QUIRINDI
NEW SOUTH WALES
TUESDAY 13TH
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
QUIRINDI

Tuesday 13 August 2019, Quirindi RSL

Registration: 8:30am for a 9am start, finish 3:00pm

AGENDA Time	 Topic	 Speaker(s)
9:00AM	**GRDC welcome**	
9:10AM	**The soil Professor! Dispersive sodic soils:** why are they hard to manage and what about ameliorating them? **Calcium and magnesium**: do ratios matter?	Neal Menzies (UQ)
9:50AM	**Upgrading nutritional strategies to feed the farming system:** P & K timing, placement and implications for N timing and placement.	Mike Bell (UQ)
10:25AM	**Targeted tillage:** modified trashworker with individual tynes activated by WEEDit® technology to selectively dig out weed survivors.	Mike Walsh (University of Sydney)
10:45AM	**Morning tea**	
11:15AM	**New frontiers in cereal breeding for a changing climate.**	Greg Rebetzke (CSIRO)
11:45AM	**Cover crops for fallow efficiency:** research observations on soil water, health, nutrition and crop performance.	David Lawrence (DAF Qld)
12:10PM	**Multi species cover cropping and optimising soil health.**	Alex Nixon (Nuffield Scholar, Drillham, Qld)
12:35PM	**Lunch**	
1:35PM	**Sowing grain sorghum early**: reducing risk of water and heat stress at flowering and increasing chances of double cropping to chickpeas or of ratooning irrigated sorghum into a second harvest.	Loretta Serafin (NSW DPI)
2:05PM	**Overview of sorghum NVT trials for the Liverpool Plains.**	Laurie Fitzgerald (GRDC)
2:25PM	**Key decisions and options for the coming crop cycle** Discussion led by Jim Hunt (Hunt Ag Solutions) and Peter McKenzie (Agricultural Consulting & Extension Services)	
3:00PM	**Close**	

Contents

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Exchangeable cations – and what they can do for you!

Neal Menzies, Mike Bell and Peter Kopittke, The University of Queensland

Key words

sodicity, salinity, alkalinity, dispersion, calcium deficiency, gypsum, ideal cation ratios

Take home messages

- Clay soils, with poor surface structure because of excessive sodium, respond well to gypsum application. Application of gypsum to these soils is typically an economically attractive proposition. Non-clay soils with poor surface structure require different management approaches, such as variety selection to improve crop establishment
- Poor subsoil structure as a result of excess sodium is difficult to address. Deep ripping with considerable gypsum placed into the rip-lines has been successful, but it is expensive and has not been widely evaluated
- The ratio of exchangeable calcium and magnesium in soil will not influence plant growth, except at extreme values seldom encountered in agricultural soils
- Evaluate "novel" nutritional strategies yourself using strip trials, before adopting them on a broad scale.

Preamble

We have been asked in this paper to address two issues

- Dispersive sodic soils – why are they hard to manage, and what about amelioration.
- Calcium and magnesium – do ratios matter?

These are both topics we have addressed previously in GRDC Updates, so in addition to the material we present here, we refer you to earlier papers.

Our 2015 paper gave a lot of the underlying chemistry that drives the adverse effects of excess exchangeable sodium, and also explains how adding calcium (as gypsum or lime) can help. We also covered some of the impacts sodic soils can have on plant nutrition. You can find this paper at:

https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/02/soil-sodicity-chemistry-physics-and-amelioration

Earlier this year we presented a paper that primarily considered salinity and sodicity impacts on subsoil conditions, and we gave some viewpoints on how we might go about ameliorating subsoil constraints. We will reproduce some of that paper here, with the full coverage available at:

https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/subsoil-constraints-the-many-challenges-of-sodium,-chloride,-and-salinity-and-what-you-can-do-about-them

Finally, the question of cation balance, and the idea of an "ideal cation ratio" was something I (Menzies) was asked to speak about in 2004. At the time I thought this was a foolish request, because we have known for a long time that no such ratio exists. However, as Peter and I researched this question we found that it has been raised repeatedly through time – so we are not really surprised that after 15 years we are asked to repeat ourselves. The 2005 paper is not available online, so it is extensively reproduced here. Please excuse this self-plagiarism!

Introduction to salinity and sodicity

The presence of excess sodium in soil presents a range of challenges for plants growing in the soil, and some significant problems for growers managing these soils. Where there is free sodium chloride (NaCl) salt in the soil (a saline soil) the plant is presented with an osmotic challenge – it is difficult for it to take up water. The high levels of chloride (Cl) can be directly toxic to some plants, and the high levels of sodium (Na) can interfere with uptake of other cations, especially calcium (Ca). At much lower levels of sodium, where there is no free salt, but where the cation exchange has reasonable levels of sodium (>6% saturation), clay can disperse causing soil structural problems (sodic soils). This is the situation we encounter most frequently and will be the focus of this paper.

Sodic soils is an enormous subject, and it would take a reasonable size book to relate the state of our understanding of the subject. For those of you who are interested, we refer you to the excellent book edited by Malcolm Sumner and Ravi Naidu "Sodic Soils, Distribution, Properties, Management and Environmental Consequences", 1998 Oxford University Press, New York. We have drawn on it liberally in this paper. Within this paper we address several sodicity constraints, in each instance initially covering the underlying science, then providing some commentary on strategies to ameliorate the problem, including when these are likely to work and when they are likely to fail.

In this paper we are primarily focusing on subsoil constraints because they represent a considerably greater challenge to correct than surface soil problems. Nevertheless, because interventions to address the subsoil problem often focus on the surface – for example surface application of gypsum - surface soil condition will frequently come into our discussion.

We recognise a field as having a subsoil constraint when crops are unable to proliferate roots at depth to exploit water and nutrients that may be present there. We most commonly see this expressed as fields where the crop is particularly susceptible to water stress – and if we go to the effort of assessing the soil profile moisture distribution under these water stressed crops, we find that the surface soil is dry, but considerable water may remain in the subsoil. Things become more complicated when we start to consider why the crop's roots have not been able to exploit the subsoil, as there are a range of problems that all result in the same endpoint; failure of roots to grow to depth. From a practical standpoint, this is a substantial problem as there is no single treatment that can be applied to address all of the problems – different problems need different interventions.

Potential subsoil constraints include salinity, high bulk density, lack of aeration, calcium deficiency, sodium and chloride toxicity. Discussion of these various constraints is made complex by their inter-related nature. A subsoil that contains a lot of sodium chloride, will impact on plant growth because of the osmotic effect of the salt making water less available. It may also result in a toxicity effect because of the high sodium and chloride concentrations present in the soil solution, or the high Na concentration may induce calcium deficiency.

Finally, there is little truly new here from a scientific perspective. That sodic soils are a problem, and that gypsum is a part of the solution, has been known for a long time. Here is a view from 120 years ago –

"**This evil admits of cure by treatment with gypsum**" (Warington 1900)

Our problem is knowing how to apply our scientific knowledge in a practical and economically attractive way – so this paper will step away from science a little in order to focus more on the practical.

Effects of sodium on the physical properties of soil

Sodic soils have extremely poor physical characteristics which, in agricultural soils, lead to problems managing soil water and air regimes. The adverse effects of sodicity on surface soils, and their impact on crop performance are well known. The lack of soil structural stability results in dispersion of the surface during rainfall to form a seal. This seal limits infiltration, partitioning a greater proportion of rainfall to runoff. This reduces water availability for crops growing in the soil and increases the risk of erosion. On drying, the seal hardens as a crust that can prevent emergence of germinating seeds and result in poor crop establishment. In addition, sodic soils are difficult to cultivate and have poor load-bearing characteristics. In the subsoil, poor structural stability as a result of excess sodium is likely a key contributor to high bulk densities, and consequent low hydraulic conductivity and poor soil aeration.

These behaviours are a result of the influence of sodium on the clay fraction in the soil. When the cation exchange is occupied by calcium or magnesium, the individual clay platelets aggregate as illustrated in Figure 1, and the soil behaves in many respects like a silt or sand because the aggregates of hundreds of clay platelets constitute ‘particles’ of similar physical size. An aggregated clay soil has good structural characteristics. When the exchange is occupied by sodium, the individual clay platelets repel each other, and these aggregates of clay platelets break up. The soil structure is destroyed, the clay disperses in water and is easily eroded. The breakaway gullies we commonly encounter in duplex soils are an excellent illustration of how easily sodium saturated clays are eroded – the soil literally melts away. In a cultivated soil, much lower levels of sodium saturation result in the various adverse agronomic outcomes that occur as a result of only a small portion of the clay dispersing. It is always important to remember that sodicity is a problem that impacts on the clay fraction of the soil. In a sand with little clay fraction, sodicity will not result in adverse physical conditions, though there may still be adverse chemical effects as we will discuss later.

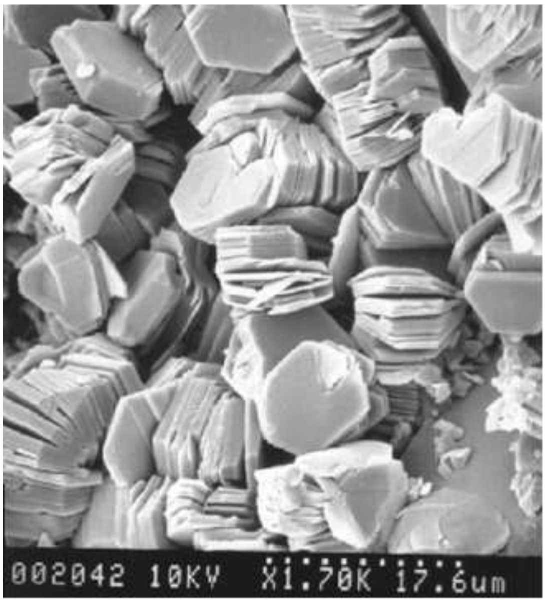

Figure 1. Scanning electron micrograph of aggregated clay platelets

Figure 2. Breakaway gully formation illustrates the ease with which sodium saturated clay can be dispersed and eroded

The composition of the soils cation exchange capacity (CEC) dictates the soils' physical behaviour, with dispersion being the interaction of multiple factors including the type of cation held on the CEC, clay mineralogy, soil texture, organic matter content, etc. Hence, rigid 'rules' and classification systems are not particularly effective at predicting soil structural behaviour. This is where an understanding of the underlying processes (and a great deal of experience) are needed to permit us to manage soil sodicity.

At a mechanistic level, two processes, 'swelling and dispersion', are responsible for the behaviour of sodic soils, with these two processes governed by the soil surface charge and how it is balanced by exchangeable cations. You can find our refresher on introductory soil science in the 2015 paper flagged on the first page. We will not repeat this material here, other than to restate the take-home message that the extent of soil swelling in soils with montmorillonite type minerals (Vertosols), and the risk of dispersion of clay particles, increases as the level of exchangeable sodium increases.

The most common ameliorant applied to sodic soils to correct soil structural problems is gypsum. It acts to promote flocculation through two mechanisms; increasing soil solution ionic strength and by supplying divalent calcium ions to displace monovalent sodium from exchange sites. The first of these effects (increased ionic strength) is immediate and can be achieved by relatively low rates of gypsum application, but the effect is short lived (especially if the application rate is low). The effect of replacing sodium with calcium is permanent, unless additional sodium is supplied which will displace the calcium (for example, through the use of poor-quality irrigation water).

Gypsum application can be particularly effective as a means of improving soil surface conditions, providing better soil tilth and reducing crusting. However, the effectiveness of gypsum application in improving subsoil conditions is less well established. If we are considering surface application of gypsum, then the rates of application needed to displace sodium from the exchange throughout the soil profile would be considerable. In Table 1, we have provided data for a grey clay soil and the calculated rate of gypsum required to reduce the sodium saturation of the cation exchange capacity to below 5%. The assumptions here are that replacement is perfect, i.e. that all of the calcium from gypsum replaces sodium and none is leached, the gypsum is pure, and the soil bulk density is 1.2g/cm^3. For this soil, 17 t/ha would be required to replace sodium to 60 cm, and 33 t to treat to 90 cm. Clearly these rates of application would not be economically attractive! Even if they were, we would need to consider the time it would take to move the gypsum derived calcium through the soil profile. Gypsum solubility is approximately 2.5 g/L, so it will take 40 mm of rainfall to dissolve 1 t/ha of gypsum. In an environment with 700 mm/year rainfall, it would take 2 years for the gypsum to dissolve from the soil surface. However, it will take a great deal longer for the gypsum to move to depth. If we assume that 10 mm/year leaches beyond 90 cm (this estimate is derived from salinity / leaching work on the western Darling Downs), then it would take 65 years for the gypsum to reach the bottom of the soil profile.

Table 1 provides us with a couple of really important points to keep in mind when thinking about sodic subsoils and their management. If the only option we have available to address subsoil sodicity is the surface application of gypsum, then it will take a considerable investment in gypsum, and a long time to see the benefit. There is also some cause to question if simply leaching calcium into a compacted sodic subsoil would help. The high bulk densities in sodic subsoils reflect the effect of high overburden pressure (the weight of the overlying soil) limiting shrink swell behaviour. In order for aggregation of the subsoil to occur, reducing the bulk density and permitting water and air movement, the overlying soil must be moved upward. As a thinking exercise; if we wanted to reduce the bulk density of a soil from 1.6 to 1.4, from 30 cm to 100 cm depth in the soil profile, the surface level of the soil would need to rise by 10 cm – effectively lifting 15,000 t/ha. Where would the energy to do this come from?

Deep ripping combined with gypsum application has been reported to result in increased crop yields, but the effect has often been short lived (2-3 years). However, it is important to look at what was done, and if we would expect long-term benefits. For example, McBeath *et al.* (2010) used a gypsum slurry to place gypsum into the subsoil, but the rate of application they could achieve was limited; in one soil they applied 0.5 t/ha, in another 1.4 t/ha. If we consider this in the light of the preceding discussion of short-term (increased soil solution ionic strength) and long-term (replacement of sodium by calcium) effects, the low application rate used would only provide the short-term benefit. In contrast, Armstrong *et al.* (2015) used deep ripping with 7.5 t/ha of gypsum placed into the slot with a boot on the ripping tine. This rate of gypsum would be expected to provide both a short-term benefit, and a longer-term benefit by lowering exchangeable sodium levels. Substantial yield benefits were obtained for the four-year duration of the trial, and it is reasonable to expect that they would be sustained beyond the life of the trial.

Table 1. Exchangeable cation data for a grey clay soil, and the estimated gypsum requirement for different depth increments in the profile, and rainfall required to leach this gypsum into the soil.

Depth	CEC	Sodium (Na)	5% of CEC	Na reduction	Gypsum	Leaching requirement
cm	$\text{cmol}_{(+)}$/kg	$\text{cmol}_{(+)}$/kg	$\text{cmol}_{(+)}$/kg	$\text{cmol}_{(+)}$/kg	t/ha	mm
0-10	29	2.3	1.5	0.8	0.8	30
10-20	30	4.2	1.5	2.7	2.8	110
20-30	29	4.0	1.5	2.5	2.6	100
30-60	32	5.1	1.6	3.5	10.8	430
60-90	30	6.8	1.5	5.3	16.3	650
					33.3	1320

Ripping gypsum into the subsoil speeds the rate at which a beneficial effect on the subsoil could be expected. Deep placement would also be expected to reduce the total amount of gypsum needed. This is because we do not need to treat the entire volume of subsoil in order to exploit the water it contains – water can move from untreated soil to roots growing in treated rip-lines. Ripping invariably brings some of the highly sodic subsoil to the surface, so a surface application of gypsum is also needed to ameliorate this subsoil material.

While the preceding discussion of remediation of subsoil sodicity has indicated that we still have much to learn, the situation for surface soils is much more clear-cut. Surface soil amelioration is achieved at much lower rates of gypsum application than is required to displace all of the sodium. The expectation from these smaller additions is that they will help to ameliorate the surface soil, increasing infiltration, and encouraging more uniform crop establishment. Repeat applications are typically needed to sustain the surface soil improvement. Such small applications can be economically attractive. In the GRDC funded Combating Subsoil Constraints project (SIP08), a one-time surface applied gypsum @2.5 t/ha increased cumulative gross margins by $207/ha over 4 crops (wheat 2005, chickpea 2007, wheat 2008 and sorghum 2009-10), removed 115 t sodium chloride from the rooting depth and increased plant available water capacity by 15 mm (Dang *et al*. 2010). Unfortunately, gypsum application is not always profitable, and more effective prediction of gypsum response is needed.

We need to divert briefly here to discuss alkalinity. Where sodium is the dominant cation in soil solution, the pH can rise to higher values than occurs where calcium or magnesium is the dominant cation. This is a simple reflection of the solubility of the respective carbonates of these cations. Calcium and magnesium carbonates are not very soluble, while sodium and potassium carbonates dissolve readily in water to form solutions with very high pH (once again, more detail in the 2015 GRDC Update paper). So, we can have soils that contain a great deal of calcium present as $CaCO_3$ but still have a high level of sodium on the CEC. If we add gypsum to an alkaline subsoil to try to increase the exchangeable calcium, the calcium supplied will precipitate as $CaCO_3$. This will lower the soil pH but will not raise the exchangeable calcium concentration as much as desired. If the soil pH is greater than 8.5, precipitation of calcium as $CaCO_3$ is likely. An alternative approach to this problem would be to add an acidifying agent (like elemental sulfur) to lower the pH, increasing the solubility of the $CaCO_3$ present, and in this way reducing the exchangeable sodium. The rate of sulfur needed to achieve a pH change is much lower than the rate of gypsum to achieve the same pH change, so deep injection of sulfur with ripping may be an effective strategy for dealing with sodic subsoils containing $CaCO_3$. While plants growing on alkaline soils express a range of nutritional problems, most of these would only be apparent when the whole soil profile is alkaline and are unlikely to be a problem when it is only the subsoil that has an excessively high pH. Sulfur application as suggested above is intended to address soil physical problems, rather than nutritional ones.

Finally, it is worth considering by what mechanism a sodic subsoil may be limiting root growth, and the likelihood that this can be ameliorated. The most direct effect of a sodic subsoil on root growth would be that the high bulk density, and resultant high soil strength, prevent roots from penetrating into the soil. Amelioration of this effect would require a change in bulk density and soil strength; something that may be achieved rapidly through deep ripping (and hopefully stabilised by deep placement of gypsum) within the cultivated layers, or potentially achieved over a much longer timeframe through gradual leaching of calcium to depth and the effects of repeated wetting and drying to develop soil structure. Closely related is the potential that root growth into sodic subsoils is limited by poor aeration. Given the very low air-filled porosities that are considered to exist in these dense subsoils, this is a very likely limitation to root growth and function. Like the soil strength limitation, this could only be overcome by changing subsoil structure. Another potential limitation to root growth is calcium deficiency. Under conditions of inherently low soil solution calcium, combined with high concentrations of soil solution sodium, plant roots may suffer calcium deficiency. Calcium cannot be translocated through the plant to growing root tips - it must be present in adequate levels in the soil solution at the place the root is growing. Root elongation is profoundly affected by calcium deficiency, without any distinctive symptoms showing on plant tops – other than the crop being susceptible to drought because of its poor root system. If calcium deficiency was limiting root growth, simply supplying more calcium, without the need for soil structural change, should improve root growth. Of course, these various limitations do not exist in isolation from each other, and poor root growth in a sodic subsoil is likely to be the net result of several limitations.

Effects on excess salt on plant growth

Salinity is considered to reduce plant growth and performance by several mechanisms including alterations in water relations within the plant, deficiencies or toxicities, and oxidative stress. Salinity is also considered to reduce the plant availability of soil water, with the osmotic effect on soil water potential reducing plant water uptake. As the salinity of the soil increases, so does the soil water content at which permanent wilting point (PWP) is reached. Saline subsoils may therefore remain wet even when the crop growing above them has wilted.

The amount of salt in a soil profile, and its distribution, reflects the balance between long-term input of salt, and the leaching of this salt from the profile in deep drainage. In dryland systems salt input is predominantly in rainfall, while in irrigated systems salt input in irrigation water is likely to dominate. If we change the hydrology of the soil profile, causing more leaching without adding to the salt input, then the profile salt content will drop. This effect is well demonstrated by the Brigalow Catchment Study, where an area of brigalow scrub was cleared in 1982 for pasture and for cropping, and the salinity in the profile monitored periodically (1983, 1985, 1987, 1990, 1997, 2000). Silburn *et al.* (2009) provide an excellent analysis of the study and its implications. Before clearing, soil under the brigalow scrub contained about 40 t/ha of sodium chloride (NaCl) in the surface 1.5 m of soil, and the level of deep drainage was low (0.13 to 0.34 mm/yr). Use of the land for cropping, increased deep drainage to 19.8 mm/yr, causing displacement of salt from the soil profile. At the new equilibrium for the cropped soil profile, almost all of the 40 t/ha of salt in the surface 1.5 m will have been displaced. The approach to equilibrium is exponential, with rapid gains initially as salt is displaced from the upper layers of the profile, but progressively slower changes as salt is leached from lower levels. Silburn *et al.* (2009) calculated time to equilibrium at 50 to 200 years – but considerable reduction in the surface 1m was apparent within the first 6 years.

In dryland agriculture, our only option for increasing the leaching increment (beyond the change already achieved by converting native vegetation to cropping) is by increasing infiltration. If we can improve surface soil structure, resulting in greater infiltration and less runoff, we should be able to displace salt from the subsoil, increasing the depth of water extraction by the crop and the lower-limit soil water content. It is interesting to note that this did not happen in the brigalow catchment study where no change in lower-limit water contents or depths of soil water extraction were recorded. In this instance, the starting salinity levels were only marginally limiting to crop growth, so perhaps a change in crop performance should not have been expected. However, other factors complicate our analysis of the system. Leaching sodium chloride from a saline soil can leave us with a sodic soil, with its attendant poor soil structure and permeability. Of course, improving surface soil structure and infiltration will provide yield benefits in many years – reduction of subsoil salinity would be a bonus!

The preceding discussion has primarily considered the osmotic effect of salinity. Salinity may also limit crop growth through toxicity of sodium and chloride. While the mechanism of limitation to the crop is different, the same solution to the problem works for specific toxicities and the osmotic effect – reduce the levels of sodium and chloride by leaching them out of the root zone.

Of course, it may not be possible to remove the salt, so we need to consider strategies to “live with” the problem. Selection of crops that are more tolerant of salinity/sodium/chloride provides an option to manage the problem, and investment in screening/breeding for tolerance to high sodium and chloride could considerably improve this option for the future.

Introduction to cation balance

Our early understanding of crop nutritional requirements and their response to soil conditions came through observation; the progressive development of hypotheses about soil-plant relationships which could then be rigorously tested. An example of this is the pH – nutrient availability diagram that we see used everywhere to describe the effect of pH on nutrient availability (you can find this in Helen McMillan and John Small's update paper in the reference section). This diagram was initially proposed by Pettinger (1935) and later modified by Truog (1946). We now understand that the relationships depicted in Turog's diagram describe what was common for the soils on which he was working (north-eastern US) but are by no means universally applicable. Indeed, the diagram is probably wrong as often as it is right, and it is a shame that it is so frequently reproduced.

The concept of ideal cation saturation ratios has a similar history. During the 1940's and 1950's there were a series of reports proposing "ideal" proportions of exchangeable cations in soil (Bear *et al.* 1945; Bear and Toth 1948; Graham 1959). The proposed ranges were 65 to 75% Ca^{2+}, about 10% Mg^{2+}, 2.5 to 5% K^+, and 10 to 20% H^+, or approximate ratios of 7:1 for Ca/Mg, 15:1 for Ca/K, and 3:1 for Mg/K. Without question, soils with this cation make-up would not present any problems for plant growth with respect to these nutrients. However, our question is, "will plants grow better if we adjust the cation ratios of the soil to these values?" A couple of key points need to be made about this approach

- The method was proposed by scientists working in areas of the USA where there are very good soils with negligible nutrient element deficiencies. At the time this work was performed, fertiliser applications were not required to overcome deficiency of the cationic nutrient elements to achieve profitable production. That is, adding cationic fertiliser to these soils usually had no impact on production. The method requires measuring the cation exchange capacity of soils that is balanced by calcium, magnesium and potassium. Then fertiliser advice is provided to achieve the desired ratio of these elements balancing the surface charge. The method does not involve measuring production responses to the added fertiliser.
- We now understand that most of the exchangeable H^+ that we measure in soils is an experimental artifact; it does not really exist. The exchangeable H^+ that was measured resulted from an increase in surface charge capacity (CEC) as a result of using a high ionic strength saturating solution (commonly 1 M) (van Olphen 1977). With the development of more appropriate methods of measuring cation exchange capacity (eg (Gillman and Sumpter 1986) exchangeable H^+ is not found at measurable concentrations except in the most acid soils (pH<4.5).

During the 1940's, Bear and co-workers conducted a series of studies at the New Jersey Agricultural Experiment Station investigating the growth of alfalfa (*Medicago sativa* L.). As part of this research Bear and co-workers proposed the "ideal ratio" of exchangeable cations in the soil. Since the publication of these ratio by Bear, it has been assumed by many that optimum plant growth will **only** occur when these 'ideal' conditions are met. This is despite Bear and co-workers' acknowledgement that maximum growth will occur over a wide variety of cation ratios. In their work, the purpose of providing a high calcium saturation (65 %) was to allow maximum growth whilst also minimising luxury K uptake. Indeed, Bear and co-workers logic was as follows: (1) good growth occurs across a wide range of Ca:K ratios, (2) a high calcium saturation percentage limits luxury potassium uptake, and (3) "potassium is a much more expensive element than the calcium which it replaces" (Bear and Toth, 1948). Thus, the application of calcium to reduce potassium uptake was cheaper than applying potassium which would be taken up by the plant in luxurious amounts. All good science with pragmatic advice to growers.

At about the same time that Bear was conducting his investigations, Albrecht and co-workers were also conducting a series of experiments at the Missouri Agricultural Experiment Station. Much of their research investigated the growth (and N_2-fixation) of legumes, and examined the effect of soil fertility on plant palatability and the nutrition of grazing animals. In many of these studies conducted by Albrecht, clay minerals were extracted from the soil, subjected to electrodialysis which replaces the exchangeable cations with H^+, the clay was then saturated with various cations such as calcium, potassium, magnesium, and barium. By mixing these clays at different ratios, Albrecht was able to investigate the effect of cation saturation on plant growth. As we will discuss shortly, this approach was profoundly misguided. In this following material we have provided more detailed referencing than typical in an update paper – as we are directly critical of individual studies, it's reasonable to provide the reference so our viewpoint can be checked.

Albrecht concluded that it is important to maintain a high calcium saturation percentage. Indeed, it was this observation which would eventually form the basis for much of Albrecht's concept of the 'balanced soil'. However, it would seem that the design and interpretation of the experiments used to demonstrate the need for a high calcium saturation were fundamentally flawed. Based on experiments with soybean (*Glycine max* L.), Albrecht (1937) concluded that (1) the nodulation of legumes in acidic soils is limited by low calcium concentrations more than by the acidity itself, and (2) plant growth and nodulation increase as calcium saturation increases. In fact, Albrecht later stated that "plants are not sensitive to, or limited by, a particular pH value of the soil" (Albrecht, 1975) and that "nitrogen fixation is related to acidity, or pH, only as this represents a decreasing supply of calcium as a plant nutrient" (Albrecht, 1939). However, examination of the data of Albrecht (1937) reveals that nodulation is indeed inhibited by soil acidity; nodulation only occurred when the pH was ≥ 5.5, and no nodulation occurred at pH 4.0, 4.5, or 5.0 at any calcium concentration. Similarly, although Albrecht concluded that growth and nodulation improve as calcium saturation percentage increases, soil pH values were not reported for any treatment, and due to the methodology used, any increase in calcium saturation would have undoubtedly been confounded by a decrease in acidity. Indeed, the various calcium saturations were achieved by mixing H-saturated clay (pH 3.6) (Albrecht, 1939; Albrecht and McCalla, 1938) with calcium-saturated clay (approximately pH 7.0) (Albrecht, 1939; Hutchings, 1936), thus giving clays of varying acidity (Albrecht, 1939). Using the same experimental system, Hutchings (1936) (who was working with Albrecht in Missouri) reported that a treatment containing 0 % Ca-clay (100 % H-clay) had a pH of 3.5, 25 % Ca-clay a pH of 4.3, 50 % Ca-clay a pH of 5.0, 75 % Ca-clay a pH of 5.7, and 100 % Ca-clay a pH of 6.9. In another experiment conducted by Albrecht (1937), calcium-saturated clay was mixed with barium-saturated clay. Here, the poor growth observed at low calcium-saturation (high barium-saturation) was most likely due to (1) barium toxicity (Barium is phytotoxic at < 500 µM), and/or (2) sulfur deficiency, due to the very low solubility of $BaSO_4$. All very poor science indeed!

According to 'The Albrecht Papers' (Albrecht, 1975), Albrecht (1939) demonstrated that for a 'balanced soil', "65 % of that clay's capacity (needs to be) loaded with calcium, 15% with magnesium". However, it is unclear how these 'balanced' percentages were derived, as examination reveals that the rate of N_2-fixation (measured as the difference in nitrogen content between the plant and the seed) increased linearly with calcium-saturation – the greatest fixation actually occurring at the highest rate of calcium-saturation, i.e. 88 % (vs. the 'balanced' calcium saturation of 65 %) (Figure 2). Similarly, the work of Albrecht (1937) showed that both plant mass and nodulation rate increased linearly with increasing calcium saturation. Later, and notably after the work of Bear and Graham had been published, Albrecht stated that "extensive research projects served up this working code for balanced plant nutrition: H, 10 %; Ca, 60-75 %; Mg, 10-20 %; K, 2-5 %; Na, 0.5-5.0 %; and other cations, 5 %" (Albrecht, 1975). Whilst it is unclear as to the exact origin of Albrecht's 'balanced soil', it appears likely that it relied, at least to some extent, upon the 'ideal soil' of Bear and co-workers.

That the "ideal" cation exchange ratio idea received so much attention at the time is surprising, given that, at the same time, other researchers were reporting that it did not work. Hunter and associates in New Jersey (Hunter 1949) could find no ideal Ca/Mg or Ca/K ratios for alfalfa

(*Medicago sativa* L.), nor did Foy and Barber (1958) find yield response of maize (*Zea mays* L.) to varying K/Mg ratio in Indiana. A comprehensive and elegant demonstration of the failure of the approach is presented by the glasshouse and field studies of McLean and co-workers (Eckert and McLean 1981; McLean et al. 1983), where calcium, magnesium and potassium were varied relative to each other. They concluded that the ratio had essentially no impact on yields except at extremely wide ratios where a deficiency of one element was caused by excesses of others. They emphasised the need for assuring that sufficient levels of each cation were present, rather than attempting adjustment to a non-existent ideal cation saturation ratio.

One of the reasons that the cation saturation ratio idea has persisted, is that, in very general terms, there is just enough "truth" in it to make it seem reasonable. The "truth" here being that if one cation is present at high levels, it can interfere with the uptake of other cations. So, let's explore cation nutrition of plants a little more deeply - if you can do without a refresher in "Plant Science 101", feel free to skip the next section.

Plant cation uptake

Some people view the general finding that cation ratios do not matter as difficult to reconcile with their apparent success in predicting nutritional difficulties under extreme conditions. To understand this question, we need to consider the process of cation uptake by plants.

Let's start with potassium, as it is the cation plants require in the greatest amount, and the cationic nutrient with the most specific uptake pathway. A key feature of potassium nutrition is the high rate and efficient means by which potassium is taken up and distributed throughout the plant. There are various potassium uptake systems, mainly specific (meaning they only work for potassium) channels in the plasmalemma (the outer membrane of plant cells). Two main groups of transporters can be identified; a high affinity group which are very selective for potassium and reach their maximum uptake rate at low soil solution potassium concentrations, and a low affinity group which are less selective and require much higher soil solution potassium concentrations to reach their highest uptake rate. Both types of uptake system work in conjunction with a plasmalemma proton (H^+) pump (Figure 3). The proton pump pushes H^+ out through the plasmalemma, creating an electrochemical gradient (more negative on the inside). This gradient then provides a driving force to push potassium into the cell, but it also provides the same driving force for other cations. The low-affinity transporters can be viewed as a gate which shows a preference for potassium – the gate will only open to permit a potassium ion to enter. However, this uptake approach will only work when there is a reasonable concentration of K^+ in the soil solution. At low solution concentrations the uptake process has to work against a strong concentration gradient. The soil solution may contain only 10 µM of potassium, while the cytoplasm (the semi-fluid contents of the cell) will contain around 80,000 µM K^+. This concentration gradient more than cancels out the electrochemical gradient (the inside of the cell is at -120 to -180 mV) – so potassium uptake is prevented. The plant can get around this problem by using its high affinity transporter, but this costs a lot more energy. When you consider that 25 to 50% of the energy flow in a root hair cell is used to drive the proton pump, to spend still further energy on nutrient uptake is something the plant would only do when it needs to.

The benefit that the plant derives from having these two mechanisms is that it can obtain its potassium requirement in the most efficient manner. As a result, the capacity of the plant to take up potassium is not directly related to potassium in solution. The uptake relationship for potassium in Figure 4 is strongly curved – the plant can obtain a lot of potassium despite low soil solution levels.

The presence of high concentrations of other cations in the soil solution (e.g. Na^+, Ca^{2+}, Mg^{2+}), can interfere with the potassium transporters. Thus, high concentrations of these other nutrients can reduce potassium uptake, especially by the low-affinity uptake system. However, the high-affinity uptake mechanism is so specific, interference by other cations is never so great as to produce a true deficiency of potassium in the plant. In very saline situations, uptake of sodium into the plant is sufficient to interfere with the plants use of potassium in the leaves, but it does not prevent potassium uptake from the soil.

Calcium represents the opposite end of the selectivity of uptake spectrum for cations. The principal role of calcium in the plant is to stabilise cell membrane and wall components – this is the outside of the "living" part of the cell. Inside the cell, the concentration of calcium is VERY low, and the plant expends a lot of energy to ensure that this condition is maintained. So, unlike potassium where the plant is actively transporting K^+ into the cell, for Ca^{2+} the plant has transporters to pump it out of the cell. Uptake of calcium is almost exclusively through the cell walls of young cells, with transport through the plant by the xylem (the "plumbing" system that moves water from the roots to the leaves). Calcium is required at the growing tips of the plant – without a continuous supply of calcium the growing tip dies (Figure 4). For shoot tips it is moved up from the roots by the xylem, for root tips the calcium must be in the soil solution where the root is growing. The symptoms of calcium deficiency are very apparent.

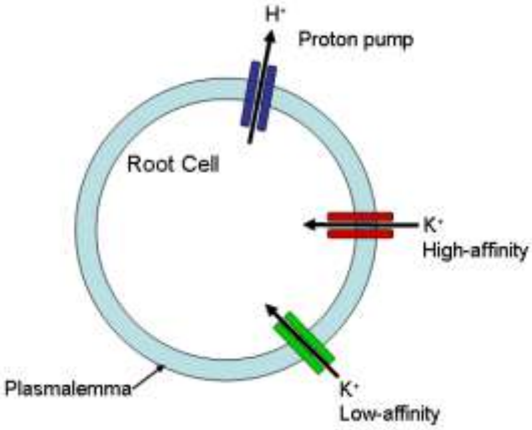

Figure 3. Schematic representation of a root hair cell showing the proton pump and potassium transporters

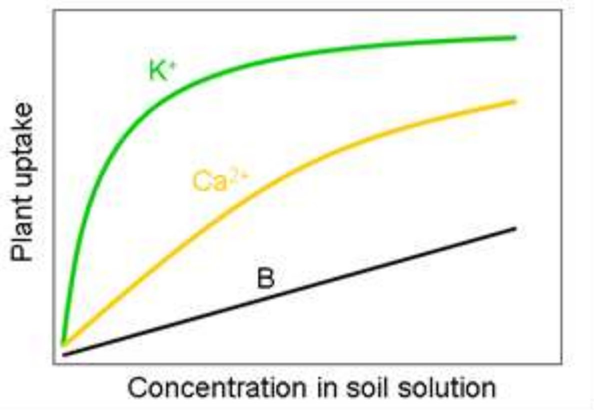

Figure 4. Schematic representation of the relationship between nutrient supply and uptake. The curved response for potassium reflects the plants specific uptake mechanisms for potassium, while the straight line response for boron indicates passive uptake (not actively controlled)

For calcium, the presence of other cations can result in the displacement of Ca^{2+} from the cell membranes and cell wall. This can be sufficient to cause calcium deficiency – deficiency induced by aluminium and manganese are common in acid soils. Of particular interest to us here is the potential for magnesium to displace calcium – is there any basis for the Ca:Mg ratio. Magnesium, because of its identical charge (2+) is an effective competitor with calcium for sites on cell components.

Calcium deficiency case studies

We present two case studies to demonstrate the failure of the ideal cation ratio to predict plant response. The first is the absolute extreme case where there is so much of one cation present that it does interfere with the uptake of other cations (the little bit of truth that sustains the rest of the fiction). The second case study considers less extreme conditions.

Example 1. Calcium deficiency induced through the use of magnesium oxide as a liming material

With the development of a magnesium mining and refining industry in Queensland, the opportunity to use by-product MgO as a liming material became possible, and was considered a practical approach to ameliorating acid, magnesium deficient soils. Kylie Hailes undertook research on this issue for her PhD. In her work Kylie investigated amelioration of acidity using MgO, mixtures of MgO and $CaSO_4$ (gypsum), and compared this to lime. She measured short term root elongation of maize and mungbean as an indication of aluminium toxicity and of calcium deficiency, this is expressed as relative root elongation, the rate of elongation in a treatment as a percentage of the control treatment. We have removed the low pH values, where aluminium toxicity will have limited root growth, so that the primary factor influencing root growth is calcium supply. As you can see from the data in Figures 5 and 6, mung bean root growth reaches a maximum by 10% calcium saturation of the exchange, or a Ca/Mg ratio of 0.1.

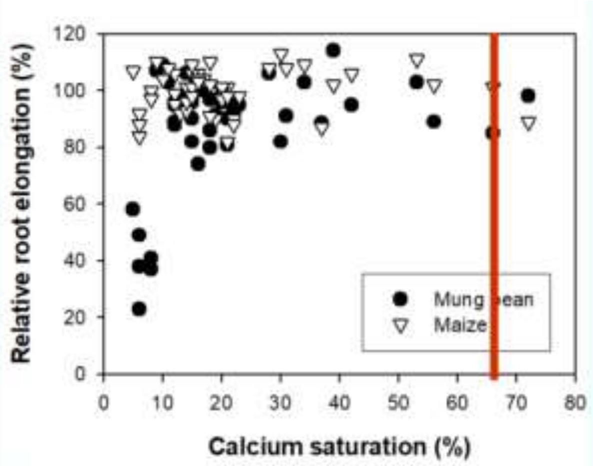

Figure 5. The effect of Ca saturation on the rate of root elongation (a measure of Ca deficiency) for maize and mungbean in acid soils limed with MgO and mixtures of MgO and $CaSO_4$

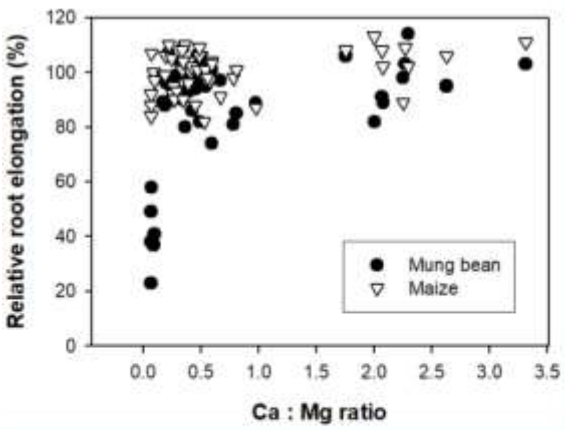

Figure 6. The effect of Ca to Mg ratio on the rate of root elongation (a measure of Ca deficiency) for maize and mungbean in acid soils limed with MgO and mixtures of MgO and $CaSO_4$

This data demonstrates the competition effect on cation uptake. When there is sufficient magnesium present it can interfere with calcium uptake to the extent that the plant was calcium deficient the root growth was impacted. We see this for mung bean when calcium saturation drops below 10% - a long way short of the 65% required by the Albrecht approach. There is no consistent effect on maize, so the critical values would be even lower.

Example 2. Calcium deficiency investigations by Albrecht's co-workers

In reviewing this topic for a 2005 update paper, we (Kopittke and Menzies) considered many papers that directly evaluated the effect of cation ratios on plant growth, as well as other unrelated research that had produced data sets that were relevant to this question. This review was published in the Soil Science Society of America Journal (2007, 27:259-265). As part of this paper we reviewed the effect of cation ratios on soil chemical fertility, soil biological activity, and soil physical properties, all without finding any evidence to support the idea of an ideal ratio in any of these areas. The following are a couple of studies from Albrecht's co-workers to demonstrate the lack of an effect on yield.

Specific cation ratios (i.e. Ca/Mg, Ca/K, and K/Mg ratios) were investigated by McLean, who had worked with Albrecht in Missouri during the 1940s, studied the effect of the soil Ca/Mg ratio on the growth of German millet [*Setaria italica* (L.) P. Beauv. cv. German] and alfalfa (McLean and Carbonell, 1972). It was concluded that plant yields were not affected by the Ca/Mg ratio within the Ca/Mg range studied (2.2:1–14.3:1; Figure 7).

Similarly, Hunter (1949), who had worked with Bear in New Jersey during the early 1940s, investigated the influence of the Ca/Mg ratio on the yield of alfalfa. Even though the experiment covered a wide range of Ca/Mg ratios (0.25:1–31:1), Hunter concluded that there was no "best" Ca/Mg ratio for optimum growth (Figure 8). Indeed, the Ca/Mg ratios of agricultural soils are seldom found outside of the range investigated by Hunter.

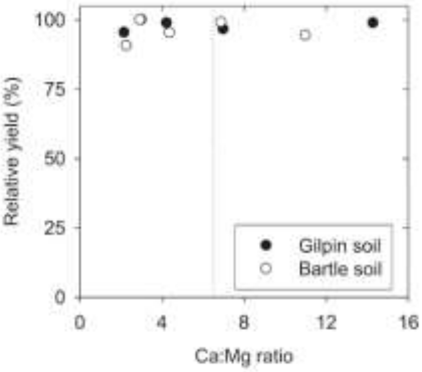

Figure 7. Effect of the exchangeable Ca/Mg ratio (2.2:1–14:1) on the relative dry matter yield of German millet in two soils. Data taken from McLean and Carbonell (1972). The dotted line indicates the "ideal" Ca/Mg ratio of 6.5:1 as stated by Bear *et al.* (1945)

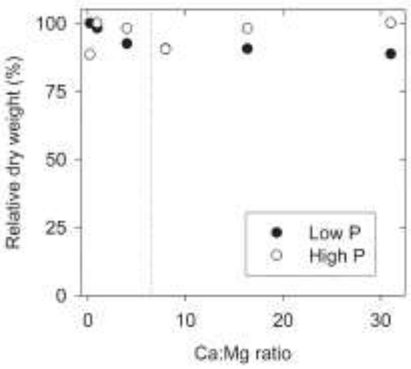

Figure 8. Effect of the exchangeable Ca/Mg ratio (0.25:1–31:1) on the relative shoot dry weight of alfalfa at two P fertilisation levels. Soils were prepared by mixing calcium and magnesium saturated clays at various ratios, with K-saturated clays accounting for 10% of the total. Data taken from Hunter (1949). The dotted line indicates the "ideal" Ca/Mg ratio of 6.5:1 as stated by Bear *et al.* (1945).

Finally, and as an aside on the cation saturation ratio issue, advocates of the cation saturation ratios approach present an "ideal" situation as being a soil with a pH of 6.0 to 6.5, and a distribution of cations including 12% of the cation occupancy being by H^+. To a soil chemist, this really calls into question the credibility of the approach; for the simple reason that it would not be possible for the exchange to have so much exchangeable H^+ at this pH. Vietch (Veitch 1904) recognized at the turn of the century that acid soil was aluminium saturated, rather than H^+ saturated. Indeed, even if you deliberately saturate the exchange of a soil with H^+, the acidity dissolves the soil minerals releasing aluminium which occupies exchange sites. So we never find H^+ saturated soils. Furthermore, the higher the charge on a cation, the greater the extent to which it is retained by the soil. For example, the cation exchange of soils is dominated by calcium and magnesium (2+ ions) despite the soil solution being dominated by sodium (a 1+ ion); the divalent cations are typically held at least 10 times more strongly. Given that calcium is typically present at concentrations of 1 mM or higher in near neutral soils, then H^+ would have to be present at this concentration or higher to give the level of saturation listed as ideal. Here is our problem – 1 mM of H^+ is a very acid soil, pH 3.

The reason for the high H^+ levels reported is the use of inappropriate (and very out of date) analytical approaches. Without going into detail, we now recognize that the amount of cation exchange on a soil varies with the pH and the ionic strength (concentration) of the soil solution. As you increase either the pH or the ionic strength, the soil gets more negatively charged (higher cation exchange capacity), and it does this by losing H^+ from the surface. By measuring cation exchange with concentrated solutions at high pH, you get a cation exchange measurement that is too large, and you incorrectly measure a lot of H^+ as being present.

To conclude this section on cation ratios we restate the take-home message we started with,

The ratio of exchangeable calcium and magnesium in soil will not influence plant growth, except at extreme values seldom encountered in agricultural soils.

And add to it Lipman's conclusion from 1916 (Lipman 1916) when he reviewed the same topic.

"I have known of measures employed in soil management in this state, based on theory of the lime-magnesia ratio as first enunciated by Loew and later exploited by unscientific men, which to the rational-minded experimenter in soils and plants, appeared to be the veriest folly"

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Nutritional strategies to support productive farming systems

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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.

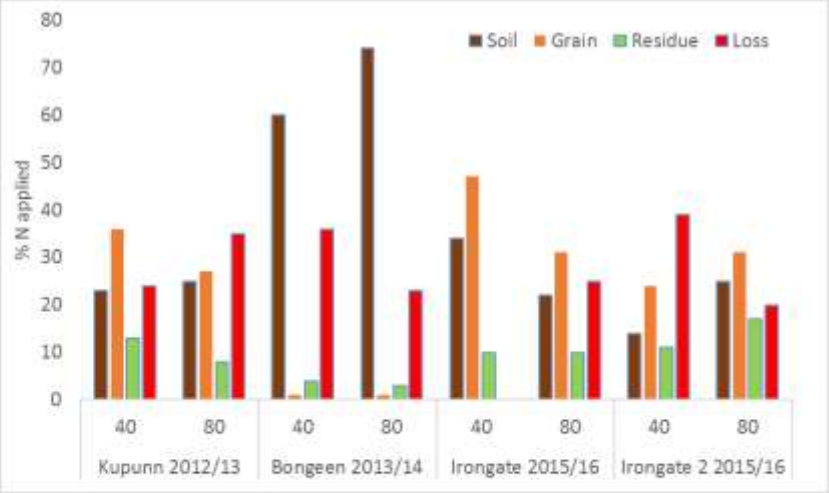


Figure 1. Partitioning of fertiliser N between soil, plant and environmental loss pools for summer sorghum crops grown on the Darling Downs in UQ00066 from 2012 – 2016.

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.

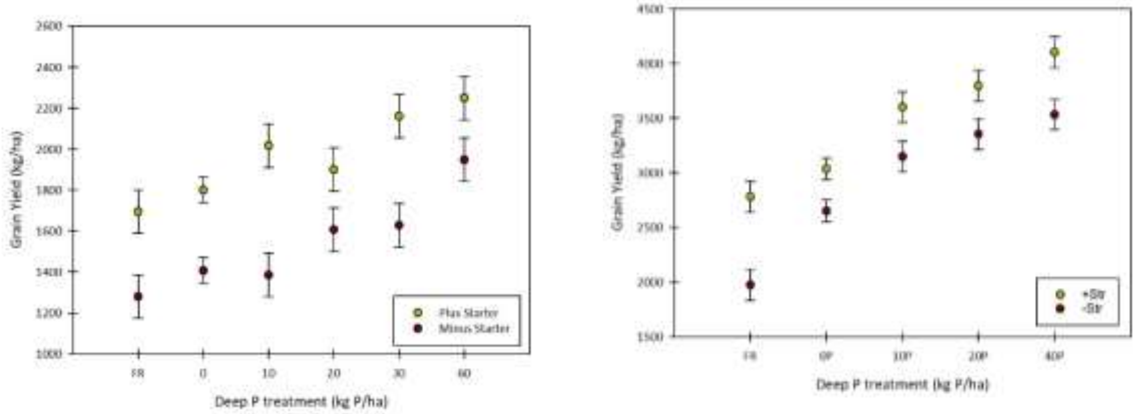


Figure 2. Response to different rates of deep P with and without applications of starter P fertiliser in (a) a wheat crop at Condamine in 2018, and (b) a sorghum crop at Dysart in 2018/19. Grain yield for deep-placed P treatments (kg P/ha) with or without starter application. The vertical bars represent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

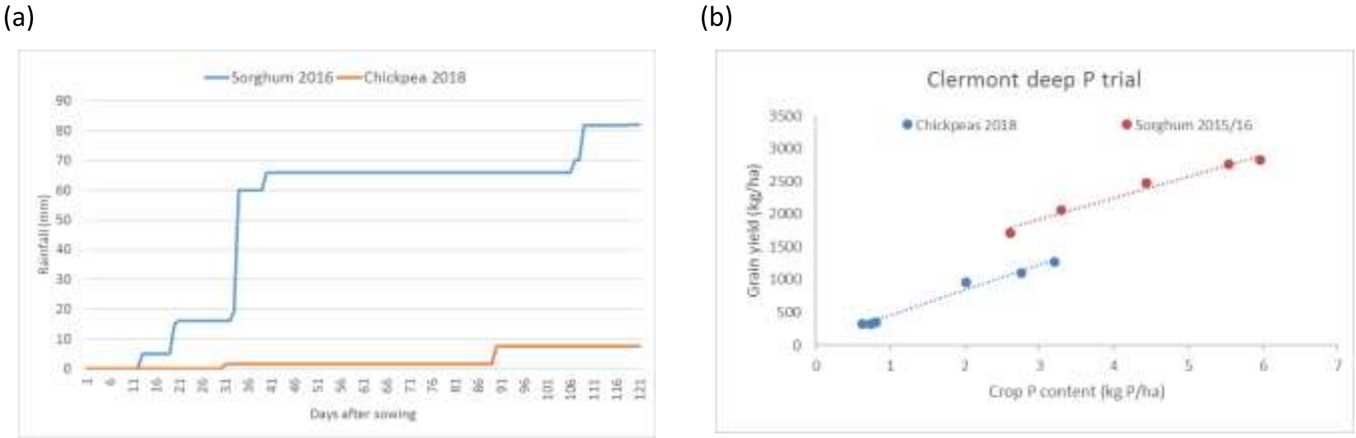
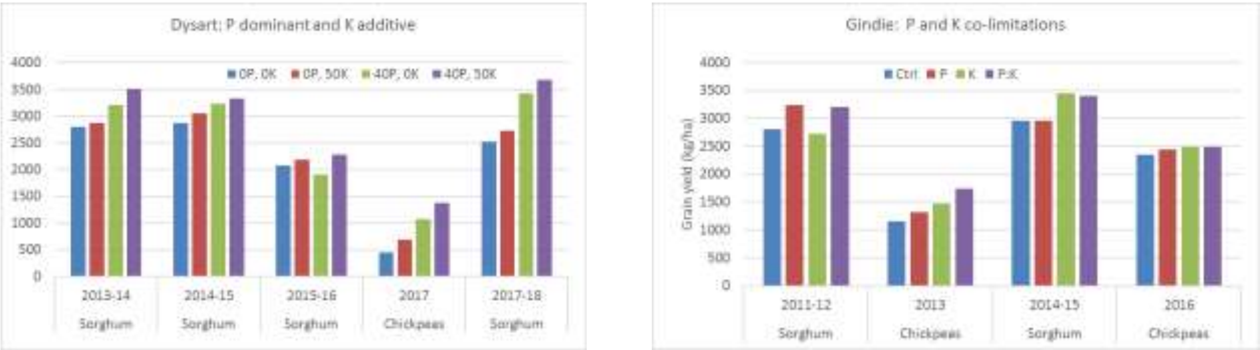


Figure 3. (a) Cumulative in-crop rainfall and (b) the relationship between crop P content and grain yield for consecutive crops of sorghum (2015/16) and chickpea (2018) grown at a site near Clermont, in Central Queensland (Sands et al., 2019).

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.

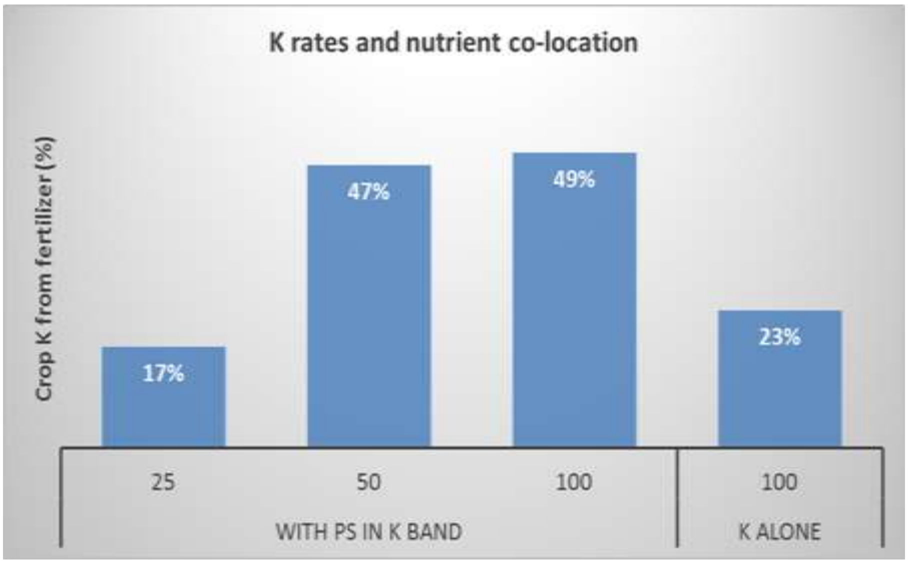


Figure 5. The impact of rate of applied K and co-location of K with other nutrients in a band (in this case P and S) on the proportion of crop K that was derived from applied fertiliser. The net result is an increasing frequency of dislocated reserves of stored soil water and nutrients, with in-crop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

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Current and future site-specific weed control options

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Targeted tillage, site-specific weed control, SSWC, rapid response tyne, energy requirements

GRDC codes

UWA 00171, US00084

Take home messages

- "Weed Chipper" is a targeted tillage system developed for site-specific fallow weed control based on a rapid response tyne
- Site specific weed control (SSWC) creates the opportunity to use alternative physical weed control technologies.

Background

The reliance on herbicidal weed control in northern region fallows has led to widespread herbicide resistance evolution in major weed species. As glyphosate is the most widely used herbicide for fallow weed control resistance to this herbicide is increasing at an alarming rate. There is also increasing frequency of resistance to selective herbicides that are being introduced to try and manage glyphosate resistant populations. Alternate non-chemical weed control techniques are desperately needed that are suited to routine use in northern region cropping systems.

Physical and thermal weed control techniques were in use well before herbicides were introduced and the development of new options has continued throughout the herbicide era. However, most of these technologies have not been adopted, primarily due to cost, speed of operation and fit with new farming systems. The introduction of weed detection and actuation technologies creates the opportunity to target individual weeds i.e. site-specific weed control (SSWC). This greatly increases the potential cost-effectiveness of many directional physical weed control techniques in conservation cropping systems.

Aims

1. To develop a rapid response tyne based on a hydraulic break-out tyne
2. Use energy required for effective weed control to compare the efficiency of alternate weed control techniques

Method

Development of a rapid response tyne

A rapid response tyne system has been developed with the operational specifications of being able to specifically cultivate targeted weeds when present in a field at densities of up to 1.0 plant/10 m^2 at an operation speed of 10 km/h. To permit timely development, the rapid response tyne concept was based on the retrofit of a Shearer Trashworker tyne with a hydraulic breakout system. The Shearer Trashworker was chosen due to its robust build, reputation and prevalence across Australian cropping systems. Its hydraulic breakout system is typical of many other manufacturers thus permitting a design approach which could be adapted to accommodate other arrangements. Although hydraulic systems are not traditionally used in such dynamic environments, to aid timely adoption and acceptance by farmers it seemed sensible to not deviate too far from current accepted and widely adopted agricultural principles.

Whilst focusing on the development of the rapid response tyne around a conventional cultivator, achieving the outcome efficiently and elegantly was not straightforward. As traditional cultivator bars are designed for continuous tillage and full-time tool-soil interaction, the new application required detailed engineering to modify the hydraulic system, mechanism functionality and optimise performance all whilst being highly constrained by the existing geometry.

The initial proof-of-concept design focussed the engineering on minimising the number of additional components and keeping the design simple whilst achieving the chipping action similar to a conventional hoe in well under half a second. A modular approach to the design was taken so as to permit the system to be scaled readily as confidence in system performance was achieved. The Shenton Park rig provided the initial proof-of-concept and the other rigs were used for weed kill testing (Figure 1A to C).

Weed control efficacy

Field testing using the two prototype rigs at the two northern region locations (QDAF and Narrabri) was conducted on a range of fallow weed species. The targeted tillage system was evaluated in a series of field trials for efficacy on weeds of winter fallows (annual ryegrass, wild oats, sowthistle and wild turnip) and summer fallows (barnyard grass, feathertop Rhodes grass, fleabane and sowthistle). At Narrabri, summer and winter field trials investigated the efficacy of the response tyne on the targeted weeds species established at eight growth stages (Table 1).

As the initial mandate for the project was to develop the mechanical response tyne and not the sensor system, the evaluation experiments used a simple photo detector arrangement to trigger the response tyne. A reflector was aligned next to each plant in the plot trial and together with the known travel speed, the system was calibrated to trigger the rapid response tyne when the light beam aligned with the reflector and hence with the weed.

Comparison of weed control technologies

The direct energy requirements for the control of two-leaf weed seedlings were estimated from published reports on the weed control efficacy of a comprehensive range of physical weed control techniques (Table 3). To determine the energy requirement per unit area, a weed density of 5.0 plants/m^2 was chosen to represent a typical weed density in Australian grain fields, based on results from a recent survey of Australian grain growers (Llewellyn *et al.* 2016).

Results

Development of a rapid response tyne

Significant engineering research, development and testing were conducted predominantly around the Shenton Park test rig at UWA (Figure 1A). As with any engineering design, the process involved iterative improvements to the design layout. Once the system was able to achieve a chipping cycle time of less than 400 ms from actuation to return to standby position and the design had been simplified and deemed reliable, the pre-commercial rig was designed and built. Detailed explanation of the engineering process and results will be presented in forthcoming publications.

Figure 1. Initial proof-of-concept rig (Shenton Park) (A), Narrabri trailer mounted self-powered rig (B) and QDAF 3-point-linkage rig (C) and Pre-commercial rig – the 'Weed Chipper' (D) used in the testing and validation of targeted tillage fallow weed control.

Weed kill field testing demonstrated very high efficacy on all targeted summer and winter annual weeds regardless of growth stage (Tables 1 and 2). The survival of any weeds during testing was due to cultivator sweeps not being suitable for targeted tillage. Weed control was 100% effective when the weed was targeted by the point of the sweep, however there was high weed survival when the weed was hit by sweep side. There was also reduced efficacy when weeds were excessively large. When feathertop Rhodes grass was >50cm diameter there was only poor control (Table 2). The system is highly effective on both broadleaf and grass weeds with potentially little resulting soil disturbance (Figure 2).

Table 1. Response tyne efficacy following direct or partial sweep impact on four winter and three summer weed species at eight growth stages, Narrabri NSW 2017 and 2018

Planting date	Wild oats (% control)		Turnip weed (% control)		Sowthistle (% control)		Annual ryegrass (% control)		Feathertop Rhodes grass		Barnyard grass		Fleabane	
	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact	Direct contact	Partial contact
2 leaf	100	0	100	100	100		100	0	100	-	100	-	100	-
4 leaf	100	-	100	0	100	-	100	0	100	-	100	-	100	-
6 leaf	100	-	100	100	100	-	100	0	100	-	100	-	100	-
8 leaf	100	0	100	-	100		100	0	100	-	100	-	100	-
10 leaf	100	0	100	-	100	-	100	0	100	-	100	-	100	-
Bolting/tillering	100	0	100	-	100	-	100	0	100	-	100	-	100	-
Early flowering/heading	100	0	100	-	100		100	0	100	-	100	-	100	-
Flowering	100	-	100	-	100	-	100	0	100	-	100	-	100	0

- indicates no treatments where there was partial contact of the tyne with the weed.

Figure 2. Wild oats pre- targeted tillage (A), post-targeted tillage (B) and the resulting "divot" (C)

Table 2. Weed control efficacy of the rapid response tyne on four weed species at three growth stages combined results from Warwick and Gatton 2018

Weed species	Growth stage	Control (%)
Barnyard grass	Small (<30cm)	100a
	Medium (30-50cm)	97.8ab
	Large (>50cm)	95.6ab
Feathertop Rhodes grass	Small (<30cm)	97.4ab
	Medium (30-50cm)	92ab
	Large (>50cm)	86.1bc
Wild oats	Small (<30cm)	99.1a
	Medium (30-50cm)	98.7a
	Large (>50cm)	98.1ab
Sowthistle	Small (<30cm)	89.9b
	Medium (30-50cm)	79.4c
	Large (>50cm)	73.8c
LSD P=0.05		8.2

Inclusion of weed detection technologies

The efficacy of targeted tillage for weed control is entirely reliant on accurate weed detection. Given that the initial use of targeted tillage will be in fallow, then it is appropriate that current available real-time detection technologies be incorporated in preparation for commercial use. Current boom spray mounted detection systems (WeedSeeker® and WEEDit®) are coupled to spray nozzles that can be rapidly triggered. Preliminary tests using the WEEDit sensing system to trigger the hydraulics on the Shenton Park rig demonstrated its high suitability to the fallow application. The WEEDit system was chosen as being more suitable system for targeted tillage and has now been incorporated into the pre-commercial Weed Chipper rig. Trials using the system coupled with the 6m pre-commercial Weed Chipper, Figure 1D, are currently underway.

There are a group of thermal weed control technologies (flaming, hot water foaming, steaming, etc.) using chemical or electrical energy that may be used for broadcast weed control (Table 3). In comparison to tillage and herbicide-based options, these approaches are considerably more energy expensive. With 100 to 1000-fold higher energy requirements, it is not surprising that these technologies have not been widely adopted for use in large scale cropping systems, although in more intensive operations, flaming is used to some extent.

Table 3. Total energy requirement estimates for alternative weed control options applied as broadcast treatments. Estimates are based on the control of two-leaf weeds present at five plants/m^2.

Weed control method	Energy consumption (MJ/ha)
Flex tine harrow	4
Sweep cultivator	11
Rotary hoe	13
Organic mulching	16
Rod weeding	18
Spring tooth harrow	22
Basket weeder	29
Roller harrow	29
Disc mower	31
Tandem disk harrow	36
Flail mower	57
Offset disk harrow	64
UV	1701
Flaming	3002
Infrared	3002
Hot water	5519
Hot foam	8339
Steam	8734
Freezing	9020
Hot air	16902
Microwaves	42001
Plastic mulching	211003

Site-specific weed control (SSWC)

The opportunity for substantial cost savings and the introduction of novel tactics are driving the future of weed control towards SSWC. This approach is made possible by the accurate identification of weeds in cropping systems using machine vision typically incorporating artificial intelligence. Once identified, these weeds can be controlled through the strategic application of weed control treatments. This precision approach to weed control creates the potential for substantial cost savings (up to 90%) and the reduction in environmental and off-target impacts (Keller et al. 2014). More importantly for weed control sustainability, SSWC creates the opportunity to use alternative physical weed control options that currently are not suited for whole paddock use.

Accurate weed detection allows physical weed control treatments to be applied specifically to the targeted weed. As weed identification processes develop to include weed species, size and growth stage, there exists the potential for some approaches (such as electrical weeding, microwaving and lasers) to be applied at a prescribed lethal dose. This dramatically reduces the amount of energy required for effective weed control (Table 3). For example, microwaving, as one of the most energy expensive weed control treatments as a broadcast treatment (42,001 MJ/ha), requires substantially less energy when applied directly to the weed targets (17.8 MJ/ha). Therefore, even though the same number of weeds are being controlled (five plants/m^2), the specific targeting of these weeds results in a 99% reduction in energy requirements.

The accurate identification of weeds allows the use of alternative weed control technologies that are not practically suited for use as whole paddock treatments. For example, lasers are typically a narrow beam of light focused on a point target. In a SSWC approach with highly accurate weed identification and actuation, lasers can be focused precisely on the growing points of targeted weeds, concentrating thermal damage. By reducing the treated area of the weed, off-target losses are further reduced allowing additional energy savings.

Table 4. Total energy requirement estimates for alternative weed control options when applied as site-specific treatment. Estimates are based on the control of two-leaf weeds present at five plants/m^2.

Weed control method	Energy consumption (MJ/ha)
Concentrated solar radiation	14.4
Precise cutting	14.4
Pulling	14.4
Electrocution: spark discharge	14.5
Nd:YAG IR laser pyrolysis	15.1
Herbicides	14.8
Hoeing	15.7
Water jet cutting	15.8
Stamping	16.5
Nd:YAG IR laser pyrolysis	16.9
Microwaves	17.8
Abrasive grit	24.5
Thulium laser pyrolysis	25.9
CO_2 laser cutting	54.8
Targeted flaming	59.9
Electrocution: continuous contact	60.9
Nd:YAG laser pyrolysis	84.4
CO_2 laser pyrolysis	92.3
Nd:YAG UV laser cutting	129.4
Hot foam	131.3
Dioide laser pyrolysis	133.1
Nd:YAG IR laser cutting	204.4
Targeted hot water	517.6

Conclusion

The response tyne’s mechanical nature enables it to control weeds with greater flexibility around environmental conditions such as wind, humidity and heat. Its ability to handle a vast range of plant stages of weeds will likely reduce the number of passes required to manage fallow weeds compared to current herbicide practice and help mitigate the current slower travel speed and narrower coverage. The periodic tilling action required for low-density weed populations will also permit the

Weed Chipper to be coupled to low horsepower tractors. With no direct need for chemical use for this system there are likely to be significant cost savings to growers using the Weed Chipper system.

Targeting treatments on individual plants such as in SSWC, results in significant energy savings and makes previously impractical options on a broadcast basis available for use on a site-specific basis. The focus for SSWC research is now dually focussed on the development of weed recognition systems and the evaluation of alternate weed control technologies such as lasers and electrical weeding.

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Further reading

Site-specific weed control – GRDC Grains Research Update paper, July 2018 (https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/site-specific-physical-weed-control)

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New genetics to improve wheat establishment and weed competitiveness

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Key words

wheat, breeding, genetics, dwarfing genes, coleoptile length, establishment

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Take home messages

- Current Australian wheat cultivars contain dwarfing genes that reduce coleoptile length by 40%. New dwarfing genes are available that reduce plant height but don't reduce coleoptile length
- A gene increasing coleoptile length was identified and tagged with DNA markers. Breeding lines and DNA markers for new dwarfing and coleoptile length genes have been delivered to Australian breeders for efficient selection of improved crop establishment
- Deep-sowing studies in WA and NSW Managed Environment Facilities show benefit with new dwarfing and coleoptile length promoting genes in increasing emergence at sowing depths of up to 120mm but without changing plant height
- Moisture-seeking points coupled with new genetics should reliably allow seed placement and emergence from sowing depths of 100mm or greater, and/or with warmer soils
- Genetic variability exists with potential to suppress weeds through greater shoot and/or root competitiveness.

Background

In rainfed environments typical of the eastern and southern wheatbelts, crops are typically sown on the first breaking rains but sometimes moisture accumulated through summer is too deep for sowing with conventional variety × drilling systems. Key to good leaf area development for tillering, growth and weed competitiveness is good crop establishment. An ability to establish wheat crops from seed placed 80mm or deeper in the soil would be useful in situations where the subsoil is moist but the surface dry. Seeding onto moisture at depth can assist to extend the opportunities for a greater portion of the cropping program to be sown in the traditional sowing months of May and June or earlier in April following summer rain. A separate but concerning issue is the influence of increasingly warmer soil temperatures on reductions in coleoptile (the shoot that grows from the seed and allows seedling emergence through the soil) length. Earlier sowing into warmer soils will reduce coleoptile length by as much as 60% so that a variety such as Mace with a 75mm coleoptile at 15°C will likely have a 40mm coleoptile at 25°C soil temperature. Some seed dressings and pre-emergent herbicides can further reduce this coleoptile length and affect establishment.

The green revolution *Rht-B1b (syn. Rht1)* and *Rht-D1b (syn. Rht2)* dwarfing genes reduced plant heights to reduce lodging and increase grain yields and so are present in most wheat varieties worldwide. Their presence also reduces the length of the coleoptile by as much as 40%. This reduces crop emergence when sown at depths greater than 50mm, tiller number and leaf size to reduce water-use efficiency and weed competitiveness.

New dwarfing genes

A range of alternative dwarfing genes have been identified in overseas wheats with potential to reduce plant height and increase yields, while maintaining longer coleoptiles and greater early vigour. Some of these genes (e.g. *Rht8* and *Rht18*) have been used commercially overseas but have not been assessed for use here in Australia. We reduced the larger global set of alternative dwarfing genes to *Rht4, Rht5, Rht8, Rht12, Rht13* and *Rht18*, and then developed linked DNA-markers to assist with breeding of these genes in a commercial breeding program. Separately, we then bred these genes using conventional and DNA-based methods into the old, tall wheat variety Halberd for testing and disseminating to Australian wheat breeders.

Genes that promote coleoptile growth

While switching to new dwarfing genes will remove the growth inhibition on early growth, there is a need to promote coleoptile growth, particularly in the presence of conventional dwarfing genes. A gene with major effect on coleoptile length was identified in current wheat cultivars. Through a GRDC funded project, we demonstrated that the gene not only increased coleoptile length but also emergence with deep sowing in field trials conducted over three years at Yanco NSW (Figure 1). The gene was tagged with molecular markers and tested in a wide range of Australian wheat germplasm. We estimated that only 10% of recently released cultivars carry the coleoptile growth promoting gene. The markers were distributed to Australian breeding companies to assist with the selection and the expected increase of gene frequency in future cultivars. Additional genetic variation for coleoptile length and early growth exists in elite germplasm. For breeders to take full advantage of this variation, additional genes controlling this trait need to be identified and tagged with markers for efficient selection and combining growth promoting genes for even better performance.

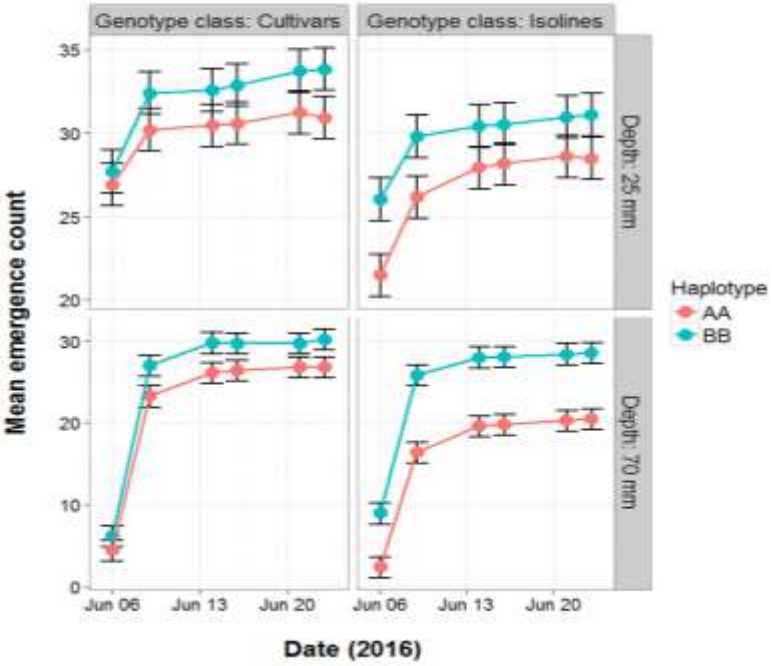

Figure 1. Emergence of wheat commercial cultivars carrying conventional dwarfing genes and tall isolines in Young background in the NSW MEF at Yanco in 2016. Sowing depth treatments were 25 mm and 70 mm depth. 12 cultivars and 12 isolines were grouped according to the presence of the coleoptile length promoting gene (BB, long coleoptiles) and the lack of the gene (AA short coleoptiles).

Preliminary sowing depth field studies

Field studies have commenced on the Halberd-based dwarfing gene lines and show that lines containing these new dwarfing genes produced coleoptiles of equivalent length to Halberd (up to 135mm in length; Figure 2) and established well when sown at 100mm depth in deep sowing experiments conducted at Mullewa and Merredin in 2016 (Figure. 3). Grain yields of lines containing the new dwarfing genes were equivalent to the yields of lines containing the commonly used *Rht-B1b* and *Rht-D1b* dwarfing genes while previous studies have shown the new dwarfing genes were linked to greater grain yields when sown deep, owing to greater plant number with improved establishment.

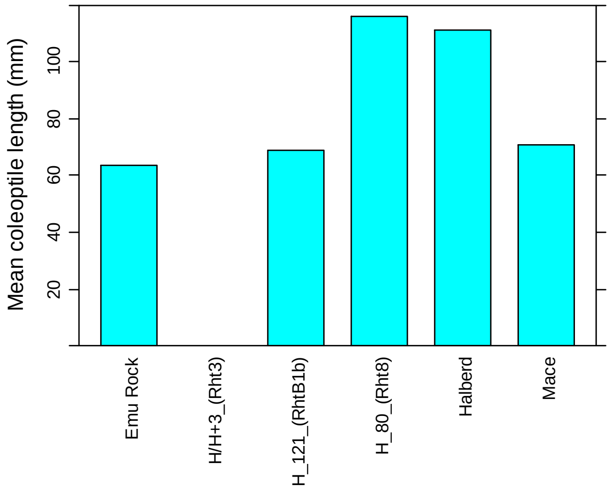

Figure 2. Coleoptile lengths of a tall wheat genotype (Halberd) and genotypes with dwarfing genes *Rht-B1b (syn. Rht1)* and *Rht8* emerging in the field in a Halberd background. Emu Rock and Mace are current commercial cultivars with *Rht-B1b* and *Rht-D1b*, respectively.

The most likely useful new dwarfing genes, *Rht13* and *Rht18*, have been bred into a range of current commercial wheats (Figures 4 and 5). Long coleoptile wheat breeding lines in Mace, Scout, Espada, EGA Gregory and Magenta have been delivered to Australian breeders for testing and use in breeding. If there are no problems with these new dwarfing genes, we may see the first of the long coleoptile wheat varieties in 3-4 years in NVT testing!

Agronomic opportunities

Although there is real promise in the new genetics, there is significant opportunity in coupling new genetics with new existing seeding technologies. Deep sowing is an issue overseas and in the eastern Australian states. The availability of moisture-seeking points commonly used elsewhere should allow the reliable placement of seed at depths of 100mm or greater. These points produce a slot deep into the soil at the base of which a seed is sown at 10-50mm depth. That said, further research is required aimed at tools and methods assessing across different moisture-seeking points to optimise seed placement at depth across a wide range of soil types.

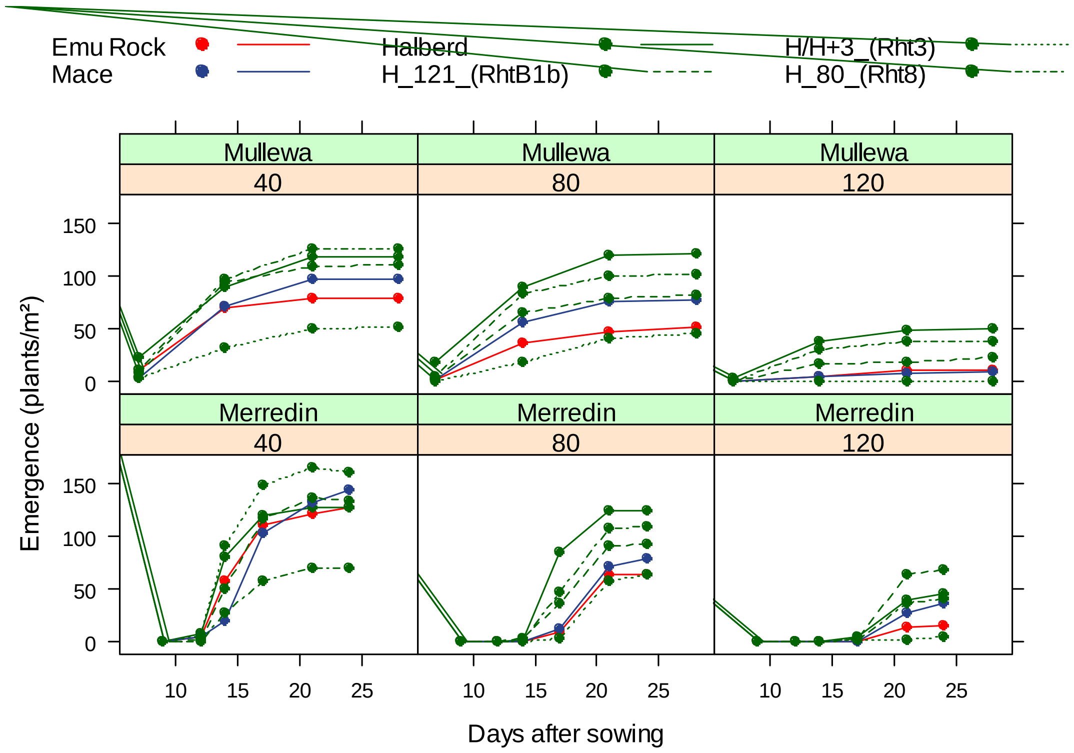

Figure 3. Patterns of emergence of wheat genotypes with different dwarfing genes sown at target depths of 40, 80, or 120 mm at Mullewa and Merredin in 2016 (after French *et al.* 2017).

Weed competitiveness

Weeds cost Australian grain growers an estimated $4B annually through lost production, reductions in crop quality, and herbicide use. These costs are unlikely to reduce with pressure on new actives in the widespread development of herbicide resistance in multiple weed species. Observed differences across cereal species and wheat varietal differences in crop competitiveness with weeds, provides impetus to use breeding and genetic improvement to aid in-crop weed control. In wheat, comparisons across a historic 100-year set of varieties highlighted that older varieties were more competitive with weeds. Presumably, this reflects selection for improved performance in the absence of in-crop herbicides. Overseas studies have demonstrated a reduction in herbicide use of up to 50% when using weed-competitive wheats, while a broader benefit is in integrating competitive varieties with cultural management (e.g. weed seed harvest and tillage) to slow herbicide resistance and reduce herbicide use.

Competitiveness can be thought of as the partial to complete suppression of competing weeds to increase crop yield, or the ability of a variety to tolerate a competitor to maintain higher yields. Selection for greater tolerance is a breeding strategy for many crop insects and diseases but is of less value in weed management as low numbers of weed survivors replenish the seed bank for the next season. In turn, breeding of competitive crops has focussed on selection of genotypes that can better access light, water and nutrients to suppress the growth of weeds. Greater early vigour, as rapid leaf area development and biomass at stem elongation and altered root architecture are mechanisms that contribute to the ability to out compete weeds. Root exudates used in plant defence (allelopathy) may also slow the growth of neighbouring competitors.

In cereals, greater leaf size and rapid early leaf area development are associated with larger seed embryos, higher leaf area, and new dwarfing genes for reducing stem height. Unfortunately, commercial wheat varieties selected for increased yield potential often exhibit poor early growth. A global survey identified 30 wide-leafed, wheat donors which were subsequently used in a CSIRO long-term breeding activity to accumulate favourable genes to increase early vigour. High vigour lines derived from this program have been used to develop wheats with capacity to suppress the growth of ryegrass by up to 50% (Zerner et al. 2016). Field comparisons between current semi-dwarf wheat varieties and weed-competitive wheat breeding lines indicate wheat yield loss and weed suppression is greater in the weed-competitive lines (Figure 4).

Breeding companies are limited in their ability to develop and deliver new traits. The identification of new opportunities that will deliver greater grower profitability together with development of a clear value proposition will allow for pre-breeders to identify those traits and their underlying genetics and methods in selection for uptake by commercial breeders. In the case of weed competitiveness, the genes for weed suppression have come from outside existing breeding programs and include old Australian varieties and overseas landraces. Parental germplasm has been developed over many years and intercrossed into modern Australian varieties. Together with high-throughput selection methods, these populations have been delivered to Australian breeders for use in their commercial breeding efforts toward new weed competitive wheat varieties.

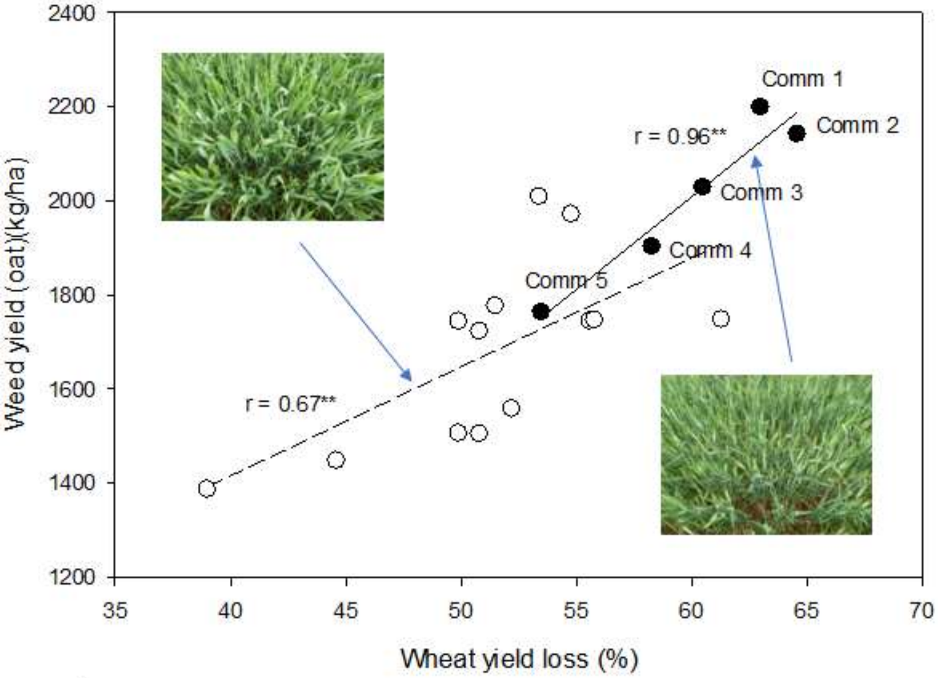

Figure 4. Relationship for yield loss in wheat and growth (as yield) of a weed mimic (oats) for breeding lines (○) and commercial wheat varieties (●) in field plots.

Summary

Wheat breeders now have the new dwarfing genes to breed longer coleoptile wheat varieties. Genes that increase coleoptile length have also been identified and tagged with markers. These genes are expected to play an important role in improving emergence from depth in the presence of conventional dwarfing genes. Matching new genetics with appropriate agronomy and technologies should ensure the emergence and establishment of deep-sown wheats, particularly when sown early to make use of summer rains sitting deep in the soil profile or to increase sowing opportunities in the traditional months of May and June.

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Figure 5. Wheat variety Mace (left) side-by-side with long coleoptile, Mace containing the *Rht18* dwarfing gene (right) at Condobolin in 2017.

Figure 6. Wheat variety EGA Gregory (left) side-by-side with long coleoptile, EGA Gregory containing the *Rht18* dwarfing gene (right) at Condobolin in 2017.

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

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Key words

cover crops, millet, ground cover, soil water storage, fallow management, stubble, evaporation, infiltration, plant available water

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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.

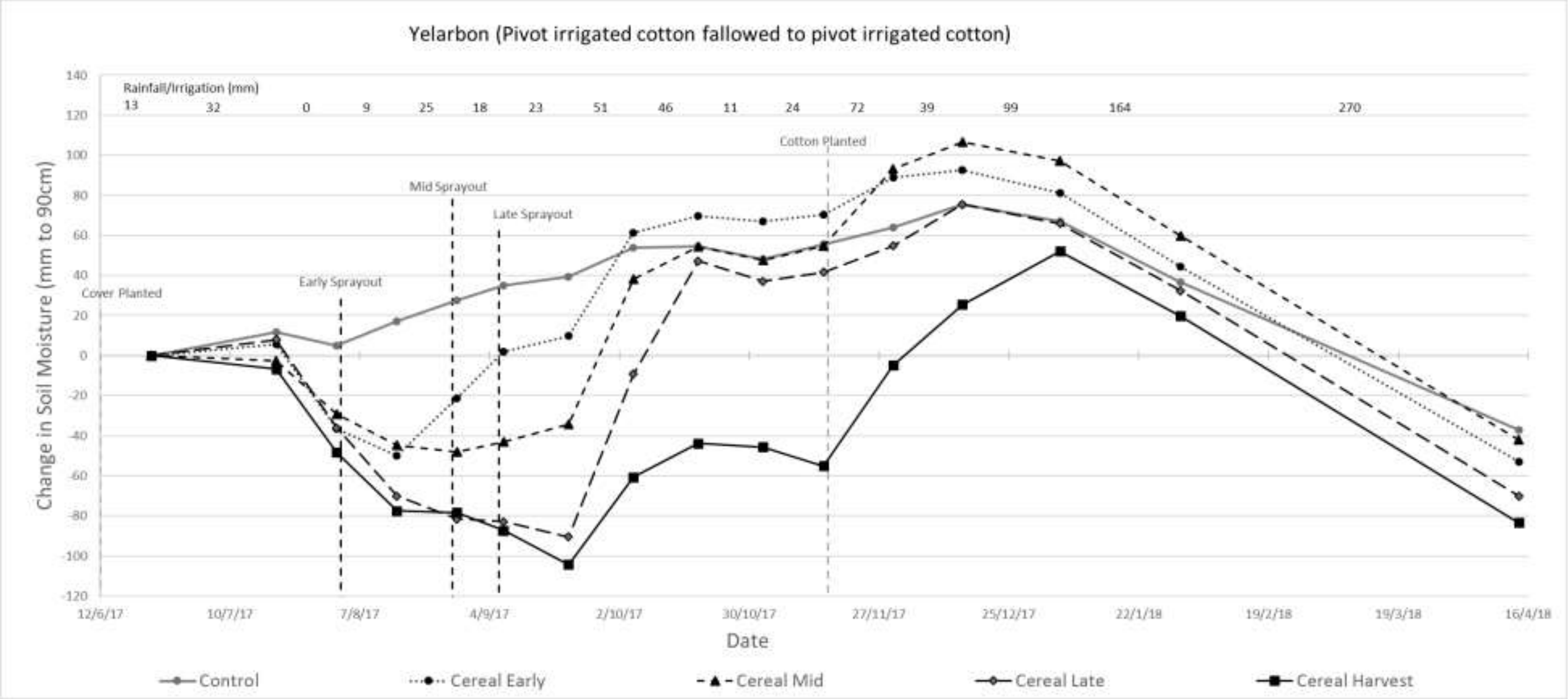

Figure 1. Changes in soil water (mm to 90 cm) from planting of key cover crop treatments until defoliation of the subsequent cotton crop at Yelarbon

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.

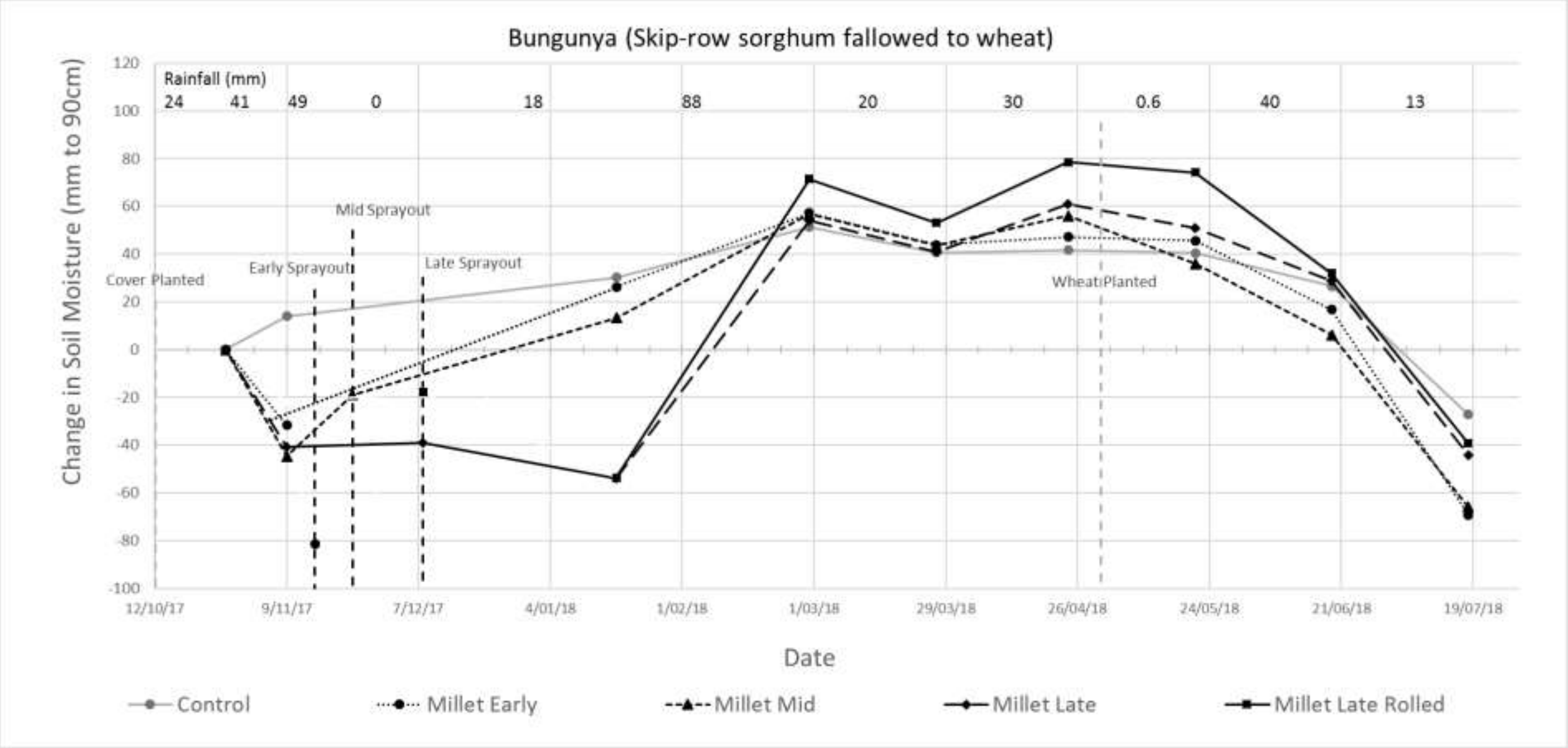

Figure 2. Changes in soil water (mm to 90 cm) from planting of the millet cover crop treatments sprayed out at different crop growth stages until harvest of the later wheat crop at Bungunya

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.

Acknowledgements

The research undertaken in this project was possible through the significant contributions of growers through both trial cooperation and the support of the GRDC, the CRDC, DAF Queensland, CSIRO and DPINSW. The authors would like to thank them all for their continued support. Special thanks to Glen Smith at 'Koarlo', David Woods at 'Coorangy', and the DAF Biometry, Technical and Research Infrastructure staff that supported the heavy management and monitoring loads of these experiments.

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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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Sowing sorghum super early – after two years is it still a good idea?

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Key words

Grain sorghum, cold tolerance, heat stress, flowering

GRDC code

Optimising sorghum agronomy project (UOQ 1808-001RTX)

Take home messages

- Sowing time for sorghum can be moved earlier than the traditional 16 – 18 °C soil temperature without negatively impacting on crop establishment and grain yield
- Defining the minimum soil temperature required for establishment is still tenuous as temperatures are variable in the late winter/ early spring and the risk of mild and severe frosts are still present. However, a minimum of 12° C seems to be the current limit from these experiments to ensure even and timely establishment
- Sowing earlier at both Moree and Breeza moved the flowering window forward and, in both sites, resulted in improved grain yields through reduced exposure to heat and moisture stress during flowering and grain filling.

Introduction

The traditional sowing window for grain sorghum in northern NSW has been challenged in recent years by increasing climate variability predisposing the crop to heat and moisture stress during the critical stages of flowering and grain fill. The impacts have been devastating, resulting in reduced yields and grain quality and even crop failure in some instances. This is ultimately costing grower's money in lost returns.

Similar to the changes we have seen in the adoption of early sowing time with wheat, growers are making incremental changes to the time of sowing with their sorghum crops. Traditionally, the recommendation was to delay sowing until the frost risk period had past and when soil temperatures at sowing depth reached 16-18 °C and were rising, with measurements taken at 8 am for three days. However, in recent years, particularly last season, many crops were sown when soil temperatures were closer to 14 °C, especially in the Moree region where a missed winter crop and continuing dry conditions were driving the need for cash flow.

Since 2017, the GRDC, University of Queensland and NSW DPI have partnered in a research program to test the boundaries of sowing sorghum earlier and measuring the impacts on plant establishment, crop development, grain yield and quality. Research trials have been conducted from Emerald (with QDAF joining the team this season), Southern Qld, Moree and the Liverpool Plains.

Experiments were designed to develop a data set to define how early growers can plant sorghum in each of these environments and what are the potential benefits and risks from adopting this strategy of "winter sown sorghum". In this study we considered effects on the sorghum crop as well as follow-on impacts on crop rotation intensity and the possibility of ratooned sorghum.

In 2017-18 three sites were conducted in northern NSW at Mallawa, Gurley and Breeza. During 2018-19 two sites were conducted at Moree and Breeza; with the Breeza site containing both a dryland and a supplementary irrigated trial. Only the results from the two dryland trials in 2018-19 are reported here.

Trial details 2018-2019

Table 1. Site characteristics for two sorghum time of sowing trials sown during the 2018/19 season

Time of sowing (TOS)	Sowing date	Soil temp. at 8 am[#] (°C)	Soil water[##] at sowing (mm)	In-crop rainfall (mm)	Irrigation (mm)
"Ponjola" Moree, NSW (dryland)					
1	7 & 8 Aug	12.3	97.5	199.7	33*
2	11 & 12 Sept	17.1	112.8	153.2	-
3	27 Sept	18.9	115.7	153.2	-
"LPFS" Breeza, NSW (dryland)					
1	6 Sept	11.2	Pre-irrigated	222.9	-
2	17 Sept	10.3	Pre-irrigated	222.9	-
3	23 Oct	18.8	Pre-irrigated	170	-

[#]Average soil temperature (°C) at sowing depth for seven days after sowing

[##]Soil water (mm, 0-1.2 m) at the time of sowing

*33 mm of water was applied post sowing on the 14th August using dripper lines to ensure even establishment due to dry seedbed conditions.

Table 2. Description of treatments (sowing dates, target populations and hybrids)

Time of sowing (TOS)	Sowing date	Target plant population (pl/m²)	Hybrids
"Ponjola" Moree, NSW (dryland)			
1	7 Aug	3, 6, 9, 12	MR Buster, MR Apollo, MR Taurus, Agitator, Cracka, HGS114, A66, G33
2	11 & 12 Sept		
3	27 Sept		
"LPFS" Breeza, NSW (dryland)			
1	6 Sept	3,6,9,12	MR Buster, MR Apollo, Agitator,Cracka, HGS114, G33
2	17 Sept		
3	23 Oct		

Results and discussion

"Ponjola" Moree

Plant establishment

The first time of sowing (TOS) occurred under dry seedbed conditions, so to ensure even establishment at the desired soil temperature, a total of 33 mm of water was applied one-week post sowing using dripper lines. The first establishment counts which recorded plants emerging were taken on the 31st August, 3 weeks post sowing and 2 weeks post watering. Plants emerged slower under TOS1, than TOS 2 and TOS 3 which had more even and quicker establishment.

There was no impact of time of sowing on any of the final established plant populations except the 120,000 plants/ha treatment which established more plants as the TOS became later (Table 3).

Table 3. Impact of time of sowing on plant establishment at "Ponjola"

Target plant population (plants/m^2)	TOS 1 (7 August)	TOS 2 (11 Sept)	TOS 3 (27 Sept)
3	2.44 f	2.63 f	2.77 f
6	5.22 e	5.23 e	5.34 e
9	7.60 d	8.32 cd	8.35 cd
12	8.94 c	10.80 b	11.83 a
L.s.d: 1.02, $P<0.05$			

There was an interaction between TOS and hybrid. Comparing across times of sowing, Agitator had the poorest establishment at nearly all TOS. TOS 2 and TOS 3 had improved establishment for nearly all hybrids when compared to TOS 1 but the differences were not always statistically significant (data not shown).

Impacts of time of sowing and plant population on crop development

Increasing plant population reduced the number of fertile tillers produced as did delaying the TOS. Averaged across populations and hybrids; TOS 1 resulted in more fertile tillers, 4.34/ m^2 compared to 2.88 / m^2 tillers for TOS 2 and 1.78 / m^2 for TOS 3. Hybrids also produced different numbers of tillers with Agitator, which had the lowest plant establishment, producing the highest number of fertile tillers. In contrast MR-Apollo had the lowest number of fertile tillers (data not shown).

Time of sowing, hybrid and plant population all impacted on the number of heads produced. More heads were produced from TOS 1 than TOS 3. The differences between TOS 1 and TOS 2 were not significant. As plant population increased so did the number of primary heads. Hybrids varied in their number of heads produced. The lowest numbers of primary heads were produced by MR-Apollo and Agitator (data not shown).

Did sowing earlier impact on flowering?

There was a significant impact of sowing time, population and hybrid on the number of days taken to reach 50% flowering.

Sowing timing had a significant impact on days to flowering; the earlier we sowed, the longer the time taken to reach flowering. TOS 1 took an average of 106 days to reach 50% flowering which reduced to 82 days for TOS 2 and 75 days for TOS 3.

Delaying sowing from TOS 1 to TOS 2; a period of 4 weeks; reduced the time to 50% flowering by 24 days. The days to flowering difference between TOS 2 and TOS 3 was much smaller, only 7 days, even though there as a 16-day difference in sowing time.

In TOS 1, the slowest hybrid to reach 50% flowering was MR-Apollo at 115 days, and the quickest was Agitator at 99 days, a spread of 16 days over the eight hybrids examined. In contrast by TOS 3, MR-Apollo flowered in 81 days, while Agitator was 70 days, a difference of 11 days. Agitator was consistently the quickest and MR-Apollo consistently the slowest of the hybrids tested to reach 50% flowering (Figure 1).

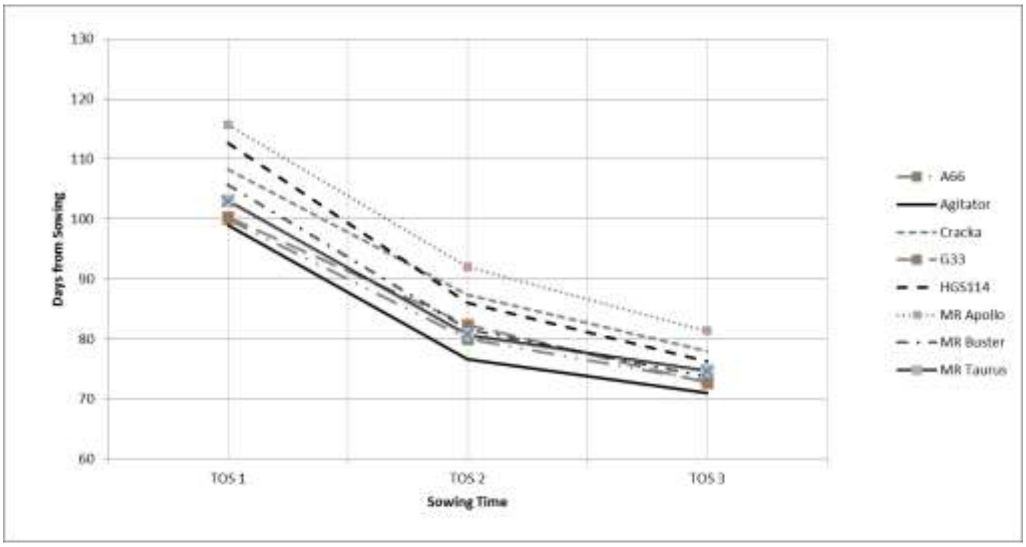

Figure 1. Days to 50% flowering at "Ponjola" for 6 plants/m^2 target population.

TOS 1 moved the flowering window for all hybrids forward by around three weeks compared to sowing at the recommended soil temperature (TOS 3). This meant flowering was completed prior to the onset of very high temperatures at the beginning of December (Figure 2).

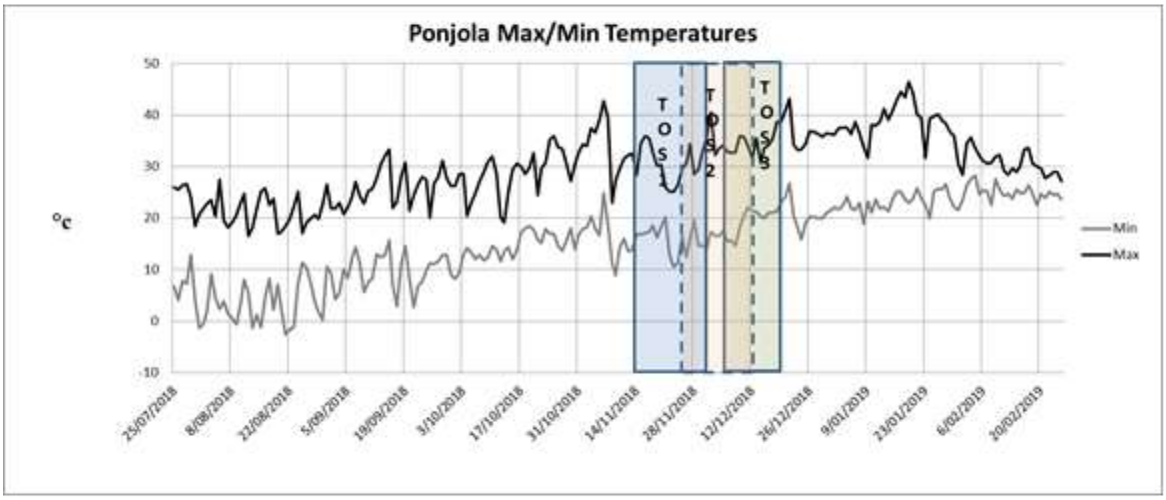

Figure 2. The flowering windows for TOS 1, TOS 2 and TOS 3 at "Ponjola" Moree in 2018-19

What was the impact on grain yield and quality?

The site mean yield was 1.78 t/ha at “Ponjola” in 2018-19. There was a significant interaction between time of sowing and hybrid yields (Figure 3). Plant population did not have a significant impact on grain yield. TOS 1 was the highest yielding at 2.14 t/ha. There was no significant difference in yields achieved between TOS 2 and TOS 3 being 1.51 and 1.68 t/ha respectively.

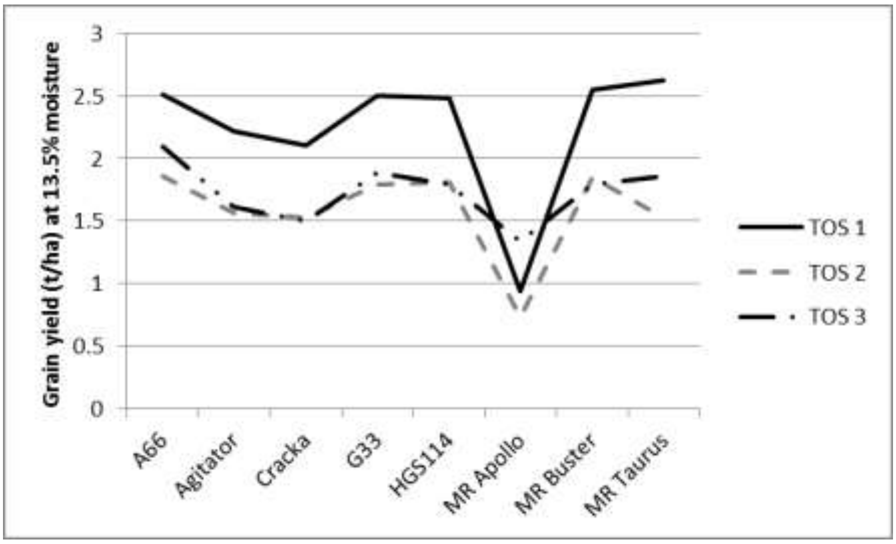

Figure 3. Grain yield at three times of sowing (TOS) at "Ponjola" Moree in 2018-19

Grain protein achieved was significantly less at TOS 1 (10.7%) compared to the TOS 2 and TOS 3 planting times at 11.1% and 11.2% respectively. However, all grain proteins were still at an acceptable level to show that nitrogen was not limiting.

Screenings were impacted by TOS, population and hybrid. TOS 1 had significantly lower screenings at 10% compared to TOS 2 at 16.6% and TOS 3 at 17.9%. The hybrid interaction was also significant with Agitator averaging the lowest screenings at 10.5% while G33 and MR-Buster had the highest between 18-19%. The 120,000 plants/ha target population was the only treatment to show significantly higher screenings at 15.9% while all other target plant populations were between 14-15%, when averaged across hybrids and sowing times. This means that only TOS 1 met the sorghum 1 standards for screenings.

Test weights were generally low. No hybrid averaged the required test weight to achieve grade 1 sorghum (>71 kg/hL). The only treatment to achieve sorghum 1 was Cracka at TOS 3 with 71.3kg/hL (data not shown).

Breeza dryland

Plant establishment

At Breeza the soil temperatures with TOS 1 were cooler than the Moree site (11.2°C vs 12.3°C; (Table 1)), even though the first sowing date at Breeza was close to one month later than Moree on the 6th September. Soil temperatures rose at Breeza during mid-September but then plummeted again following TOS 2 resulting in a 7-day average of 10.3 °C. At these cooler soil temperatures, time of sowing had a significant impact on plant establishment. TOS 1 and TOS 2 had significantly reduced plant establishment compared to the standard (TOS 3) sowing date.

Most hybrids did not achieve the four target plant populations of 3, 6, 9 and 12 plants/m^2 for TOS 1 or TOS2. TOS 3 which established in soil temperatures closer to 18 °C was better.

There were a couple of small differences between hybrids. Agitator had a significantly lower establishment than all other hybrids and G33 established fewer plants than MR-Buster (Figure 4).

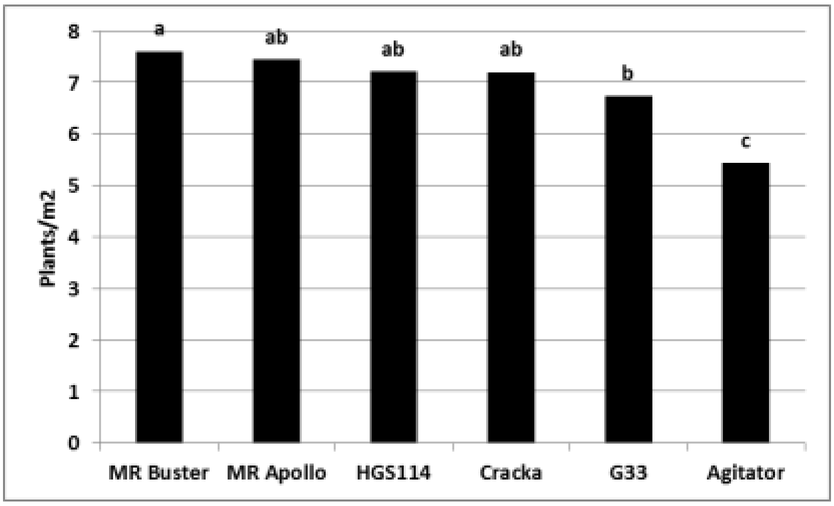

Figure 4. Hybrid establishment (plants/m^2) averaged across times of sowing and plant population

Impact of time of sowing and plant population on crop development

There was a significant interaction between time of sowing and population. The number of fertile tillers declined as the plant population increased at all sowing times. TOS 3 had much lower levels of tillering compared to TOS 1 and TOS 2 (Figure 5).

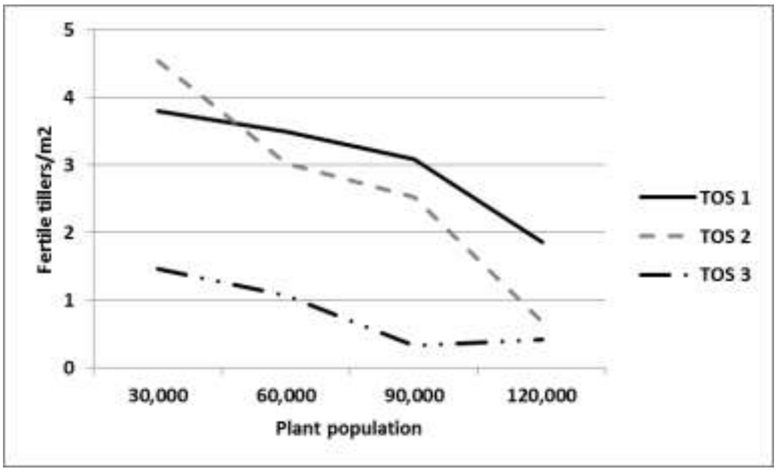

Figure 5. Interaction between time of sowing and target plant population on fertile tillers/m^2

Time of sowing did not have an impact on the number of primary heads at Breeza. There were more primary heads produced with higher plant populations. Agitator and MR Apollo produced the lowest number of heads (data not shown).

Did sowing earlier impact on flowering?

The number of days taken to reach 50 % flowering reduced as TOS was delayed. For TOS 1 it was 95 days, TOS 2 was 10 days faster at 85 days and for the standard sowing time at TOS 3, 69 days. Between TOS 1 and 2, delaying sowing by 15 days resulted in a 10-day difference in flowering. TOS 3 developed in much warmer conditions meaning even though there was a 30-day difference in sowing this only caused a 16-day difference in flowering compared to TOS 2.

There was a much smaller difference between the hybrids for time to flowering at Breeza compared with Moree in 2018-19. However, Agitator was still the quickest hybrid for all times of sowing, although by TOS 3 MR-Buster was as quick. MR-Apollo remained the slowest of the hybrids examined (Figure 6).

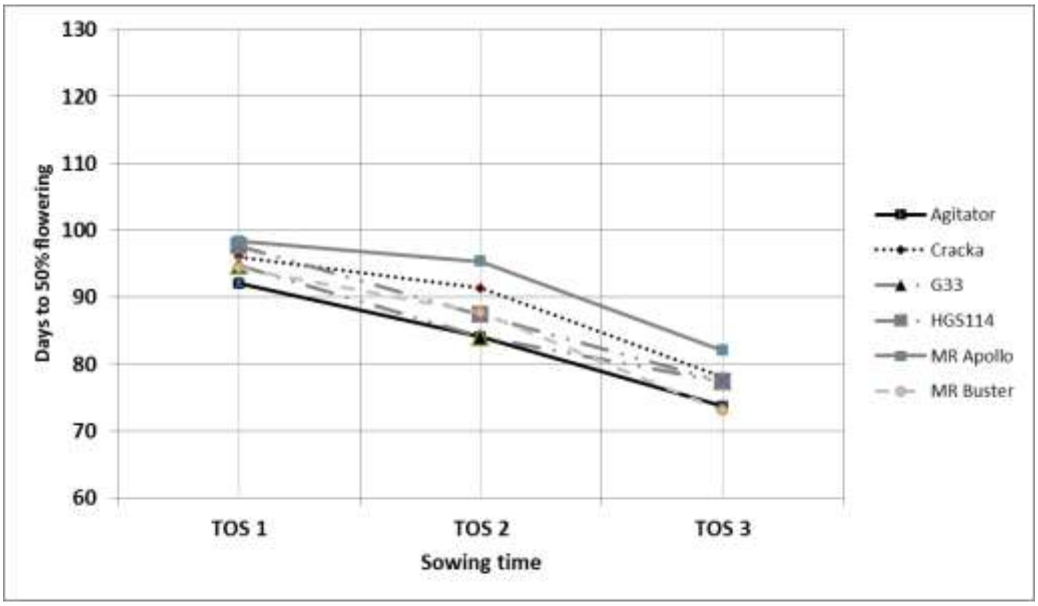

Figure 6. Days to 50% flowering at Breeza – Dryland at 6 plants/ha target plant population

What was the final impact on grain yield and quality?

The site mean yield was 1.73 t/ha at Breeza in 2018-19. There was a significant impact of TOS and hybrid on final grain yield (Table 4). TOS 1 (2.23 t/ha) and TOS 2 (2.12 t/ha) had significantly higher grain yield than TOS 3 (0.85 t/ha), averaged across hybrids and plant populations. There was no significant impact of plant population on grain yield.

Table 4. Impact of time of sowing (TOS) and hybrid on grain yield (t/ha) at 13.5% moisture Breeza – dryland in 2018-19

Hybrid	TOS 1	TOS 2	TOS 3
MR- Buster	2.61 a	2.41 ab	1.26 def
G33	2.59 a	2.43 ab	0.83 eg
Agitator	2.57 a	2.31 ab	0.88 eg
HGS114	2.22 bc	2.32 ab	0.87 eg
Cracka	2.16 bc	1.91 acd	1.00 efg
MR-Apollo	1.25 defg	1.32 e	0.26 h
L.s.d: 0.75, P<0.05			

Test weights were significantly lower at TOS 3 (54.8 kg/hl) compared to TOS 1(62.7 kg/hl) and TOS 2 (62.8 kg/hl), although neither made sorghum 1 classification. Similarly, no hybrid averaged the required test weight to achieve grade 1 sorghum (>71 kg/hl).

Screenings were impacted by TOS, plant population and hybrid at Breeza with all screenings levels being relatively high. TOS 1 and TOS 2 had significantly lower screenings at 12.6% and 13.2 % compared with TOS 3 at 27.4%. The hybrid interaction was also significant with Agitator and Cracka producing the lowest screenings at 15.3% at 15.7%. G33 had the highest at 21.5%. Higher screenings also occurred as plant population increased (data not shown).

Conclusions

At the Moree site, there was little impact on plant establishment from sowing in mid-august when soil temperatures were 12.3°C for the 7 days following sowing. In contrast sowing into slightly cooler temperatures (10-11°C) at Breeza had a significant impact on sorghum establishment.

At both Moree and Breeza, the flowering window was moved forward from sowing earlier in this season. This helped to ensure flowering occurred before the peak of heat and moisture stress set in. The earlier sowing time resulted in improved yields at both sites, even though average yields at Breeza and Moree were not high due to drought conditions. Varying plant population, from 3 to 12 plants/m^2 did not impact final grain yield. The plants modified their tiller and head production in response to the surrounding competition and seasonal conditions. For example, as plant population increased the number of primary heads increased and the number of fertile tillers decreased.

While the benefits of sowing sorghum earlier than traditionally recommended appear to be improved yields and grain quality, the risks have not been fully evaluated. The impact of frost in particular needs to be further assessed including determining the actual temperature where plant death occurs.

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NVT sorghum performance report

Laurie Fitzgerald, GRDC

Key words

NVT hybrid sorghum performance report

GRDC code

EAS1808-001SAX, DAN1809-001 SAX, KAL1809-001SAX

Take home messages

- Sorghum is the first summer crop in the annual National Variety Trials database
- Results across NSW and Queensland will assist growers select hybrids best suited to their requirements
- It must be emphasized that the NVT sorghum results are from only two seasons and should be taken in context to the seasons experienced
- When assessing a sorghum hybrid's performance, it is imperative to consider the seasonal effects.

A mainstay in many northern farming systems, Australian grain sorghum is predominantly used as poultry and pig feed, as a feedstock for biofuel production and in China to produce baijiu (sorghum wine). With an average area of 650,000 hectares and production of 1.89 million tonnes, sorghum is Australia's fifth-largest crop overall and largest summer crop.

Following extensive consultation with growers and industry, sorghum in 2017 became the first summer crop to join the National Variety Trial program. The trialling program encompasses the following regions; Central Queensland, Southern Queensland, Northern New South Wales and the Liverpool Plains.

Following the success of the 2017-18 trials, GRDC last year invested in a further three years extending the NVT sorghum program to 2021.

Breeding companies were invited to submit hybrids for inclusion in the sorghum NVT project that they felt were suitable for the environments under evaluation. In the 2018-19 season, A total of 30 commercial and advanced pre-commercial hybrids from Advanta (Pacific) Seeds, Elders, Heritage Seeds, Nuseed, Pioneer Seeds, SV Genetics Pty Ltd and Radicle Seeds have been evaluated. This is up from the 24 varieties tested in the initial season.

The climatic conditions experienced leading up to and during the growing periods varied greatly between and within the four trialling regions. The 2017/18 season began with variable rainfall which required some sites to be relocated and caused others to struggle, however 19 of the proposed 21 sites were established. Cold conditions soon after sowing slowed growth but temperatures increased to well above average in late December and January. The 2018/19 season proved challenging to find suitable trial sites, nonetheless, 19 of the proposed 23 sites were established. Some sites experienced average to good in-crop rainfall while others were drought stressed (some terminal), suffered hail damage or were compromised due to uneven run-off from high-intensity storms.

Each trial underwent a rigorous auditing schedule to determine suitability on agronomic criteria for inclusion. The analysis and interpretation of these trial results deemed suitable for inclusion were managed by the GRDC's Statistics for Australian Grains Industry (SAGI), a world class project team who employed a world class statistical package to apply further rigour to ensure a robust dataset. Of the 19 trials planted in 2017/18, 15 were deemed suitable to be included and of the 19 trials established in 2018/19, 11 sites have been deemed suitable and fulfilled the NVT testing program criteria for the analysis.

The results for the NVT sorghum trials can be obtained from https://www.nvtonline.com.au/ and will also be published in the 2019 Hybrid Sorghum Performance Report on the GRDC website.

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Key decisions and options for the coming crop cycle - a discussion session

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