knock application within 7-14 days. While there is no weed size recommended on the permit, it should be noted that trial work has consistently shown that clethodim is generally slightly less effective than 'fops' on FTR, so limiting application to seedlings or very early tillering is strongly advised.

The importance of weed growth stage is critical for the performance of Group A herbicides (Figure 7 & 8). As weed size increases, translocation of the herbicide reduces throughout the plant. Once plants move from vegetative production to reproductive growth, production of the enzyme targeted by the Group A herbicide reduces in the plant. Further information explaining this can be found in the GRDC Fact Sheet 'Group A Herbicides in Fallow'. http://www.grdc.com.au/GRDC-FS-GroupAinFallow

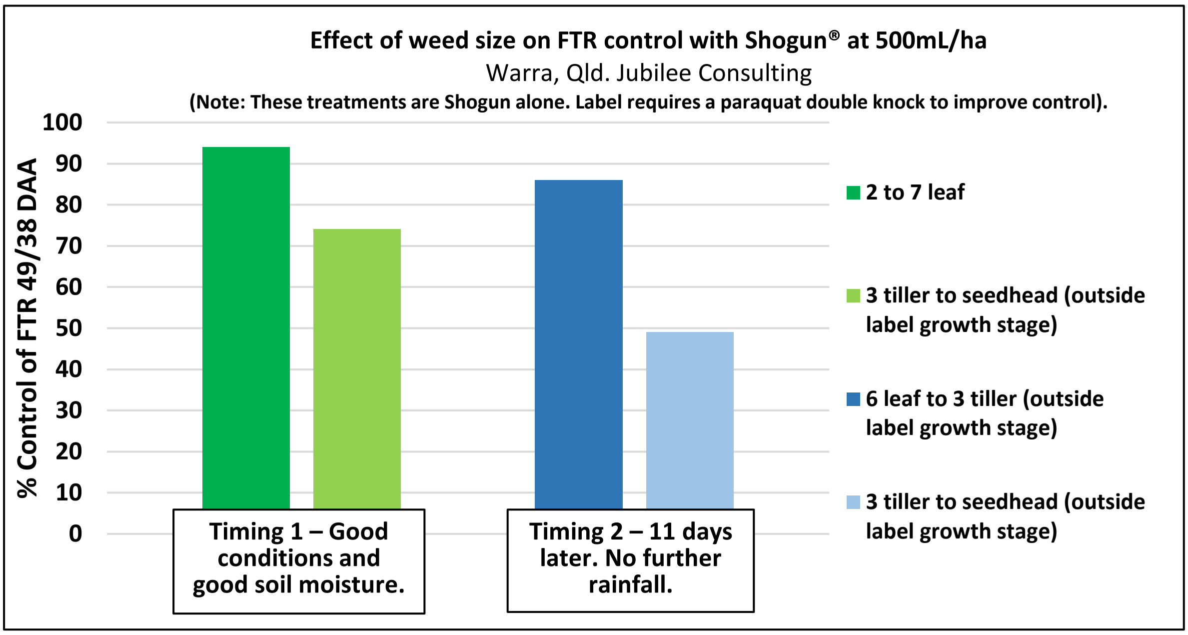

Figure 7. Effect of weed size and timing of Shogun on FTR (Adama, unpublished)

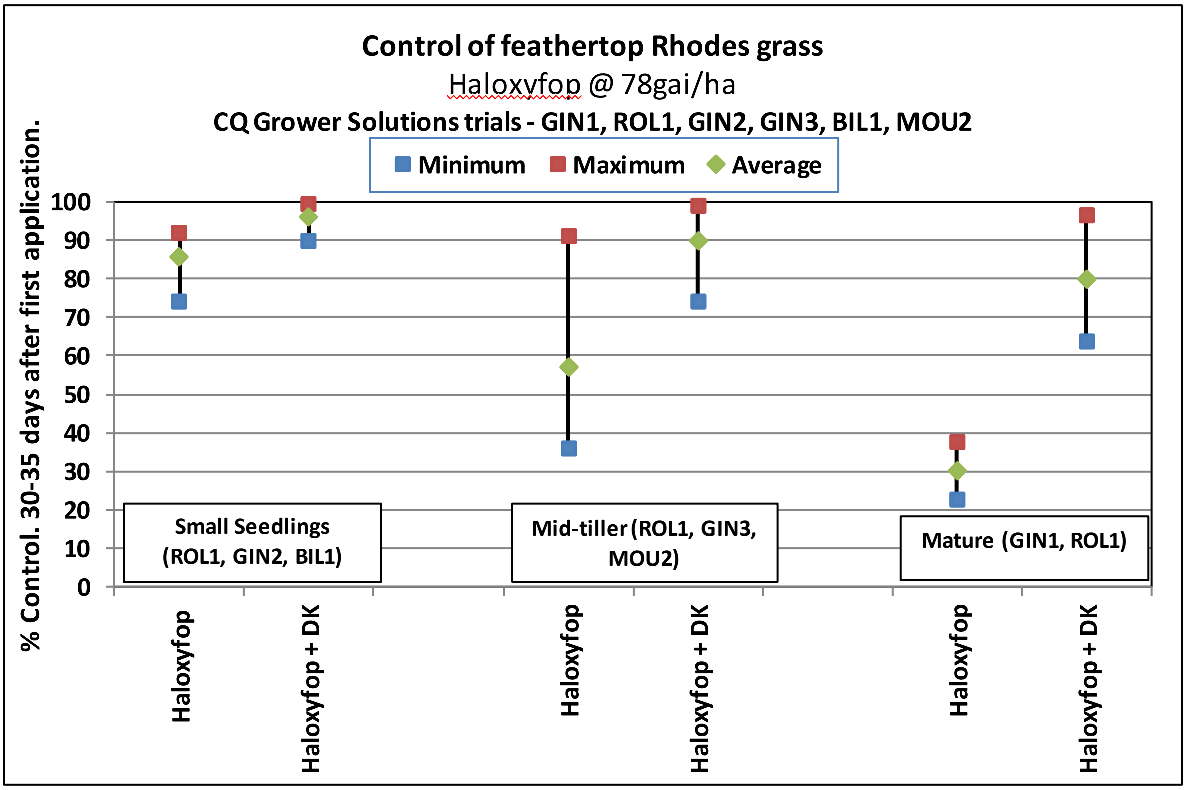

Figure 8. Effect of weed size +/- double knock of haloxyfop on FTR
(Central Queensland Grower Solutions Project 2011-15)

When applying Group A herbicides, ensure the correct adjuvant is used and application set up is optimised for coverage. Typically, this will be a medium-coarse spray quality, with water rates of 80 to 100 L/ha.

Avoid tank-mixing other herbicides which may reduce the performance of Group A herbicides (Figure 9).

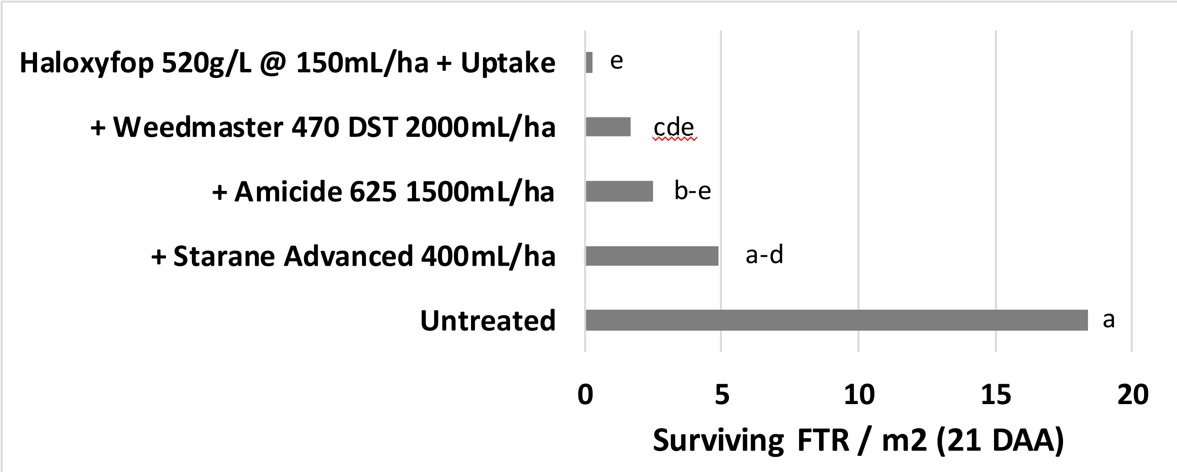

Figure 9. Haloxyfop tank mixes against FTR (NGA, Crooble 2014. RN1433)

Experience in other grass weed species has shown that Group A herbicides are one of the quickest modes of action to select for resistance as there is typically a high frequency of resistant individuals in the natural population.

For this reason, all Group A applications in fallow must be followed by a double knock; they should only be targeted at small weeds; and should not be used more than once per season.

It is essential that this mode of action is protected from resistance selection. Group A herbicides are the mainstay of post-emergent grass weed control in summer broadleaf crops.

The third punch – tactical cultivation

Where FTR has got out of hand and established plants are present, it is likely that tillage will be needed to remove existing weeds.

It is unlikely that any herbicide treatment will provide consistent cost-effective control of mature plants. Where old, established plants remain from last summer they can frequently shade herbicide application, thus leading to unsatisfactory results from subsequent knockdown or residual herbicide applications.

Removing mature plants via cultivation can be very effective. Burial of seed below 5cm can also reduce emergence and this seed will lose viability within about 12 months (providing it is not subsequently returned to the soil surface by further tillage).

While an effective cultivation may bury the vast majority of seed, there is always a small percent of seed remaining at the soil surface in the preferred germination zone. If something is not done to prevent these seeds from germinating and establishing, then the cycle recommences.

A plan should be in place to manage these subsequent germinations via either tillage, knockdown or residual herbicides.

The knockout blow – residual herbicides

The most successful strategies employed by growers for managing FTR have included the use of residual herbicides. Either directly targeted at known FTR problem paddocks, or more broadly, by keeping FTR at bay when targeting other grass weed problems on the farm. The viability of most other grass weed seeds in the soil is much longer than for FTR, so where growers are incorporating residual herbicides into their program to manage grass weeds such as awnless barnyard grass, FTR is often also controlled or suppressed.

Balance® can be a particularly effective option for fallow management. In addition to residual control of FTR, it will also control flaxleaf fleabane and common sowthistle with suppression of awnless barnyard grass, however significant plantback periods apply for many summer crop options.

Dual® Gold is registered for residual control of FTR prior to planting a wide range of summer crops and also in fallow situations, with minimal plantback constraints. A new use pattern also allows for a top-up application in sorghum after crop emergence.

Valor, applied at rates for residual control, is also an option prior to planting selected summer crops. Plantback periods apply for some summer crops when using Valor, so always check the label. In addition to control of FTR, Valor can also provide residual control of a range of difficult to control broadleaf weeds such as fleabane, sowthistle, red pigweed, caltrop, bladder ketmia and the *Ipomea* species such as bell vine and morning glory.

Most residual 'grass' herbicides are active on FTR however the length of residual control is a function of environment at the site; the soil type and stubble; and the individual properties of the herbicides. Chose the 'grass' residual herbicide that fits the farming system within that paddock.

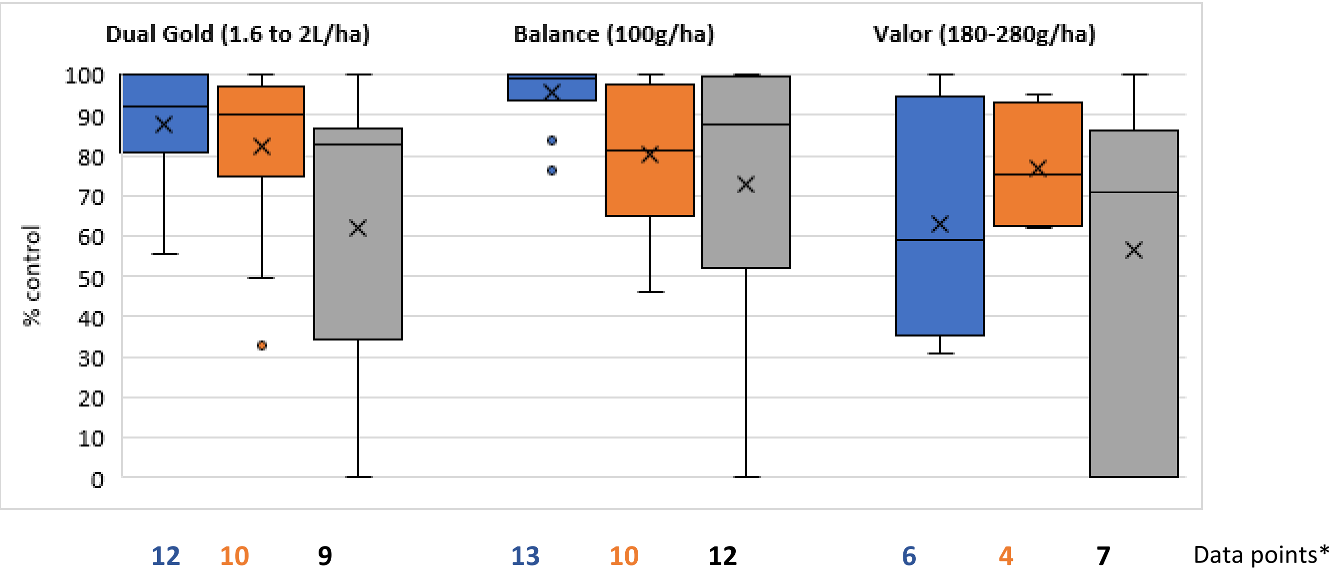

Figure 10. Summary of 22 residual herbicide trials (2007-2016) (NGA, QDAF, GOA, NSW DPI)
Blue 14-48 DAA Orange 58-77 DAA Grey 81-147 DAA
*Not all treatments in all trials. Some trials had more than one rate. Some trials had two ratings within the same time grouping.

Screening of residual herbicides registered for use in winter cereal or pulses is showing a promising range of options that can suppress FTR emergence for periods of three to four months. These may be options to consider in areas where spring temperatures are warmer and FTR is establishing in-crop during spring.

Going the full ten rounds – pulling it all together

Where there has been a 'blow out' and a paddock has become infested with FTR, it is likely that a management strategy will look something like the following:

- Cultivation of established plants (before seed has been shed)
- Residual herbicide applied if there is still the possibility of further germination before winter
- Aggressive crop competition (and pre-emergent herbicides) in the winter crop

- Decide on your strategy for summer before the first spring rainfall event, and potential weed germination
    - If fallowing over summer, apply a residual herbicide before spring rainfall. Monitor frequently for any escapes or breakdown of the residual herbicide. Access to an optical (camera) sprayer can be beneficial in cost effectively treating isolated escapes. Once the residual treatment has broken down, a double knock application will be required, with consideration given to including another residual application with the second knock
    - Where soil moisture is adequate, consider a summer broadleaf crop (or cotton where suitable). Use a pre-emergent herbicide effective on grass weeds; keep row spacing narrow and plant population high to increase the benefit of crop competition; and utilise a selective Group A 'fop' herbicide in-crop to control any escapes. Inter-row tillage is also a valid strategy in wide row summer crops.
- Do not plant sorghum or maize into paddocks with a high FTR seed bank population. Pre-emergent herbicide options such as Dual Gold are unlikely to provide full season residual control, even at the highest application rate – especially in wet seasons. Late season germinations can establish after the pre-emergent herbicide has broken down
- If FTR is not allowed to set seed, then seed bank viability should be low the following year. Continue vigilant management for another season to ensure depletion of the seed bank.

Unfortunately, the best management strategies for this difficult to manage weed place great reliance on herbicides; and therefore, selection of resistant individuals. Glyphosate is ineffective and Group A herbicides are known to be of significant risk of rapid selection for resistance. While there is currently negligible resistance in the northern grains region to many of the pre-emergent herbicides with efficacy on this weed, one thing we have learnt from history is that if we over-rely on a particular herbicide or herbicide group and don't stop weed seed set of survivors, then we will break it.

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Contact details

Richard Daniel
NGA
PO Box 78, Harlaxton Qld 4350
Ph: 0428 657 782
Email: richard.daniel@nga.org.au

Hanwen Wu
Wagga Wagga Agricultural Institute
NSW Department of Primary Industries
Pine Gully Road, Wagga Wagga, NSW 2650
Ph: 02 6938 1602
Email: hanwen.wu@dpi.nsw.gov.au

Mark Congreve
ICAN
PO Box 718, Hornsby. NSW 1630
Ph: 0427 209 234
Email: mark@icanrural.com.au

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KEY CONTACTS

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

NORTHERN REGION

TOOWOOMBA
214 Herries Street
TOOWOOMBA, QLD 4350

P:+61 7 4571 4800
northern@grdc.com.au

OPERATIONS GROUP

SENIOR REGIONAL MANAGER
Gillian Meppem
Gillian.Meppem@grdc.com.au
M: +61 4 0927 9328

CONTRACT ADMINISTRATOR AND PANEL SUPPORT
Tegan Slade
Tegan.Slade@grdc.com.au
M: +61 4 2728 9783

CONTRACT AND TEAM ADMINISTRATOR
Brianna Robins
Brianna.Robins@grdc.com.au
P: +61 7 4571 4800

APPLIED RESEARCH AND DEVELOPMENT GROUP

SENIOR MANAGER CROP PROTECTION (NATIONAL)
Emma Colson
Emma.Colson@grdc.com.au
M: +61 4 5595 8283

SENIOR MANAGER AGRONOMY, SOILS, NUTRITION AND FARMING SYSTEMS (NATIONAL)
Michael Bange
Michael.Bange@grdc.com.au
M: +61 4 4876 6881

MANAGER AGRONOMY, SOILS, NUTRITION AND FARMING SYSTEMS
Kaara Klepper
Kaara.Klepper@grdc.com.au
M: +61 4 7774 2926

MANAGER AGRONOMY, SOILS, NUTRITION AND FARMING SYSTEMS
John Rochecouste
John.Rochecouste@grdc.com.au
M: +61 4 7774 2924

MANAGER CHEMICAL REGULATION (NATIONAL)
Gordon Cumming
Gordon.Cumming@grdc.com.au
M: +61 4 2863 7642

CROP PROTECTION MANAGER
Vicki Green
Vicki.Green@grdc.com.au
M: +61 4 2904 6007

CONTRACT ADMINISTRATOR
Linda McDougall
Linda.McDougall@grdc.com.au
M: +61 4 7283 2502

GENETICS AND ENABLING TECHNOLOGIES GROUP

NATIONAL VARIETY TRIALS OFFICER
Laurie Fitzgerald
Laurie.Fitzgerald@grdc.com.au
M: +61 4 5595 7712

GROWER EXTENSION AND COMMUNICATIONS GROUP

SENIOR MANAGER EXTENSION AND COMMUNICATION (NATIONAL)
Luke Gaynor
Luke.Gaynor@grdc.com.au
M: +61 4 3666 5367

GROWER RELATIONS MANAGER
Richard Holzknecht
Richard.Holzknecht@grdc.com.au
M: +61 4 0877 3865

GROWER RELATIONS MANAGER
Susan McDonnell
Susan.McDonnell@grdc.com.au
M: +61 4 3662 2649

COMMUNICATIONS MANAGER
Toni Somes
Toni.Somes@grdc.com.au
M: +61 4 3662 2645

BUSINESS AND COMMERCIAL GROUP

MANAGER COMMERCIALISATION
Chris Murphy
Chris.Murphy@grdc.com.au
M: +61 4 2277 2070