DALBY
QUEENSLAND
FRIDAY 2ND
AUGUST 2019

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

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GRDC Welcome

Welcome to the 2019 GRDC Grains Research Updates

Growers, advisers and industry stakeholders are constantly faced with challenges to farm profitability and productivity, which makes staying informed about the latest research and development outcomes a critical part of being in business.

Keeping growers and advisers informed is the key role of the annual Grains Research and Development Corporation (GRDC) Grains Research Updates, which are premiere events on the northern grains industry calendar and bring together some of Australia's leading grain research scientists and expert consultants.

For more than 25 years the GRDC has been driving grains research capability and capacity with the understanding that the continued viability of the industry hinges on rigorous, innovative research that delivers genuine profit gains. GRDC's purpose is to invest in research, development, and extension (RD&E) to create enduring profitability for Australian grain growers.

Despite the tough seasonal conditions currently being experienced across much of the Queensland and New South Wales grainbelts, the industry remains confident about the future and committed to learning more about innovation and technology and embracing practice change that has the potential to make a tangible difference to on-farm profits.

In response, this year's GRDC Grains Research Updates offer regionally relevant, credible and new science-based information covering priority issues like climate and environmental variability, new technology and market conditions to ensure growers and their advisers have up-to-date knowledge to make informed decisions on-farm.

So, I hope you enjoy the 2019 Updates and that the events provide an invaluable opportunity for learning, knowledge sharing and networking.

Luke Gaynor,

GRDC Senior Manager Extension and Communication

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GRDC Grains Research Update
DALBY

Friday 2 August 2019, Knowles Room - Dalby Event Centre

Registration: 8:30am for a 9am start, finish 3:10pm

AGENDA Time	Topic	Speaker(s)
9:00 AM	**GRDC welcome**	
9:10 AM	**Learning from southern region experience with pre-emergent herbicides incorporated by sowing:** how, why, which weeds, seeding systems and soil types.	Maurie Street (GOA) and Mark Congreve (ICAN)
9:40 AM	***Conyza sumatrensis***: a 2-metre-high fleabane species on the Darling Downs that is tolerant of paraquat.	Bhagirath Chauhan (QAAFI)
9:55 AM	**Value of tactical decisions on crop sequencing:** opt in/opt out on PAW triggers.	Jeremy Whish (CSIRO)
10:20 AM	**Measuring and predicting plant available water to drive decision-making and crop resourcing:** extrapolating data from limited site numbers across paddocks.	Brett Cocks and Mark Thomas (CSIRO)
10:50 AM	**Morning tea**	
11:20 AM	**Cover crops to increase fallow efficiency:** research observations on soil water, health, nutrition and crop performance.	David Lawrence (DAF Qld)
11:50 AM	**Multi species cover cropping and optimising soil health.**	Alex Nixon (Nuffield Scholar, Drillham, Qld)
12:15 PM	**Sowing grain sorghum early:** to reduce risk of water and heat stress at flowering and benefits for following crops – double cropping to chickpeas and ratooning cropping of sorghum.	Joe Eyre (UQ-QAAFI)
12:35 PM	**Grower experiences with early sowing sorghum:** pros and pitfalls.	Dan Wegener ("Ferndale")
12:50 PM	**Early sowing sorghum discussion**	
1:05 PM	**Lunch**	
2:05 PM	**Upgrading nutritional strategies to feed the farming system:** P & K timing, placement and implications for N timing and placement.	Mike Bell (UQ)
2:30 PM	**5 years of nitrogen research:** do we have the system right? o N movement, use efficiency, application timing & impact on N uptake - should we fertilise the system or the crop? o N in pulse crops? o N impacts on screenings	Richard Daniel (Northern Grower Alliance)
2:55 PM	**Nutrition discussion:** key decisions in the next crop cycle.	
3:10 PM	**Close**	

Contents

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Achieving crop selectively when using pre-emergent grass herbicides in winter cereal crops

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Key words

Pre-emergent herbicides, winter cereals, crop safety

GRDC code

ICN 1811-001SAX, GOA00002

Take home messages

- The use of pre-emergent herbicides at planting of winter cereals is on the rise, mainly as a result of resistance to post-emergent herbicides
- Some pre-emergent grass herbicides can damage winter cereals. Care must be taken to achieve acceptable crop selectivity
- Understanding the properties of the herbicide, where the herbicide is located relative to the crop seed, the soil type and the rainfall will guide how the herbicide should be applied and incorporated
- To achieve crop safety with some herbicides, attention to the planter type and set-up is essential to position the crop seed away from the herbicide.

Growers increasingly find it more difficult to achieve acceptable post-emergent control of grass weeds in winter crops due to herbicide resistance. This is resulting in increased use of pre-emergent herbicides applied at sowing.

Most pre-emergent grass herbicides can damage winter cereals, if they are taken up by the crop in sufficient concentration. Crop safety is a combination of herbicide properties, the rate applied, soil type, rainfall after application and crop type along with planter set up to create spatial separation of the herbicide and seed. Understanding these interactions assists in minimising the potential for crop injury.

Herbicide properties influence how they can be used

There are a wide range of pre-emergent herbicides available in Australia that control grass weeds

Table 1. Pre-emergent grass herbicides commonly used in key crops in Australia

Mode of action	Herbicide	Example	Wheat	Barley	Canola	Chickpea	Faba bean
D	Trifluralin	TriflurX®	✔	✔	✔	✔	✔
D	Pendimethalin	Stomp®	✔	✔	✔	✔	✔
D	Propyzamide	Rustler®			✔	✔	✔
G	Flumioxazin	Terrain®	✔			✔	✔
J	Tri-allate	Avadex®	✔	✔	✔	✔	✔
J	Prosulfocarb	Arcade®	✔	✔			
J+K	Prosulfocarb + s-metolachlor	Boxer® Gold	✔	✔		✔	✔
K	S-metolachlor	Dual® Gold	✔	✔	✔		
K	Metazachlor	Butisan®			✔		
K	Pyroxasulfone	Sakura®	✔			✔	
Several additional pre-emergent herbicides are scheduled for commercial release in 2020/2021							

These herbicides are active on a wide range of grass weeds. Herbicide selection is often based more on crop tolerance, resistance status, rotational crop and compatibility with the farming system (disc *vs* tyne planters; tilled *vs* non-tilled; amount of stubble retained).

One key to reducing the likelihood of crop damage when using pre-emergent herbicides is to keep the herbicide away from the germinating seedling. This can be achieved in modern farming techniques through the timing of the herbicide application and the use of the sowing process to move the herbicide away from the seed. This is discussed further below.

However, under certain circumstances, herbicides can move from their intended position in the soil. This movement may occur via movement in soil solution (water) or physical movement, whereby soil with herbicide bound to it can move back closer to the seed.

Mobility in the soil solution is largely dictated by the properties of the herbicide i.e. an interaction between the solubility of the herbicide and its ability to bind to organic matter and soil, along with the soil type and amount, timing and intensity of rainfall. Herbicides with lower mobility in soil solution are generally safer to use, provided physical separation can be achieved in the first instance. More mobile herbicides can move despite the best attempts at physical separation and as such may be too dangerous to use in cereal crops and limited to use in broadleaf crops only.

Table 2. Soil mobility of key pre-emergent cereal herbicides

N.B. Check labels for use patterns in individual cereal crops

Tight binding. Very low mobility	**Relatively tight binding**	**Low mobility**	**Some mobility**	**Mobile**
pendimethalin trifluralin	prosulfocarb tri-allate	flumioxazin	pyroxasulfone	s-metolachlor
Well suited to IBS (incorporate by sowing) with tynes				Higher potential for crop damage

Sandy soils, or soils with very low organic matter and other soils with low cation exchange capacity (i.e. CEC <5) have fewer binding sites and therefore less ability to bind all herbicides than heavier soils. This results in more herbicide available in the soil water, and therefore more available to be taken up by the crop. All other things being equal, more damage will result in these lighter soils where more of the applied herbicide is likely to be available to the crop and the weeds.

Binding to soil and organic matter takes some time to occur, even with herbicides of lower mobility. Where herbicide has been applied to the soil surface and a large rainfall event occurs before the herbicide has been incorporated and had time to bind, substantial damage may still occur. This will be particularly problematic where the soil profile is dry and the wetting front rapidly moves through the profile, taking the herbicide with it before it has a chance to bind.

Conversely, a mobile herbicide applied to the soil surface may often result in no crop injury should there be no, or only small rainfall events, between planting and emergence and the herbicide is not washed into the seed zone.

However, the physical movement of herbicide is much less predictable and manageable. In the northern grain region, the unpredictability in rainfall intensity during the critical period from planting to emergence, ranging from no rainfall through to a heavy storm event, can make the use of pre-emergents more challenging. A large rainfall event that also results in temporary waterlogging, and reduces the crops ability to metabolise the herbicide, can be particularly damaging.

These conditions can also impact on early crop nutrition which can further exacerbate crop damage. For example, where a sulfonyl urea herbicide has been applied and temporary waterlogging occurs, this can limit to ability of the crop to take up adequate zinc from the soil and therefore display zinc deficiency.

Where are the weed seeds?

To achieve good outcomes from the use of pre-emergent herbicides it is also important to understand where the weed seeds are located in the soil, as this will influence the ability to control them when they germinate.

In recently tilled paddocks it is likely that weed seeds will be mixed to the depth of cultivation. Self-mulching soils can also have a similar effect, incorporating a proportion of the seed bank below the soil surface. Seeds of wild oats can also work their way deeper in the soil profile, even in the absence of cultivation.

Weeds emerging from depth are likely to be poorly controlled by non-mobile pre-emergent herbicides positioned near the soil surface.

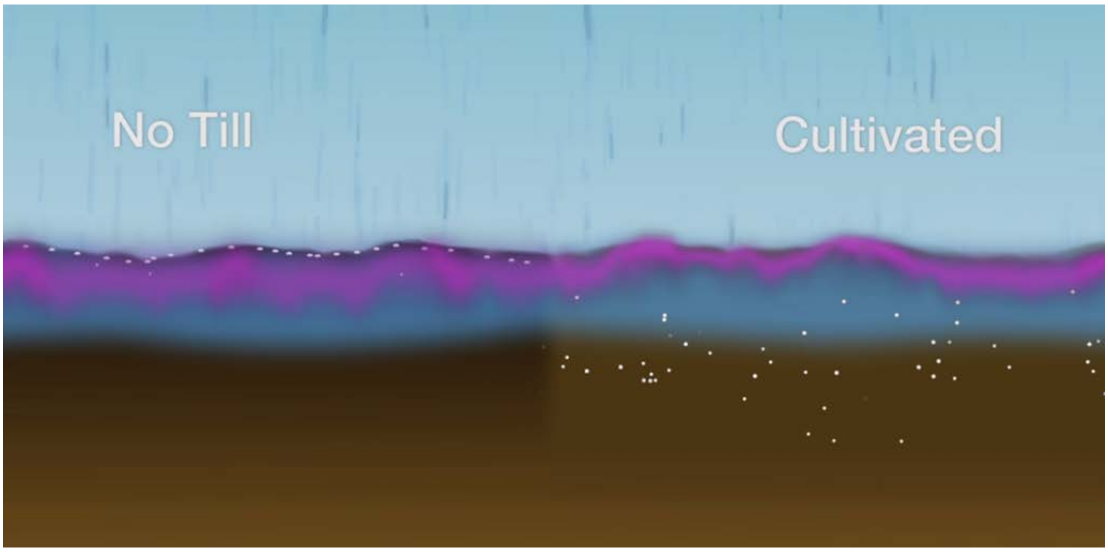

Figure 1. Difference in location of weed seeds (represented by white dots) in no till (left) or cultivated (right) situations

To reach weeds seeds germinating at depth either:

- A mobile herbicide will be required, or
- If a non-mobile herbicide is used, it will require mechanical incorporation immediately after application to the depth of weed seeds.

Either of these strategies increase the risk for crop injury if the herbicide is not kept away from the germinating crop.

After a few years of zero / minimum tillage, most grass weed seeds at depth have died or germinated, with the remaining grass weed seeds located near the soil surface. In these situations, less mobile herbicides can be effective when applied near the surface with shallow incorporation. Concentrating herbicide and weed seed in a narrow band near the surface may also result in improved weed control.

How can we use pre-emergent herbicides to get the best control with limited crop damage?

Positional selectivity

Cereals have a degree of sensitivity to all the registered pre-emergent herbicide options available. It is therefore desirable to place the seed away from these herbicides to minimise any impact. Placing the seed away from the herbicide introduces what is termed "positional selectivity".

In placing the seed away from the herbicide, both the horizontal and vertical separation is important.

Vertical separation – think of this as placing the seed under the herbicide band. Depending upon the individual pre-emergent herbicide, it will enter the seedling either though the roots taking up herbicide dissolved in the soil water, or by transfer of herbicide through the emerging shoot, in particular through the coleoptile node.

Positioning a low mobile herbicide near the soil surface should keep it above the roots of the crops (unless there is excessive rainfall on soils with low ability to bind the herbicide). This can allow for acceptable safety for non-mobile herbicide reliant on root uptake.

For herbicides that enter via the coleoptile node (e.g. trifluralin, pendimethalin, tri-allate, s-metolachlor in particular) it is important to keep the coleoptile node away from the herbicide. This is easier to achieve in wheat and barley as the coleoptile node stays close to the seed (right of Figure

2). In most grass weeds (and crops such as oats, sorghum, maize) the mesocotyl elongates during emergence (left of Figure 2) and pushes the coleoptile node towards the surface. Weed control with these herbicides primarily results from herbicide absorption through the coleoptile node as it moves into the herbicide zone near the seed surface.

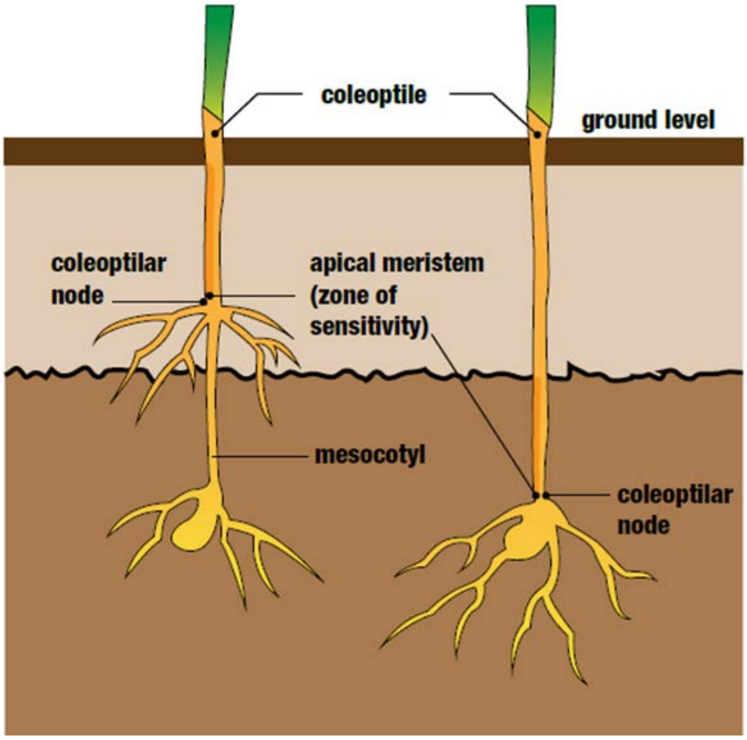

Figure 2. In wheat and barley the coleoptile node stays close to the seed (right) compared to most grass weeds (and crops such as oats, sorghum, maize) where the mesocotyl elongates during emergence (left) and pushes the coleoptile node towards the surface (Hall, Beckie & Wolfe (1999) How Herbicides Work).

Additional horizontal separation can be achieved by using the planting operation to throw herbicide treated soil out of the furrow and into the inter-row, commonly referred to as 'incorporation by sowing using knife points and press wheels', or IBS for short.

The principle of IBS works well for herbicides with low mobility (e.g. trifluralin, tri-allate, prosulfocarb). Soil-throw from the planting furrow removes a significant quantity of herbicide treated soil into the inter-row, and the low solubility means that the herbicide is less likely to move horizontally in the soil water following rainfall.

Additionally, weed seeds present on the soil surface in a zero till situation are also thrown into the inter-row, where the majority of herbicide is present. For herbicides that are volatile (e.g. trifluralin, tri-allate in particular), incorporation by the sowing operation is also required soon after application to avoid significant volatility losses.

Figure 3. The principle of incorporated by sowing (IBS). Soil-throw from the planting furrow removes a significant quantity of herbicide treated soil into the inter-row, and the low solubility of the herbicide means that the herbicide is less likely to move horizontally in the soil water following rainfall.

However, where there have been high seed banks over several years it is likely that seed is abundantly mixed in the surface soils from previous years seeding. In this case, herbicide displaced from the seeding row may allow remaining seeds within the row to establish in the drill line.

The vertical and horizontal separation in minimum tillage tyne systems is generally simple to achieve, as illustrated in the Figure3. However, there are four scenarios to be mindful of:

1. When sowing in wet, heavy soils, the slot may not be adequately closed or back filled by untreated soil. Where the planting slot is left open, even small rainfall events may concentrate herbicide directly in and around the seed.
2. Soil displaced from one row may be thrown into the adjacent row. This places herbicide treated soil over the seed in the adjacent row, while also has the effect of increasing seed depth that may exceed coleoptile length of the planted crop. Selection of point or opener design to match soil throw to row spacing will be required, along with calibration of ground speed to match prevailing soil conditions
3. Heavy rainfall after planting, physically moving treated soil back into the planting furrow
4. Soil prone to furrow walls collapsing.

As such growers need to be mindful of their planter set up when considering using pre-emergent herbicides. Narrow row spacing make it more difficult to contain soil throw to the inter-row, however this will be highly influenced by planting speed. Conversely, very wide row spacings (>30cm) may result in more volatile herbicides not being adequately covered by soil and potential for reduced herbicide performance due to volatility losses. Heavy soils can be “cheesy” when wet and less consistent in their flow, compared to lighter or red soils.

The point design used can also influence the amount of soil throw as well. Inverted T boot points can increase soil throw, but also increase tilth created. Therefore, they can get better back fill over the seed but increased risk of overthrow to the adjacent furrow. Strait knife points may not achieve as much herbicide displacement and may also leave the slot open, due to the lack of tilth created.

Double or split boot systems designed to create separation between fertiliser and seed often requires increased planting depth, as is the also the case when moisture seeking (planting deeper into sub-soil moisture). Increased seeding depth will result in increased movement of soil to the interrow and increased potential to throw treated soil into adjacent rows.

With so many variables involved in soil throw it is hard to make specific recommendations. A useful approach is to use urea as a visual surrogate for herbicides in paddocks where pre-emergent herbicides are being considered. To do this simply hand spread a relatively heavy rate of urea on a small area (1M x 1M) of the paddock. Use a liberal rate to ensure it is easy to see the granules. Run the planter through this area at your decided depth and speed. Following the machine pass, check to see where the urea has been moved to assess soil throw, and the seed placement in relation to the urea granules. Where problems are observed adjust the planter or travel speed and repeat the operation on a new part of the soil.

A GRDC video demonstrating how this can be done can be accessed at https://www.youtube.com/watch?v=LJNjuMWS57U&t=13s

Another method to assess soil throw "on the go" in variable conditions is to observe the soil throw on the outside tine of the seeder. If a significant amount of soil is thrown further than the distance to the next row this can suggest there may be potential for damage.

Soil throw from disc seeders vary greatly, although commonly results in minimal soil-throw. This often means herbicide is not sufficiently moved away from the emerging cereal which results in greater crop injury. The potential for crop damage is further increased when there is shallow seeding depth and an incompletely closed seed furrow. The lack of soil-throw also does not protect volatile herbicides from volatility losses. Some disc seeder designs and/or modification can result in more soil throw and better displacement of the herbicide from on top of the seed row; however they can be variable in their performance.

Further information

GRDC: Pre-emergent herbicides - Pt 1 Solubility & binding
https://www.youtube.com/watch?v=s63GYYyflzw&t=13s

GRDC: Pre-emergent herbicides - Pt 2 Incorporation by sowing
https://www.youtube.com/watch?v=LJNjuMWS57U&t=13s

Herbicides in Australian farming systems: A reference manual for agronomic advisers
https://grdc.com.au/SoilBehaviourPreEmergentHerbicides

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Tall fleabane: An emerging threat in grain and cotton cropping systems

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Key words

Conyza sumatrensis, fleabane, glyphosate-resistant, paraquat-resistant

Take home messages

- The three most common fleabane species in the northern grain region of Australia are: flaxleaf, tall and Canadian fleabane
- Tall fleabane is an emerging threat in this region because its biotypes have evolved resistance to glyphosate and paraquat
- Targeting early growth stages is critical to controlling this weed species using herbicides
- The standard double knock approach will not work on these biotypes and therefore, there is a need to evaluate alternatives to glyphosate and paraquat.

Identification

The three most common species of fleabane in the northern grain region of Australia are flaxleaf fleabane (*Conyza bonariensis*), Canadian fleabane (*Conyza canadensis*) and tall fleabane (*Conyza sumatrensis*). In some cases, all three species grow together in the same area. This can be morphologically confusing, especially at early growth stages. Correct identification is important when selecting effective management options.

Tall fleabane grows up to 2 m in height and it has a single stem with a pyramidal inflorescence (Figure 1). This contrasts with flaxleaf, which grows up to 1 m in height and has multiple erect branching stems covered with stiff hairs. Tall fleabane leaves are less indented than flaxleaf fleabane. Tall fleabane has a roughly pitted receptacle (stalk of the flowering head), while flaxleaf fleabane has a smoothly pitted receptacle. Flowers of tall fleabane are greenish white, while flaxleaf fleabane flowers are whitish.

Figure 1. Tall fleabane plants

Germination and seed bank

Tall fleabane reproduces by seeds, which are easily dispersed by the wind. Our initial trials suggest that its seeds have very low or no dormancy, suggesting that seeds can germinate immediately after dispersal provided that moisture conditions are favourable. Tall fleabane seeds can germinate throughout the year, but growth remains slow during winter.

Tall fleabane has the potential to produce high seed numbers. Similar to flaxleaf fleabane, tall fleabane seeds carry their own pappus, enabling them to be easily lifted and dispersed by wind over a long distance. Such traits make tall fleabane a problematic weed, especially if its biotypes have evolved resistance to non-selective herbicides. These seed traits also highlight the importance of controlling weeds on irrigation channels, embankments, and along fence lines and roadsides.

Flaxleaf fleabane seeds may lose their viability within two years when present in the surface layer. Although there is no such information available for tall fleabane, the lack of dormancy in tall fleabane seeds suggests that the prevention of seed set over two years should be effective in running down its seed bank.

Resistance to herbicides

Recently, tall fleabane biotypes resistant to paraquat and glyphosate have been identified. We collected one resistant biotype from Dalby (Dalby biotype, hereafter) and one susceptible biotype from Gatton (Gatton biotype, hereafter). The rate response analysis showed that the Dalby biotype was 6 times more resistance to paraquat than the Gatton biotype, requiring 3.5 L/ha paraquat (250 g ai/L) to kill 50% of the plants (6-leaf stage) of the resistant (Dalby) biotype compared to 0.6 L/ha paraquat (250 g ai/L) to achieve the same result for the susceptible (Gatton) biotype (Figure 2). Note: the maximum label rate for use of paraquat as a broadacre fallow application (Gramoxone 250 g ai/L label) is 2.4 L/ha.

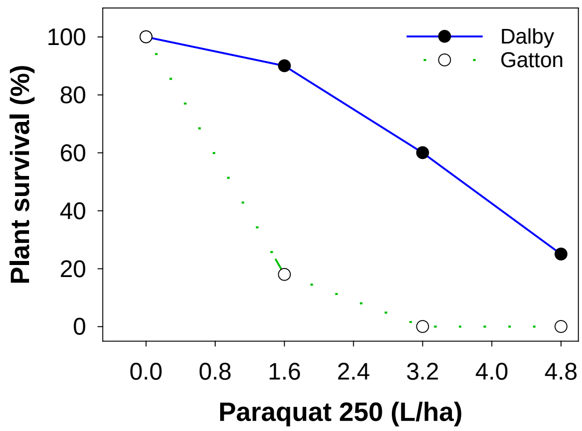

Figure 2. Effect of paraquat (250 g ai/L) (L/ha) dose on plant survival (as a % of the untreated control treatment) of the Dalby and Gatton populations of tall fleabane

While glyphosate 450 g ai/L used alone is not effective and is not a recommended treatment for any fleabane species in fallow, the Dalby biotype was 3.5 times more resistant to glyphosate than the Gatton biotype. Under near ideal conditions, the susceptible biotype required 1.2 L/ha glyphosate (450 g ai/L) to kill 50% of the plants (4-leaf stage), compared to 4.3 L/ha glyphosate (450 g ai/L) to achieve the same result for the resistant biotype (Figure 3). Note: the maximum label rate for use of 450 g ai/L glyphosate as a broadacre fallow application is 2.4 L/ha.

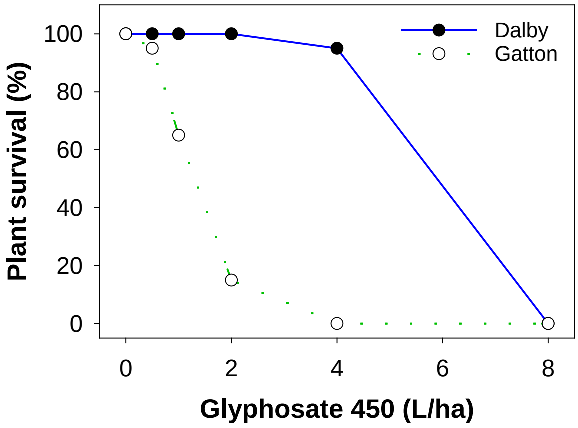

Figure 3. Effect of glyphosate (450 g ai/L) (L/ha) dose on plant survival (% of the non-treated control treatment) of the Dalby and Gatton populations of tall fleabane

In another pot trial at the University of Queensland, Gatton, tall fleabane plants were sprayed at 4-leaf (3-cm in diameter) and 14-leaf (12-14 cm in diameter) stages with different herbicide treatments: glyphosate (450 g ai/L) (1.5 L/ha), paraquat (250 g ai/L) (2 L/ha), 2,4-D (700 g ai/L) (1.5 L/ha), 2,4-D (300 g ai/L) plus picloram (75 g ai/L) (1 L/ha), and saflufenacil (700 g ai/L) (17 g/ha+ 1% Hasten). There was an untreated control for both leaf stages. More than 95% of the Dalby biotype plants survived following the application of glyphosate at the 4-leaf stage, whereas no plants survived for the Gatton biotype (Figure 4a), again suggesting a high level of glyphosate resistance in the Dalby biotype. Regardless of biotype, other herbicides applied at the 4-leaf stage had no surviving plants. Note: the maximum label rate for use of 700 gai/L 2,4-D (Amicide Advance 700) as a broadacre fallow application is 2L/ha and is not recommended as a stand-alone treatment for fleabane in the fallow.

Under ideal conditions in the laboratory, only saflufenacil provided 100% kill of the plants of both biotypes when applied at the 14-leaf stage (Figure 4b). Such an outcome would not be expected at this rate on weeds of this size in the field and there is no label recommendation for this weed stage at this rate. Regardless of biotype, more than 75% plants survived following the application of glyphosate, 2,4-D and 2,4-D plus picloram. Except for saflufenacil, all other herbicide-treated pots had 100% survival of the Dalby biotype. Paraquat application at this stage was still effective on the Gatton biotype (only 8% plant survival).

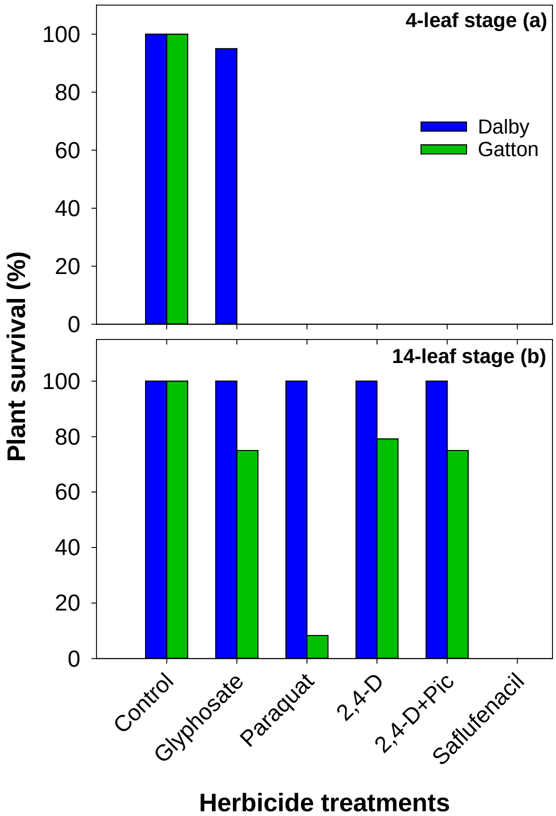

Figure 4. Effect of different herbicide treatments on survival (% of the non-treated control treatment) of the Dalby and Gatton populations of tall fleabane when applied at 4-leaf (a) and 14-leaf stage (b).

The results clearly highlight the importance of growth stage, regardless of biotype, when applying herbicides. Leaf stage or plant growth stage becomes very important when the target plant is herbicide resistant. Tolerance to herbicides in large plants is very common due to their ability to rapidly metabolise the herbicides. In general, it can be difficult to consistently time spraying operations on very small plants. Growers may wait for more weeds to emerge so that they can target a larger number of weed plants, or spraying could be delayed due to unsuitable weather patterns. Also, all weeds are not found at the same stage in field conditions. Therefore, there is a need to evaluate the effect of herbicide mixtures and double-knock herbicides. As the Dalby biotype was resistant to both glyphosate and paraquat, the standard double-knock herbicide components may not work on this and similar biotypes. Saflufenacil could be included as a potential second-knock option for the control of tall fleabane biotypes.

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Tactical decisions on crop sequencing - opt in/opt out decisions based on PAW triggers

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Key words

Rotation, stored soil water, opportunistic crops

GRDC code

CSA00050

Take home messages

- Planting an opportunistic crop to reduce fallow lengths can improve economic returns if strict rules are followed
- Increasing the intensity of a rotation beyond the environmental potential of the area reduces the returns across the whole rotation.
- Planting on less than 100 mm of stored soil water in eastern environments and less than 150 mm in western environments significantly increases the probability of failed (negative gross margin) crops.

Introduction

This paper reports on some of the work conducted as part of GRDC's Northern Farming Systems project. One of the goals of this project is to use both experimental research and simulation modelling to understand the benefits and trade-offs associated with different crop rotations across the northern grains region. For this paper we will use the term rotation to mean a sequence of crops and fallows that regularly follow each other in a cyclic pattern. We are aware that not all grain growers follow a structured fixed rotation and we are not advocating this approach. However, by examining rotations in this structured way, key features (benefits and costs) of the sequence can be observed.

Long fallows are a feature of northern grain production and are mainly used to move between summer and winter phases and to accumulate water to reduce the risk of crop failure. However, there are times when the crop sequence could be intensified by replacing a long fallow with a double crop to move between summer and winter phases or to incorporate an additional wheat crop that reduces a long fallow to a short fallow.

Our previous modelling analyses have shown that time in fallow/crop are key drivers of system water use efficiency, profitability and risk. In most production environments, cropping sequences with higher intensity (i.e. more time in crop) have higher average returns over the long-term, however, this comes with increased risk (frequency of crops with negative gross margins). However, our previous analysis only considered strict rotations where all crops were sown irrespective of soil water conditions and as a result, crops are frequently sown on marginal soil water levels in higher intensity systems. Hence, the question we have examined here, how much can risk be mitigated by only taking opportunities to sow double crops in the rotation when soil water triggers are met. We have tested some opportunistic rules to try and identify when to plant an opportunity crop and what effect it has on the overall rotation. In particular we aim to identify where, when and how the rotation can be intensified to increase profitability without significantly increasing production risk, and what triggers to use to make these decisions. This analysis will help guide answers to the questions:

1. What amount of soil water do I need to put that additional opportunity crop in?
2. What affect will it have on the rest of the rotation and subsequent crops?
3. Is it worth the additional risk?

Methods

Simulations

This study is a simulation analysis that uses the APSIM systems framework (Holzworth *et al.*, 2015) to simulate crop rotations from historic climate records (1957-2017). APSIM has a long history of simulating northern farming systems (Whish *et al*., 2007;Carberry *et al*., 2009) and uses environmental signals to trigger appropriate management decisions. However, these simulations only considered the dynamics of water and nutrients. Losses due to waterlogging, heat or frost shock events, disease, pests, weeds or crop nutrition other than nitrogen were not considered by these simulations.

The simulations of all crop sequences were phased, so that each year of the rotation was exposed to each year of the climate record (1956-2016). All rotations were run at each of 6 sites (Table 1) to highlight the importance of matching crop choice and intensity to the environmental conditions. The sites were selected to represent an east-west rainfall gradient at both a northern (Pampas – Billa Billa – Mungindi) and southern latitude (Breeza – Gilgandra – Nyngan). This paper will focus on the northern transect only. Each site used a locally representative soil (Table 1).

Table 1. Soil details used in simulations at the 6 locations across the northern grains region

Location	Soil description	APSoil No.	Soil plant available water capacity (PAWC) (mm)				Annual rain
			Wheat	Sorghum	Chickpea	Mungbean	(mm)
Pampas	**Black Vertosol**	**006**	**290**	**234**	**290**	**211**	**698**
Billa Billa	**Grey Vertosol**	**220**	**188**	**188**	**167**	**140**	**619**
Mungindi	**Grey Vertosol**	**157**	**186**	**201**	**186**	**141**	**505**
Breeza	Black Vertosol	123	264	273	210	207	680
Gilgandra	Clay loam	249	195	195	195	89	560
Nyngan	Sandy clay	1162	188	188	188	108	445

Rotations

This analysis is designed to look in detail at increasing intensity both in a fixed pattern and using opportunistic crop inclusion. A set of three base crop sequences were simulated each with a low and a high crop intensity, with varying lengths of fallows and time in crop (Table 2). The three sequences were chosen to span different cropping intensities that match the different production environments of the east west transect. In these base rotations (high and low intensity) the crops in the sequence were sown every year (must sow crops) in a fixed pattern within their sowing window (Table 2). If the sowing rule had not been met by the end of the sowing window then the crop was sown at this time. In contrast to these higher and lower intensity systems, an opportunistic sequence was simulated where a crop was either sown or remained in fallow based on the volume of soil water. Crops were sown when the volume of soil water exceeded the critical threshold during the sowing window (Table 3). Simulations were also conducted with two different soil water thresholds used to trigger a planting event (base – higher PAW at sowing, and aggressive – lower PAW at sowing) (Table 3). To ensure that the rotations did not get out of sequence and could be phased, specific parts of the rotation were fixed so these crops were sown every year despite the rules.

Table 2. Description of low and high intensity rotations where all crops are sown every year and opportunistic crop rotation where some crops are only grown when soil water exceeds a minimum threshold (shown in grey with an underline).

Rotation Intensity	***Winter***		***Balanced - conservative***		***Balanced - aggressive***	
	Crops	/yr	Crops	/yr	Crops	/yr
Low	xW|xx|xCh|xx	0.5	Sx|xCh|xW|xx	0.75	Sx|xW|xx	1.0
High	xW|xW|xCh|xW	1.0	Sx|xCh|xW|Mgx	1.0	SCh|xW|Mgx	1.33
Opportunity	xW|xW|xCh|xW	0.5-1.0	Sx|xCh|xW|Mgx	0.75-1.0	SCh|xW|Mgx	0.66-1.33
Moderate Intensity					SCh|xW|xx	1
Mod-Int Opportunity					SCh|xW|xx	0.5-1.0

W= Wheat, Ch = Chickpea, Mg = Mungbean, x= 6 month fallow.

Table 3. Summary of key management rules to trigger sowing, and crop agronomic management rules applied to crops across the set of simulations

Crop	Sowing window	Minimum planting soil water (mm)		APSIM variety used	Row spacing (cm)	Plant density (#/m²)	Starter fertiliser (N kg/ha)
		base	agg.				
Wheat	15 May-1 Jul	150	100	Gregory	25	100	25
Chickpea	1 May-1 Jul	150	100	Amethyst	50	30	0
Sorghum	15 Oct – 15 Jan	150	100	Buster	100	7	25
Mungbean (spring)	15 Oct-15 Nov	100	60	Green Diamond	50	30	0
Mungbean (double)	15 Nov – 15 Jan	100	60				

Economic analysis parameters

Average annual gross margin (GM) analysis was conducted for each phased crop sequence using the equation below. Long-term average grain prices (2008-2017) and current variable input prices were used and these were held constant across all locations. Insurance and levy costs together were 2% of the grain income value and were deducted from grain prices. The price for nitrogen (N) fertiliser applied was set at $1.30/kg N and the cost of each fallow spray was set at $17/ha. The simulations did not account for application losses of N fertilisers; therefore, an additional 30% of applied N was used to ensure fertiliser N reached the soil mineral N pool. The baseline “variable cost” for each crop included planting, non-N nutrients and in-crop pesticide applications. Harvesting costs, N fertiliser and fallow spray frequency were included separately, as these varied between the crop sequences or if crops failed. Crops were considered as failed if the yield was less than the thresholds (Table 4) and harvesting costs were not included. Machinery costs were based on an owner-operated production system; therefore, fuel, oil, repairs and maintenance (FORM) costs where included in the variable costs.

$$GM_{seq}(\$/\mathrm{ha/yr}) = \frac{\sum\{(\text{Grain yield} \times \text{price}) - (\text{kg N} \times 1.3) - (sprays \times 17) - \text{variable costs} - \text{harvest costs}\}}{no.of\ years}$$

Table 4. Crop prices and variable costs used in gross margin calculations for crop sequences

Crop	Average price ($/t)#	Harvest cost ($/ha)	Variable costs ($/ha)
Wheat	264	40	175
Sorghum	225	55	218
Chickpea	569	45	284
Mungbean	710	55	276

#farm gate price with grading & additional harvesting costs already deducted

Results

There are a large range of combinations of crop sequence by locations that were generated in this analysis. Only a selection of the most illustrative results are presented to highlight how the different options behave in the different environments.

Winter crop sequence

This conservative low intensity rotation (xW|xx|xCh|xx) is commonly used in more marginal western sites and has been previously shown to be effective for minimising risk in such environments. A large gap exists between the low intensity rotation (xW|xx|xCh|xx) and the more intensive sequence (xW|xW|xCh|xW) when sown at Pampas or Billa Billa because these environments are too reliable for such a conservative strategy and can support a more intensive crop rotation. However, at Mungindi about 50% of the time either the high or low intensity sequences have the best gross margin - the higher intensity is best in the better seasons and the low intensity in poorer years (Figure 1). This analysis shows an opportunistic strategy fills the gap between the conservative and the high intensity strategy to capitalise on the good seasons and remain conservative in the poor.

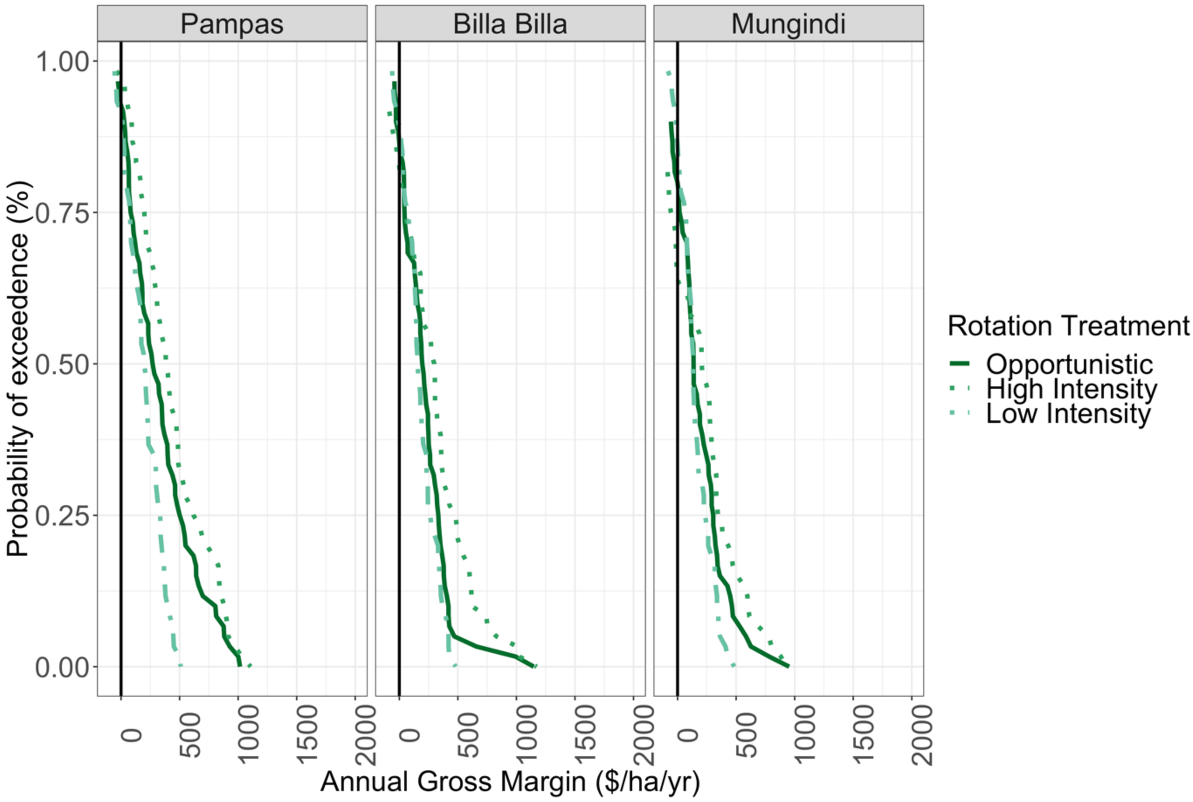

Figure 1. Comparison of the three winter-based crop rotations for low intensity (dot dash), high intensity (dot dot), and with opportunistic crop decisions (solid) at each of the three sites examining their probability of exceeding an annual rotation gross margin. The solid black line marks the zero gross margin point with negative gross margins occurring to the left of this line.

Increasing risk is associated with increasing intensity and the chance of returning a negative gross margin is one way to assess this risk (Figure 2). The environments of Pampas and Billa Billa have few failed crops with less than 20% of crops not breaking-even. However, in the more marginal area of Mungindi, imposing a rotation that has an intensity of 1 crop per year (xW|xW|xCh|xW) resulted in more than 30% of crops failing. Using the opportunistic rule the average gross margin was similar to the more intensive system, but the risk was significantly reduced to around 20% or 1 crop in 5 failing. The aggressive sowing rule increased both the risk and the returns for the opportunistic strategy in Mungindi, but reduced the risk while improving returns at Billa Billa and had no effect in Pampas.

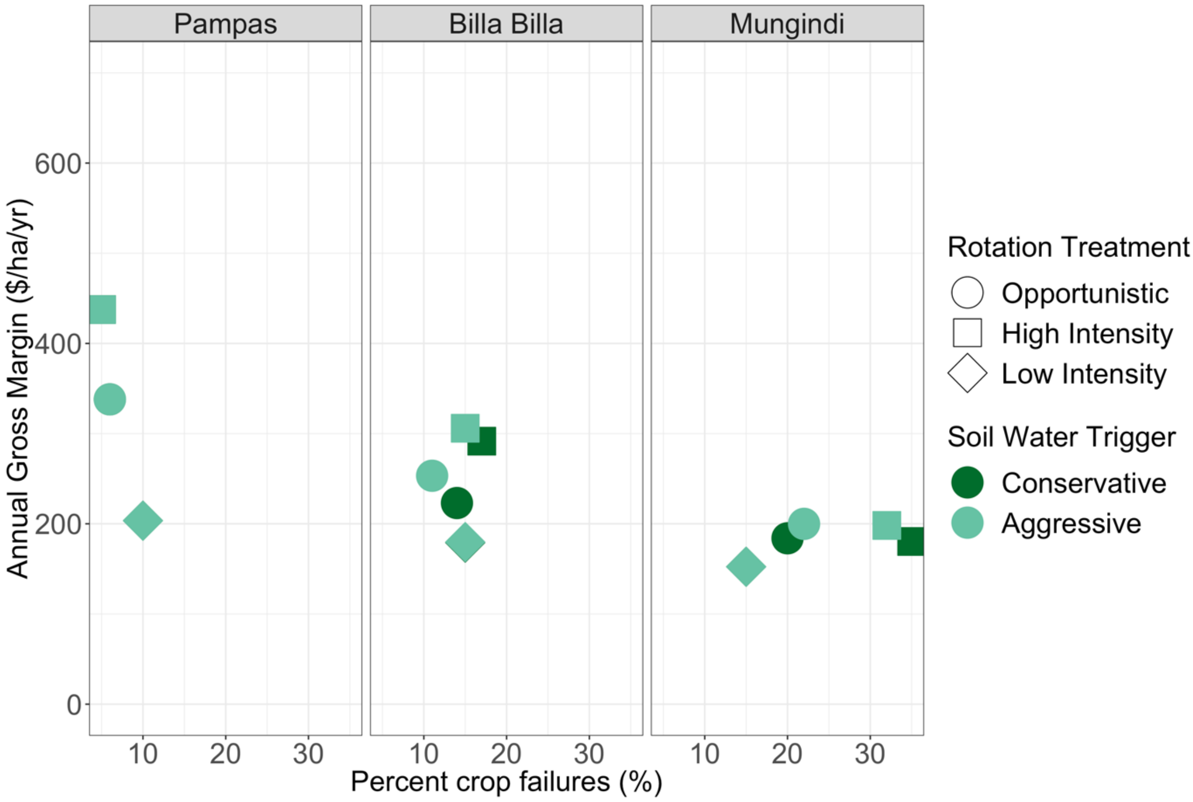

Figure 2. Mean annual gross margin compared to the percentage of failed crops for winter-based rotations of low intensity (Dimond), high intensity (Square) and using an opportunistic sowing rule (Circle). The light coloured symbols indicate an aggressive soil water trigger (100mm-wheat) and the dark symbols indicate a conservative soil water trigger (150mm-wheat).

Looking more closely at the individual components of the rotation (Table 5) highlights how the opportunistic decision, but more importantly, the decision not to sow, affects the rotation.

The second and third wheat crops (wheat_2, wheat_3) were the opportunistic crops and were only sown when 150 mm of soil water had accumulated in the sowing window. At Mungindi this meant that only 1 in 3 years would one of the additional wheat crops be sown. Hence, crop intensity over the long term only increases from 0.5 crops per year in the low intensity system to 0.66 crops per year. The average return from these crops sown only when the soil water threshold was met was more than 36% higher than the average return from crops that were sown every year. The returns from the fixed crops wheat_1 and chickpea_1 (sown every 2 years) was also increased in the opportunistic rotation. This was because when crops are sown on marginal soil water and fail, they consume resources that are no longer available to the following crops, thus reducing the subsequent yields and gross margins of these crops. On average the opportunistic strategy improved returns over the low intensity rotation by $30 and $48 if a more aggressive soil water trigger was applied.

Table 5. Individual crop performance for the conservative rotation at the low rainfall site of Mungindi. All crops are sown each year in the low and high intensity rotations, in the opportunistic rotation wheat crops may be sown in the long fallow when soil water exceeds 150 mm (base) or 100mm (aggressive) during the sowing window.

site	State	Low intensity xW|xx|xCh|xx			High intensity xW|xW|xCh|xW			Opportunistic xW|xW|xCh|xW		
		% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)
Mungindi	**60 yr ave**	**0.5**	**15**	**152**	**1.0**	**35**	**181**	**0.66**	**20**	**182**
Base soil water rule	Chickpea_1	100	8	395	100	27	282	100	12	377
	Wheat_1	100	22	214	100	40	132	100	28	190
	Wheat_2	0	0	0	100	40	129	33	25	251
	Wheat_3	0	0	0	100	32	179	30	17	283
Mungindi	**60 yr ave**	**0.5**	**15**	**152**	**1.0**	**32**	**198**	**0.71**	**22**	**200**
Aggressive soil water rule	Chickpea_1	100	8	395	100	25	311	100	13	376
	Wheat_1	100	22	214	100	38	142	100	30	178
	Wheat_2	0	0	0	100	38	136	43	27	255
	Wheat_3	0	0	0	100	27	204	42	16	323

†refers to the number of crops that failed relative to the percentage of crops sown

Balanced - conservative

The balanced- conservative rotation is designed to have both summer and winter phases (Sx|xCh|xW|xx), which was intensified through the use of either a scheduled (sown every year) or opportunistic mungbean crop (Sx|xCh|xW|Mgx) to move between the winter and summer phase. At Pampas and Billa Billa the inclusion of mungbeans opportunistically matched the returns of the high intensity strategy where they were sown every year for the majority of the seasons. A few occurrences occurred around the average when the opportunistic crop was not sown and subsequently a good season enabled a good yield and the intense system had higher returns. Pampas and Breeza show a distinct difference between the conservative 3 crops in four year rotation (SxxChxWxx) and the higher intensity system which has 1 crop per year (Sx|xCh|xW|Mgx). This suggests that in these environments there is still room for intensification to at least 1 crop per year. The minimal difference between the different rotations at Mungindi suggest this level of intensity is too high for this environment and the low intensity option is no worse than the either of the others.

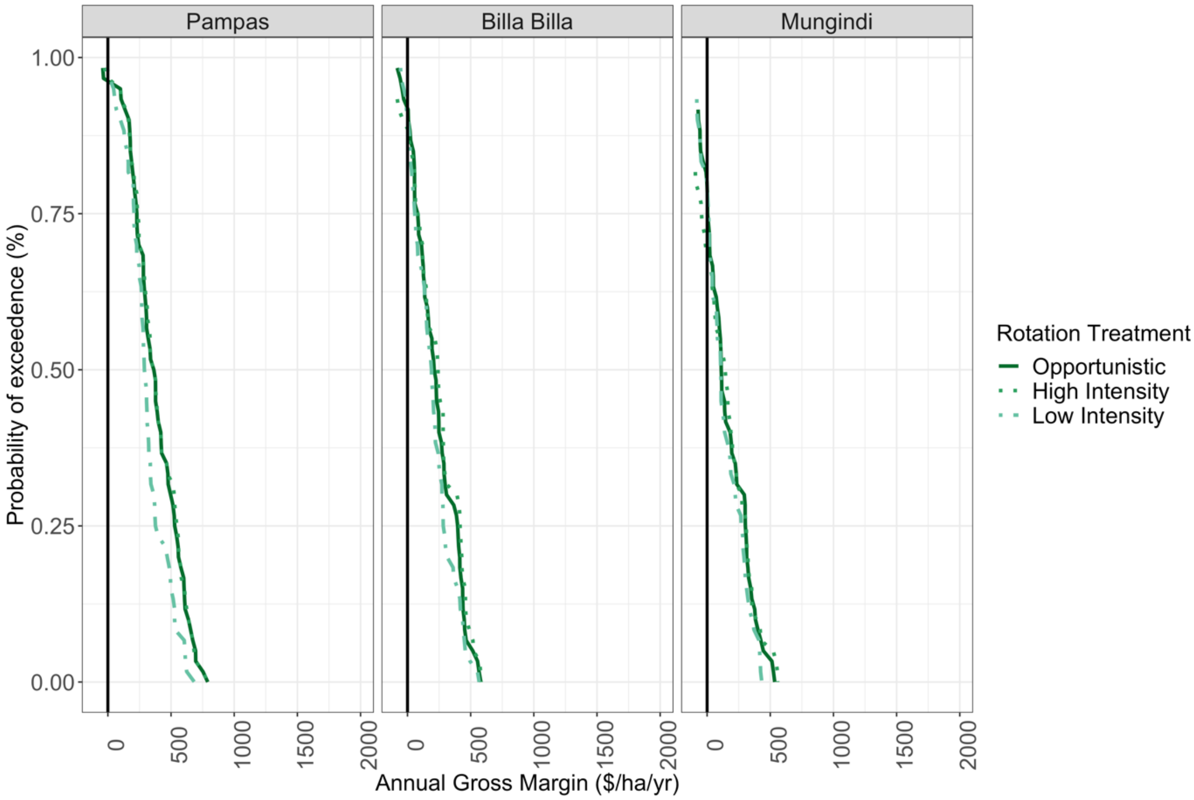

Figure 3. Comparison of the three balanced-conservative crop rotations of low intensity (dot dash), high intensity (dot dot), and with opportunistic crop decisions (solid) at each of the three sites examining their probability of exceeding an annual rotation gross margin. The solid black line marks the zero gross margin point with negative gross margins occurring to the left of this line.

The Opportunistic use of mungbeans reduced the risk of crops with negative gross margins compared to a crop sequence where these were sown every year. In fact the risk of crop failures was hardly higher than the low intensity system where mungbeans were not used at all. The examination of the number of failed crops highlights the limitations of intensifying a crop sequence in the dryer environment of Mungindi (one in three crop failures) and the minimal difference between treatments at pampas show there is still potential to intensify more in this environment. The aggressive sowing strategy had no effect on the low intensity rotation at Billa Billa, but increased risk and lowered the average returns for the opportunistic and intense sequences.

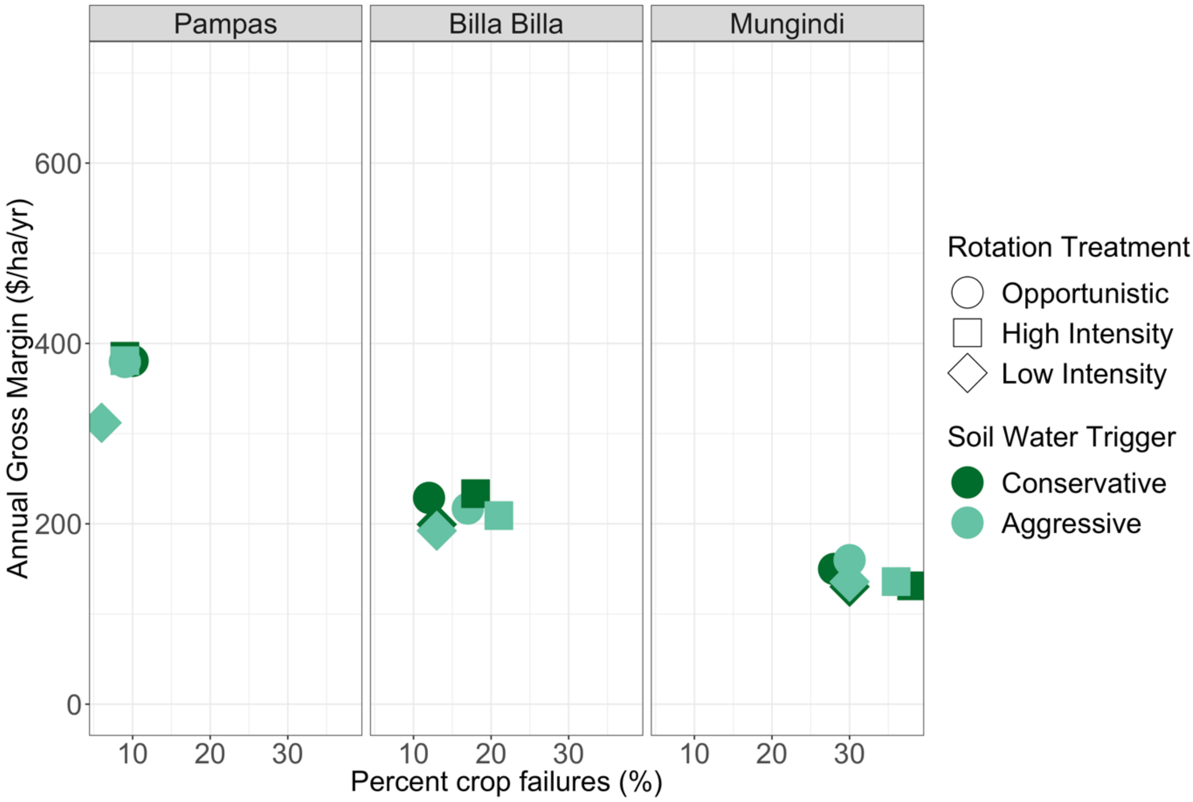

Figure 4. Mean annual gross margin compared to the percentage of failed crops for the balanced conservative rotations of low intensity (Dimond), high intensity (Square) and using an opportunistic sowing rule (Circle). The light coloured symbols indicate an aggressive soil water trigger (100mm-wheat) and the dark symbols indicate a conservative soil water trigger (150mm-wheat). The opportunistic sowing of mungbean achieved a gross margin similar to or better than the high intensity rotation with similar risk to the low intensity rotation at all sites when the conservative (base) sowing rule was applied.

Examining the components of the rotation (Table 6) highlights the importance of only planting a crop when resources are present to give it the best possible chance of success. The fixed rotation that sowed mungbeans every year had 38% and 44% of crops failing at Billa Billa for the base and aggressive sowing water strategies. In comparison, the opportunistic rotation had 11% failed mungbean crops for the base soil water trigger, but 39% for the aggressive strategy. At the same time the annual gross margin was similar but 60% fewer crops were planted using the conservative base sowing trigger and 31% fewer crops were sown with the aggressive sowing strategy.

Table 6. Individual crop behaviour for the balanced rotations conducted at the medium rainfall site of Billa Billa

site	State	Low intensity Sx|xCh|xW|xx			High intensity Sx|xCh|xW|Mgx			Opportunistic Sx|xCh|xW|Mgx		
		% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)
Billa Billa	**60 yr ave**	**75**	**13**	**266**	**100**	**19**	**311**	**85**	**12**	**298**
Base soil water rule	Chickpea_1	100	9	500	100	9	510	100	9	508
	Mungbean_1	0			100	38	113	40	11	313
	Sorghum_1	100	11	351	100	16	396	100	11	370
	Wheat_1	100	18	210	100	11	224	100	18	215
Billa Billa	**60 yr ave**	**75**	**13**	**267**	**100**	**21**	**280**	**92**	**19**	**279**
Aggressive soil water rule	Chickpea_1	100	9	503	100	9	535	100	9	522
	Mungbean_1	0			100	44	76	69	39	168
	Sorghum_1	100	14	311	100	20	276	100	18	298
	Wheat_1	100	11	216	100	11	231	100	11	225

†refers to the number of crops that failed relative to the percentage of crops sown

Balanced - aggressive

The intense rotations tested here were examined to push the environment and capitalise on the higher rainfall conditions in the more eastern environment of Pampas. In these sequences two options for intensifying the farming system were used. These were: 1. involving a chickpea double crop sown either every year or opportunistically following sorghum (S**Ch**|xW|xx) and 2. further intensifying the system with a mungbean double crop sown either every year or opportunistically following wheat (S**Ch**|xW|**Mg**x). These three different options provide a wide range of crop intensities, ranging from 2 crops in 3 years (0.66 crops/yr) to 4 crops in 3 years (1.3 crops per yr). The data falls into 2 clumps, but the key message is that in the eastern environment of Pampas the opportunistic rotations matched the fixed rotations in terms of gross margin for the majority of seasons with little difference between the opportunistic and the intense rotation (Figure 5) apart from risk (Figure 6).

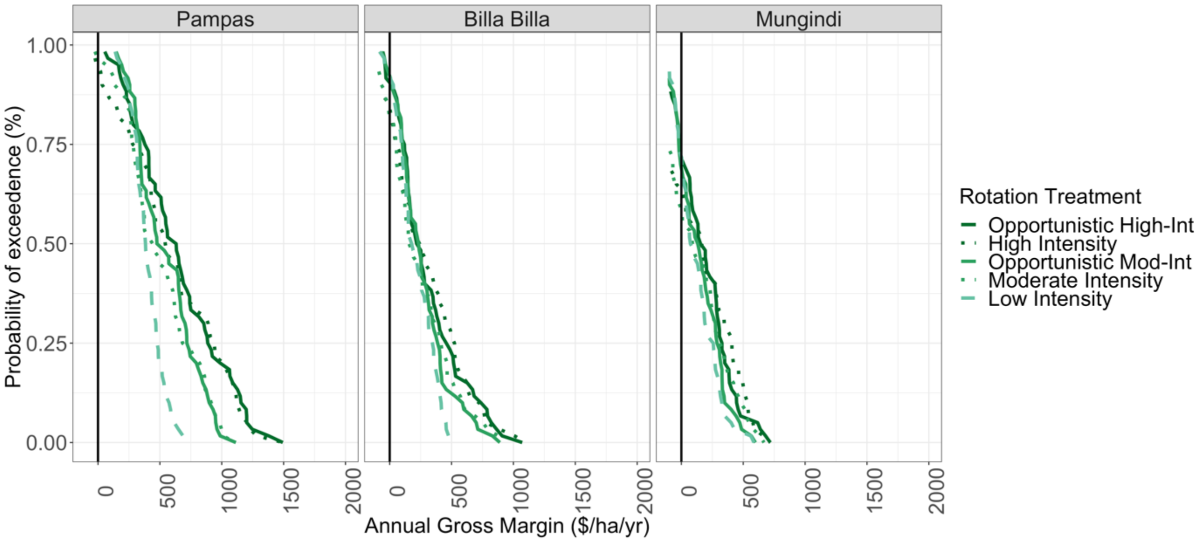

Figure 5. Comparison of the balanced- aggressive crop rotations of low intensity (light grey dash), high intensity (dot dot), and with opportunistic crop decisions (solid). The summer opportunity rotations are dark and the winter rotations are grey. The solid black line marks the zero gross margin point with negative gross margins occurring to the left of this line.

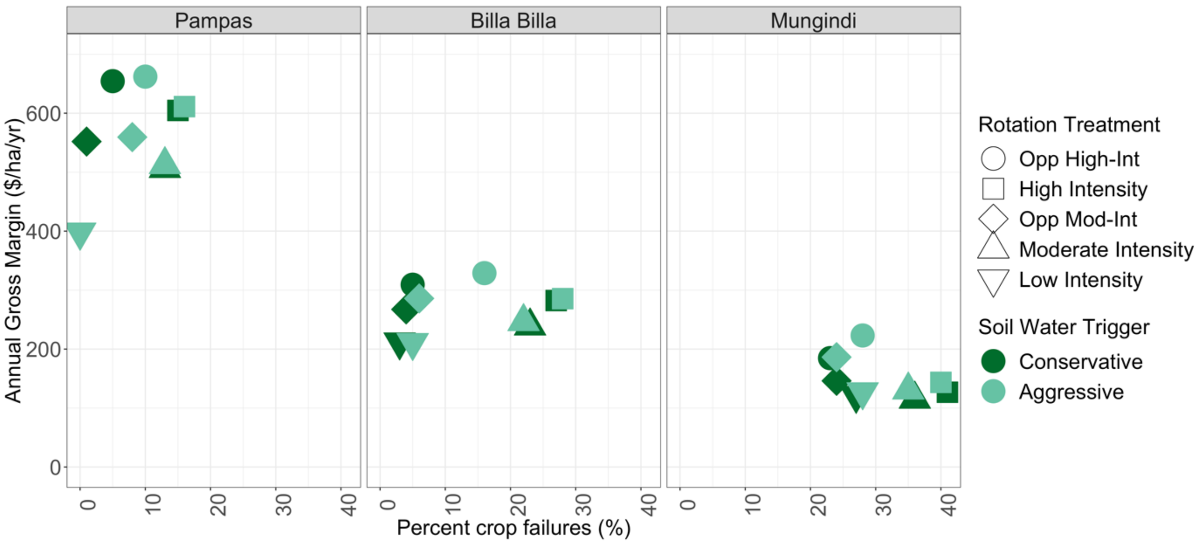

Figure 6. Mean annual gross margin compared to the percentage of failed crops for balanced-aggressive rotations of low intensity (downward triangle), high intensity summer(square), high intensity winter (upward triangle), using an opportunistic sowing rule for summer (circle) and using an opportunistic sowing rule for winter (diamond). The light coloured symbols indicate an aggressive soil water trigger (100mm-wheat) and the dark symbols indicate a conservative soil water trigger (150mm-wheat). The opportunistic sowing of mungbean and chickpea reduce the fallow length and achieved a high gross margin with minimal risk when sown in the eastern environments of Pampas.

The use of the opportunistic planting rules significantly reduced the number of crops producing a negative gross margin while increasing the average returns from each of the individual crops. For example, by only sowing the chickpea double crop after sorghum when 150 mm of soil water was present, reduced the frequency of crop failures from 38% at Pampas to 6%. This also increased the average gross margin for chickpea by over $400/ha. A similar story was also true for the opportunistic incorporation of mungbeans into the cropping system. Overall, using an opportunistic approach to double-crops of chickpea and mungbeans in this environment was predicted to achieve equal or higher overall average annual returns and dramatically reduced risk compared to a scheduled approach. The use of a lower threshold for sowing decisions did increase the risk and reduced the returns from each individual crop; however, the increased number of crops sown increased long term returns on average by about $10/ha/yr. (Table 7)

Table 7. Individual crop behaviour for each of the intense rotations conducted at the high rainfall sites of Pampas

Site	State	Low intensity Sx|xW|xx			Moderate intensity SCh|xW|xx			Opportunistic Mod- intensity SCh|xW|xx			High intensity SCh|xW|Mgx			Opportunistic High- intensity SCh|xW|Mgx		
		% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)	% crops sown	% crops fail†	GM ($/ha)
Pampas	**60 yr ave**	**0.66**	**0**	**395**	**1**	**14**	**508**	**0.86**	**3**	**546**	**1.33**	**17**	**604**	**1.11**	**7**	**652**
Base soil water rule	Chickpea_1	0	0	0	100	38	176	60	6	610	100	42	153	48	10	623
	Mungbean_1	0	0	0	0	0	0	0	0	0	100	17	395	85	14	412
	Sorghum_1	100	0	807	100	0	886	100	0	851	100	2	803	100	2	832
	Wheat_1	100	0	391	100	5	462	100	3	444	100	5	467	100	3	484
Pampas	**60 yr ave**	**0.66**	**0**	**396**	**1**	**14**	**515**	**0.94**	**9**	**550**	**1.33**	**17**	**611**	**1.25**	**12**	**662**
Aggressive soil water rule	Chickpea_1	0	0	0	100	38	198	83	24	439	100	38	198	77	24	434
	Mungbean_1	0	0	0	0	0	0	0	0	0	100	22	353	100	18	378
	Sorghum_1	100	0	807	100	0	885	100	63	867	100	3	807	100	3	823
	Wheat_1	100	0	392	100	5	462	100	35	452	100	3	480	100	3	482

†refers to the number of crops that failed relative to the percentage of crops sown

Conclusions

This paper has demonstrated that opportunistic sowing rules can be employed to increase the intensity of the farming system and increase returns relative to low intensity conservative approaches at the same time as managing risk. Two different sowing rules were examined: base (150 mm of stored water at sowing for all crops apart from mungbean that used 100 mm) vs aggressive (100mm of stored water at sowing for all crops apart from mungbean that used 60 mm). Reducing the soil water trigger marginally improved returns, but also increased risk. However, it is one tactic to intensify a rotation without including new crops. Alternatively, Increasing the soil trigger can reduce risk in some environments, but will come at the cost of cash flow and issues associated with increasing fallow length. The higher rainfall environment of Pampas was expected to significantly benefit from the more aggressive sowing strategy. However, despite significantly planting more crops, the overall returns were not dramatically increased. This suggests that even in these reliable rainfall environments a conservative soil water trigger has value in increasing production efficiency.

This work shows there are considerable benefits of opting out of a crop if the conditions are not favourable or opting in to crops opportunistically based on soil water triggers. The rules presented are robust when run over a 60 year period and show the carryover effect of a failed crop can reduce the returns of those crops that follow. However, it is always easier to not plant a crop while sitting on a computer and not looking at a pile of expensive seed in the shed. This is a difficult decision, but knowing how much water you have in the soil and how forgiving your environment is, can help answer the question should I opt in or opt out.

References

Carberry, P.S., Hochman, Z., Hunt, J.R., Dalgliesh, N., McCown, R.L., Whish, J.P.M., Robertson, M.J., Foale, M., Poulton, P.L., van Rees, H. (2009) Re-inventing model-based decision support with Australian dryland farmers. 3. Relevance of APSIM to commercial crops. Crop Pasture Sci. 60:1044–1056. doi:10.1071/CP09052

Holzworth, D.P., Snow, V.O., Janssen, S., Athanasiadis, I.N., Donatelli, M., Hoogenboom, G., White, J.W., Thorburn, P. (2015) Agricultural production systems modelling and software: Current status and future prospects. Environmental Modelling & Software 72:276–286. doi:10.1016/j.envsoft.2014.12.013

Whish, J.P.M., Castor, P.A., Carberry, P.S. (2007) Managing production constraints to the reliability of chickpea (*Cicer arietinum* L.) within marginal areas of the northern grains region of Australia. Crop Pasture Sci. 58:396–405. doi:10.1071/AR06179

Whish, J.P.M., Price, L., Castor, P.A. (2009) Do spring cover crops rob water and so reduce wheat yields in the northern grain zone of eastern Australia? Crop Pasture Sci. 60:517–525. doi:10.1071/CP08397

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Measuring and predicting plant available water capacity (PAWC) to drive decision-making and crop resourcing: extrapolating data in the Central Darling Downs from limited site numbers across paddocks helped by soil-landscape understanding

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Key words

Plant Available Water Capacity (PAWC), PAWC estimation, APSoil, soil survey, soil processes, soil constraints, soil-landscapes

GRDC code

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Take home messages

- Information regarding the plant available water (PAW) at a point in time, particularly at planting, can be useful in a range of crop management decisions. Estimating PAW, whether through use of a soil water monitoring device or a push probe, requires knowledge of the plant available water capacity (PAWC) and/or the crop lower limit (CLL)
- A wide variety of soils in the northern region have been characterised for PAWC and details are available to growers in the APSoil database, which can be viewed in Google Earth and in the 'SoilMapp' application for iPad
- Knowledge of physical and chemical soil properties like texture or particle size distribution and (sub) soil constraints helps interpret the size and shape of the PAWC profiles of different soils. It can also assist in choosing a similar soil from the APSoil database
- Knowing something about how soils are distributed across the landscape - helped by understanding how the soils have been formed - boosts the ability to find a suitable soil type in APSoil or from other publicly available local soil and land resources (mapping, resource guides and field manuals, etc.), or allows users to reasonably predict the PAWC at a site
- Once the match between the soil of interest and the soil type is made, the PAWC can be adjusted using soil, land and chemical information, and if necessary, should constraints to crop roots be noted in the soil profile.

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 recognized. 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), 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 characteristics 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 more than 1100 sites around Australia for PAWC. The data are publicly available in the APSoil database, including via a Google Earth file and in the 'SoilMapp' application for iPad (see Resources section).

Many farmers and advisers, especially in southern Australia, are using the PAWC data in conjunction with Yield Prophet® to assist with crop management decisions. Yield Prophet® is a tool that interprets the predictions of the APSIM cropping systems model. It uses the information on PAWC along with on pre-season soil moisture and mineral nitrogen, agronomic inputs and local climate data to forecast, at any time during the growing season, the possible yield outcomes. Yield Prophet® simulates soil water and nitrogen dynamics as well as crop growth with the weather conditions experienced to date and then uses long term historical weather records to simulate what would have happened from this date onwards in each year of the climate record. The resulting range of expected yield outcomes can be compared with the expected outcomes of alternative varieties, time of sowing, topdressing, etc. to inform management decisions.

Others use the PAWC data more informally in conjunction with assessments of soil water (soil core, soil water monitoring device or depth of wet soil with a push probe) to estimate the amount of plant available water. Local rules of thumb are then used to inform the management decisions.

The APSoil database provides geo-referenced data (i.e. located on a map), but the PAWC characterisations are for points in the landscape. To use this information to predict PAWC for the soil in a paddock of interest, the challenge is to find a similar soil in the APSoil database. Similarities between soils are related to parent material and the conditions under which the soil formed, or the material was deposited. This is often related to landscape position. Information on soil-landscape associations, therefore, provide an avenue to assist with PAWC prediction. The soil-landscape information is captured by the soil surveys undertaken by state government departments and other research organisations and is increasingly becoming available online.

This paper describes the concepts behind PAWC and outlines where to find existing information. It discusses how soil-landscape associations can be used to inform extrapolation from existing PAWC sites and assist with predictions. This is illustrated by current work from the Central Darling Downs in which relationships between landscapes, soil and PAWC are being explored to inform better PAWC predictions for growers to inform management decisions.

Plant available water capacity (PAWC)

To characterise a soil's PAWC, or 'soil water bucket size', we need to determine (Figure 1a):

- drained upper limit (DUL) or field capacity – the amount of water a soil can hold against gravity;
- crop lower limit (CLL) – the amount of water remaining after a particular crop has extracted all the water available to it from the soil; and
- bulk density (BD) – the density of the soil, which is required to convert measurements of gravimetric water content to volumetric.

In addition, soil chemical data are obtained to provide an indication whether subsoil constraints (e.g. salinity, sodicity, boron and aluminium) may affect a soil's ability to store water, or the plant's ability to extract water from the soil.

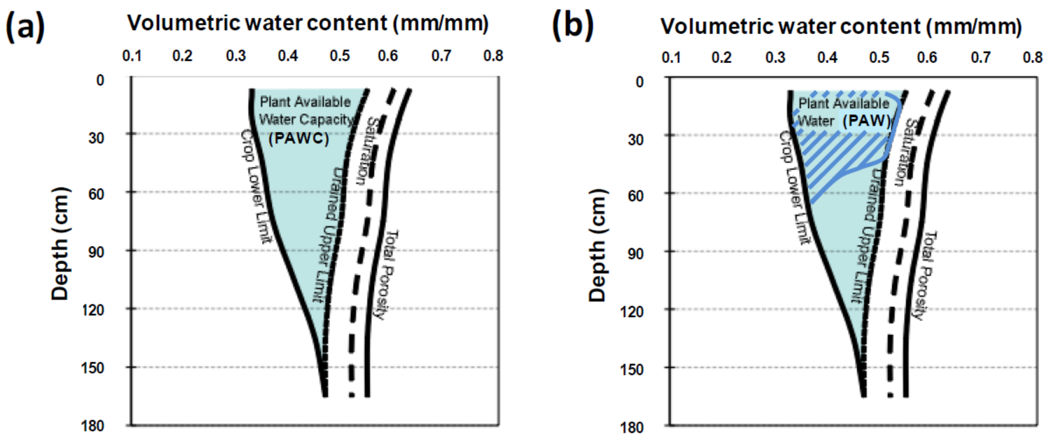

Figure 1. (a) The plant available water capacity (PAWC) is the total amount of water that each soil type can store and release to different crops and is defined by its drained upper limit (DUL) and its crop specific crop lower limit (CLL); (b) plant available water (PAW) represents the volume of water 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 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 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).

Knowledge of PAW can inform management decisions and many growers in the GRDC Northern Region have, formally or informally, adopted this. Several papers at recent GRDC Updates have illustrated the impact of PAW at sowing on crop yield in the context of management decisions.

Field measurement of PAWC

Field measurement of DUL, CLL and BD are described in detail in the *GRDC PAWC Booklet* 'Estimating plant available water capacity' (see Resources section). Briefly, to determine the DUL an area of approximately 4 m x 4 m is slowly wet up using drip tubing that has been laid out in spiral (see Figure 2a). The area is covered with plastic to prevent evaporation and after the slow wetting up it is allowed to drain (see *GRDC PAWC booklet* for indicative rates of wetting up and drainage times). The soil is then sampled for soil moisture and bulk density.

The CLL is measured either opportunistically at the end of a very dry season or in an area protected by a rainout shelter between anthesis/flowering and time of sampling at harvest (Figure 2b). This method assumes the crop will have explored all available soil water to the maximum extent and it accounts for any subsoil constraints that affect the plant's ability to extract water from the soil.

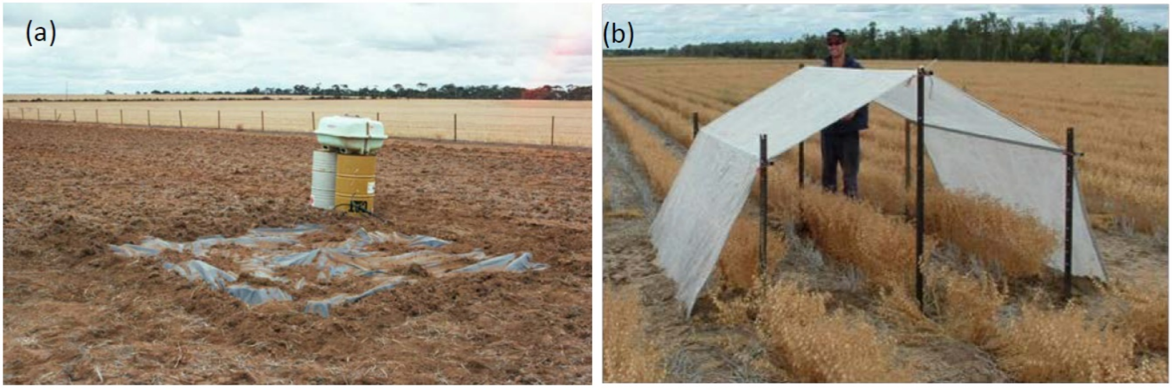

Figure 2. (a) Wetting up for DUL determination and (b) rainout shelter used for CLL determination (source: CSIRO).

Where to find existing information on PAWC

Characterisations of PAWC for more than 1100 soils across Australia have been collated in the APSoil database and are freely available to farmers, advisors and researchers. The database software and data can be downloaded from https://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 the iPad available from the App store. The industry yield forecasting tool Yield Prophet® also draws on this database.

In Google Earth the APSoil characterisation sites are marked by a shovel symbol (see Figure 3a), with information about the PAWC profile appearing in a pop-up box if one clicks on the site. The pop-up box also provides links to download the data in APSoil database or spreadsheet format.

In SoilMapp the APSoil sites are represented by green dots (see Figure 3b). Tapping on the map results in a pop-up that allows one to 'discover' nearby APSoil sites (tap green arrow) or other soil (survey) characterisations. The discovery screen then shows the PAWC characterisation as well as any other soil physical or chemical analysis data and available descriptive information.

Most of the PAWC data included in the APSoil database has been obtained through the field methodology outlined above, although for some soils estimates have been used for DUL or CLL. Some generic, estimated profiles are also available. While field measured profiles are mostly geo-referenced to the site of measurement (+/- accuracy of GPS unit), generic soils are identified with the nearest, or regional town.

Factors that influence PAWC

An important determinant of the PAWC is the soil's texture. The particle size distribution of sand, silt and clay determines how much water and how tightly it is held. Clay particles are small (<2 microns in size), but collectively have a larger surface area than sand particles occupying the same volume. This is important because water is held on the surface of soil particles which results in clay soils having the ability to hold more water than a sand. Because the spaces between the soil particles tend to be smaller in clays than in sands, plant roots have more difficulty accessing the space and the water is thus more tightly held in clay soils. This affects the amount of water a soil can hold against drainage (DUL) as well as how much of the water can be extracted by the crop (CLL).

The effect of texture on PAWC can be seen by comparing some of the APSoil characterisations from the GRDC northern region, as illustrated below (Figure 4). The soil's structure and its chemistry and mineralogy affect PAWC as well. For example, subsoil sodicity may impede internal drainage and subsoil constraints such as salinity, toxicity from aluminium or boron and extremely high-density subsoil may limit root exploration, sometimes reducing the PAWC bucket significantly.

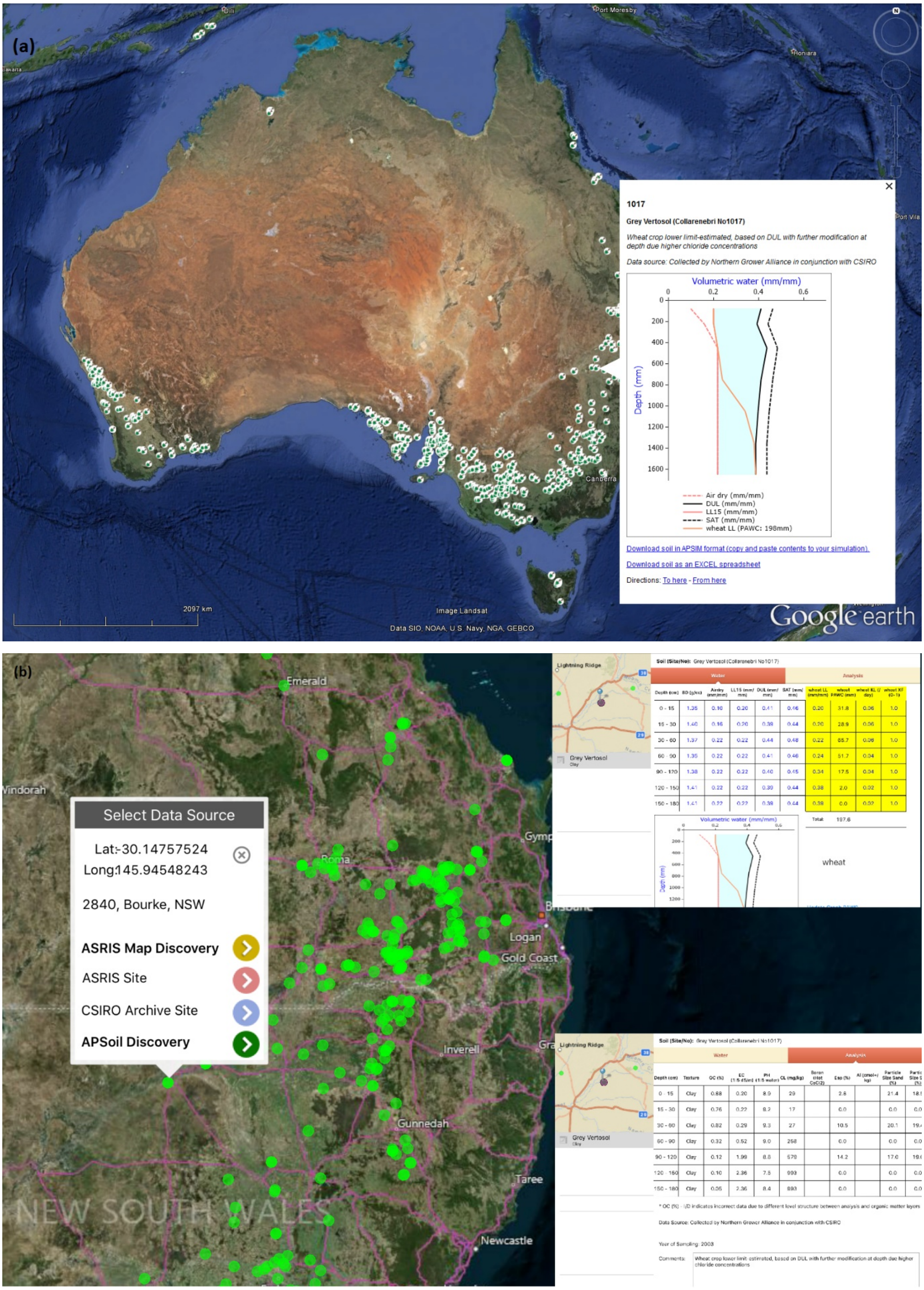

Figure 3. Access to geo-referenced soil PAWC characterisations of the APSoil database via (top) Google Earth and (bottom) SoilMapp (APSoil discovery screens as inserts).

The CLL may differ for different crops due to differences in root density, root depth, crop demand and duration of crop growth (Figure 4b, c). Some APSoil characterisations only determined the CLL for a single crop. The CLL for deeper rooting crops are often considered the same, but care needs to be taken with such rules of thumb as different tolerances for subsoil constraints can cause variation between crops. A detailed explanation of the factors influencing PAWC is included in the *Soil Matters – Monitoring soil water and nutrients in dryland farming* book by Dalgliesh and Foale (1998).

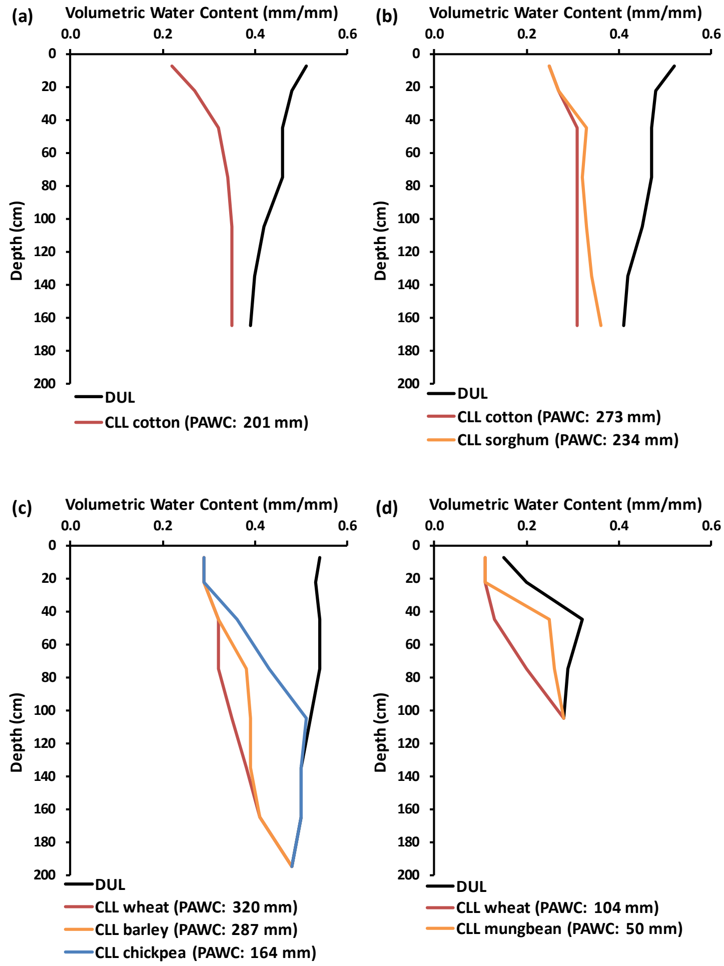

Figure 4. Selected soil PAWC characterisations from the central Darling Downs

(a,b) Variation within the broad level recent alluvial plains (LRA unit 1a) stems from the mixed basaltic and sandstone origin of the alluvium and from particle size of the sediments in response to position within the plains. The Condamine soil is a deep, coarse structured black cracking clay adjacent to the Condamine river. It has coarse sand and gravel throughout and moderate to high subsoil salinity, both of which limit PAWC to about 150-200 mm, as seen in the example of APSoil 8 from near Yandilla, Qld (a). The Anchorfield black cracking clay has a finer structure which is reflected in its larger PAWC (usually >250 mm) as illustrated by APSoil 6 from near Brookstead (b).

(c) The Waco soil is more common in the broad level older alluvial plains of basaltic alluvium. The high clay content of these soils along with the smectite clay minerals contributed by the basaltic origin are responsible for the severe cracking and self-mulching nature of these soils and their large PAWC (APSoil site 16 near Jimbour, Qld).

(d) The undulating to steep, low hills and rises of Walloon sandstone of the Brigalow Uplands (LRA unit 6b) are characterised by grey-brown cracking clays with brown sands over brown clays. The Diamondy soil of APSoil site 88 near Jinghi, Qld is a texture contrast soil with a hardsetting surface and impermeable subsoil. The lower PAWC (50-100 mm) is in response to the limited depth, lower water holding capacity of the sandy surface layer and sodicity and salinity at depth.

Linking central Darling Downs soil-landscapes to PAWC

When it is not feasible to measure PAWC locally, one can try to estimate it by extrapolating from existing characterisations. This is not an easy task. The nearest PAWC characterisation may not be the most appropriate as its soil properties could be quite different. The presence or level of subsoil constraints may vary too. The challenge is therefore, to find a PAWC characterisation for a soil with similar properties.

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. In the Central Darling Downs, soil and land mapping spanning the 1960s to 1990s have been drawn from, along with new survey, to create land resource area (LRA) mapping and associated documentation, including an overview of the soils and landscapes from a land and farming capability/limitations perspective (Harris et al., 1999b), the landscape and soils within them ("*Field Manual*", Harris et al., 1999a) and soil chemistry (Biggs et al., 1999) (see Resources section). Combined, the references describe the local soils and how they fit within the landscape.

The current project is testing whether we can draw on this information to predict PAWC or find a similar soil in the APSoil database. Below we illustrate for two transects how the soil properties change and are likely to affect PAWC.

The central Darling Downs is on southeast Queensland's western flanks of the Great Divide and covers an area of approximately 2M ha of the upper Condamine river catchment (Figure 5). The regional geology features basalt along the Great Divide that mostly overlays sandstones. The area forms a broad valley and the soil characteristics are governed by source materials (sediments, basalt, sometimes granites) and the sequence of weathering, erosion and redistribution, i.e. the history of soil development. The alluvial soils in the broad valley floor are generally very fertile clays, as are the soils on the upper basalts (clays, and loams).

The central Darling Downs area contains 73 APSoil characterisations shown in Figure 5. These include the earliest APSoil described, and because techniques were still evolving, many lack the physical and chemical data that is standard in the current protocol described in the *PAWC Booklet*.

Generally speaking the soils are suited to dryland cropping by virtue of the rainfall and soil types, e.g. deep clay or loamy soils often resulting in very high PAWCs (>250 mm).

Early in the study a conceptual understanding of soil processes was drawn together in discussion with local experts (Qld. government, agricultural advisers, growers) and through a desktop evaluation of data including terrain, soil mapping, geology, APSoil profiles, etc.. Following, a soil survey was devised based on transects along ridge-to-valley bottom soil sequences (toposequences), typically 15-20 km long. Four soil survey sites were positioned along each transect, with one site at an APSoil site to 'calibrate' our PAWC understanding. The remaining three sites spread to cover soil-landscape variations (Figure 5).

Soil samples were analysed for physical and chemical properties, and site and profile characteristics recorded (e.g. depth to bedrock, coarse fragments, rooting depth).

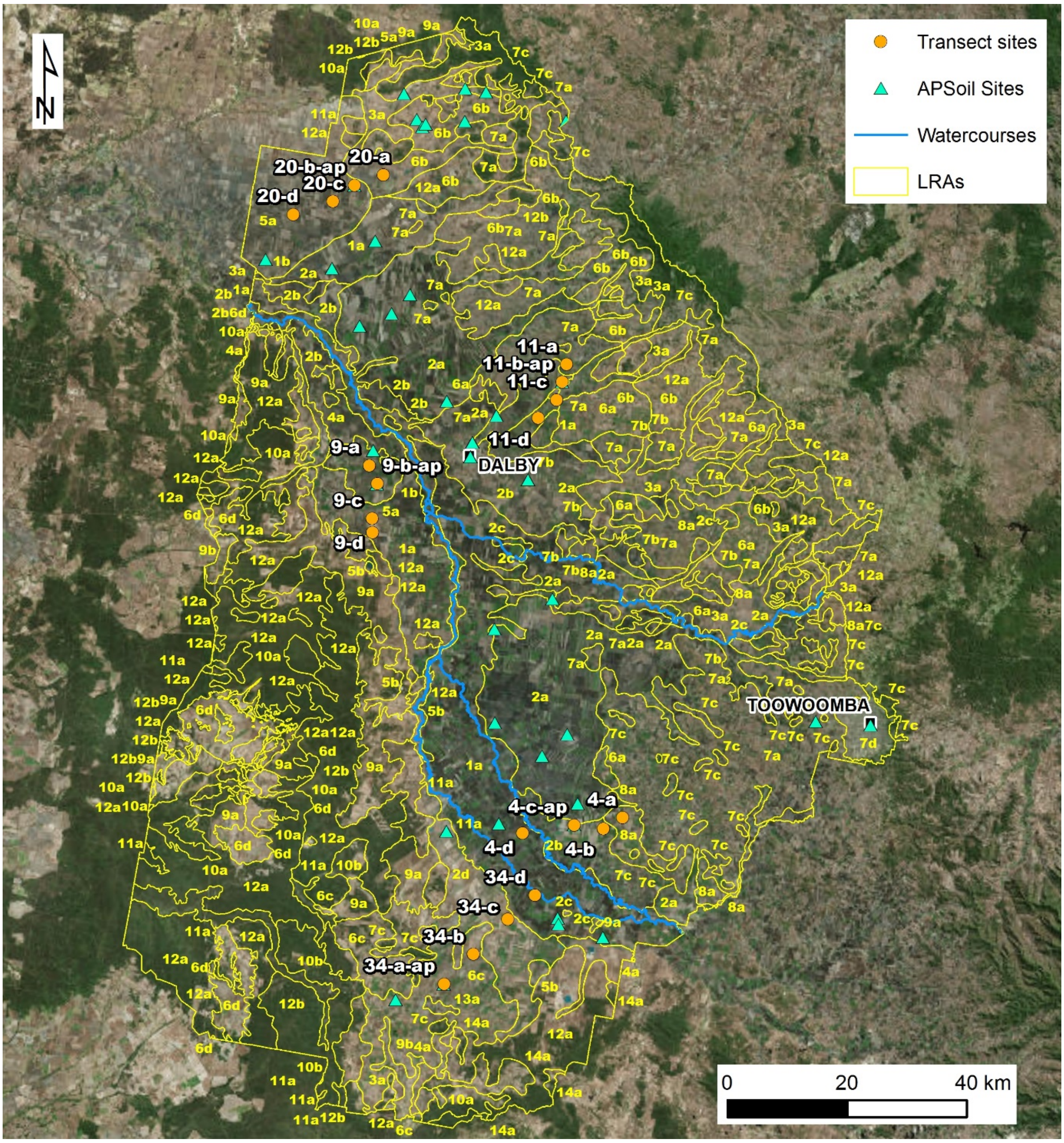

Figure 5. Survey transects and sampling points (orange dots) overlaid on LRA mapping

Using soil landscape information to help estimate PAWC

The current project is testing whether we can draw on the information that is available to growers in the Central Darling Downs information (e.g. from APSoil, SoilMapp, LRA mapping, etc.) to predict PAWC or find a similar soil in the APSoil database. The steps below indicate how this may be done. We illustrate the steps using one/two soil sampling transects undertaken in our project. The initial steps reflect those in the LRA *Field Manual*.

Step 1: Find the LRA for your site of interest.

a) A map of LRA is available through the Queensland Globe: https://qldglobe.information.qld.gov.au/. In this online mapping tool, select 'Add Layers', then choose 'Land resource area mapping' under 'Geoscientific information' and zoom into the area of interest.

b) Compare the LRA unit number with its description in Table 2.1 of the *Field Manual* and the diagrams of the relationships between different LRAs in Figure 2.2 of the *Field Manual* to confirm this LRA provides a good description of the landscape position of the location of interest.

Step 2: Consider the main differences between soils that are found within this LRA. Table 2.1 of the *Field Manual* lists the major soil types and indicative positions within the LRA are given in Figure 2.3 of the *Field Manual*.

Step 3: Considering the position in the landscape (e.g. higher or lower on hill slope, location on levee or in depression) as well as soil observations such as depth to bedrock, stones and gravel, rooting depth, pH, salinity, sodicity, identify the likely soil type and compare with the description of this soil type in the back of the *Field Manual*. Rooting depth is an important observation because it indicates the limits of root exploration in the soil caused by limiting constraints, regardless of the type or combination of constraints.

Step 4: Most APSoils in the area have been classified using the soil type classification in the *Field Manual*. In addition to this source of reference, table 1 provides a means to identify likely APSoil profiles for several the soil types in the area. Work is in progress to extend this list. Where a soil type does not have a matching APSoil, use the PAWC range from the *Field Manual* as a starting point for selection of possible APSoils.

Step 5: Use observations on rooting depth that will reflect any subsoil constraints to adjust the PAWC. In this preliminary approach pending refinement, the PAWC should be adjusted by using the rooting depth observations if available, or failing this, a reasoned estimate of root depth in the soil. The reasoned approach may draw on past cropping performance of the soil, or observations made in similar soils. The adjustment takes into consideration the crop root architecture, which is likely to diminish in density in response to the type of response; a chemical constraint (e.g. pH, salinity) is likely to progressively strengthen with depth and cause roots to peter out, so the adjustment to the "bucket" should be non-linear with depth. For example, for a saline-constrained soil where roots are observed to 100 cm, and the *Field Manual* indicates a PAWC of 200 mm for 150 cm (maximum depth) non-constrained profile, the adjusted PAWC would not be a 30% (100 versus 150 cm) but rather 50% of the full potential, i.e. 100 mm PAWC. For a depth-constrained profile where the roots meet an abrupt stop (e.g. at bedrock), the adjustment should subtract the proportion of 'missing' subsoil depth given indicatively in the *Field Manual* for the soil. For soil containing stones or gravels, yet the profile depth matches the *Field Manual*, the PAWC adjustment should account for the proportion of stones and gravels.

The above provides a *first* estimate of PAWC. It is likely to require further refinement over time as yield predictions based on the PAWC are compared with achieved yields.

The project has undertaken sampling along five transects in the Central Darling Downs to evaluate the above approach. Below we present two of the transects to illustrate the steps above. The transect figures show the sites projected on the survey slope, the LRA boundaries, whether salinity or sodicity were measured in the soil, course (>2 mm) fragments, indicative PAWC range for the LRA (from *Field Manual*), and the APSoil PAWC (wheat) if co-located with the site. In line with Step 3, the soil analyses, and site and landscape observations enabled each site along the transect to be matched to a soil type from the *Field Manual* and the PAWC adjusted if the data dictated. One site in each transect was located as close to an existing APSoil site to reference the PAWC.

Transect 4 (Figure 6) is 20 km long and in the southern part of the Central Darling Downs. It traverses LRA 8a "Poplar Box Walloons" formed on fine grained Walloon sandstone and has a gently sloping relief featuring undulating rises and low hills. The major soils are self-mulching, black cracking clays. This LRA gently transitions to LRA 2b "Older Alluvial Plains" on older, broad level plains of mixed basaltic and sandstone alluvium. Major soils for LRA 2b are grey cracking clays. The transect finishes at the base of the hillslope with LRA 1a, which is formed on recent, broad alluvial plains, again of mixed basaltic and sandstone origins. Common soils include black and grey cracking clays or texture

Table 1. Selected soils from the Central Darling Downs and possible APSoil profile candidates

Soil Type[1]	LRAs[2]	PAWC range (mm)[3]	APSoil profiles
Black Vertosol Anchorfield	1a, 1b, 2a	> 250	6, 7 (observed in 1a)
Grey Vertosol Cecilvale	1a, 1b, 2a, 2b, 2c, 3a,	200-250	17, 115 (observed in 1a) 10 (observed in 5a)
Black Vertosol Condamine	1a, 1b, 3a	150-200	8 (observed in 1a)
Black Vertosol Mywybilla	1a, 2a, 2b, 2c,	>250	1 (observed in 2a)
Black Vertosol Waco	1a, 2a, 2b, 2c, 7a, 7c	> 250	3, 1012, 14, 16 (observed in 2a) 30 (observed in 7a)
Brown Vertosol Millmerran	2d, 3a, 4a,	100-150	74 (observed in 3a)
Brown Sodosol Downfall	1a, 2b, 2d, 3a, 9a, 11,	100-150	69 (observed in 3a)
Grey Vertosol Kupunn	5a, 5b	200-250	9, 19, 20 (observed in 5a)
Grey Vertosol Moola	6a, 6b, 6c,	100-150	73 (observed in 6b, Mungbean only)
Grey Sodosol Walker	6a, 6c	100-150	72 (observed in 6b, Mungbean only)
Brown Sodosol Diamondy	6b	50-100	88 (observed in 6b)

[1] from local soil classification in the *Field Manual*; [2] as a main soil type; 3 from *Field Manual*

contrast bleached sands or loams over brown or black clays. The four sites in the transect are 4a (LRA 8a), 4b and 4c (LRA 2b) and 4d (LRA 1a).

The soils associated with each of the LRAs that were crossed are presented in the table in the Appendix, which also shows the site match to soil type. Site 4a is an Elphinstone soil on slopes (2-6%) of gently undulating plains and rises and consists of deep (100-150 cm) self-mulching black cracking clay that grades to brownish and yellowish and is formed on fine grained sandstone. At depth it can be highly sodic and saline and the PAWC is moderate (100-150 mm). Site 4b matches the Waco soil on gently sloping to flat alluvial plains. This soil comprises deep to very deep (100-180 cm), fine, self-mulching, dark cracking clay becoming browner at depth and formed on basaltic alluvium. It may be sodic and saline at depth. The unconstrained PAWC is very high (>250 mm). Lower in the landscape, site 4c is a Mywybilla soil on gently sloping to flat alluvial plains. The PAWC may be very high (>250 mm). This site is near APSoil # 4, which has a PAWC recorded as 281 mm and consistent with the *Field Manual*. Finally, 4d matches the Waco soil (gently sloping to flat alluvial plains), and with a very high PAWC (>250 mm). Roots were seen over the full length of all four profiles, meaning that none were constrained and so likely to reflect the PAWCs allocated to each soil in the *Field Manual*.

Transect 11 is 12 km long (Figure 7) and in the northern part of Central Darling Downs on the south-facing range. It firstly traverses LRA 7a, “Basaltic Uplands”, which comprises undulating rises and rolling low hills. The major soils of the LRA include grey-brown and brown clays or clay loams. Lower in the landscape it cuts across LRA 2a of “Older Alluvial Plains” and occupies broad level plains of basaltic alluvium. The major soils include black, self-mulching cracking clays. The transect then moves into LRA 1a, “Recent Alluvial Plains”. The LRA is also featured in Transect 4 and is part of the same valley system, so, again, is formed on recent, broad alluvial plains of mixed basaltic and sandstone origins. Common soils include black and grey cracking clays or texture contrast bleached sands or loams over brown or black clays. The four sites in the transect are 11a (LRA 7a), 11b (LRA 2a), 11c and 11d in LRA 1a.

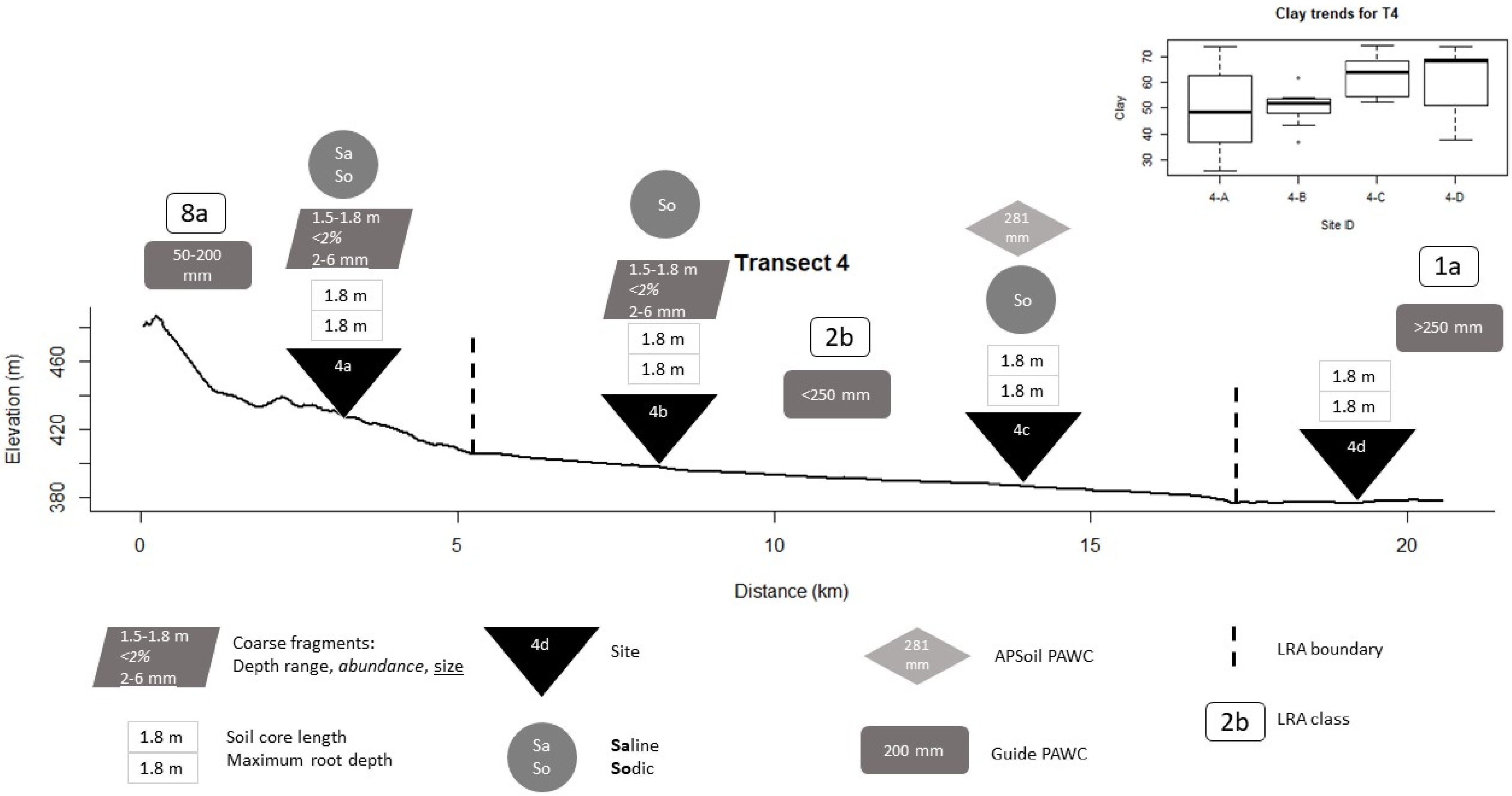

Figure 6. Transect 4 sites positioned on terrain with accompanying LRA boundaries, coarse fragments, profile and root depth, saline and sodic conditions, APSoil PAWC and clay %

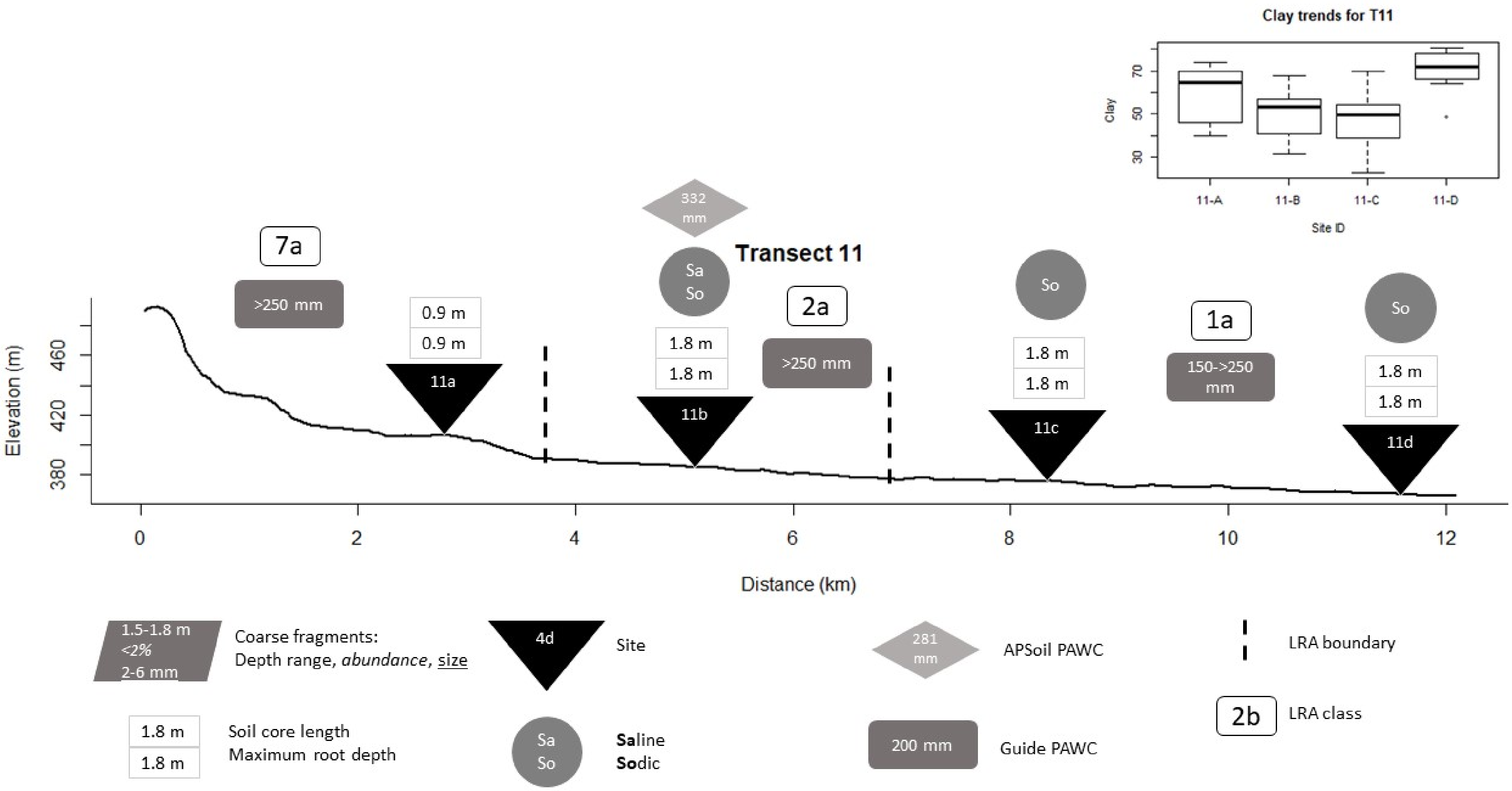

Figure 7. Transect 11 sites positioned on terrain with accompanying LRA boundaries, coarse fragments, profile and root depth, saline and sodic conditions, APSoil PAWC and clay %

The soils associated with the LRAs covered by transect 11 are presented in the Appendix. Site 11a is a Burton soil on long gentle slopes and broad flat basalt ridges and features moderately deep to deep (75-150 cm) non-cracking red-brown to red clay. The PAWC is moderate (100-150 mm), and given the observed soil depth was 90 cm, the PAWC is likely to be ~110 mm after adjustment. Site 11b is a Waco soil on gently sloping to flat alluvial plains. This soil is deep to very deep (100-180 cm), fine, self-mulching, dark cracking clay becoming browner at depth and formed on basaltic alluvium, and may be sodic and saline at depth. PAWC from the *Field Manual* is very high (>250 mm) and consistent with the APSoil PAWC near the site (# 11; 332 mm). Roots were seen all the way through the soil. Sites 11c and 11d match the Anchorfield soil on gently sloping to flat alluvial plains. This is a self-mulching, dark clay becoming grey, yellow or brown at depth. The soil may be sodic and moderately to highly saline at depth and the unconstrained PAWC can be very high (>250 mm). Roots were noted throughout both soil profiles so the PAWC at the site was not constrained.

Conclusions

Plant Available Water Capacity (PAWC) is an important soil parameter that assists dryland growers in particular to plan and manage their crops. PAWC data for over 1100 Australian soils are freely available to growers through the APSoil database, Google Earth or SoilMapp for iPad. However, not every soil is covered so that most growers need to use the resources available to match their soil to APSoil. These resources include soil and land mapping and reports that can lead the farmer to make a strong match. This paper illustrates one such approach being tested in the Central Darling Downs that applies a knowledge of the soils in the landscape, how they were formed and their distributions. Once the match between the soil of interest and the PAWC from APSoil or other resources has been made, the PAWC for the soil of interest can be adjusted based on the depth of roots observed in the soil profile, which is an indicator of depth to PAWC constraining factors, if any.

Work is currently underway to develop and evaluate digital soil maps. These are maps that predict soil properties on a 90 m x 90 m grid (http://www.clw.csiro.au/aclep/soilandlandscapegrid/). This provides the opportunity to map within LRA unit variability, but this is still research in progress.

Resources

Queensland soils and others

LRA (and other) mapping available through the Queensland Globe:
https://qldglobe.information.qld.gov.au/ (Select 'Add Layers', then choose 'Land resource area mapping' under 'Geoscientific information' and zoom into the area of interest)

LRA manuals from: https://publications.qld.gov.au/dataset?q=land+managament+manual

APSoil, PAWC characterisation protocols

The APSoil database is freely available here: http://www.apsim.info/Products/APSoil.aspx includes link to Google Earth file)

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

Soil Matters book: http://www.apsim.info/Portals/0/APSoil/SoilMatters/pdf/Default.htm

SoilMapp: for Apple iPad devices, see www.csiro.au/soilmapp and links to Apple App Store

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The research undertaken as part of this project is made possible by the significant contributions of growers throughout the Central Darling Downs - especially those allowing entry on their land the generous spend time with us in discussion. Our thanks also go for the good discussions we have had with Drs Andrew Biggs and Mark Silburn from the Queensland Government Department of Natural Resources and Mines.

References

Biggs, A.J.W., Coutts, A.J., Harris, P.S. (Eds.), (1999) Central Darling Downs Land Management Manual - Soil Chemical Data Book, DNRQ990102. Government of Queensland, Coorparoo, Qld, 107 pp.

Dalgliesh, N. and Foale, M.A., (1998) Soil Matters: Monitoring Soil Water and Nutrients in Dryland Farming. CSIRO Tropical Agriculture, Agricultural Production Systems Research Unit, Toowoomba, Qld.

Harris, P.S., Biggs, A.J.W., Coutts, A.J. (Eds.), (1999a) Central Darling Downs Land Management Manual - Field Manual, DNRQ990102. Government of Queensland, Coorparoo, Qld, 191 pp.

Harris, P.S., Biggs, A.J.W., Stone, B.J., Crane, L.N., Douglas (Eds.), (1999b) Central Darling Downs Land Management Manual - Resource Information Book, DNRQ990102. Government of Queensland, Coorparoo, Qld, 321 pp.

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Appendix

Table 2. Transect 4 Land Resource Areas and component soils (descriptions adapted from the Field Manual; Harris et al. 1999a).

LRA	Site	Soil type d = dominant s = subdominant	Setting	Description	PAWC
LRA 8a "Poplar Box Walloons" on fine grained Walloon sandstone	4a	Elphinstone (d)	slopes (2-6%) of gently undulating plains and rises	deep (100-150 cm) self-mulching black cracking clay that grades to brownish and yellowish and formed on fine grained sandstone. At depth it can be highly sodic and saline	moderate (100-150 mm)
		Talgai (s)	slopes (3-6% and hilltops and dissected low sandstone hills	black or grey cracking clay with brown clay subsoils, sodic and moderately saline at depth	moderate (100-150 mm)
		Charlton (s)	mid to upper slopes on basalt rises and low hills	coarse self-mulching black cracking clay on basalts	moderate (100-150 mm)
		Purrawunda (s)	mid to lower slopes (4-8%) of basalt rises and low hills, and on broad basalt crests	fine self-mulching, brown black cracking clay on basalt	moderate (100-150 mm)
		Toolburra (s)	gently undulating to undulating broad sandstone ridges	moderately deep to deep, red-brown cracking light clay	moderately high (150-200 mm)
		Kenmiur (s)	steep slopes and scarps and crests of flat-topped and rounded low hills, including basalt	very shallow gravelly or stony brown loam or clay loam	very low PAWC (<50 mm)
		Walker (d)	upper slopes of undulating sandstone rises	moderately deep to deep texture contrast soil with a dark brown to grey-brown loam sandy loam to clay loam over dark brown to dark grey-brown clay; highly sodic and saline at depth	moderate (100-150 mm)

LRA	Site	Soil type d = dominant s = subdominant	Setting	Description	PAWC
LRA 2b “Older Alluvial Plains” on older, broad level plains of mixed basaltic and sandstone alluvium		Cecilvale (d)	elevated plains of mixed alluvium	deep crusting, grey cracking clay. It may be strongly sodic, becoming strongly saline at depth	high (200-250 mm)
	(4c)	Mywybilla (s)	gently sloping to flat alluvial plains	deep to very deep self-mulching dark clay with a subsoil that is black or very dark grey grading to light brownish grey heavy clay. It can be sodic and moderately saline at depth	very high (>250 mm)
	(4b)	Waco (s)	gently sloping to flat alluvial plains	deep to very deep (100-180 cm), fine, self-mulching, dark cracking clay becoming browner at depth and formed on basaltic alluvium, may be sodic and saline at depth	very high (>250 mm)
		Downfall (s)	flat plains and very gently sloping (<1%) valley floors of mixed alluvium	found on the back plain and is a hardsetting loam over brown clay on sandstone becoming, and increasingly sodic and saline at depth	moderate (100-150 mm)
		Oakley (s)	flat plains, very gently sloping valley floors (<2%)	thin reddish brown hardsetting loamy surface, and red-brown clay subsoils of mixed origin. Can be moderately saline	moderate (100-150 mm)
LRA 1a “Recent Alluvial Plains” on broad level plains of mixed basaltic and sandstone alluvium		Condamine (d)	along active river floodplains, terraces and stream banks	deep to very deep (80-100 cm) coarse self-mulching black cracking clay. The soil may be sodic and highly saline at depth	moderately high (150-200 mm)
		Mywybilla (d)	gently sloping to flat alluvial plains	deep to very deep self-mulching dark clay with a subsoil that is black or very dark grey grading to light brownish grey heavy clay. It can be sodic and moderately saline at depth	very high (>250 mm)
		Anchorfield (d)	gently sloping to flat alluvial plains	a self-mulching, dark clay becoming grey, yellow or brown at depth. The soil may be sodic and moderately to highly saline at depth	very high (>250 mm)

LRA	Site	Soil type d = dominant s = subdominant	Setting	Description	PAWC
		Haslemere (d)	slight rises on the Condomine River floodplain	deep texture contrast soil with thin (<20 cm) bleached sandy loam to clay loam surface over black clay subsoils, on alluvia of mixed origin. It can be highly saline	low (50-100 mm)
	4d	Waco (s)	gently sloping to flat alluvial plains	deep to very deep (100-180 cm), fine, self-mulching, dark cracking clay becoming browner at depth and formed on basaltic alluvium, may be sodic and saline at depth	very high (>250 mm)
		Cecilvale (s)	elevated plains of mixed alluvium	deep crusting, grey cracking clay. It may be strongly sodic, becoming strongly saline at depth	high (200-250 mm)
		Downfall (s)	flat plains and very gently sloping (<1%) valley floors of mixed alluvium	found on the back plain and is a hardsetting loam over brown clay on sandstone becoming, and increasingly sodic and saline at depth	moderate (100-150 mm)
		Combidiban (s)	low sandy banks in flat to gently undulating alluvial plains	a deep texture contrast soil with yellow, grey or brown sandy clay subsoils. Located on low sandy banks on alluvial plains and is sodic at depth	small (<50 mm)

Table 3. Transect 11 Land Resource Areas and component soils (descriptions adapted from the Field Manual; Harris et al. 1999a).

LRA	**Site**	**Soil type** d = dominant s = subdominant	**Setting**	**Description**	**PAWC**
LRA 7a, “Basaltic Uplands” on undulating rises and rolling low hills		Craigmore (d)	mid to lower slopes of basalt rises and hills	deep to very deep (100-180 cm) self-mulching cracking clay with distinct red-brown subsoil	very high (>250 mm)
		Irving (d)	mid to lower slopes of low basalt hills	deep to very deep (100-180 cm) fine self-mulching cracking clay with brown or reddish brown subsoils o	very high (>250 mm)
		Charlton (d)	mid to upper slopes on basalt rises and low hills	coarse self-mulching black cracking clay	moderate (100-150 mm)
		Purrawunda (d)	mid to lower slopes (4-8%) of basalt rises and low hills, and on broad basalt crests	fine self-mulching, brown black cracking clay	moderate (100-150 mm)
		Kenmiur (d)	steep slopes and scarps and crests of flat-topped and rounded low hills, including basalt	very shallow gravelly or stony brown loam or clay loam	very low PAWC (<50 mm)
		Beauaraba (s)	upper slopes on low basalt hills and crests	very shallow, very dark cracking clay	low (<50 mm)
		Aubigny (s)	gently undulating low basalt hills and rises	shallow to moderately deep (30-70 cm), non-cracking reddish brown clay	low (<50 mm)
		Southbrook (s)	upper slopes, benches and flat-topped ridges of basalt rises and low hills	moderately deep (50-100 cm) non-cracking clay on basalt	moderate (50-150 mm)

LRA	Site	Soil type d = dominant s = subdominant	Setting	Description	PAWC
		Mallard (s)	upper slopes and broad flat basalt ridges	very shallow to shallow (20-40 cm) brown to grey-brown clay loam over brown and red clay	low (<50 mm)
	11a	Burton (s)	long gentle slopes and broad flat basalt ridges	moderately deep to deep (75-150 cm) non-cracking red-brown to red clay	moderate (100-150 mm
		Aberdeen (s)	in marginal areas between dark cracking clays and red soils	moderately deep to deep (50-130 cm) reddish brown coarsely structure clay	very high (>250 mm)
		Yargullen (s)	lower slopes, valley floors and alluvial fans from basalt	moderately deep (50-130 cm) black heavy clay	low (50-100 mm)
2a “Older Alluvial Plains” on broad level plains of basaltic alluvium	11b	Waco (d)	gently sloping to flat alluvial plains	deep to very deep (100-180 cm), fine, self-mulching, dark cracking clay becoming browner at depth and formed on basaltic alluvium, may be sodic and saline at depth	very high (>250 mm)
		Anchorfield (s)	gently sloping to flat alluvial plains	a self-mulching, dark clay becoming grey, yellow or brown at depth. The soil may be sodic and moderately to highly saline at depth	very high (>250 mm)
		Mywybilla (s)	gently sloping to flat alluvial plains	deep to very deep self-mulching dark clay with a subsoil that is black or very dark grey grading to light brownish grey heavy clay. It can be sodic and moderately saline at depth	very high (>250 mm)
		Cecilvale (s)	elevated plains of mixed alluvium	deep crusting, grey cracking clay. It may be strongly sodic, becoming strongly saline at depth	high (200-250 mm)
		Yargullen (s)	lower slopes and valley floors	moderately deep black heavy clay with fine to moderate granular surface of soft white carbonate. Strong alkalinity.	low (50-100 mm)

LRA	Site	Soil type d = dominant s = subdominant	Setting	Description	PAWC
LRA 1a "Recent Alluvial Plains" on broad level plains of mixed basaltic and sandstone alluvium		Condamine (d)	along active river floodplains, terraces and stream banks	deep to very deep (80-100 cm) coarse self-mulching black cracking clay. The soil may be sodic and highly saline at depth	moderately high (150-200 mm)
		Mywybilla (d)	gently sloping to flat alluvial plains	deep to very deep self-mulching dark clay with a subsoil that is black or very dark grey grading to light brownish grey heavy clay. It can be sodic and moderately saline at depth	very high (>250 mm)
	11c, 11d	Anchorfield (d)	gently sloping to flat alluvial plains	self-mulching, dark clay becoming grey, yellow or brown at depth. The soil may be sodic and moderately to highly saline at depth	very high (>250 mm)
		Haslemere (d)	slight rises on the Condomine River floodplain	deep texture contrast soil with thin (<20 cm) bleached sandy loam to clay loam surface over black clay subsoils, on alluvia of mixed origin. It can be highly saline	low (50-100 mm)
		Waco (s)	gently sloping to flat alluvial plains	deep to very deep (100-180 cm), fine, self-mulching, dark cracking clay becoming browner at depth and formed on basaltic alluvium, may be sodic and saline at depth	very high (>250 mm)
		Cecilvale (s)	elevated plains of mixed alluvium	deep crusting, grey cracking clay. It may be strongly sodic, becoming strongly saline at depth	high (200-250 mm)
		Downfall (s)	flat plains and very gently sloping (<1%) valley floors of mixed alluvium	found on the back plain and is a hardsetting loam over brown clay on sandstone becoming, and increasingly sodic and saline at depth	moderate (100-150 mm)
		Combidiban (s)	low sandy banks in flat to gently undulating alluvial plains	a deep texture contrast soil with yellow, grey or brown sandy clay subsoils. Located on low sandy banks on alluvial plains and is sodic at depth	small (<50 mm)

Cover crops can boost soil water and protect the soil for higher crop yields

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Take home messages

- Cover crops can increase fallow water storage, and improve crop performance and returns in northern farming systems
- In each experiment, a cover crop treatment provided the highest plant available soil water by the end of the fallow
- The best cover crop treatment depended on the length of the fallow. A later spray-out, with more resilient cover, was best in the longer fallow. However, delaying spray-out too long had a dramatic effect on water storage
- Cover crop saved 2-3 fallow herbicide sprays and dramatically improved establishment at one of the sites
- Yields and returns were increased by the best cover crop treatment at each trial, but yield effects appear to be in excess of those expected from the increased soil water storage
- Biology effects must be considered carefully; white French millet cover crops in the northern region have previously been shown to dramatically increase mycorrhizal colonisation of wheat (good), increase free-living nematodes (good), increase cellulase activity and bacterial abundance from additional fresh crop residues (good), but also increase root-lesion nematode populations (bad).

Cover crops in the northern region

Cover crops are not new. They have been used (mostly) by organic and low-input growers to protect the soil from erosion in low stubble situations, return biomass that helps maintain soil organic matter and biological activity, and to provide additional nitrogen when legumes are used.

However, growing cover crops uses water, and storing Plant Available Water (PAW) is 'king' in northern farming systems; only 20-40% of the northern region's rainfall is typically transpired by dryland crops, up to 60% of rainfall is lost to evaporation, and a further 5-20% is lost in runoff and deep drainage. Every 10 mm of extra stored soil water available to crops could increase dryland grain yields by up to 150 kg/ha, with corresponding benefits to dryland cotton growers as well. So, growing crops that do not produce grain or fibre is understandably considered 'wasteful' of both rainfall and irrigation water.

Yet, research is now supporting growers' experience that cover crops can provide many of their benefits with little or no net loss of soil water at the end of the fallow period. GRDC's Eastern Farming Systems project and Northern Growers Alliance (NGA) trials have both shown that cover crops and increased stubble loads can reduce evaporation, increase infiltration and provide net gains in plant available water over traditional fallow periods. This suggests cover crops may be a key part of improved farming systems; providing increased productivity, profitability and sustainability.

The science of stubble and evaporation

Retained stubble provides ground cover that protects the soil from rainfall impacts and so improves infiltration to store more water in the soil. Conventional wisdom is that increased stubble loads can slow down the initial rate of evaporation, but that these gains are short-lived and lost from accumulated evaporation after several weeks. However, further rain within this period and the manipulation of stubble to concentrate stubble loads in specific areas, provide an opportunity to reduce total evaporation and to accumulate more plant available water.

In southern Queensland and northern NSW, cover crops are used to overcome a lack of stubble and protect the soil following low residue crops (e.g. chickpea, cotton) or following skip-row sorghum with uneven stubble and exposed soil in the ‘skips’.

Growers typically plant white French millet or sorghum and spray them out within ~60 days to allow recharge in what are normally long fallows across the summer to the next winter crop. Allowing these ‘cover crops’ to grow through to maturity led to significant soil water deficits and yield losses in subsequent winter crops. However, the Eastern Farming Systems project showed only small deficits (and even water gains) accrued to the subsequent crops when millets were sprayed out after 6 weeks, with average grain yield increases of 0.36 t/ha. Furthermore, the Northern Growers Alliance showed that the addition of extra stubble (from 5-40 t/ha) after winter crop harvest appeared to reduce evaporation, with initial studies showing between 19 mm and 87 mm increases in plant available water. These gains will be valuable if validated in further research and captured in commercial practice.

Our current project is monitoring sites intensively to quantify the impact of different stubble loads on the accumulation of rainfall, the amount of water required to grow cover crops with sufficient stubble loads, the net water gains/losses for the following crops and the impacts on their growth and yield. This paper reports on the first two sites in southern Queensland, which will be used in simulation/modelling later in the project to assess the wider potential and economic impacts of cover crops in both grain and cotton production systems.

Experiment 1 – Yelarbon (pivot-irrigated cotton, short fallowed to pivot irrigated cotton)

The Yelarbon experiment was on a pivot-irrigated paddock that grew cotton in 2016/17. The crop was picked and root cut in May, before offset discs were used on 12 June 2017 to pupae-bust and to level wheel tracks of the pivot irrigator. Nine cover treatments (Table 1) with five replicates were planted on the same day using barley (100 plants/m^2), barley and vetch mixtures (30 plants/m^2 each) and tillage radish (30 plants/m^2). Rain that night aided establishment, and the surrounding paddock was planted two weeks later to wheat for stubble cover.

Three planned termination times matched key growth stages of the main cereal treatments: Early-termination at first node (Z31) when the crop begins stem development; Mid-termination at flag leaf emergence (Z41) when the reproductive phase begins; and Late-termination at anthesis (Z65) for peak biomass production. Biomass of the cover crop treatments at their relevant termination times ranged from 1166 kg dry matter (DM)/ha (early) to 8175 kg DM/ha when the crop was grown through to grain harvest (Table 1).

The subsequent cotton crop was planted on 15 November 2017 and irrigated on a schedule determined by the surrounding wheat crop that was harvested for grain. We included a ‘grain harvest’ treatment in our experimental plots to align with the farmer’s practice. Above ground biomass was also monitored across the growth of the cover crops until termination and through the subsequent fallow. Establishment was counted in all plots and hand cuts used to estimate cotton yields.

Table 1. Cover treatments applied at the Yelarbon site prior to planting cotton

Treatment	Cover crop	Termination time	Biomass (kg/ha)
1.	Control (Bare)		
2.	Cereal	Early-sprayout	1166
3.	Cereal	Mid-sprayout	4200
4.	Cereal	Late-sprayout	5104
5.	Cereal	Mid-sprayout + Roll	4200
6.	Cereal	Grain harvest	8175
7.	Cereal + legume	Mid-sprayout	4928
8.	Cereal + legume	Late-sprayout	4149
9.	Tillage radish	Mid-sprayout	4692

Soil water

Soil water was estimated using soil cores to measure gravimetric soil water at key times across the fallow and the subsequent cotton, along with regular neutron moisture meters (NMM) and EM38 readings in each plot. These NMM and EM38 readings and the percentage ground cover were recorded every two-to-four weeks while the cover crops were growing, and every four weeks once all cover crops were terminated, and until canopy closure of the following cotton was achieved. Final EM38 and NMM readings were recorded at cotton defoliation.

The water cost of growing the barley cover crops, relative to the control treatment in the early stages of the fallow was ~40 mm for the early-termination, ~70 mm for the mid-termination and ~120 mm for the late-termination (Figure 1). However, by the end of the fallow, and a subsequent 170 mm of rainfall/irrigation in 8 events from mid-termination to cotton plant, the mid-termination treatment caught up to the control, and the early-termination had accumulated an additional 14 mm of water. Not surprisingly, this early-termination proved to be the best cover crop treatment on the short fallow. The crop that continued to harvest was ~145 mm behind by the end of the fallow. This treatment mirrored the wider paddock and so set the following pivot irrigation schedule.

Crop performance

The irrigation schedule matched to the harvested crop provided more than adequate water across the cover crop treatments and yields for all cover crop treatments were similar. However, the Control with limited ground cover was the poorest performer, with ~3 bales/ha lower yield, lower infiltration in early growth stages and less extraction of water late in the crop.

The nominal costs to plant the cover crops ($50/ha) and to spray them out ($20/ha) were almost matched by the savings from three less fallow weed sprays ($60); so the measured cotton yield responses were very profitable. For grain growers, the extra 14 mm stored moisture from the early-termination cover crop would typically produce ~200 kg/ha grain in wheat at a water use efficiency of 15 kg grain/mm water, which is worth ~$50/ha (at $270/t) and would produce an overall return of $40/ha. Any further possible benefits from cover crops, which appear to have occurred in the cotton crop, have not been included.

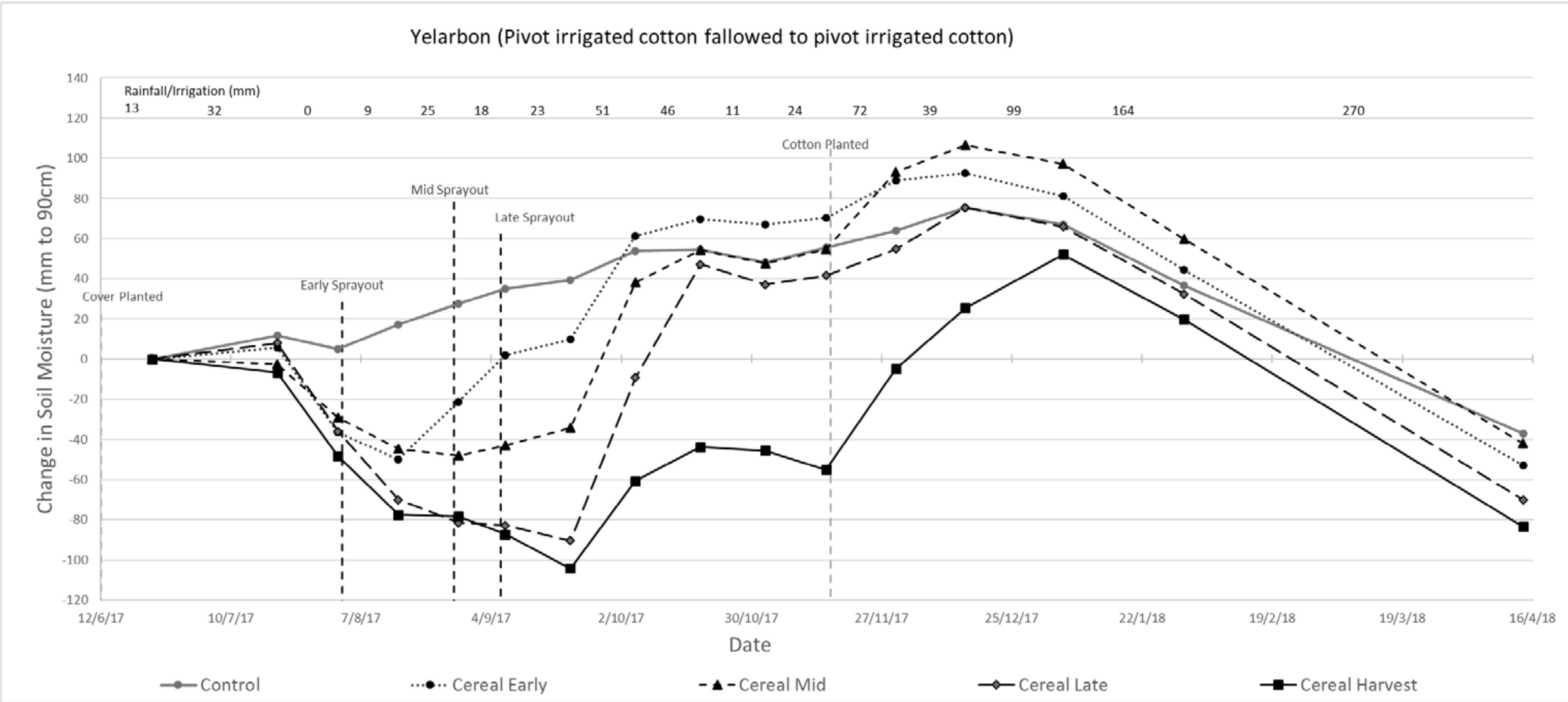

Figure 1. Changes in soil water (mm to 90 cm) from planting of key cover crop treatments until defoliation of the subsequent cotton crop at Yelarbon

Table 2. Net change in water storage over the life of the fallow (relative to the Control) and final cotton yield for each cover crop treatment at Yelarbon.

Treatment	Cover crop	Terminated	Water gain (cf control)	Cotton yield (bales/ha)
1.	Control (bare) Starting water ~100mm PAW		56 mm (fallow gain)	9.3
2.	Cereal	Early	+14 mm	12.9
3.	Cereal	Mid	-1 mm	12.7
4.	Cereal	Late	-14 mm	11.9
5.	Cereal	Mid + Roll	-2 mm	12.6
6.	Cereal	Harvest	-111 mm	14.1
7.	Cereal + legume	Mid	-16 mm	11.9
8.	Cereal + legume	Late	-7 mm	13.9
9.	Tillage radish	Mid	-40 mm	14.4

Experiment 2 – Bungunya (Skip-row sorghum, long- fallowed to dryland wheat)

The Bungunya experiment was in a long-fallow paddock following skip-row sorghum harvested in early February 2017. The paddock had deep phosphorus applied in August 2017 and was 'Kelly-chained' in September 2017 to level the paddock, which left it with little cover until the planned wheat crop. Cover crops were planted into ~120 mm of plant available soil water on 11 October. The subsequent wheat crop was planted on 1 May 2018, with hand cuts for yield done on 12 October and mechanical harvesting on 26 October. Soil water, cover crop and stubble biomass, ground cover, wheat establishment and yields were measured in the same way as the experiment at Yelarbon.

Table 3. Cover treatments applied at the Bungunya site prior to planting wheat

Treatment	Cover crop	Termination time	Biomass (kg/ha)
1.	Control (Bare)		
2.	Millet (White French)	Early-sprayout	1533
3.	Millet (White French)	Mid-sprayout	2327
4.	Millet (White French)	Late-sprayout	4365
5.	Millet (White French)	Mid-sprayout + Roll	2476
6.	Millet (White French)	Late-sprayout + Roll	4737
7.	Sorghum	Mid-sprayout	2481
8.	Lab Lab	Mid-sprayout	1238
9.	Multi-species (millet, lab lab, radish)	Mid-sprayout	1214

Soil water

The water cost of growing the millet cover crops, relative to the Control treatment in the early stages of the fallow was ~50mm for the early-termination, ~40 mm for the mid-termination and ~60 mm for the late-termination (Figure 2). The lab lab mid-termination treatment also cost ~60 mm to grow, relative to the Control treatment. These figures reflect rainfall and different rates of infiltration between soil water measurements:

- Plant to mid-termination, 65 mm in 3 events (12/10/17 to 22/11/17)
- Mid-termination to plant, 205 mm in 11 events (22/11/17 to 1/5/18)

- Follow crop plant to maturity 41mm in 3 events (1/5/18 to 10/10/18)
- Follow crop maturity to soil sample 72mm in 7 events (10/10/18 to 5/11/18)

By early March, with a subsequent 175 mm of rain in ten falls after the mid-termination, the millet treatments had all recovered to have effectively the same soil water as the Control, except where the late-terminated millet was rolled; it had gained ~20 mm more water than the other treatments.

When the subsequent wheat crop was planted, the mid-terminated millet had ~14 mm more soil water than the Control treatment, the late millet ~19 mm more, and the late millet that was also rolled had ~36mm more soil water (Table 4). Interestingly, water extraction by the wheat crop was greater from all of the millet cover crop plots than the Control, which had lower yields; perhaps due to, or resulting in less root development.

Crop performance

All cover crop treatments increased the yield of the final wheat crop (Table 4) and saved two fallow weed sprays (~$40/ha). However, the biggest yield increases were from the cereal cover crops, especially the late-terminated millet and the sorghum.

The water differences at planting (end of the fallow) may explain some of the yield difference. However, the establishment of the wheat crop was dramatically better where cover crops were used, more so where cereals were used but also for lab lab. The expected yield increases from the higher fallow water storage alone would typically be ~200 kg grain in wheat (WUE 15 kg grain/mm water) for the mid-terminated millet (worth ~$50/ha), ~280 kg grain for the late millet (worth $75/ha) and ~540 kg grain for the late +rolled millet (worth $150/ha). These gains would represent net returns of $20/ha, $45/ha and $120/ha respectively. However, the measured yield gains for these treatments were 950 kg/ha, 1461 kg/ha and 1129 kg/ha respectively, representing increase returns of between $250 and $380 /ha.

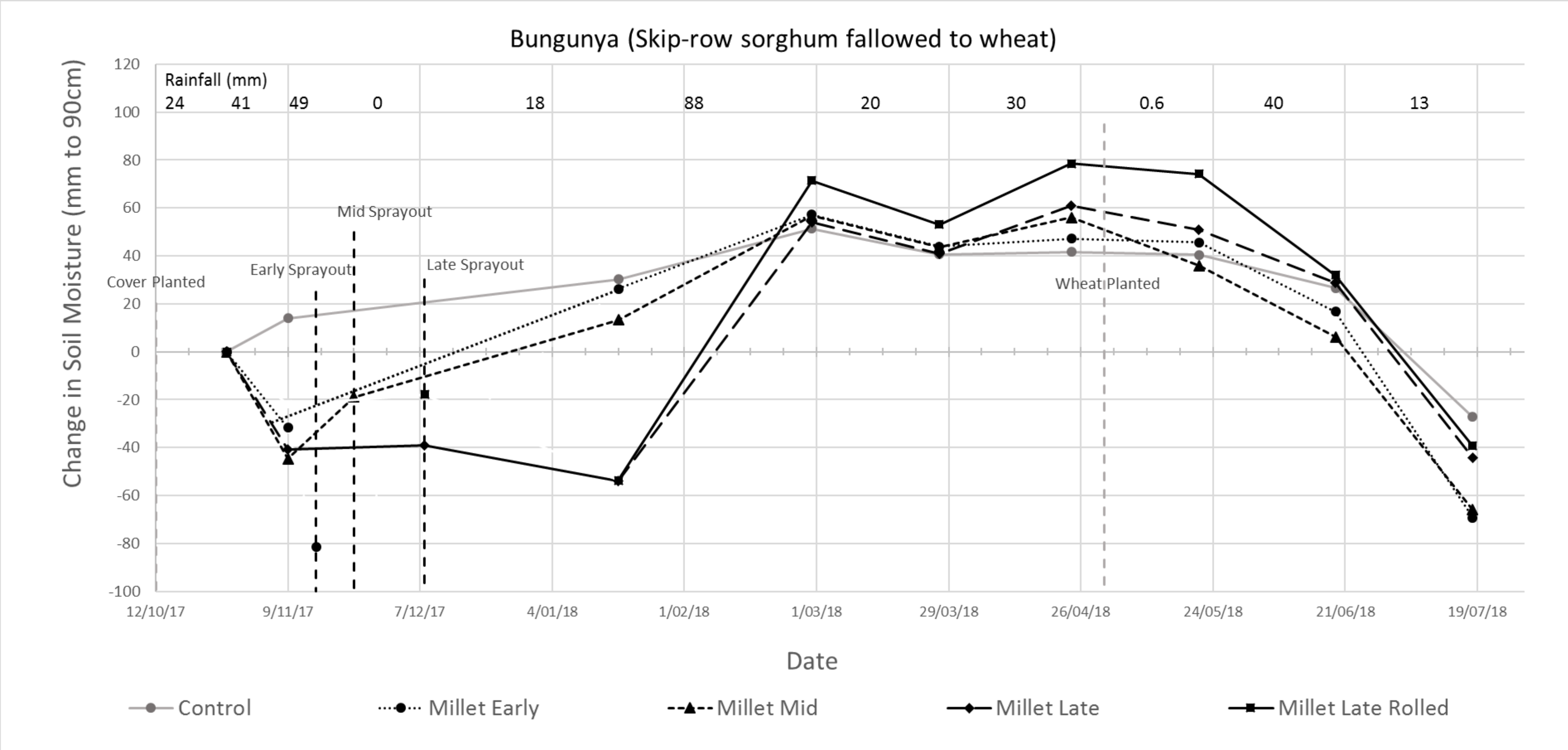

Figure 2. Changes in soil water (mm to 90 cm) from planting of the millet cover crop treatments sprayed out at different crop growth stages until harvest of the later wheat crop at Bungunya

Table 4. Net change in water storage over the life of the fallow (relative to the Control) and final wheat yield for each cover crop treatment at Bungunya.

Treatment	**Cover crop**	**Terminated**	**Water gain (cf control)**	**Wheat yield (kg/ha)**
1.	Control (bare) Starting water ~120mm PAW		42mm (fallow gain)	1436[f]
2.	Millet (White French)	Early	+5 mm	2223 [cd]
3.	Millet (White French)	Mid	+14 mm	2386 [bc]
4.	Millet (White French)	Late	+19 mm	2897 [a]
5.	Millet (White French)	Mid + Roll	+17 mm	2359 [bc]
6.	Millet (White French)	Late + Roll	+36 mm	2565 [b]
7.	Sorghum	Mid	+17 mm	2634 [ab]
8.	Lab Lab	Mid	-4 mm	1795 [e]
9.	Multi-species (millet, lab lab, radish)	Mid	+21 mm	1954 [de]

Potential biological impacts

These two experiments focused on soil water accumulation. Biological analysis was not undertaken, but some exploratory analyses will be included for selected treatments in future trials. However, past biological assessments on the Eastern Farming Systems project sites around Goondiwindi highlighted a range of biological effects following white French millet cover crops.

Mycorrhizal colonisation of roots in six-week-old wheat from 1.8% in the long-fallow following skip-row sorghum to 8.3% following an early terminated millet cover crop in the fallow (Seymour *et al.* 2006); crop growth was much stronger following the cover crop. Other positive biological effects included increases in free-living nematodes and cellulase activity that indicate a more active biological system with a greater food source from more residues; and increased Nematode Channel Ratios, which indicates greater bacterial activity from more disturbance and addition of higher quality residues (Table 5). Unfortunately, the white French millet cover crop also boosted root-lesion nematodes (*Pratylenchus* sp.), and so cover crop species must be selected carefully where root-lesion nematodes are a problem.

Table 5. Selected biological effects at wheat planting after a 15 month fallow from skip-row sorghum +/- a white French millet cover crop with different termination dates near Goondiwindi (Seymour *et al.* 2006)

District	**Treatment**	***Pratylenchus* sp/g soil**	**Free living nematodes/g soil**	**Nematode channel ration (0= fungal; 1= bacterial)**	**Cellulase assay**
Lundavra	Fallow	0.64	0.58	0.39	0.21
	Short-term millet	1.31	2.76	0.39	0.59
	Mature millet	2.51	7.33	0.57	0.89
North Star	Fallow	0.92	0.65	0.52	0.03
	Short-term millet	0.92	7.41	0.79	0.23
	Mature millet	1.45	5.25	0.87	0.11
LSD	(*P*=0.05)	0.51	2.96	0.19	0.31

Conclusions

The project results show that cover crops can indeed help increase net water storage across fallows that have limited ground cover. Importantly, these results were achieved in drier than normal seasons. For example, the Bungunya site with millet cover crops had a wet spring that allowed a well grown cover crop to develop, but was then followed by well below average rainfall through the fallow, with a few good storms in February/March. How often these soil water results will occur across different seasons will be explored across the rest of the project with further experiments and simulation modelling.

However, more dramatic are the early yield results for the subsequent cotton and wheat crops at each site. These yield responses are very large and represent big improvements in returns; far beyond what could be expected from the increases in net soil water storage across the fallows. Wheat establishment dramatically improved in the Bungunya experiment, and there was greater water extraction (especially at depth) in the Yelarbon experiment. How much of the responses can be attributed to these factors, how often such results might occur, and the contributions of other factors to these gains remains to be explored.

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References

Seymour NP, Bell MJ, Price LJ, Stirling GR and Stirling AM (2006) Improving soil biology through using millet (*Panicum mileaceum*) as a short-term fallow cover crop. 4th Australasian Soilborne Diseases Symposium. Queenstown New Zealand. 3-6 September 2006

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Farming for the future: optimising soil health for a sustainable future in Australian broadacre cropping

Alexander Nixon, Nuffield Scholar, Drillham, Qld

Key words

Nuffield, cover crop, multi-species, soil function, soil health

Take home messages

- Observations from overseas are that incorporating multi-species cover crops is an effective and efficient means to improve soil function and health
- Multi-species cover rotations are a financially viable option for Australian broadacre cropping operations seeking to improve their soil and reap the subsequent benefits through increased cash crop yields
- Careful planning and management of the rotation schedule and seed-mix selection is required to optimise benefits.

Introduction

For many years conventional farming practices have been degrading the state of our soils. The zero-till farming revolution has instigated a push towards improved soil health. New research indicates that bio-diversity and groundcover are essential contributing factors to optimal soil health, and many farms in the USA and England have been implementing multi-species cover crop rotations in conjunction with zero-till practices with amazing results in soil rejuvenation and increased cash crop yields. The sustainability of Australian broadacre dryland cash cropping operations, and the agricultural industry in general, hinges heavily on a soil health focus. Incorporating multi-species cover crops into cash crop rotations is the most effective way to improve soil health.

Cover crops for ground cover

Maintaining ground cover is essential to soil health on multiple levels. As the name implies, cover crops aim to achieve exactly that. They are intended to be sown after the completion of a cash crop, in place of long-fallowing. Cover crops are typically left to grow until the milky stage of seed production, or until sufficient biomass has been obtained, after which point, they are terminated – usually either lightly tilled in, mowed or rolled/crimped or sprayed – with the residue remaining as ground cover. Weed suppression, prevention of erosion, increased soil organic matter (SOM) levels and improved water infiltration/moisture retention, can potentially be achieved by cover cropping.

Soil function and bio-diversity through multi-species cover crops

The soil ecosystem is complex with many aspects of soil chemistry and physics are inter-related. Plant bio-diversity has proven to be a key factor when considering soil health, as different plants serve a variety of purposes both above and below the soil surface. Maintaining a diverse range of plant roots aids in preserving an array of different microbe communities and helps sustain the balance between fungi and bacteria, and also moderates the Carbon:Nitrogen (C:N) ratio. Concurrently, different plant types achieve varying degrees of cover on the soil surface and each species contributes in different ways to both the carbon and nutrient cycles. Species diversity is valuable to soil health due to its reliance on a range of functions which are often heavily inter-connected and overlapping.

Financial viability of cover crop rotations in broadacre dryland farming

Optimal soil health is important to future sustainable and financially viable broadacre cropping. Multi-species cover crops are a method for rejuvenating and maintaining soil conditions. However, broadacre dryland farming businesses face several issues when moving towards such conservation management practices. Firstly, upfront costs of cover crop seed currently remain high. Machinery investments, such as rollers, mowers or crimpers are costly and are not yet readily available in Australia. The logistical implications associated with the scale of Australian farms could incur increased expenses. And finally, business cashflow can become compromised if input costs to establish the cover crop exceed the expected returns for the season.

Logistics and considerations

Most research, trials and recommendations for implementing cover crops currently stems from the USA. When considering applying this knowledge to Australian broadacre cropping systems the information must be adapted, though many of the basic theories remain the same. Factors for consideration include, but are not limited to:

- Climate
- Soil type
- Current management practices
- Existing cropping schedules.

Species selection

Species selection is perhaps the most important element to successful cover cropping. Several factors must be considered when choosing a cover crop mix, being:

- Current soil conditions – soil testing prior to seed mix selection is advisable to establish what functions are required and thus which species can best fulfil the requirements
- Subsequent cash crop – it is important to keep this in mind to avoid any potentially negative impacts from undesirable soil changes or pathogenic species to the following crop. Varieties selected must be compatible together, and with the subsequent cash crop
- Seasonal and climatic conditions – rainfall, temperatures and time of year should all be considered when choosing each variety for a multi-species cover
- Plant functional group – a selection of cereals, grasses, legumes, brassicas and chenopods is recommended for optimal soil health benefits.

Financial viability

The effectiveness of incorporating cover crop rotations for rejuvenating and maintaining soil has been substantiated in many farming situations around the globe. Research for this report was conducted on several properties in the USA and England, with notable success in restoring soil health recorded at each. However, one common concern was the financial viability while transitioning to this management practice. A business, or business decision, is considered financially viable when generated income exceeds costs.

Another important point to note is the relative size and scale of the business. Some of the farms visited were as small as 600 acres (approximately 243 hectares), while the average farm size in Australia is 4,331 hectares (Australian Bureau of Statistics, 2017). Appropriating business funds for cover-cropping to such a scale as to fit the average Australian farm, could initially pose the following issues and risks:

- Increased upfront costs for seed and planting
- Compromised business cashflow
- Time allotted for planting/termination could result in the necessity for multiple machines to be operating to achieve the task within ideal timeframes, resulting in more business funds being absorbed by capital investments
- Soil types can vary dramatically from one end of a largescale paddock to another, impacting cover-mix selection and effectiveness.

Some suggestions to alleviate and manage these problems are to:

- Start small – one paddock at a time
- Consider frequency and size of cover rotations based on benefits produced, and increase accordingly over time
- Consider value-adding - Controlled grazing of cover crops can provide extra income/soil benefits over the cover-crop season. Investing in livestock or offering short-term agistment are two potential options.

While some financial difficulties may arise when farming operations initiate cover-crop rotations, the long-term monetary benefits are purportedly profitable. Some of the economic benefits of multi-species cover cropping are:

- Decreased fertiliser costs
- Reduced requirement for herbicides and pesticides
- Higher yields – due to improved soil health.

Conclusion

The sustainability of Australian broadacre dryland cash cropping operations, and the agricultural industry in general, hinges heavily on a soil health focus. Incorporating multispecies cover crops into cash crop rotations is a way to improve soil health.

The evidence presented in this report demonstrates that multi-species covers can alleviate several environmental factors affecting soil health by:

- reducing or preventing erosion
- increasing water infiltration
- inhibiting weed growth
- stabilising losses of or increasing soil organic matter.

Further, this report emphasises the importance of bio-diversity within a cover crop, showing how a species-rich environment creates synergy between multiple soil components. Bio-diversity encourages:

- effective carbon and nutrient cycling
- a balance of C:N ratios
- microbial growth and activity
- healthy bacteria to fungi ratios.

Though implementing diverse cover-crops can pose initial economic issues, the long-term environmental and economic benefits prove to outweigh the financial deficit associated with the transition phase. Through careful management and mix-selection, multi-species cover cropping can certainly be a viable option for Australian broadacre farmers seeking to improve soil health.

Recommendations

1. Employ zero-till farming practices wherever possible to lessen soil degradation.
2. Create a cover crop rotation schedule – based on soil test results and current cash crop rotations. It is imperative to have a plan, goal and strategy in place in order to be effective and efficient in any business venture.
3. Implement a business plan for the transition phase – expect that multi-species cover cropping is a long-term investment, interim alternative income sources may be required to support the associated expenditure.
4. Conduct regular soil testing – knowing your soil and monitoring soil changes will ensure that appropriate actions can be taken e.g. which paddocks require attention, what soil health issues are arising, and which plant species are most suited for rectification.
5. Research plant varieties suitable for the region – understanding species for both their benefits and their required growing conditions is advisable. Consider contacting a local agronomist if necessary and remember, the more species the better!
6. Construct a "seed budget". Seed will be the primary input cost. Pricing different varieties and options available and adhering to a budget will minimise any negative financial impacts in the initial season.
7. Decide which methods will be employed for planting and termination – performing an opportunity cost analysis may assist when considering alternatives.
8. Consider value-adding (such as livestock grazing). It is important to closely monitor and control any grazing to ensure the best results from plant growth benefits.
9. Encourage neighbours to get involved – a local cooperative initiative could be an option for capital investment of plant and machinery, bulk seed purchases to obtain discounts and disseminating local knowledge, information and findings from trials.
10. Consider applying for government grants and subsidies associated with agricultural conservation practices.

Further information

This Update paper contains excerpts from the author's Nuffield Scholar Report. The unabridged report is available here: https://nuffieldinternational.org/live/Report/AU/2017/alex-nixon

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Dryland and irrigated winter-sown sorghum

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Key words

frost tolerance, GxExM, grain sorghum, heat stress, soil temperature

GRDC code

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Take home messages

- Winter sowing sorghum didn't penalise yields in eight trials sites from Liverpool plains to Central Queensland and across two seasons
- In dryland cropping, winter sown sorghum provides additional sowing opportunities, reduces the chances of heat stress, and increases the chances of double cropping a winter crop
- In irrigated cropping, ratooned winter sown sorghum can compete with cotton on profits and is less risky
- Commercially available hybrids can successfully germinate and emerge in cooler soils than previously recommended, though the seed must be tested for vigour at low temperatures
- Sorghum seedlings can withstand mild frost, though so far, we haven't been able to frost kill a crop, meaning that frost risk is unknown.

Background

Water stress and extreme heat at flowering are common stresses limiting yield in sorghum across the Northern Grains Region. Earlier sowing of sorghum could avoid heat and water stress at flowering. However earlier sowing or winter sowing of sorghum in southern Queensland requires the crop to be sown into soil moisture in cold soils.

Dryland farmers are already successfully sowing maize and sorghum earlier than recommended, though the benefits for yield and the cropping system and the likely risks are not known. Previous research by Muchow, et al., (1994) identified that winter sown sorghum crops show high yield potentials with increased frost risk and a larger canopy increasing water stress risk. However, these risks require re-evaluation because frost risk thresholds (thresholds were assumed in previous research) are unknown and modern hybrids have a smaller canopy.

In irrigated systems, sorghum is a profitable option when irrigation water is limited, though it is often assumed to be a less profitable option than cotton in fully irrigated systems. Winter-sowing and opportunistically ratooning sorghum allows growers to manage risk when water supply is limiting at the beginning of the season and intensify production and profits if rainfall is greater than expected.

Previous research shows that ratooned irrigated sorghum crops yield 80% of the sown crop yield on average (Gerik et al., 1990). Growers in Central Queensland successfully ratoon irrigated sorghum crops, though questions remain on the suitability of the system in southern regions and crop sequences.

Here we report on irrigated and dryland trials conducted by UQ-QAAFI in the 2018-2019 seasons. This series of trials is part of the multi-environment sorghum agronomy experiment in collaboration with DAFQ and NSW DPI. The experiment was designed to develop a data set to support the present trend in advancing sowing times of sorghum and assess potential benefits and risks from adopting the strategy at the crop and cropping system levels.

Trial details

Two trials were sown in the 2018-2019 season at Surat and Warra, Qld. Trials included three times of sowing, four plant populations and nine commercial hybrids (Table 1). In addition, after the harvest of the second time of sowing at Surat, the crop residues were mulched, fertilised, irrigated and allowed to ratoon into a second harvest. A third time of sowing occurred at the same time when sowing 2 was ratooned (Table 1). This allowed us to also compare the yield of the ratooned sorghum crop with the yield of a sown crop.

Table 1. Winter-sown sorghum agronomy trial locations and treatments

Time of sowing (TOS)	Sowing date	Target plant population (pl/m^2)	Hybrids
"Austin Downs" Surat, Qld (irrigated)		3, 6, 9, 12	MR Buster, MR Apollo, MR Taurus, Agitator, Cracker, HGS 114, A66, G33, G44
1	8th August 2018		
2	28th August 2018 & ratooned		
3	24th January 2019		
"Wywurrie", Warra, Qld (dryland)			
1	27th July 2018		
2	19th October 2018		
3	9th November 2018		

Results and discussion

Optimum flowering windows

Crop growth conditions around flowering are important in determining final grain number and grain yield. At flowering, grain number can be reduced by temperature extremes, both heat and chilling (i.e. cold but non-freezing temperatures). Analyses of long-term climate records (see CliMate App), can be used to quantify the likelihood of these stresses around flowering and identify ideal flowering windows.

For example, Figure 1A shows that chilling or heat stress temperatures are least likely in narrow and regionally specific windows during spring and autumn. These windows have a lower likelihood of heat (>38°C) and chilling (<13°C) events in a 10-day period corresponding to the sensitive flowering phase. However, the impacts of extreme temperatures on yield depend on duration of the heat/chilling exposure, crop water status and cultivar. Research on the relationships between extreme temperatures and the yield of early sown sorghum will continue throughout the GRDC funded project "Optimising Sorghum Agronomy".

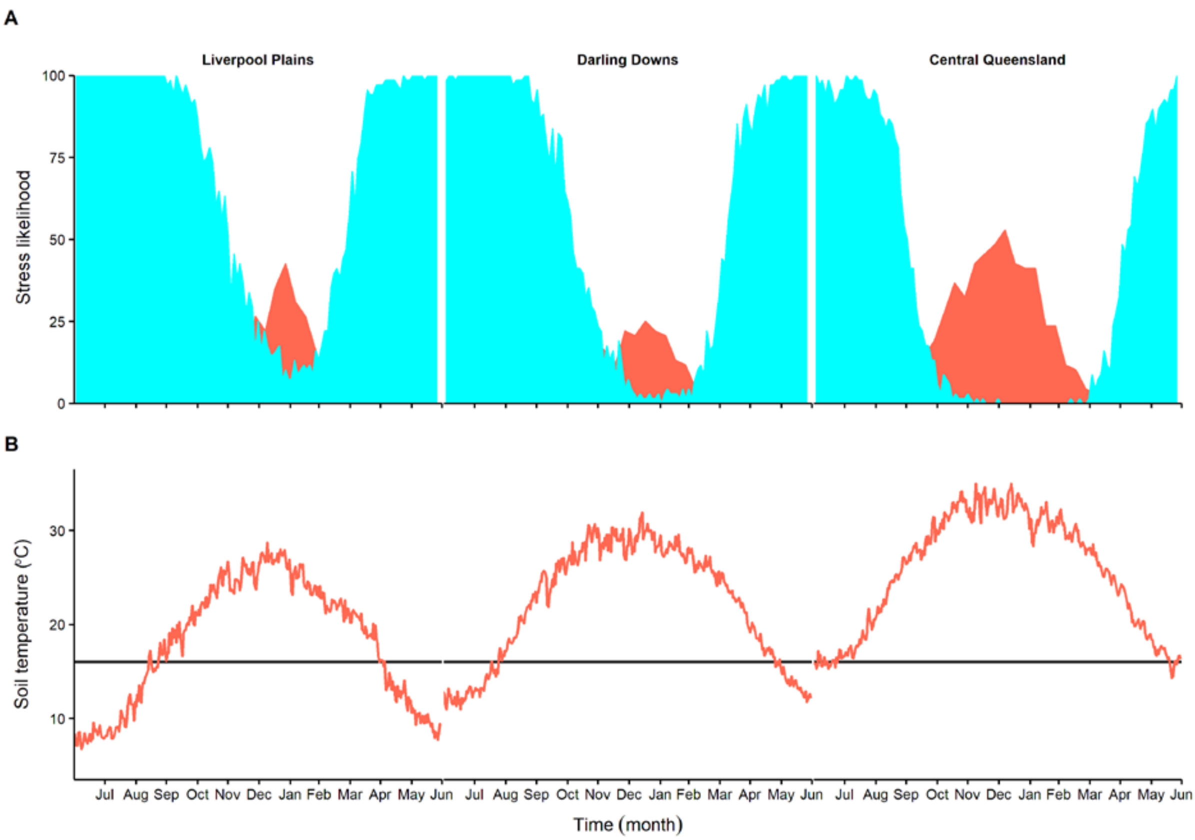

Figure 1. The likelihood or percentage of seasons exposed to heat (>38°C; **dark**) or chilling (<13°C; **light**) during a 10-day temperature sensitive period around flowering (A); and (B) the mean 9:00 am soil temperature measured at 50 mm depth in three sorghum growing regions, the Liverpool Plains, Darling Downs and Central Queensland. The horizontal line in Figure 3B shows the recommended minimum seeding depth temperature threshold for sorghum. (Note: 9:00am soil temperatures are shown because high quality long-term data for the conventional 8:00 am or minimum daily 100 mm deep soil temperatures were not available).

Targeting optimum flowering windows

The easiest way for growers to move the flowering window is to plant at a different time to their standard sowing time or to select a quicker maturity hybrid. As there is limited variation in maturity type among the commercial hybrids, moving the sowing window is the more effective option. This means sowing sorghum crops much earlier than normal, potentially moving sowing into the months of July and August depending on local climate. Soil temperatures during this period are cooler than the recommended (>16-18°C measured at sowing depth during the coolest period of the day or 8:00am; Figure 1B). Long-term trends show that July to August soil temperatures are coldest in the southern regions of Darling Downs and Liverpool Plains. However, time of sowing decisions require information on each field because of varying weather, topography, soil type, water content and ground cover, all of which strongly influence seedbed temperature.

Regardless of the sowing time, achieving rapid and uniform crop establishment is also required to realise yield potential. The decision on sowing time will then need to evaluate the trade-off between likely benefits of reducing heat stress around flowering, with the higher risk of early frost damage, higher establishment losses and potential for less even crop canopy uniformity.

Temperature effects on sorghum germination in 2018-2019

Planting sorghum into moist soils at extremely low or high temperatures can reduce crop establishment and reduce crop uniformity. Crop establishment is the result of several distinct plant development stages including seed germination, emergence, root proliferation and leaf growth. Here we studied the impact of extreme temperatures on the germination for a range of commercial sorghum hybrids in the lab.

Results showed that the lowest and highest observed seedbed temperatures from Figure 1B, reduced the proportion of sorghum seeds that successfully germinated in the lab (Figure 2).

Eight of the ten most widely grown sorghum hybrids showed germination values greater than 90%, when incubated with ideal moisture and at constant temperatures between 13 and 32.1°C (Figure 2). At 9.4°C, two of the ten tested hybrid seedlots still showed germination values larger than 90%.

Higher temperatures (≥34.9°C) reduced the germination of five out of the ten tested seedlots, yet three hybrids showed germination rates greater than 90% at extreme hot temperatures (39.5°C).

In these experiments, seeds were exposed to constant high temperatures for multiple days, whereas in the field, seedbed temperatures fluctuate diurnally. Maximum daily seedbed temperatures of 45°C were recorded during the 2018-2019 sorghum agronomy trial at Emerald, though those temperatures only exceeded the high thresholds for a short period each day (< 1 hour).

Seed production, storage, handling, seed treatment and genetics will all determine the germination rate for each hybrid-seedlot. Therefore, germination must be evaluated every year for each hybrid-seedlot. Understanding the drivers for low germination in Australian germplasm remains a priority research question.

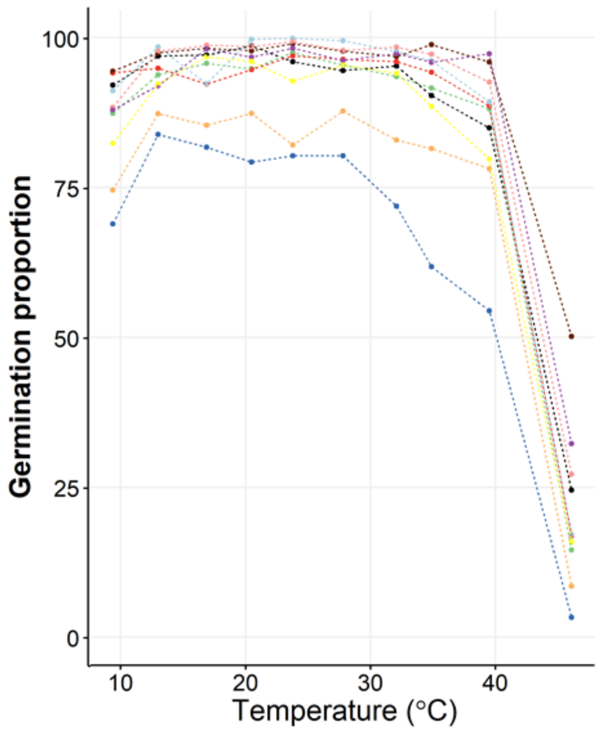

Figure 2. The proportion of sorghum seeds that successfully germinated when incubated at constant temperatures. Each colour represents one hybrid seedlot but they are not identified as the experiment doesn't differentiate if the result is due to genetic, seed production or storage factors.

2018-2019 temperature effects on predicted time required for successful sorghum germination

Low temperatures delay the period from sowing to germination and emergence. Therefore, quantifying the number of growing degree days is important. Growing degree days (GDD) are a measure of the accumulation heat and are used to predict plant development. GDD = ∑(Tmax – Tmin)/2 – Tbase. Tmax and Tmin are the daily maximum and minimum temperatures. Tbase is a crop specific minimum temperature for development. Here we estimated the required number of cumulative heat units for ten commercial hybrid seedlots under a controlled temperature environment. The results show that the first 10% of seeds germinate with 5 days but it took 9 days to achieve >90% germination at Surat in 2018 (Figure. 3). Results also show that germination time is similar across diverse sites on some dates, but germination timing is also highly variable for different sowing dates at any site (Figure. 3).

This means that July-August soil temperatures ≥9.4°C do not limit germination of commercially available sorghum hybrid-seedlots. However, germination will take a long time and will be spread over several days, meaning that the seedbed must remain moist for at least 9 days for successful germination and longer for emergence.

Investigations into the impacts of low seedbed temperatures on emergence continue in 2019-2020 through the GRDC funded project "Optimising Sorghum Agronomy".

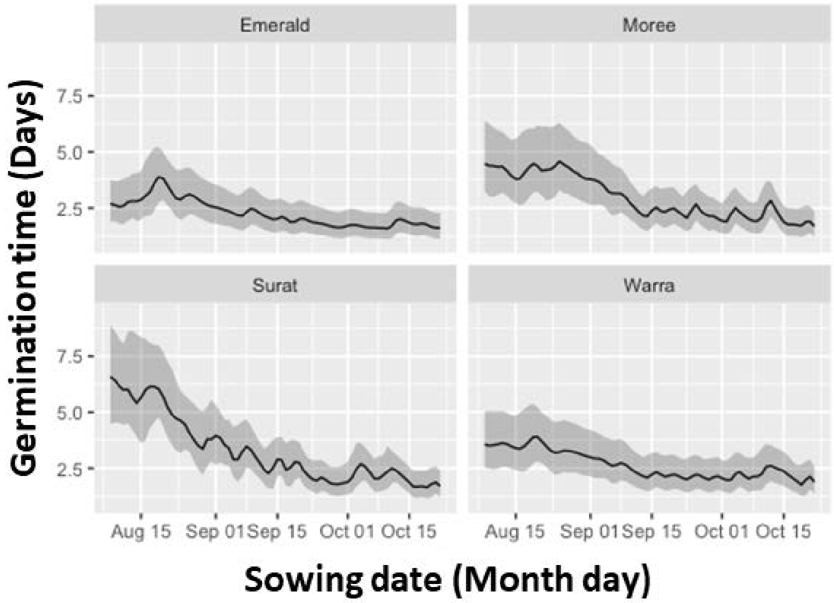

Figure 3. The predicted number of days from sowing until germination for sowing dates between 1st August and November 2018 based on seedbed temperatures recorded at four on-farm trial sites. Black line shows 50% seed germination and the grey shading shows the spread from 10 to 90% germinated seeds. (Note: data is for seed germination and not for crop emergence which will take far longer)

Climatic conditions for 2018-2019 trials

The 8:00am seedbed temperature at Surat for sowing time one was 8°C and it emerged 20 days later with seedbed temperatures of 10°C. Seedlings survived two mild frosts (~0°C) in late August and mid-September (Figure 1C). The earliest flowering hybrids in the first time of sowing had the highest photo-thermal quotient during flowering, meaning that growth and yield formation potential was greatest (Figure 4A). Flowering time of the latest flowering hybrids in the first time of sowing overlapped with the earliest flowering hybrids for the second time of sowing, meaning that combinations of hybrid and sowing time are required to target flowering (Figure 4A). Water was sufficiently available for all treatments, except irrigation ran out before time of sowing three finished flowering (Figure 4B). Maximum temperatures were high for all sowing times (Figure 4C).

Seedbed temperatures at 8:00 am measured at sowing depth (75mm) for the first time of sowing were 12°C and seed germinated 2 days later on the 30th July. Soil temperatures decreased to 10°C and seedlings emerged between 8 and 17th August. The first time of sowing at Warra had four consecutive frost days with minimum daily temperatures of 0, -4, -5 and -2°C without seedling death (Figure 5C). Pre-flowering rainfalls prevented water stress at flowering for time of sowing one and two, but time of sowing three was water stressed at flowering (Figure 5B). High temperatures occurred during flowering for all three sowing times (Figure 5C).

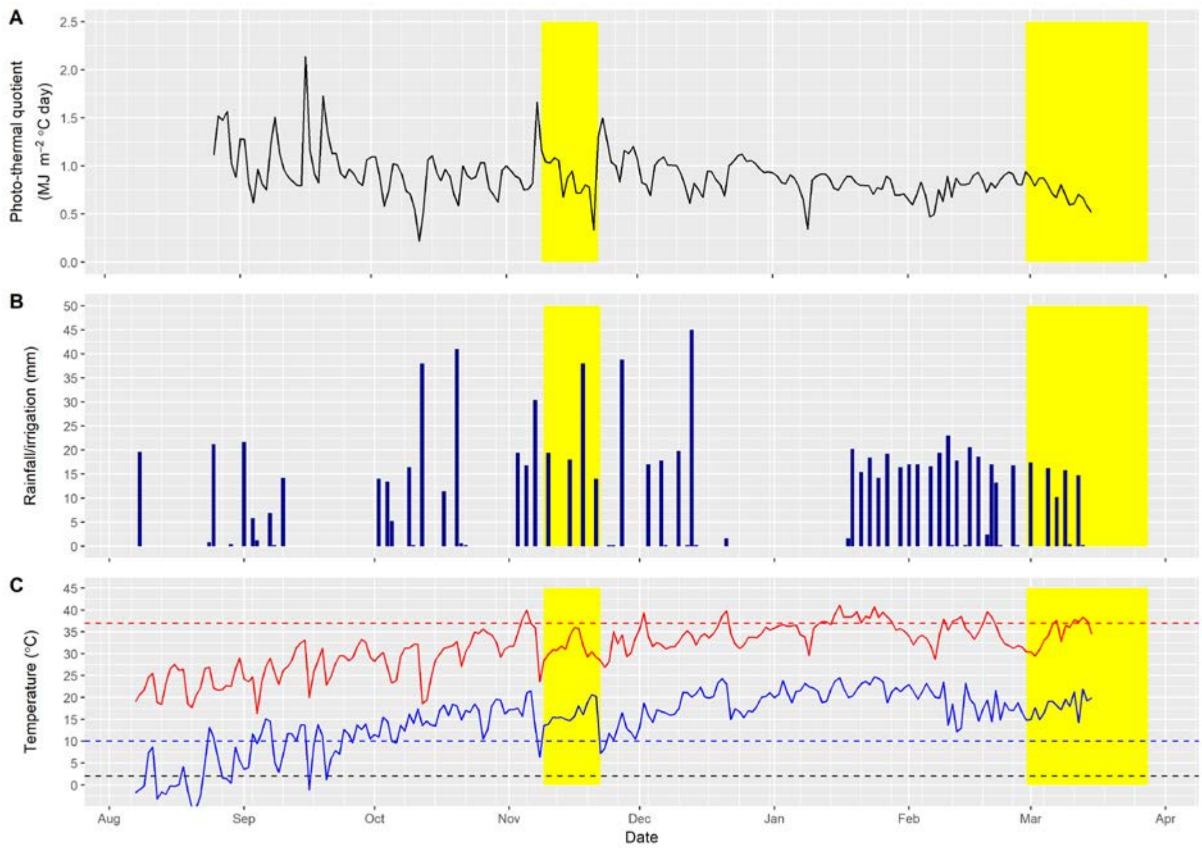

Figure 4. Photothermal quotient (A), rainfall (B) and ambient temperatures (C) at Surat, Qld for the 2018-2019 summer cropping season. The two yellow rectangles indicate the overlapping flowering timing for the 8th and 28th August 2018 sowing dates and 24th January and ratoon crop flowering dates, respectively. Solid blue and red lines represent daily maximum and minimum temperatures, respectively. Dashed horizontal represent the reported minimum (blue) and maximum (red) temperatures stress thresholds at flowering and frost (black).

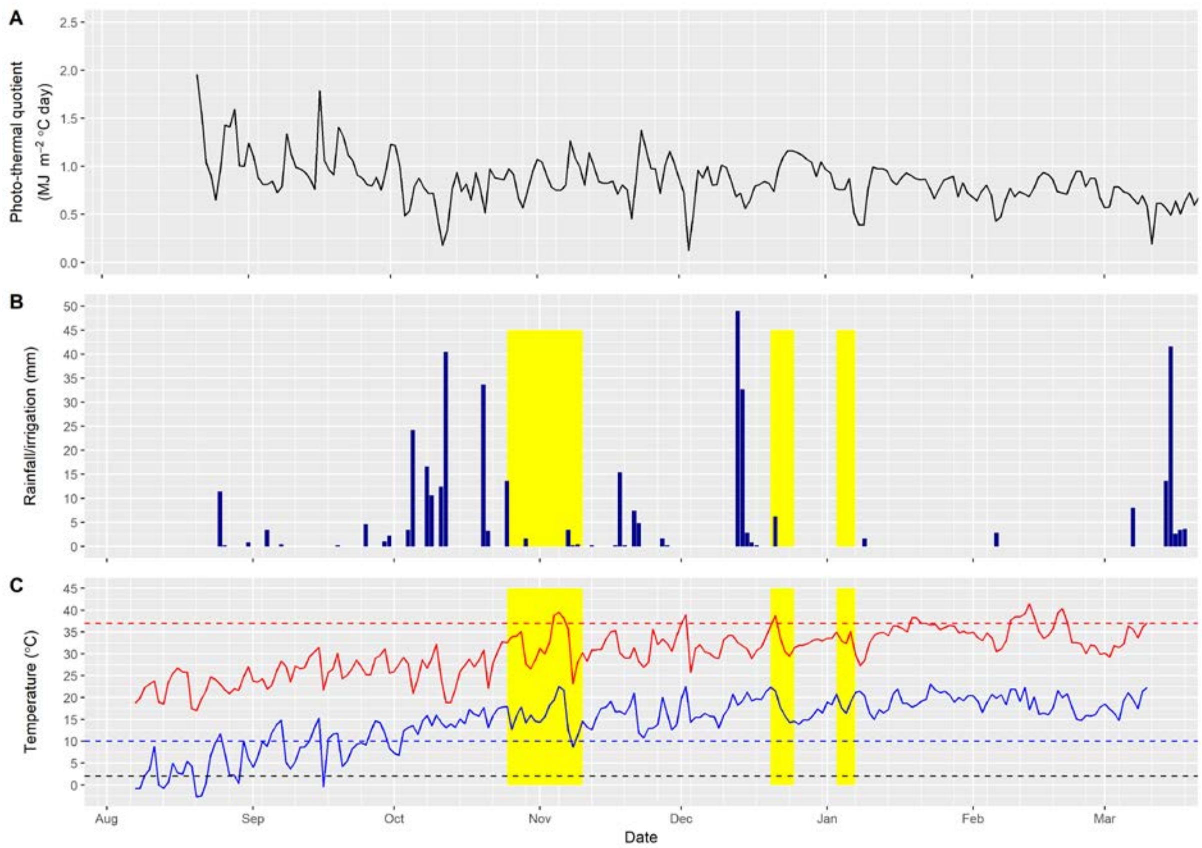

Figure 5. Photothermal quotient (A), rainfall (B) and ambient temperatures (C) at Warra, Qld for the 2018-2019 summer cropping season. The three yellow rectangles indicate flowering timing for each sowing date (see **Table 1**). Solid blue and red lines represent daily maximum and minimum temperatures, respectively. Dashed horizontal represent the reported minimum (blue) and maximum (red) temperatures stress thresholds at flowering and frost (black).

Winter sown sorghum yields

We expect high yields for early sown sorghum crops when water is sufficient, because sunny spring days with cool temperatures (high photo-thermal quotient) should maximise growth rate. However, cool non-freezing "chilling" temperatures can stress some crops and cultivars. Low temperature limits for sorghum growth and development are not characterised for modern Australian hybrids.

At Surat, grain yields averaged across all hybrids were approximately 10 t/ha (11.3 t/ha at 13% moisture content) for all plant populations sown on 8th and 28th of August (i.e. time of sowing 1 & 2; Figure 6). Lack of tillering and water stress contributed to lower yields for time of sowing three (sown 29th Jan 2019) at Surat. The ratooned time of sowing two (28th Aug 2018) crop yielded approximately 75% of the sown time of sowing two crop yield, but similar yield to time of sowing three (24th Jan 2019). The ratoon crop yields were similar to reported yield potential, but time of sowing three that grow during a similar time showed a yield gap. This result will be further analysed in the new GRDC funded project that investigates the impacts of early sowing and ratooning on root growth and water stress.

At Warra, grain yields averaged across all hybrids decreased with latter sowing dates, especially for lowest plant population densities (Fig 6) despite substantially lower pre-flowering rainfall (Figure 5C).

These results mean that sorghum crops can be sown much earlier without yield penalty, supporting 2017-2018 results. Further research on sorghum growth, development and root function at frost and chilling temperatures is required to understand early sown sorghum yield potential.

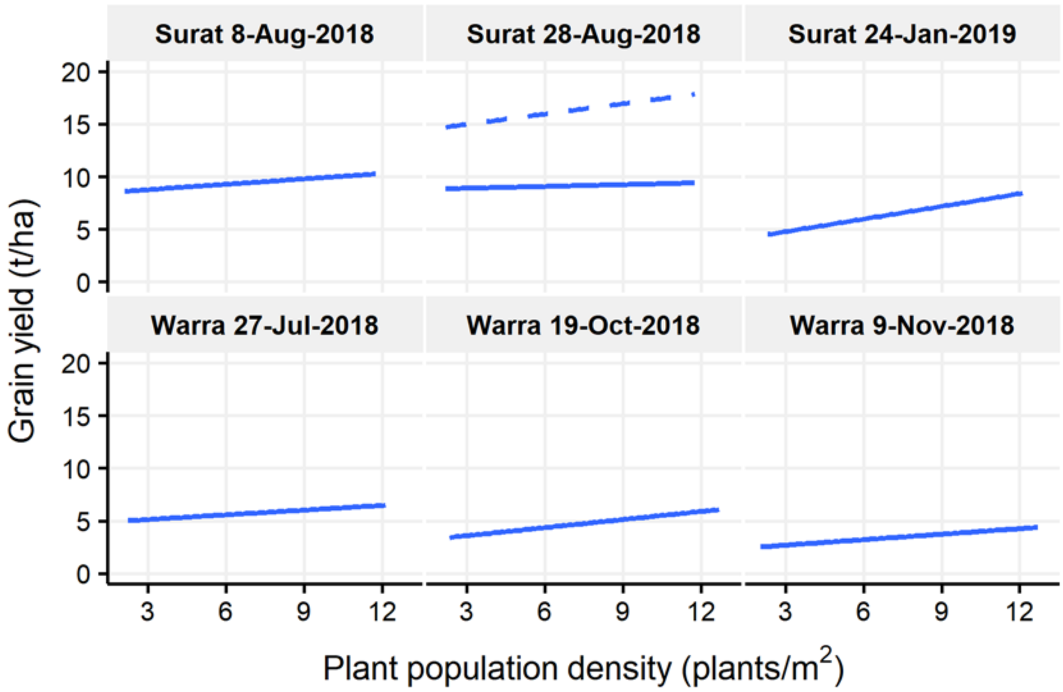

Figure 6. The effect of plant population density on sorghum grain yields averaged across all hybrids for three sowing times at Surat and Warra trial sites for the 2018-2019 summer cropping season. Solid lines indicate grain yield (dry weights) for sown crops and dashed lines show combined sown and ratoon crop yields for the Surat 28-Aug-2018 sowing.

Conclusion

Sorghum can be sown into soil moisture much earlier than recommended, but seedbed temperatures must be monitored in each field and the seed must have high germination rates at low temperatures. Treated stored seed from previous seasons should not be used.

Ratooning of sorghum provides an alternative to cotton, particularly in seasons with low water availability.

The Optimising Sorghum Agronomy project is developing agronomic packages for winter-sown sorghum. For more information follow us on Twitter @Queensland_fsr and at https://www.qld-fsr.info/

Acknowledgements

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In particular, the support of the Bidstrup, Warra and Milla, Surat families is gratefully acknowledged.

Optimising sorghum agronomy is a collaboration between the Grains Research and Development Corporation, University of Queensland, NSW Department of Primary Industries and Queensland Department of Agriculture and Fisheries.

References

Gerik, T.J., Rosenthal, W.D. and Seavey, W.F. (1990) Phenology, early growth, and yield of planted and ratoon grain sorghum. Field Crops Research 23: 205-219. doi:https://doi.org/10.1016/0378-4290(90)90055-G.

Muchow, R.C., Hammer G.L. and Vanderlip, R.L. (1994) Assessing climatic risk to sorghum production in water-limited subtropical environments II. Effects of planting date, soil water at planting, and cultivar phenology. Field Crops Research 36: 235-246. doi:https://doi.org/10.1016/0378-4290(94)90115-5.

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Grower experiences with early sowing sorghum: pros and pitfalls

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Notes

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Nutritional strategies to support productive farming systems

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Key words

fertilisers, placement, blends, recovery efficiency, application strategies

GRDC code

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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 fertiliser combinations will be needed to meet crop.

Introduction

This will not be a traditional paper that reports results of a specific research trial or set of trials from specific research projects. Rather, it is a set of observations made from the projects listed above, as well as those made by Richard Daniel (NGA) 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 fertility management programs.

Do we have successful fertility management systems?

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) to maximize the chance of achieving effective use of available moisture. 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 agonizing 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 (i.e. replacing what we remove in grain). In many cases the rate we can afford is not always the rate we need to apply to optimize 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. At the same time, our background soil fertility reserves have fallen and our crops are becoming increasingly reliant on inputs of fertility (fertilisers, manures etc) to sustain productivity. It is this increasing reliance on fertilisers, especially N and P and (increasingly) K, that allows us to really see the inefficiency in use practices. The impact of these inefficiencies in terms of lost productivity can often dwarf any of the considerations of rate, and highlights 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 50 kg N/ha and 9% for 100 kg 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 only 15% was in the crop (grain and stubble). The fate of the other 20% of applied N could not be determined. Some of that N will carry over until the next season, but it means that you need **last** year's fertiliser to get you through **this** year, but if you had a big year last year, leaving little residual N, or a lot of N was lost due to a wet season, the current crop may see little of the N applied in the previous year and will suffer as a result.

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 Qld 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.

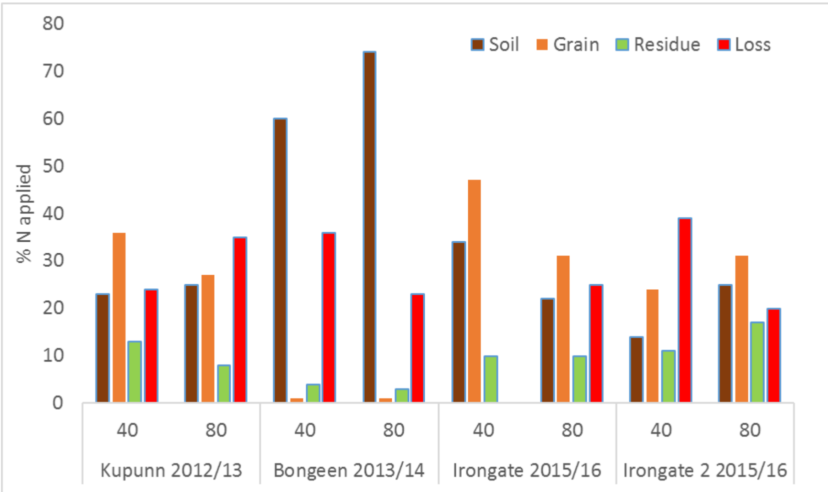


Figure 1. Partitioning of fertiliser N between soil, plant and environmental loss pools for summer sorghum crops grown on the Darling Downs in UQ00066 from 2012 – 2016.

Both extensive 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 (i.e. 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 (i.e. 200-300mm). Even after a subsequent fallow, the Daniels *et al.* (2018) paper found that 50-60% of the mineral N residual from fertiliser applied in the previous season was still only in the top 45cm, with as much as half 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 – e.g. 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 (3-5 kg P/ha) is substantially greater than that from starter P alone (1-1.5 kg P/ha) in all bar exceptionally dry seasons.

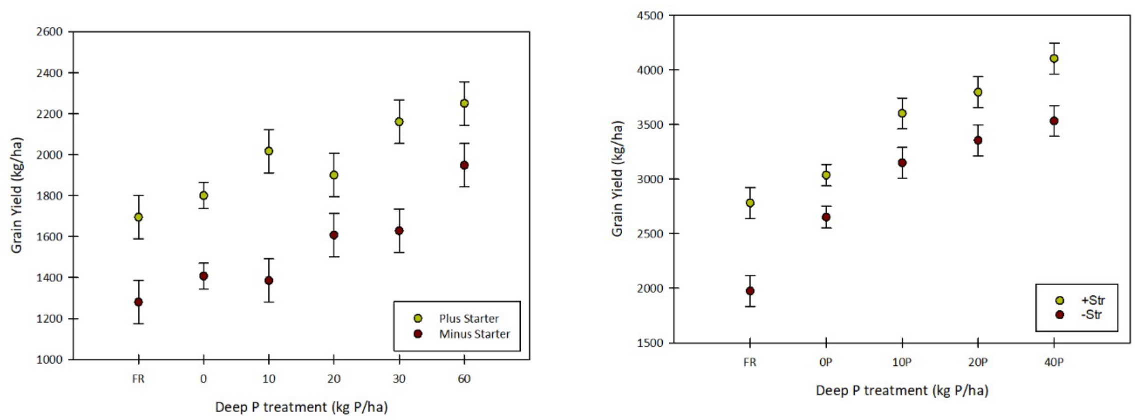


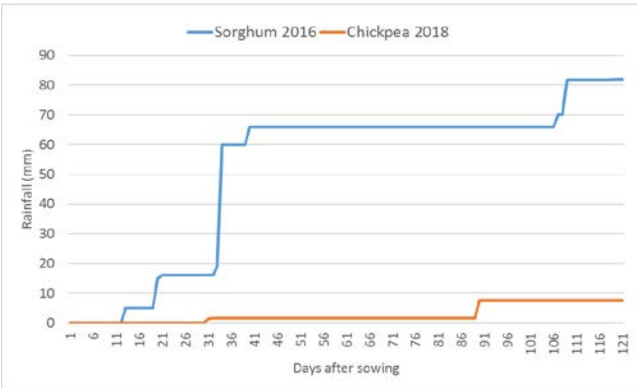
Figure 2. Response to different rates of deep P with and without applications of starter P fertiliser in (a) a wheat crop at Condamine in 2018, and (b) a sorghum crop at Dysart in 2018/19. Grain yield for deep-placed P treatments (kg P/ha) with or without starter application. The vertical bars represent 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 Queensland 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 else to find elsewhere 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 1-1.5 kg 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 a greater importance on access to P in the topsoil, which means that seasonal rainfall distribution has 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 1100 kg and 960 kg for the sorghum and chickpea, relative to the untreated farmer reference treatment, and by 720 kg and 970 kg/ha for the same crops relative to the nil applied P treatment (0P) that received ripping and background nutrients. The similar quantum 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 responses 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 was similar (3.3 kg P/ha in the sorghum and 2.7 kg 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 2.9 kg P/ha in the sorghum crop but only 0.6 kg 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 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 re-wet 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)

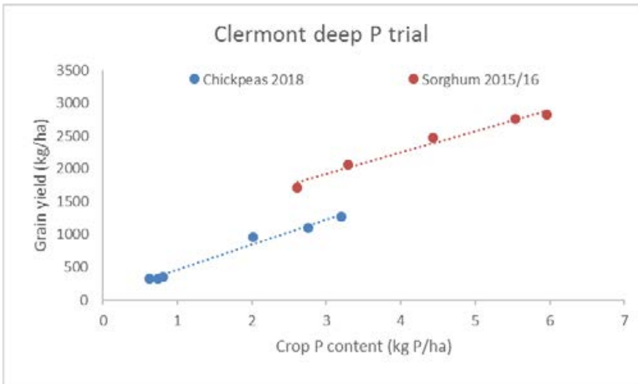


Figure 3. (a) Cumulative in-crop rainfall and (b) the relationship between crop P content and grain yield for consecutive crops of sorghum (2015/16) and chickpea (2018) grown at a site near Clermont, in Central Queensland (Sands et al., 2019).

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. This is further complicated as the relative severity of each constraint can change 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 Central Queensland, 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 use 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 interactions between P and K applied together in concentrated bands that can reduce the availability of both nutrients. The current GRDC project 'UQ00086' is 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.

(a) (b)

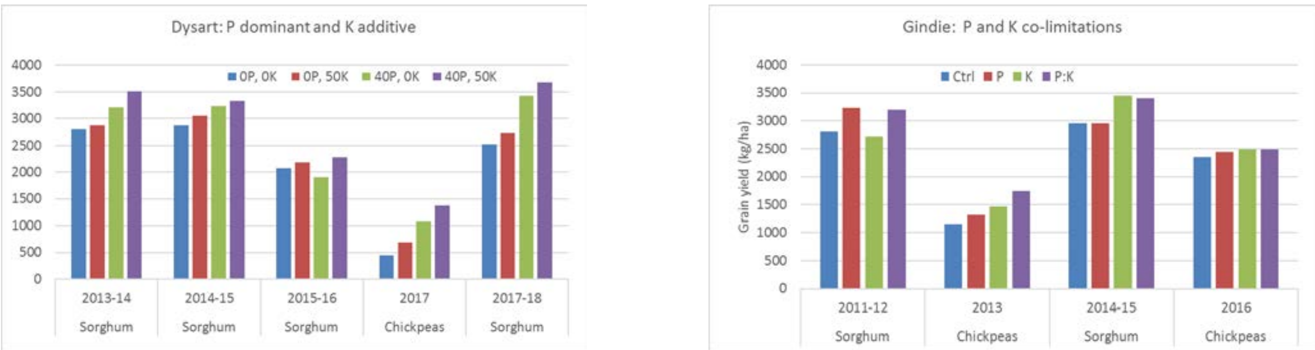


Figure 4. Examples of combinations of P and K limitations to crop performance at (a) Dysart and (b) Gindie, and the response to deep banded applications of those nutrients alone, or in combination.

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 much 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 that are dry. The co-location of water, nutrients and active crop roots enables 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 that the crop could 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 season crop use.

Our soils are now 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 unable to move far enough into the soil profile to match the distribution of water – at least in the current 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 mineralized later in the fallow, again with less chance to move deeper into the soil profile for co-location with stored water.

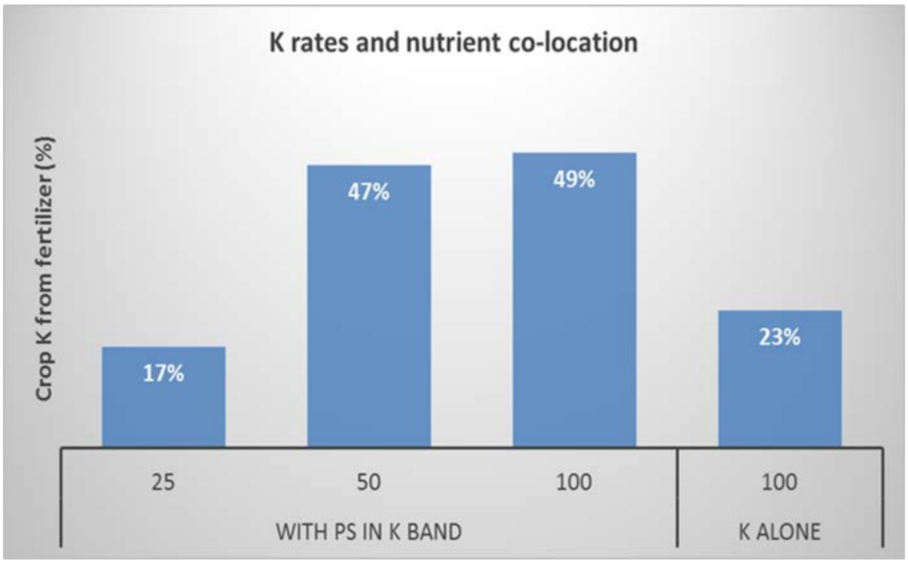


Figure 5. The impact of rate of applied K and co-location of K with other nutrients in a band (in this case P and S) on the proportion of crop K that was derived from applied fertiliser. The net result is an increasing frequency of dislocated reserves of stored soil water and nutrients, with in-crop 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 – placement, timing and product choice/combination.

In the concluding section of this paper, we provide a brief outline of what we feel are going to be key strategies that nutrient management programs of the future will need to consider. We note that a number of these have not yet been extensively validated or are simply hypotheses that are worth testing. However, they do show what we think are opportunities to address some of the main nutrient supply issues outlined in 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 maximizes the chance of having nutrients co-located with water when future crops need it. Leaving these decisions to when the profile water has largely accumulated and the planting decision is more certain, is frequently leading to 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 fertiliser management, 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 for multiple nutrients. 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

N

- 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, increasing the likelihood of N availability to support 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 strategies have been developed. 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? How would you respond to an unseasonal rainfall event after N applications had been made?
- Legume residues should help to better synchronize the release of N with the recharge of profile moisture during a fallow. This should result in soil N that is readily accessible during a following crop, as well as lowering the fertiliser N requirement.

P and 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. Starter P has an important role to play in early season growth and establishing yield potential, but 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. Fluid forms of P may possibly have a role. The 'saved' P should be diverted into increase rates or frequencies of deep P application
- Starter P is especially important in very dry seasonal conditions, and can make 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 applied 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. Minimize the risk by applying products in more closely spaced bands (i.e. at lower in-band concentrations) more often (i.e. lower application rates more frequently)
- 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 achieved 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. Crop nutrient concentrations in foliage and grains still show signs of being P deficient in many situations, and it is obvious that the more of the subsoil volume that can be fertilized (more bands, more often) the greater the chance we have of meeting demand.

Acknowledgements

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References

Bell M, Schwenke G and Lester D (2016). Understanding and managing N loss pathways. GRDC Updates in Coonabarabran and Goondiwindi, March 2016.

Bell MJ, Mallarino AP, Moody PW, Thompson ML, Murrell AS (2017). Soil characteristics and cultural practices that influence potassium recovery efficiency and placement decisions. Proc., Frontiers of Potassium Workshop, Rome 25-27 January 2017.

Johnston AM and Bruulsema T.W. (2014). 4R Nutrient Stewardship for Improved Nutrient Use Efficiency. Procedia Engineering 83: 365 – 370.

Daniel R, Norton R, Mitchell A, Bailey L, Kilby D, Duric B (2018). Nitrogen use (in)efficiency in wheat – key messages from 2014-2017. GRDC Update Goondiwindi, March 2018.

Lester D and Bell M (2019a). Responses to phosphorus and potassium by grain crops in southern Queensland. Pp. 26-29. In: Weir D and Grundy T (Eds). Queensland Grains Research 2018-19. Regional Research Agronomy Report, QDAF.

Lester D, Bell M and Hagan J (2019b). Deep P update 2019 – Multi-year grain yield impacts and economic returns for southern Queensland cropping. GRDC Update Warra, March 2019.

Sands D, Bell M and Lester D (2018). Getting nutrition right in Central Queensland. GRDC Updates at Emerald and Biloela, December 2018.

Sands D, Lester D, Bell M and Hagan J (2019). Responses to deep placement of phosphorus and potassium in chickpea – Clermont. Pp 45-52. In: Weir D and Grundy T (Eds). Queensland Grains Research 2018-19. Regional Research Agronomy Report, QDAF.

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

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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.

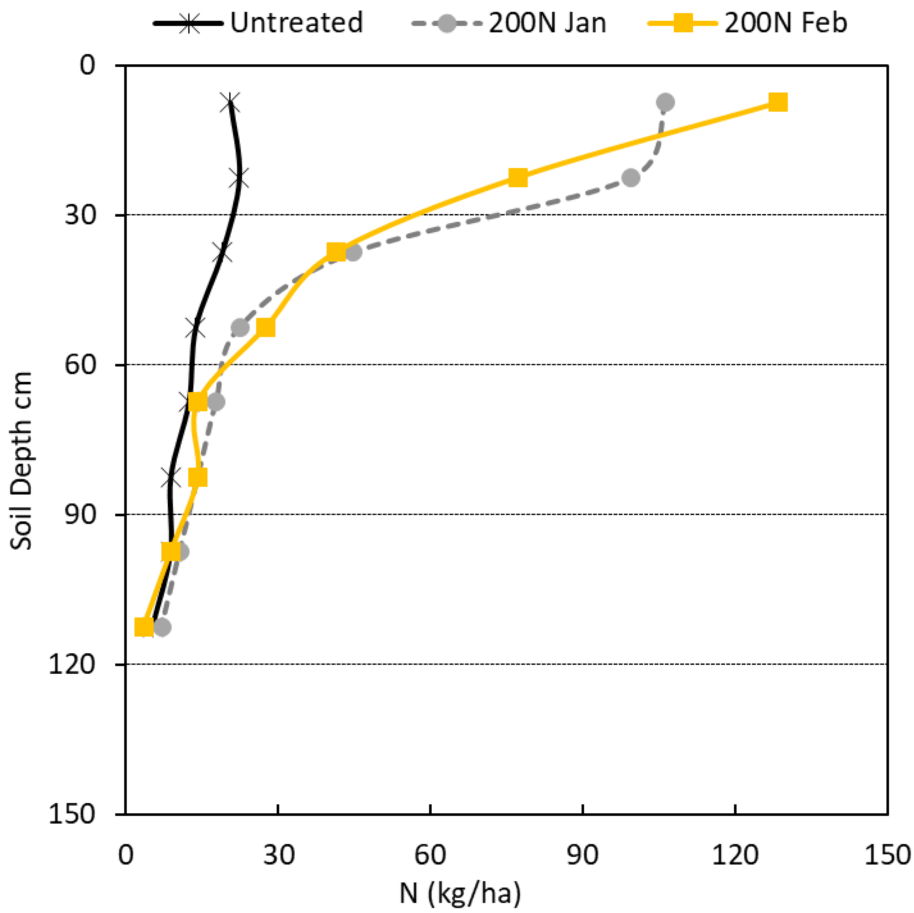


Figure 1. Soil distribution of N at Mullaley at planting (May 2017) following application of urea in January or February 2017. 175mm of rain was recorded between the January application and planting. 140mm of rain was recorded between the February application and planting.
(NB: Both N applications were 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.)

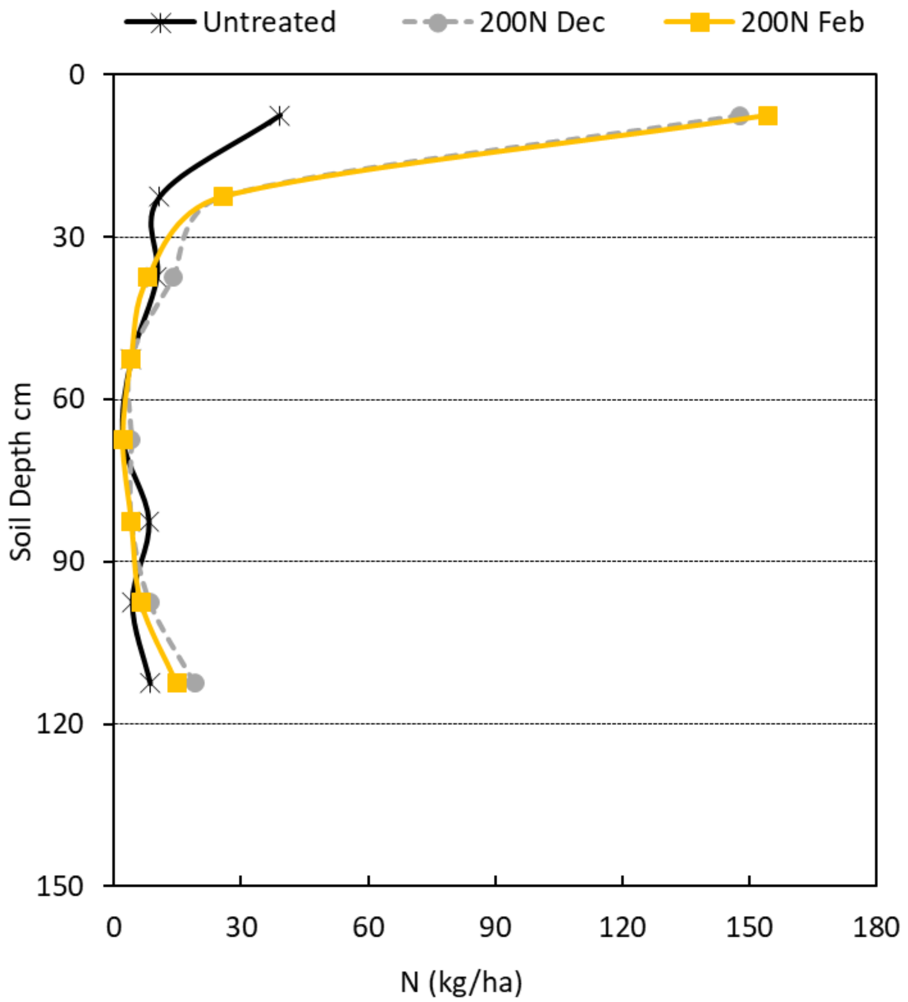


Figure 2. Soil distribution of N at Tulloona at planting (June 2016) following application of urea in December 2015 or February 2016. 225mm of rain was recorded between the December application (spread and incorporated) and planting. 65mm of rain was recorded between the February application (spread 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.

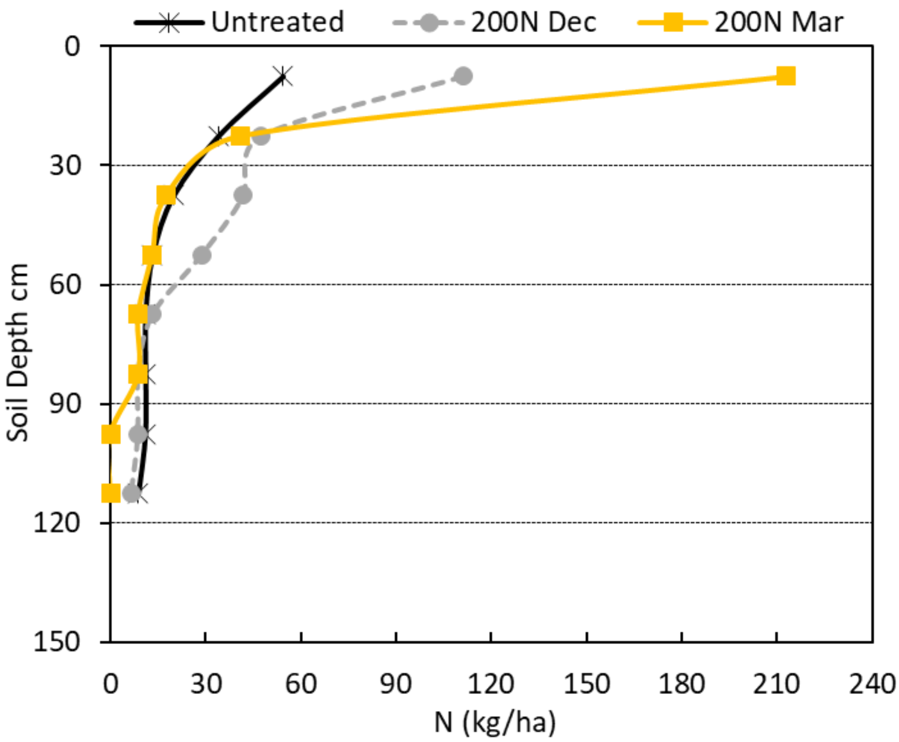


Figure 3. Soil distribution of N at Billa Billa at planting (May 2017) following application of urea in December 2016 or March 2017. 279mm of rain was recorded between the December application and planting. 154mm of rain was recorded between the March application and planting.
(NB: Both applications 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).

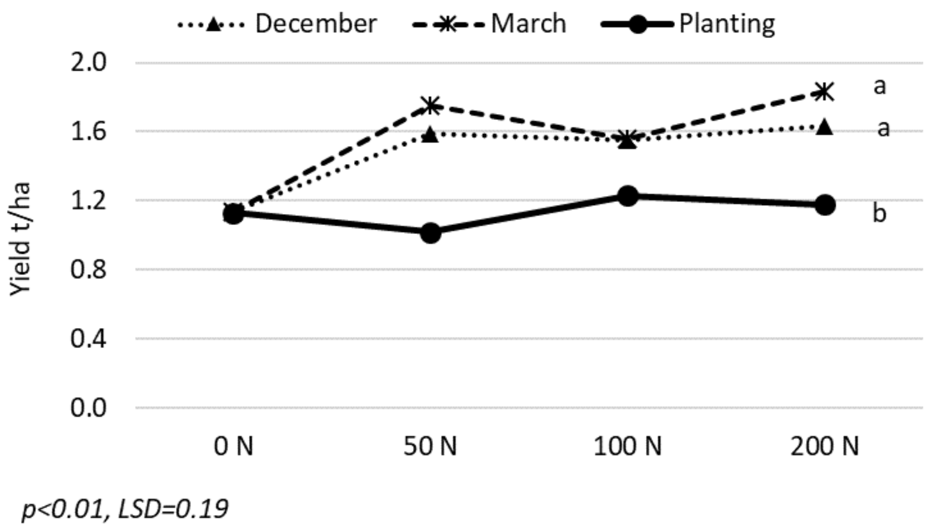


Figure 4. Effect of application timing and N rate on yield, Billa Billa 2017
(Treatments that share the same letter are not significantly different at P=0.05. All N rates were spread only)

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*

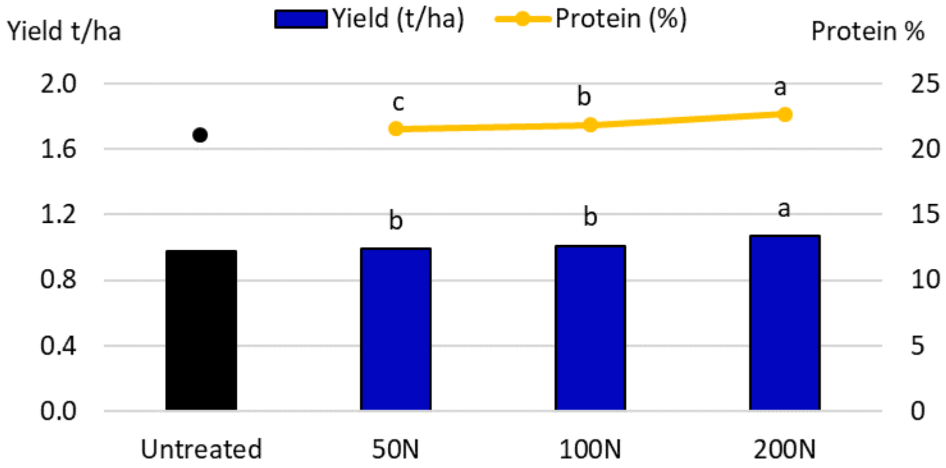
NB Sampling method - 4 individual 0-120cm depth cores taken per plot. Samples were separated into 0-30 and 30-90cm intervals with each depth bulked and a single sub sample taken for analysis. 4 replicates sampled in each treatment

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.

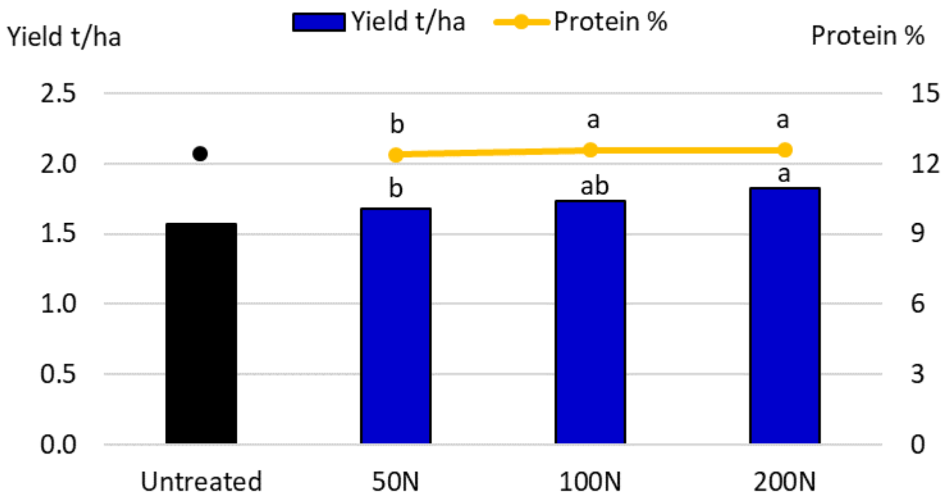
NB At the Tulloona site, ~60 % of the additional soil N was still found in the top 45cm with 45% found between 15 and 45cm. At the Macalister site, ~49 % of the additional soil N was still found in the top 45cm with 31% found between 15 and 45cm.

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

Nutrition discussion: key decisions in the next crop cycle

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