Queensland grains research 2018-19

Regional Research Agronomy

GRDC
GRAINS RESEARCH & DEVELOPMENT CORPORATION

Queensland Government

This publication has been compiled by Duncan Weir and Tonia Grundy on behalf of the Regional Research Agronomy team of Crop and Food Science, Department of Agriculture and Fisheries (DAF).

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Foreword

Welcome to the fourth edition of *Queensland Grains Research*. This body of work shows that the Department of Agriculture and Fisheries (DAF) Regional Research Agronomy team continues to regionally validate many contemporary grains productivity management options across Queensland. With Regional Research Agronomy teams based in Goondiwindi, Toowoomba and Emerald, along with farming systems experts based in Bundaberg, Biloela and North Queensland, a broad range of topics are being researched in most of Queensland's broadacre farming regions.

Of course conducting research is one thing, but communicating the results and implications of those trials to the producer and agronomist community is the next challenge. Our trial reports are structured to provide the information required in several access modes. A quick summary of what the trial tested and the summary of results, a more detailed insight into the trial methodology and ensuing results and implications, and tabular/graphical representations of the results to help give a sense of the 'response curve' being investigated. As always, we provide details of the Regional Research Agronomy team so that readers can put a face and name to team members. This creates opportunities to discuss with them various issues about results and conclusions gained over the past season from our research program.

As part of our challenge in bringing these research outcomes to you, we value your feedback to enable us to continually improve the way we undertake and report our regional agronomy trials.

We fully acknowledge and sincerely thank producers, advisers and agricultural supply chain businesses who have contributed to the success of these trials. This research is co-funded by the Grains Research and Development Corporation who, with their continuous investment cycle and significant corporate footprint within Queensland, help to provide valuable guidance on DAF's strategic investments in grains research and development.

Garry Fullelove
General Manager, Crop and Food Science
Department of Agriculture and Fisheries, Queensland

The Grains Research and Development Corporation (GRDC) plays a pivotal role investing in research, development and extension (RD&E) to create enduring profitability for, and on behalf of, Australian grain growers.

Through collaboration with specialist teams the GRDC is firmly focused on research that improves our knowledge and understanding of key areas including farming systems, agronomy, phenology, nutrition, soils, pests, weeds and disease—in a way that informs grower practices and on-farm decision making.

In partnership with the Queensland Department of Agriculture and Fisheries (DAF), the GRDC has invested in a significant regional agronomy program the results from which have been collated in this 2019 DAF *Queensland Grains Research* trial book.

This publication offers growers and advisers in-depth updates and analysis of the latest regional trial results, as well as valuable information to guide on-farm decision making in response to ongoing and emerging farm management challenges.

Ken Young
Acting General Manager Applied Research and Development
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The DAF biometry team and Statistics for the Australian Grains Industry (SAGI—co-funded by GRDC) have provided statistical analysis of the data presented in papers when identified in the acknowledgement section.

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Research facilities

The regional research trials reported here would not have been possible without the support of dedicated technical and operational officers at the Department of Agriculture and Fisheries' major research facilities across the grain region. Thanks to all those staff at the Hermitage Research Station (near Warwick), the Leslie Research Facility (Toowoomba), the Bjelke-Petersen Research Station at Kingaroy, and staff based at the Queensland Agricultural Training College (Emerald) for their operation of heavy plant and research machinery.

Cereals research

Winter and 'summer' cereal phenology and agronomy research continues to be a strong focus of the Regional Research Agronomy team. The two cereal research projects in 2018 focused on observing growth stage characteristics across a range of genotypes, and whether manipulation of the plants' agronomic management can significantly alter development and ultimately yield.

Working with our project lead partners, New South Wales Department of Primary Industries, the Grains Research and Development (GRDC)-funded 'Optimising grain yield potential of winter cereals in the Northern Grains Region' (BLG104) focus is to map the development of 32 genotypes across eight locations. The aims are to understand varietal differences in phenology both between the eight locations the trial was planted into in 2018, and between different sowing dates.

The 2018 data was very different to what was observed in 2017, primarily due to a very dry winter season across the northern grains region, and there were significant reductions in both yield and biomass accumulation across all sowing dates. Quick maturing spring wheats had the highest yields for all four sowing dates in Central Queensland (CQ) while longer season varieties (traditionally favoured for early sowing dates) were significantly impacted, producing yields more than 1 t/ha lower, even for the earliest sowing date.

The team has also been working with Queensland Alliance for Agriculture and Food Innovation (QAAFI) on the project Optimising Sorghum Agronomy (UOQ 1808-001RTX). This innovative new GRDC project builds on some of the findings in the UQ000075 'Tactical Agronomy for Sorghum and Maize' project. An early August trial planting in 2017 on the Darling Downs was observed to not only out-yield later sowing dates, but it was also able to germinate at temperatures well below the recommend temperatures of 16 °C and rising and seedlings were able to survive multiple frost conditions to as low as –2 °C.

Sowing of sorghum in CQ occurred on 25 July 2018, 16 August 2018 and 17 January 2019. For this trial, while germination at low temperatures is important to understand, soil temperatures even for the early sowings remained above 16 °C so there was limited effect on emergence observed. The primary aim was to try to achieve an identified 4-week 'sweet spot' flowering window. Unfortunately the flowering period for both early sowing treatments overshot our target window, however there was a notable difference in phenology response between the two sowing dates.

Yield response for the earliest sowing date was up to 1 tonne/ha better and plant height was 10 cm lower compared to the second sowing date. Screenings for both early sowing dates were high, but were better for the first sowing date, and there was an average of 10 days difference in time to flowering.

Early planting sorghum—Emerald

Darren Aisthorpe and Jane Auer
Department of Agriculture and Fisheries

Research Question: *Can sowing sorghum early avoid heat and water stress in cropping systems in Central Queensland?*

Key findings

1. Preliminary results show better yields and slightly improved grain quality from the earliest sowing date (25 July).
2. There was a difference in plant phenology and physiology between the two early sowing dates (25 July and 16 August).

Background

Water stress and extreme heat at flowering are common abiotic stresses limiting yield in cereal crop production across the northern grains region. Early sown sorghum crops in Central Queensland (CQ) have shown high yield potentials, but with an increase in perceived risk due to water/heat stress at flowering or frost damage at emergence. The Grains Research and Development Corporation (GRDC) research project, Optimising Sorghum Agronomy (UOQ 1808-001RTX), led by the Queensland Alliance for Agriculture and Food Innovation (QAAFI) in partnership with the Queensland Department of Agriculture and Fisheries (DAF) and New South Wales Department of Primary Industries (DPI NSW), looks to challenge these perceptions. This project will test the ability of sorghum to germinate and withstand cold temperatures during early growth stages in order to reduce heat stress during flowering and grain fill.

The early sowing dates were selected using *CliMate* to target a suitable flowering temperature window; maximum temperatures <35 °C to minimise heat stress and minimum temperatures >10 °C to reduce the chance of ergot infection. Planting dates were determined so head emergence began mid-September (Figure 1).

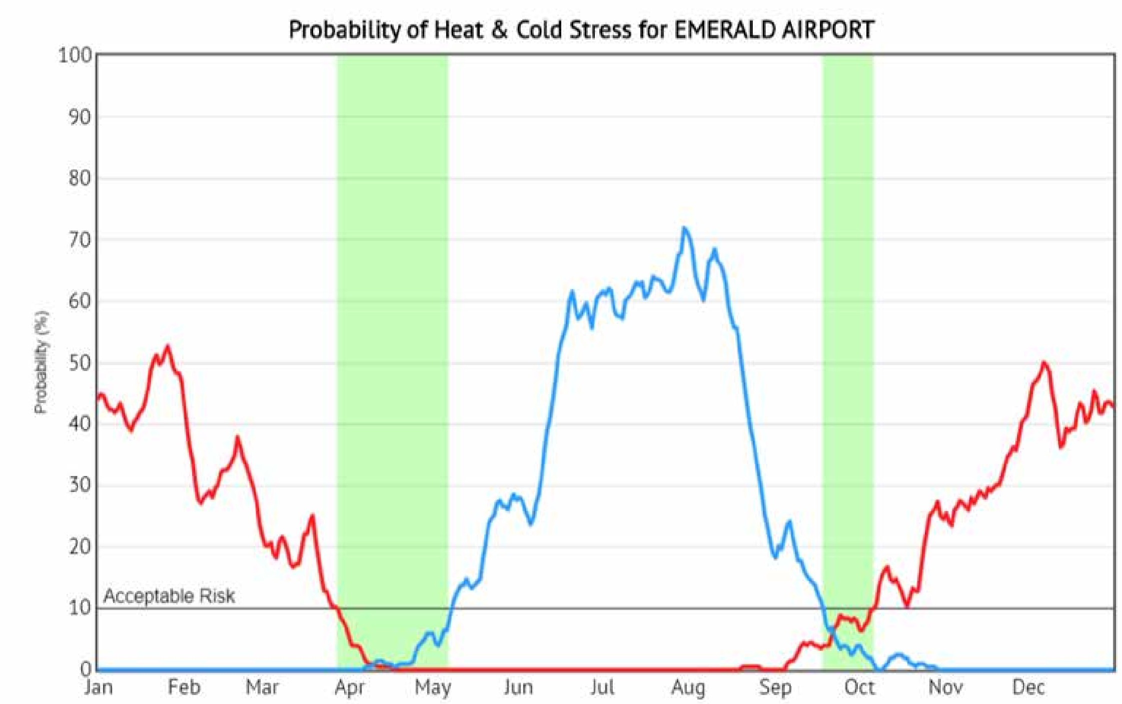

Figure 1. ***CliMate*** **data showing the likelihood of a temperature 'sweet spot' for flowering and grain fill. The green bars on the graph indicate, based on historical climate data back to 1990, there was a less than 1 in 10 year chance of receiving temperatures below 10 °C and above 35 °C in those periods.**

What was done

The trial was planted on 1 m solid row spacing, using a tyned parallelogram with vSet® precision seeding system on the Emerald Research Facility. Eight hybrids with a range of maturities were planted across three times of sowing (TOS) at four populations ranging from 3-12 plants/m². Early sowing dates were 25 July 2018 and16 August 2018 with a third 'traditional' sowing date of 17 January 2019 (Table 1).

Table 1. Treatments and sowing dates for the three times of sowing in the 2018/19 trial.

Hybrids used
A66 (Pioneer)
Agitator (Radical Seeds)
Cracka (NuSeed)
G33 (Pioneer)
HGS-114 (Heritage Seeds)
MR Apollo (Pacific Seeds)
MR Buster (Pacific Seeds)
MR Taurus (Pacific Seeds)
Target populations (plants/ha)
30,000
60,000
90,000
120,000
Time of sowing (TOS) dates
TOS 1: 25 July 2018
TOS 2: 16 August 2018
TOS 3: 17 January 2019*

* limited data available at time of publication.

Results

Establishment

Soil temperatures at TOS 1 (17.8 °C) and TOS 2 (17.3 °C) were already above the industry-recommend minimum planting temperature of 16 °C. As a result, good establishment was achieved (Figure 2) with minimal post emergent mortalities, despite minimum air temperatures regularly dropping to below 5 °C between 25 July (TOS 1) and 24 August.

Conversely, establishment was challenging for TOS 3 (Figure 2). The field received 25 mm of rain on 22 December 2018 and an additional 60 mm of overhead irrigation prior to planting, however soil temperature often exceeded 40 °C in the first 10 days post-plant (Table 2) resulting in lower establishment.

Table 2. Soil temperature readings (°C) for the first 10 days after TOS 3, 17 January 2019 (measured using a probe placed in the trench at seed depth).

	@ 8am	min	max	Daily avg.
17/01/2019	29.5	29.3	41.3	31.3
18/01/2019	28.8	27.1	36.9	31.2
19/01/2019	28.3	26.5	38.1	31.6
20/01/2019	28.1	26.6	39.2	32.1
21/01/2019	28.9	27.1	38.5	31.8
22/01/2019	28.6	27.2	39.4	32.2
23/01/2019	29.2	26.7	42	33.1
24/01/2019	29.9	28.1	42.2	33.7
25/01/2019	30.2	27.8	41.4	33.5
26/01/2019	30.7	28.6	40.1	33.1
27/01/2019	30.1	27.9	41.3	33.2

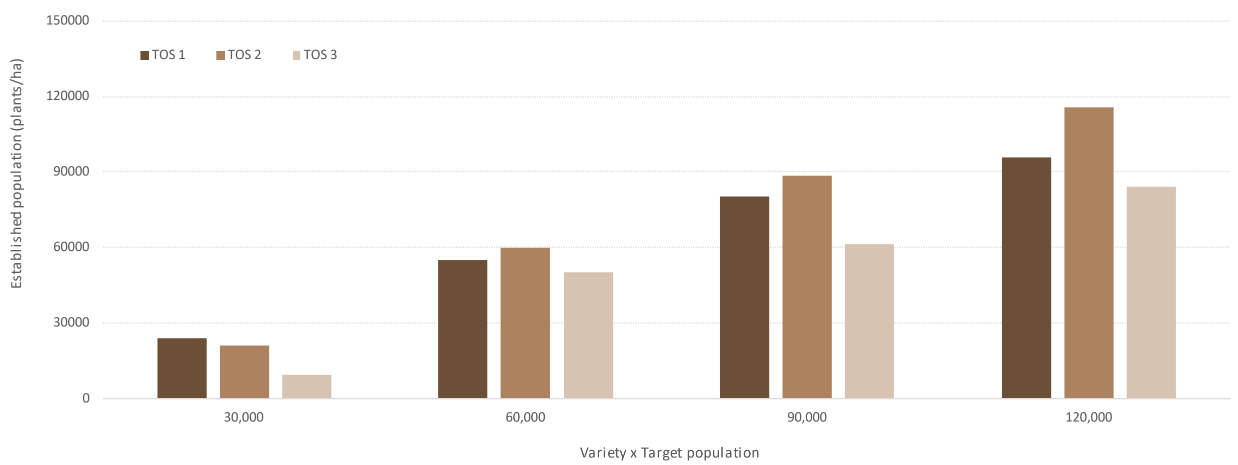

Figure 2. Average emergence across the three TOS dates for the four target populations.
Statistical analysis yet to be completed.

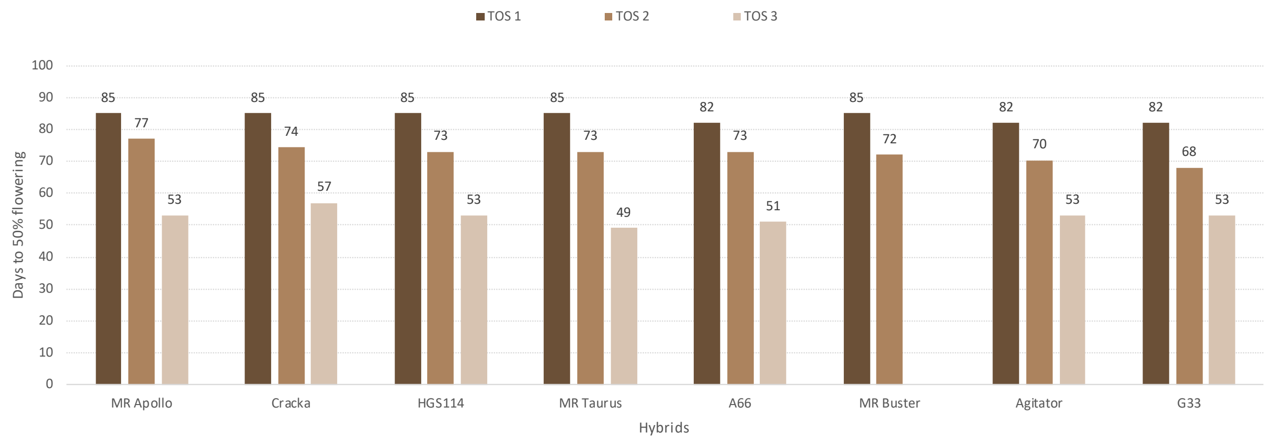

Figure 3. Average days to flowering for each of the eight varieties across the three different times of sowing.
Statistics not available at time of publishing (statistical analysis yet to be completed).

Flowering

Days to 50% flowering varied across TOS dates; average days to 50% flowering were 84 days (TOS1) and 73 days (TOS2), with TOS 3 only taking 53 days (Figure 3). The target window for flowering for TOS 1 and TOS 2 was to commence flowering by mid-September to early October; this was missed by TOS 1 by 10–15 days (50% flowering achieved on 15/10/18) and TOS 2 by more than 20 days (first variety achieving 50% flowering on 23/10/2018).

The quickest of the hybrids to 50% flowering was G33; MR Apollo and Cracka were the longest to flowering, depending on TOS (MR Apollo was faster in TOS 3, but the longest in TOS 2).

Plant height

There was a significant effect on plant height by TOS date. On average, TOS 1 main stems were 12 cm shorter than TOS 2 across all treatments (Figure 4). G33 showed the greatest variation between the two sowing dates of 15 cm difference while HGS-114 and MR Apollo showed the least difference with only 7.5 cm on average.

Population also had a significant effect on plant height; as population increased, average plant height decreased in TOS 1 (98 to 95 cm) whereas it increased in TOS 2 (10.6 to 11.1 cm) (Figure 5).

Grain yield

Grain yield was significantly different (P(0.01)) between TOS 1 and 2, with average yields of 3.8 t/ha for TOS 1 and 2.4 t/ha for TOS 2 across all varieties. However, crop yield was affected by bird damage and lodging, particularly in TOS 2.

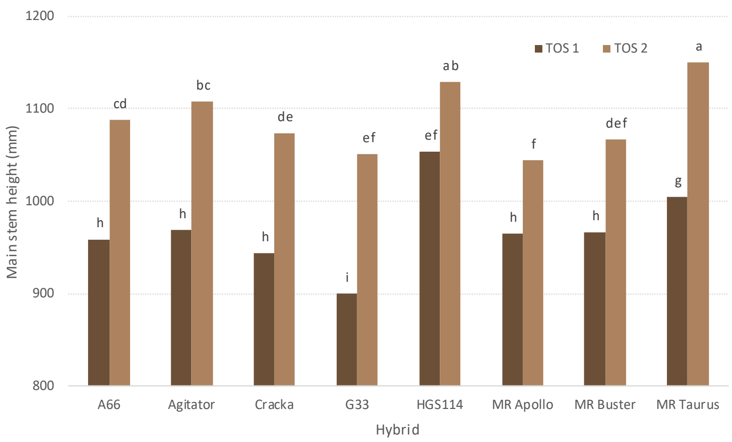

Figure 4. Main stem plant height for TOS 1 and 2. P(0.001); lsd = 27.1 mm.

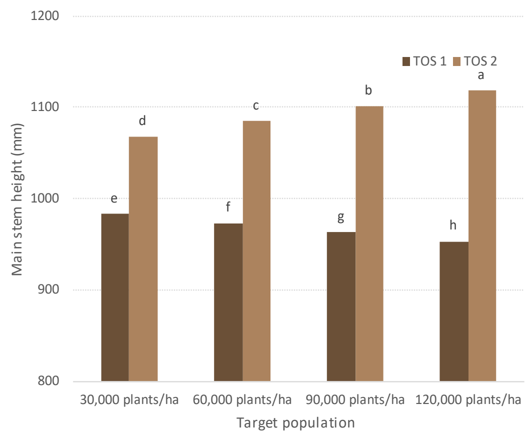

Figure 5. Effect of population on main stem height. P(0.001); lsd = 11.8 mm.

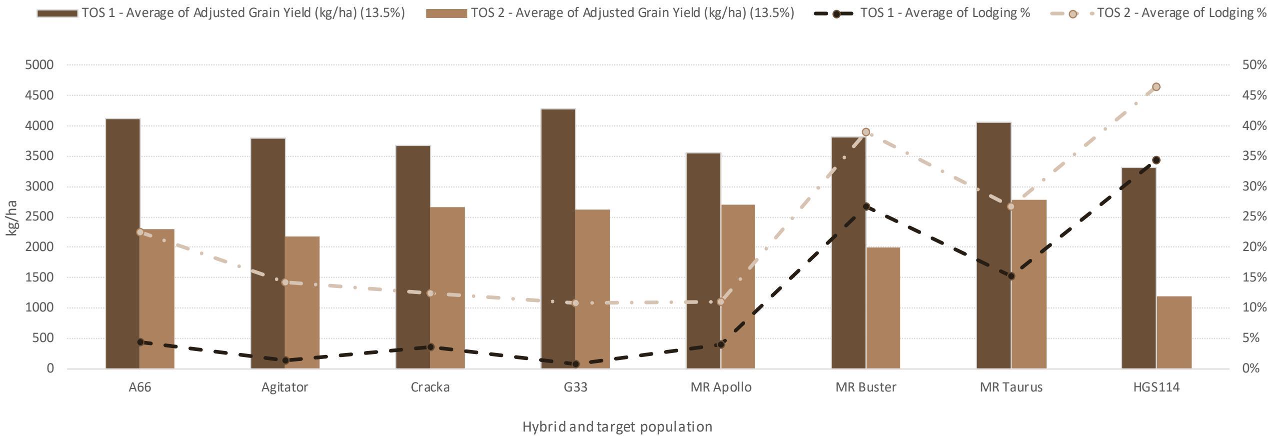

Figure 6. Grain yield for TOS 1 and 2 overlayed with percentage (%) of heads lodged (unharvestable). There was a significant difference between TOS P(0.001) yield. There was also a significant difference in average lodging (%) between varieties.

MR Buster, MR Taurus and HGS-114 were significantly affected by lodging in TOS 1, while all varieties had levels of lodging above 10% for TOS 2. A66, MR Buster, MR Taurus and HGS-114 had more than 20% of heads on the ground (Figure 6) in TOS 2. Much of the lodging occurred post-spray-out, however HGS-114 and MR Buster were showing signs well before physiological maturity. Charcoal rot was observed in a number of treatments during biomass cuts. Other stems showed no sign of any infection, yet appeared quite fibrous and weak, despite the size of the plant.

Screenings for both early TOS dates were above grain receival specifications, however TOS 1 had significantly lower screenings (P(0.003)) compared to TOS 2, except at the lowest target population (Figure 7). Screenings generally decreased in TOS 1 as populations increased, with the highest population treatments (and the most heads per m^2) on average having lower screenings than both TOS 1 and TOS 2 low population treatments. TOS 2 displayed a more typical response to population, with screenings increasing as population and viable heads per m^2 increased (Figure 7).

Implications for growers

The progression into summer 2018/19 was exceptionally dry and hot; despite this, it was interesting to observe how little stress appeared to be showing as both early times of sowing progressed towards head emergence.

Just under 80 mm of rain on 13 and 14 October 2018 (Figure 8) had a transformational effect on the crop, by seemingly accelerating development. Additional secondary tillers developed because of this rain and maturity was dragged out considerably for both sowing dates. There was no additional useful rainfall before harvest.

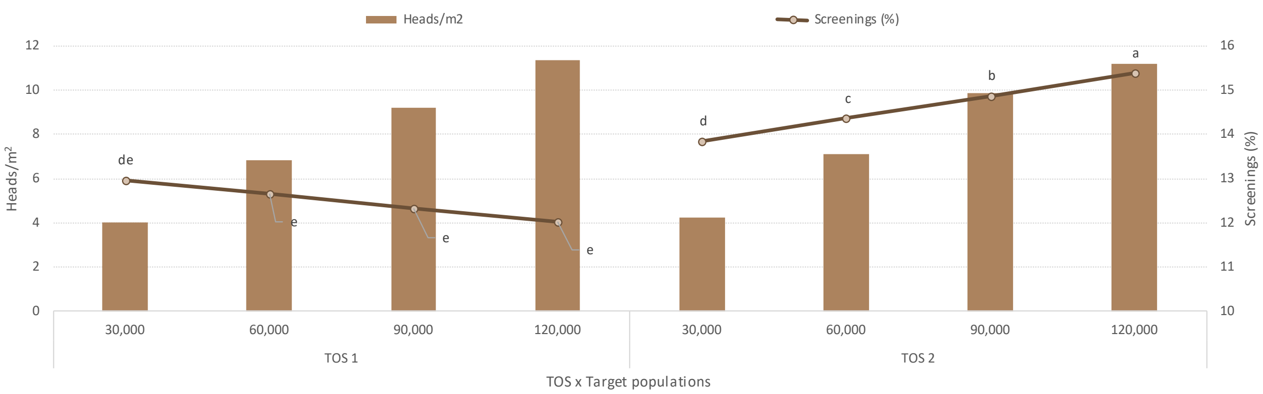

Figure 7: Relationship between heads per m^2 and REML assessed screenings across the four populations for the first two sowing dates. There was no significant difference in screenings between the four populations in TOS 1; however, there was a significant difference in TOS 2; P(0.002), lsd = 0.81%. There was no significant difference in head number/m^2 between TOS for each population, however there was a population difference; P(0.001).

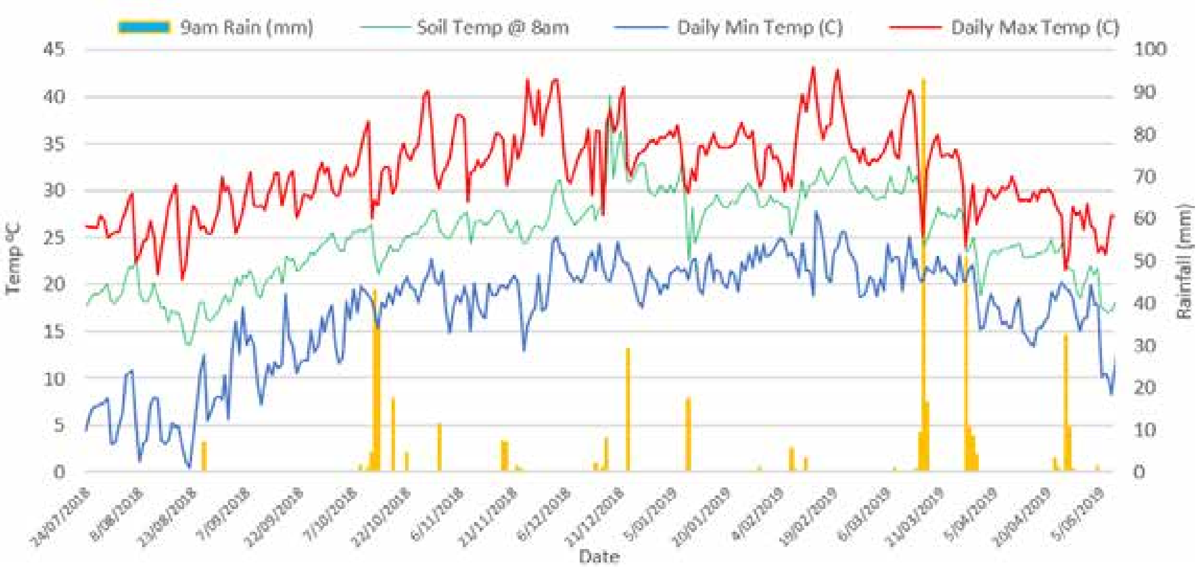

Figure 8: Daily climate observations throughout the duration of the 2018/2019 trial.
Note that due to soil cracking, the soil temp probe became exposed from 16 December to 11 January 2019; hence the spike in soil temperature readings over that period.

The 2018 trial was the first of four years of research focused on understanding the agronomy and phenology effects of winter-sown sorghum in a range of sub-climates across Queensland and northern New South Wales. While initial yield results indicate a potential yield increase from planting earlier, further research is required to confirm these results.

This research will improve our understanding in regards to the effect of sowing date on time to flowering, allowing us to better target the flowering window between mid-September and mid-October in CQ. Research partners in Southern Queensland and northern NSW have shown that seedlings can emerge in soil temperatures as low as 12 °C, and can withstand -2 °C frosts. The 2019/20 trial brings sowing dates forward to mid-June and mid-July, along with irrigation versus dryland treatments.

Possibly the greatest challenge for this type of out-of-season cropping is pest management. Birds were very attracted to this sorghum as it was the only crop on the Emerald Research Facility (due to very dry conditions). Despite significant efforts to move the birds on, they were as keen to share in the new learning experience as we were.

Acknowledgements

Thanks to Queensland Alliance for Agriculture and Food Innovation Toowoomba, New South Wales Department of Primary Industries, the Department of Agriculture and Fisheries and the Grains Research Development Corporation for funding the project Optimising Sorghum Agronomy (UOQ 1808-001RTX).

The DAF biometry team and SAGI (co-funded by GRDC) have provided statistical analysis of the data presented.

Thank you to Cotton Seed Distributors for allowing us to utilise their FastStart™ Soil Temperature Network data set while on-site logging equipment was established.

Trial details

Location:	Emerald Research Facility
Crop:	Sorghum
Soil type:	Cracking, self-mulching, Grey Vertosol in excess of 1.5 m deep. Estimated PAWC to 1.5 m of approximately 240 mm. Starting PAW at planting was 195 mm. Post-harvest PAW indicated average PAW was approx. 140 mm to 1.5 m, with more than 70 mm sitting below 1 m depth.
In-crop rainfall:	See Figure 8

Optimising the phenology and grain yield of wheat genotypes—Emerald

Darren Aisthorpe and Ellie McCosker
Department of Agriculture and Fisheries

Research Question: *How does sowing time influence the phenology and grain yield responses of varied wheat genotypes?*

Key findings

1. Heat and drought significantly influenced phenology and grain yield responses in 2018.
2. Higher grain yields were achieved by faster developing genotypes, with significant reductions in grain yield with delayed sowing (associated with later flowering dates).
3. Whilst 2018 conditions favoured faster-developing genotypes, some newer genotypes such as LongReach Mustang$^{(\phi)}$ and Sunprime$^{(\phi)}$ showed flexibility with stable grain yields across a wide range of sowing dates.
4. It is important to consider long-term data to determine suitability of varieties based on matching phenology and sowing time for your growing environment.

Background

In 2018, field experiments were conducted across ten sites in the northern grains region in Central and Southern Queensland, and northern, central and southern New South Wales to determine optimal grain yield potential of wheat genotypes. This paper presents results from the Emerald site (Central Queensland; CQ) and discusses the influence of phenology on the grain yield responses to sowing date for a diverse set of 32 wheat genotypes.

Weather conditions during the 2018 trial were abnormally dry, even by CQ standards. The site recorded below average rainfall, warmer daytime temperatures and cooler than average minimum temperatures in 2018, which had a significant effect on experimental results. In 2018, the site recorded 46 mm of in-crop rainfall (April-September), compared with the long-term average of 160 mm. Despite the 240 mm received in January and February, there was no effective rainfall until the first sowing date. The site was pre-irrigated with 100 mm prior to the first sowing time, and a further 40 mm was applied between TOS 1 and 2. A third irrigation of 40 mm was applied between TOS 3 and 4 to ensure effective establishment.

Monthly rainfall was well below average for the duration of the trial (Table 1) and average monthly maximum temperatures were all above average during the growing season, with July in particular being almost 2 °C above the 100-year average. Significant variation in diurnal temperatures (>20 °C) occurred throughout much

Table 1. Climatic conditions in 2018, showing lowest and highest observed temperatures for each month and comparing monthly rainfall and average minimum/maximum temperatures against the 100-year average.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min °C observed	17.8	15.8	15.7	10.9	4.6	-1.1	0.5	0.4	5.6	11.6	12.9	17.6
Avg. min °C	21.9	20.0	20.3	17.3	11.2	7.7	7.0	5.8	12.7	18.3	18.3	21.6
100 year mean min °C	21.6	21.3	19.8	16.1	12.1	9.0	7.6	8.8	12.4	16.4	19.1	20.8
Difference to 100 year min °C	0.3	-1.3	0.5	1.2	-0.9	-1.3	-0.6	-3.0	0.3	1.9	-0.8	0.8
Max °C observed	40.0	43.2	35.7	34.4	30.9	28.5	27.8	31.4	33.0	40.6	41.8	41.8
Avg. max °C	35.3	35.8	32.1	31.5	26.5	23.7	24.6	26.1	29.8	32.9	35.2	35.3
100 year mean max °C	34.4	33.4	32.3	29.7	26.1	23.1	22.8	25.1	28.5	31.6	33.6	34.7
Difference to 100 year max °C	0.9	2.4	-0.2	1.8	0.4	0.6	1.8	1.0	1.3	1.3	1.6	0.6
Monthly rainfall (mm)	36.2	196.6	7.8	6.8	10.6	17.7	4.8	7.0	0.0	118.2	16.6	40.2
Mean monthly rainfall	97.5	94.2	64.4	33.3	30.2	31.0	26.0	18.5	21.9	39.0	58.3	88.5
Difference to 100 year rainfall	-61.3	102.4	-56.6	-26.5	-19.6	-13.3	-21.2	-11.5	-21.9	79.2	-41.7	-48.3

Negative numbers in the difference rows indicate below average, positive numbers indicate above the 100-year average.

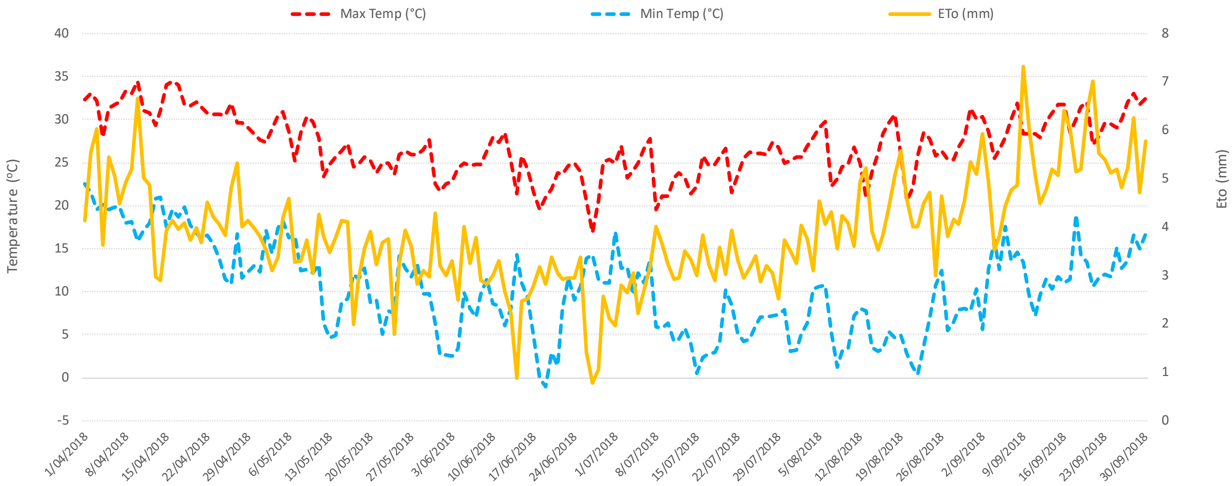

Figure 1. ETo (mm) measured during the trial period. Note the rapid increase during August, increasing the stress load on plants still trying to fill grain.

of the growing season (Figure 1). The site also recorded constant dry S-SE wind speeds of up to 30 km/h and low humidity throughout August. These combined conditions resulted in a rapid increase in evapotranspiration (ETo) (mm) from August, and a loss of >5 mm per day (Figure 1).

What was done

Thirty-two core genotypes varying in maturity (Table 2) were sown on four sowing dates: 6 April (TOS 1), 20 April (TOS 2), 4 May (TOS 3) and 21 May (TOS 4). The Emerald trial was sown on a 50 cm row spacing; plots were 12 m long x 2 m wide. The previous crop was a lablab break crop, incorporated with offset discs prior to the first sowing date.

Table 2. The 32 genotypes used in the main TOS trial at Emerald.

Phenology type	Genotypes
Winter (W)	Longsword⁽ᵈ⁾ (Fast), LongReach Kittyhawk⁽ᵈ⁾
Very Slow (VS)	EGA Eaglehawk⁽ᵈ⁾, Sunlamb⁽ᵈ⁾, RGT Zanzibar⁽ᵈ⁾, LPB14_0392
Slow (S)	Sunmax⁽ᵈ⁾, Cutlass⁽ᵈ⁾
Mid (M)	Mitch⁽ᵈ⁾, LongReach Lancer⁽ᵈ⁾, Coolah⁽ᵈ⁾, DS Pascal⁽ᵈ⁾, EGA Gregory⁽ᵈ⁾, LongReach Trojan⁽ᵈ⁾
Mid-fast (MF)	Janz, Beckom⁽ᵈ⁾, Sunvale⁽ᵈ⁾ , Suntop⁽ᵈ⁾, LPB14_3634, IGW 4279
Fast (F)	Scepter⁽ᵈ⁾, Corack⁽ᵈ⁾, LongReach Reliant⁽ᵈ⁾, Mace⁽ᵈ⁾, LongReach Mustang⁽ᵈ⁾, LongReach Spitfire⁽ᵈ⁾, Sunprime⁽ᵈ⁾, RAC2388
Very fast (VF)	Condo⁽ᵈ⁾, LongReach Dart⁽ᵈ⁾, H45⁽ᵈ⁾, TenFour⁽ᵈ⁾

Maturities range from quick spring wheats (which require no vernalisation) through to long season winter wheats (which typically required significant vernalisation to progress past the reproductive stage).

Results

Phenology

In wheat, flowering time is a critical determinant of grain yield potential. Across environments of the northern grains region, the optimal flowering period is often defined by decreasing risk of frost, and increasing risk of moisture and heat stress. Generally, flowering date is a strong predictor of yield, with genotype and sowing date combinations that flower mid-late June at Emerald capable of achieving the highest grain yields. In 2018, the flowering window spanned 5 June to 30 September, with significant variation in phasic duration and grain yield responses for genotype × sowing date (Figure 2).

Sowing to flowering time in faster-maturing genotypes that are responsive to warmer temperatures varied across sowing dates. LongReach Mustang⁽ᵈ⁾ flowered just 60 days after sowing in TOS1, however took 78 days in TOS4, whilst slower-developing spring wheats (with some response to vernalisation) such as Coolah⁽ᵈ⁾, Mitch⁽ᵈ⁾, LongReach Lancer⁽ᵈ⁾ and EGA Gregory⁽ᵈ⁾ were relatively stable in days to flowering across the four sowing dates. (Figure 2)

Slow developing winter genotypes such as Kittyhawk⁽ᵈ⁾, Sunlamb⁽ᵈ⁾, Sunmax⁽ᵈ⁾ and Longsword⁽ᵈ⁾ did not progress to flowering, as they were not able to saturate their vernalisation requirements, and were significantly impacted by terminal drought seasonal conditions later in the season. Slower developing, spring types, such as Sunmax⁽ᵈ⁾, EGA Eaglehawk⁽ᵈ⁾ and Sunlamb⁽ᵈ⁾, were also too slow, flowering much later than optimal and had significant grain yield penalties (Table 3).

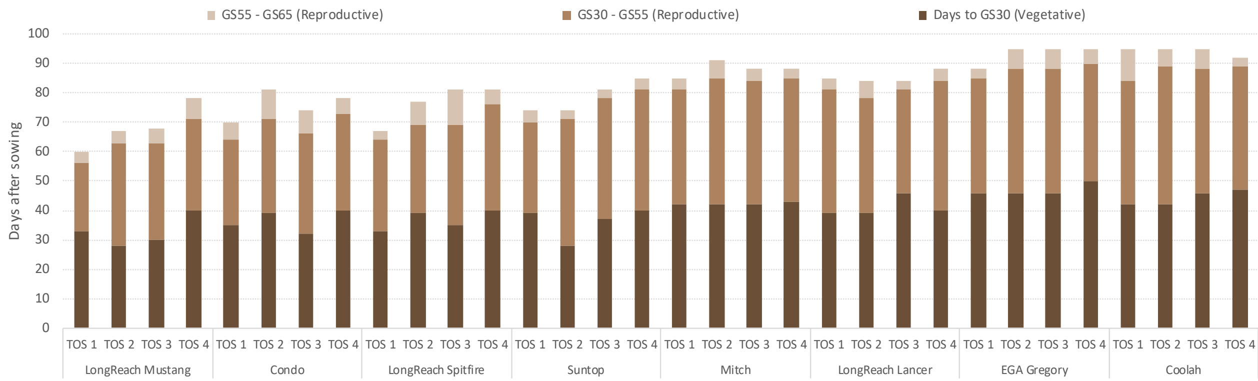

Figure 2. Phasic variation during the vegetative and reproductive stages of crop development (GS=growth stage). Dark bars represent time to GS30 (stem elongation), medium bars represent time to GS55 (awn peep out of the flag) and light bars represent time to GS65 (50% flowering).

When the phasic development of all four sowing dates are graphed (Figure 3), using eight different maturity types, you can see that the flowering spread includes the start of June 2018, through to 23 August. The dotted shape outlines represent the 'sweet spot' for flowering conditions based on 100 years of climate data for Emerald. Within those periods, the risk of getting a frost event (2 °C or lower) or heat stress event (30 °C or higher) is less than a 1 in 10 years chance.

Biomass

Total biomass accumulation in 2018 was down significantly compared to the equivalent sowing dates in 2017. Across all times of sowing and varieties, the average reduction compared to 2017 was 50% in 2018 (Table 3), with the lowest average reduction of 47% (TOS 2), while TOS 4 saw an average reduction of 55% across the eight selected varieties.

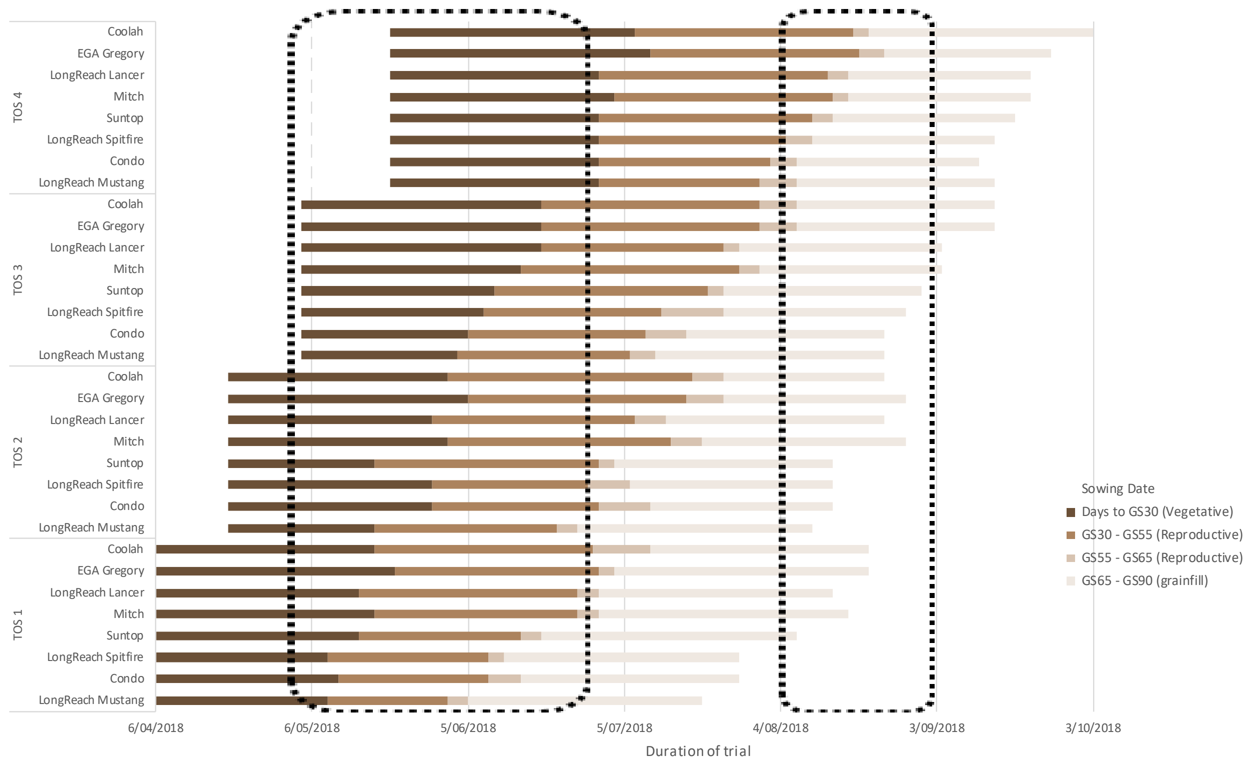

Figure 3. Phasic development of selected genotypes across four sowing dates at Emerald, 2018. Vegetative phase from sowing to start of stem elongation (GS30), to head emergence (GS55) flowering (GS65) through to physiological maturity (GS90). There was a significant P(0.001) difference among genotypes. Dotted outline indicate periods, based on historical climate data, which have a less than 1 in 10 year chance of a frost or heat stress event.

Across all genotype x TOS treatments in 2018, total biomass accumulated was on average 50% lower than recorded in 2017. For example, Condo$^{\phi}$ accumulated between 4500-6000 kg/ha (progressively less with each delayed sowing treatment; Figure 4), whilst in 2017, Condo$^{\phi}$ was able to consistently accumulate just over 9000 kg/ha across the three sowing dates.

In 2017, increases in biomass from flowering to maturity remained relatively constant across the treatments. In 2018, the slower development of genotypes such as Coolah$^{\phi}$, Mitch$^{\phi}$ and EGA Gregory$^{\phi}$ coincided with moisture and temperature stress from mid-July onwards, causing premature senescence and limited grain filling, and resulting in declining total biomass at maturity.

Grain yield

As sowing was delayed, mean grain yield and grain quality declined (Table 4). Generally, in 2018, highest yields across all sowing time treatments were achieved by faster developing varieties (Figure 5; Table 5), whilst slower developing genotypes suffered yield penalties. In contrast, in 2017, slower developing varieties were able to achieve higher or equal grain yields in earlier sowing times, then declined as sowing and development was delayed. For example, Mitch$^{\phi}$ comfortably out-yielded the quick maturities by almost 1 t/ha, while Coolah$^{\phi}$ and LongReach Lancer$^{\phi}$ matched the quicker maturities for TOS 2.

Statistically there was no significant yield difference between the top yielding varieties for TOS 1 to TOS 3 in 2018. However, if a long season variety was used for TOS 1, such as LongReach Lancer$^{\phi}$ or EGA Gregory$^{\phi}$ (not unreasonable for an early April planting date), the yield difference would have been 0.9 t/ha and 1.2 t/ha respectively in 2018 compared to H45$^{\phi}$ or Sunprime$^{\phi}$.

Grain quality

Only LongReach Lancer$^{\phi}$, EGA Gregory$^{\phi}$ and Coolah$^{\phi}$ were able to stay below the 5% threshold for screenings by TOS 4 in the 2018 trial. Generally, screenings increased as sowing (and flowering time) was delayed (Table 4), from an average of 3% in TOS1 to 8.4% in TOS4, which is likely reflective of the corresponding conditions at flowering (Figure 3). Slower developing Mitch$^{\phi}$ had significantly higher screenings in the later three sowing times, whilst the faster developing types only exceeded 5% in the later TOS dates.

Both average test weight and 1000 seed weight across all genotype x sowing time treatments responded similarly to other grain quality parameters (Table 4). TOS 1 and TOS 2 achieved average test weights of 82 kg/hL and grain weight of 33 g, but dropped to 76.9 kg/hL and 30.1 g respectively in TOS 4.

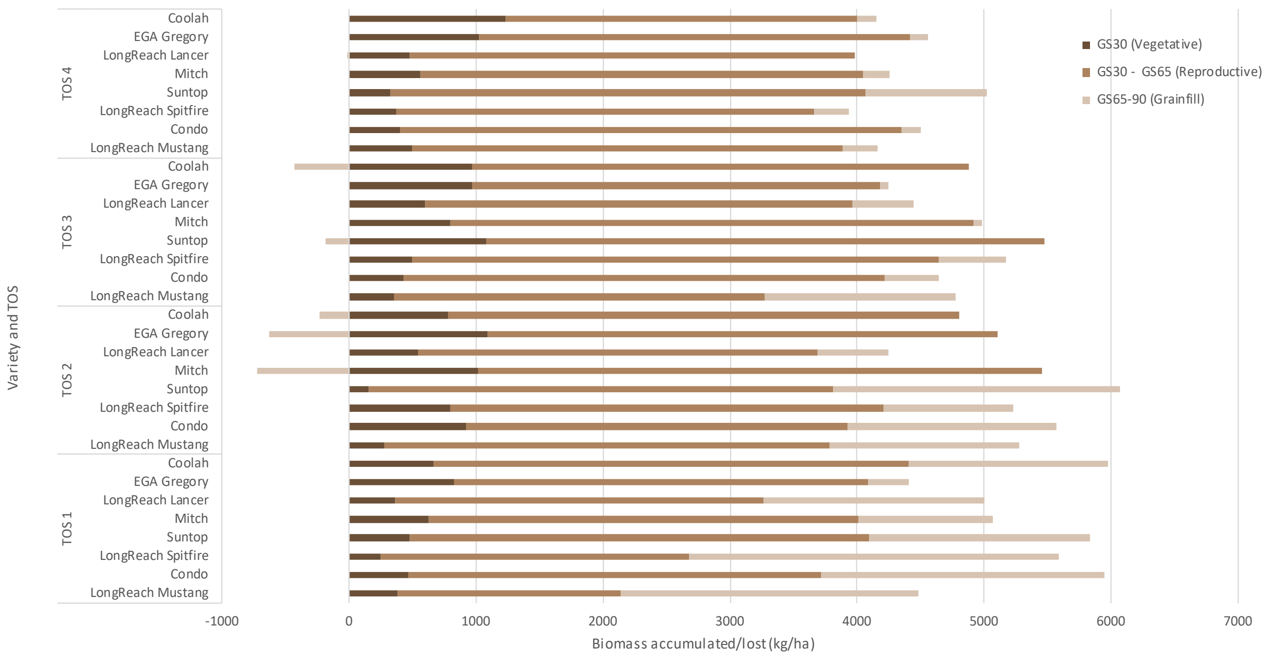

Figure 4. Biomass accumulation x variety for all four times of sowing. There was a significant P(0.001) interaction effect between genotype and TOS.

Table 3. Phenology observations for all varieties across all times of sowing.

Genotype	Days to GS65 (flowering)				GS65 (kg/ha)				Days to GS90 (maturity)				GS90 (kg/ha)				Plant height (cm)			
	TOS 1	TOS 2	TOS 3	TOS 4	TOS 1	TOS 2	TOS 3	TOS 4	TOS 1	TOS 2	TOS 3	TOS 4	TOS 1	TOS 2	TOS 3	TOS 4	TOS 1	TOS 2	TOS 3	TOS 4
Beckom$^{\phi}$	74	77	81	81	3387	3739	4183	3861	116	119	119	120	4995	4639	4876	4560	52.7	53.1	58.0	55.8
Condo$^{\phi}$	70	81	74	78	3718	3924	4221	4351	112	116	112	113	5944	5574	4639	4499	67.8	70.2	67.1	66.0
Coolah$^{\phi}$	95	95	95	92	4405	4801	4880	3999	137	126	133	135	5972	4571	4453	4154	66.2	60.2	60.4	57.8
Corack$^{\phi}$	74	77	81	81	3435	3823	3860	4067	116	123	119	116	5003	5146	4699	4198	49.1	55.3	57.1	51.8
Cutlass$^{\phi}$	98	95	93	99	3815	5337	4663	2530	147	133	133	135	4023	4875	4717	3780	58.9	64.0	62.2	54.0
DS_Pascal$^{\phi}$	91	95	91	92	4407	5115	4169	4741	137	133	130	127	4914	4360	3970	4748	57.6	58.2	52.4	54.9
EGA_Eaglehawk$^{\phi}$											149		4593	4190		3681	44.4	42.7	43.3	45.3
EGA_Gregory$^{\phi}$	88	95	95	95	4085	5110	4183	4421	137	130	133	127	4409	4479	4244	4559	65.3	64.4	61.6	62.0
H45$^{\phi}$	63	67	74	78	2381	4210	3785	3905	109	109	116	113	5870	5969	5165	4897	66.0	65.1	66.2	69.8
IGW4279	70	81	74	78	4806	3808	3752	3642	112	119	116	113	5106	4863	4235	4395	51.3	59.8	53.8	48.9
Janz	70	81	81	81	2983	5565	3973	3771	116	123	119	120	5061	4751	5161	4434	58.7	63.8	61.6	57.8
LongReach Dart$^{\phi}$	74	74	74	78	3713	4085	3601	4185	112	112	116	113	5873	5220	4701	4419	64.7	64.2	66.9	63.6
LongReach Kittyhawk$^{\phi}$																				
LongReach Lancer$^{\phi}$	85	84	84	88	3265	3693	3959	3981	130	126	123	123	4999	4249	4443	3968	54.0	55.6	55.1	52.2
LongReach Mustang$^{\phi}$	60	67	68	78	2139	3781	3276	3892	105	112	112	116	4486	5279	4773	4162	56.2	54.2	61.1	62.4
LongReach Reliant$^{\phi}$	88	95	88	88	4041	5135	5072	4230	130	137	126	123	5925	4757	4962	4483	74.2	70.4	67.6	66.4
LongReach Spitfire$^{\phi}$	67	77	81	81	2676	4208	4647	3659	112	116	116	116	5585	5234	5168	3931	63.3	62.9	62.0	61.6
LongReach Trojan$^{\phi}$	98	95	88	88	3635	4969	5041	3772	144	137	130	127	4149	4838	4611	4208	59.8	59.6	57.3	52.0
Longsword$^{\phi}$																				
LPB14-0392	123	133	130	132					151	151	145	135	3768	4086		3244		44.2	39.8	40.7
LPB14-3634	70	77	74	88	3537	3499	3942	4458	112	119	116	116	5492	4256	4272	4493	60.4	59.1	59.1	57.6
Mace$^{\phi}$	88	81	81	81	3619	3627	4053	3365	133	123	119	116	4414	3854	4943	3854	59.3	60.7	58.9	51.3
Mitch$^{\phi}$	85	91	88	88	4007	5455	4921	4053	133	130	123	123	5065	4728	4985	4254	56.9	64.4	64.4	62.0
RAC2388	77	77	81	78	3729	3191	4690	3577	123	119	119	116	4946	4848	5037	3788	54.0	56.2	55.3	51.1
RGT_Zanzibar$^{\phi}$	98	103	102	106	3752	3569	3167	3120	144	151	137	135	3868	3499	3258	3061	57.1	38.7	42.4	41.8
Scepter$^{\phi}$	88	84	81	85	3489	4017	4128	4041	130	126	123	120	4946	4237	4378	4290	61.1	58.7	58.0	54.2
SunPrime$^{\phi}$	63	67	70	78	2923	3519	3255	3957	109	112	112	113	5497	5282	5193	3969	65.3	64.0	69.3	64.4
Sunlamb$^{\phi}$																				
Sunmax$^{\phi}$													3951	3929	3707	3922	47.8	45.6	46.2	43.8
Suntop$^{\phi}$	74	74	81	85	4095	3815	5479	4065	123	116	119	120	5832	6075	5298	5018	72.4	70.4	74.7	68.0
Sunvale$^{\phi}$	81	88	88	88	3562	4779	5044	3337	126	126	126	123	4795	4698	4600	4391	53.3	59.3	65.1	58.4
TenFour$^{\phi}$	67	71	74	81	2699	4012	4383	3584	105	109	112	116	5261	5717	4581	4567	58.9	60.7	58.4	56.7
lsd within TOS					963								897				4.18			
lsd between TOS					976								933				4.21			

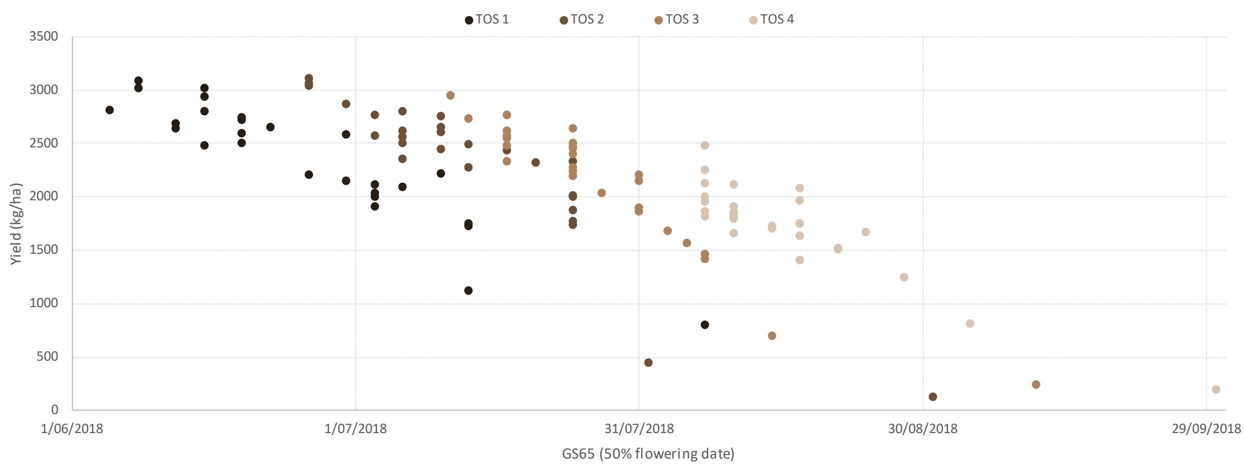

Figure 5. Yield response to flowering date for all four times of sowing. The highest yielding variety for each time of sowing was one of the first to flower for that sowing date.

Table 4. Grain yield and quality details for all varieties across all times of sowing.

Genotype	Yield (kg/ha)				Test weight (kg/hL)				Screenings (%)				1000 grain weight (g)				Harvest index			
	TOS 1	TOS 2	TOS 3	TOS 4	TOS 1	TOS 2	TOS 3	TOS 4	TOS 1	TOS 2	TOS 3	TOS 4	TOS 1	TOS 2	TOS 3	TOS 4	TOS 1	TOS 2	TOS 3	TOS 4
Beckom$^{\phi}$	2599	2505	2506	2120	82.1	82.9	82.2	78.5	2.8	2.9	6.7	9.9	34.0	31.6	27.4	28.8	0.51	0.45	0.50	0.42
Condo$^{\phi}$	2935	2751	2551	1953	83.9	83.7	81.3	78.1	2.4	2.6	5.5	8.4	35.6	35.9	29.1	29.2	0.48	0.48	0.48	0.37
Coolah$^{\phi}$	2217	2007	1462	1508	83.0	82.7	80.6	79.2	2.2	2.1	4.0	3.5	35.3	30.7	31.3	32.5	0.39	0.39	0.32	0.30
Corack$^{\phi}$	2501	2797	2642	1916	82.5	82.5	79.8	74.8	2.3	2.4	4.3	7.5	39.7	35.9	31.1	30.0	0.48	0.51	0.52	0.40
Cutlass$^{\phi}$	1729	2337	1567	1249	81.5	80.8	79.3	75.1	2.5	4.4	4.3	3.9	33.7	31.0	32.6	33.8	0.39	0.42	0.38	0.33
DS_Pascal$^{\phi}$	2099	1740	1682	1519	81.4	78.5	80.4	75.0	2.2	5.8	5.4	7.9	30.7	28.6	28.3	28.6	0.40	0.35	0.34	0.34
EGA_Eaglehawk$^{\phi}$	242	250	390	641													0.06	0.07		0.18
EGA_Gregory$^{\phi}$	1913	1774	1421	1668	82.5	82.8	81.5	78.7	2.5	2.5	4.6	3.8	33.5	29.5	32.5	33.7	0.38	0.32	0.34	0.34
H45$^{\phi}$	3083	3066	2765	2255	84.2	84.3	80.9	78.9	3.5	1.8	10.8	10.8	32.2	34.1	26.3	29.8	0.57	0.53	0.45	0.41
IGW4279	2796	2604	2478	2001	81.9	80.5	80.0	75.5	4.0	4.9	8.4	9.3	39.9	32.9	29.3	30.0	0.53	0.48	0.57	0.42
Janz	2487	2651	2201	1818	82.8	84.1	81.8	78.0	1.6	1.9	3.5	7.1	35.5	32.5	29.0	29.1	0.47	0.53	0.44	0.37
LongReach Dart$^{\phi}$	2716	2766	2334	1816	82.2	81.6	78.8	71.1	5.1	4.8	12.3	12.4	34.5	33.6	28.1	29.3	0.50	0.46	0.48	0.36
LongReach Kittyhawk$^{\phi}$	64	62	29	8																
LongReach Lancer$^{\phi}$	2152	2490	2037	1634	82.1	82.0	81.9	79.7	1.9	2.8	3.1	4.8	34.6	29.0	29.4	31.1	0.43	0.55	0.46	0.38
LongReach Mustang$^{\phi}$	2809	3043	2948	2477	83.4	84.7	83.5	79.7	3.8	2.7	4.4	5.6	35.0	36.3	29.6	31.1	0.55	0.54	0.58	0.46
LongReach Reliant$^{\phi}$	2034	2011	1901	1969	82.4	82.2	81.4	78.9	3.4	2.4	3.8	5.7	36.0	31.7	34.3	32.3	0.36	0.38	0.38	0.40
LongReach Spitfire$^{\phi}$	2690	2617	2467	1654	82.2	83.6	79.9	77.5	3.5	2.4	6.7	5.8	39.4	40.3	30.0	34.3	0.50	0.46	0.40	0.37
LongReach Trojan$^{\phi}$	1755	1872	1865	1405	83.1	83.0	81.1	78.6	1.8	3.4	5.9	11.5	32.6	29.5	30.6	30.1	0.37	0.38	0.37	0.34
Longsword$^{\phi}$	54	54	73	51																
LPB14-0392	802	126	244	199													0.18	0.04		0.05
LPB14-3634	3018	2358	2616	2086	82.7	83.3	80.2	78.0	3.0	2.2	5.6	5.2	40.1	40.9	29.6	32.6	0.47	0.48	0.52	0.39
Mace$^{\phi}$	1998	2449	2243	1800	81.4	81.9	80.2	74.6	2.3	4.1	6.3	13.6	37.1	33.5	30.2	28.5	0.42	0.58	0.45	0.37
Mitch$^{\phi}$	2586	2323	2154	1754	80.4	78.5	78.4	73.3	4.1	10.6	13.1	14.2	34.8	29.8	28.1	30.1	0.46	0.46	0.40	0.39
RAC2388	2650	2566	2460	1864	81.2	82.3	80.5	73.7	2.9	2.8	9.4	14.8	39.4	36.0	30.3	29.7	0.49	0.49	0.48	0.37
RGT_Zanzibar$^{\phi}$	1120	446	702	815													0.30	0.09	0.22	0.27
Scepter$^{\phi}$	2119	2280	2399	1708	82.4	80.7	80.4	74.0	2.9	5.8	6.5	11.2	38.8	32.4	32.5	29.8	0.40	0.52	0.48	0.43
SunPrime$^{\phi}$	3021	3110	2731	2127	81.8	83.0	81.0	78.1	4.5	4.0	7.6	6.4	38.7	39.9	31.9	33.3	0.55	0.52	0.46	0.41
Sunlamb$^{\phi}$			97	64																
Sunmax$^{\phi}$	284	160	396	583													0.06	0.04	0.07	0.15
Suntop$^{\phi}$	2741	2575	2279	1724	82.7	82.6	81.5	79.4	3.3	5.0	9.1	8.8	37.5	35.6	32.4	34.8	0.44	0.41	0.37	0.33
Sunvale$^{\phi}$	2213	2439	2207	1748	83.7	83.8	83.2	78.8	1.8	2.1	3.8	9.1	32.1	27.3	28.5	27.5	0.43	0.42	0.43	0.38
TenFour$^{\phi}$	2642	2870	2577	1849	81.5	81.6	77.3	75.0	4.1	3.5	7.0	9.0	33.4	35.6	30.1	30.0	0.47	0.50	0.53	0.42
lsd within TOS	228				1.70				1.02				1.71				0.05			
lsd between TOS	240				1.87				1.02				1.72				0.05			

Table 5. Top five yielding varieties from each sowing date in 2018.

Rank	TOS 1		TOS 2		TOS 3		TOS 4	
	Variety	Yield (kg/ha)	Variety	Yield (kg/ha)	Variety	Yield (kg/ha)	Variety	Yield (kg/ha)
1	H45$^{\phi}$	3083	SunPrime$^{\phi}$	3110	LongReach Mustang$^{\phi}$	2948	LongReach Mustang$^{\phi}$	2477
2	SunPrime$^{\phi}$	3021	H45$^{\phi}$	3066	H45$^{\phi}$	2765	H45$^{\phi}$	2255
3	Condo$^{\phi}$	2935	LongReach Mustang$^{\phi}$	3043	SunPrime$^{\phi}$	2731	SunPrime$^{\phi}$	2127
4	LongReach Mustang$^{\phi}$	2809	TenFour$^{\phi}$	2870	Corack$^{\phi}$	2642	Beckom$^{\phi}$	2120
5	Suntop$^{\phi}$	2741	Corack$^{\phi}$	2797	TenFour$^{\phi}$	2577	LongReach Reliant$^{\phi}$	1969

lsd within a TOS = 228 kg/ha; lsd between TOS dates = 240 kg/ha; P(0.05)

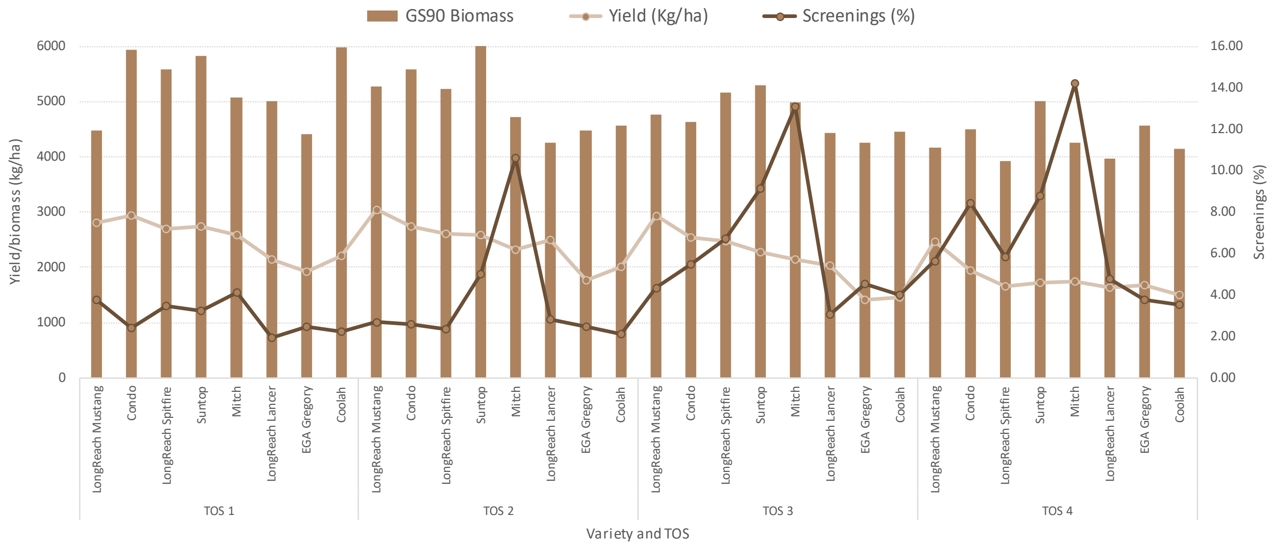

Figure 6. Total GS90 biomass (kg/ha), grain yield (kg/ha) and screenings (%). There was a significant P(0.001) interaction effect between genotype and TOS in screenings (%), yield (kg/ha) and biomass accumulation

Water use

Starting plant available water (PAW) for each time of sowing, and then post-harvest PAW were collected in EGA Gregory⦶ plots (Figure 7). Total in-crop irrigation applied was 80 mm. Statistically, the yield difference for EGA Gregory⦶ across the four times of sowing was minimal (Table 6) with only TOS 3 being significantly different to TOS 1 and 2.

Table 6. Breakdown of plant available water and water use efficiency (WUE) for EGA Gregory⦶.

	TOS 1	TOS 2	TOS 3	TOS 4
PAW planting to 150 cm (mm)	127.2	149.8	142.1	139.9
Irrigation in-crop (mm)	80.0	40.0	40.0	0
Rainfall (mm)	45.2	40.1	40.1	29.5
PAW harvest to 150 cm (mm)	46.4	49.9	26.6	45.5
Available water to crop (mm)	206	180	195.6	123.9
Yield (kg/ha)	1913 a	1774 a	1421 b	1668 ab
WUE (kg/mm/ha)	9.3	9.9	7.3	13.5

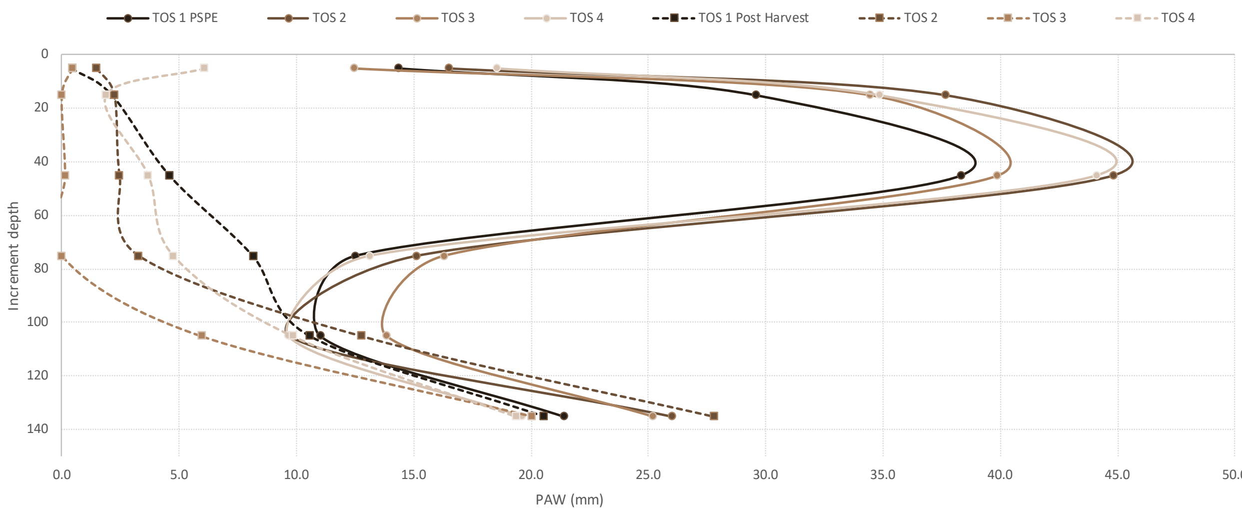

Figure 7. Starting and finishing (EGA Gregory⦶) PAW for all four times of sowing. Table 6 shows rainfall and irrigation for the four sowing dates.

Implications for growers

Seasonal conditions in 2018 had a significant effect on the phenology, yield and grain quality responses reported for the Emerald site. The genotype x sowing time combinations that achieved highest yields were fast to flowering, and as a result, there was little yield penalty by flowering earlier than the optimal period in this relatively low frost risk environment (Figure 5).

The 2018 results showed that for many genotypes sown within the traditional sowing window (20 April – 5 May) in Central Queensland, flowering occurred within a higher frost risk period, and later flowering dates had significant yield penalties associated with severe seasonal conditions. Slower developing genotypes in particular, where flowering coincided with significant heat and moisture stress conditions (from mid-July onwards), suffered yield penalties.

Whilst some slower spring genotypes such as Sunmax$^{\phi}$ and Eaglehawk$^{\phi}$, which have achieved comparable grain yields, although typically below average in previous seasons, this year they failed to achieve yields in excess of 0.3 t/ha, even in TOS 1. This highlights the need to consider experimental results across a range of seasons.

Whilst the Emerald site has a low frost risk, growers must consider their risk at both a paddock and farm level and varietal phenology responses when making sowing decisions. The vast majority of varieties in TOS 2 (April 20) and TOS 3 (May 5), considered the traditional flowering times in CQ, were flowering in historically higher frost risk periods. This raises the question, do you wait for a late May plant to avoid the higher risk flowering period, and potentially take a yield penalty, or do you consider targeting the early May to late June window if the water is there to use?

Despite the challenging seasonal conditions in 2018, some genotypes showed flexibility, and were able to achieve above average grain yields across a range of sowing dates. LongReach Mustang$^{\phi}$ and newly released Sunprime$^{\phi}$ (Table 4) were two of the stand-outs in 2018.

In a more favourable year, it would still be expected that mid to longer maturity varieties like Mitch$^{\phi}$, Coolah$^{\phi}$ and LongReach Lancer$^{\phi}$ would match or surpass the quicker varieties when planted early. Hence the need to spread your risk by using a range of suitable genotypes.

Acknowledgements

This experiment was part of the project Optimising grain yield potential of winter cereals in the Northern Grains Region (BLG104), a joint investment by the Grains Research and Development Corporation and the New South Wales Department of Primary Industries under the Grains Agronomy and Pathology Partnership (GAPP), in collaboration with the Queensland Department of Agriculture and Fisheries (DAF).

The DAF biometry team and SAGI (co-funded by GRDC) have provided statistical analysis of the data presented.

Trial details

Location:	Emerald Research Facility
Crop:	32 wheat genotypes
Soil type:	Black Vertosol, strongly self-mulching down to 1.25 m, sitting on a more alkaline red to brown medium to heavy alkaline clay.
In-crop rainfall:	46 mm from first sowing date to last harvest date
Irrigations:	40 mm between TOS 1 and 2, an additional 40 mm applied between TOS 3 and 4.
Fertiliser:	35 kg/ha of Granulock® Z (sowing), no nitrogen applied (planting N 212 kg/ha down to 90 cm)

Pulse research

The 2017-18 season marked the end of the Queensland Pulse Agronomy Initiative, which over five years has examined the interaction between genetics, environment and management (GEM) for mungbean, chickpea, faba bean and soybean. This project had a strong focus on plant physiology and hence a number of the outcomes were measured not only by grain yield but also by dry matter production, harvest index and water use efficiency.

Trials were conducted across both Central Queensland (CQ) and Southern Queensland (SQ) environments and have incorporated spatial variability (populations and row spacing), weather impacts (time of sowing), water use efficiency (irrigated and dryland), and biomass manipulation across a number of commercial varieties (genetics). These trials not only gave information that can be directly related to best practice agronomic recommendations but can also help define the plants' key physiological characteristics, which in turn can be used to inform future areas of productivity improvement.

The 2018 mungbean trials were the last data collected for this project and have basically confirmed a number of key findings from previous mungbean trial data. For example, yield differences in row spacing were not significant this year, however given the hard season (hot and dry), yields were low and narrow rows do not generally give any advantage until yields get close to 1.5 ton/ha; as demonstrated by previous data.

Time of sowing continues to play a major role in yield potential with the February plantings in CQ more than doubling yield compared to planting in December. Mungbeans particularly are vulnerable to stress situations being driven by plant-water relationships that are impacted by temperature, humidity and evaporative demand. Timely irrigation events can mitigate the effects of high evaporative conditions but cannot completely insulate the crop from environmental stresses. Irrigated yield potential is higher when planted earlier in the summer as long as water balance in the plant can be maintained. Under dryland conditions late summer TOS are consistently higher yielding with less exposure to the risk of high heat conditions at flowering.

Field research into the management of mungbean agronomy will continue under a new project (Mungbean Agronomy, DAQ1805-003RTX), which will continue to examine specific components of mungbean management such as nutrition; to improve both the reliability and the productivity of the mungbean plant across the northern grain growing region.

Interactions of mungbean physiology in relation to timing of rainfall and time of sowing—Emerald

Doug Sands
Department of Agriculture and Fisheries

Research Question: *What impact does the timing of rainfall have on the grain and vegetative yield of early and late-planted mungbeans?*

Key findings

1. In dryland conditions, planting in February increased yield of dryland mungbeans by 475 kg/ha over December planting.
2. Irrigation treatments increased mungbean yields by a maximum of 298 kg/ha and 653 kg/ha (planted in February and December respectively).
3. Application of water during mid pod-fill increased grain yield in the December planting but not the February planting.

Background

Over the past three years the Queensland Pulse Agronomy Initiative project (UQ00067) has been using time of sowing (TOS) trials to measure the impact of weather events on the production and physiology of mungbeans. These trials have highlighted that temperature, humidity, radiation and rainfall all have an impact on the plants' ability to set vegetative and reproductive yield. Previous trial data indicates that grain yield is maximised at a harvest index (HI) of 0.3-0.35 when conditions are ideal; therefore bigger yields require more vegetative production.

Mungbean is categorised as a vegetatively determinant crop, therefore it is surprising that previous TOS trials in Central Queensland (CQ) have recorded significant increases in vegetative dry matter after flowering has begun, although this has not been a consistent anomaly as the early summer TOS tends to be affected to a greater degree than the late summer TOS.

This vegetative growth habit is often linked to poor harvest index in the earlier sowings. It would seem that weather conditions are influencing the accumulation of dry matter prior to flowering and this is then having a negative impact on the resources available for flowering and setting grain yield.

This experiment has attempted to use rainfall timing (imitated by overhead irrigation) to mitigate the negative weather impacts on dry matter production both before and after flowering in an early and late summer TOS. A wide gap between TOS was deliberately used to create the largest contrast in weather conditions that the crop would experience and then monitor how the plant's physiological development changes in relation to changing soil water conditions.

What was done

This trial was located at the Emerald Research Facility. The design of this experiment was as a mixed split-plot/strip-plot structure with Jade-AU⊕ mungbeans planted on two sowing dates; 18 December and 13 February and replicated three times. Each TOS block was split into four irrigation treatments. Each of the four irrigation treatments was further split to allow two row spacings and a 'with' and 'without' foliar nitrogen (N) application.

Each plot was a maximum of four metres wide by 24 m long and planted at a rate of 35 seeds/m^2. A standard rate of Granulock® SuPreme Z™ (30 kg/ha) was applied at planting with the seed. Peat inoculant was delivered by water injection with the seed at planting.

Table 1. Summary of trial treatments.

TOS	In-crop irrigation	Row spacing	Foliar nitrogen*
• 18 December 2017 • 13 February 2018	• Dryland (no irrigation) • Irrigation at bud initiation • Irrigation at bud initiation and first flower • Irrigation at bud initiation, first flower and mid-pod fill	• 50 cm • 100 cm	Each row spacing +/- foliar N treatment.

*Foliar N was applied three times two weeks apart starting at bud initiation at a rate of 10 kg/ha as urea dissolved in 200 L/ha of water.

Table 2. Summary of agronomic information for each TOS.

Time of Sowing	Physiological stage	Date	Days after sowing (DAS)	Growing day degrees (°Cd)	Rainfall (mm)	Starting PAWC (mm)
December	Planting	18/12/2017				80
	First flower	22/1/2018	35	659	40	
	Desiccation#	20/2/2018	64	1187	99	
February	Planting	13/2/2018				84
	First flower	23/3/2018	38	660	155	
	Desiccation#	28/4/2018	74	1204	162	

#Desiccation timing was based on the maturity of the dryland plots.

This trial was planted into old sorghum stubble that was used as a cover crop the previous summer and irrigation was applied in December prior to the first TOS being planted in an effort to get a full profile of stored moisture. Unfortunately, the trial site could not be irrigated twice before planting and as a result the soil profile was not fully wet to one metre.

Irrigation treatments were applied with hand shift aluminium piping and sprinklers. Sprinklers were run for four hours, delivering a minimum of 50 mm per hectare across the treated plots.

Neutron probe tubes were placed in half the plots for each TOS. Plots that had foliar N applied were not monitored. Readings were taken twice weekly at 10 cm increments down to a depth of 120 cm. Tubes were installed just prior to bud initiation and the last reading was taken just after the crop was defoliated. Harvesting was carried out by a two metre wide plot harvester, 10 days after defoliation (which was applied based on an assessment of the maturity of the dryland treatments).

Plants counts, light interception, dry matter cuts, hand harvesting and machine harvest yields were also measured. Weather data was recorded close by the trial site at 15 minute intervals; also measured was starting plant available water content and a full soil analysis at planting.

Results

The key agronomic data (Table 2) shows that neither TOS had a full profile at planting despite site irrigation prior to the first planting. Starting moisture was about two thirds of what would normally be expected for a full profile down to one metre. Nearly all the available moisture was in the top 60-70 cm of the soil profile.

Rainfall distribution was quite different for each TOS. The December TOS had small amounts of rainfall both leading up to flowering and at the end of flowering (Figure 1). Maximum temperatures remained above 35 °C for most of the crop's life with some periods hitting 40 °C prior to flowering (35 days after sowing; DAS).

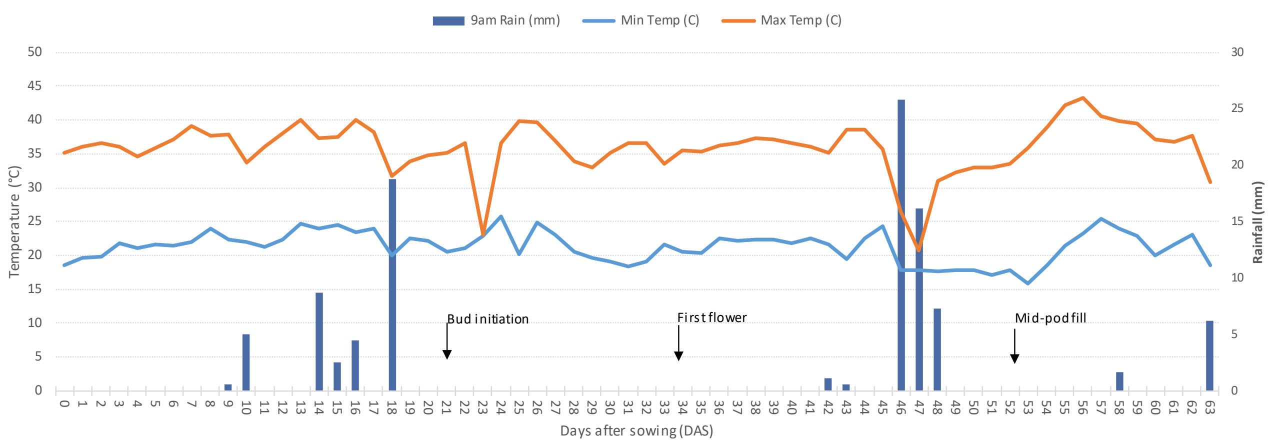

Figure 1. Rainfall and temperature distribution for the December TOS.

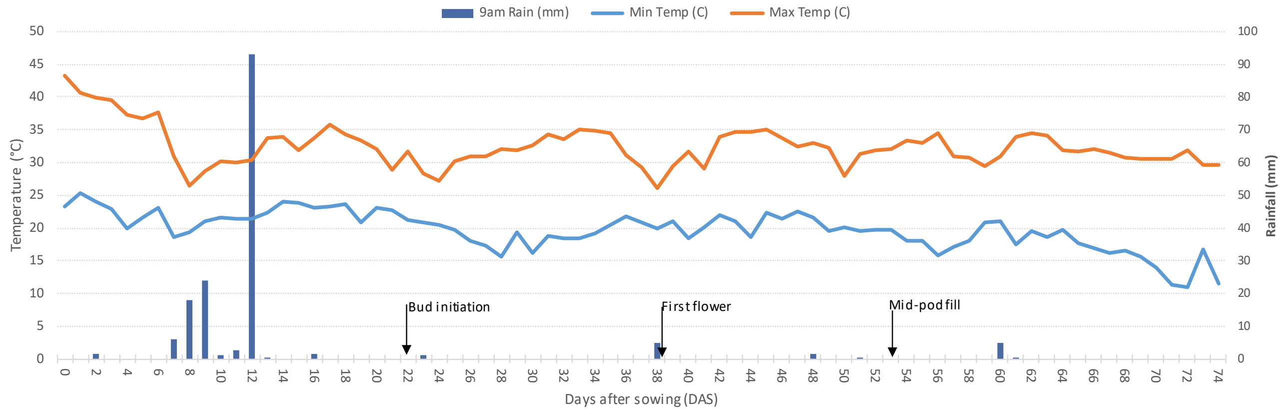

Figure 2. Rainfall and temperature distribution for the February TOS.

The February TOS had most of its rainfall (155 mm) in the first two weeks after planting, causing some early waterlogging issues. Less than 10 mm of rainfall fell for the rest of the crop's duration (Figure 2). Maximum temperatures were below 35 °C for most of the crop's life, which meant it took 10 days longer than the earlier TOS to reach maturity.

Overall, the December TOS had to cope with much hotter maximum temperatures and less in-crop rainfall.

Grain yield

The most significant interaction in relation to grain yield was between TOS and irrigation treatments (Figure 3). Although overall plot yields were low, particularly in the early TOS, the differences were obvious. The dryland treatment comparison illustrates the direct benefit of changing TOS with a 475 kg/ha (198% increase) benefit achieved by the February TOS. The differences between the two TOS yields across the increasing water applications remains significant until the last treatment (mid-pod fill).

Clearly, the irrigation treatments had the largest relative effect in the December TOS where the plants were under stress and made the best use of the extra soil water available despite both TOS starting with almost the same profile of stored soil moisture.

Additional irrigation at first flower showed the greatest increase in yields within both TOS, however an extra irrigation at mid-pod fill had a significant impact in the December TOS only. This was a surprising development as it is widely considered that irrigating the crop at mid-pod fill would be too late to impact on yield. Considering the short maturation of the December TOS (64 days), there was only 12 days between this irrigation and the first desiccation treatment, so the extra pods that formed (Figure 4) did not have long to mature. The first desiccation on 20 February was not effective and there was significant rainfall after this application, potentially allowing immature pods time to mature before the second application.

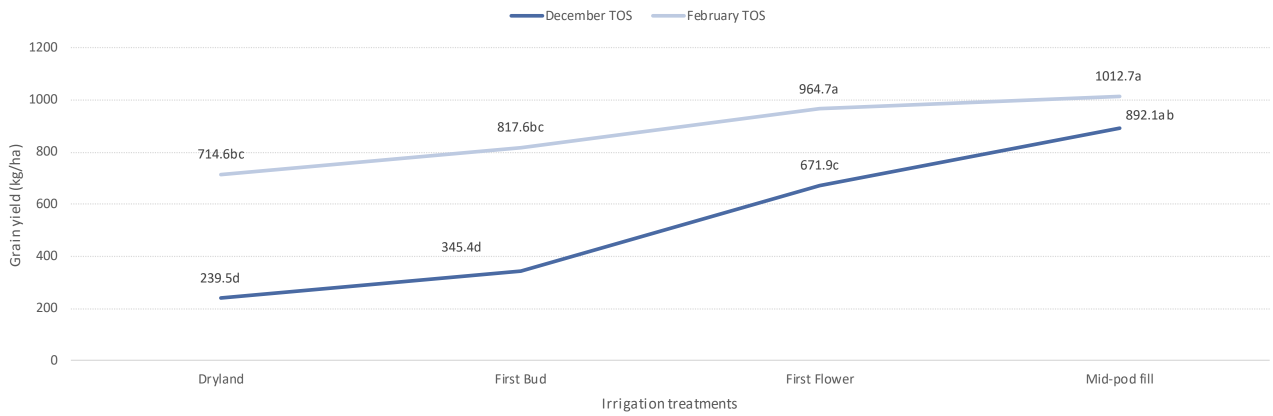

Figure 3. Grain yield comparison for each irrigation treatment across both TOS.
Means with the same letters are not significantly different; lsd = 174.

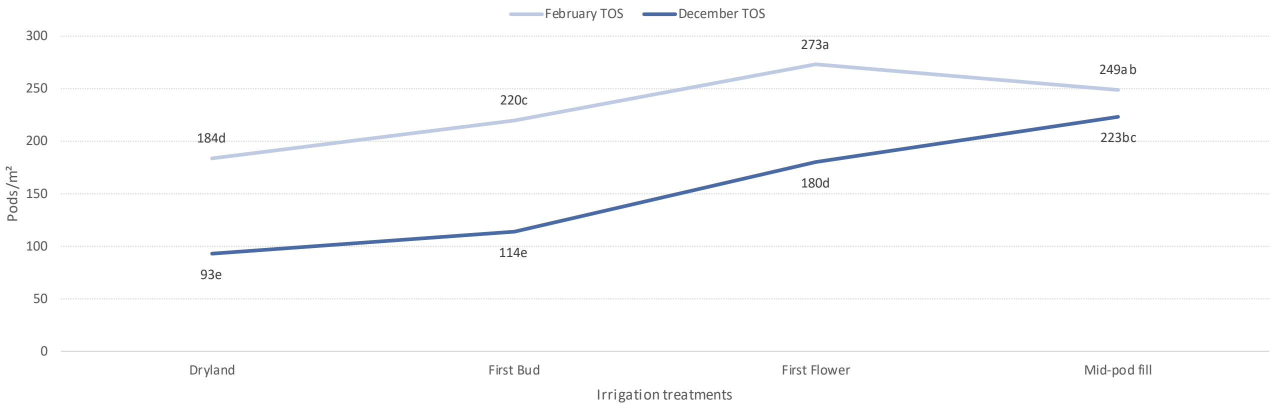

Figure 4. Comparison of hand harvested pods across TOS and irrigation treatments.
Means with the same letters are not significantly different; lsd = 28.65.

Alternatively, the young pods may have already formed and the irrigation at mid-pod fill may have avoided those pods being aborted in the December TOS. The February TOS did not have the same pattern; the later irrigation treatment caused pod numbers to decline but not significantly (Figure 4).

There was no significant differences between wide and narrow row spacing (50 cm, 100 cm) and no significant differences for foliar N application. This is not unexpected given the relatively low yields across the trial as previous trial data suggest there is no real difference between row spacing until yields are above 1.3–1.5 t/ha.

Dry matter and harvest index

Data collected from TOS trials conducted in 2016-17 and 2015-16 showed that the mungbean plant had the capacity to increase vegetative dry matter production after flowering has commenced, particularly in planting dates that experience the highest summer temperatures. This phenomenon goes against the general understanding of plant physiology where mungbean is classed as a vegetatively determinant crop. Data collected in this TOS trial compliments the vegetative dry matter data collected in past trials where there are significant increases in vegetative dry matter yield after first flowers are set.

When this data is converted into a percentage increase over vegetative dry matter yields at first flower (Figure 5) it shows some stark contrasts between TOS and irrigation treatments. In the February TOS there is an almost linear increase in vegetative dry matter as the access to soil water increases. In the December TOS, the increase is less dramatic except where additional irrigation was applied mid-pod fill and vegetative dry matter doubled after flowering started.

All treatments had extra vegetative growth after flowering, however the dryland treatments in both TOS were the smallest (Figure 5). Weather conditions for the February TOS were milder than the earlier TOS, which may explain some of the differences. When the plant cannot keep up with its evaporative demand it goes into stress mode which then severely restricts growth. When extra water is added the plant can continue normal growth.

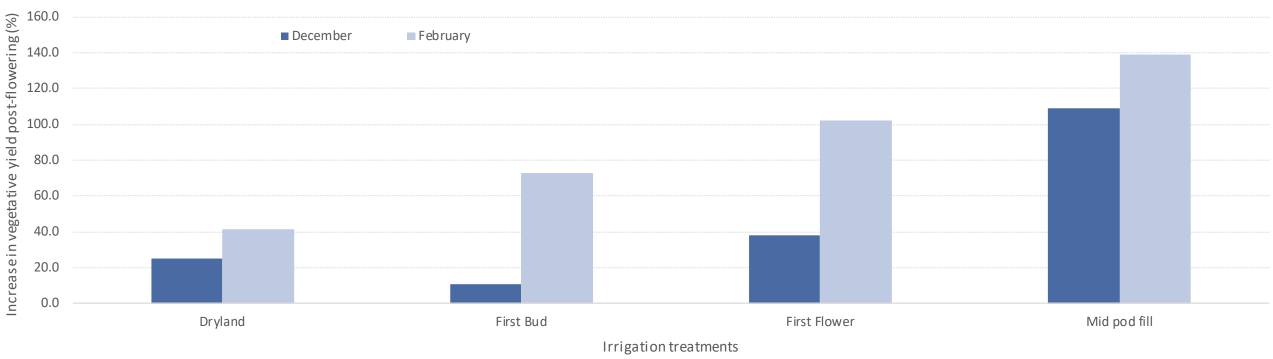

Figure 5. Comparative increase in vegetative dry matter after flowering has started as a percentage of the vegetative yield at first flower.

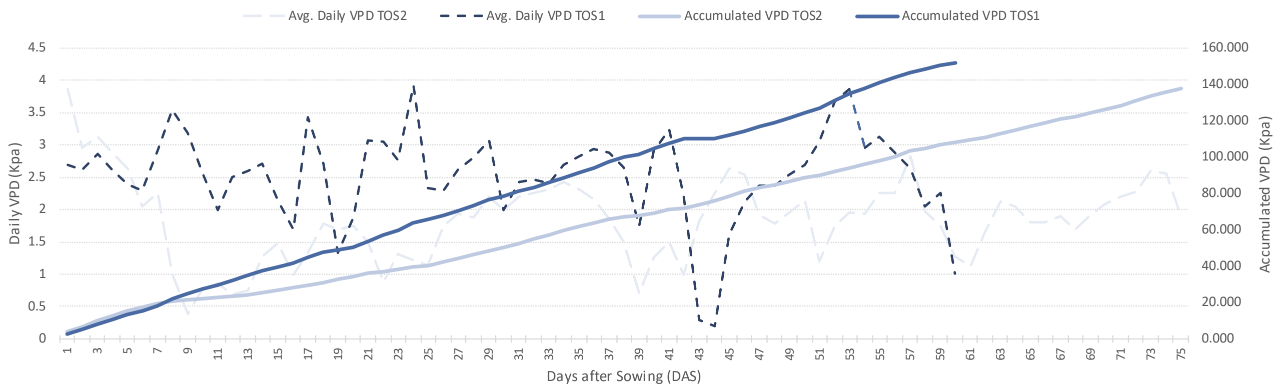

Figure 6. Comparison of daily vapour pressure deficit (VPD) and accumulated daily VPD data across December and February TOS.

In the December TOS, growth was still being suppressed despite increasingly better soil water conditions (first bud, first flower); it was not until the mid-pod fill irrigation that substantial extra vegetative growth occurred. This particular irrigation also had a rainfall event in the same week so soil moisture conditions would have been enhanced even further. This might also indicate that the earlier irrigations within this TOS (50 mm per application) were not substantial enough for the plant to maintain a normal water balance in such high evaporative conditions.

Vapour pressure deficit (VPD) data (Figure 6) would suggest that there were differences in evaporative demand on the plant between the two TOSs. While the daily VPD data was highly variable; when the same data is accumulated over the life of the crop, the overall trend is easier to detect. In this case (Figure 6), the comparison between the December and February TOS shows a clear difference in VPD conditions over the cropping period.

Total dry matter production (Figure 7) shows a similar pattern to grain yield (Figure 3) with a clear significant difference between the December and February TOS of at least 1000 kg/ha for the first three irrigation treatments. Theoretically, this much difference in dry matter should be worth another 300 kg/ha in grain yield if all plant requirements were met (HI of 0.3) to the February TOS, however grain yield results would suggest that some of the differences are actually greater than that between the two planting dates.

There is no significant difference in the dry matter yield in the mid-pod fill irrigation treatment between the two TOS, in both grain yield (Figure 3) and dry matter production (Figure 7). This would suggest that the extra in-crop water benefited the December TOS far more than the February TOS; this is surprising given that the timing of this treatment is quite late in the crop's development and the December TOS had quite short reproductive period (29 days).

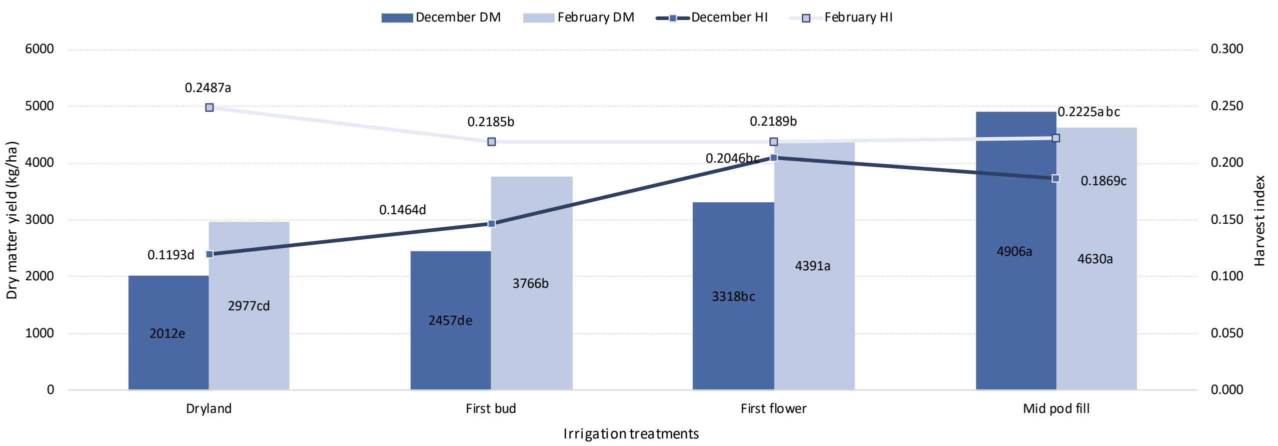

Figure 7. Comparison of total dry matter and harvest index between TOS and irrigation treatments.
Means with the same letters are not significantly different; lsd = 579 (TDM), lsd = 0.029 (HI).

The HI data (Figure 7) suggests that there has been some inconsistency in the plants' ability to convert dry matter into grain yield between the two TOS and the four irrigation treatments. Generally HI is quite low with none of the treatments reaching a HI of 0.3. This would indicate that, in general, seasonal conditions have made an impact on reproductive capacity regardless of in-crop soil moisture conditions.

The biggest contrast in HI across TOS is in the dryland treatments, with the February TOS creating the highest HI for the entire trial. Apart from the dryland treatment, the HI for the February TOS is almost a flat line despite dry matter production increasing at almost a linear rate. This means that grain yield increased at the same rate as dry matter production across the increasing irrigation applications. This coincides with the February TOS having a close to linear increase in vegetative growth after flowering has started (Figure 5). This may have split the resources of the plant between vegetative and reproductive processes and therefore the plant did not maximise its grain yield, and HI could not improve.

In the December TOS the total dry matter production increased significantly for the last two irrigation treatments (Figure 7), however HI was similar. Considering vegetative dry matter doubled during the flowering period for this treatment (Figure 5), it would seem that the balance between vegetative growth and reproductive development slightly favoured vegetative growth.

The improvement in soil water supply from consecutive irrigation applications has particularly favoured the December TOS in terms of HI, especially between the irrigations at first bud and first flower. The irrigation at mid-pod fill did not largely improve HI for either TOS; and dry matter production was only enhanced in the December TOS.

Soil water balance

This experiment has largely focused on the response of TOS to changing soil water conditions. Data presented so far shows improved performance for the crop planted in the February TOS but also that the additional in-crop water treatments have favoured stronger improvement in the December TOS.

Although the two TOS started with similar starting soil moisture at planting (Table 2), the neutron data recorded in each of the dryland treatments (Figure 8) would suggest the February TOS had a much higher soil moisture content by 20 DAS. This was due mainly to a week of wet weather where 150 mm of rain fell between 7 and 14 DAS. This extra 25mm of stored moisture may have made a significant contribution to the large yield difference between the two TOS in the dryland treatment; although daily draw down would seem to be quite similar between the two TOS until 40 DAS.

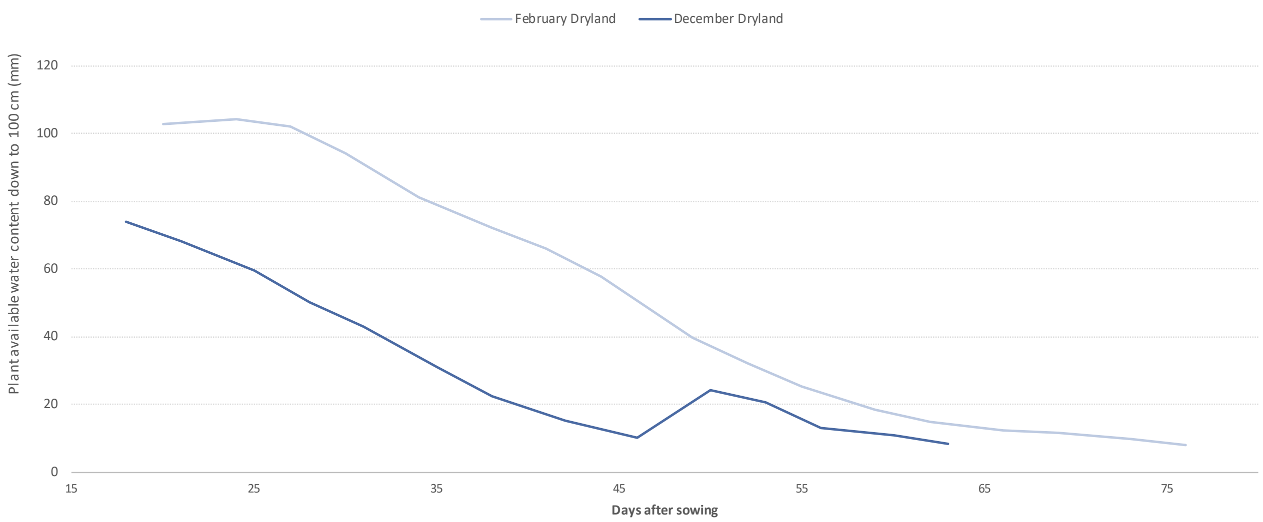

Figure 8. Comparison of PAW between the dryland treatments for the December and February TOS.

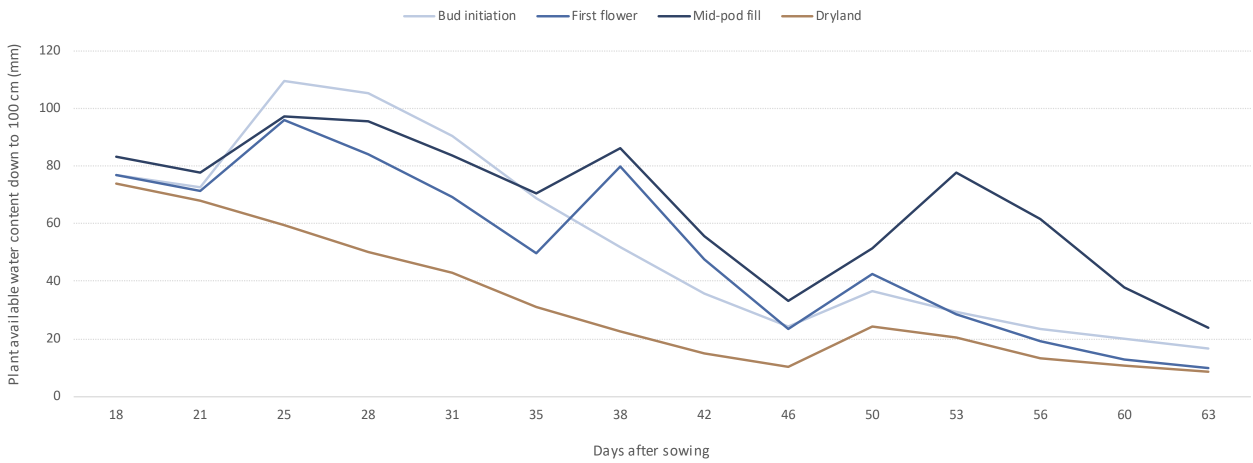

Figure 9. Comparison of PAW between irrigation treatments in the December TOS.

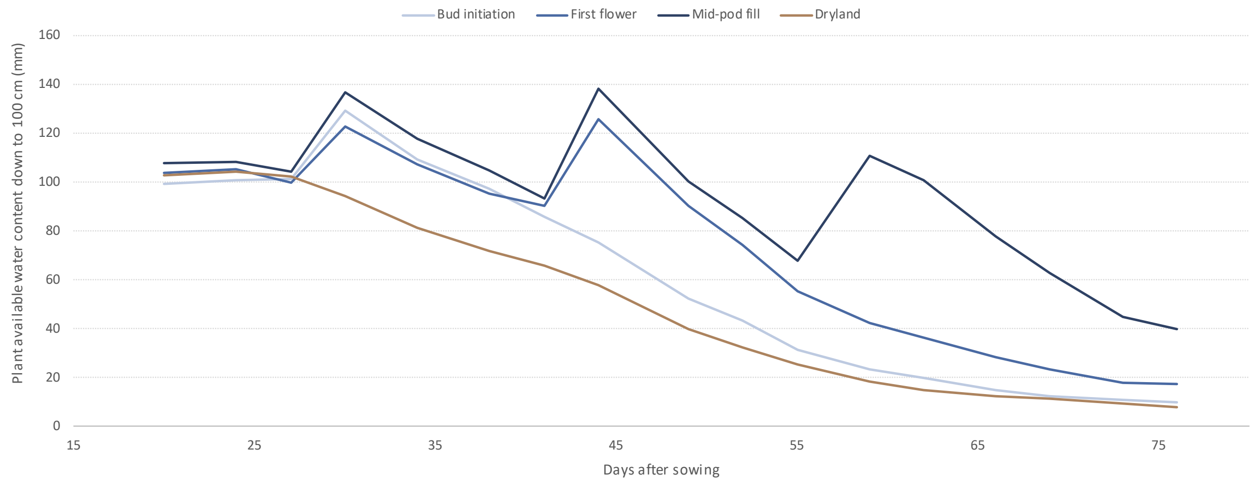

Figure 10. Comparison of PAW between irrigation treatments in the February TOS.

In contrast to the dryland treatments, it is clear that the plant is capable of much faster draw down of water on a daily basis (Figure 9). After each irrigation application in the December TOS, the slope of the draw down is much steeper compared to the dryland treatment particularly around the flowering period (40 DAS). This may indicate that the dryland treatment is constantly under stress in regards to the water balance of the plant and this may then flow through into reduced biomass production.

It is worth noting in the mid-pod fill treatment that despite the relatively late application of irrigation in the crop cycle, the plant has still managed to utilise nearly all the available water (Figure 9). This lines up with the fact that this treatment produced a lot of vegetative biomass and grain yield in comparison to the irrigation treatment at first flower (Figure 3 and Figure 7).

Despite the February TOS (Figure 10) starting with a fuller profile, the draw down during the flowering period is still much steeper than the dryland treatment. Draw down (slope) between the irrigation treatments and the dryland treatment are similar in the first period between first bud and first flower, which may indicate easier growing conditions and evaporative demand is being met by all treatments. This changes from flowering to pod fill, and even into the later pod fill period, where drawn down by the plant after irrigation is much steeper than the other treatments.

The mid-pod fill treatment for the February TOS (Figure 10) has not utilised all the soil moisture before defoliation, which would indicate that general crop demand has slowed. Based on the yield and dry matter production, this last irrigation did not add any significant increase in grain or biomass.

A comparison of daily evapotranspiration (ETo) data (Figure 11) shows a clear difference in the relative evaporative pressure that each TOS experienced. This data, taken in conjunction with the vapour pressure deficit data (Figure 6), would indicate that the plants in the December TOS had to work much harder to maintain the appropriate water balance for the plant to continue to function normally and have a normal growth pattern. The difference in water uptake by these plants in dryland conditions (Figure 8) and after irrigation (Figure 9) would indicate that the plants in the dryland treatment were constantly under stress and hence normal dry matter accumulation could not occur.

Increasing the amount of soil water available in the top 20 cm (by rainfall /irrigation) has allowed the plant to access moisture easily and quickly. This has helped the plant to maintain its water balance and continue normal dry matter production. When dry matter production is suppressed prior to flowering it would seem the plant can compensate by continuing to build vegetative dry matter after flowering has started (Figure 5). This may, however interfere with the plant being able to set its true yield potential in relation to HI.

The HI data (Figure 7), particularly for the February TOS, indicates that while vegetative production and grain yield was enhanced by increasing applications of water, the HI was not maximised. High temperatures and evapotranspiration demands continued through the flowering period for the December TOS and this may have suppressed flower set and also any compensatory vegetative dry matter accumulation. In both TOS cases the fact that vegetative potential was not fulfilled by early flowering meant that HI was always going to be compromised; even though the mechanism of that compromise was slightly different for each TOS. Overall, the later TOS had the best performance mainly due to milder environmental conditions.

Implications for growers

Time of sowing can have a big impact on mungbean yields and it is not simply just a matter of too much heat at flowering. The period leading up to flowering is just as important as it essentially sets the level of vegetative biomass which in turn sets the potential yield of the crop. Warm temperatures, long day length and high levels of radiation all promote strong vegetative growth conditions, however if that growth is interrupted by stress then that potential growth is not met. This stress seems to be based around the plant's inability to utilise stored soil moisture to maintain its water balance in high evaporative conditions (high heat and low humidity). When extra water is added (either rainfall or irrigation) the plant can utilise this moisture quite quickly and increase both vegetative and reproductive yield, but the timing of that rainfall will impact on whether the true potential of the plant is met in relation to HI.

It is evident that irrigation can minimise the impacts of environmental conditions, so much so that there was no significant difference between the highest irrigation treatments in both TOS. This then creates a contrast between an irrigated farming system and a dryland farming system. The highest potential biomass accumulation occurs in the earlier TOS, however this is dependent on the plant being able to maintain its water balance all through the vegetative period.

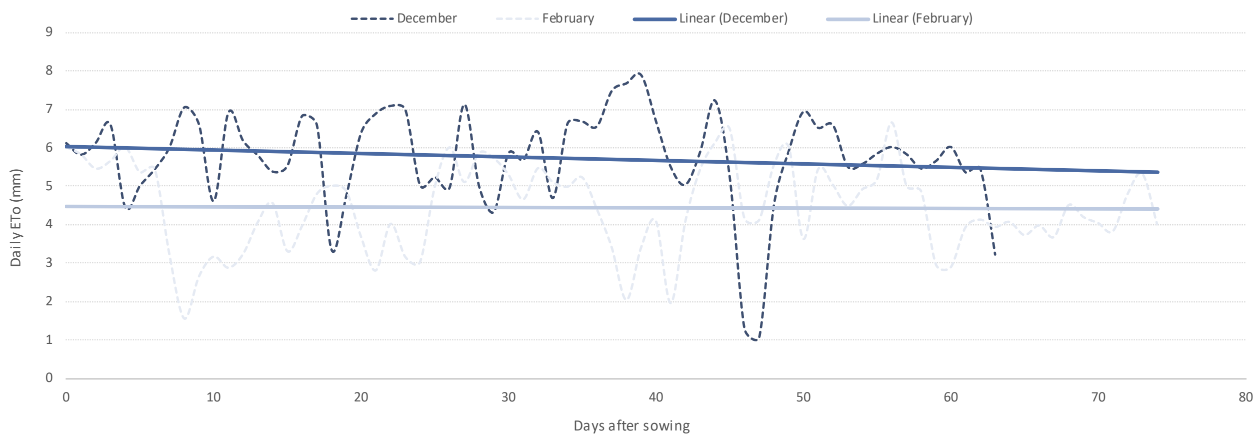

Figure 11. Comparison of daily evapotranspiration between December TOS and February TOS.

The plant cannot maintain its water balance on stored moisture under normal environmental conditions of a CQ summer; it has far more success when evaporative stresses are much lower. This means in a dryland scenario a later TOS has a far more reliable yield as it can produce more grain for the same amount of stored moisture. For an irrigator, an earlier planting window can produce more yield as long as evaporative demand can be met without waterlogging the plant.

This contrast in the plant may well be a direct attribute of the plant's tap root structure which has a low surface area. When evaporative conditions are high, the root system cannot supply enough water fast enough for the plant to maintain full turgor pressure in its cells and therefore transitions into stress mode. It is possible that the plant is stressing before visual symptoms are apparent and consequently normal biomass production is constantly being interrupted.

Based on these findings it would be expected that mungbeans would be more suited to situations where evaporative pressure is lower (lower temperature and/or higher humidity); which means planting later (February-March) in the summer for CQ regions. Irrigated systems can offset the impacts of high evaporative demand to some extent and can therefore benefit from an earlier summer TOS (December-January) which has longer day length and higher radiation levels, which in turn can promote bigger vegetative yields. High maximum temperatures can still affect the length and intensity of flowering regardless of soil water conditions, so early summer plantings always have a higher risk factor in achieving optimum yields.

Acknowledgements

The Queensland Pulse Agronomy Initiative (UQ00063) is funded by the Grains Research and Development Corporation, the Queensland Alliance for Agricultural and Food Innovation and the Department of Agriculture and Fisheries.

The DAF biometry team and SAGI (co-funded by GRDC) have provided statistical analysis of the data presented.

Trial details

Location:	Emerald Research Facility
Crop:	Mungbeans
Soil type:	Black / Grey cracking Vertosol
In-crop rainfall:	99 to 162 mm
Fertiliser:	Granulock® SuPreme Z™ at planting (30 kg/ha)

Selected soil fertility characteristics of the trial site:

Depth (cm)	Nitrate nitrogen	Phosphorus Colwell	Sulfur (KCl-40)	Exc. potassium	Phosphorus BSES	CEC
0-10	10	14	7	0.65	21	32
10-30	8	6	3	0.49	11	33
30-60	5	<2	9	0.38	5	33

Drone image of December TOS on 18 January.

December TOS (left, 51 DAS) and February TOS (right, 64 DAS), bud initiation irrigation treatments on 1 m rows.

Nutrition research

Productivity gains through nutrition research have again been delivered in Central and Southern Queensland. Examples of yield increases for the 2017-18 summer and 2018 winter sowing were:

- sorghum by up to 35%
- mungbean by 15%
- wheat by up to 40%
- chickpea by 20%.

At the GRDC grower updates in early 2019, several growers communicated the beneficial impact that improved nutrition practices can have on their business. "*It is about increasing productivity, not controlling cost. Few practices allow you to grow more grain, but nutrition is one of them*," said one producer.

The economic evaluation of deep-placing phosphorus (P) and potassium (K) is providing clear evidence of the positive outcomes potentially available.

Several research projects into deep-placement of P and K are approaching the end of their project cycle, with 2019 being the final cropping year for some trials. We look forward to finalising our field research work and distilling the messages for growers from them.

Nitrogen response and phosphorus stratification trials, Western Downs.

Responses to phosphorus and potassium by winter crops in Southern Queensland

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[1]Department of Agriculture and Fisheries
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Research Questions: *Does putting phosphorus (an immobile nutrient) in the soil at 15-20 cm deep increase grain yields? | How does starter phosphorus interact with deep-placed phosphorus? | For soil with low subsoil K, does applying potassium at 15-20 cm deep in the soil, either with or without phosphorus, increase grain yields?*

Key findings

1. Wheat at Condamine and late barley at Jimbour West both had yield increases with starter and deep-P independently.
2. Chickpea at both Roma sites had no effect of starter or deep-P on grain yield, with little in-crop rain restricting yield potential.
3. Potassium (K) had no yield effect on late barley at Jimbour West.

Background

As the length of time we have been cropping land increases, immobile nutrients such as phosphorus (P) are being taken up by plants from the soil in the 10-30 cm and lower layers, however crop residues are depositing P onto the surface. This is creating a stratified distribution of higher nutrient availability in the surface and lower availability below. Root activity in the soil surface can be limited through faster loss of soil moisture and limited in-crop rainfall. Potentially, deeper soil layers can support periods of root activity for longer as they are not as prone to evaporative moisture loss. This research is questioning if placing immobile nutrients deeper into the soil can increase grain yield.

What was done

Four continuing nutrition experiments were sown to winter crop in 2018 (Table 1). The two Mt Bindango sites west of Roma were deep-planted to chickpea in late May and early June. These were the third crops sown following wheat on the northern site and chickpea at the southern site in 2016; both were sown to wheat in 2017. The Condamine south site was sown to early wheat in late April. This was the fifth crop at the site following chickpea (2014), wheat (2015), chickpea (2016), and wheat (2017). At Jimbour West, the barley sown in July was also the fifth crop following barley (2014), mungbean (2014-15), sorghum (2015-16) and chickpea (2017). Full details on the experimental sites and treatment methodologies are in the *Queensland Grains Research 2017* book. Biomass was not cut at the Jimbour West experiment due to hail damage in October.

Table 1. Agronomic details for 2018 winter experiments.

Site	Mt Bindango Nth	Mt Bindango Sth	Condamine Sth	Jimbour West
Date sown	8 June 2018	30 May 2018	24 April 2018	13 July 2018
Variety	Chickpea (PBA-Seamer$^{(D)}$)	Chickpea (Kyabra$^{(D)}$)	Wheat (SunMax$^{(D)}$)	Barley (Spartacus CL$^{(D)}$)
Row spacing (m)	0.75	0.75	0.33	0.33
Planting rate (kg/ha)	60	60	48	55
Starter product	Starter-Z	Starter-Z	Starter-Z	Starter-Z
Starter rate (kg/ha)	35	35	20	37
Maturity biomass date	16 October 2018	16 October 2018	27 September 2018	NA
Harvest date	5 November 2018	6 November 2018	2 November 2018	20 November 2018
In-crop rainfall (mm)	81	84	135	187

Results

Phosphorus (P)

At Roma, P has had little influence on chickpea grain yields (Table 2) with late season rain the only substantial rainfall for the crop (Figure 1). Neither site had any significant yield impact from starter P application. There was a significant treatment effect at the northern site, but that appears to be related to either the tillage and/or basal nutrient applications (Figure 2a). With deep-P rate having no effect on yield, presumably it is some other component of the treatments responsible for the yield increase. This same influence was not observed at the southern site (Figure 2b).

Table 2. Statistical significance for starter or deep phosphorus treatments for winter trials in 2018.

Treatment	Mt Bindango		Condamine Sth	Jimbour West
	Nth	Sth		
Starter	NS	NS	**	**
Deep-P	*	NS	***	***
Starter.Deep-P	NS	NS	NS	NS

NS = not significant P(0.05); Significant results * P(0.05), ** P(0.01), *** P(0.001)

Significant dry matter increases with deep-P were measured at both the northern and southern sites (data not shown), suggesting P can influence the amount of biomass accumulated, however the mechanisms relating biomass production to grain yield for chickpea remain uncertain. In this season it may simply relate to exhaustion of available moisture in a very tough season (more biomass = more water use, possibly compromising yields).

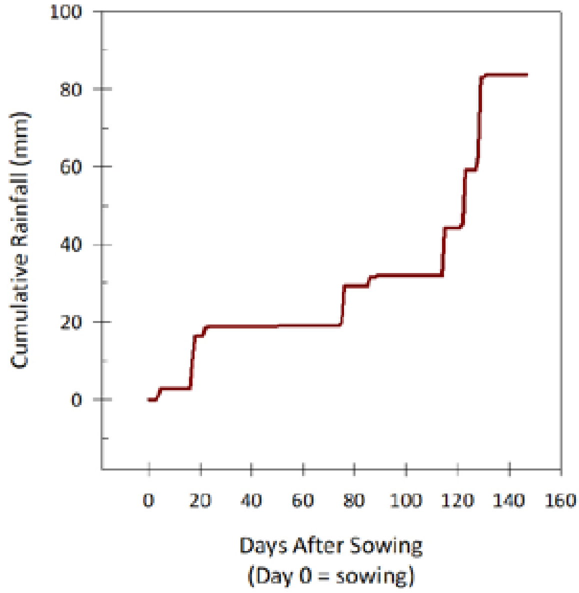

Figure 1. Cumulative rainfall at the Mt Bindango sites for 2018 winter growing season.

However, the conversion of biomass responses into yield responses was more consistent in Central Queensland in similar tough seasonal conditions (see Clermont trial report, page 45), suggesting there is more to this than a 'haying off' response.

For the cereal experiments, both starter and deep-P treatments were independently highly significant on grain yield (Table 2). Neither site has recorded an interaction between starter and deep-placed P. The grain yields for both experiments clearly demonstrate the potential contribution each can make to increasing yield with the plus starter treatments greater than the minus starter across the range of deep-placed P rates (Figures 3 and 4).

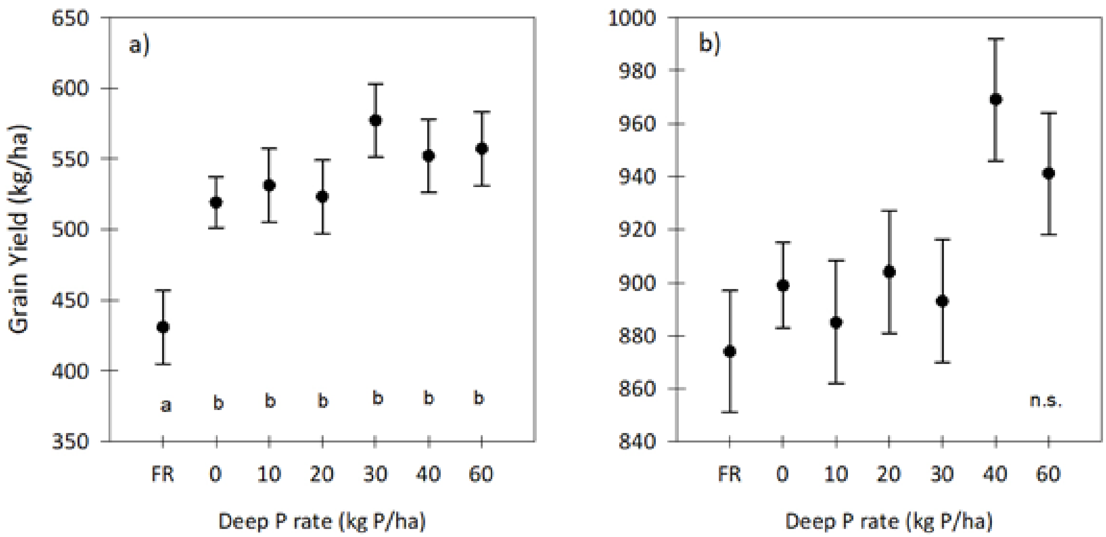

Figure 2. Mt Bindango 2018 chickpea yield for a) North and b) South sites for deep-placed phosphorus treatments (kg P/ha). Error bar are standard error for each mean. FR=farmer reference plots (no additional fertiliser beyond normal farming practice)..

Table 3. Mean wheat grain yield for deep-placed phosphorus treatments at Condamine South in 2018.

Treatment	FR	0	10	20	30	60
Yield (kg/ha)	1487 a	1603 ab	1701 abc	1754 bc	1894 cd	2099 d
Delta yield (kg/ha)	-	116	214	267	410	610
Relative yield (%)	-	7.8	14.4	18.0	27.4	41.1

Table 4. Mean barley grain yield for deep-placed phosphorus treatments at Jimbour West in 2018.

Treatment	FR	0	10	20	30	60
Yield (kg/ha)	1531 ab	1497 a	1569 ab	1705 bc	1783 c	1883 c
Delta yield (kg/ha)	-	-34	38	174	252	352
Relative yield (%)	-	-2	2	11	16	23

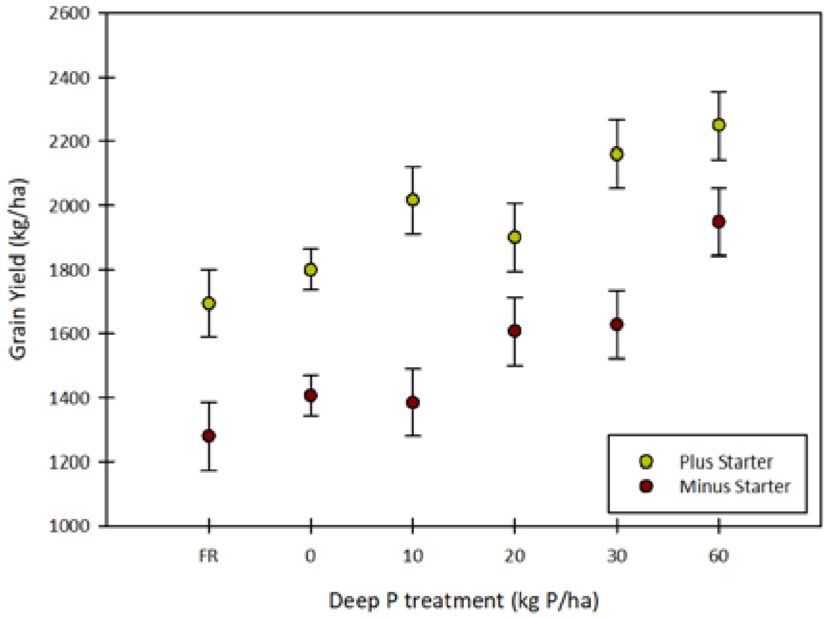

Figure 3. Condamine south 2018 wheat grain yield for deep-placed phosphorus treatments (kg P/ha) with or without starter application. Error bar are standard error for each mean.

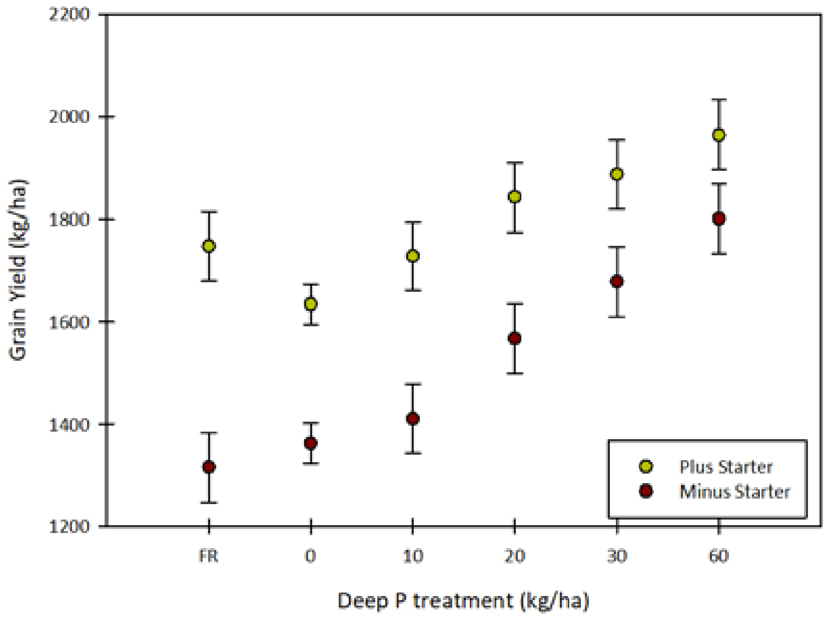

Figure 4. Jimbour West 2018 barley grain yield (kg/ha) for deep-placed phosphorus treatment (kg P/ha) with or without starter application. Error bar are standard error for each mean.

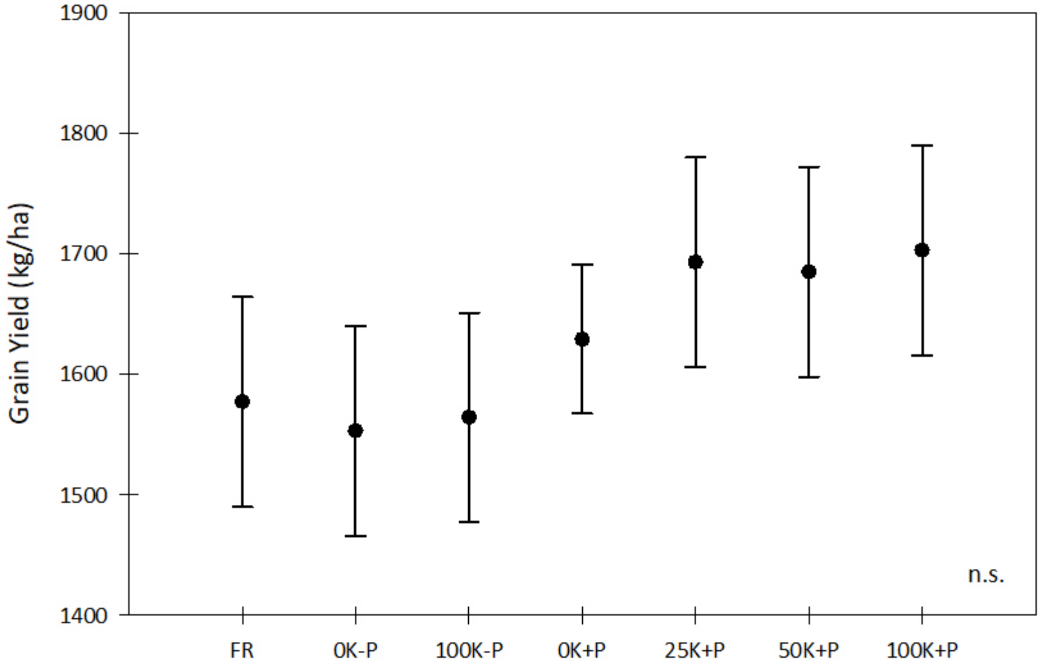

Figure 5. Jimbour West 2018 barley grain yield for deep phosphorus and potassium treatments.

At Condamine, starter application had a highly significant effect on yield. If we examine the starter effect in just the FR and 0P plots (no deep-P) it reveals a yield increase of 409 kg/ha (30%) to 1752±103 kg/ha from an average of 1343±103 kg/ha.

The effect of deep-placed P is examined using the mean result of both the minus and plus starter treatments (Table 3). As the rate of deep-placed P increases, the yield also improves. The net yield gain increases from 210 kg/ha at 10 kg P/ha to 610 kg/ha with 60 kg P. These translate to relative grain yield increases from 12 to 40%.

At the Jimbour West site, similar effects were recorded with the barley from both starter and deep-placed P (Figure 4). Averaged across the FR and 0P treatments, plus starter increased yield to 1687±66 kg/ha, a gain of 387 kg/ha (30%).

Deep-placed treatments increased grain yields with increasing rate (Table 4). At 20-60 kg P/ha deep yield increases of >11% were measured.

Potassium (K)

Grain yield was not significantly affected in the K experiment in 2018 (Figure 5) by either K or P treatment. Late sowing and reduced yield potential may have also decreased K demand by the crop.

Implications for growers

For winter cereal crops in 2018, the application of phosphorus as both starter application and deep-placing into the soil delivered substantial yield increases.

Challenging seasonal conditions for the Maranoa diminished chickpea performance so no new information was gathered about the relationships between P supply and chickpea yield.

This research has been conducted under controlled experimental conditions. Before commencing a large scale nutrient application program, growers are urged to appropriately soil test their fields to establish available nutrient levels for the surface and subsurface layers, and to quantify any other potential constraints to yield. They are then encouraged to evaluate the responses on their soils using an appropriate program of strip-trials and on-farm exploration to validate responses for themselves.

Acknowledgements

This work is funded by the Grains Research and Development Corporation under project UQ00063 Regional soil testing guidelines for the northern grains region.

Five years of grain production on deep placement treatments of phosphorus and potassium in scrub soils—Dysart

Doug Sands[1], Dr David Lester[1], Prof Michael Bell[2] and James Hagan[1]
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Research Question: *Does the deep placement of phosphorus (P), potassium (K) and sulfur (S) have an impact on sorghum yields five years after the original deep applications?*

Key findings

1. There was a 35% (970 kg/ha) grain yield response to the highest deep-P treatments in the 2018 sorghum crop.
2. There was no significant response to K in the 2018 sorghum crop.
3. Over 5 crops the deep-P treatments have produced between 2500-3000 kg/ha of extra grain over the zero P treatments.
4. After 5 crops the return on investment for 20 kg and 40 kg P/ha are 4.7 and 3.4 respectively.

Background

Over the last five years the UQ00063 project (Regional soil testing guidelines) has been monitoring a series of nutrition-based trial sites across Central Queensland (CQ). These trial sites were chosen based on soil testing evidence showing varying degrees of nutrient depletion in the surface and subsurface layers. This is particularly evident in the non-mobile nutrients of phosphorus (P) and potassium (K). In some established zero tillage production systems there is a marked difference between the nutrient concentration in the top 10 cm of the soil profile and the deeper layers (10-30 cm and 30–60 cm), that cannot be explained by natural stratification. It would seem that this pattern is becoming more evident across CQ, particularly in the brigalow scrub and open downs soil types.

This project is gathering data from these trial sites to ascertain whether the one-off application of either P, K or sulfur (S) placed in these deeper more depleted layers can provide a grain yield benefit and whether that benefit can be maintained over several years. These results can also be used to define the economic benefit of adding these non-mobile nutrients over successive cropping cycles.

What was done?

Initial soil testing was conducted (see Trial details) and the treatments were established in August 2013. Three successive sorghum crops were harvested from the site in 2014, 2015 and 2016; followed by a chickpea crop in 2017, before the site was planted to sorghum again, which was harvested on 21 June 2018.

Each of these crops was monitored for response to the original deep-placed fertiliser treatments, both in grain yield and dry matter production. Additionally, the dry matter samples and grain samples have had tissue analysis done to quantify the nutrient uptake by the crop.

Phosphorus (P)

There were seven unique treatments (Table 1; the 0P plots were doubled up to give eight plots per replicate), which included four P rates; 0, 10, 20, and 40 kg P/ha. These treatments had background fertiliser applied at the same time to negate any other potentially limiting nutrients. This background fertiliser included; 80 kg nitrogen (N), 50 kg K, 20 kg sulfur (S) and 0.5 kg zinc (Zn) per hectare. The next two treatments included 0P and 40P without background fertiliser except N and Zn (0P-KS, 40P-KS). The final treatment was a farmer reference (FR), which had nothing extra applied compared to normal commercial practice (Table 1).

Table 1. Summary of nutrient application rates (kg/ha) for all three trials.

Treatment	N	P	K	S	Zn
Phosphorus					
0P	80	0	50	20	0.5
10P	80	10	50	20	0.5
20P	80	20	50	20	0.5
40P	80	40	50	20	0.5
0P -KS	80	0	0	0	0.5
40P -KS	80	40	0	0	0.5
FR	0	0	0	0	0
Potassium					
0K	80	20	0	20	0.5
25K	80	20	25	20	0.5
50K	80	20	50	20	0.5
100K	80	20	100	20	0.5
0K -PS	80	0	0	0	0.5
100K -PS	80	0	100	0	0.5
FR	0	0	0	0	0
Sulfur					
0S	80	20	50	0	0.5
10S	80	20	50	10	0.5
20S	80	20	50	20	0.5
30S	80	20	50	30	0.5
0S -PK	80	0	0	0	0.5
30S -PK	80	0	0	30	0.5
FR	0	0	0	0	0

Treatments were applied using a fixed tyne implement which delivered the P and K at 20 cm depth and the N and S 10–15 cm deep. The bands of fertiliser were placed 50 cm apart in plots that were eight metres (m) wide by 32 m long. The bands were placed in the same direction as the old stubble rows. There were six replicates making a total of 48 plots for the trial.

The 2018 sorghum crop had 200 kg/ha of urea applied in the fallow, 6 weeks prior to planting. This rate is double the normal commercial practice for the rest of the farm. Starter fertiliser was applied at planting (10 L/ha polyphosphate plus 2.5 L/ha Foundation™) as a liquid injection with the seed. This starter rate was split in the P trial so that all treatments could have a 'with' and 'without' starter treatment. This effectively doubled the number of plots in the P trial from 48 to 96. The sorghum variety MR Bazley was planted at 50,000 seeds/ha on 14 February 2018. The crop received 159 mm of in-crop rainfall, with over 85% occurring within two weeks of planting.

Potassium (K)

There were seven unique treatments (Table 1; the 0K plots were doubled up to give eight plots per replicate) which included four K rates; 0, 25, 50, 100 kg K/ha. These treatments had background fertiliser applied at the same time to negate any other potentially limiting nutrients. This background fertiliser included; 80 kg N, 20 kg P, 20 kg S and 0.5 kg Zn per hectare. The next two treatments included 0K and 100K without any background fertiliser except N and Zn (0K-PS, 100K-PS). The final treatment was fa armer reference (FR), which had nothing extra applied compared to normal commercial practice (Table 1).

Applications were done in the same way as the phosphorous trial and the other trial details remain the same.

Sulfur (S)

There were seven unique treatments (Table 1; the 0S plots were doubled up to give eight plots per replicate) which included four S rates; 0, 10, 20, 30 kg S/ha. These treatments had background fertiliser applied at the same time to negate any other potentially limiting nutrients. This background fertiliser included; 80 kg N, 20 kg P, 50 kg K and next two treatments included 0S and 30S without any background fertiliser except N and Zn (0S-PK, 30S-PK). The final treatment was a farmer reference (FR), which had nothing extra applied compared to normal commercial practice (Table 1).

Results

Each trial's results are presented separately. The 2018 sorghum crop represents the fifth crop harvested off this site since the initial treatments were applied. Results include the cumulative mean yield data from all five crops.

Phosphorus

The P trial has shown a consistent significant yield response across the past four years to deep applied P. The sorghum crop in 2018 is no different with the 20P and 40P treatments showing a 25% to 35% yield increase (Table 2). This amounts to just under a 1 tonne/ha yield increase for the top P treatment, and during a year when sorghum prices ranged from $300-350 per tonne this would have paid for the total application cost back in 2013. However as this is the fifth crop since application the yield benefit is now going straight to profit as treatment costs were covered in the second year of production.

Table 2. Mean grain yield comparison across treatments in phosphorus trial for sorghum 2018.

Treatments	Mean grain yields (kg/ha)		Relative difference to '0P' plots (kg/ha)	(%)
FR	2349	a	-469	-16.6
0P -KS	2569	ab	-249	-8.8
0P	2817	b	0	0.0
10P	3349	c	532	18.9
20P	3548	cd	731	25.9
40P	3788	d	971	34.5
40P -KS	3481	cd	663	23.6

Letters indicate least significant difference (lsd) P(0.05). Means with a common letter are not significantly different (lsd = 342)

This site does have a high degree of variability in its nutritional status which is why the lsd of 342 kg/ha is relatively large and means there is no clear significant difference between the 20P and 40P treatments rates. This is despite the fact that there has been sizeable difference in grain yield between the 20P and 40P treatments in the last two crops (chickpea 2017, sorghum 2018).

The impact of starter fertiliser within the P trial was also significant (Table 3). Across all treatments the addition of starter fertiliser added an extra 504 kg/ha. Within each deep-P treatment the difference was consistently significant (Table 3). Despite this there was no significant interaction between Starter P and the deep-P treatments. This means the size of the response to deep-P (for example, difference between 0P and 40P was consistent in both starter P treatments.

Table 3. Mean grain yield results for plus and minus starter application at planting.

Deep-P treatments	Mean grain yields (kg/ha) No Starter	Starter	Difference
FR	1942	2755	814
0P -KS	2260	2877	617
0P	2618	3016	397
10P	3123	3575	452
20P	3319	3777	458
40P	3502	4074	572
40P -KS	3320	3641	322
Mean difference			**504**

lsd P(0.05) = 198

A comparison between all crops grown on the P trial site since 2014 (Figure 1) shows the response to the deep-P treatments has not diminished, with the best results recorded in the most recent seasons. It is particularly interesting that the performance of sorghum has improved from the 2015-16 sorghum season to the 2018 season, despite the fact that the 2015-16 sorghum crop received 43 mm more in-crop rainfall. Analysis of the yield and protein data of the two sorghum crops suggests that the nitrogen status of the site has likely played a part in the relative response to deep-P (Figure 2).

There is no significant differences in grain protein between the deep-P treatments but there is up to a 4% difference in protein between sorghum in 2015-16 and 2018 (Figure 2.) The 2018 sorghum crop has also produced 1 tonne more grain (averaged over P plots) with 43 mm less rainfall than 2015-16. The deep-P response in 2018 was 21% bigger in the 40P treatment and11% bigger in the 20P treatment than in 2015-16 (Figure 1).

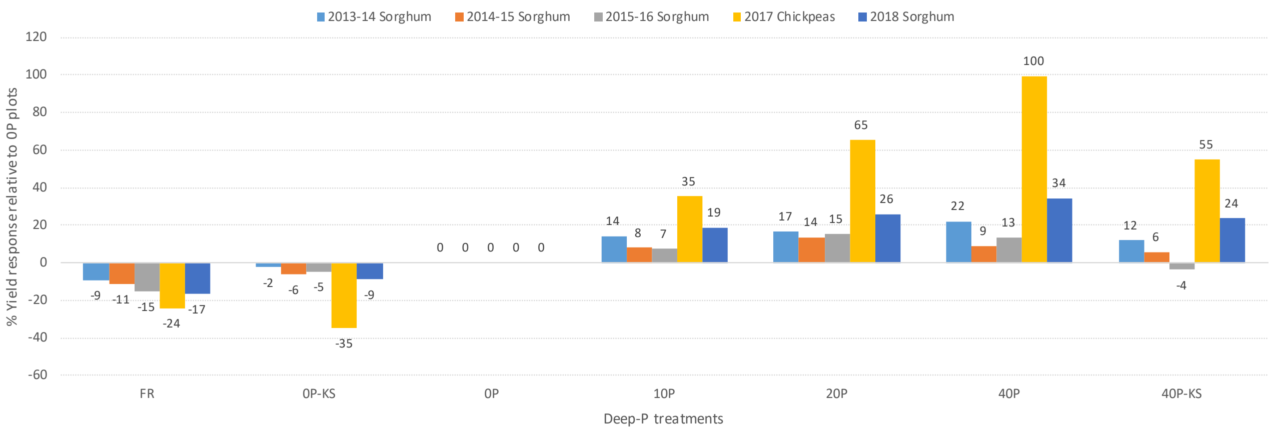

Figure 1. Relative response in grain yield as a percentage of 0P plots for all crops since first treatment.

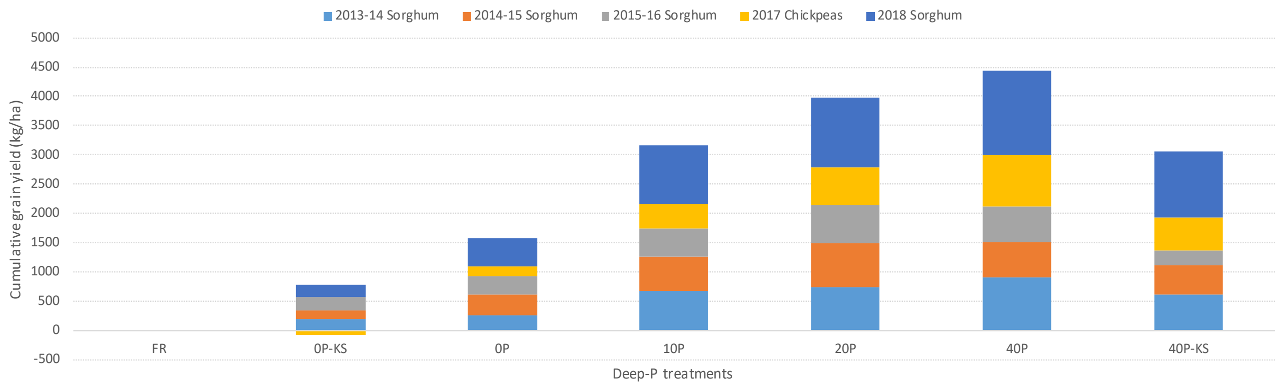

Figure 2. Comparative grain yield and grain protein for the 2015-16 and 2018 sorghum crops in the phosphorus trial site.

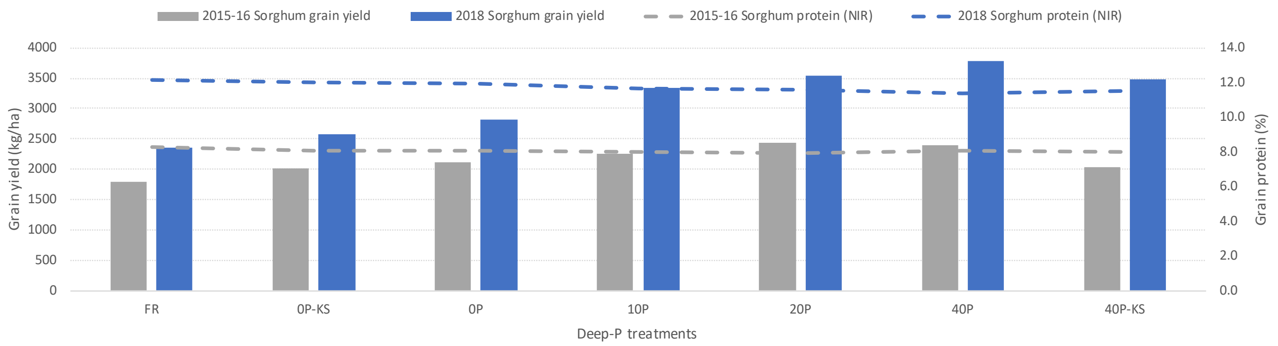

Figure 3. Comparison of the cumulative differences in grain yield (kg/ha) across all the deep-P treatments relative to the FR plots across all years.

The main management difference between the two sorghum crops has been the doubling of the nitrogen fertiliser applied to the site. The 2018 sorghum crop had 200 kg/ha of urea applied as a band in the top 5 cm, across the site prior to planting; whereas the 2015-16 crop had 100 kg/ha of urea side-dressed three weeks after planting.

This comparison of the two sorghum crops from 2015-16 and 2018 along with the large differences in chickpea performance measured across the deep-P treatments (Figure 1) in 2017; suggests that with P and K constraints addressed, the nitrogen status of the site is once again having a strong influence on the relative yield responses to the deep-P treatments.

Data collected from this site has given the best indicator of the long term gains in yield and economic viability for the use of deep placement nutrition. One way of measuring this is by adding the differences in grain yield between the FR plots and the other deep-P treatments (Figure 3).

Same plots across different crops (2018 sorghum and 2017 chickpea); 40P plot on the left and 0P plot on the right.

Table 4. Cumulative benefit ($/ha) analysis across the five crops in the deep-P trial*.

P rate (kg/ha)	2014 Sorghum	2015 Sorghum	2016 Sorghum	2017 Chickpea	2018 Sorghum	ROI
FR	$0	$0	$0	$0	$0	**0.0**
0	-$96	-$11	$80	$149	$312	**1.6**
10	$2	$179	$328	$659	$974	**4.2**
20	-$10	$219	$419	$915	$1,278	**4.7**
40	-$70	$100	$174	$737	$1,156	**3.4**
0P -KS	-$42	$4	$73	$15	$89	**0.9**
40P -KS	-$48	$108	$125	$565	$910	**3.7**

(Courtesy: Hagan.J, 2018) *Costs included additional background fertiliser that was used in the initial application of these treatments on this trial site.

The data demonstrates that the 40P application has produced 4500 kg/ha more grain than the FR plots over five crops whilst the 20P treatment generated 4000 kg/ha. A proportion of this difference could be attributed to deep ripping and additional N, however comparing the treatments to the 0P rate shows 3000 kg/ha improvement for 40P and a 2500 kg/ha increase for the 20P.

These accumulated grain yield increases have generated significant economic benefits (Table 4). After five years of significant responses, it is worth noting that despite the 40P treatment giving the highest increase in cumulative yield, it is the 20P treatment that has given the best return on investment (ROI) at 4.7 due to lower upfront costs. If there is a continued difference in crop responses to the 40P and 20P treatments in future years then the ROI results may change.

Potassium

The differences in grain yield across the potassium trial are reasonably consistent with an 8% response (280 kg/ha) across all the K treatments that had background P and S applied in relation to the 0K plots (Table 5).

Table 5. Mean sorghum grain yield comparison across treatments in the potassium trial 2018.

Treatments	Mean grain yields (kg/ha)		Relative difference to '0K' plots (kg/ha)	(%)
FR	3041	a	-483	-13.7
0K -PS	2964	a	-560	-15.9
0K	3524	b	0	0.0
25K	3815	b	291	8.3
50K	3808	b	283	8.0
100K	3799	b	275	7.8
100K -PS	3009	a	-515	-14.6

Letters indicate least significant difference (lsd) P(0.05). Means with the same letters are not significantly different (lsd = 405)

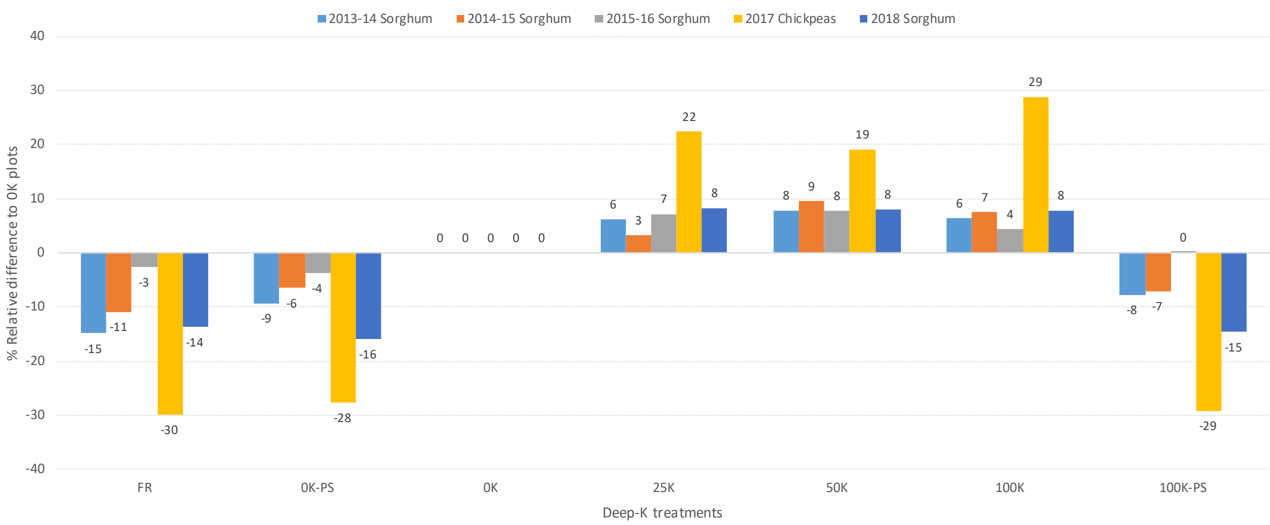

Figure 4. The relative difference in grain yield between deep-K treatments and the 0K plots across all crops grown on-site.

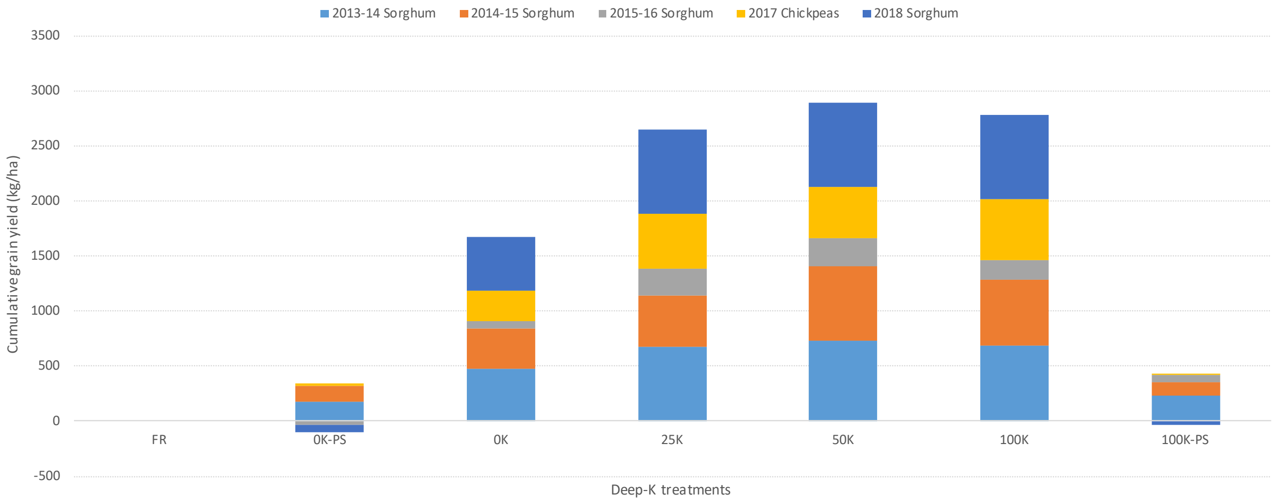

Figure 5. Comparison of the cumulative differences in grain yield (in kg/ha) across all the deep-K treatments relative to the FR plots across all years.

Table 6. Cumulative benefit ($/ha) analysis across the 5 crops in the deep-K trial*.

K rate (kg/ha)	2014 Sorghum	2015 Sorghum	2016 Sorghum	2017 Chickpea	2018 Sorghum	ROI
0	-$45	$62	$81	$307	$446	2.4
25	-$11	$128	$201	$595	$820	3.8
50	-$19	$182	$259	$629	$852	3.6
100	-$84	$97	$149	$592	$811	2.8
0K - PS	-$46	-$3	$12	$12	-$22	-0.2
100K - PS	-$131	-$94	-$48	-$59	-$76	-0.4

(Courtesy: Hagan.J, 2018) *Costs included additional background fertiliser that was used in the initial application of these treatments on this trial site.

Any plot that had no P applied as a background nutrition had a 15% yield penalty. This K response is comparable to previous sorghum crop performance with most responses occurring between 6-9% over the past four crops. In the 2018 sorghum results, the statistical analysis has not been able to find any significant difference in the K treatments. The natural variability in the data has contributed to the lsd being too high for an equivalent 8% response in yield to be significant.

Sorghum responses in the K trial are consistent across the five year data set (Figure 4), whilst chickpea had a far more significant response. This may indicate differences between crop species in ability to forage for potassium down the soil profile.

It may also indicate that the potassium levels are not as limiting as P at this site. Once the P limitation is addressed then the K levels may be just approaching a deficient level leading to some small responses in those crop species that have a robust root system.

Over the long term, the cumulative improvement in grain yield over the FR plots is just under 3 t/ha (Figure 5). Approximately half of this increase can be attributable to background P with yields jumping from 242 kg/ha (0K-PS) to 1668 kg/ha (0K). Despite the increments in grain yield being modest in most seasons (Figure 4), after 5 successive crops the accumulated benefit is substantial with 50K providing an additional 1224 kg/ha over the 0K treatment.

This is backed up in the economic analysis (Table 6) with the 50K treatment producing a ROI of 3.6 and payback occurred in the second crop harvested off this site. Interestingly the 25K treatment produced a slightly higher ROI (3.8) with a lower accumulated grain yield benefit which shows that when there are no significant differences between the different rates of K in terms of yield the economics favours the lower rate. However it would be expected responses to higher rates of K will last longer and improve in ROI over time.

Sulfur

The yield data from the sulfur trial shows no response to the main deep S treatments (Table 7), which has been consistent for every crop monitored in this trial.

As in previous crops there is a pattern where those treatments without background P have a much lower yield performance. In past trial data these differences have been statistically significant; however in the 2018 sorghum crop the statistical analysis has not shown this. The reason for this change from previous years is unknown.

There were no significant differences identified in the grain protein analysis from the samples taken at harvest.

Table 7. Mean grain yield comparison across treatments in the sulfur trial for 2018 sorghum.

Treatments	Mean grain yields (kg/ha)	Relative difference to '0S' plots	
		(kg/ha)	(%)
FR	3179	-514	-13.9
0S -PK	3326	-367	-9.9
0S	3693	0	0.0
10S	4031	339	9.2
20S	3706	13	0.4
30S	3863	170	4.6
30S -PK	3195	-498	-13.5

No significant differences across treatments.

Implications for growers

The results from the 2018 sorghum crop have shown another strong response to the deep banding of P and also a strong response to starter P. This site has been P responsive in every year however the size of the response has fluctuated from season to season. The 2018 sorghum crop has shown the strongest relative response (34.5%) out of the four sorghum crops grown at the site and this is unexpected given the first sorghum crop had the benefit of extra nitrogen and deep ripping in the first year. The 2018 sorghum crop also had the least amount of in-crop rainfall out of the four crops.

Starter P responses at this site have not always been consistent even though soil analysis shows that surface P is low (see 0-10 cm in Trial details). This may relate to how quickly the surface profile dries out after planting which then governs how long the plant gets access to the starter P. In this case early in-crop rainfall (137 mm in first 10 days) may have extended the plant access to the starter P application and consequently improved grain yield.

This trial site has proven that deep placement of P at rates of 20 to 40 kg/ha can continue to provide economic responses for at least five consecutive crops over a period of five years. It is also clear that once subsoil P constraints are addressed that nitrogen may once again be the crop-limiting nutrient. The 2017 chickpea crop showed very high relative responses (60-100%) even though yields were restricted by seasonal conditions.

Defining the best rate of P is still not clear even though there has been a bigger spread of yields between the 20P and 40P rates over the last two crops. The statistical analysis cannot split the performance of the two rates so far and this may be a result of the inherent variability at the site. Economically the 20P rate is just ahead in return on investment, however there will be another crop monitored on this site before the end of the project and those results may change the long term analysis.

The deep placed potassium has once again shown a pattern of small responses to the deep band placements but not enough to be considered statistically significant in the 2018 sorghum crop. The long term grain response to potassium over the last five years has shown that the addition of K has been economically viable although at a lower ROI then the P trial.

This site is proving that the most limiting nutrient will always make the biggest difference to yield but once the nutrient has been lifted then other nutrients, particularly K and N, can have an impact on yield. While K has only contributed marginally to stronger yield performance it is an indicator that this nutrient could become limiting if nothing was done.

Nitrogen fertility has shown it has the capacity to strongly limit response to P and K, even though soil analysis would suggest that P should be the most limiting factor. The data collected at this trial site has been focused on crop response to P, K and S; however it is emerging from the variations between crops and seasons that N fertility at this site is playing a large role in the size of the response that is being achieved by deep placement of P and K.

Acknowledgements

It is greatly appreciated to have the continued support of trial co-operators, by hosting this trial site. This work is funded by the Grains Research and Development Corporation, University of Queensland and the Department of Agriculture and Fisheries under project UQ00063 Regional soil testing guidelines for the northern grains region.

Trial details

Location:	Dysart
Crop:	Sorghum (MR Bazley)
Soil type:	Grey Vertosol (Brigalow scrub) on minor slopes
In-crop rainfall:	159 mm
Fertiliser:	Fallow-applied urea @ 200 kg/ha

Selected soil fertility characteristics:

Depth (cm)	Nitrates	Sulfur (KCl-40)	Col P	BSES P	Exc. K	ECEC
0-10	2	1.7	5	8	0.25	36
10-30	1	1.6	1	3	0.12	29
30-60	1	2.6	1	4	0.09	31

Responses to deep placement of phosphorus and potassium in mungbeans—Dululu

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Research Question: *Do mungbeans respond to residual bands of deep-placed phosphorus and potassium in the same way as chickpeas?*

Key findings

1. Mungbeans did not respond to deep phosphorus treatments.
2. Mungbeans had a 15% yield response to deep potassium treatments.
3. After 3 years of cropping the return on investment to 20 kg deep banded phosphorus is 1.6 and 100 kg deep banded potassium is 1.7.

Background

Over the last four years the UQ00063 project (Regional soil testing guidelines) has been monitoring a series of nutrition based trial sites across Central Queensland (CQ). These trial sites were chosen based on soil testing evidence showing varying degrees of nutrient depletion in the surface and subsurface layers. This is particularly evident in the non-mobile nutrients of phosphorus (P) and potassium (K). In some established zero tillage production systems there is a marked difference between the nutrient concentration in the top 10 cm of the soil profile and the deeper layers (10-30 cm and 30-60 cm); that cannot be explained by natural stratification. It would seem that this pattern of soil analysis is becoming more evident across CQ, particularly in the brigalow scrub and open downs soil types.

This project is gathering data from these trial sites to ascertain whether an application of P or K placed as a band in the subsurface profile can provide a grain yield benefit and whether that benefit (response) can be maintained over several years. These results are being used to define the economic benefit of adding these non-mobile nutrients over successive cropping cycles.

What was done?

The Dululu trial site was first treated with deep banded fertiliser treatments in November of 2015 and has had three crops planted and harvested since then (wheat 2016 and chickpea 2017). The third crop, mungbeans, was planted on 27 November 2017 and harvested on 23 February 2018. The original soil test from the site (Table 1) would indicated adequate levels of P and K in the top 10 cm but a significant change in that analysis in the deeper layers (10-30 cm, 30-60 cm).

Phosphorus (P)

There were seven unique treatments (Table 2; 0P was doubled up to make eight plots per replicate), which included four P rates; 0, 10, 20, and 40 kg P/ha. These treatments had background fertiliser applied at the same time to negate any other potentially limiting nutrients. This background fertiliser included; 80 kg nitrogen (N), 50 kg K, 20 kg sulfur (S) and 0.5 kg zinc (Zn) per hectare. The next two treatments included 0P and 40P without background fertiliser except N and Zn (0P -KS, 40P -KS). The last treatment was a farmer reference (FR), to act as a benchmark control treatment. The FR

Table 1. Original soil analysis for the Dululu site.

Depth (cm)	Nitrate nitrogen (mg/kg)	Phosphorus Colwell (mg/kg)	Sulfur (KCl-40) (mg/kg)	Exc. potassium (meq/100g)	Phosphorus BSES (mg/kg)	PBI	ECEC (meq/100g)
0-10	7	17	4	0.23	21	99	22
10-30	22	3	7	0.12	5	109	28
30-60	18	1	18	0.09	4	81	29

treatments had nothing applied except what the farmer applied in line with normal commercial practice from season to season (Table 2).

These treatments were banded using a fixed tyne implement which delivered the P and K at 25 cm depth; the N and S at 15 cm depth. The bands of fertiliser were placed 50 cm apart in plots that were six metres (m) wide by 28 m long. The bands were placed in the same direction as the old stubble rows. A split starter P treatment was also added to this trial so that each deep-P treatment was doubled to make a 'with' and 'without' starter P treatment. This effectively doubled the treatments from 8 to 16 and there were four replicates of each making a total of 64 plots for the trial.

In the 2018 mungbean crop, Granulock® Z was applied as the starter P treatment at 40 kg/ha and the variety Crystal⚭ was planted at 20 kg/ha. The crop received 139 mm of in-crop rainfall.

Potassium (K)

There were seven unique treatments (Table 2; 0K was doubled up to make eight plots per replicate), which included four K rates; 0, 25, 50, 100 kg K/ha. All of these treatments had background fertiliser applied at the same time to negate any other potentially limiting nutrients. This background fertiliser included; 80 kg N, 20 kg P, 20 kg S and 0.5 kg Zn per hectare. The next two treatments included 0K and 100K without any background fertiliser except N and Zn (0K-PS, 100K-PS). The last treatment was a farmer reference (FR) to act as a second control. The FR plots were not treated with anything except what the farmer applied in line with normal commercial practice (Table 2).

Applications were done in the same way as the phosphorous trial and the other trial details remain the same. There were no split starter P treatments in the K trial; every plot received starter P (Granulock® Z @ 40 kg/ha).

Data collection for both trials included emergence plant counts, with starting soil water and N measurements taken shortly after emergence. Total dry matter cuts were taken at physiological maturity and yield measurements were taken with a plot harvester when commercial harvesting started in the same paddock. A grain sample was kept from each plot for nutrient analysis. Both the dry matter samples and the grain samples were ground and subsampled for a wet chemistry analysis.

Table 2. Summary of nutrient application rates (kg/ha) for both trials.

Treatment	N	P	K	S	Zn
Phosphorus					
0P	80	0	50	20	0.5
10P	80	10	50	20	0.5
20P	80	20	50	20	0.5
40P	80	40	50	20	0.5
0P-KS	80	0	0	0	0.5
40P-KS	80	40	0	0	0.5
FR	0	0	0	0	0
Potassium					
0K	80	20	0	20	0.5
25K	80	20	25	20	0.5
50K	80	20	50	20	0.5
100K	80	20	100	20	0.5
0K-PS	80	0	0	0	0.5
100K-PS	80	0	100	0	0.5
FR	0	0	0	0	0

Results

Phosphorus

Despite this crop receiving 139 mm of in-crop rainfall its general yield performance was not high with yields between 0.7 to 0.8 t/ha. It is quite often difficult to extract clear significant differences from low-yielding crops. The yield data (Table 3) would suggest there was no response to the deep placement of P despite there being a close to a 15% response in the previous chickpea crop (Figure 1).

Table 3. Mean grain yields for 2018 deep-P trial in mungbeans.

Treatment	Mean grain yield (kg/ha)		Relative yield difference to '0P' plots (kg/ha)	(%)
FR	717	a	-151	-17
0P-KS	793	ab	-75	-9
0P	868	c	0	0
10P	839	bc	-29	-3
20P	843	bc	-26	-3
40P	858	bc	-10	-1
40P-KS	821	bc	-47	-5

Letters indicate least significant difference P(0.05). Means with the same letters are not significantly different (lsd = 69) .

The only significant difference in the P trial was the relative poor performance of the FR treatment in comparison with all other treatments (Table 3). There will be a background K influence on this performance as proven

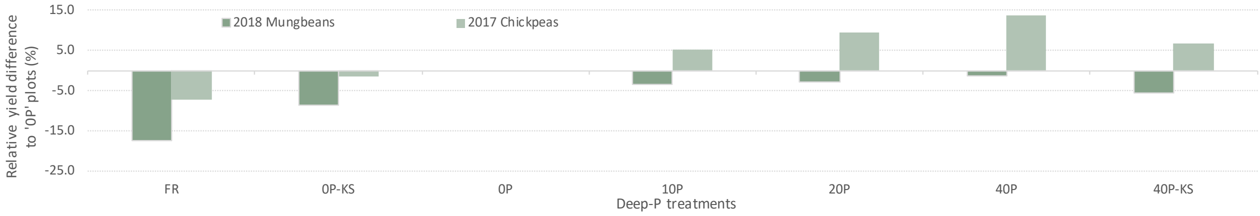

Figure 1. Comparison of relative yield response to deep-P between 2017 chickpea and 2018 mungbean crops.

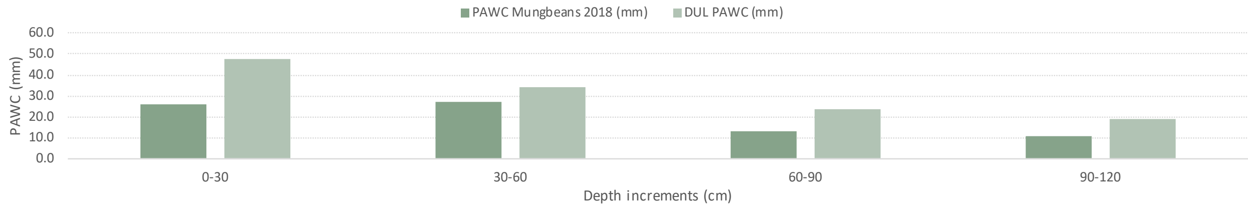

Figure 2. Mean starting plant available water content (PAWC) in comparison to estimated drained upper limit for this site soil type (full moisture profile).

by the results in the K section of this report however there was a significant difference between the FR plots and the 40P -KS treatments (Table 3), which may indicate another factor (not easily defined) is having a small impact on the mungbean yields.

The poor crop result from such good in-crop rainfall (Figure 4) seems contradictory; however part of the reason could be attributable to the modest starting soil moisture levels at planting (Figure 2). The profile was not full at planting which means through redistribution of moisture over time the plants may have been running dry before rainfall was received in early January (Figure 4). Stressing plants through the vegetative growth phase has the potential to limit yield, as has been proven by other project data (Queensland Pulse Agronomy Initiative, 2013-2018).

Plant analysis would indicate that the mungbean crop did not access the P nutrition bands in the same way that the chickpea crop did in the previous year (Figure 3). It is also worth noting that the P concentration in the dry matter (%) for the mungbeans is consistently higher, however mean plant uptake (kg/ha) matches the levels attained in the chickpea where deep-P was supplied (Figure 3).

This would indicate that the mungbeans in 2018 had enough access to P to not limit yield without having to utilise the deep-placed bands. Recent soil analysis from the P trial (Table 4) would suggest that the surface soil (0-10 cm) has more than adequate soluble P supplies. This may also explain why there was no response to starter P at planting in this trial (data not shown). However the subsurface layers (10-30, 30-60 cm) are the opposite with soluble P levels almost non-existent. This would mean that the mungbean crop extracted enough P to meet demand from the surface soil however this could only occur while the surface soil is wet enough for nutrient extraction to occur.

Rainfall figures would suggest that the surface soil was wet from 30 DAS through to 50 DAS. Later rainfall at 68 DAS would have been largely irrelevant as the crop was defoliated by 75 DAS. This means a large proportion of the P required

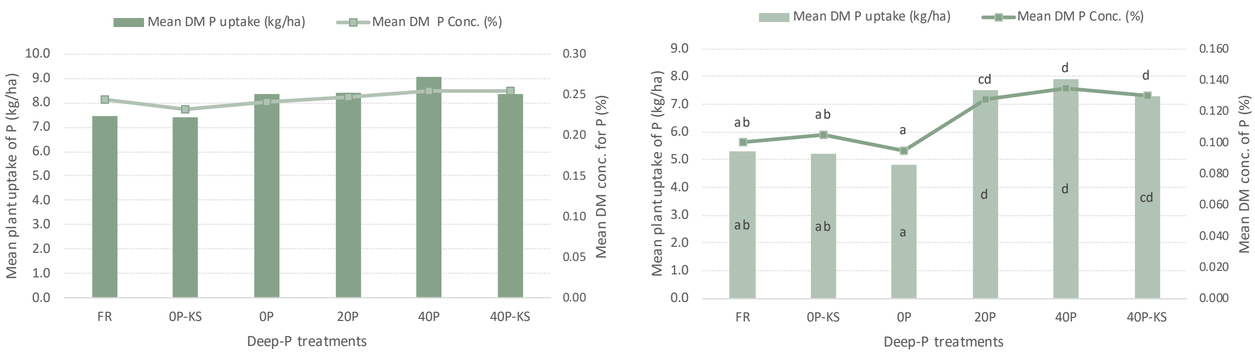

Figure 3. Phosphorus concentration in total dry matter and overall plant uptake in kg/ha for 2018 mungbean (left) and 2017 chickpea (right).

Table 4. Soil analysis taken from FR plots in each replicate of the P trial at the planting of the 2018 mungbean trial.

Depth (cm)	Replicate	Values (mg/kg)*	
		Colwell P	BSES P
0-10	1	20	18
	2	19	22
	3	30	32
	4	29	30
10-30	1	2	1
	2	1	1
	3	1	2
	4	1	2
30-60	1	1	1
	2	1	1
	3	1	2
	4	1	2

* Laboratory analysis cannot measure less than 2 mg/kg. This result is represented in the table as a 1.

by the plant was taken during the 20 day period starting just before flowering (first flower 40 DAS). Moisture at planting would have provided some opportunity to access P in the surface layers however the plant would have had a limited root system during the first two weeks after planting and uptake of P would have been limited by this.

Days above 35 °C were rare for this crop (Figure 4) and humidity levels were generally above 45%, so surface soil layers may have retained moisture for longer giving better access to surface nutrients. Mungbeans may also be able to redistribute P around the plant better than other crops. This is an unknown aspect as this is the only mungbean crop that has been grown on a deep-P site so there is no other data to compare.

Canopy closure had not occurred close to flowering. This indicates some stress in the vegetative growth phase slowing down biomass accumulation.

Potassium

In contrast to the P trial, there has been a significant response to the deep-applied K treatments. All treatments that had K supplied (25K, 50K, 100K and 100K-PS) were significantly different to the 0K treatments (Table 5). Also worth noting is that treatments where the background P and S was not supplied (100K-PS and 0K-PS) were not significantly different to yields where P and S ere included, further confirming the results in the P trial where there was no significant response to P.

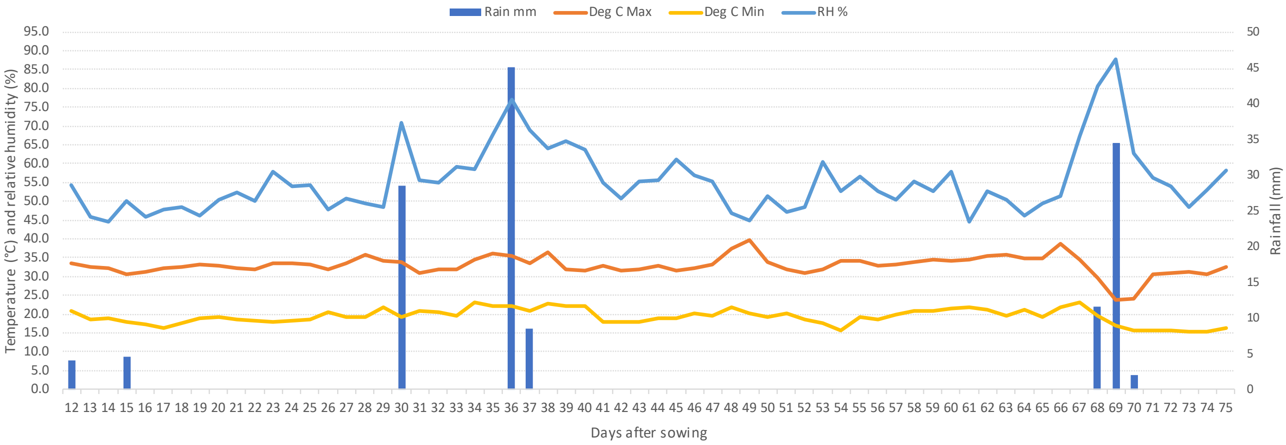

Figure 4. Rainfall, temperature and relative humidity data recorded for the duration of the 2018 mungbean crop.

Table 5. Mean grain yields for 2018-19 deep-K trial in mungbeans.

Treatment	Mean grain yield (kg/ha)		Relative yield difference to '0K' plots (kg/ha)	(%)
FR	665	a	26	4.0
0K-PS	619	a	-20	-3.1
0K	639	a	0	0.0
25K	725	b	86	13.4
50K	741	b	102	15.9
100K	735	b	96	15.0
100K-PS	759	b	120	18.7

Letters indicate least significant difference P(0.05). Means with the same letters are not significantly different (lsd = 47).

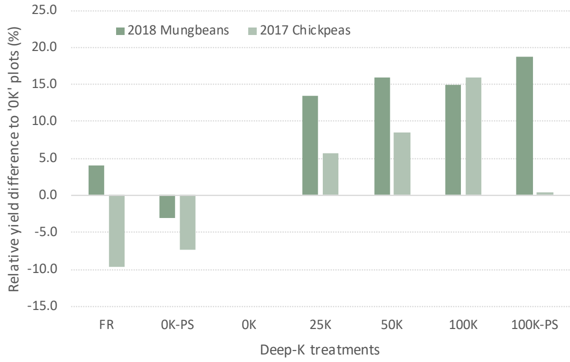

Figure 5. Comparison of relative yield response to deep-K between 2017 chickpea and 2018 mungbean crops.

While mean yields are generally considered low, the relative yield differences (%) are similar to the previous chickpea crop grown on the site in 2017 (Figure 5).

The 2018 mungbean crop has shown a more consistent response to the deep-applied K than chickpea, however the chickpeas were also clearly responsive to P bands at the same time as demonstrated by the change in yield response when the background P was removed from the treatment (100K -PS and 0K –PS) (Figure 5). Plant analysis can confirm that the mungbean crop was accessing the deep-applied K bands (Figure 6).

The plant analysis data shows that both the chickpeas (2017) and the mungbeans (2018) had similar patterns of uptake when comparing the 0K treatment and all other treatments that contained K. An interesting point in this comparison is the concentration of K in dry matter (DM) is higher in the mungbeans than in chickpeas and subsequently total K uptake (kg/ha) is also higher in mungbeans. This is surprising given that the chickpeas in 2018 produced, on average, 5.2 t/ha of DM versus the mungbeans that produced, on average 3.5 t/ha.

This means that in general terms mungbeans have either a higher requirement for K than chickpeas or the mungbeans have taken up luxury levels of K, given the response values at this site.

There is some conflict in the data between the K trial and the P trial in respect to the 2018 mungbean crop. It is clear that the mungbean plants had access to the deep bands of fertiliser in regards to K uptake but seemingly did not take up P even though both elements were placed in the same band. Logic would suggest that if the circumstances were good enough (moisture, soil conditions) for K uptake out of the deep fertiliser bands than P should have also been taken up.

Soil analysis taken at the planting of the 2018 mungbean crop (Table 6) shows a similar pattern of stratification to the P soil tests (Table 4) although not quite as dramatic. Surface levels could be termed as adequate to marginal (>0.2) with the subsurface levels then dropping down to deficient levels (<0.15) (Table 6). While both nutrients in each trial have deficient levels in the subsurface layer, for reasons unknown at this stage, the mungbean crop has only responded to the K nutrient in these deep-placement bands.

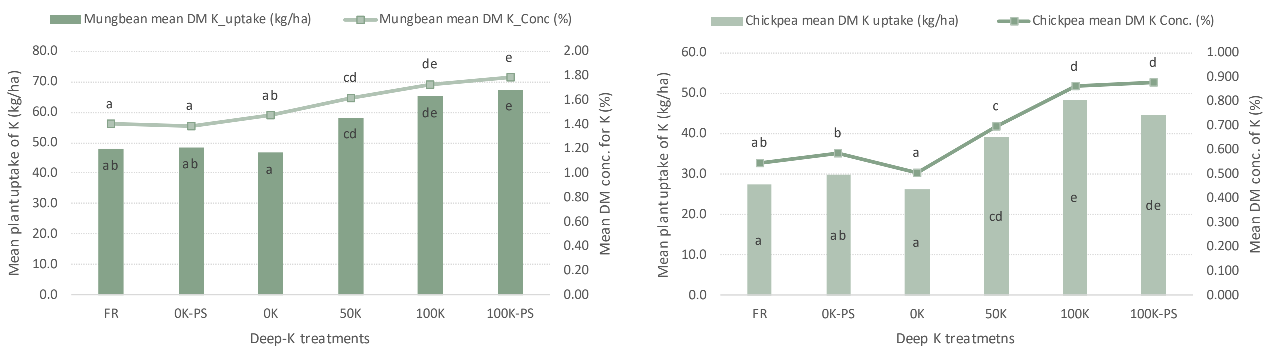

Figure 6. Potassium concentration in total dry matter and overall plant uptake in kg/ha for 2018 mungbean (left) and 2017 chickpea (right). Means with the same letters are not significantly different.

Table 6. Soil analysis taken from FR plots in each replicate of the potassium trial at the planting of the 2018 mungbean crop.

Depth (cm)	Rep	K values (meq/100g)	Mean K values (meq/100g)
0-10	1	0.237	0.212
	2	0.208	
	3	0.193	
	4	0.194	
	5	0.239	
	6	0.204	
10-30	1	0.093	0.1
	2	0.083	
	3	0.122	
	4	0.109	
	5	0.109	
	6	0.085	
30-60	1	0.084	0.104
	2	0.075	
	3	0.072	
	4	0.076	
	5	0.038	
	6	0.080	

Relative concentrations of P and K in the surface (0-10 cm) may go some way to explaining the differences in responses. The P concentration in the surface soil could be termed as luxury levels (20-30 mg/kg) whereas the K level in the surface soil could be considered marginal (0.19–0.23).

This relative difference in concentration may mean that the concentration gradient across the root membrane for P in the surface soil was a lot higher than for K and this could assist in the efficiency and quantity of uptake into the plant for P. If the concentration gradient is lower for K in the surface soil and therefore it could not take up enough K in the period when moisture in the surface soil was available; then the plant would have to meet some of its deficiency from the banded deep-K where the concentration gradient may have been more favourable for uptake. In relative terms the plant has to take up far more K (70 kg/ha) than P (8 kg/ha) to satisfy its metabolic demand which then means K may need a much wider window for uptake.

Economic analysis

Economic assessment of the P experiment treatments (Table 7) shows positive payback in the second crop (chickpea in 2017). Currently 20P and 40P with KS applied are providing the highest cumulative benefits, but the higher cost of setting up 40P over 20P is reducing the return on investment ratio (ROI) slightly. Within this three year scenario it is the chickpea response in 2017 that is driving most of the economic benefit, and paid back the original investment in the second year of production. Any further productivity gains will continue to add directly to profit and improve the ROI.

Table 7. Cumulative benefit ($/ha) analysis of three crops grown on the deep-placed phosphorus trial using the FR treatment as the baseline.

P rate (kg/ha)	Wheat 2016	Chickpea 2017	Mungbean 2018	ROI
0	-$106	$87	$267	1.4
10	-$127	$202	$348	1.5
20	-$147	$278	$428	1.6
40	-$231	$291	$459	1.4
0P -KS	-$78	$91	$181	1.8
40P -KS	-$189	$165	$289	1.3

As with P at the site, the K trial has shown the inclusion of high value pulse crops at the site has boosted economic returns (Table 8), increasing profit by the second year of production. The highest ROI has been achieved where K application rate has been greatest (100 kg K/ha) supplemented with basal P and S applications. Even though both pulse crops at this site have responded to deep-K nutrition the ROI for the K trial is similar to the P trial (Tables 7 and 8). It is worth noting that the highest rate (100K) has shown the highest ROI despite the costs for this treatment also being the highest.

Table 8. Cumulative benefit ($/ha) analysis of three crops grown on the deep-placed potassium trial using the FR treatment as the baseline.

K rate (kg/ha)	Wheat 2016	Chickpea 2017	Mungbean 2018	ROI
0	-$88	$130	$100	0.50
25	-$93	$255	$328	1.47
50	-$156	$253	$345	1.39
100	-$158	$422	$514	1.72
0K -PS	-$11	$40	-$14	-0.14
100K -PS	-$73	$156	$271	1.35

Implications for growers

The results from this trial site once again reinforce that responses to deep placed nutrients can vary in relation to crop species, seasonal weather patterns and the level of nutrient stratification. There are a number of data sets that demonstrate chickpeas can respond to deep placement of both P and K in CQ soils, however the amount of data recorded on mungbeans is limited. This Dululu site is the first deep placement trial in CQ that has had a mungbean crop harvested off it, and so no conclusion can be made in regards to the fact that the crop responded well to the K treatments but not to P despite the fact that the previous chickpea crop responded well to both P and K treatments.

Whether this pattern of response is particular to the mungbean species or more relatable to the level of stratification for each nutrient and the in-crop rainfall for the season is still difficult to determine. However, this trial's plant analyses have highlighted that a mungbean crop does have a high requirement for K in view of the plant analysis data. Further trial data will be required to ascertain the true characteristics of mungbean interaction with deep-placed P and K.

Despite the moderate yields produced in the mungbean crop in 2018 the ROI for both nutrients are positive and approaching up to two times the cost of deep placement. Future crops will boost this ROI further and will dictate which rate of nutrition will be the most economical.

Acknowledgements

Thanks to the trial co-operators for hosting these trials. This work is funded by University of Queensland, the Department of Agriculture and Fisheries and the Grains Research and Development Corporation under UQ00063 Regional soil testing guidelines for the northern grains region.

Trial details

Location:	Dululu
Crop:	Mungbeans
Soil type:	Grey, Brown Vertosols (Brigalow scrub) on minor slopes
In-crop rainfall:	138 mm
Pre-plant fertiliser:	Nil

Responses to deep placement of phosphorus and potassium in chickpea—Clermont

Doug Sands[1], Dr David Lester[1], Prof Michael Bell[2] and James Hagan[1]
[1]Department of Agriculture and Fisheries
[2]University of Queensland

Research Question: *What is the yield response in chickpea to the deep-banding application of phosphorus and potassium?*

Key findings

1. Chickpea yields increased by over 900 kg/ha on deep banded phosphorus (P) applied at 40 kg P /ha; representing a 300 % increase over the zero P treatments.
2. Chickpea yields were not responsive to deep applied potassium bands.

Background

Over the last four years the UQ00063 project (Regional soil testing guidelines) has been monitoring a series of nutrition trial sites across Central Queensland (CQ). These trial sites were chosen based on soil testing evidence showing varying degrees of nutrient depletion in the surface and subsurface layers. Subsurface depletion is particularly evident for the non-mobile nutrients phosphorus (P) and potassium (K). In some established zero tillage production systems there is a marked difference between the nutrient concentration in the top 10 cm of the soil profile and the deeper layers (10-30 cm and 30-60 cm), that cannot be explained by natural stratification. It would seem that this pattern of soil analysis is becoming more evident across CQ, particularly in the brigalow scrub and open downs soil types.

This project is gathering data from these trial sites to ascertain whether a one-off application of either P, K or sulfur (S) that is placed in these deeper, more depleted layers can provide a grain yield benefit and whether that benefit can be maintained over several years. These results can also be used to define the economic benefit of adding these non-mobile nutrients over a crop rotation, rather than the conventional approach of assessing the profitability against the next crop to be sown.

Data from these sites is also contributing to the understanding of the pathways of macro nutrient uptake and how responses to deep-banded fertiliser can be impacted by seasonal constraints and differences in crop species.

What was done?

This trial site was established in October 2015, then planted to sorghum in February 2016 and chickpea in May 2018. Based on the original soil characterisation tests (see Trial details), it was decided to locate three individual rate response trials at this site: one each for P, K and S. All trials contained a farmer reference (FR) treatment in which had nothing extra applied compared to normal commercial practice, benchmarking current production levels.

Phosphorus (P)

There were seven unique treatments (Table 1a), which included 4 P rates of 0, 10, 20, and 40 kg P/ha (0P, 10P, 20P and 40P). The 0P plots were doubled up to make eight plots replicated six times. All treatments had background fertiliser applied at the same time to negate any other limiting nutrients. This basal fertiliser was 80 kg nitrogen (N)/ha, 50 kg K/ha, 20 kg S/ha and 1 kg zinc (Zn)/ha. Two contrasting treatments included 0P and 40P without any background K and S fertiliser (0P-KS, 40P-KS) to assess the impact of P only. Table 2 lists the commercial fertiliser products that were used to make up the treatments.

These treatments were applied using a fixed tyne implement which delivered the P and K 20 cm deep and the N and S 10-15 cm deep. The fertiliser bands were placed 50 cm apart in plots that were 8 m wide by 32 m long and in the same direction as the crop rows. Under normal conditions this trial would also have had three P-based starter fertiliser treatments (0, 15 and 30 kg/ha) applied with the seed at planting, however, due to a lack of planting rain, the 2018 crop had to be deep planted with the co-operator's planter and consequently the different starter treatments could not be applied as they were for the previous sorghum crop in 2016. Instead, the trial had MAP (mono ammonium phosphate) starter fertiliser applied @ 20 kg/ha (equivalent to 3 kg/ha P) with Basis XC® applied with the MAP at 2 L/t across the entire site.

Chickpea (Kyabra⁽ᴾ⁾) was planted with a 24 m commercial planter with moisture-seeking capability on 27 May 2018 and harvested on 25 October. The crop was planted on 0.5 m rows at 20 cm deep into moisture and received a total of 51 mm of in-crop rainfall of which the crop received just 7.6 mm during the first 109 days.

Potassium (K)

The potassium experiment explored application of K with/without P and S being present. There were seven unique treatments including 4 K rates: 0, 25, 50, and 100 kg K/ha with a background fertiliser of 80 kg N/ha, 20 kg P/ha, 20 kg S/ha and 1 kg Zn/ha. The 0K plots were doubled up to make eight plots per replicate. Contrasting this are two treatments 0K and 100K without PS fertiliser (0K-PS, 100K-PS).

Applications were done in the same way as the P trial and Table 1b gives a summary of the rates of nutrition used in each treatment. The K trial was planted in the same way as the P trial with the co-operators 24m planter. Plot dimensions remain the same as the P trial. Starter fertiliser was applied to the whole trial at planting.

Sulfur (S)

There were seven unique treatments which included four S rates; 0, 10, 20, 30 kg S/ha. All treatments had background fertiliser applied at the same time to negate any other limiting nutrients. This background fertiliser included 80 kg N/ha, 20 kg P/ha, 50 kg K/ha and 1 kg Zn/ha.

The other treatments included 0S and 30S without any background fertiliser except N and Zn (0S-PK, 30S-PK). Treatments were applied in the same way as the P and K trials; application rates are summarised in Table 1c. This trial was planted by the farmer co-operator in the same way as the K trial with starter fertiliser.

Table 1a. Summary of nutrient application rates (kg/ha) for the phosphorus trial.

Treatment	N	Starter P	P	K	S	Zn
0P	80	3	0	50	20	2
10P	80	3	10	50	20	2
20P	80	3	20	50	20	2
40P	80	3	40	50	20	2
40P-KS	80	3	40	0	0	2
0P -KS	80	3	0	0	0	2
FR	0	3	0	0	0	0

Table 1b. Summary of nutrient application rates (kg/ha) for the potassium trial.

Treatment	N	P	K	S	Zn
0K	80	20	0	20	2
25K	80	20	25	20	2
50K	80	20	50	20	2
100K	80	20	100	20	2
0K-PS	80	0	0	0	2
100K-PS	80	0	100	0	2
FR	0	0	0	0	0

Table 1c. Summary of nutrient application rates (kg/ha) for the sulfur trial.

Treatment	N	P	K	S	Zn
0S	80	20	50	0	2
10S	80	20	50	10	2
20S	80	20	50	20	2
30S	80	20	50	30	2
0S-PK	80	0	0	0	2
30S-PK	80	0	0	30	2
FR	0	0	0	0	0

Table 2. Commercial products used in nutrient treatments.

Nutrient	Product source of nutrient in applications
Nitrogen (N)	Urea (46%), MAP (10%), GranAm® (20%)
Phosphorus (P)	MAP (22%)
Potassium (K)	Muriate of potash (50%)
Sulfur (S)	GranAm® (24%)
Zinc (Zn)	Supa Zinc™ (Liq) (7.5% w/v)

For all three trials, data collection was done the same way. Plant counts, starting soil water and starting nitrogen (N) measurements were taken post emergence. Total dry matter measurements were taken at physiological maturity and yield measurements were taken with a plot harvester when commercial harvesting started in the same paddock. Two harvest samples were taken from each plot and a grain sample was kept from the plot for nutrient analysis. Both the dry matter samples and the grain samples are ground down and subsampled for a wet chemistry analysis.

Results

The results for each trial are presented separately. The 2018 chickpea crop represents the second crop grown at this site since the initial deep-banded treatments were applied. This section will also include data from the previous sorghum crop harvested in 2016.

Phosphorus

Chickpea grain yields for the deep-P trial show a similar pattern to that produced by the sorghum crop two years ago (Figure 1). Although chickpea yields have been limited by very dry conditions, the relative increase in yields between the 0P treatment and the 40P treatment are of a much larger magnitude (304%) than the sorghum response (39%) in 2016. The sensitivity of the chickpea to the deep-banded P is clearly evident with each rate of P producing a significant increase in grain yield (Figure 1). This is slightly different to the sorghum pattern where any additional deep-P gave a significant response (against the 0P rate) but there was no difference between the 10P and 20P rates. The 40P rate gave a significant increase in yield again over the lower rates by 384 kg/ha. This is slightly unusual as in other trial sites the 20P and 40P rates have given a similar responses in sorghum crops.

The magnitude of the response by the chickpea was evident at the site early in the crop development stages and continued right through to maturity. Plots with no additional P were barely harvestable.

Establishment: 40P (background) and 0P (foreground).

20P plot ready for harvest (right), next to untreated tramline buffer.

Table 3. Summary of soil analysis data for phosphorus and potassium across the site (based on average of six replicates for each trial).

Depth	Colwell P (mg/kg)	BSES P (mg/kg)	K (meq/100 g)
0-10 cm	7	39	0.81
10-30 cm	1*	37	0.32
30-60 cm	1*	34	0.22

*Note: Laboratory analysis cannot read below 2 mg/kg. For ease of mean calculations a figure of <2 was represented by a numerical figure of 1.

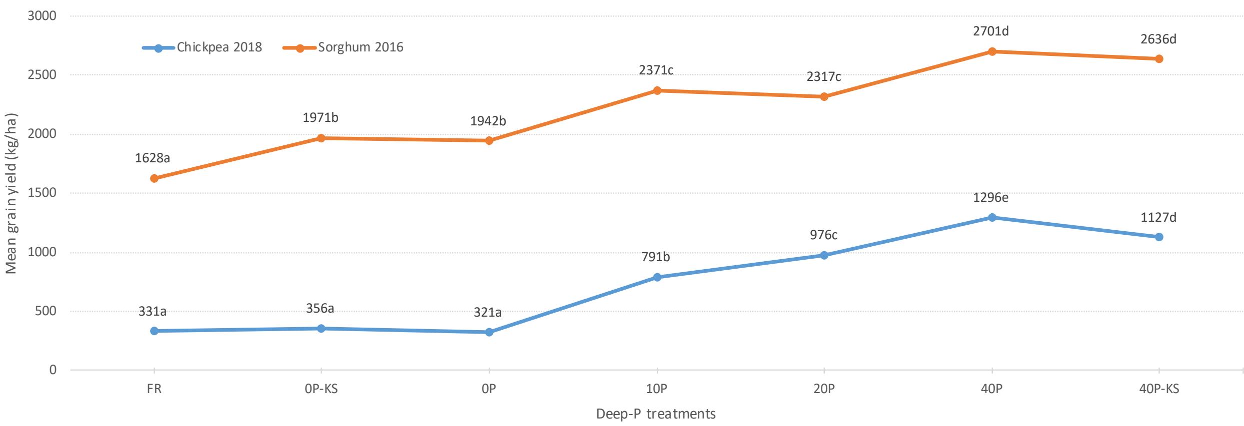

Figure 1. Mean grain yields from deep-P trial for 2016 sorghum and 2018 chickpea.
(Means with the same letters are not significantly different at the 5% level) Sorghum lsd=146, Chickpea lsd=104.

Comparison of plants starting to flower; top plant from additional P plot, bottom has no deep-P.

The most recent soil analysis of the site (Table 3) shows very low P levels in the subsurface layer (10-30 cm), in some cases not detectable for normal lab analysis. It should not be surprising that there is a very strong response to deep-P at this site, however what is surprising is the difference in response between species (pulses and cereals). There are a number of factors that could be at play to cause this result.

Firstly, chickpea (being a legume) is not constrained by nitrogen (N) fertility the same way as cereals such as sorghum can be. In this trial, N was backgrounded out at a rate of 80 kg N/ha prior to sorghum being planted in 2016, so it is unlikely the N status would have affected the P response in the sorghum.

Secondly, the structure of the root system and the plants' ability to forage for nutrients between cereals and pulses can be a factor. The foraging nature and depth of rooting by cereals such as sorghum can be an advantage in a nutrient-depleted environment. Banding P at a depth where moisture is prevalent for longer gives the chickpea plant better access to P than it normally would have if it had to rely on its tap-rooted system to explore the profile in order to extract enough P.

Thirdly, the deep banding of P creates an area of high concentration for the nutrient. This greatly assists in the uptake by the plant as it relies on diffusion and a concentration gradient to move the phosphate ion across the root membrane from an area of high concentration to low concentration. This may benefit the root structure of chickpea crops far more then sorghum crops.

Fourthly, there is a higher requirement for P in pulse crops, particularly in the amount of P that ends up in the grain in relation to cereal crops[1] (3 kg/t for chickpea, 1.9 kg/t for sorghum). This may give crops such as chickpea a higher sensitivity and therefore larger response to increasing levels of P fertility.

Lastly, in-crop rainfall is always a factor in the relative response to deep-P. The sorghum crop in 2016 had some useful in-crop rainfall 30 days after sowing whereas the 2018 chickpea crop had almost no growing season rainfall (Figure 2).

Based on the soil analysis (Table 3), some in-crop rainfall would have allowed the crop to access some of the P contained in the surface profile (0-10 cm). In the case of the chickpea crop there was so little in-crop rainfall that the surface P would have been largely unavailable, resulting in a much stronger reliance on the

[1]Based on a summary of plant analysis data collected across Southern Queensland nutrition sites (2013 to 2016).

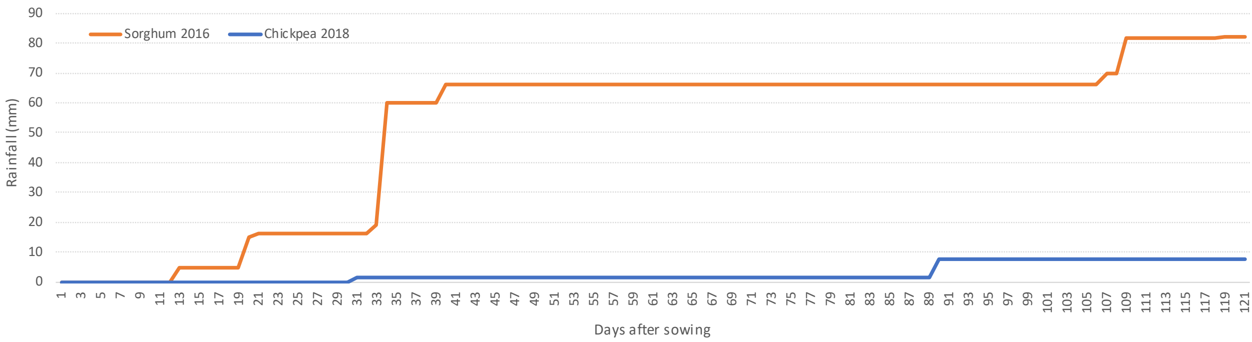

Figure 2. Accumulated in-crop rainfall totals for chickpea (2018) and sorghum (2016).

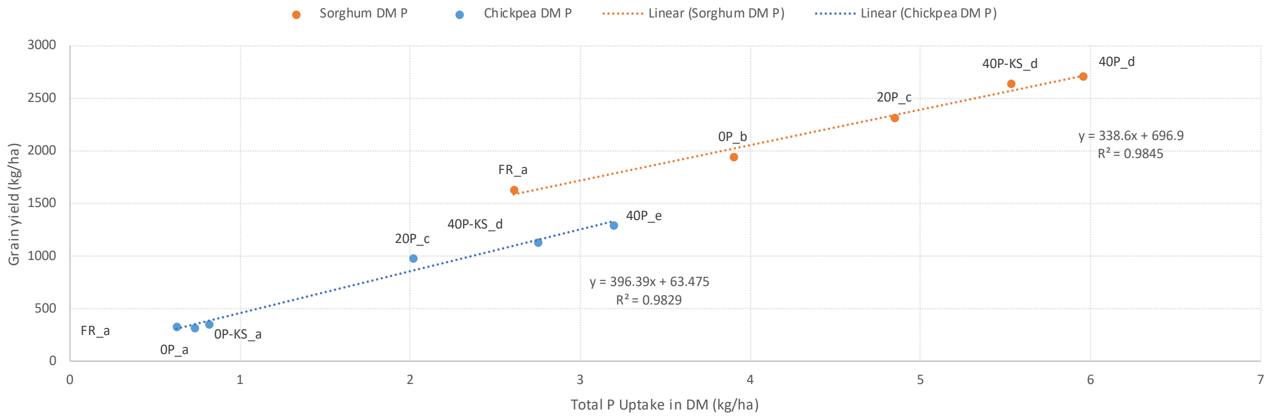

Figure 3. Comparison of plant uptake rates in the P trial across species and treatments.
Means with the same letters (lower case) are not significantly different.

P contained in the deep bands. In addition to this, the fact that the chickpea crop was deep sown (15cm) means the primary root system was established below the top 10 cm of the soil profile, effectively isolating any surface nutrients from the plant. Comparing the rates of P uptake across the two crops (Figure 3) illustrates this point.

The plots without any additional P (FR, 0P, 0P-KS) had to survive on what they could access from the soil profile. In the case of chickpea this was quite limited, as the root system only developed from the subsurface (10-30 cm) which we know had almost no P available (Table 3). These treatments were only able to acquire 0.6-0.8 kg P/ha in crop biomass (Figure 3), so the very low yields without deep-P bands were therefore not surprising.

In contrast, the sorghum had some in-crop rainfall early in the life cycle so those plots with no additional P would have been able to at least access some native P from the higher P concentrations in the surface profile (0-10cm) as well as what they could from the low P subsoil (Table 3). The sorghum crop was able to acquire 2.5 kg P/ha (FR plots), as opposed to the 0.6 kg P/ha (FR plots) in the chickpea. It is assumed most of this difference came from better access to the surface profile (0-10 cm).

Interestingly, the estimated P acquisition from the deep-P bands (difference between 40P and 0P treatments) was relatively similar for both crops – ca. 2.5 kg P/ha for the chickpea and 2.1 kg P/ha for the sorghum (Figure 3). The sorghum crop would have become reliant on the deep-P bands later in the crop life cycle as the surface soil dried out, but was still able to increase P content by 50% (Figure 3) and produce an additional tonne of grain yield (39% yield increase). While impressive, this relative yield increase would have been a lot larger if the crop had not been able to acquire the 2.5 kg P/ha from the topsoil thanks to the in-crop rainfall; with that background soil P sufficient to produce yields of ca. 2 t/ha (Figure 1).

In the chickpea circumstances the additional 2.4 kg P acquired from the deep bands represented a five-fold increase in crop P uptake compared to the treatments with no deep-P applied (Figure 3). While this additional P uptake produced a similar 1 t/ha yield increase as recorded in the sorghum crop, the lower unfertilised crop yields (300-350 kg/ha) meant the additional yield represented an increase of 300% (Figure 1).

The chickpea crop was effectively almost totally dependent on the P it could acquire from the deep-placed bands, but given the very dry season, the chickpea may have only been able to access those deep bands for a limited time, meaning the crop may well have still been P-limited. Once the moisture had been extracted from around the P bands in the 10-30 cm part of the soil profile, further P acquisition would have been impossible.

While the difference in scale of response to deep-placed P by the two crops is intriguing, the main focus is still the quantity of extra grain that has been produced by the deep-P treatments. The scale of grain yield is dissimilar between the two crops, however when they are added together the differences that the deep-P has made to grain yield is stark (Figure 4) and provides a strong basis for good economic returns for the application of deep-P. In this trial site, the 40P rate has delivered over 2 t/ha more grain yield then the FR baseline and 1.7 t/ha more than the 0P rate in just two crops.

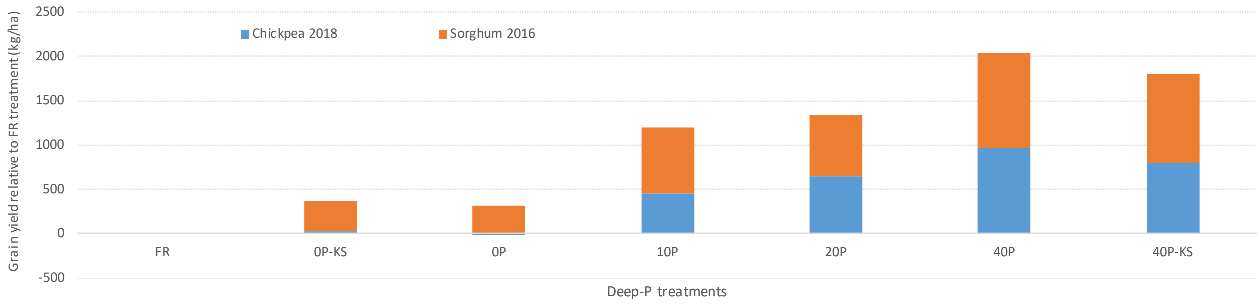

Figure 4. Accumulated grain production for each treatment in the P trial relative to the FR treatment.

Potassium

Whilst there were similarities in the P response between the sorghum and chickpea crops, the grain yield response to K shows a clear contrast (Figure 5). In 2016 the sorghum crop did show a small significant response to the two highest rates of K applied (50K, 100K). This response amounted to about 250 kg/ha of grain (9-10%) over the 0K treatment. However, the chickpea in 2018 showed no significant response to the deep-applied K treatments (Figure 5). The most significant observation from the chickpea yield data is the fact that the treatments with no background P applied (FR, 0K-PS, 100K-PS) showed a large drop in yield of over 600 kg/ha (55-60% relative difference) compared to treatments in which P was applied. This reinforces that crop performance at this site was primarily determined by the chronic P deficiency.

The soil analysis for this site (Table 3) indicates the K levels in both the 0-10 cm (0.81 meq/100 g) and 10-30 cm (0.32 meq/100 g) layers were reasonable and would not be categorized as K deficient. Therefore, the most surprising result is that the sorghum did have a small response to deep-K, rather than the chickpeas not responding at all.

Similar to the P trial, the K trial has highlighted some differences between crop species in their response to deep-applied fertiliser. Although it seems contradictory, differences in root structure may play a part in the response to deep-K. The sorghum plant may be able to develop more roots in and around the K band (with the help of accompanying background of 20 kg P/ha), thus increasing the surface area exposed to the high concentration of K in the fertiliser band. With enough root proliferation around the band, the root system of the sorghum plant has a good chance of taking up enough K out of the fertiliser band to make a difference to crop performance; especially as there was significant early season rain that would have kept those bands wetter for longer.

In contrast, chickpea crops have typically been slower to proliferate roots around a P band, and in the dry seasonal conditions where the band was never re-wet, the crop may not have had enough time or root density to acquire a significant amount of K from the band. While root activity by chickpea was sufficient for the crop to acquire 2.5 kg P/ha (Figure 3), plant tissue typically requires at least five times the K uptake per tonne of dry matter as it does P. With access to the bands limited in a very dry year, the chickpea crop may not have been able to acquire sufficient K from the bands to generate a yield response.

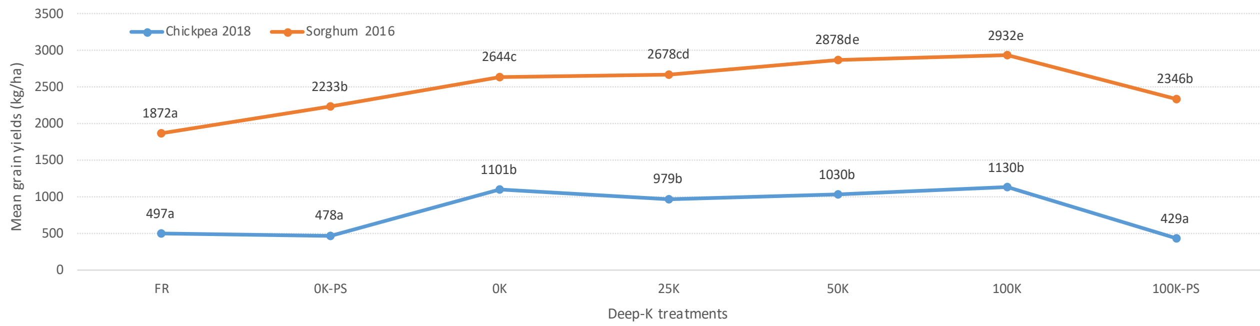

Figure 5. Mean grain yields from deep-K trial for 2016 sorghum and 2018 chickpea.

Means with the same letters are not significantly different at the 5% level; sorghum lsd = 195, chickpea lsd = 244.

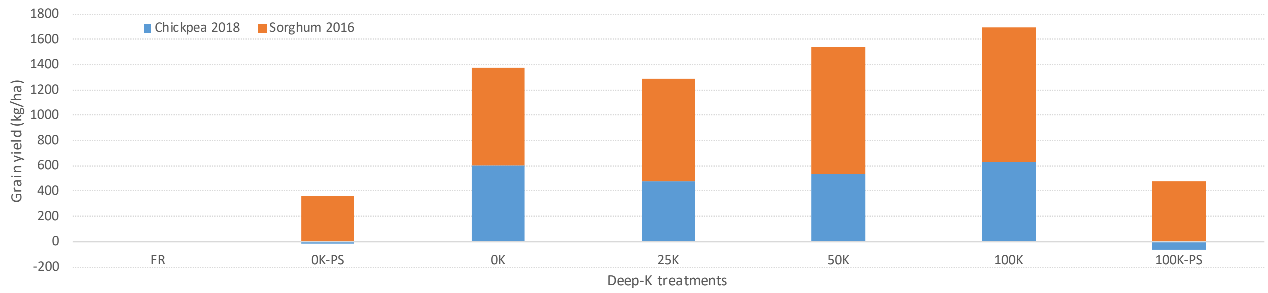

Figure 6. Accumulated grain production (kg/ha) for treatments in the potassium trial relative to the FR treatment.

Another possible confounding issue is that the background rate of P fertiliser used in the K trial was equivalent to the 20P rate used in the P trial. The yield data for the chickpea crop (Figure 1) shows similar yields in both the P and K trials when 20 kg P/ha was applied in deep bands – ca. 1100 kg/ha. However, the 40P rate in the P trial increased yield by another 30%, indicating that the plants' requirement could not be satisfied by the lower rate (20P). It is therefore possible that any additional K uptake by the chickpeas was not able to generate a yield response as P still represented the primary yield constraint.

Accumulated grain yields over the two crops (Figure 6) for the K trial show a large advantage (1693 kg/ha) over the FR plots (baseline) but only a small (317 kg/ha) advantage over the 0K treatments. It is interesting to note that on average the background P applied in the K trial (includes 0K, 25K, 50K, 100K treatments) resulted in an average of 1100 kg/ha increase in yield over the FR treatment. Without background P (the 0K-PS and 100K-PS treatments), that advantage was an average of only 374 kg/ha over the FR treatment. This means the background P was having a 2.9 times bigger effect on yield than the K treatments.

Sulfur

There was consistently no response to the banding of sulfur across both crops (Figure 7). There was a consistent significant difference between the treatments without background P and K (0S-PK, 30S-PK) and those that received it (0S, 10S, 20S and 30S) of between 500–700 kg/ha. There was a small significant difference between the FR and 0S-PK treatments in the sorghum crop (325 kg/ha), but this difference was not evident in the following chickpea crop.

Economic analysis

Economic assessment of the P experiment treatments (Table 4) show all treatments except 0P achieving positive returns in the second crop (chickpea in 2018). Currently there is minimal difference in total benefit between 40P and 40P-KS; with 40P –KS having a higher ROI due to ~$100/ha lower upfront cost. Both sorghum and chickpea have been responsive to deep-P, however there was minimal K response for deep-planted chickpea. The continuation of expected benefits in future years will no doubt add directly to the profit from deep-P applications. Whilst the ROI of treatments can change over time, it usually improves for higher rates of P as these have the longest expected duration.

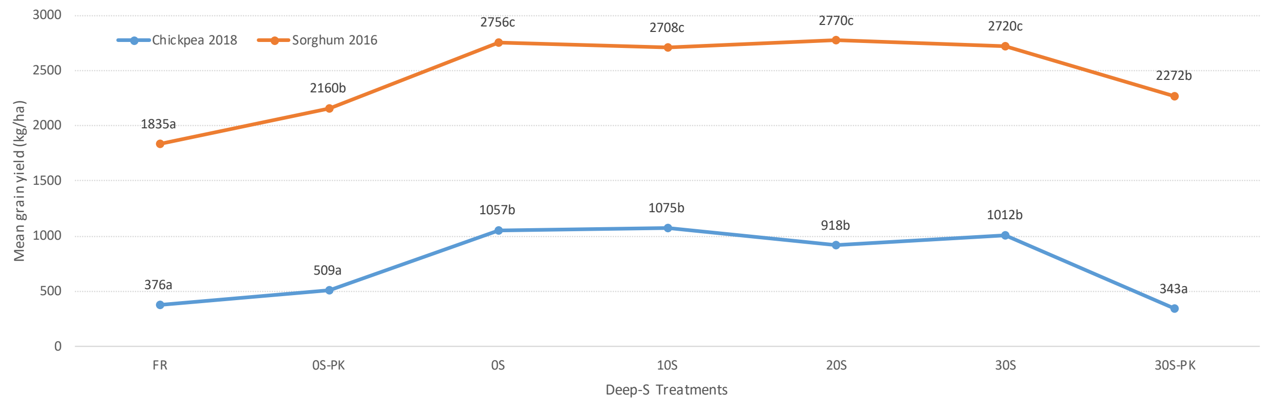

Figure 7. Mean grain yields from deep S trial for 2016 sorghum and 2018 chickpea.
Means with the same letters are not significantly different at the 5% level; sorghum lsd = 185, chickpea lsd = 213.

Table 4. Cumulative benefit ($/ha) analysis of two crops grown on the deep-placed P trial using the FR treatment as the baseline.

P rate (kg/ha)	Sorghum 2016	Chickpea 2018	ROI
0	-$106	-$114	-0.6
10	-$9	$359	1.5
20	-$58	$458	1.7
40	-$6	$766	2.3
0P - KS	-$1	$19	0.2
40P - KS	$88	$725	3.4

Table 5. Cumulative benefit ($/ha) analysis of two crops grown on the deep-placed K trial using the FR treatment as the baseline.

K rate (kg/ha)	2016 Sorghum	2018 Chickpea	ROI
0K	$64	$547	3.3
25k	$43	$428	2.2
50K	$71	$498	2.2
100K	$25	$531	1.8
0K-PS	$4	-$11	-0.1
100K-PS	-$87	-$141	-0.6

Reinforcing the primacy of P limitations at this site are the K trial results (Table 5). There were no significant differences between treatments receiving 0-100K, but where there was no background P, both 0K-PS and 100K-PS treatments were worse off than the benchmark farm reference treatment. This observation is further supported by the 0K treatment having both the highest ROI and highest net benefit.

Implications for growers

Phosphorus and potassium are often thought of as having similar characteristics in terms of nutrient mobility and plant uptake. This often means the solution to observed deficits is the same by using the deep banding of these nutrients together; therefore there is a saving in mechanical cost, soil disturbance and application time. However, there are situations where applying just one nutrient has a more favourable result.

This particular site has shown very strong responses to P nutrition and inconsistent responses to K. Based on the soil analysis this not surprising, as the soil test would indicate the response to K should be negligible. In this scenario when evaluating how much fertiliser to put down in a deep application, the trial data indicates there is far more benefit in just applying P at the highest rate possible.

The trial data would suggest that as the highest rate of P (40 kg P/ha) gave the highest grain production, there may have been even greater yield responses if higher P rates had been tested. The addition of 50kg K/ha as background fertiliser in the P trial failed to make a significant response, although as the increase in P from 20 kg/ha to 40 kg/ha did make a significant response in both crops, the K trial may have still been slightly P-limited.

The economic analysis also confirms this point; the strongest return on investment after two crops was where the maximum amount of P was applied without any associated K application (40P-KS = 3.4, 0K = 3.3). Therefore when equipment capacity and cost of application is limited, there can be ultimately a greater benefit in increasing the rate of the primary limiting nutrient and dropping the other one out of the mix altogether. This is why the decisions based around the soil analysis are ultimately so important for long term yield improvement.

Acknowledgements

It is greatly appreciated to have the continued support of trial co-operators, by hosting this trial site. This work is funded by the Grains Research and Development Corporation and the Department of Agriculture and Fisheries under project UQ 00063 Regional soil testing guidelines for the northern grains region.

Trial details

Location:	Clermont
Crop:	Chickpea
Soil type:	Dark Grey, Brown Vertosols (open downs) on minor slopes
In-crop rainfall:	8 mm
Pre-plant/plant fertiliser:	20 kg MAP/ha

Responses to deep placement of phosphorus and potassium in chickpea—Comet River

Doug Sands[1], Dr David Lester[1], Prof Michael Bell[2] and James Hagan[1]
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Research Question: *Can deep-planted chickpea respond to residual deep bands of phosphorus and potassium, with low in-crop rainfall?*

Key findings

1. 20% yield response to deep-placed phosphorus at the highest rate in the third year of production.
2. No significant response to deep-placed potassium.

Background

Over the last four years the UQ00063 project (Regional soil testing guidelines) has been monitoring a series of nutrition trial sites across Central Queensland (CQ). These trial sites were chosen based on soil testing evidence showing varying degrees of nutrient depletion in the surface and subsurface layers. Subsurface depletion is particularly evident for the non-mobile nutrients phosphorus (P) and potassium (K). In some established zero tillage production systems there is a marked difference between the nutrient concentration in the top 10 cm of the soil profile and the deeper layers (10-30 cm and 30-60 cm), that cannot be explained by natural stratification. It would seem that this pattern of soil analysis is becoming more evident across CQ, particularly in the brigalow scrub and open downs soil types.

This project is gathering data from these trial sites to ascertain whether a one-off application of either P, K or sulfur (S) placed in these deeper, more depleted layers can provide a grain yield benefit and whether that benefit can be maintained over several years. These results can also be used to define the economic benefit of adding these non-mobile nutrients over a crop rotation, rather than the conventional approach of assessing the profitability against the next crop to be sown.

Data from these sites is also contributing to the understanding of the pathways of macro nutrient uptake and how responses to deep-banded fertiliser can be impacted by seasonal constraints and differences in crop species.

What was done?

The Comet River trial site was first treated with deep-banded fertiliser treatments in November of 2015 and has had three crops planted and harvested since then (chickpea 2016 and wheat 2017). The third crop, chickpea, was planted on 25 May 2018 and harvested on 27 October 2018. The original soil test from the site (Table 1) would indicated adequate levels of P and K in the top 10 cm but a significant change in that analysis in the deeper layers (10-30 cm, 30-60 cm).

Table 1. Original soil analysis for the site.

Depth (cm)	Nitrates	Colwell P	Sulfur (KCl-40)	Exc. K	BSES P	ECEC
0-10	8	22	4.5	0.46	24	20
10-30	10	5	5.3	0.12	5	21
30-60	7	<2	4.3	0.1	3	27

Phosphorus

There were seven unique treatments (0P was doubled up to make eight plots per replicate) for the P trial (Table 2), which included four P rates; 0, 10, 20, and 40 kg P/ha. These treatments had background fertiliser applied at the same time to negate any other potentially limiting nutrients. This background fertiliser included; 80 kg nitrogen (N), 50 kg K, 20 kg sulfur (S) and 0.5 kg zinc (Zn) per hectare. The next two treatments included 0P and 40P without background fertiliser except N and Zn (0P-KS, 40P-KS). The last treatment was a farmer reference (FR) plot, to act as a benchmark control treatment. The FR treatments had nothing extra applied compared to normal commercial practice from season to season (Table 2).

Table 2. Summary of original nutrient application rates (kg/ha) for phosphorus and potassium trials.

Treatment	N	P	K	S	Zn
Phosphorus					
0P	80	0	50	20	2
0P	80	0	50	20	2
10P	80	10	50	20	2
20P	80	20	50	20	2
40P	80	40	50	20	2
0P-KS	80	0	0	0	2
40P-KS	80	40	0	0	2
FR	0	0	0	0	0
Potassium					
0K	80	20	0	20	2
0K	80	20	0	20	2
25K	80	20	25	20	2
50K	80	20	50	20	2
100K	80	20	100	20	2
0K-PS	80	0	0	0	2
100K-PS	80	0	100	0	2
FR	0	0	0	0	0

These treatments were banded using a fixed tyne implement which delivered the P and K at 25 cm depth; the N and S at 15 cm depth. The bands of fertiliser were placed 50 cm apart in plots that were six metres (m) wide by 32 m long. The bands were placed in the same direction as the old stubble rows. A split starter P treatment was also added to this trial so that each deep-P treatment was doubled to make a ‘with’ and ‘without’ starter P treatment. This effectively doubled the treatments from 8 to 16 and there were six replicates of each making a total of 96 plots for the trial.

In the 2018 chickpea crop, Granulock® Z was chosen as the starter P treatment at 40 kg/ha and the variety Kyabra was planted at a rate of 40 kg/ha. Unfortunately due to planting conditions being very dry, the crop was deep-planted with the co-operator's 18 m minimum till planter at depth of 18 cm. This meant that the ‘with’ and ‘without’ starter strips could not be incorporated into the trial, and the whole site received the blanket rate of Granulock® Z. The crop received 118 mm of in-crop rainfall, although 71 mm of this total (60%), fell after the crop had reached maturity.

Potassium

There were seven unique treatments (0K was doubled up to make eight plots per replicate) for the K trial (Table 2), which included four K rates; 0, 25, 50, 100 kg K/ha. These treatments had background fertiliser applied at the same time to negate any other potentially limiting nutrients. This background fertiliser included; 80 kg N, 20 kg P, 20 kg S and 0.5 kg Zn per hectare. The next two treatments included 0K and 100K without any background fertiliser except N and Zn (0K-PS, 100K-PS). The last treatment was farmer reference (FR) to act as a second control. The FR plots were not treated with anything except what the farmer applied in line with normal commercial practice (Table 2).

Applications were done in the same way as the phosphorous trial and the other trial details remain the same. There were no split starter P treatments in the K trial so every plot received starter P (Granulock® Z @ 40 kg/ha).

Difference between chickpea seasons; 2016 (right) and 2018 (left).

Table 3. List of commercial granular products used in nutrient treatments.

Nutrient	Product source of nutrient in applications
Nitrogen (N)	Urea (46% N), MAP (10% N), GranAm® (20% N)
Phosphorus (P)	MAP (22% P)
Potassium (K)	Muriate of potash (50% K)
Sulfur (S)	GranAm® (24% S)
Zinc (Zn)	Supa Zinc™ (Liq) (7.5% Zn w/v)

Data collection was done in the same way for both trials. Plant counts, starting soil water and starting nitrogen (N) measurements were taken post emergence. Total dry matter measurements were taken at physiological maturity and yield measurements were taken with a plot harvester when commercial harvesting started in the same paddock. At harvest, a grain sample was taken from each plot and processed for nutrient analysis. Both the dry matter samples and the grain samples were ground and subsampled for wet chemistry analysis.

Results

Phosphorus

Despite the dry seasonal conditions which forced this trial to be a deep sown crop the response to deep-P is still evident (Table 4). Any treatment that had deep-P applied gave between a 240–320 kg response (15–20%) above the 0P treatment, and a 360-460 kg response relative to the standard grower practice (25-30%).

This has been a consistent response to deep-P over the three crops that have been grown at this site (Figure 1), however the wheat in 2017 experienced very dry conditions and did not have an opportunity to develop a secondary root system. Consequently yields were low (<1.2 t/ha) and the much smaller differences were not statistically significant, despite the pattern of response being similar to previous results (Figure 1).

Table 4. Mean grain yields across all treatments in P trial for chickpea in 2018.

Treatments	Mean grain yield (kg/ha)		Relative difference to '0P' plots (kg/ha)	(%)
FR	1413	b	-114	-7.5
0P-KS	1448	b	-79	-5.2
0P	1527	b	0	0.0
10P	1810	a	283	18.5
20P	1768	a	241	15.8
40P	1841	a	314	20.6
40P-KS	1796	a	269	17.6

Least significant difference P(0.05); means with the same letter are not significantly different (lsd = 210).

While there is always fluctuation between years and seasons, the cumulative effects of the highest rate of deep-P addition after three years of cropping have been an extra 1900 kg/ha of grain compared to the FR treatments and 900 kg/ha more grain than the 0P treatment (Figure 2). It is interesting to note that the size of the cumulative response to deep-P alone (i.e. with the same background nutrient addition and tillage, at 900 kg/ha) was effectively the same as the quantum of response to the tillage and background nutrients themselves (i.e. 1000 kg/ha, Figure 2). Some of this 'background' response (25-30%, or 250-300 kg/ha) was clearly due to the application of K and S, as the '0P-KS' and '40P-KS' treatments were consistently ~5% lower yielding than the corresponding treatments with K and S added (Figure 1). The remaining response was due to the combined effects of extra N and Zn, in addition to the tillage effect presumably allowing for greater exploitation of the soil volume.

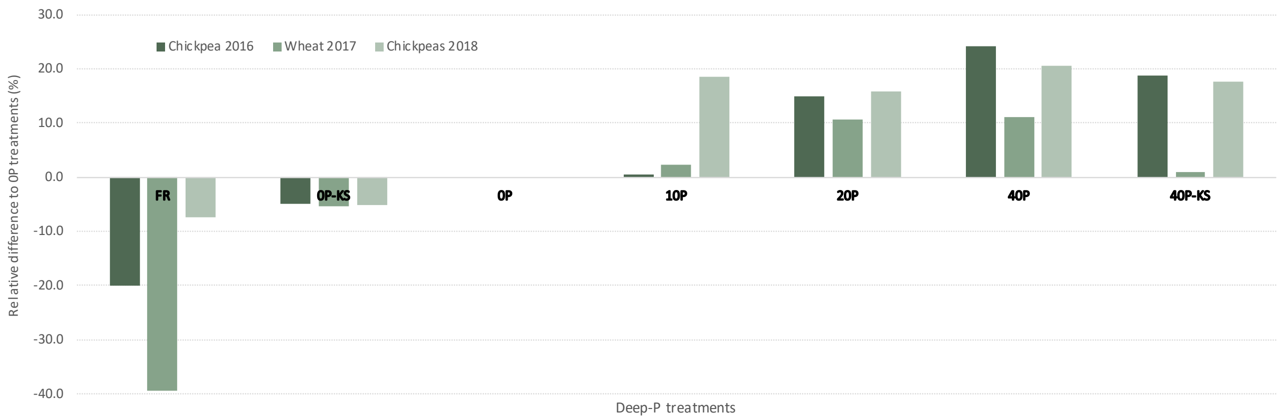

Figure 1. Comparison of relative differences in grain yield across deep-P treatments for three consecutive crops.

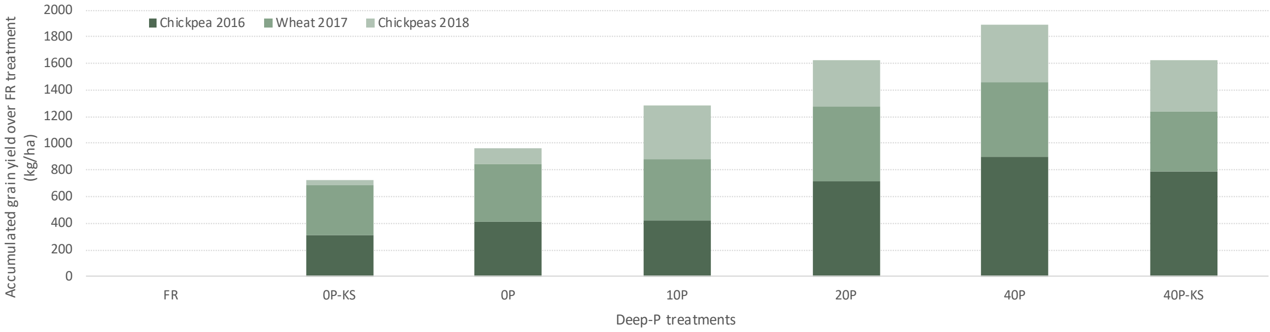

Figure 2. Mean accumulated grain production for each P treatment over and above the FR treatment.

Deep-P treatments at this site have been highly profitable, with both 20 and 40P increasing profit by ~$800/ha over 3 years (Table 5). Each of the treatments returned positive returns in the first year with subsequent years all adding directly to profit. The 20P treatment currently has the highest ROI, however 40P has generated the greatest extra profit; returns in future years will affect final ROI.

Table 5. Cumulative deep-P profit compared to FR over 3 years.

P rate	2016 - chickpea	2017 - wheat	2018 - chickpea	ROI
0P	$144	$276	$345	1.9
10P	$119	$259	$528	2.5
20P	$395	$563	$788	3.2
40P	$409	$578	$853	2.8

It is worth noting the variability in Colwell P analysis at this site. Recent soil tests show average Colwell P concentrations for each replicate showing a degree of inconsistency both in surface and subsurface levels (Figure 3). This makes it more difficult to establish clear treatment responses in grain yield, especially when yields are low. To illustrate the effects this has on crop yield in the 2018 season, the individual plot yields for the FR plots (6 replicates * 2 plots per replicate) are plotted against Colwell P in the 10-30 cm layer (Figure 4).

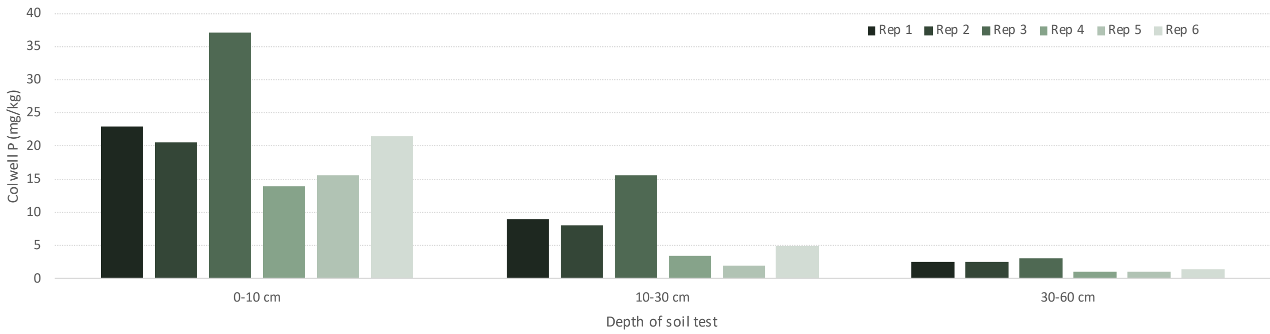

Figure 3. Results for Colwell P tests taken in each replicate across the P trial at three depths.

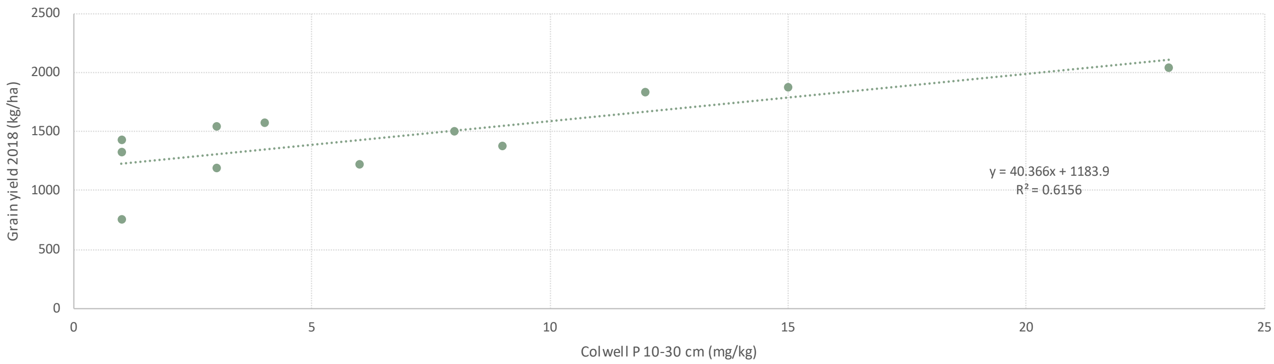

Figure 4. Relationship between Colwell P (10-30 cm layer) and grain yield for the FR plots across the P trial.

Potassium

In contrast with the P trial the grain yields from the K trial showed no statistically significant response to deep placed K, even though treatments that had additional K and background P were consistently higher-yielding than the treatment with background P but 0K (Table 6).

Table 6. Mean grain yields across all treatments in K trial for chickpea in 2018.

Treatments	Mean grain yield (kg/ha)		Relative difference to '0K' plots (kg/ha)	(%)
FR	1309	b	-199	-13.2
0K-PS	1425	ab	-83	-5.5
0K	1508	ab	0	0.0
25K	1634	a	126	8.4
50K	1579	ab	71	4.7
100K	1571	ab	63	4.2
100K-PS	1477	ab	-31	-2.1

Least significant difference P(0.05); means with the same letters are not significantly different (lsd = 260).

This trial site has shown inconsistent results in regards to responses to deep-placed K across the three crop seasons (Figure 5). The initial chickpea crop in 2016 showed no positive responses to increasing rates of applied K, which was perhaps not surprising given the relatively wet growing season (in-crop rainfall of 208 mm) and the more-than-adequate K supply in the top 10 cm layer (0.46 cmol/kg). What was surprising was that a number of the treatments that received P and K tended to yield less than with P alone, with the reasons for this not immediately obvious.

In 2017 the wheat crop showed an increasingly positive response to increasing rates of K addition, although the differences were not large enough to be statistically significant. This was largely because the crop was severely water limited (31 mm in-crop rainfall), growing on a primary root system and with a low plant population. The combination of natural variability across the trial and low yielding conditions was always going to make it difficult to find significant differences.

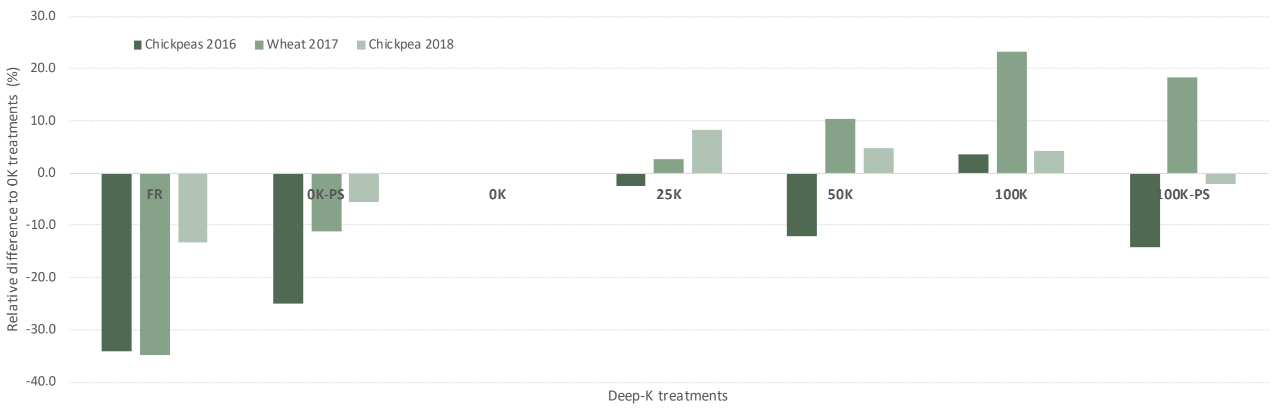

Figure 5. Comparison of relative differences in grain yield across deep-K treatments for three consecutive crops.

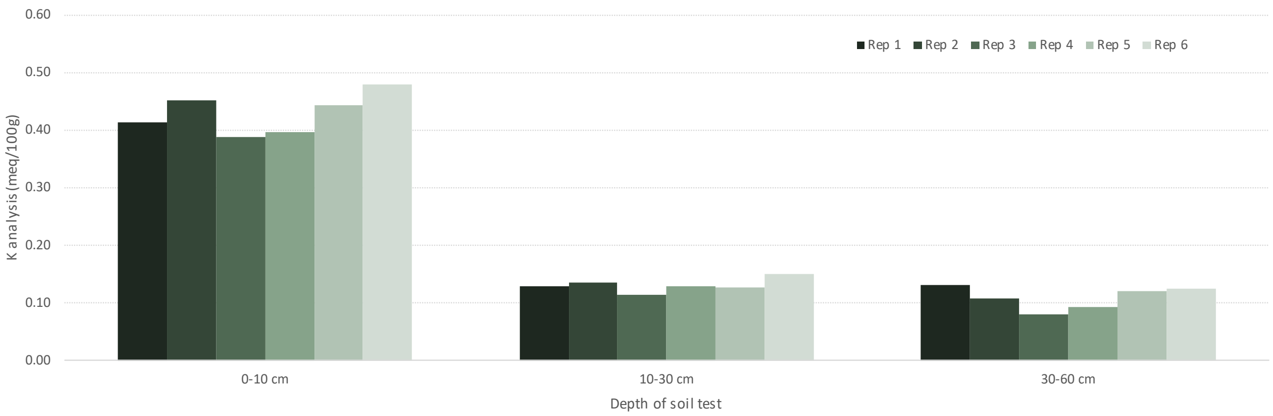

Figure 6. Results for exchangeable potassium in soil tests taken in each replicate across the potassium trial at three depths.

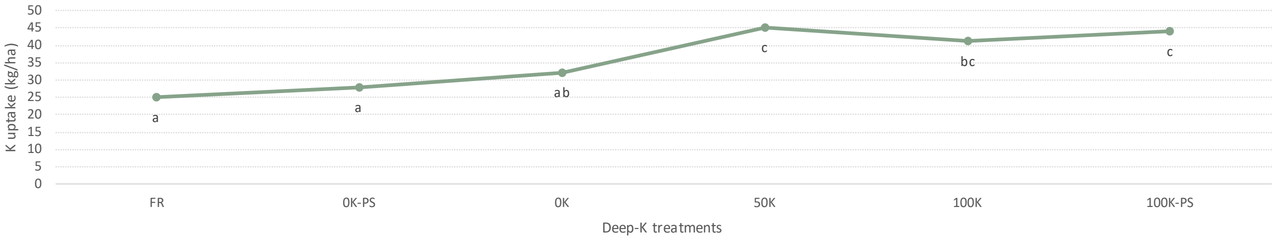

Figure 7. Results for potassium analysis in total dry matter across deep-K treatments in 2018 chickpea.

The 2018 chickpea crop was deep-planted on stored moisture with no in-crop rainfall for the first 35 days. This meant that the plant would have had no access to the surface profile (0-10 cm) and was solely reliant on the K that was available in the subsurface layers (10-30 cm, 30-60 cm). Soil analysis figures (Figure 6) across the trial showed a large decline in the amount of available K in these deeper layers, which should mean an ideal situation for a response to deep-K placement. Grain yields (Table 6) have proven to be unresponsive and in comparison to the previous crops have shown almost no change in relation to the 0K treatments.

It is interesting to note that the plant analysis (Figure 7) did indicate a significant response to deep-K placement in terms of plant K uptake. Although data variability precluded differences being statistically significant, the treatments with additional K have accumulated 8-10 kg/ha higher levels of K in total dry matter compared to treatments receiving P alone, and up to 20 kg/ha more than the FR treatment. This means that the combination of improved P nutrition and soil disturbance, combined with deep-K applications, was able to improve crop K acquisition substantially—even though there was no yield response.

The overall yields (1.3–1.6 t/ha) would suggest water was a major yield constraint in this growing season, limiting the potential K demand to meet a water-limited yield potential. Crop K acquisition in the plots without added K ranged from 25-32 kg K/ha, which was most likely adequate to grow the 3-4 tonnes of crop biomass and achieve crop yields of 0.7-1.1 t/ha. With yield potentials limited by availability of water, increased crop K uptake was therefore unable to deliver higher crop yields.

It is interesting to note that there was a difference in crop yield potential between the K trial and the P trial. While there was no significant difference between P treatments (10P, 20P, 40P, 40P-KS) the average yield across these treatments was 1800 kg/ha in contrast with the average of all the K treatments that received background P (100K, 50K, 25K, 0K), which was 1570 kg/ha. The lack of apparent P rate responses would suggest the 20 kg P/ha applied throughout the K trial (to overcome P limitations) should have been enough to allow a K response to manifest. However, the variability in P status across the site and the 15% difference in potential yields between the two trials suggest that there could have been another yield-limiting factor (perhaps low P) that was impacting the crop response to K.

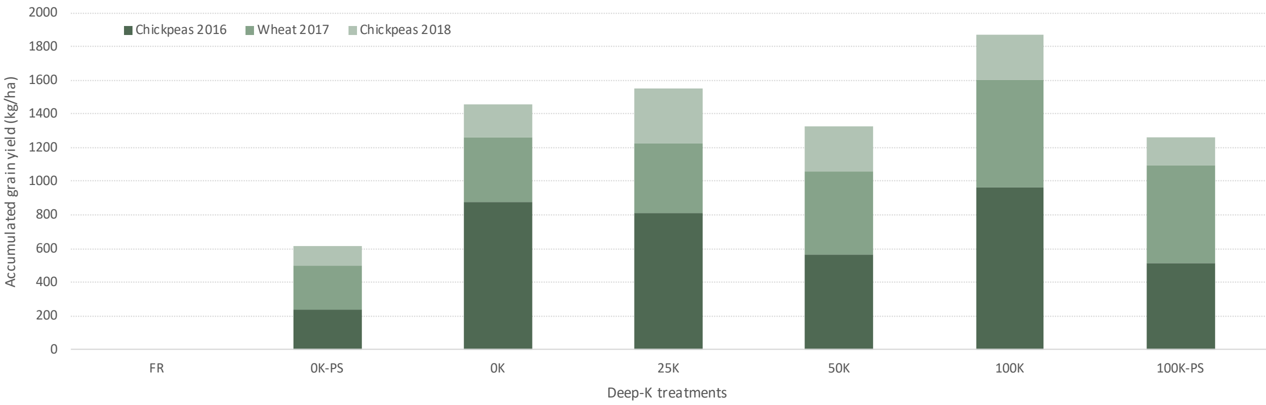

Figure 8. Mean accumulated grain production for each potassium treatment over and above the FR treatment.

The accumulated grain yields for this K trial (Figure 8) do not show as large a response to the deep-banded treatments as the P trial. While there is an 1800 kg/ha advantage over three crops for the 100K treatment over the FR treatment there is only a 400 kg/ha difference between the 0K treatment and the 100K treatment. This means the payback period on getting a return from the investment in deep-banding K will be longer. It also indicates that this site is far more responsive to P than K, and the investment in P is far more profitable over a shorter time frame.

Implications for growers

This site has been one in which the variable P status across the site has meant that clear deep banding responses can be difficult to demonstrate conclusively, especially for a secondary nutrient limitation like K in a season where water stress constrains potential yields. Not all soil types are necessarily this variable and the ones that are tend to be well known or obvious, particularly if using yield mapping data. Trials situated on these soil types can result in variability masking responses to deep P or K applications.

Well-validated critical nutrient concentrations become more important at these sites. On average, this site would seem to be mostly limited by P although the levels can change from 15 mg/kg to <2 mg/kg in the 10-30 cm layer across the site. This is reflected in the solid 15-25% yield increase with deep-P, despite some parts of the trial showing little response. Where this situation occurs the banding of deep-P can have a levelling effect across the whole management area so that yields and maturity across a field become more uniform. This has management implications for the timing of harvest and the use of pesticides.

The overall K response at this site is far more variable than P from season to season, even though soil analysis would suggest the subsurface layers are K-depleted. The data from this site would suggest that whilst low, this site may still be able to provide enough K to allow smaller crop yields to be obtained without K becoming limiting.

At these low yields, small differences in topsoil access or root morphology may make a big difference in the frequency of fertiliser responses. However, it would be expected that in seasons with higher potential yields and greater nutrient demands, this balance between supply and demand may not be sustained and fertiliser responses become more obvious. When a site is both P and K limited then it would seem that the P limitation will often dominate, and there is bigger yield gain from P than K in those circumstances. The interactions between the two nutrients when both are limiting yield is not well understood and there needs to be more crop data gathered from these particular sites.

In these variable soil types it is critical for growers and agronomists to know the chemical analysis of the profile both in depth and spatially across the paddock. Yield maps, grain quality data and EMS surveys can help with identifying the different areas that require separate soil test analysis. This information goes a long way towards making the best use of deep placement nutrition.

Acknowledgements

It is greatly appreciated to have the continued support of trial co-operators, by hosting this trial site. This work is funded by the Grains Research and Development Corporation and the Department of Agriculture and Fisheries under project UQ 00063 Regional soil testing guidelines for the northern grains region.

Trial details

Location:	Comet River
Crop:	Chickpea
Soil type:	Grey, Brown Vertosols (Brigalow scrub) on minor slopes
In-crop rainfall:	118 mm
Fertiliser:	40 kg/ha Granulock® Z at planting

Farming systems research

The Regional Research Agronomy team has an extensive field-based farming systems research program in collaboration with CSIRO and the New South Wales Department of Primary Industries (DPI NSW). The farming systems program is focused on developing systems to better use the available rainfall to increase productivity and profitability and the cover cropping program is investigating the soil water costs and benefits of growing cover crops for ground cover.

While advances in agronomy and the performance of individual crops have helped grain growers to maintain their profitability, current farming systems are underperforming, with only 30% of the crop sequences in the northern grains region achieving 75% of their water limited yield potential. Growers are facing challenges from declining soil fertility, increasing herbicide resistance, and increasing soil-borne pathogens in their farming systems. Changes will be needed to meet these challenges and to maintain the productivity and profitability of our farming systems. Consequently, the Regional Research Agronomy team is undertaking research projects on two major questions;

1. Can systems performance be improved by modifying farming systems in the Northern Region?

This research question is being addressed at two levels by the Northern Farming Systems initiative; to look at the systems performance across the whole grains region, and to provide rigorous data on the performance of local farming systems at key locations across the region.

This research, with investment from the Grains Research and Development Corporation (GRDC), began with local growers and agronomists in 2015 to identify the key limitations, consequences and economic drivers of farming systems in the Northern Region; to assess farming systems and crop sequences that can meet the emerging challenges; and to develop the systems with the most potential for use across the Northern Region.

Experiments were established at seven locations, with a large factorial experiment managed by CSIRO at Pampas near Toowoomba, and locally relevant systems being studied at six regional centres by Department of Agriculture and Fisheries (DAF) and the NSW DPI (Table 1). Several of these systems are represented at every site to allow major insights across the Northern Region, while the site-specific systems will provide insights for local conditions.

The following reports provide details of the systems being studied at each experiment in Queensland (Emerald, Billa Billa and Mungindi), how they are implemented locally, and the results after four years of crops at each site. As the first phase of the project draws to a close data and system performance indicators have been developed to compare performance across sites. We have also reported the effects different systems are having on water, nutrients, pathogens and gross margins. There are some very interesting key findings across all these reports including:

- Increasing the frequency of legumes doesn't necessarily reduce nitrogen inputs required across the crop sequence, and increases export of potassium.
- Barley and wheat crops led to increases in *P. neglectus*, while mungbean, wheat and to a lesser extent chickpea led to increases in *P. thornei*.
- Grain legumes (chickpea, faba bean, field pea, mungbean) often leave more residual soil water at harvest than cereals; this difference is diminished due to lower efficiencies of subsequent fallows and hence soil water is often similar at the sowing of the next crop.
- There have been differences of $200-700/year between systems at each site.

Table 1. Summary of the regional farming systems being studied at each location in the Northern Farming Systems initiative.

	Regional sites					
System	Emerald	Billa Billa	Mungindi	Spring Ridge	Narrabri	Trangie x2 (Red and Grey)
Baseline – represents a typical zero tillage farming system	*	*	*	*	*	*
Higher nutrient supply –as for the 'Baseline' system but with fertilisers for 100% Phosphorus replacement and nitrogen targeted at 90% of the yield potential each season	*	*	*	*	*	*
Higher legume - 50% of the crops are sown to legumes	*	*	*	*	*	*
Higher crop diversity – a wider range of crops are introduced to manage nematodes, diseases and herbicide resistance		*	*	*	*	*
Higher crop intensity – a lower soil moisture threshold is used to increase the number of crops per decade	*	*		*	*	*
Lower crop intensity – crops are only planted when there is a near full profile of soil moisture to ensure individual crops are higher yielding and more profitable		*	*	*	*	*
Grass pasture rotations – pasture rotations are used to manage soil fertility. One treatment has no additional nitrogen fertiliser, while the other has 100 kg N/ha/year to boost grass production		Grass (+/-N)				
Higher soil fertility (higher nutrient supply plus organic matter) - as in the high nutrient system but with compost/manure added	*	*				
Integrated weed management (incl. tillage) – this system is included at Emerald where crops, sowing rates, row spacings and 'strategic tillage' are included to manage weeds and herbicide resistance	*					

2. Can cover crops increase the net water accumulation (Plant Available Water) in grain and cotton systems with low ground cover (<30%) in the Northern Region?

a. **What is the net water cost to grow the cover crops?**

b. **What is the net water gain to the subsequent grain/cotton crops?**

c. **What is the impact on the yield of the subsequent grain/cotton crops?**

This research by the same collaborating agencies has investment from both the GRDC and the Cotton Research and Development Corporation (CRDC). It will assess opportunities to make greater use of the available rainfall and maintain more sustainable systems. The following reports present results from two trials; a short fallow into irrigated cotton trial and long fallow into dryland wheat. To date the research indicates that cover crops can increase fallow water storage, and improve crop performance and returns in northern farming systems:

- Ground cover was improved by both winter and summer cover crops, which in turn improved infiltration and water accumulation.
- Optimum spray-out timing varied with the length of fallow; with early spray-out suitable for a short fallow; but more resilient stubble, achieved by later spray-out, necessary for longer fallows.
- Yields and returns were increased by the best cover crop treatments, but yield effects appear to be in excess of those expected from the increased soil water storage.

This work will continue for another year, with a further three sites currently being monitored (long fallow to irrigated cotton, short fallow to dryland wheat and long fallow to dryland wheat).

Summer cover crops can increase stored soil water in long fallows and improve wheat yields—Bungunya

Andrew Erbacher and David Lawrence
Department of Agriculture and Fisheries

Research Questions: *Can summer cover crops increase the net water accumulation (plant available water) in dryland systems with low ground cover (<30%) in the Northern Region?*

- *What is the net water cost to grow summer cover crops?*
- *What is the net water gain to subsequent grain crops (fallow and early growth periods)?*
- *What is the impact on the yield of the grain crops?*

Key findings

1. Summer cover crops can be very profitable; improving ground cover and increasing fallow water storage in long fallows to improve grain yields and boost returns in northern farming systems.
2. A later spray-out produced additional levels of a cover that is more resilient and stored more water in the longer fallow. Delaying spray-out too long reduced fallow water storage considerably.
3. Using a summer cover crop saved two fallow herbicide sprays and dramatically improved establishment of the subsequent wheat crop.
4. Yields and returns were increased by the cover crops, and yields were well in excess of those expected from the increased soil water storage alone.

Background

Cover crops can protect the soil from erosion in low stubble situations, return biomass that helps maintain soil organic matter and biological activity, and provide additional nitrogen (when legumes are used). However, cover crops may also offer opportunity to increase infiltration and fallow moisture storage for higher yields and more profitable grain and cotton crops.

Advances in agronomy and support from commercial agronomists have resulted in better use of available soil water to improve individual crop performance. However, effective capture and storage of rainfall across the whole farming system remains a major challenge for grain and cotton growers in the Northern Region, where dryland crops typically transpire only 20-40% of rainfall. Up to 60% of rainfall is lost to evaporation and a further 5-20% lost in runoff and deep drainage. Indeed, every 10 mm of extra stored soil water available to crops is worth up to 150 kg/ha extra yield for grain crops.

Farming systems projects funded by the Grains Research and Development Corporation (GRDC) are assessing ways to improve the use of our total rainfall, with the aim of achieving 80% of the water and nitrogen-limited yield potential in our cropping systems. Past research from GRDC's Eastern Farming Systems and Northern Growers Alliance projects suggests that cover crops and increased stubble loads can reduce evaporation and increase infiltration to provide net gains in plant available water over traditional fallow periods. Consequently, cover crops may be a key component of improved farming systems; providing increased productivity, enhanced profitability and better sustainability.

Scientific rationale

Stubble and evaporation

Retained crop stubble protects the soil from rainfall impacts and so improves infiltration to store more water in the soil. Past research also shows 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 about three weeks. However, further rain within this three-week period provides opportunity to reduce total evaporation and so accumulate more plant available water (Photo 2).

Cover crops are used in Southern Queensland and Northern New South Wales to overcome a lack of stubble and protect the soil from rainfall impacts 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 and sorghum, and spray them out after 6–10 weeks 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 can lead to big losses of stored soil water and low yields in the 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 within six weeks, with average grain yield increases of 360 kg/ha. Furthermore, the Northern Growers Alliance suggested that the addition of 5-40 t/ha extra stubble (hay) after winter crop harvest reduced evaporation; initial studies showed 19-87 mm increases in plant available water that could increase yields by up to 1300 kg/ha. 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 'grain' site 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.

What was done

The Bungunya experiment was in a long-fallow paddock following skip-row sorghum. The sorghum was harvested in early February 2017, deep phosphorus was applied in August 2017, and the paddock was 'Kelly-chained' in September 2017 to level the surface. The paddock subsequently had little cover for the planned wheat crop.

Eight cover crop treatments were established on 11 October 2017 with ~120 mm of Plant Available Water in the soil (Table 1, Photo 1), while the rest of the paddock was sown to a White French millet cover crop by the host grower. Each treatment had five replicates to monitor for ground cover, dry matter (DM) production and fallow soil water until the subsequent wheat was planted on 1 May 2018.

Table 1. Cover treatments applied at the Bungunya site included millet, sorghum and lablab.

Cover crop treatment	Terminated	Biomass (kg/ha)
Control (bare fallow)		
Millet (White French)	Early	1533
Millet (White French)	Mid	2327
Millet (White French)	Late	4365
Millet (White French)	Late + Roll	4737
Sorghum	Mid	2481
Lablab	Mid	1238
Multi-species (millet, lablab, tillage radish)	Mid	1214

Three planned termination times matched key growth stages of the main cereal treatments:

- Early-termination at first node (Z31) when stem development began;
- Mid-termination at flag leaf emergence (Z41) when the reproductive phase began; and
- Late-termination at anthesis (Z65) for peak biomass production.

Photo 1. A range of summer cover crops were planted and sprayed out at different times at Bungunya to assess their impact on the soil water storage during a long-fallow period after skip-row sorghum, prior to planting wheat.

One millet plot was 'missed' when spraying the late-termination; its removal two weeks later provided additional unreplicated biomass data and water use figures for an 'extra late' termination.

Soil water was estimated using soil cores to measure gravimetric soil water at key times across the fallow and the subsequent wheat, along with regular neutron moisture meter (NMM) and EM38 readings in each plot. These NMM and EM38 readings and the percentage ground cover were recorded every 2–4 weeks while the cover crops were growing, and every four weeks in the fallow once all cover crops were terminated. These soil water measures continued every four weeks in the growing crop until canopy closure, with a final soil water measure at harvest. Wheat yields were estimated with hand-cuts on 12 October and mechanical harvesting on 26 October 2018.

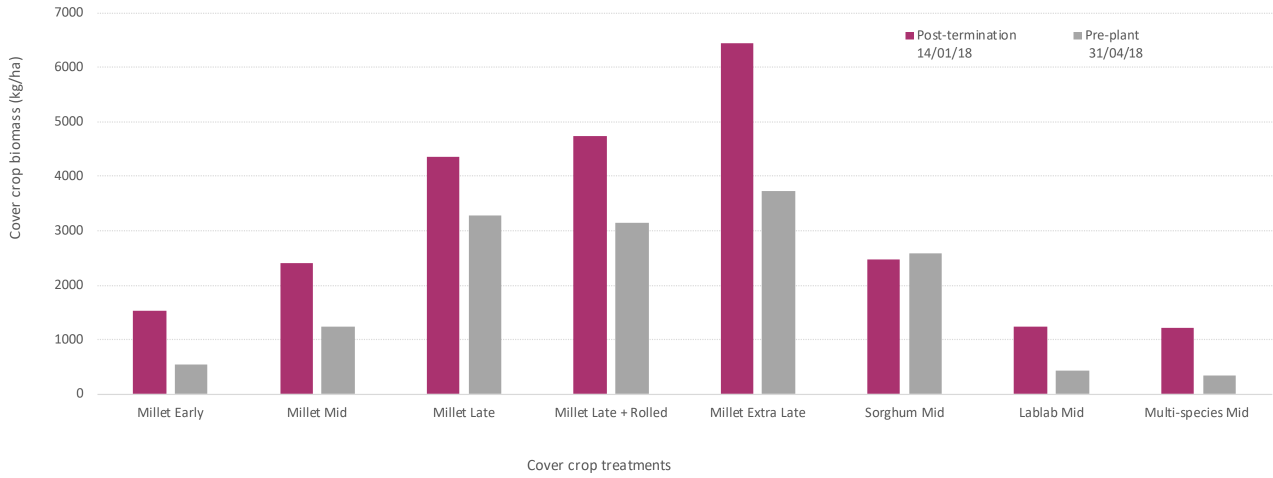

Figure 1. Above-ground biomass accumulation for the cover crop treatments at Bungunya show reduced biomass level by the end of the fallow.

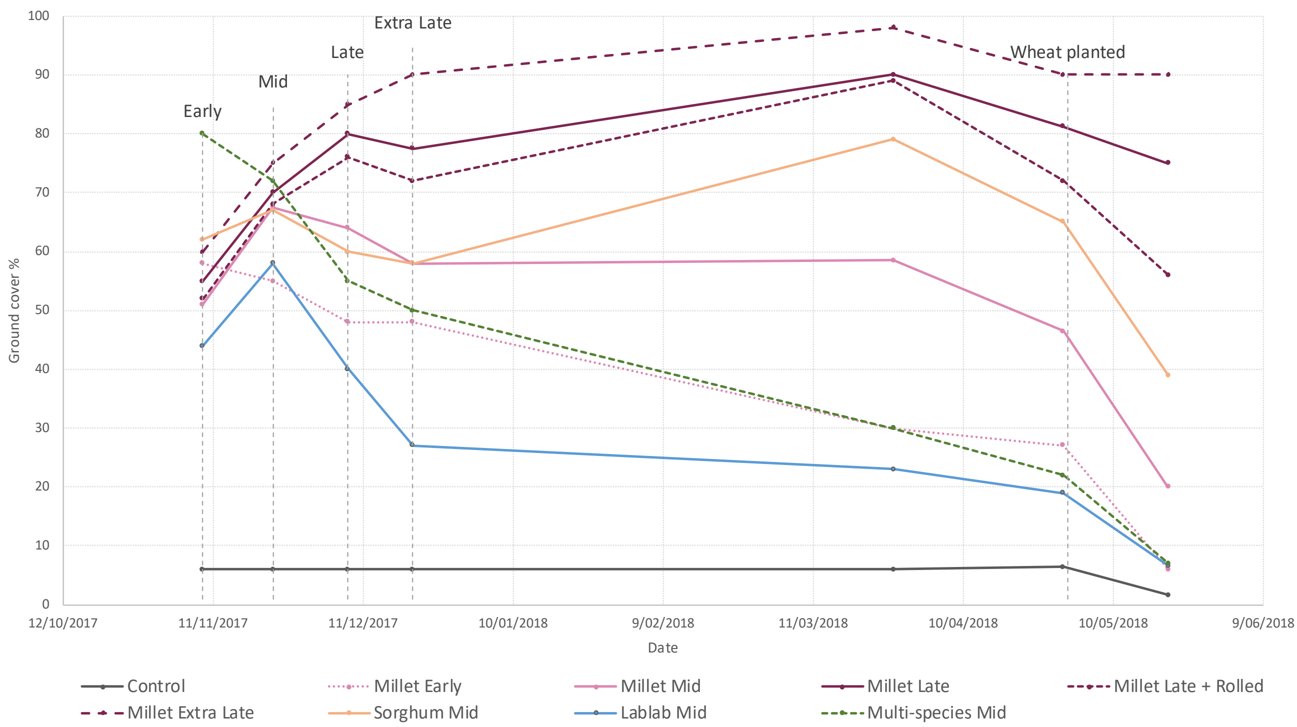

Figure 2. Visual assessments of ground cover over time at Bungunya also show reduced cover over the fallow, especially for lablab.

Results

Biomass and ground cover

Biomass of the millet cover treatments ranged from 1533 kg DM/ha for the early-termination, up to 4737 kg DM/ha for the late-termination. The lablab and multi-species treatments produced less dry matter than the cereals, and biomass fell below 1000 kg DM/ha prior to planting wheat in the early terminated millet, the lablab and the multi-species treatments (Figure 1). These three treatments also fell to only 20–30% ground cover by the end of the fallow (Figure 2).

Soil water

The water cost of growing the millet cover crops, relative to the Control treatment in the early stages of the fallow was ~50 mm for the early-termination, ~40 mm for the mid-termination and ~60 mm for the late-termination treatment (Figure 3). The lablab mid-termination treatment also cost ~60 mm to grow, relative to the Control treatment (Figure 4).

The unreplicated 'extra' late termination (two weeks later) used an additional 55 mm of water.

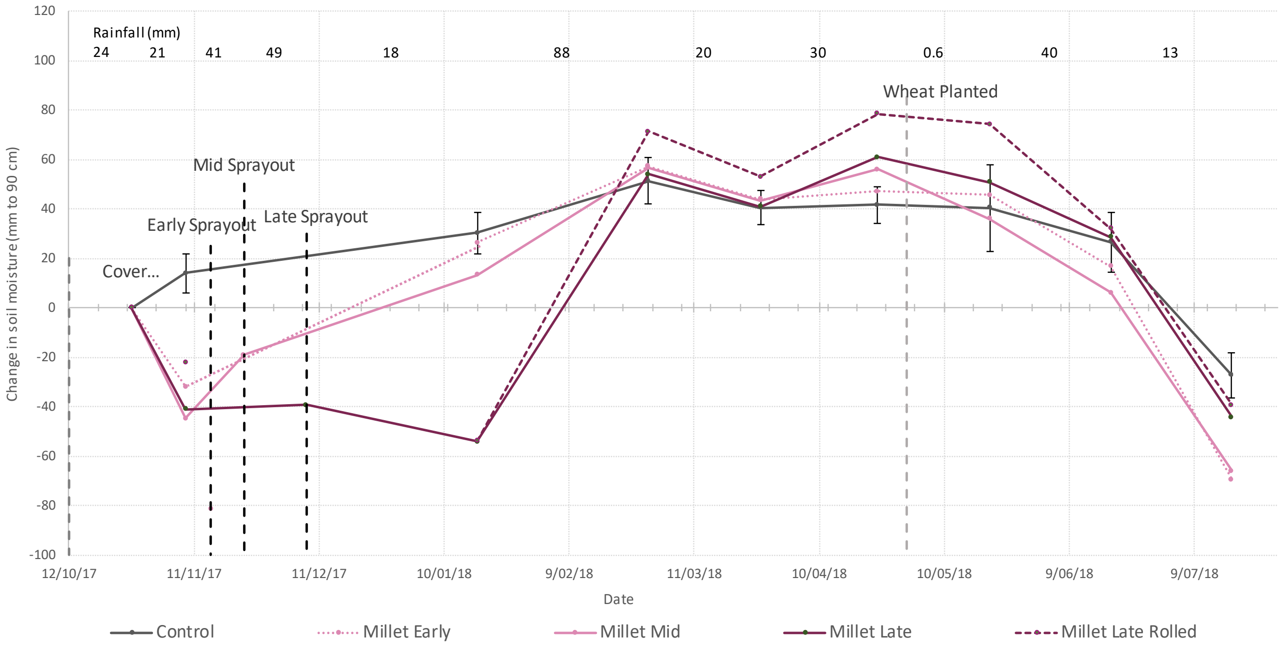

Figure 3. Changes in soil water (mm to 90 cm) from planting of millet cover crops to canopy closure of the subsequent wheat crop at Bungunya show that stored water can be increased over the fallow.

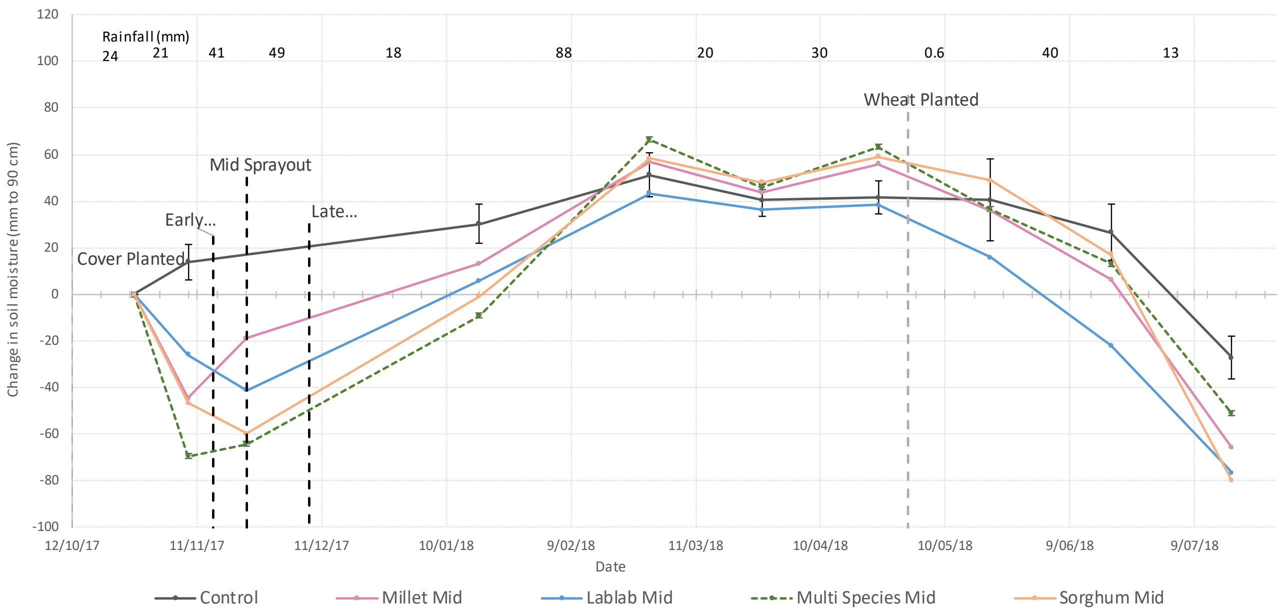

Figure 4. Changes in soil water (mm to 90 cm) after planting cover crops until canopy closure of the subsequent wheat crop at Bungunya show that soil stored less water under legume stubble than cereal stubble.

These results reflect additional rainfall and different rates of infiltration achieved in each treatment (some of which were still growing) between the soil water measurements:

- Plant of cover crops to Mid-termination, 86 mm in four events (11/10/17 to 22/11/17)
- Mid-termination to plant of wheat, 205 mm in 11 events (22/11/17 to 1/5/18)
- Plant to maturity 41 mm in 3 events (1/5/18 to 5/10/18)
- Maturity to post harvest soil sample 72 mm in 7 events (5/10/18 to 5/11/18).

Between mid-termination and early March 2018, 175mm of rainfall had fallen in 10 events, and the millet treatments had regained similar soil water levels to the Control, except the late terminated (rolled) treatment (Photo 2), which now had ~20 mm more stored water.

When the subsequent wheat crop was planted, the mid-terminated millet had ~14 mm more soil water than the Control treatment, the late terminated millet ~19 mm more, and the late terminated and rolled millet ~36mm more soil water (Table 2). Interestingly, water extraction by the wheat crop was greater from all of the millet cover crop plots than the Control, which had poorer establishment and lower yields, and probably reduced root development.

Crop performance

All cover crop treatments increased the yield of the final wheat crop (Table 2). They also required two less fallow weed sprays, a saving of ~$40/ha.

Photo 2. This photo shows the stubble effect three days after ~30 mm of rain at the site. A Late + Rolled treatment is in the foreground with a Control plot visible behind it. The theory is that stubble reduces evaporation and keeps the soil surface wetter for ~21 days, so if more rain falls in that time, more water will be stored.

However, the biggest yield increases were from the cereal cover crops, especially the late-terminated millet and the sorghum. The water differences at end of the fallow may explain some of the observed yield differences. However, the establishment of the wheat crop was also dramatically better after the cover crops, especially where cereals were used (Photo 3).

The expected yield increases from the higher fallow water storage alone would typically be ~200 kg grain in wheat (assuming 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,

Table 2. 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 shows cover crops can increase stored water.

Cover crop treatment	Terminated	Water gain (cf control)	Wheat yield (kg/ha)
Control (bare fallow) Starting water ~120 mm PAW		42 mm (fallow gain)	1436 f
Millet (White French)	Early	+5 mm	2223 cd
Millet (White French)	Mid	+14 mm	2386 bc
Millet (White French)	Late	+19 mm	2897 a
Millet (White French)	Late + Roll	+36 mm	2565 b
Sorghum	Mid	+17 mm	2634 ab
Lablab	Mid	-4 mm	1795 e
Multi-species (millet, lablab, tillage radish)	Mid	+21 mm	1954 de

the measured yield gains for these same three treatments were 950 kg/ha, 1461 kg/ha and 1129 kg/ha respectively, representing increased returns of between $250 and $380 /ha.

Implications for growers and agronomists

These results show that cover crops can indeed help increase net water storage across fallows with otherwise limited ground cover. How often these soil water results will occur across different seasons will be explored with further experiments and simulation modelling.

More dramatically, these 'initial' results and the impact on the subsequent wheat crop (and cotton at Yelarbon, page 69) are dramatic, and provide big dollar returns; far beyond what could be expected from the increases in net soil water storage across the fallows. Improved establishment of the following wheat crop is an obvious contributor in this experiment. However, there was also greater water extraction from some treatments (especially at depth) in the 'sister' cotton experiment at Yelarbon. How much of the responses can be attributed to these factors, how often such results might occur, and the contributions of different factors remains to be explored.

Acknowledgements

We very much appreciate the support of the trial co-operator and consultants for their effort and contributions to the project, along with our project team members in CSIRO (Neil Huth, Brook Anderson), David Freebairn, and the DAF Biometry, Technical and Research Infrastructure staff that supported the heavy management and monitoring loads of these experiments. Thanks also to the Grains Research and Development Corporation, Cotton Research and Development Corporation and the Department of Agriculture and Fisheries for funding the project (DAQ00211).

Trial details

Location:	Bungunya
Crop:	Wheat long-fallowed from skip-row sorghum with White French millet and other cover crops
Soil type:	Brigalow, Brown Vertosol
Rainfall:	332 mm (291 mm Cover/Fallow and 41 mm in wheat)

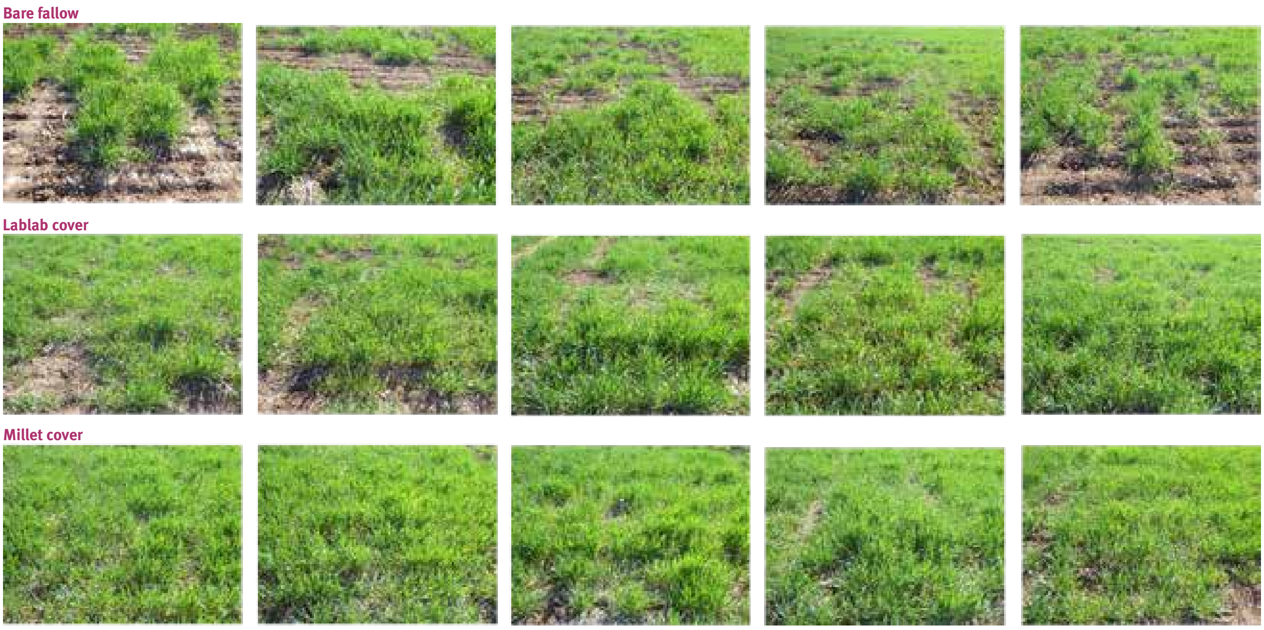

Photo 3. These photos show the poor establishment of the wheat crop following a normal low-cover fallow (Control) and a lablab cover crop, compared to a White French millet cover crop (five photos/reps of each).

Winter cover crops can increase infiltration, soil water and yields of irrigated cotton—Yelarbon

Andrew Erbacher and David Lawrence
Department of Agriculture and Fisheries

Research Questions: *Can cover crops increase infiltration and <u>net</u> water accumulation in pivot-irrigated cotton systems with low (<30%) ground cover?*

- *What is the net water cost to grow winter cover crops?*
- *What is the net water gain to subsequent cotton crops?*
- *What is the impact on the yield of the subsequent cotton crops?*

Key findings

1. Winter cover crops can improve ground cover, increase plant available water and improve subsequent cotton yields in pivot-irrigated systems.
2. The early spray-out treatment was the best cover crop for storing water over the short fallow in this study where cover did not have to last very long. However, the extra cover in the mid-terminated cover treatment continued to boost infiltration in the cotton's early growth stages.
3. All cover crop treatments improved the yields of cotton by approximately 3 bales/ha; well in excess of any gains expected from the increased fallow soil water storage.

Background

Approximately 60% of rainfall in northern farming systems is lost to evaporation, with transpiration through plants typically only 20-40%. Cover crops are good for protecting the soil from erosion, building soil organic matter and maintaining soil biological activity. However, not being harvested for grain or fibre, they are considered 'wasteful' of rainfall; widely seen to be our most limited resource in dryland farming systems.

Recent research now suggests that cover crops may provide these benefits with little or no loss of plant available water. Therefore, there is renewed interest in cover cropping to use some of this 'lost' water and help develop systems that are more productive, profitable and sustainable.

For example, we know that cotton crops can leave the soil dry and unprotected with low ground cover after picking. This reduces infiltration and makes it difficult to rebuild soil water levels for the next crop. Consequently, dryland growers plant winter cereals post-cotton to get cover back on the ground and protect the soil; the crops may be harvested in good seasons, or be sprayed-out after 6-10 weeks just to provide the necessary ground cover to maintain infiltration.

However, efficient water use is also important for irrigated cotton growers; especially overhead irrigators who are interested in cover to maximise infiltration when they are watering-up and during the early growth stages of the cotton when they may have trouble getting enough water into the soil to keep up with the later crop demand. Any additional cereal stubble will also protect the young cotton plants from hot summer winds after planting.

Our project has intensively monitored crop experiments from Goondiwindi (Qld) to Yanco (NSW) to quantify the impact of cover crops on fallow water storage and crop growth. That is, how much water is required to grow cover crops with sufficient stubble, how these stubble loads affect accumulation of rainfall, the net water gain/loss for following crops and the subsequent impacts on crop growth and yield. This paper reports on an irrigated cotton paddock between Yelarbon and Goondiwindi.

What was done

The Yelarbon experiment was on a pivot-irrigated paddock that grew cotton in 2016/17. The crop was picked and root cut in May 2017, 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/m²), barley and vetch mixtures (30 plants/m² each) and tillage radish (30 plants/m²). Rain that night aided establishment, with the surrounding paddock planted to wheat for stubble cover two weeks later as per the grower's normal practice. The grower normally takes this wheat crop through to harvest and so we included a 'grain harvest' treatment.

Table 1. Cover treatments applied at the Yelarbon site included barley, vetch and tillage radish.

Cover crop treatment	Terminated	Peak biomass (kg/ha)
Control (bare fallow)		
Cereal (barley)	Early	1166
Cereal (barley)	Mid	4200
Cereal (barley)	Late	5104
Cereal (barley)	Mid + Roll	4200
Cereal (wheat)	Grain harvest	8175
Cereal + legume (vetch)	Mid	4928
Cereal + legume (vetch)	Late	4149
Tillage radish	Mid	4692

Three termination times matched key growth stages of the main cereal treatments:

- Early-termination at first node (Z31) when stem development began;
- Mid-termination at flag leaf emergence (Z41) when the reproductive phase began; and
- Late-termination at anthesis (Z65) for peak biomass production.

The subsequent cotton crop was planted on 15 November 2017. Importantly, the grower's 'grain harvest' treatment was used to determine the irrigation schedule for the wider paddock and our experimental plots.

Above-ground biomass was monitored across the growth of the cover crops until termination and through the subsequent fallow. Establishment counts were taken on each plot and hand cuts used to estimate cotton yields.

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 meter (NMM) and EM38 readings in each plot. These NMM and EM38 readings and the percentage ground cover were recorded every 2–4 weeks while the cover crops were growing, and every four weeks once all cover crops were terminated through to canopy closure of the following cotton. Final EM38 and NMM water measurements were done at cotton defoliation.

Results

Biomass and ground cover

Biomass of the barley cover crops ranged from 1166 kg DM/ha for the early-termination, up to 5104 kg DM/ha for the late-termination and 8175 kg DM/ha for the grain harvest treatment (Table 1). The cereal/legume mix and the tillage radish produced less dry matter than the cereals. Only the early-terminated cereal (barley) fell to below 1000 kg DM/ha, with ground cover down to 35% by the time the cotton was planted with the short fallow at this site (Figure 1).

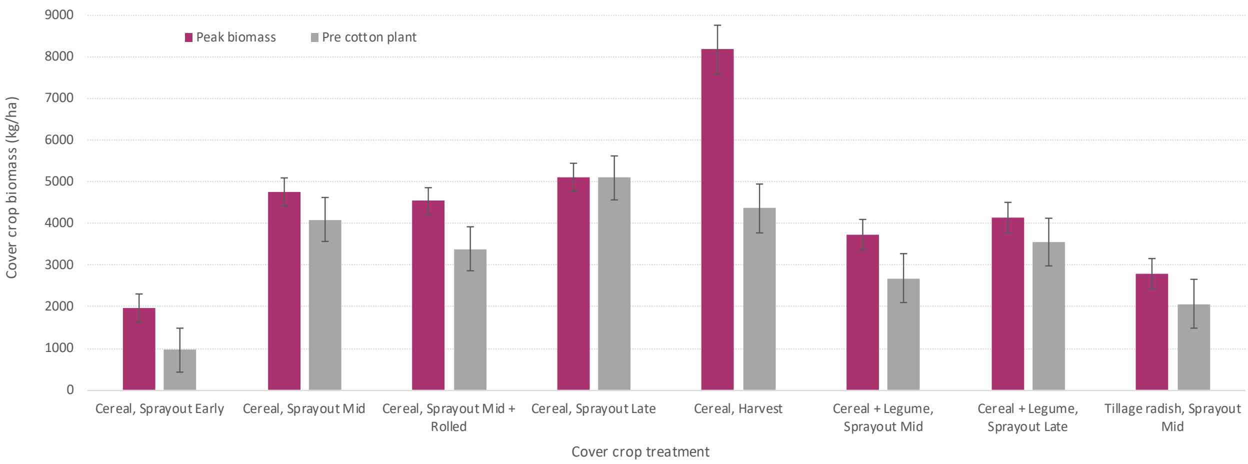

Figure 1. Above-ground biomass accumulation for each cover crop treatment (excluding old cotton stubble) showed small reductions by the end of the short fallow.

Ground cover in the tillage radish fell dramatically to ~20% ground cover, which would be of little value for infiltration in the early stages of the crop (Figure 2). Rolling had no effect on the breakdown of biomass during this short fallow.

Soil water

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 treatment (Figure 3).

However by the end of the fallow, and a subsequent 170 mm of rainfall/irrigation in eight 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 to cotton planting; it did its job and maintained over 30% ground cover until planting. However, the mid-terminated cereal maintained over 50% cover, which presumably led to it accumulating more moisture throughout the early stages of the following cotton.

The 'cover' crop that continued through to grain harvest was ~145 mm behind by the end of the fallow. Again, this treatment mirrored the wider paddock that set the pivot irrigation schedule.

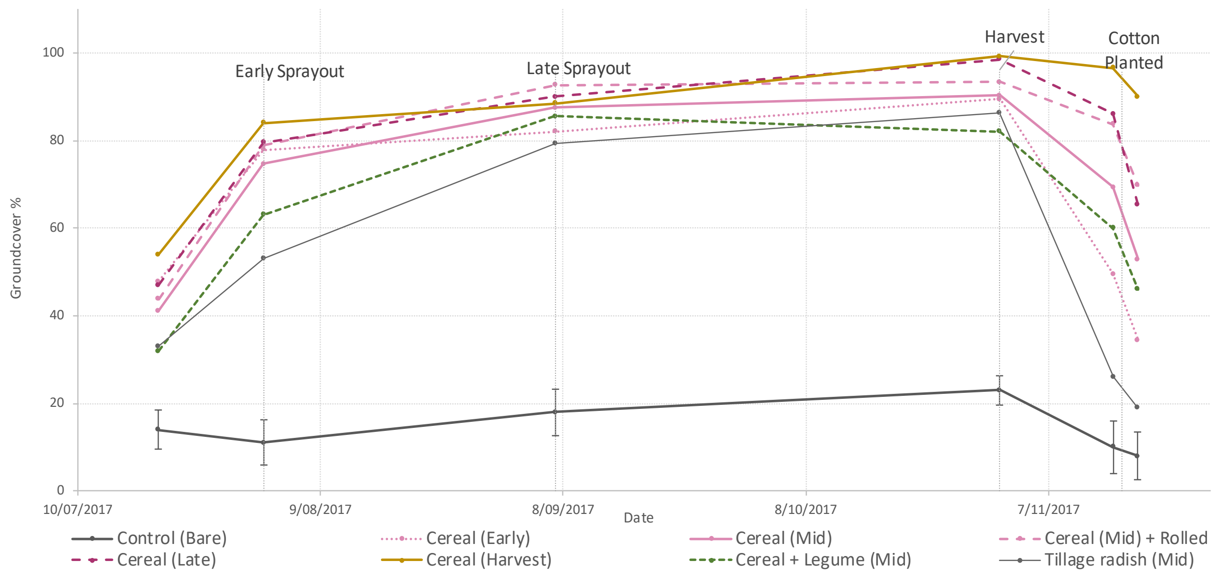

Figure 2. Ground cover assessments showed the largest decline under the tillage radish treatment.

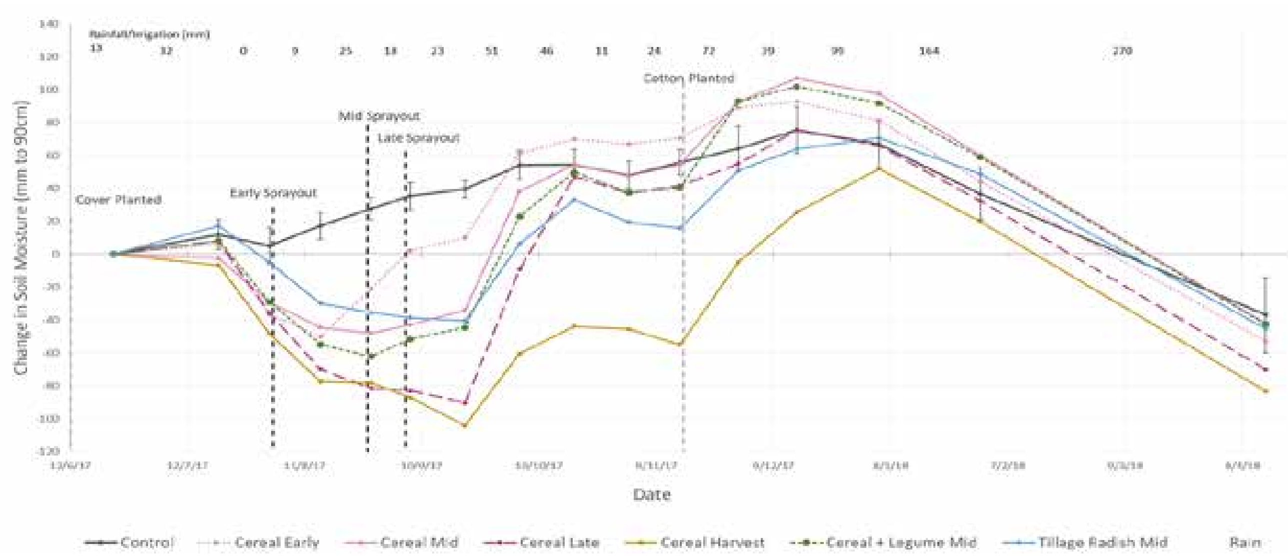

Figure 3. There were large changes in soil water (mm to 90 cm) from planting of the winter cover crop treatments and defoliation of the subsequent cotton crop at Yelarbon.

Crop performance

Matching the irrigation schedule to the harvested crop appears to have provided more than adequate water across the cover crop treatments; yields for all cover crop treatments were similar. However, the Control with limited ground cover was the poorest performer with at least 2.6 bales/ha lower yield, lower infiltration in early growth stages, and less water extracted late in the crop than treatments with cover crops.

The costs to plant the cover crops (~$50/ha) and to spray them out (~$20/ha) almost matched the savings from three less weed sprays during the fallow (~$60). Consequently, the measured cotton yield responses were very profitable, and appear to have been due to more than water alone.

For people who also grow grain, the 14 mm of extra stored water from this early-termination cover crop would typically produce ~200 kg grain (assuming 15 kg grain/mm water). This is worth ~$50/ha (at $270/t) for a net return of ~$40/ha.

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 ranged from -111 mm to +14 mm.

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

Implications for growers and agronomists

The project results show that cover crops can indeed help increase net water storage across fallows that have limited ground cover. How often these soil water results will occur across different seasons will be explored with further experiments and simulation modelling.

The yield results for the subsequent cotton crop (and the wheat crop at Bungunya, page 63) are dramatic. These very large responses represent big improvements in returns; far beyond what could be expected from the increases in net soil water storage across the fallows. There also appears to have been greater water extraction in some cover crop treatments in this Yelarbon experiment.

While wheat establishment was dramatically better after cover crops at Bungunya, the trial planter configuration and the alignment of plots in the paddock at Yelarbon led to the cotton rows crossing over rows of cover crop stubble, making establishment hard to assess. The grower ensures his cover crop planter bar and row alignment is configured so that the cotton is planted between the rows of stubble to ensure good establishment. How much of the final responses can be attributed to these factors, how often such results are likely, and the contributions of other factors to these gains remains to be explored.

Acknowledgements

We very much appreciate the support of the trial co-operator and consultants for their effort and contributions to the project, along with our project team members in CSIRO (Neil Huth, Brook Anderson), David Freebairn, and the DAF Biometry, Technical and Research Infrastructure staff that supported the heavy management and monitoring loads of these experiments.

Thanks also to the Grains Research and Development Corporation, Cotton Research and Development Corporation and the Department of Agriculture and Fisheries for funding the project (DAQ00211).

Trial details

Location:	Yelarbon
Crop:	Cover crops, cotton
Soil type:	Brigalow, Grey Vertosol
In-crop rainfall and irrigation:	895 mm (253 mm Cover/Fallow and 642 mm in cotton)

Northern Farming Systems site—Emerald

Darren Aisthorpe and Ellie McCosker
Department of Agriculture and Fisheries

Research Question: *What are the long-term impacts on systems performance (e.g. productivity, profitability and soil health) when six strategically different 'farming systems' are applied to one geographic location over a five year period?*

Key findings

1. *Higher soil fertility* was the most profitable and highest yielding system for the 2018 sorghum crop.
2. *Higher legume* is cumulatively the most profitable system thus far.
3. The *Baseline* system is falling behind four of the six systems in the trial on most comparisons.

Background

In early 2015, the project developed six locally relevant farming systems to investigate in Emerald that were consistent with those being studied by the Northern Farming Systems Initiative. A range of agronomic practices (i.e. row spacing, plant populations), crop types and rotations, crop frequency, planting time/windows, tillage practices, fertiliser rates and planting moisture triggers were adopted and strategically used to develop the following six farming system treatments:

1. **Baseline** is a conservative zero tillage system targeting one crop/year. Crops include wheat, chickpea and sorghum, with nitrogen rates on cereals targeting median seasonal yield potential.
2. **Higher legume** increases the frequency of pulses (i.e. 1 pulse every 2 years) to assess the impact of more legumes on profitability, soil fertility, disease and weeds.
3. **Higher crop intensity** increases cropping intensity to 1.5 crops/year when water allows. Crops include wheat, chickpea, sorghum, mungbean and forage crops/legumes.
4. **Higher nutrient supply** examines the economic and agronomic implications of increased nitrogen and phosphorus rates targeting 90% of yield potential based on soil moisture in an environment of variable climate. Crops and other practices are the same as the *Baseline* system.
5. **Higher soil fertility** repeats the *Higher nutrient supply* system but with the addition of 60 t/ha of manure. Designed to see if higher initial soil fertility can be maintained with greater nutrient inputs (targeting 90% of yield potential based on soil moisture).

Table 1. Crop rotations used for all treatments since 2015 to winter 2019.

Treatment	Winter 2015	Summer 2015/16	Winter 2016	Summer 2016/17	Winter 2017	Summer 2017/18	Winter 2018	Summer 2018/19	Winter 2019
Baseline	Wheat EGA Gregory⊕	Fallow	Chickpea Kyabra⊕	Fallow	Wheat Sunguard⊕	Sorghum MR-Buster	Fallow	Fallow	Wheat Mitch⊕
Higher crop intensity	Wheat EGA Gregory⊕	Mungbean Jade-AU⊕	Wheat Condo⊕	Fallow	Wheat Sunguard⊕	Sorghum MR-Buster	Fallow	Fallow	Chickpea Kyabra⊕
Higher legume	Chickpea Kyabra	Fallow	Wheat Condo⊕	Fallow	Chickpea Seamer⊕	Sorghum MR-Buster	Fallow	Fallow	Chickpea Kyabra⊕
Higher nutrient	Wheat EGA Gregory⊕	Fallow	Chickpea Kyabra⊕	Fallow	Wheat Sunguard⊕	Sorghum MR-Buster	Fallow	Fallow	Wheat Mitch⊕
Higher soil fertility	Wheat EGA Gregory⊕	Fallow	Chickpea Kyabra⊕	Fallow	Wheat Sunguard⊕	Sorghum MR-Buster	Fallow	Fallow	Wheat Mitch⊕
Integrated weed management	Wheat EGA Gregory⊕	Fallow	Chickpea Kyabra⊕	Fallow	Wheat Sunguard⊕	Sorghum MR-Buster	Fallow	Fallow	Wheat Mitch⊕

6. **Integrated weed management** is a minimum tillage system focused on one crop/year but employing a wide range of practices to reduce reliance on traditional knockdown herbicides in Central Queensland (CQ) farming systems. Crops include wheat, chickpea, sorghum and mungbean.

What was done

2018 summer crop

The site received 363 mm of rainfall between the 2017 winter crop harvest and planting sorghum on 23 January 2018. All treatments were planted to MR-Buster, with the *Integrated Weed Management* treatment planted on a 50 cm spacing; all other treatments were planted on 1 m spacing. The sorghum received an additional 212 mm of rainfall in-crop (200 mm fell before the end of February). Physiological maturity was at the end of April, with an additional 11 mm falling prior to harvest.

Winter 2018 to now

No further rainfall was received until late June (18 mm), which was insufficient for any winter crop plantings. The next significant rainfall was received mid-October (82 mm), however no cropping window was open at this time. Isolated showers and storms over the summer did increase accumulated rainfall totals, however high temperatures and low humidity quickly negated any benefit these provided.

Results

Early in-crop rainfall helped the sorghum to establish and develop quickly, with 196 mm of rain received in the first month post-planting. However, only 15 mm was received in-crop from 25 February until physiological maturity around 10 May. Temperatures were above average for February and April 2018; 36 °C (long-term average 33.4 °C) and 31.5 °C (long term average 29.5 °C), respectively.

Despite good starting plant available water (PAW) and significant early in-crop rainfall, the crop showed signs of moisture stress during the flowering/grain fill period and senesced quickly after filling as much grain as it could. Grain yields and qualities highlighted differences between the treatments. *Higher soil fertility* produced the highest yield and lowest screenings (still quite high).

Baseline, *Higher legume* and *Higher nutrient supply* produced lower yields and higher screenings than *Higher soil fertility*, but were similar to each other. *Higher intensity* had the lowest starting PAW resulting in lowest yield and highest screenings. (Figure 1). For most systems, screenings decreased as grain yield increased (Figure 1).

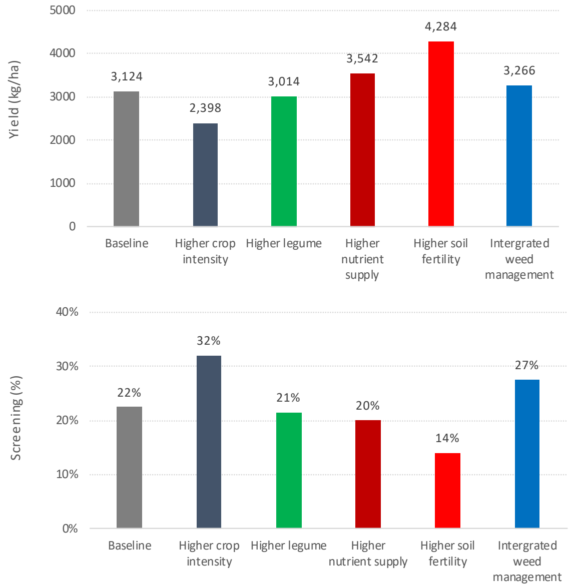

Figure 1. Grain yield (kg/ha) and screenings (%) for 2018 sorghum crop in all systems.

Pre-plant and post-harvest PAW measurements (Figure 2) show the *Higher crop intensity* treatment, had the lowest PAW at planting (at least 26 mm less) compared to any of the other systems that had come out of wheat), despite having the same cropping regime as *Baseline* since winter 2016. The *Higher legume* treatment, where the previous crop was chickpea, also had lower PAW than *Baseline*, but had on average 10 mm more PAW at planting than the *Higher crop intensity* system.

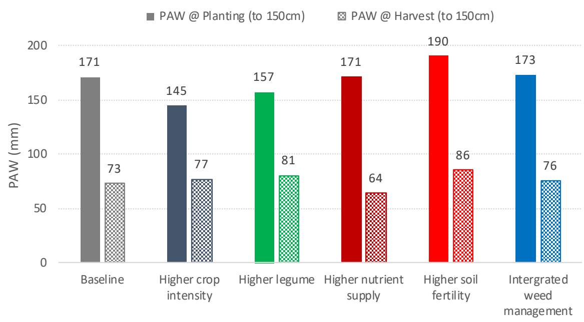

Figure 2: Average planting and harvest PAW for the 2018 sorghum crop for all treatments.

The PAW spread at planting was 45 mm between treatments. The spread at harvest was still 22 mm; the *Higher nutrient supply* had the largest variation between starting and finishing PAW at 107 mm, and *Higher intensity* had the lowest spread at 68 mm.

Crop water use efficiency (WUE) mirrored grain yield; the *Higher soil fertility* system had the best conversion of available water to grain (13.4 kg of grain per ha for every mm of water used by the crop). The lowest yielding system, *Higher crop intensity*, also had the lowest WUE (8.6 kg/ha/mm) (Figure 3).

Planting the 2018 sorghum treatments.

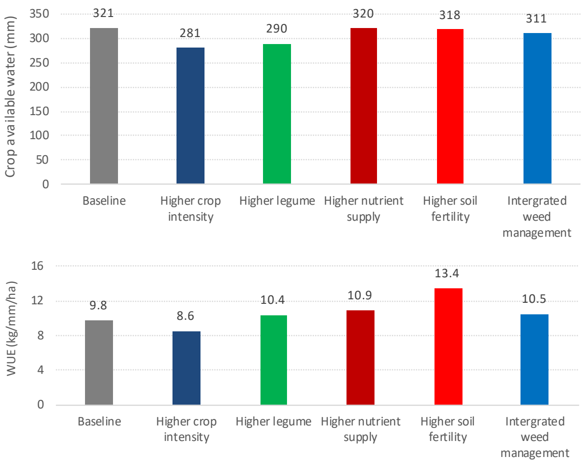

Figure 3. Crop available water and the WUE (kg/ha/mm) of each of the treatments.

Nitrogen and phosphorous removal by grain mirrored yield, as expected (Figure 4). However, when total biomass production is considered, it is highly probable that nutrient stratification on the surface over time may be higher in the *Integrated weed management* treatment. The narrower row spacing and higher established populations in this system allowed it to grow considerably more biomass, but with the dry finish it was not able to convert this biomass into a yield advantage.

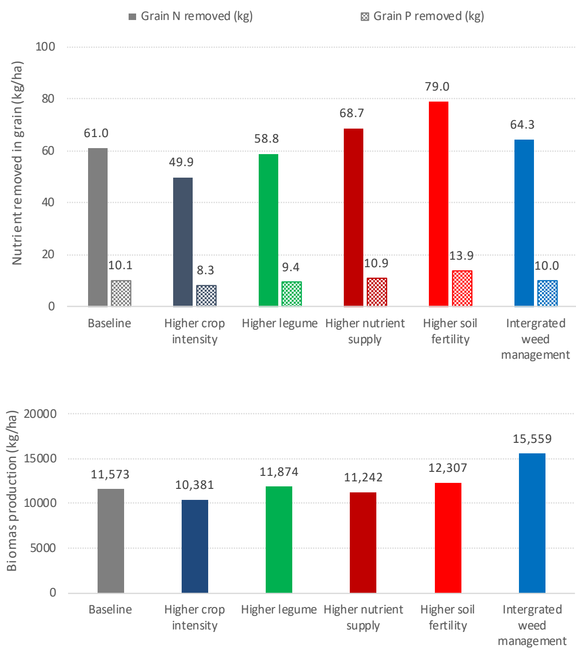

Figure 4. Grain nutrient removal (kg/ha) and crop biomass production (kg/ha).

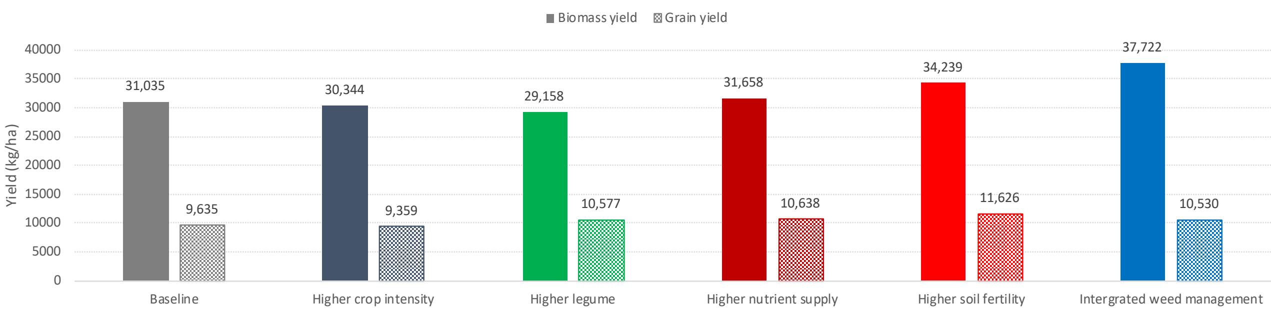

Figure 5. Cumulative biomass and grain yield production since 2015 for all six treatments.

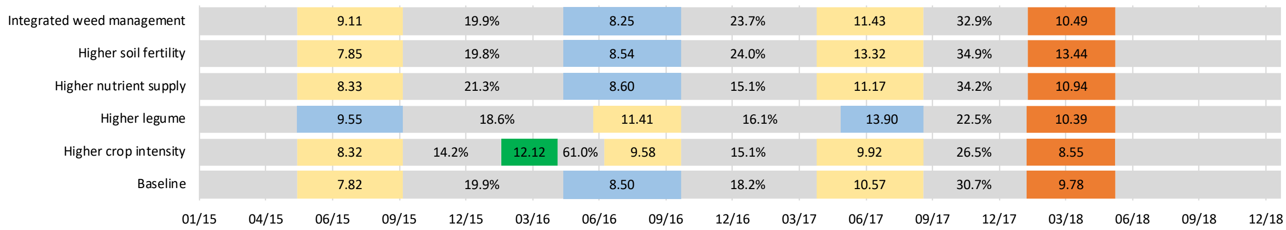

Figure 6. Water use efficiency (kg/ha/mm) and fallow efficiency (%) since the start of the trial in 2015. WUE indicates grain produced by the crop in each treatment per mm of water available to it.
Yellow bars represent wheat, blue bars are chickpea, orange bars are sorghum and the green bar is mungbean. The percentage number indicates how much of the fallow rainfall was captured and available at the next planting event.

Project life analysis

Now into the fifth year of the project, we are able to make some longer-term system observations. Total biomass and grain produced for each system (Figure 5) indicates that the *Integrated weed management* system stands out for having produced the greatest amount of biomass, most likely due to the narrower row spacing and higher plant establishment over time. However, the *Higher soil fertility* system has produced the highest overall grain yield.

Water use efficiency (kg/mm/ha) and fallow efficiency, is an interesting way to compare differences between systems over time. The rotations for each of the farming systems have varied (Figure 6).

Early in the trial, the *Higher legume* system produced the highest WUE, however as the manure treatments started to take effect, the *Higher soil fertility* system has now pushed slightly ahead (Figure 6). Despite producing significantly more biomass (and therefore ground cover) than any other system over the duration of the trial, the *Integrated weed management* system has not been able to beat the *Higher soil fertility* or *Higher nutrient supply* systems for fallow efficiency.

When cumulative gross margins are calculated for all systems/crops and compared to WUE (Figure 7), the highest return per mm/ha to date has been for the *Higher legume* system. The cumulative gross margin for each system (Figure 8), shows very little margin between the top two systems; all systems except the *Higher crop intensity* have outperformed the *Baseline.*

While implementing a *Higher legume* system has produced the highest cumulative gross margin and the highest cumulative $/mm/ha return to date, there are downsides when nutritional balances are considered.

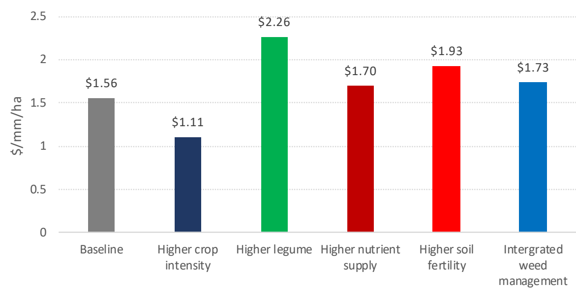

Figure 7. Gross margin of $ per mm available to the crop over the growing season.

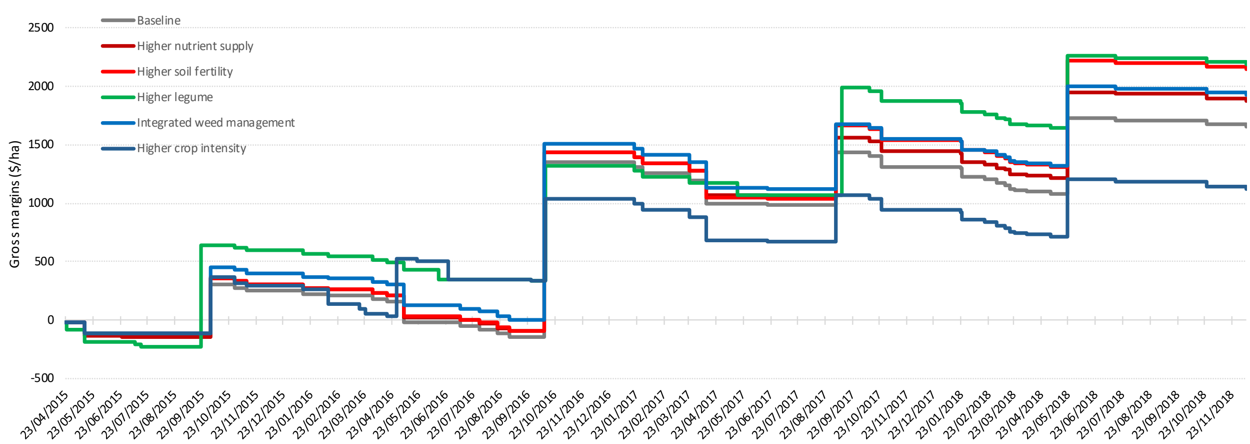

Figure 8. Cumulative gross margin for each of the treatments over the trial duration.

Only the *Higher nutrient supply* system is matching grain phosphorus (P) removal with application rates of starter fertiliser (Figure 9). *Higher legume* had the highest deficit of 14.72 kg/ha of P (equivalent to 70 kg/ha of MAP fertiliser) by the end of 2018. It should be noted that the initial manure application in the *Higher soil fertility* system added 422 kg P/ha, which has not included in these P balance calculations.

Removal of nitrogen (N) by grain (Figure 10) also shows that we have exported considerably more N in grain than what has been applied to the systems. Again, *Higher legume* has the greatest deficit with 280 kg/ha of N removed (equivalent to 609 kg/ha of urea). However this does not take into consideration mineralisation of organic carbon in the soil, nor any N produced by legume crops.

Organic carbon soil tests compare how much draw down has occurred from the organic carbon pool over the life of the project. Starting organic carbon levels in 2015 on-site were already lower than ideal, on average 0.8% in the top 10 cm (Figure 11). These levels have dropped by as much as 0.16% since then, with only the *Higher soil fertility* system showing an increase in the top 30 cm over the past five years, (a result of 10.6 t/ha of carbon added in the first year when it received 60 t/ha of manure). *Higher legume* has utilised the greatest amount in the top 10 cm (and overall), closely followed by the *Baseline* system. Interestingly, the *Higher nutrient supply* system maintained its organic carbon in the 0–10 cm increment, but has drawn more at the 10–30 cm increment.

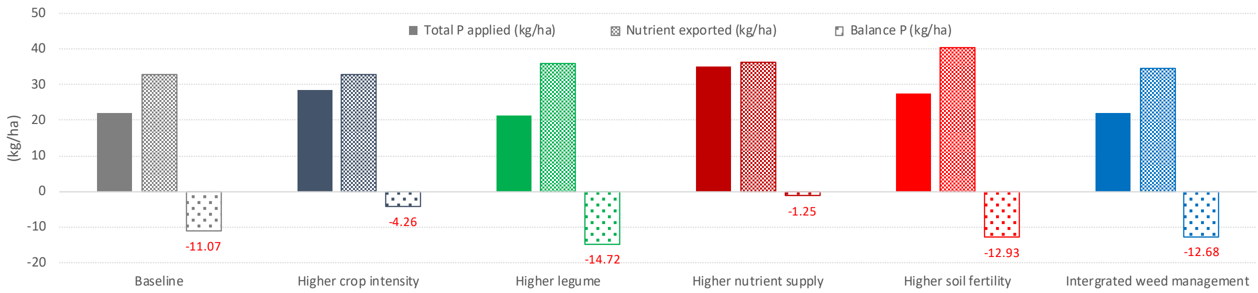

Figure 9. Phosphorous (P) application and removal (kg/ha) over the duration of the trial.

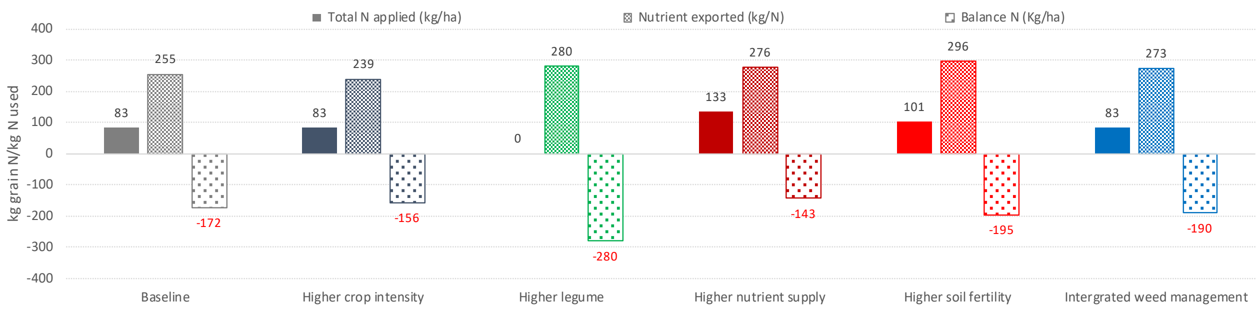

Figure 10. Nitrogen (N) application and removal (kg/ha) over the duration of the trial.

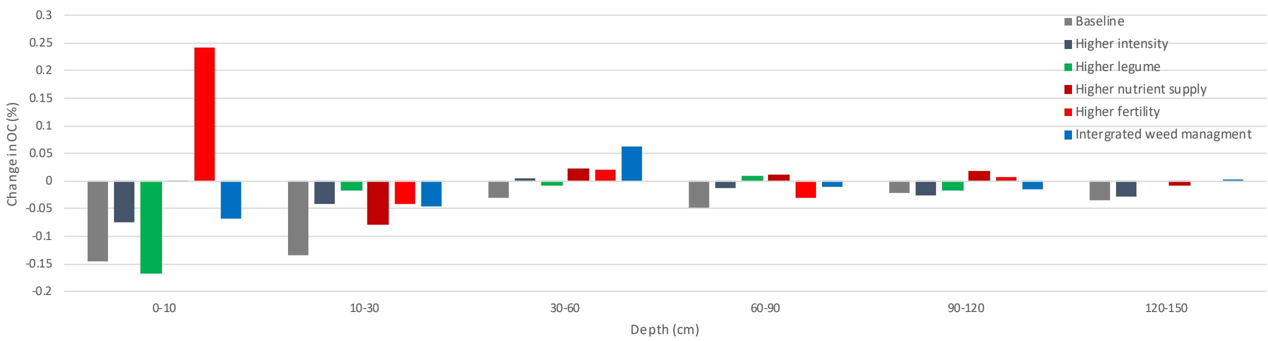

Figure 11. The change in organic carbon levels for all soil increments tested over the life of the trial to date.

Implications for growers

The six systems are now starting to show differences across various parameters due to modifications in the rotation, nutrition and agronomic management. The *Baseline* system has slipped behind most systems on most indices, showing a conservative nutrient approach may not be ideal for CQ. The *Higher legume* system has benefited significantly from the two chickpea crops in 2015 and 2018. The manure applied in the *Higher soil fertility* system has resulted in the system leading in most indices.

Integrated weed management has the highest nutritional demand as a direct result of the higher target plant populations and improved establishment due to the narrower row spacing. Yield response has been good to date because of the improved populations. Weed densities have been low; however, this has been similar for most systems.

From a sustainability point of view, only the *Higher nutrient supply* system is holding ground with respect to nutrient run-down. All other treatments (except *Higher soil fertility*) are seeing declines in P, N and organic carbon. This raises a number of questions, particularly about the sustainability of both the *Higher legume* system, because of the nutrient removal in the grain, but also the *Integrated weed management* system with the significantly higher biomass productions for no extra grain to date.

Acknowledgements

We would like to thank the local growers and consultants that have supported and contributed to the project. The Grains Research and Development Corporation, along with the Department of Agriculture and Fisheries in Queensland and the Department of Primary Industries in New South Wales, fund the project.

Trial details

Location:	Emerald Research Facility	
Soil type:	Cracking, self-mulching, Grey Vertosol, >1.5 m deep, estimated plant water holding capacity of approx. 240 mm	
In-crop rainfall:	212 mm	
Row spacing (cm) 2018:	Baseline	100
	Higher crop intensity	100
	Higher legume	100
	Higher nutrient supply	100
	Higher soil fertility	100
	Integrated weed management	50
Phosphorus applied with seed (kg/ha) for 2018:	Baseline	5.5
	Higher crop intensity	5.5
	Higher legume	7.9
	Higher nutrient supply	7.9
	Higher soil fertility	5.5
	Integrated weed management	50

Integrated weed management's narrow row treatment running out of water while still trying to fill grain.

Northern Farming Systems site—Billa Billa

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Department of Agriculture and Fisheries

Research Questions: *Can systems performance be improved by modifying farming systems in the northern grains region? | In Goondiwindi: (i) What are the trends that are expected in our farming systems? and (ii) How will these changes impact on the performance and status of our farming systems?*

Key findings

1. The district practice *Baseline* system is the most profitable to date. However apart from the 2016 winter crop there is very little difference between the seven grain systems.
2. Water use efficiency is higher for cereals than pulses and is highest in high-yielding crops.
3. Subsoil constraints are limiting PAW extraction by pulse crops.

Background

Grain production in the Goondiwindi area is largely based on a winter cropping system with summer crops grown as a disease break. Most farms operate on a zero or minimum tillage system, with strong reliance on stored fallow moisture. Summer crops are seen as an important part of the system, however are often grown on a greater water profile than winter crops as an insurance against hot growing seasons with variable rainfall.

The Farm Practices Research project (DAQ00192) was established in 2014 with the first crops planted winter 2015. This report investigates the activities and insights from the Billa Billa site in 2017-18 summer and 2018 winter seasons. Previous activities and insights can be found in *Queensland grains research* (2015, 2016 and 2017/18).

The Billa Billa site is located 50 km north of Goondiwindi on the Leichhardt Highway. The soil is a Duplex, with a sandy surface over a grey clay. The original belah and brigalow trees were cleared and the paddock used as long-term pasture before being developed for crops in the late 1990s.

What was done

Consultation meetings in late 2014 and early 2015 developed nine locally relevant systems to investigate at Billa Billa:

1. **Baseline** is typical of local zero tillage farming systems with ~1 crop per year grown using moderate planting moisture triggers of 90 mm plant available water (PAW) for winter and 120 mm PAW for summer. Crops grown are limited to wheat/barley, chickpea and sorghum, and are fertilised (nitrogen (N) and phosphorus (P)) to achieve average seasonal yield potential for the PAW prior to planting.
2. **Lower crop intensity** reflects a conservative rotation accumulating more PAW prior to planting the next crop. Long fallows provide a cropping frequency of 4 crops in 5 years (0.8/year), with the same nutrient management as the *Baseline* system.
3. **Higher crop diversity** allows a greater suite of crops to be grown to better manage disease, root lesion nematodes and herbicide resistance. Moderate PAW levels for planting each crop (90-120 mm) manage individual crop risk and target one crop per year. The unique rules for this system focus on managing root lesion nematodes, with 1 in 2 of the selected crops to be resistant to *Pratylenchus thornei*, and 1 in 4 crops resistant to *Pratylenchus neglectus*. To manage herbicide resistance, two crops utilising the same in-crop herbicide mode-of-action cannot follow each other. Crops grown in this system include wheat/barley, chickpea, sorghum, mungbean, maize, faba bean, field pea, canola/mustard and millet. These crops are fertilised (N and P) to achieve average seasonal yield potential for the PAW prior to planting.

4. **Higher legume** aims to minimise the use of nitrogen fertiliser by growing every second crop as a pulse (legume), with a preference for greater biomass and greater carry-over nitrogen benefits. Crops grown are similar to the *Baseline* (wheat/barley, chickpea, sorghum) with additional pulse options (faba bean, field pea, and mungbean). Moderate planting triggers of 90-120 mm PAW. Crops are fertilised (N and P) to achieve average yield potential for the PAW, with nitrogen only applied to the cereal crops.
5. **Higher crop intensity** aims to minimise the fallow periods within the system and potentially grow three crops every two years. Crops are planted on lower PAW (50 mm for winter and 70 mm for summer) and have a greater reliance on in-crop rainfall. Crop choice is the same as the *Baseline* system, but with mungbean added as a short double-crop option. These crops are fertilised (N and P) to achieve average seasonal yield potential for the PAW prior to planting.
6. **Higher nutrient supply** has N and P fertiliser applied to allow the crops to achieve 90% of the maximum seasonal yield potential for the PAW at planting; with the risk that crops will be over-fertilised in some years. Planted to the same crop as the *Baseline* each year; the only difference is the amount of nutrients applied.
7. **Higher soil fertility (Higher nutrient supply + organic matter)** is treated the same as the *Higher nutrient supply* system, but with an upfront addition of 10 t/ha organic carbon (70 t/ha compost) at the start of the experiment to raise the inherent fertility of the site and to see if this fertility level can be sustained with the higher nutrient inputs.
8. **Grass ley pasture** uses the perennial Bambatsi grass pasture to increase the soil carbon levels naturally. The pasture will removed after 3-5 years and returned to the *Baseline* cropping system to quantify the benefits gained by the pasture phase. The pasture will be managed with simulated grazing with a forage harvester to utilise a pre-determined amount of biomass.
9. **Grass ley pasture + nitrogen fertiliser** repeats the *Grass ley pasture* but with 100 kg N/ha (217 kg/ha urea) applied each year over the growing season to boost dry matter production, which is nearly always constrained by nitrogen deficiency in grass-based pastures, to improve the rate of soil carbon increase.

Table 1. Crops grown at the Billa Billa site

Wheat	Faba bean	Sorghum
Barley	Field pea	Canola
Fallow	Chickpea	
Grass pasture	Mungbean	

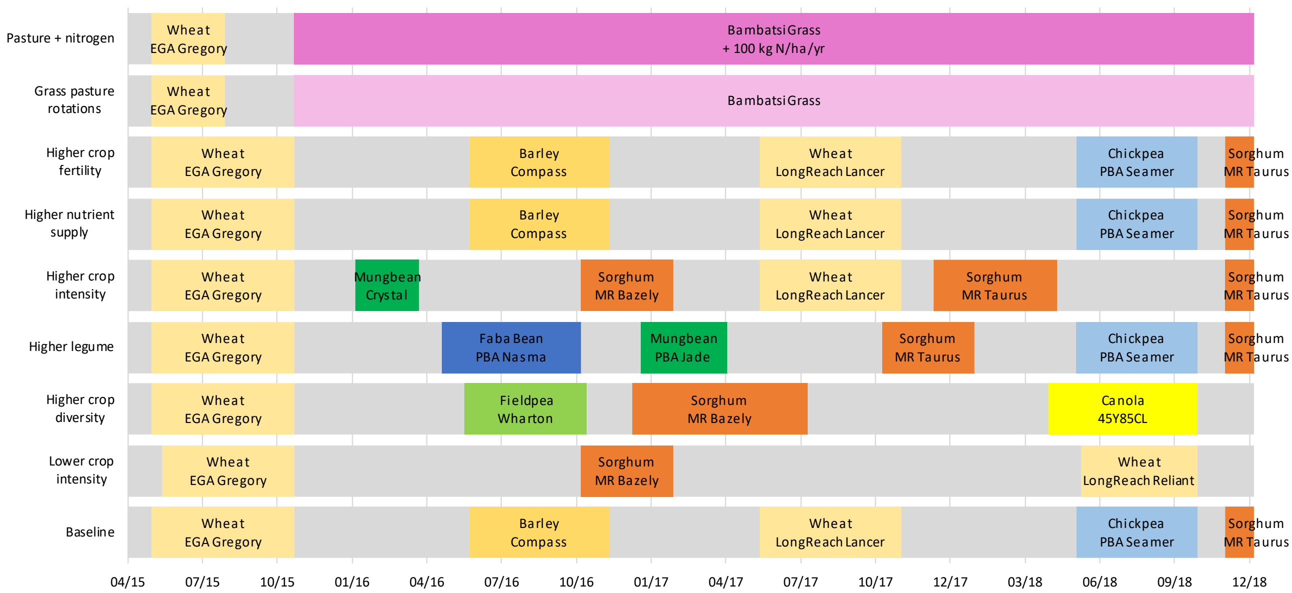

Figure 1. Crop sequences grown at Billa Billa following the defined system rules, plotted on a time scale. Colours represent the crop type as indicated in Table 1.

Results

The low-yielding mungbeans grown in the *Higher legume* system in 2016-17 left a wet profile below 30 cm, but the dry winter in 2017 did not allow it to be double cropped to wheat. This system was then planted to spring sorghum on 10 October 2017 (Figure 1). 245 mm of in-crop rainfall (most prior to flowering) grew a big crop, but a dry grain-fill period resulted in yields of 2.9 t/ha with 11.4 % protein and 40% screenings.

The *Higher crop intensity* system was also planted to MR-Taurus sorghum on 11 December 2017, double cropped after wheat. This crop was planted at the end of the wet spring period of 2017, but with 190 mm of in-crop rain, achieved 2.35 t/ha grain yield with 3% screenings and 12.6% protein.

The *Higher crop diversity* system was planted to sorghum at the same time as the *Higher legume* system mungbeans in 2016, however the later harvest date (July 2017) and greater water extraction by the sorghum crop meant this system did not accumulate enough PAW to be planted to a summer crop in 2017/18. On 28 April 2018, canola was planted after a 10 mm rainfall event with 180 mm PAW. Crop establishment was approximately 30% of the target, so trickle tape was used to establish more plants. Hand cuts were taken at the recommended timing for windrowing (50–70% of seeds changed colour to red, brown or black), with harvest planned as direct heading when 90% of seeds changed colour. The crop received 45 mm in-crop rain prior to the hand cuts for a grain yield of 1.46 t/ha. An additional 90 mm rain fell between hand cuts (windrowing) and harvest and maximum wind speed was measured at 68 km/h five days prior to harvest, resulting in a reduced header yield of 0.8 t/ha.

After a dry May in 2018, it was decided to deep plant five systems. *Baseline*, *Higher nutrient supply* and *Higher fertility* had chickpea planted with 180 mm PAW. *Higher legume* was also double cropped to chickpea with 150 mm PAW and *Lower intensity* was planted to wheat after a long fallow, with 200 mm PAW. Like the canola, these crops only received 45 mm of rain prior to crop maturity. The fallowed chickpea (*Baseline*, *Higher nutrient supply* and *Higher soil fertility*) yielded 1.8 t/ha, double cropped chickpea (*Higher legume*) yielded 1 t/ha and the wheat (*Lower crop intensity*) yielded 3.0 t/ha.

The chickpea appeared to have extracted very little water below 60 cm this season, which combined with 135 mm rainfall from crop maturity to the end of November, provided an opportunity to double crop these systems to sorghum. The *Higher crop intensity* system was fallowed from May 2018 so also achieved its planting trigger for sorghum. On 26 November 2018, *Baseline*, *Higher nutrient supply*, *Higher soil fertility* and *Higher legume* were planted to MR-Taurus sorghum, with 140 mm PAW. *Higher crop intensity* was also planted to MR-Taurus sorghum on this date, but with 100 mm PAW.

The Bambatsi pastures were only harvested once in 2018 (on 27 March). Total dry matter cuts revealed an extra 450 kg DM/ha grown by the grass + nitrogen pasture (11,420 kg/ha versus 10,970 kg/ha), but an extra 700 kg DM/ha was removed from this system (4250 kg/ha versus 3535 kg/ha), with the same cutting height maintained for all plots. There was also an extra 2% protein (10.3% versus 8.3%) in the removed portion of the fertilised pasture.

Similar to previous seasons, 75% of the macro-nutrients removed in the previous summer were replaced on 16 November 2018 to compensate for nutrient removal that would normally be recycled by grazing animals.

Sufficient rain was received in the spring of 2018 to incorporate broadcast fertiliser and start pasture growth. However, with no rain after November the grass did not grow enough to warrant a spring cut as has been the practice in previous years.

Crops grown at the Billa Billa site are represented by specific colours for all figures and graphs through this report (Table 1).

Lower crop intensity **wheat at anthesis.**

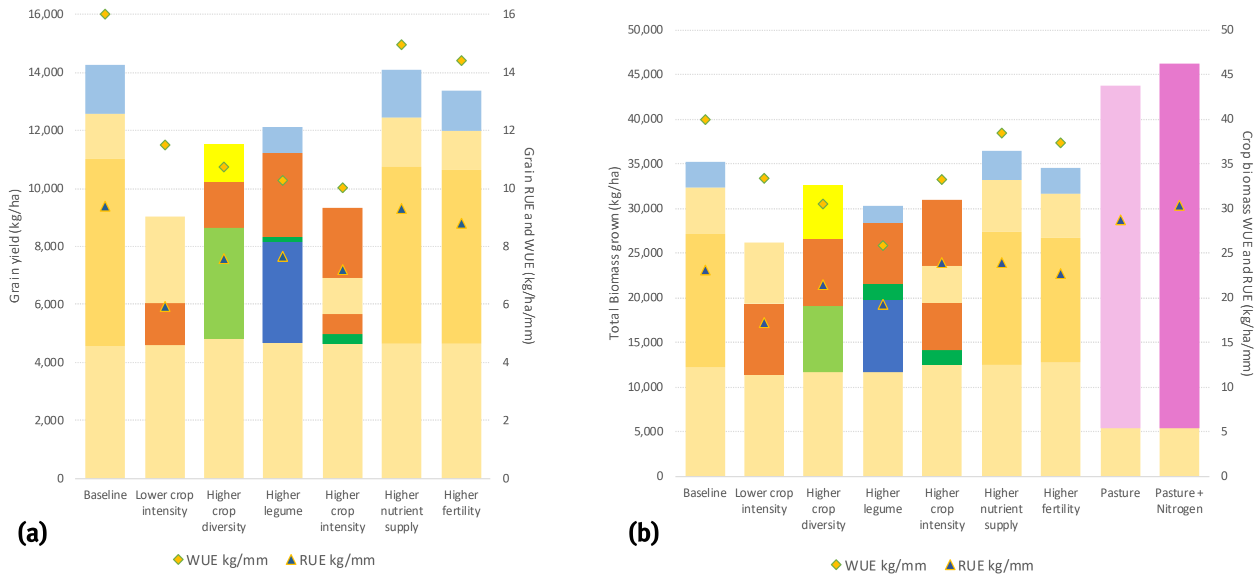

Figure 2. Cumulative (a) grain yield and (b) total dry matter grown for the systems at Billa Billa, with water use efficiency (kg of grain or kg/ha or dry matter per mm of PAW and in-crop rain used) and rainfall-use-efficiency (kg of grain or kg/ha of dry matter per mm of rain), including fallow rain.

Overall system performance 2015-2018

Accumulated grain yield (Figure 2a) across all years indicates the *Baseline*, *Higher nutrient supply* and *Higher soil fertility* systems are the highest yielding (14.2, 14.1 and 13.3 t/ha), with a similar trend for biomass production (32, 36 and 35 t/ha) (Figure 2b).

It is interesting to note that the *Lower crop intensity* and *Higher crop intensity* systems have produced a similar, lower accumulative grain yield (9 t/ha and 9.3 t/ha). However, the *Lower crop intensity* system has produced the least biomass (26.2 t/ha), approximately 4 t/ha behind the second lowest, *Higher legume*, and 9 t/ha behind the *Baseline* (35.2 t/ha). This lower biomass production (hence low stubble cover) is one of the main potential problems with the *Lower crop intensity* systems (leading to increased risk of erosion and organic carbon run-down).

As expected both the *Ley pasture* systems produced the largest amount of biomass (44 t/ha without N, 46 t/ha with N) (Figure 2b). Total biomass of the grass pastures is less than what was originally expected (grass only system ~10 t/ha more than the *Baseline* system), which is potentially a factor of higher winter rainfall in the first two years and three of four summers receiving below average rainfall (overall rainfall ~400 mm below average to December 2018), and pasture set-backs by forage harvesting rather than grazing. It will be interesting to assess if these differences in biomass production impact on soil carbon levels when the final comprehensive soil samples have been analysed.

Crop water use efficiency (WUE, efficiency of converting stored PAW and in-crop rainfall to yield) and rainfall use efficiency (RUE, efficiency of converting rainfall to yield) followed the same trends for both dry matter production and grain yield for all of the systems (Figure 2). WUE and RUE were highest for the highest-yielding crops. In six of the systems RUE was relative to the yield achieved, the exception being *Higher crop intensity* which was able to increase the proportion of rain used to grow biomass and grain with increased fallow efficiency. Conversely WUE favoured the *Lower crop intensity* system (relative to yield) with this system able to more efficiently convert the extra stored PAW to yield. *Higher legume* and *Higher crop diversity* had the lowest WUE relative to yield, due to these systems growing more canola and pulse crops.

All of the pulse crops to date have had significant amounts of PAW left deep in the profile at harvest, which has led to double crop opportunities after every pulse crop grown at this site (Figure 1). This has also meant the *Higher legume* system has grown the same number of crops as the *Higher crop intensity* system (six), despite having the same moderate planting water triggers as the *Baseline* system, which has grown two less crops.

The days in fallow versus in-crop varies dramatically between systems, with the *Lower crop intensity* system having the largest number (903 days) versus the *Higher crop intensity* system with the smallest (613 days) number of fallow days. The moderate crop intensity *Baseline* system was similar to the *Higher crop intensity* system at 630 days in fallow.

This site started with 350 kg N/ha (Figure 3). The cereal crops have reduced the available nitrogen levels more than the pulse crops grown in the same seasons, particularly in the high yielding 2016 winter crops. In 2018 the canola crop in *Higher crop diversity*, appears to have decreased available nitrogen more than the wheat in *Lower crop intensity*, which was more than chickpeas in *Baseline*. The long fallows in *Lower crop intensity* have allowed more nitrogen mineralisation; when combined with the lower yields this system has maintained the highest plant available nitrogen levels. The 70 t/ha of compost added to the *Higher soil fertility* system in November 2015 has allowed this system to increase mineralisation slightly, so plant available nitrogen levels are gradually increasing relative to the *Baseline* and *Higher nutrient supply* systems, for the same crop rotation.

Profitability of the systems to date has largely been driven by the high yields in two seasons; 2015 and 2016 winter crops (Figure 2a, Figure 4). The high starting available nitrogen levels at this site has allowed the *Baseline*, *Higher nutrient supply* and *Higher soil fertility* systems to grow 11 t/ha of cereal grain over the first two years, without the expense of nitrogen fertiliser. As such, these three systems have been the most profitable, with their only point of difference being a higher starter P fertiliser rate in the *Higher nutrient supply* and *Higher soil fertility* systems.

The *Higher legume* and *Higher crop diversity* systems were both planted to pulses in winter 2016 that yielded less than the barley, but the higher value of faba bean and field pea meant their income was similar to the much higher yielding barley (Figure 2a, Figure 4).

To date the *Lower crop intensity* system grew three crops, compared to six crops in the *Higher crop intensity* system, and achieved similar cumulative gross margins. These two systems were in fallow for the highly profitable crop achieved by the other systems in winter 2016. As a result the *Higher crop intensity* and *Lower crop intensity* systems are providing the lowest economic returns to date, but have provided similar returns to the *Baseline* since 2016.

Implications for growers

Preliminary gross margin analysis (Figure 4) shows the *Baseline* to be the most profitable system to date. This is largely driven by the exceptionally high yielding cereal crops in the first two years of the trial reaching close to water unlimited yield potential. The summer crops for the same period experienced below average rainfall and temperatures in the hottest 10% of years, and so achieved lower grain yield, crop WUE and the gross margins in the *Lower crop intensity* and *Higher crop intensity* systems

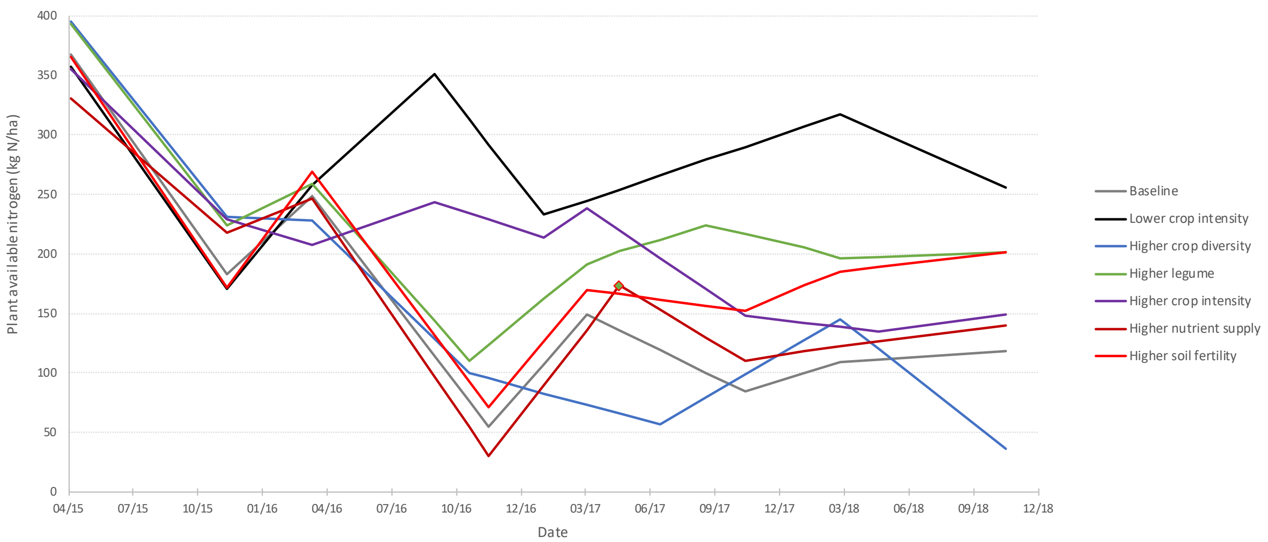

Figure 3. Dynamics of plant available soil nitrogen (nitrate and ammonia), measured prior to planting and at harvest of each crop. ◊ includes nitrogen added as urea in *Higher nutrient supply* system.

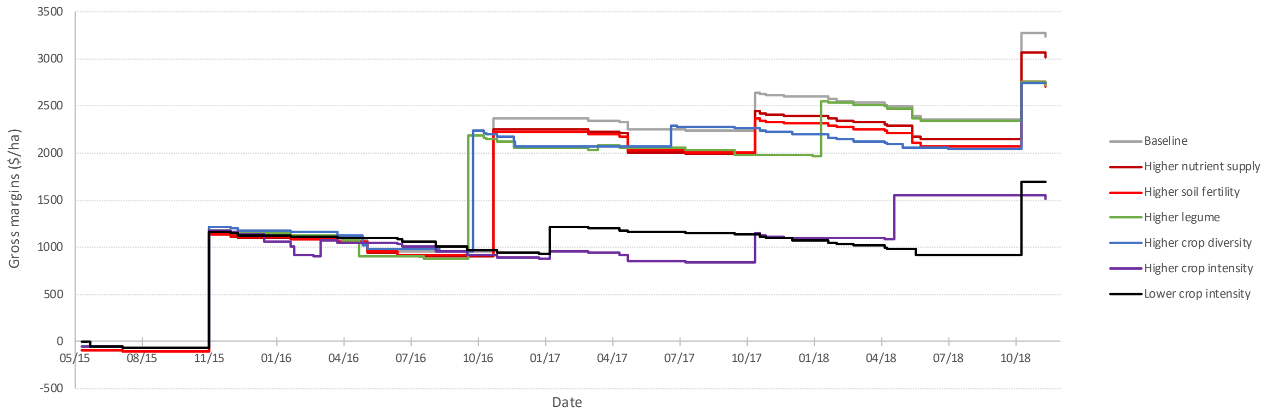

Figure 4. Cumulative cash flow for each of the systems at the Billa Billa site.

in this period. These systems are performing quite similarly to each other for both total grain yield and gross margin, despite the *Higher crop intensity* system growing an extra three crops. If this trend continues through the life of the trial it would suggest there is no financial difference between long-fallowing or taking double-crop opportunities to change between winter and summer crops.

Pulse crops are not using water as efficiently as the cereal crops to produce biomass and grain at this site, however the higher value of these commodities means the gross margin return (and $/mm) are equal to the cereal dominated systems. Additionally, the high sodium content of the soil below 30 cm has meant pulse crops have left extra water behind at harvest, providing more opportunities to double-crop.

Deep planting chickpea with a precision planter at the Billa Billa farming systems site.

Acknowledgements

The team would like to thank the trial co-operator, local growers and consultants for their ongoing support and contribution to the project. Thanks also to the Grains Research and Development Corporation and the Department of Agriculture and Fisheries for funding the project (DAQ00192).

Trial details

Location:	Billa Billa
Crops:	Bambatsi grass, sorghum, canola, chickpea and wheat
Soil type:	Belah, Duplex
2018 rainfall:	420 mm

Canola starting to flower in *Higher crop diversity*, with wheat in *Lower crop intensity* behind.

Northern Farming Systems site—Mungindi

Andrew Erbacher
Department of Agriculture and Fisheries

RESEARCH QUESTIONS: *Can systems performance be improved by modifying farming systems in the northern grains region? | What are the trends that are expected and how will these changes impact on the performance and status of our farming systems?*

Key findings

1. Summer break crops reduced levels of cereal soil-borne disease and allowed more even and higher yielding wheat crops in 2018, however they were the least profitable.
2. Root lesion nematodes continued to decline, even under susceptible crops due to the dry growing conditions of 2017 and 2018.
3. Higher nitrogen supply did not increase plant uptake or yield due to low in-crop rainfall, but this extra nitrogen is still available in the soil profile for following crops.

Background

The Mungindi dryland farming area is based mainly on winter cropping systems; primarily cereals (wheat and barley) with pulses (chickpea) and limited opportunity summer cropping (dryland cotton and sorghum). Local rainfall is variable and winter cropping relies heavily upon stored moisture, typically from the highest rainfall months in late summer.

Most farms operate on a zero or minimum tillage system with a fairly set rotation of cereal/cereal/chickpea. Local knowledge of root lesion nematodes (RLN) is limited, however soil samples taken in some long-term cropping areas north of the border have shown significant numbers while RLN levels are typically lower to the south.

The trial site is located 22 km north-west of Mungindi towards Thallon on a Grey Vertosol soil with a plant available water capacity (PAWC) of 180 mm. The site has been cropped for 30 years and is representative of a large proportion of cropping in the region. The site had high RLN populations (*Pratylenchus thornei*; 6-26/g of soil). The trial area has been fenced to protect the trial site from local wildlife.

What was done

Six systems were identified as research priorities through consultation with farmers and advisers in the Mungindi Cropping Group.

1. **Baseline** represents a standard cropping system for the Mungindi region. The area is winter dominant with three main crops of wheat, barley and chickpea on a fairly set rotation of wheat/wheat/chickpea (with an average of one crop per year) and fertilised for 50% of seasonal yield potential for nitrogen, and a standard starter phosphorus rate.

Trial site location and layout.

2. **Lower crop intensity (winter)** is designed to be planted at a lower frequency i.e. when the profile is at least 3/4 full. The rotation includes wheat/barley/chickpea and the option of a cover crop when ground cover is below 30%.
3. **Lower crop intensity (mixed)** is similar to the *Lower crop intensity (winter)* system, but may also include summer crop options including dryland cotton as a high value crop followed by wheat that is able to be planted on a lower soil moisture trigger for stubble cover.
4. **Higher crop diversity** investigates alternative crop options to help manage and reduce nematode populations, soil-borne diseases and herbicide resistance. The profitability of these alternative systems will be critical. A wider range of 'profitable' crops may enable growers to maintain soil health and sustainability as the age of their cropping lands increase. Crop options include: wheat/barley, chickpea, sorghum, maize, sunflowers, canola/mustard, field pea, faba bean and mungbeans.
5. **Higher legume** focuses on improving soil fertility and reducing the amount of nitrogen input required through fertiliser by growing more pulse (legume) crops. One in every two crops is a legume and the suite of crops available are: wheat/barley, chickpea, faba beans and field peas all based on a *Baseline* moisture trigger. Non-pulse crops are fertilised at the same regime as *Baseline*.
6. **Higher nutrient supply** identifies the impacts of fertilising for a higher yield potential (90% of yield potential for nitrogen, and 100% replacement of phosphorus), in this environment. Nutrient supply is an area that is currently very conservative in the Mungindi region. The same crop as the baseline is grown, to compare the two treatments.

Systems were implemented in 2015 with a range of crops grown in 2015 and 2016 across the different systems (Figure 1). Unfortunately, low rainfall in 2017 did not accumulate sufficient PAW to plant any systems, so a wheat cover crop was planted in *Baseline*, *Higher nutrient supply*, *Higher legume* and *Lower crop intensity (winter)* systems to maintain ground cover above 30%. There was sufficient fallow rain to plant all systems to winter crops in 2018.

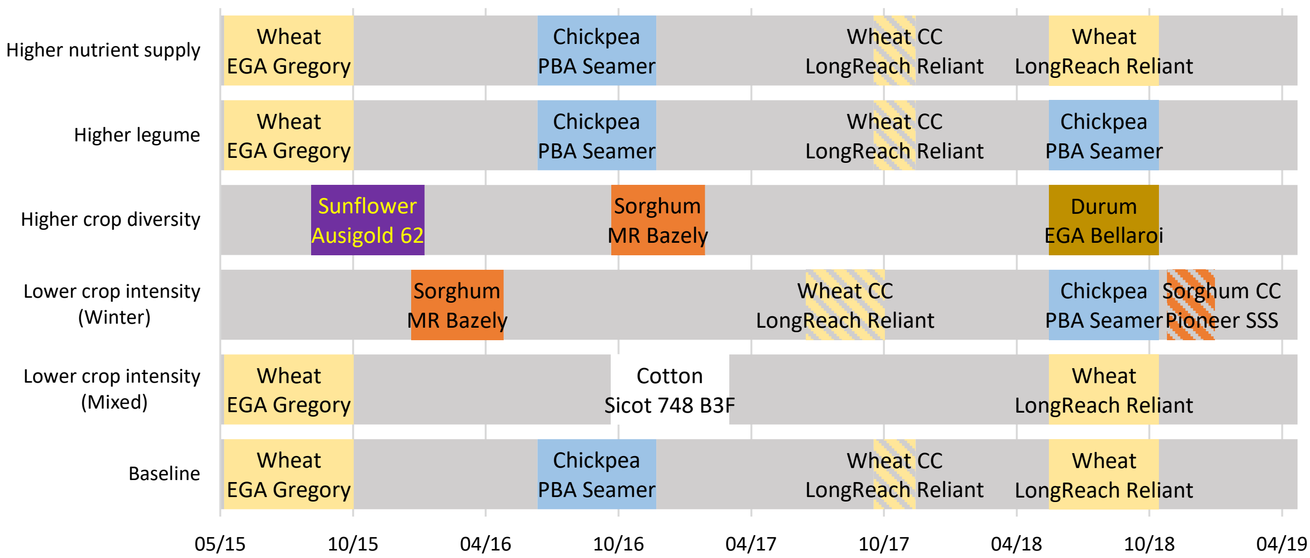

Figure 1. Crop sequences grown at Mungindi following the defined system rules, plotted on a time scale.

Crops grown at the Mungindi site will be represented by specific colours for all figures and graphs throughout this report (key provided right).

Results

Rain in February and March 2018 provided a good profile of moisture. Due to an extended dry period after this rainfall, the moist soil was 200 mm deep at planting on 29 May. As a result chickpeas were deep-sown into moisture, but limitations of research planting equipment meant wheat could only be planted to 150 mm with 100 mm soil above the seed. Since this was not deep enough to plant into moisture, it was decided to proceed at that depth then apply water to the seed row using trickle tape to establish these plots. As a result all systems were planted to winter crops in 2018 (Figure 1).

Baseline and *Higher nutrient supply* were planted to wheat with the *Higher legume* and *Lower crop intensity (winter)* systems planted to chickpea in 2018 after their cover crop in 2017. The *Lower crop intensity (mixed)* system was planted to wheat to provide stubble cover following the 2016/17 cotton crop. The *Higher crop diversity* system grew two crops resistant to *Pratylenchus thornei* prior to 2018 which reduced populations to 2.1/g soil, so durum wheat (EGA Bellaroi⏀—ranked as moderately resistant) was selected to bring the populations back below damaging levels (2/g soil) and also to provide stubble cover.

The three systems planted to wheat in 2018 had similar starting water. However the *Baseline* and *Higher nutrient supply* plots had sparse patches which were not present in the *Lower crop intensity (mixed)* system. These patches had an impact on yield and water use efficiencies (WUE), with *Lower crop intensity (mixed)* yielding 1.25 t/ha and a WUE of 11.1 kg/mm compared to a yield of 0.84 t/ha and WUE of 8.4 kg/mm for both the *Baseline* and *Higher nutrient supply* systems. The durum in *Higher crop diversity* was an even crop, but suffered from terminal drought, maturing earlier with tipped-out heads, producing a grain yield of 0.85 t/ha. Grain proteins were high for all wheat and durum plots (average 14.3% for wheat and 15.7% for durum), so nitrogen had no impact on yield differences this season. The deep-planted chickpea had a patchy establishment with ~50% of the plot area not germinating across both systems. The *Lower crop intensity (winter)* system had 50 mm more PAW (110 mm versus 60 mm) than the *Higher legume* system, but with low in-crop rainfall, both systems yielded similarly. *Higher legume* produced 0.20 t/ha of grain yield and *Lower crop intensity (winter)* yielded 0.23 t/ha.

With 65 mm of rain falling just prior to harvest all six systems had similar PAW post-harvest as at planting. That is ~120 mm in *Lower crop intensity (winter)* and ~70 mm in the other five systems. The *Lower crop intensity (winter)* system had very little stubble post-harvest, this rain provided an opportunity to plant a sorghum cover crop to improve ground cover at the start of a long fallow.

Overall system performance 2015-2018

The Mungindi environment has been challenging, with excessive rainfall in 2016 moving into an extended low rainfall period until 2019. This has severely impacted yields and number of crops planted.

Over the four years of the trial the most productive system has been the *Baseline* system, with two wheat crops and a chickpea crop (Figure 2). The *Higher nutrient supply* system

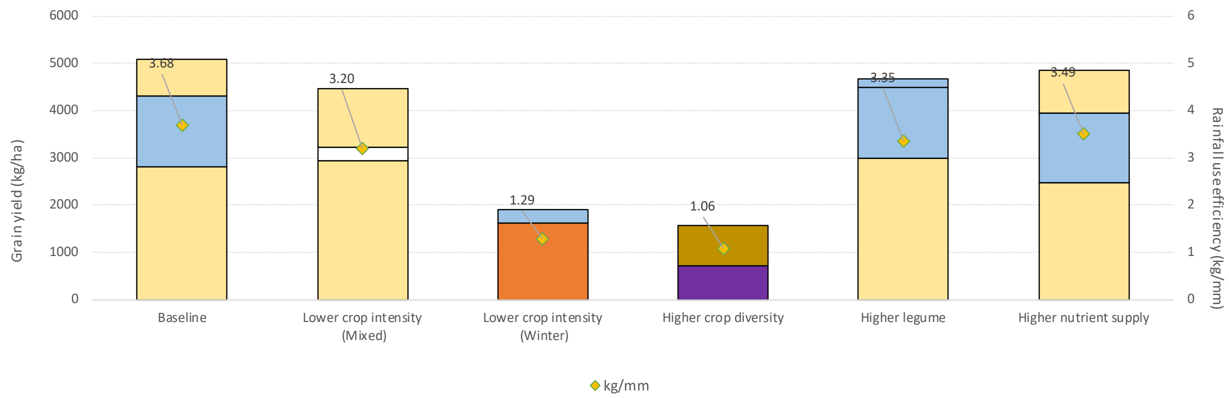

Figure 2. Cumulative grain yield and rainfall-use-efficiency. Colours represent crop types as indicated in Figure 1.

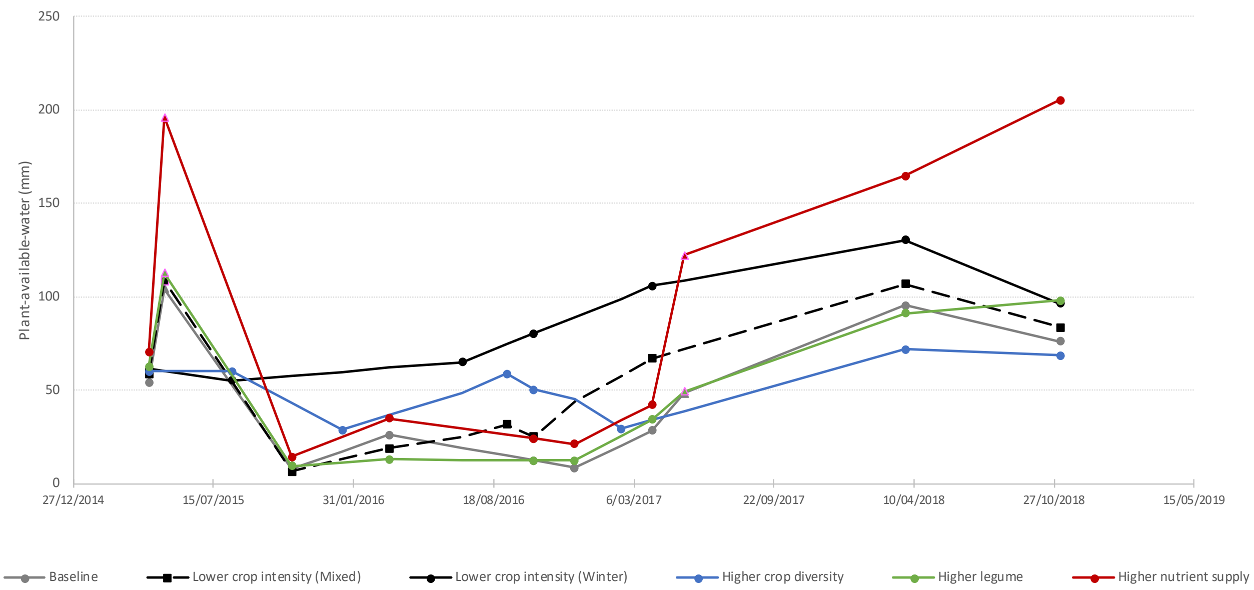

Figure 3. Dynamics of measured soil plant available nitrogen. ∆ is soil N plus added urea N.

has had the same crop rotation, but the higher nitrogen supply in 2015 caused the wheat crop to grow higher biomass early, which resulted in reduced grain yield and increased screenings under a dry finish. There is currently an extra 130 kg N/ha available in *Higher nutrient supply* over the *Baseline* (Figure 3). The 2018 wheat crops were also planted into similar nitrogen situations to 2015, with 95 kg N/ha in *Baseline* versus 165 kg N/ha in *Higher nutrient supply*, but with the lack of in-crop rain, neither crop grew excessive biomass, and both had similar N unlimited yields.

Baseline, *Lower crop intensity (mixed)*, *Higher legume* and *Higher nutrient supply* were dominated by winter crops, so all produced similar accumulated grain yields (4.5–5 t/ha) over the past four years (Figure 2). However, the use of summer crops in *Lower crop intensity* and *Higher crop diversity* systems has produced far less grain yield (at only 1.9 and 1.6 t/ha).

It is interesting to note that the biomass results do not follow the same pattern (Figure 4). The *Baseline*, *Lower crop intensity (mixed)*, *Higher legume* and *Higher nutrient supply* all have similar biomass, however the greatest amount of biomass was produced on the lowest-yielding system, *Higher crop diversity*, indicating that although the summer crops grew well in this system, they were not able to transfer this biomass to grain with high temperatures and low rainfall during anthesis and grain-fill.

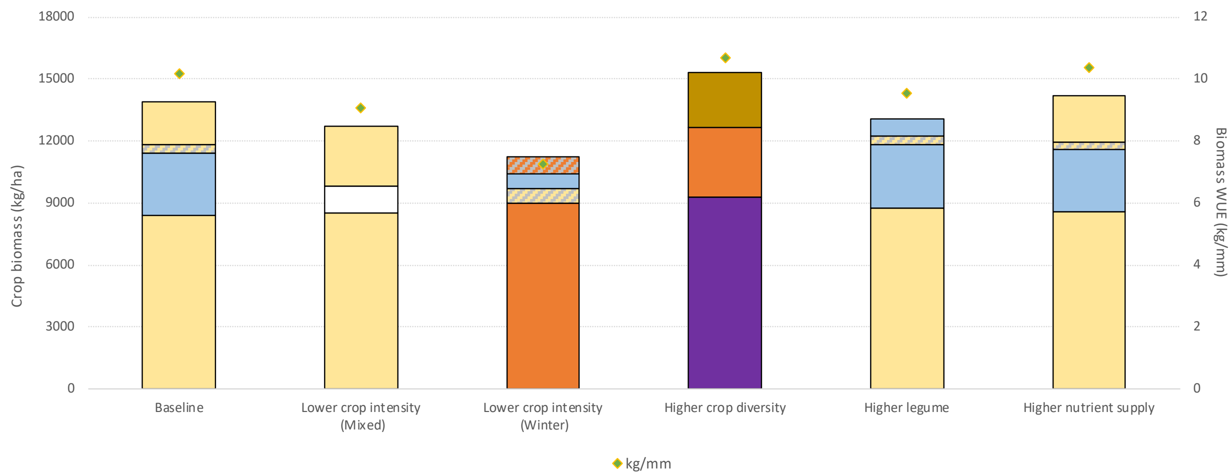

Figure 4. Cumulative total dry matter production for each of the systems. Colours represent crop types as indicated in Figure 1.

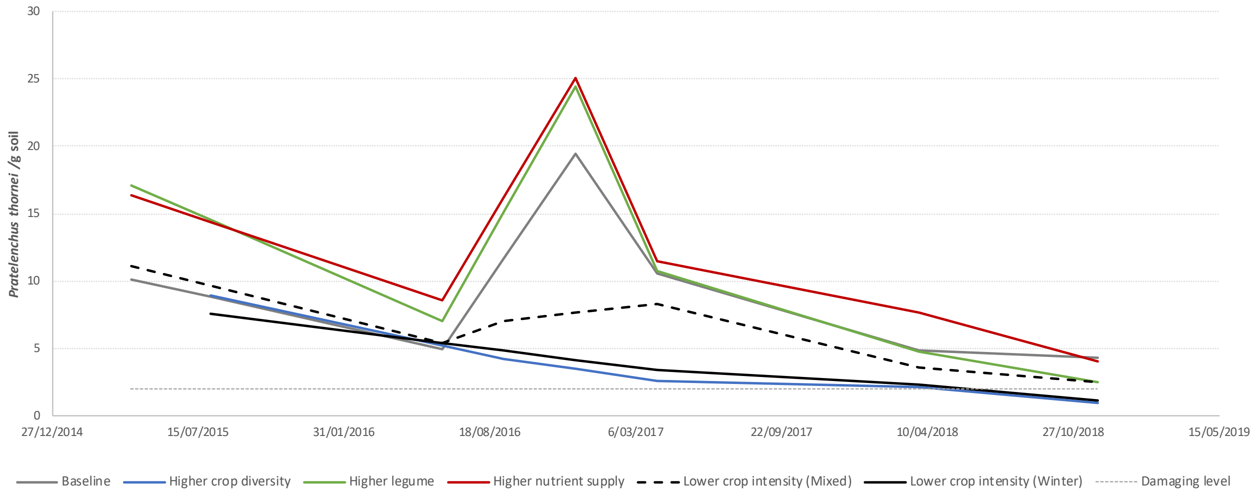

Figure 5. Dynamics of root-lesion-nematode populations over the life of the experiment.

Despite the yield outcomes of the summer crops, their inclusion in the *Higher crop diversity* system has had the greatest effect on reducing the high RLN (*Pratylenchus thornei*) populations present at this site (Figure 5). The *Lower crop intensity (winter)* system that had a RLN resistant crop in 2015-16, then remained fallow until 2018 has had a similar reduction in RLN over the same period, as the *Higher crop diversity*'s two resistant crops. Similarly as previously mentioned, the 2018 wheat yields in the *Lower crop intensity (mixed)* system benefited from the summer break-crop, although with only one resistant crop, RLN populations are not as low as the *Higher crop diversity* system.

This site has been quite dry since 2017, as such RLN have decreased in all systems despite susceptible crops being grown (Figure 5). This means the four systems with RLN populations above damaging levels are a result of the RLN increases in 2015 and 2016 winter crops. As such the two systems growing either resistant crops or fallowed in these wet years, RLN populations have reduced and are now below levels likely to cause damage to a susceptible crop. This will put these systems at an advantage on a return to better seasons.

To date, the most profitable rotation has been a wheat and chickpea rotation. *Baseline* and *Higher legume* had the same cropping history and gross margin until 2018. The *Baseline* system was planted to wheat and *Higher legume* to chickpea in 2018, with the higher wheat yields and lower input costs making the wheat crop more profitable in this season. The *Higher nutrient supply* system had the same crop history as *Baseline*, but had the extra expense of higher rates of urea applied prior to the two wheat crops. With no yield advantage and reduced yield in 2015 from the applied fertiliser, profitability of the *Higher nutrient supply* wheat crops was lower than those in the *Baseline* (Figure 6).

The poor reliability of summer crops in this environment has meant the *Lower crop intensity (mixed)*, *Lower crop intensity (winter)* and *Higher crop diversity* systems have had the lowest returns to date. The most profitable summer crop to date has been sunflowers.

It is interesting to note that apart from the extra nitrogen fertiliser applied to three systems in 2015 and two systems 2017, the expenses of all the systems have been very similar to date, however with very large differences in income achieved (Figure 6).

Implications for growers

In 2015, the moderate nutrient supply strategy adopted in the *Baseline* system provided greater grain yields and profitability than the *Higher nutrient supply* system, because the *Higher nutrient supply* wheat crop used more water early in the season, grew more biomass, and flowered later, so then suffered from heat stress and terminal drought under a dry finish. Under the drier growing conditions of 2018, the extra nitrogen applied was not taken up by the crop, hence is still available for use by following crops.

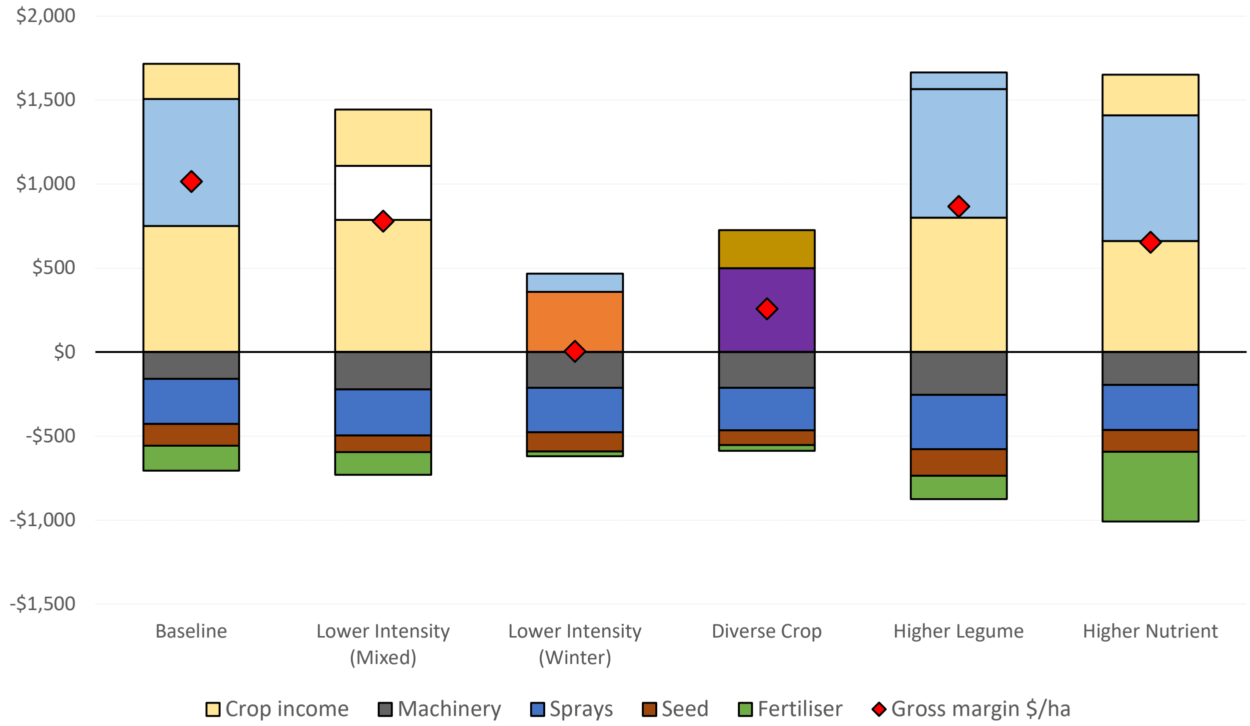

Figure 6. System gross margins, showing break-down of income and expenses.
Crop income colours displayed above the X axis represent crop types as indicated in Figure 1.

The use of summer crops and long fallows have proven useful in reducing soil-borne pathogens (specifically RLN, but not exclusively). Unfortunately, the summer crops grown have not been as successful at producing grain yield as the winter crop options. This is due to the crops experiencing hotter and drier summers than average, however these conditions are not unexpected in this environment.

These summer crops have been able to produce the highest biomass yields, which offers the opportunity to further investigate agronomic strategies to better convert this biomass to grain yield or the use of summer forage crops as an alternative to fill this break-crop role.

Acknowledgements

The team would like to thank the trial co-operator, local growers and consultants for their ongoing support and contribution to the project. Thanks also to the Grains Research and Development Corporation and the Department of Agriculture and Fisheries for funding the project (DAQ00192).

Trial details

Location:	Mungindi
Soil Type:	Grey Vertosol
Rainfall:	261mm (2018)

Even wheat following a summer break crop (L) beside weak patches of wheat in a continuous wheat, chickpea rotation (R).

The impact different farming systems have on soil nitrogen, phosphorus and potassium—Northern Region

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Research Questions: *Can systems performance be improved by modifying farming systems? | How does increasing legume frequency or nutrient inputs impact on system nutrient balance and use?*

Key findings

1. Most farming systems extract more nutrients than are supplied by common fertilisation strategies.
2. Increasing the frequency of legumes doesn't necessarily reduce nitrogen inputs required across the crop sequence and increases export of potassium.
3. Higher fertiliser application has maintained higher soil mineral nitrogen levels but rarely increased grain yield or total system nitrogen use.

Background

Growers face challenges from declining soil fertility, increasing herbicide resistance, and increasing soil-borne pathogens in their farming systems, hence change is needed to maintain farming system productivity and profitability. Consequently, Queensland Department of Agriculture and Fisheries (DAF), New South Wales Department of Primary Industries (NSW DPI) and CSIRO are collaborating on an extensive field-based farming systems research program, focused on developing farming systems to better use the available rainfall to increase productivity and profitability.

One of the central aspects was to examine how farming systems compared in terms of their requirements for nutrient inputs and their long-term impacts on soil nutrient status and cycling. Several system modifications explicitly targeted increasing the nutrient efficiency and overall nutrient supply in the farming system.

Table 1. Nutrient status of sites at the beginning of the project

Site	Mineral N (kg/ha)	Colwell P (mg/kg)		BSES P (mg/kg)		Colwell K (mg/kg)	
	0–90 cm	0-10 cm	10-30 cm	0-10 cm	10-30 cm	0-10 cm	10-30 cm
Billa Billa	366	22	3	33	7	518	243
Pampas	200	64	35	728	711	480	291
Spring Ridge	199	66	19	71	40	670	286
Trangie (grey)	106	50	6	62	10	506	235
Emerald	99	45	12	70	21	438	225
Narrabri	58	44	10	433	407	588	209
Mungindi	61	19	5	111	86	752	428
Trangie (red)	19	30	9	53	15	427	268

What was done

In 2014 research began in consultation with local growers and agronomists to identify the key limitations, consequences and economic drivers of farming systems in the Northern Region; to assess farming systems and crop sequences that can meet the emerging challenges; and to develop the systems with the most potential.

Experiments were established at seven locations; a large factorial experiment at Pampas, and locally relevant systems at six regional centres (Emerald, Billa Billa, Mungindi, Spring Ridge, Narrabri and Trangie (red and grey soils)).

The following report focuses on comparisons between the following systems implemented across the range of sites:

- **Baseline** represents common farming system practice in each district: dominant crops; sowing on moderate soil water threshold to approximate common crop intensities (often 0.75-0.8 crops per year); and fertilising to 50% crop yield potential.

- **Higher legume frequency** ensures every second crop is a legume across the crop sequence and uses high biomass legumes (e.g. faba bean) when possible.
- **Higher nutrient supply** increases the fertiliser budget for each crop based on a 90% of yield potential.

Sites were selected to represent a range of climatic conditions, soil types, nutritional status and paddock history. Each site was comprehensively soil tested at the beginning of the project. There is a considerable range in soil fertility across the sites (Table 1) which dramatically influenced the requirements for inputs of nitrogen (N) fertilisers.

Experimental procedures included measuring mineral nitrogen (nitrate and ammonium), both pre-sowing and post-harvest for each crop planted over the past four years. Grain content was also analysed for nitrogen (N), phosphorus (P) and potassium (K).

Results

How does increasing legume frequency impact on system N, P and K inputs and use?

Results indicate there was little impact in the requirement of N fertiliser when legume intensity was increased. Some sites (e.g. Emerald) did reduce the required N fertiliser (by 83 kg N/ha). At other sites, such as Trangie (grey soil) and Pampas, the *Higher legume* system increased N fertiliser required in subsequent crops by 25 kg N/ha compared to the local *Baseline* system. These findings can be explained by the *Higher legume* system exporting more N (avg. 30 kg N/ha) from the cropping system (through grain harvest) than *Baseline* (8 of 11 sites) (Table 2).

Table 2. Cumulative nitrogen dynamics for the *Baseline* and *Higher legume* systems (2015–2018).

Site	N export (kg/ha)		Applied N (kg N/ha)		Δ mineral N (kg N/ha)		System total N use (kg N/ha)	
	Baseline	Higher legume	Baseline	Higher legume	Baseline	Higher legume	Baseline	Higher legume
Billa Billa	220	259	12	17	249	194	261	211
Emerald	227	249	91	8	52	47	143	55
Mungindi	79	80	54	54	-22	-6	32	48
Narrabri	177	227	127	127	43	36	170	163
Spring Ridge	227	305	211	211	25	35	236	246
Trangie (grey)	113	106	54	80	-213	-221	-167	-141
Trangie (red)	108	117	84	78	-31	-38	53	40
Pampas (mod int.)	271	309	13	39	248	257	261	296
Pampas (high int.)	249	303	101	108	285	280	386	388
Pampas (summer)	237	233	78	109	288	231	366	340
Pampas (winter)	287	347	42	17	275	274	317	291

Note: Total N use is calculated from applied fertiliser and the mineral N balance - (ammonium and nitrate N) prior to sowing 2015 minus the mineral N post the 2018 harvest

Table 3. Cumulative phosphorus and potassium removal for *Baseline* and *Higher legume* systems (2015–2018).

Site	P export (kg/ha)		Applied fertiliser P (kg P/ha)		K export (kg K/ha)	
	Baseline	Higher legume	Baseline	Higher legume	Baseline	Higher legume
Billa Billa	41	34	27	36	57	66
Emerald	29	32	22	21	56	63
Mungindi	12	14	7	7	24	25
Narrabri	26	34	24	24	42	54
Spring Ridge	32	35	33	33	53	64
Trangie (grey)	15	14	35	35	19	22
Trangie (red)	17	19	35	35	23	26
Pampas (mod int.)	37	42	23	20	53	84
Pampas (high int.)	41	41	25	29	59	87
Pampas (summer)	40	33	21	21	45	70
Pampas (winter)	40	46	18	22	66	95

Note: P and K export calculated by grain content (%) x DW grain yield (kg/ha)

This was also reflected in total system N use (soil mineral N depletion plus fertiliser N inputs), with only six of the 11 *Higher legume* systems reducing total N use compared to *Baseline*; the largest reduction was 88 kg N/ha at Emerald.

Phosphorous export was variable across sites (Table 3). However, the *Higher legume* system increased the amount of potassium exported across all sites relative to *Baseline* (avg. 14 kg K/ha), with Pampas (moderate intensity) exporting 31 kg K/ha more compared to the *Baseline* system (2015 to 2018).

What are the consequences of increasing fertiliser inputs on system nutrient balance and use?

As predicted the *Higher nutrient* system increased the amount of N fertiliser applied at each site over the cropping sequence (avg. 83 kg N/ha extra) between 2015 and 2018 relative to *Baseline*. Results show that applying N fertiliser to aim for a 90th percentile yield potential may reduce the mining of soil available N, especially in soils with high fertility (e.g. Billa Billa). Also significant amounts of additional N applied remained in the mineral N pool, hence available in subsequent crops. Additional applied N in the *Higher nutrient* system resulted in an increase of exported N at seven of the 11 sites (Table 4).

Additional N applied in the *Higher nutrient* system reduced the depletion of background soil mineral N status at ten sites. On average across all sites the higher nutrient system had 43 kg N/ha more soil mineral N than the *Baseline* – i.e. about 55% of additional N applied

Field peas 2016 at Billa Billa.

was found in the mineral N pool. However, this varied greatly across sites. This data is highly dependent on the timing of sampling and previous crop, residue loads and types, and soil moisture conditions.

The additional P applied to *Higher nutrient* systems did not influence grain P export. There was no difference between K export compared to the *Baseline* systems at all sites. This was not unexpected as we did not see significant yield responses to the higher nutrient application strategies.

How do different crops impact N cycling and fallow mineralisation?

Given the diversity of crops grown across the sites in this project comparisons can be made between the mineral N dynamics in-crop and also in the fallow period after harvest for wheat and chickpea across multiple seasons and locations. In three of four comparisons (Emerald 2015 and 2016, Pampas 2016), there was no additional N accumulation after chickpea compared to wheat during the subsequent fallow after harvest. Where higher mineral N was recorded after a chickpea crop, it was associated with higher N at sowing (Table 5).

Table 4. Cumulative nitrogen dynamics for the *Baseline* and *Higher nutrient* systems (2015–2018).

Site	N export (kg N/ha)		Applied N (kg N/ha)		Δ mineral N (kg N/ha)		System total N use (kg N/ha)	
	Baseline	Higher nutrient	Baseline	Higher nutrient	Baseline	Higher nutrient	Baseline	Higher nutrient
Billa Billa	220	253	12	62	249	190	261	252
Emerald	227	246	91	147	52	33	143	180
Mungindi	79	86	54	125	-22	-26	32	99
Narrabri	177	158	127	201	43	15	170	215
Spring Ridge	227	235	211	316	25	-2	236	314
Trangie (grey)	113	96	54	160	-213	-174	-157	-14
Trangie (red)	108	157	84	261	-31	-225	53	36
Pampas (mod int)	271	257	13	89	248	229	261	318
Pampas (high int)	249	278	101	209	285	193	386	402
Pampas (summer)	237	243	78	116	288	235	366	351
Pampas (winter)	287	277	42	100	275	267	317	367

Note: Total N use is calculated from applied fertiliser and the mineral N balance - (ammonium and nitrate N) prior to sowing 2015 minus the mineral N post the 2018 harvest.

Table 5. Comparisons of wheat and chickpea influence on soil N use and subsequent fallow N accumulation across multiple sites and seasons.

Site/Season	Crop	Sowing mineral N (kg N/ha)	Harvest mineral N (kg N/ha)	End of fallow mineral N (kg N/ha)	Subsequent fallow mineral N accumulation (kg N/ha)
Emerald 2015	Wheat	105	59	153	94
	Chickpea	78	32	126	94
Emerald 2016	Wheat	126	12	114	102
	Chickpea	153	23	141	118
Pampas 2015	Wheat	184	117	179	62
(long fallow)	Chickpea	203	68	168	100
Pampas 2016	Wheat	83	17	61	44
(short fallow)	Chickpea	93	34	76	42

Note: Total N use is calculated from applied fertiliser and the mineral N balance - (ammonium and nitrate N) prior to sowing 2015 minus the mineral N post the 2018 harvest.

Implications for growers

Overall these results indicate that across our farming system sites the implementation of additional legume crops in the crop sequence has not reduced N fertiliser input needs nor reduced soil N use. The legumes are utilising soil mineral N to the same extent as cereal crops and have higher N export which offsets N fixation inputs. This result is consistent across a wide range of starting soil N conditions, from very high to low mineral N status where legumes would be required to fix N to meet their needs. These results significantly challenge the commonly held assumption that grain legumes will reduce N fertiliser needs in the crop sequence. As our capacity to grow high-yielding grain legumes has increased, so too has our harvest index and hence the ratio of N removed in grain to that left in biomass, thereby diminishing the contributions of residual N after the crop.

Phosphorous export was variable across sites, so no conclusions have been drawn regarding P, however the *Higher legume* system did increase the amount of potassium exported across all sites relative to *Baseline*—although this is not unexpected as legume seed has more than double the K content than cereal grains. In situations where K deficiency may be an emerging issue or where levels are marginal, this greater export under a *Higher legume* system may mean that nutrients will need to be replaced sooner or a higher level of replacement will be required.

It must be noted that although nutritional benefits were limited in the first four years of the project between systems, there were legumes (in particular chickpea) planted commonly within the *Baseline* systems (20-33% of crops planted). Growing chickpea in the *Baseline* system has followed current local grower practice, however has resulted in smaller differences between the *Higher legume*, *Higher nutrients* and *Baseline* systems.

The first four years of the farming system project showed that modifying crop systems through higher nutrients did balance the net export of nutrients (N, P) relative to the inputs in several cases. However, there have been few cases where we have seen a positive yield advantage from providing these additional nutrients. This may change as soils age and their inherent fertility declines.

Future comprehensive soil analysis across all sites will be interesting to investigate to detect changes in other parameters such as total N and organic carbon levels. Longer-term examination of cropping systems may lead to greater differentiation between systems and geographical location, providing greater insights into the impact different farming systems have on nutrient balances and long-term soil fertility.

Acknowledgements

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Impact of crop species and crop sequencing on nematode, crown rot and common root rot inoculum loads—Northern Region

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Research Questions: *Can systems performance be improved by modifying farming systems in the northern grains region? Specifically, what impact do crop species and crop sequences have on soil- and stubble-borne pathogens?*

Key findings

1. Barley and wheat crops led to increases in *P. neglectus*, while mungbeans, wheat and chickpea led to increases in *P. thornei*.
2. The non-host summer crops (cotton, maize, mungbean and sorghum) provided the greatest reduction in crown rot inoculum while most non-host winter crops had virtually no impact.
3. There was little impact from most species on common root rot levels with wheat the worst crop option, while common root rot declined under the moderately resistant barley variety Compass⁽ᴰ⁾.

Background

While advances in agronomy and improved performance of individual crops have helped grain growers maintain their profitability, current farming systems are underperforming. Soil- and stubble-borne pathogens are believed to be a major cause of the poor performance of the farming systems across the northern grains region. The three most common pathogens responsible for yield reductions are root lesion nematodes (RLN—*Pratylenchus thornei* and *Pratylenchus neglectus*), crown rot (CR—*Fusarium* spp.) and common root rot (CRR—*Bipolaris sorokiniana*). *P. thornei* are widespread particularly on Vertosols and can feed throughout the soil profile while *P. neglectus* occur on most soils and are mainly confined to the top 10 cm. RLNs have a wide host range; the main crops used in the region host *P. thornei*, hence their populations have increased in the absence of profitable non-host (break) crops. Significant yield loss (>40%) occurs in susceptible genotypes but more tolerant genotypes can reduce their impact.

Crown rot, a stubble-borne disease of winter cereals, is endemic across the northern grains region. Yield loss can be as high as 90% in wheat and the fungus can survive in wheat stubble for up to four years. Common root rot, hosted by winter cereals, is most severe in wheat and barley. Good resistance exists in wheat cultivars but barley cultivars vary widely in susceptibility.

Using crops resistant to these diseases with greater regularity in crop rotations, is one way to mitigate yield reduction. While past research has been conducted on each of these pathogens alone, rarely have the impacts of crop rotations on the full complement of soil-borne pathogens been assessed over several years. Results from the northern farming systems research sites have been examined to see how crop species and crop sequences have altered the pathogen complex through the crop rotation.

What was done

Experiments were established at seven locations; Pampas, Emerald, Billa Billa, Mungindi, Spring Ridge, Narrabri and Trangie (red and grey soils). These sites are investigating how several modifications to farming systems will impact on the performance of the cropping system as a whole over several crops in the sequence. Soil- and stubble-borne pathogens (0-30 cm) were monitored twice per year; pre-sow and post-harvest, using the PREDICTA® B DNA-based soil test. A total of 14 pathogens are being monitored across the cropping systems.

Results

The diversity of crops grown across sites in this project provides an opportunity to compare the change in pathogen loads for various crop types across multiple seasons. *P. neglectus* levels remained unchanged for the majority of crops except barley and wheat (Figure 1a). Barley showed an increase in *P. neglectus* while wheat had a number of outliers where nematodes increased from 2-4 /g soil. All of the wheat outliers were cultivar LongReach Spitfire⏀ which is rated moderately susceptible to susceptible (MS-S) for *P. neglectus*. Changes in *P. thornei* levels due to individual crops were mixed (Figure 1b). *P. thornei* numbers increased under mungbeans, while both chickpea and faba beans also showed a tendency for *P. thornei* levels to increase. The summer crops, cotton, maize, sorghum and sunflowers all showed declines in *P. thornei* levels at harvest. Responses in wheat were quite varied with outliers showing increases of 2-15 nematodes/g soil, but equally levels fell by 2-13 nematodes/g soil in some cases. There was no varietal effect due to wheat cultivar as all the outliers, both increasing and decreasing in nematodes, were crops sown to LongReach Gauntlet⏀, which is rated moderately resistant (MR) to *P. thornei*.

The primary host, wheat, recorded the biggest increase in CR levels along with barley (Figure 1c). The non-host winter crops; canola, chickpea and faba bean showed no reduction in CR levels while field peas showed a significant decline in the pathogen at harvest. The biggest decline was recorded in the non-host summer crops; cotton, maize, mungbean and sorghum.

Wheat, the primary host, showed no real increase in CRR, however, there were a number of outliers (Figure 1d). All bread wheat varieties sown were rated MS-S for CRR. The other crops showed no change or slight declines; the biggest decline came from the MR barley cultivar Compass⏀.

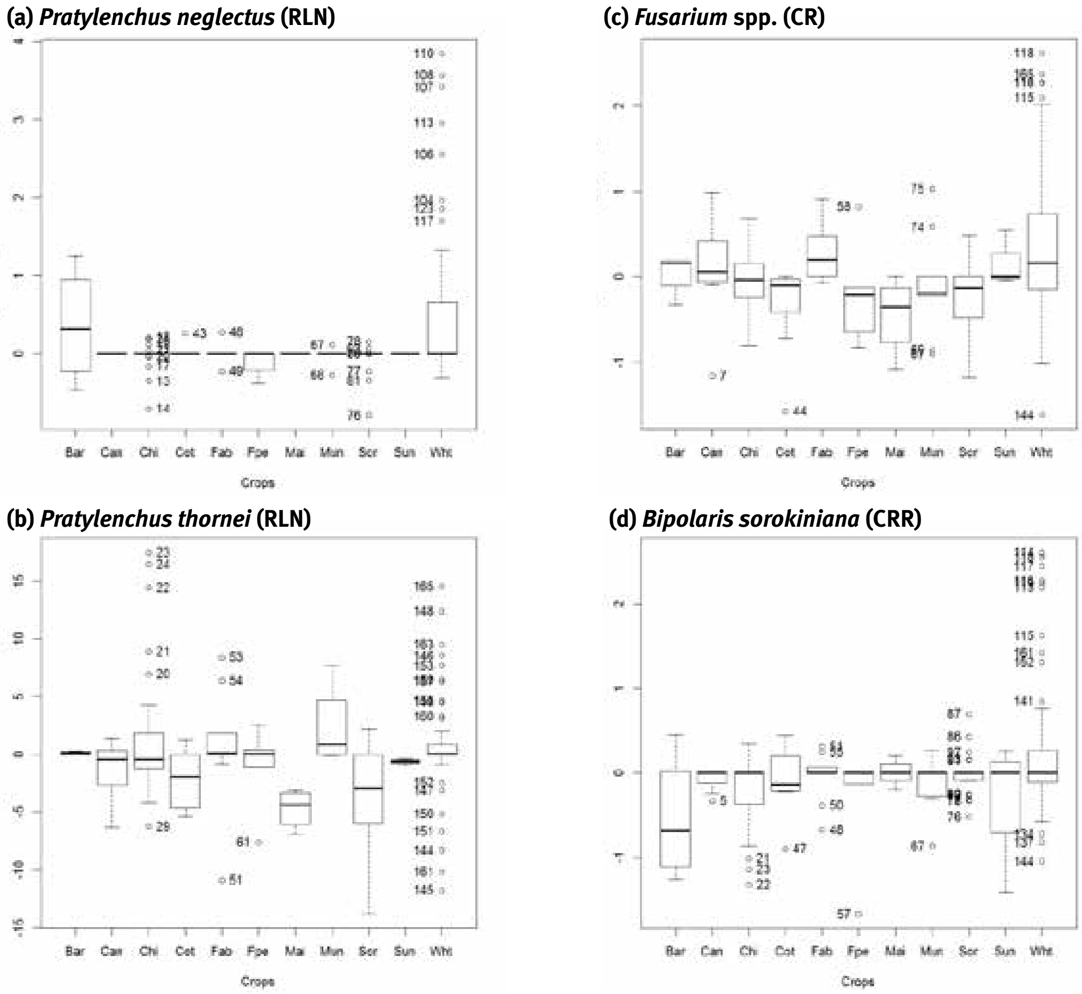

Figure 1 . The change in pathogen DNA levels, transformed to log10 or number of nematodes/g soil, from sowing to harvest, for a range of crops. Crops are barley (Bar), canola (Can), chickpea (Chi), cotton (Cot), faba bean (Fab), field pea (Fpe), maize (Mai), mungbean (Mun), sorghum (Sor), sunflower (Sun) and wheat (Wht).

The change in pathogen loads of selected three-phase crop sequences from March 2015 to March 2018 after summer fallow or harvest of a 2017 summer crop were also investigated. The high crop intensity sequence consists of five crops in three years with a range of winter and summer crops. The majority had mungbean double cropped in 2015/16 followed by a range of sorghum and winter crops. All these sequences, except wheat/long fallow/cotton, were duplicated under high nutrition inputs (*), mainly high nitrogen (N) in cereals.

The crop sequences saw virtually no change in *P. neglectus* numbers except for continuous wheat which led to an increase in nematodes over three years (Fig 2a). The *Higher crop intensity* sequence led to reductions in *P. thornei* nematodes. The wheat/long fallow/sorghum sequence also saw a decline in *P. thornei* numbers, and in both sequences the addition of high N inputs resulted in a greater decline in *P. thornei*. The wheat/chickpea/wheat and continuous wheat sequences led to modest increases in *P. thornei* numbers (Fig 2b).

The high N *Higher crop intensity* and wheat/long fallow/sorghum systems had large declines in CR inoculum, however, the addition of high N into a continuous wheat system led to a large increase in CR inoculum (2c). The popular wheat/chickpea/wheat system had no effect on CR inoculum loads (Fig 2c). The wheat/long fallow/cotton sequence had the biggest impact on reducing CRR inoculum (Fig 2d). The *Higher crop intensity* and wheat/long fallow/sorghum systems led to modest increases while the continuous wheat system gave the biggest increase in CRR inoculum (Fig. 2d).

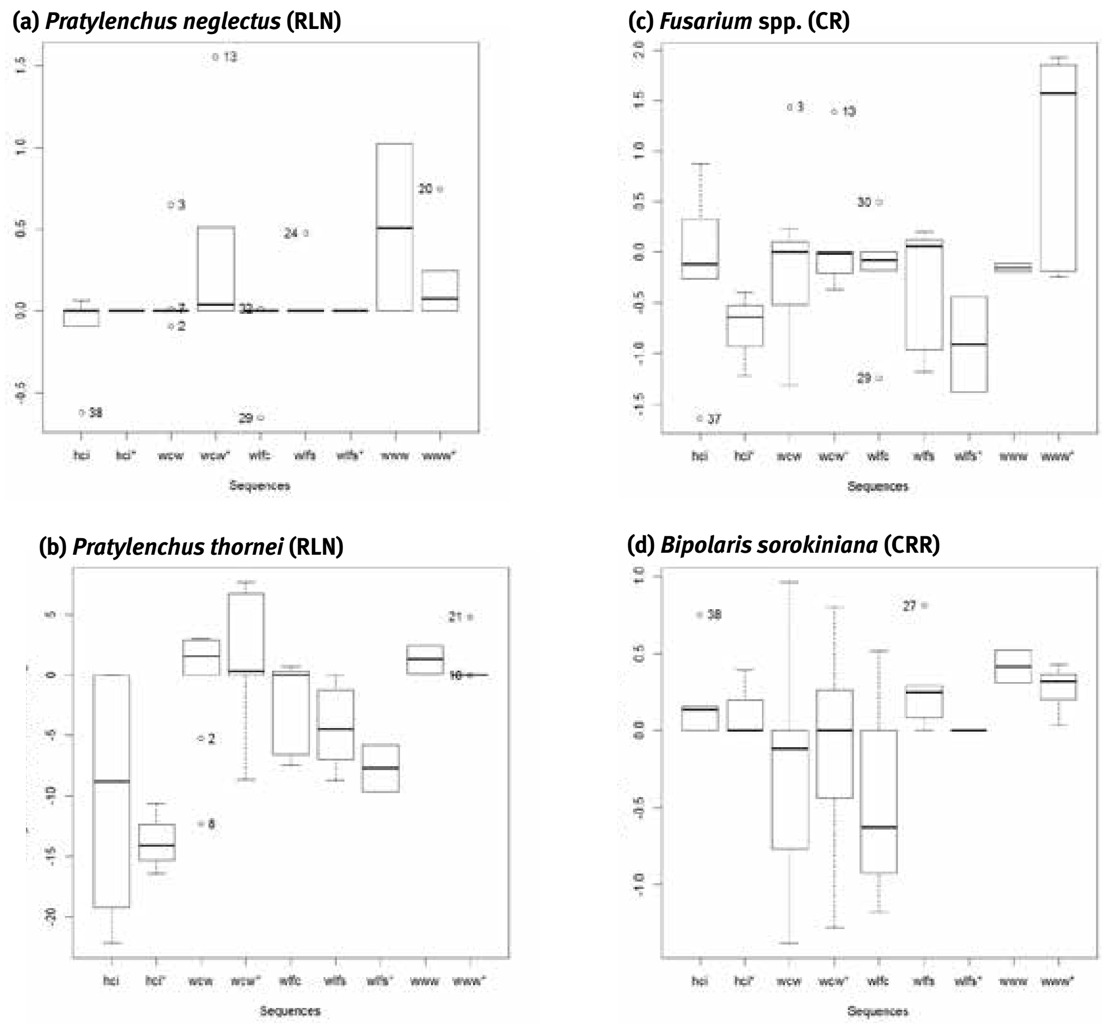

Figure 2 . The change in pathogen DNA levels, transformed to log10, or number of nematodes/g soil, from pre-sow in March 2015 to post fallow or harvest in March 2018 for a range of cropping and high nutrition (*) sequences. Sequences are; *Higher crop intensity* (hci), wheat/chickpea/wheat (wcw), wheat/long fallow/cotton (wlfc), wheat/long fallow/sorghum (wlfs), wheat/wheat/wheat (www).

Implications for growers

In terms of individual crop response to RLN, both barley and wheat led to increases in *P. neglectus*, while mungbeans, wheat and to a lesser extent chickpea led to increases in *P. thornei*. *P. thornei* numbers declined following cotton, maize and sorghum crops. The non-CR host crops (cotton, maize, mungbean and sorghum) provided the best way to reduce CR inoculum while the non-host winter crops (canola, chickpea and faba bean) had virtually no impact on CR inoculum. There was little impact from most species on CRR levels with the primary host, wheat, the worst crop option while CRR declined under the MR barley variety Compass⌽.

The sequencing of crops can provide the biggest changes in pathogen loads. In regards to *P. neglectus*, the monoculture wheat system increased numbers, yet the remaining rotations had virtually no impact on population numbers.

Wheat/chickpea/wheat sequences are common in the northern grains region, but this study suggests that this sequence is prone to increase *P. thornei* numbers. *Higher crop intensity* systems using resistant host crops such as sorghum and maize under high nutrition reduced *P. thornei* numbers dramatically, but these systems are environment specific and are only economically viable in the higher rainfall regions.

In addition to increasing *P. thornei* numbers, the common sequence wheat/chickpea/wheat, with a single non-host pulse crop had no impact on CR levels, while the high crop intensity and long fallow summer crop systems had the biggest reductions in CR inoculum. This was probably due to these systems providing more time or an improved environment for stubble breakdown. High N input continuous wheat systems led to the largest increase in CR inoculum and highlights why this rotation is actively discouraged, especially in environments where stubble breakdown is slow.

CRR inoculum increased under continuous wheat, its primary host, but also under sorghum which warrants further investigation regarding its host status for this fungus. This observation is of concern, with the inclusion of summer crops such as sorghum providing a disease break for other pathogens such as CR and *P. thornei*.

Resistant or non-host crops may reduce inoculum loads, but several consecutive resistant crops coupled with fallows offer the best rotation option to reduce very high pathogen loads. Once reduced, applying rules to limit the consecutive use of host crops may reduce the rate of population growth and keep pathogens under threshold levels.

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PREDICTA® B sampling conducted on the row post-harvest at Emerald.

Impact of crops and crop sequences on soil water accumulation and use in farming systems—Northern Region

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Research Questions: *Can systems performance be improved by modifying farming systems in the northern grains region? | What are the impacts of crops and crop sequences on soil water accumulation and use?*

Key findings

1. Grain legumes (chickpea, faba bean, field pea, mungbean) often leave more residual soil water at harvest than cereals, this difference is diminished due to lower subsequent fallow efficiencies and hence soil water is often similar at the sowing of the next crop.
2. Higher intensity systems have higher fallow efficiencies while lower intensity systems and those with more legumes have lower fallow efficiencies.

Background

The efficiency of soil water accumulation during fallows and the availability of that soil water for use by crops are key drivers of northern farming system productivity and profitability. Fallow water is stored and used as a buffer for more reliable grain production in highly variable rainfall patterns. So, fallow efficiency (i.e. the proportion of rain that accumulates in the soil profile) is critical, and is influenced by ground cover levels, seasonality or timing of rainfall events, the length of the fallow and the amount of water currently in the soil profile.

While advances in agronomy and the performance of individual crops have helped grain growers maintain their profitability, current farming systems are underperforming. In light of this CSIRO, Queensland Department of Agriculture and Fisheries (DAF), and New South Wales Department of Primary Industries (NSW DPI) collaborated to establish farming systems trial sites at seven northern grains region locations from Central Queensland to Central New South Wales (Emerald, Pampas, Billa Billa, Mungindi, Narrabri, Spring Ridge and Trangie) to evaluate the question; *Can systems performance be improved by modifying farming systems in the northern grains region?*

What was done

Here we compare the differences between different farming system strategies over the four experimental years in terms of fallow efficiency and water use efficiency (WUE) and the resultant impact on gross margin return per mm of rainfall ($/mm). We compare a range of modifications to the *Baseline* farming system strategy:

- **Baseline** approximates common farming system practice in each district: dominant crops only used; sowing on moderate soil water threshold to approximate common crop intensities (often 0.8 crops per year); and fertilising to median crop yield potential.
- **Higher crop intensity** increases the proportion of time that crops are growing by reducing the soil water threshold required to trigger a planting opportunity (e.g. 30% full profile).
- **Lower crop intensity** ensures soil water is >80% full before a crop is sown and higher value crops are used when possible.
- **Higher legume frequency** aims to have every second crop as a legume across the crop sequence and uses high biomass legumes (e.g. faba bean) when possible.
- **Higher crop diversity** uses a greater set of crops with the aim of managing soil-borne pathogens and weeds. Includes 50% of crops resistant to root lesion nematodes (preferably two in a row) and two alternative crops are required before the same crop is grown.
- **Higher nutrient supply** increases the fertiliser budget for each crop based on a 90% of yield potential rather than the baseline of 50% of yield potential.

Results

Crop type effect on subsequent fallow efficiency

Over four years at the seven farming systems sites, we have monitored water accumulation in the fallow following 306 crops. The collated data has been used to compare how different crop types impact on subsequent fallow efficiencies (Figure 1). This data shows the high variability in fallow efficiency that occurs from year to year but it also demonstrates some clear crop effects on subsequent fallow efficiencies.

Higher fallow efficiencies were achieved after winter cereal crops than winter grain legumes and canola. The median fallow efficiency following winter cereals was 0.27, while following chickpea and other grain legumes it was 0.14, with canola intermediate at 0.19. Median fallow efficiencies following sorghum were similar to wheat (0.26), but short fallows after sorghum were more efficient than long fallows. This difference between fallow length was less obvious following winter cereals, most likely due to lower evaporation losses in winter fallows, making them more efficient than summer fallows. Hence, short fallows after sorghum occurring in winter were the most efficient, while long-fallows spanning into summer were less efficient. This also explains the similar fallow efficiency of short (summer) and long fallows (summer + winter) after winter cereals.

Consequently, crop type and its impact on the accumulation of soil water in the following fallow is a key factor to consider in the cropping sequence. For example, a fallow receiving 400 mm of rain after a winter cereal would accumulate 108 mm on average, while the same fallow after a grain legume may only accumulate 56 mm. This difference could have a significant impact on the opportunity to sow a crop and/or the gross margin of the following crop in the cropping sequence.

Fallow efficiency in different farming systems

We have analysed how the different system strategies and their modifications have affected the efficiency of water accumulation over the fallow. Most *Baseline* systems achieve fallow efficiencies of at least 0.20 over the whole cropping sequence.

Higher legume and *Higher crop diversity* systems at some sites have increased the number of non-cereal crops grown. This appears to have reduced fallow efficiency in these systems (Table 1), perhaps from reduced stubble loads and ground cover. Conversely, *Higher nutrient supply* produced crops with greater biomass, which in some cases has allowed small increases in fallow efficiency. Another less obvious trend was that systems with a higher proportion of summer crops had higher fallow efficiency, which may be due to having more fallow periods during the winter when the evaporative potential is lower.

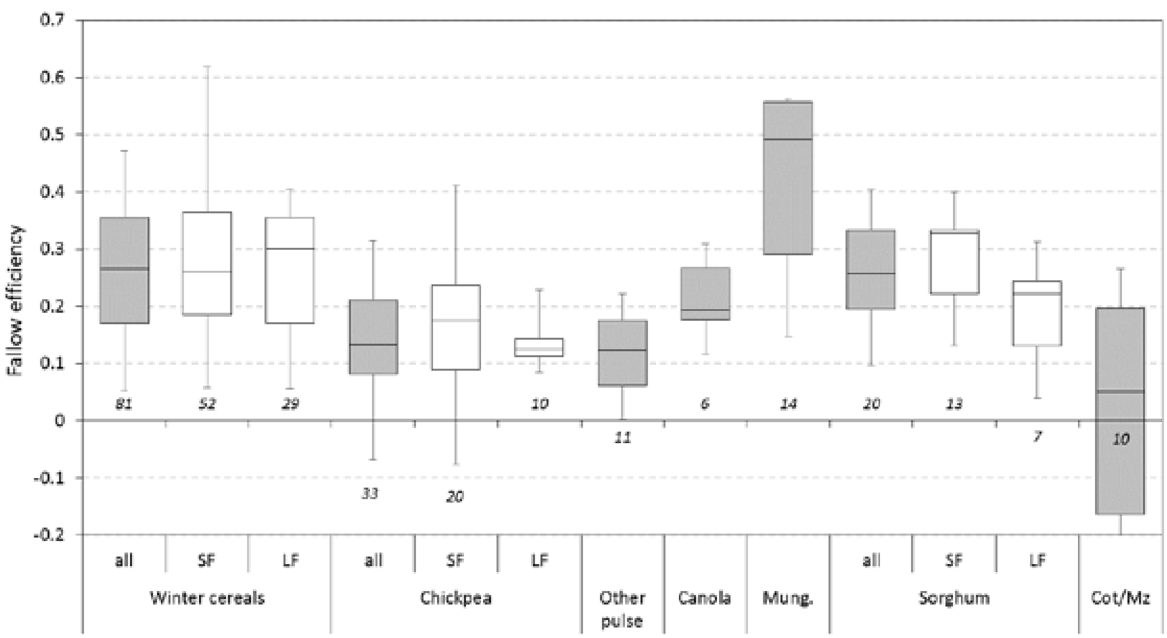

Figure 1. Summary of observed fallow efficiencies following different crops and fallow lengths (SF = short fallows 4-8 months, LF = long fallows 9-18 months) across all farming systems sites and treatments 2015-2018; winter cereals include wheat, durum and barley; other pulses include faba bean and field pea. Boxes indicate 50% of all observations with the line the median, and the bars indicate the 10th and 90th percentile of all observations. Italicised numbers indicate the number of fallows included for each crop.

Table 1. Comparison of efficiencies of fallow water accumulation (i.e. change in soil water/fallow rainfall) amongst different cropping system strategies at 7 locations across the northern grains region.

Crop system	CORE - Pampas			Billa Billa	Narrabri	Spring Ridge	Emerald	Mungindi	Trangie (red soil)	Trangie (grey soil)	All site average
	Mix	Winter	Summer								
Baseline	0.26	0.30	0.25	0.24	0.30	0.20	0.23	0.17	0.08	0.20	0.22
Higher crop diversity	0.21	0.27	0.28	0.28	0.25	0.12		0.34	-0.13	0.23	0.21
Higher legume	0.13	0.21	0.25	0.22	0.25	0.13	0.19	0.14	-0.08	0.28	0.17
Higher nutrient supply	0.23	0.28	0.32	0.29	0.29	0.16	0.23	0.17	0.13	0.29	0.24
Higher crop intensity	0.48			0.35	*	0.28	0.22				0.37
Lower crop intensity	*	0.07	0.21	0.29	0.12	0.16		0.19	-0.03	0.19	0.16

Colouring of numbers indicate the difference from the baseline system: black = similar to baseline; red = large reduction; orange = moderate reduction; light green = moderate increase; dark green = large increase.
***Crop system does not yet vary from the baseline in this regard**

The greatest differences in fallow efficiencies resulted from changing the cropping intensity in systems. Shorter fallows and double crops increased fallow efficiency, while having more long fallows reduced fallow efficiencies.

Fallow length effects on crop water use efficiency and gross margin

The previous section demonstrated the system differences in their ability to capture and store fallow rainfall. Consequently, the challenge becomes how to convert that stored water to higher grain yield and returns in the following crops.

Across the seven farming systems sites, 42 fallows of varying length were planted to one of eight common crops allowing a direct comparison of their impact on that crop (i.e. wheat after long or short fallow) (Table 2). These comparisons showed that longer fallow periods (under the same seasonal conditions) have resulted in more plant available water (PAW) at planting of the common crop in 41 of these 42 sequences.

In every comparison, the longer fallow resulted in increased grain yield, which in seven of the eight comparisons improved crop water use efficiency (WUE) i.e. grain yield/(in-crop rain + Δ soil water). The exception was the highest yielding crop, which had the highest WUE in these comparisons (sorghum at Pampas in 2016/17).

It is important to also factor in the fallow rain required to achieve the higher plant available water at sowing. Here we have calculated this as the rainfall use efficiency (RUE) of these crops, i.e. grain yield/ (prior fallow rain + in-crop rain). This shows that once the efficiency of fallow water accumulation is taken into account then, in most cases, there was little difference in productivity of the systems in terms of kg of grain produced per mm of rain, (exclusions were a chickpea crop following a 18-month fallow at Pampas in 2017 and a heat-stressed sorghum double-crop at Pampas in 17/18). Comparing these crops in terms of gross margin per mm of rain ($/mm—including fallow rain) showed that in most cases the best returns were from short fallows, which is the cropping intensity targeted by our *Baseline* systems (Table 2). Table 3 supports this, showing that the *Baseline* systems, with an average of 1 crop per year, had higher crop WUE, RUE and $/mm than both the *Higher crop intensity* and *Lower crop intensity* systems. The *Higher intensity* and *Lower intensity* systems had similar crop WUE to each other, but the *Higher crop intensity* systems achieved a higher RUE than the *Lower crop intensity* systems due to their higher fallow efficiency. Despite the differences in RUE, the gross margin return per mm of rainfall is similar for *Higher crop intensity* and *Lower crop intensity* systems, which is likely a result of incurring more planting and harvesting costs in the *Higher crop intensity* systems, balanced by the potential to grow more higher-value and higher-risk crops in the *Lower crop intensity* systems.

Table 2. Comparison of yield and water use of crops with varying lengths of preceding fallow, for a range of crops and locations. Double crop is 0-4 month fallow; Short fallow is 4-8 month; long fallow is 9-18 months.

Site	Fallow prior	Pre-plant PAW (mm)	Grain yield (t/ha DW)	Crop WUE (kg/mm)	Rainfall UE (kg/mm)	Crop gross margin ($/ha)	$/mm rain
Wheat							
Emerald, 2016	Double crop	100	2.35	8.3	5.3	512	1.15
	Short fallow	177	3.36	9.9	4.2	678	0.85
Billa Billa, 2017	Double crop	65	1.13	5.6	4.2	211	0.78
	Short fallow	125	1.49	6.7	4.5	278	0.84
Pampas, 2017	Double crop	53	1.56	3.4	3.4	258	0.56
	Short fallow	169	1.83	5.2	3.5	424	0.81
Sorghum							
Billa Billa, 16/17	Short fallow	131	0.62	2.3	1.7	-138	-0.37
	Long fallow	212	1.31	3.8	2.3	34	0.06
Pampas, 16/17	Short fallow	147	4.51	10.8	8.2	1033	1.88
	Long fallow	238	5.66	10.6	6.8	1082	1.30
Pampas, 17/18	Double crop	96	0.65	2.2	2.2	30	0.10
	Short fallow	146	4.02	8.4	7.2	775	1.39
Chickpea							
Pampas, 2017	Double crop	45	1.30	3.6	3.6	455	1.26
	Short fallow	169	1.68	6.4	3.8	651	1.47
	Long fallow	162	1.80	6.6	1.6	547	0.49
Billa Billa, 2018	Double crop	163	0.82	4.5	2.7	209	0.69
	Short fallow	203	1.48	6.8	3.1	628	1.31

Implications for growers

These trials show that the systems that most efficiently converted water (stored and rainfall) to grain and gross margin were those with a higher proportion of cereal crops and a cropping intensity of one crop per year. This strategy will ultimately lead to weed and disease problems across the northern grains region, so growers using these systems will need to change the seasonality of their cropping program to provide a disease or weed break. Our results suggest that, despite seasonal outcomes, the average crop WUE and the $/mm returns were similar for a long-fallowed transitions and double-cropped transitions between summer and winter cropping.

Acknowledgements

The research undertaken as part of this project (CSA00050, DAQ00192) is made possible by the significant contributions of growers through both trial cooperation and the support of the Grains Research and Development Corporation and Queensland Department of Agriculture and Fisheries. We would also specifically like to thank all the farm and field staff contributing to the implementation and management of these experiments, the trial co-operators and host farmers.

Table 3. Comparison of water converted to grain yield (crop WUE) efficiencies at the system level for the four sites with both *Higher crop intensity* and *Lower crop intensity* systems. Included are values averaged across the four sites for rainfall use efficiency (RUE), and gross margin returns per mm of rainfall for the life of the trials.

Crop system	CORE - Pampas			Billa Billa	Narrabri	Spring Ridge	System average		
	Mix	Winter	Summer				Crop WUE	RUE	$/mm
Baseline	8.7	7.8	7.8	12.3	5.2	10.9	8.4	6.4	1.67
Higher crop intensity	7.0			6.5	4.8	10.6	6.9	5.4	1.28
Lower crop intensity	5.1	8.0	10.2	8.9	3.8	6.8	6.9	3.8	1.33

Economic performance and system water-use-efficiency of farming systems

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Research Questions: *Can systems performance be improved by modifying farming systems in the northern grains region? | What is the impact on system WUE ($ gross margin return per mm of system water use)?*

Key findings

1. Differences of $204-670/year were found between systems across sites.
2. Cropping intensity is the major factor driving good/poor economic performance.
3. A system water use efficiency of $2.50 of crop income/mm of rainfall over the cropping sequence is achievable and could be used to benchmark current farming systems.

Background

Leading farmers in Australia's northern grains region perform well in terms of achieving the yield potential of individual crops. However, the performance of the overall system is harder to measure and less frequently well considered. Analysis suggests that fewer than one third of crop sequences achieve more than 80% of their potential water use efficiency despite having adequate nitrogen fertiliser inputs (Hochman *et al.* 2014). The key factors appear not to be related to in-crop agronomy but to the impact of crop rotations and are thought to relate to issues occurring across the crop sequence such as poor weed management, disease and pest losses, sub-optimal fallow management and cropping frequency. Similarly, farming systems are threatened by the emerging challenges of increasing herbicide resistance, declining soil fertility and increasing soil-borne pathogens, all of which require responses to maintain total system productivity. Questions are emerging about how systems should evolve to integrate practices that: maximise capture and utilisation of rainfall particularly when using high-value, low-residue crops; reduce costs of production and the likelihood of climate-induced risk; respond to declining chemical, physical and biological fertility; improve crop nutrition and synchrony of nutrient supply; suppress or manage crop pathogen populations; and reduce weed populations and slow the onset, prevalence and impact of herbicide resistance.

Because of the multi-faceted nature of these challenges, an important need is for a farming systems research approach that develops an understanding of how various practices or interventions come together, quantifies synergies or trade-offs and shows how these interventions impact on whole-of-system productivity, risk, economic performance and sustainability of farming systems. In this research we used the key metric of 'system water use efficiency' (WUE) to compare system productivity or profitability per mm of rain across environments and cropping systems. Importantly, this differs from commonly used 'crop water use efficiency' as it captures multiple years, with different crops, and accounts for both rainfall capture and loss during the fallow over a sequence of crops, the differences in the inputs required, as well as the productivity of different crops which may be influenced both positively, or negatively, by previous crops in the sequence or rotation. Hence, we have evaluated the system WUE as the $ gross margin return per mm of system water use (i.e. rain minus the change in soil water content) over the period of interest.

$$System\ WUE\ (\$\ GM/mm) = \frac{\sum\{(\text{yield} \times \text{price}) - \text{variable costs}\}}{(\sum rain + \Delta\ Soil\ water)}$$

What was done

Experiments were established at seven locations; Pampas near Toowoomba (referred to as Core site with 38 systems) and six regional centres in Queensland (Emerald, Billa Billa, Mungindi) and northern New South Wales (Spring Ridge, Narrabri and Trangie) where 6-9 locally relevant systems are being studied. Across these experiments the farming systems differed in strategies that modify crop intensity, crop choice and fertiliser input approach. These different farming system strategies are not predetermined and hence play out differently in different locations, based on the environmental (climate and soil) conditions at that location.

1. **Baseline** approximates current best management practice in each district against which each of the system modifications are compared. It involves only dominant crops used in the district; sowing on a moderate soil water threshold (i.e. 50-60% full profile) to approximate moderately conservative crop intensities (often 0.75-1 crop per year); and fertilising to median crop yield potential.
2. **Higher crop intensity** aims to increase the proportion of rainfall transpired and reduce unproductive losses by increasing the proportion of time that crops are growing; this is implemented by reducing the soil water threshold required to trigger a planting opportunity (e.g. 30% full profile) so that cropping intensity is increased relative to the *Baseline.*
3. **Lower crop intensity** aims to minimise risk by only sowing crops when plant available soil water approaches full (i.e. >80% full), and higher value crops are used when possible. This requires longer fallows and will lower crop intensity relative to the *Baseline.*
4. **Higher legume frequency** aims for every second crop to be a legume across the crop sequence using high biomass legumes (e.g. faba bean) when possible.
5. **Higher crop diversity** uses a greater set of crops with the aim of managing soil-borne pathogens and weed herbicide resistance risk through crop rotations. This is implemented by growing 50% of crops resistant to root lesion nematodes (preferably two in a row) and two alternative crops are required before the same crop is grown in the crop sequence.
6. **Higher nutrient supply** increases the fertiliser budget for each crop based on 90% of yield potential rather than the *Baseline* of 50% of yield potential.

System water use efficiency

Over the 3.5 years of experiments conducted for each system, data has been collected on the grain yields of crops, the total inputs of fertilisers, seed, herbicides and other pesticides, and operations. This has allowed the calculation of the accumulated income and gross margins for each of the cropping systems deployed at each location. Consistent prices for each commodity (10-year average adjusted for inflation) and inputs across locations were used to avoid introducing discrepancies in the data (Table 1). Grain yields were corrected to 12% moisture to account for variable harvest moistures.

Table 1. Commodity prices (10-year average) for each crop grown across the farming systems experiments.

Crop	$/t grain#
Barley	218
Wheat (durum and APH)	269
Canola	503
Chickpea	504
Faba bean	382
Field pea	350
Sorghum	221
Maize	281
Mungbean	667
Sunflower	700
Cotton	1090 ($480/bale lint)

#farm gate price with grading and additional harvesting costs already deducted.

Prices for inputs of fertilisers, herbicides, other pesticides and seed were based on market prices at purchase for each input. Costs for operations differed by crop to reflect different contract rates or machinery requirements. It should be noted we have not attempted to correct for overhead or other fixed costs associated with the farming enterprise; these are likely to vary significantly from farm to farm and region to region.

Results

As would be expected the total income and gross margins varied substantially across all sites, owing to the difference in rainfall, and hence crop productivity, and input costs required. There are large cost differences incurred between sites, due to differences in starting nutrient levels and weed status, which greatly influence the gross margin outcome between sites. For this reason, we focus mainly on comparing the economic outcomes between systems at the same site.

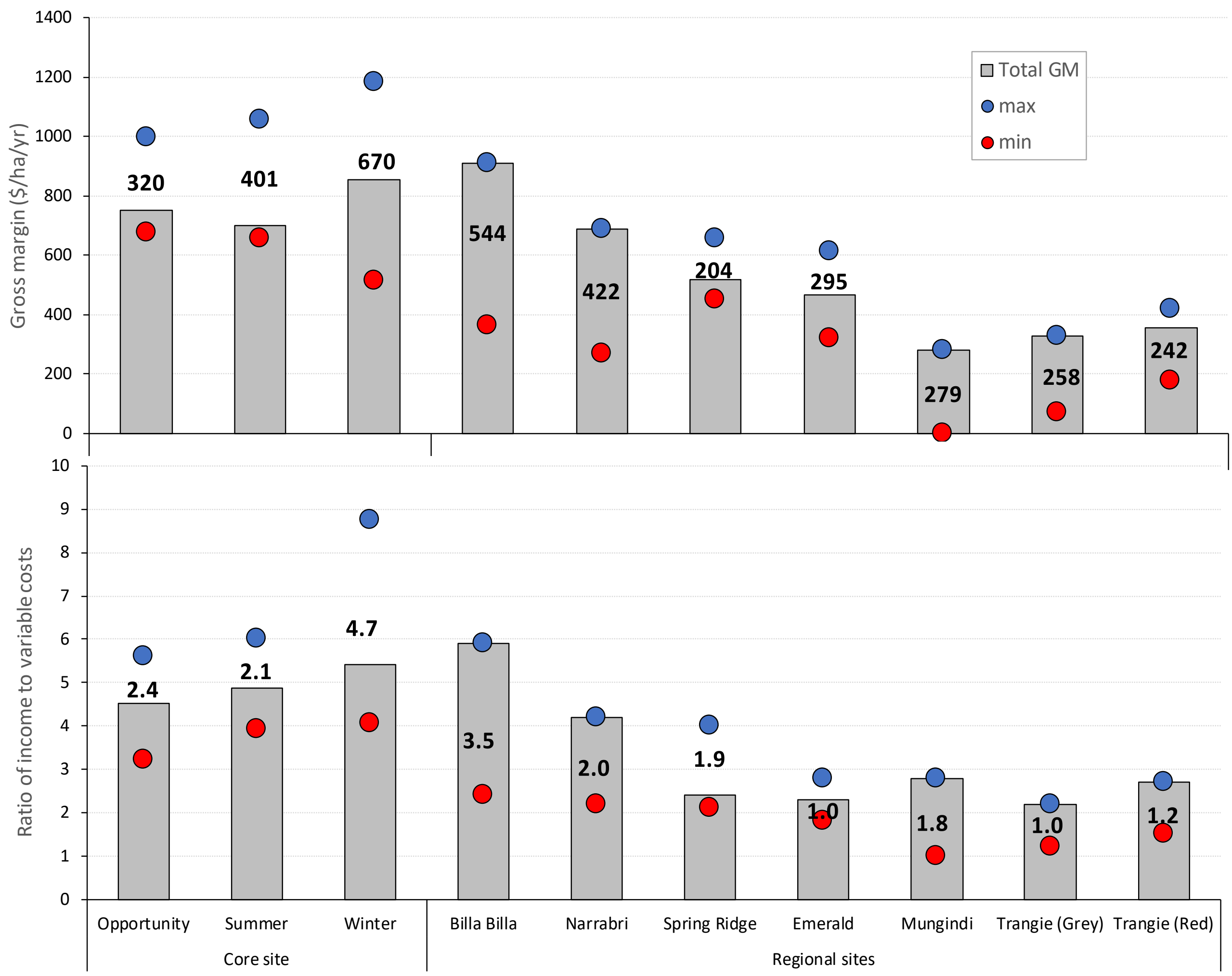

Figure 1. Range in system gross margin ($/ha/yr) and ratio of income to variable costs between the best and the worst performing farming systems, compared to the *Baseline* across 8 farming systems experimental sites.

Within each experimental comparison there was a significant gap between the best and the worst cropping system (Figure 1). The gap was highest at the core site in the winter rotation systems ($670/ha/yr) and lowest at Spring Ridge ($204/ha/yr). Similarly large gaps were observed in the return on variable cost ratios across the sites (1.0–4.7 difference), though the systems that were the best/worst for this metric were not necessarily the same. Overall, this highlights that there is a large difference in the profitability of farming systems within a particular situation. The best (or worst) system at each location was also not consistent. At most regional sites (except Emerald), the *Baseline* cropping system (designed to replicate current best management practice in a district) performed the best or as well as any altered system. At Emerald, the *Higher legume* and *Higher soil fertility* systems performed the best, $150/ha/yr higher than the *Baseline*. Amongst the Core site systems, the gross margin returns of the *Baseline* systems was exceeded by systems with *Higher crop diversity* or *Higher legume* by $120-$380 per year over the experimental period.

While there are several interesting differences between different farming systems at each experimental location, here we examine across the full range of sites how modifications to the farming system that were common across several sites (i.e. *Higher nutrient supply*, *Higher legume*, *Higher crop diversity*, *Higher crop intensity*, *Lower crop intensity*) have influenced the economic performance compared to the *Baseline* at each site. This was done by calculating the system WUE ($ GM/mm) in order to take out climatic influences and presented as a proportion of that achieved in the *Baseline* (Figure 2). This shows that systems employing the *Higher legume* and *Higher nutrient supply* systems were able to achieve similar system WUE to the *Baselines* at most sites. However, *Higher crop diversity* systems had highly variable impacts on system WUE, some sites

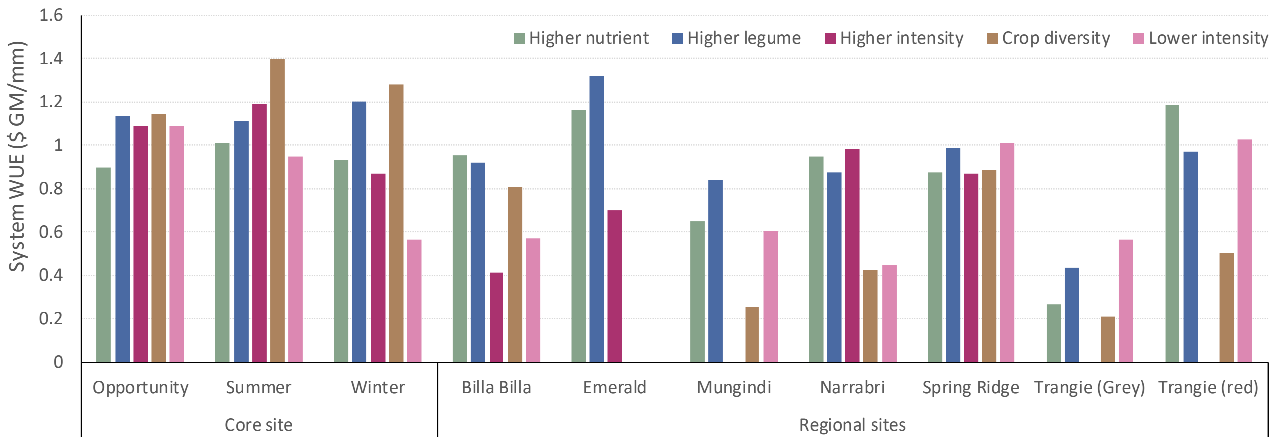

Figure 2. Relative system water use efficiency (i.e. $ GM/mm) of modifying farming systems compared to the *Baseline* at five regional sites and under three different seasonal crops at the Core site (Pampas).

increasing while other sites incurring a large cost. At the most favourable environments (Pampas, Spring Ridge and Narrabri), *Higher crop intensity* was able to maintain similar or slightly higher system WUE, however, there was a large cost from this strategy at other locations. Similarly, *Lower crop intensity* systems also reduced system WUE at several sites, but others achieved similarly to the *Baseline*.

Implications for growers

The economic performance of the farming system integrates many of the various factors that may influence their short and long-term productivity (water use efficiency, nutrient inputs and balance, yield responses to crop rotation). Across all farming systems sites, several of the modified farming systems could achieve similar or even greater profits, however this was not consistent across all sites. That is, in many cases there are options to address particular challenges (e.g. soil-borne diseases or weeds, nutrient run-down) that can be profitable. However, in some locations the options seem much more limited, particularly where risky climatic conditions (or challenging soils) limit the reliability of alternative crops in the farming system. The results here provide a snapshot in time over only a 3.5 year period. The longer term impacts of some of these farming systems strategies may yet to be fully realised and hence, some consideration of these results against this longer-term view is also required.

Acknowledgements

This research was conducted as part of Grains Research and Development Corporation funded projects CSA00050 and DAQ00192. We thank all the contributing field and farm staff for their hard work and participating farmers and advisors hosting these experimental sites.

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Core site 2017.

Weeds research

Herbicide-resistant weeds are becoming commonplace in farming systems throughout Australia. In the subtropical cropping regions of Queensland and New South Wales (NSW), herbicide resistance to fallow-applied knockdown herbicides, especially glyphosate (Group M), is making reliable control of key summer and winter fallow weeds difficult. There are now eight weed species resistant to glyphosate including flaxleaf fleabane (*Conyza bonariensis*), awnless barnyard grass (*Echinochloa colona*), feathertop Rhodes grass (*Chloris virgata*), windmill grass (*Chloris truncata*), liverseed grass (*Urochloa panicoides*), annual ryegrass (*Lolium rigidum*) and sweet summer grass (*Brachiaria eruciformis*). The most recently confirmed species is common sowthistle (*Sonchus oleraceus*).

The first population of glyphosate-resistant common sowthistle in Australia was confirmed in 2014, in a population from the Liverpool Plains, NSW (Heap, 2019). A recent collection of sowthistle populations from throughout Queensland and NSW is currently being evaluated by the Department of Agriculture and Fisheries weed science team for susceptibility to glyphosate. Results to date have shown that out of 154 populations tested, 26 have been confirmed resistant to glyphosate (≥20% survival) while another 17 have been identified as developing resistance (11-19% survival) (pers comm Jalaludin and Widderick 2019). The resistant populations are distributed throughout the northern cropping region (Figure 1).

In addition to glyphosate resistance, there are sowthistle populations with resistance to chlorsulfuron (Group B). Also, poor control of sowthistle is achieved with the commonly applied fallow herbicide mixture of glyphosate + 2,4-D, due to antagonism.

Herbicide resistance has been caused by an over-reliance on the same herbicide and herbicide modes of action. Herbicide resistance is best managed and prevented by using a diverse range of weed management tactics in combination. Such an integrated approach may include both chemical and non-chemical weed management tactics.

Alternative tactics for weed control are required. This includes examining the impact of non-chemical approaches such as targeted tillage, growing a competitive crop and cover cropping. However, there are also some potential herbicide-based options for effective fallow weed control which when used in combination with non-chemical approaches could provide effective control of sowthistle.

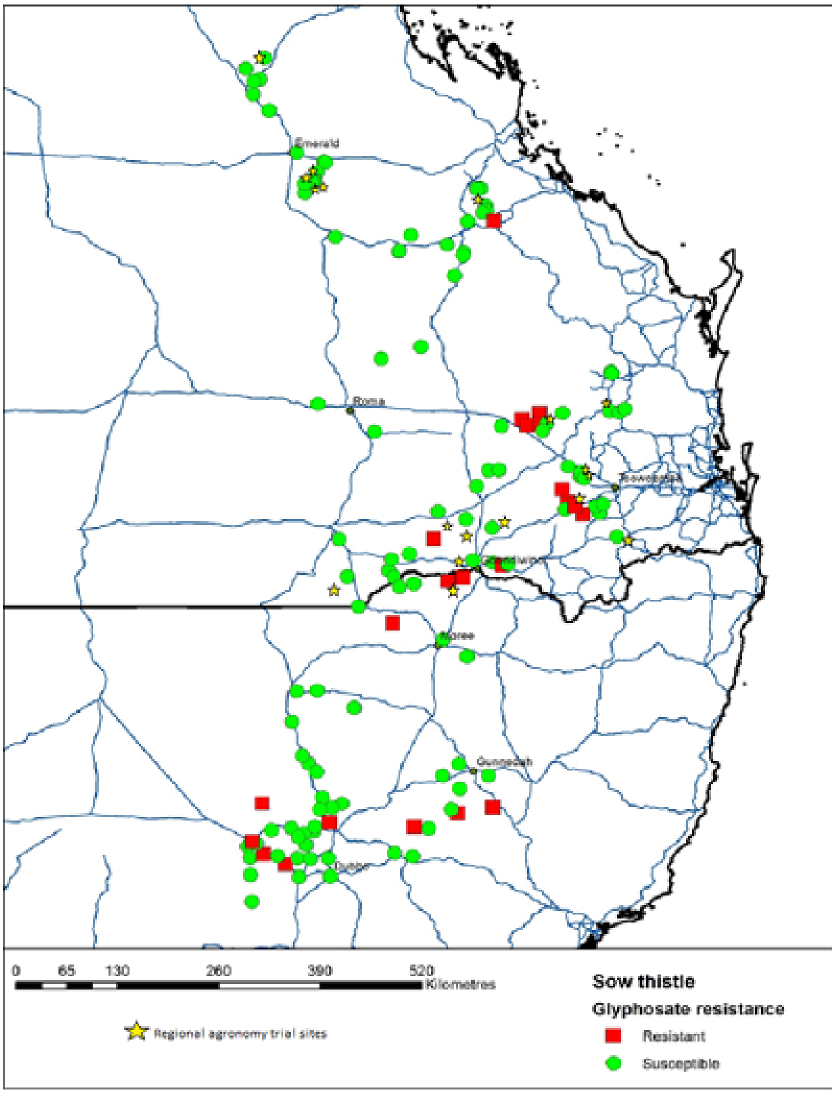

Figure 1. Map of glyphosate resistant and susceptible sowthistle (*Sonchus oleraceus*) populations across the northern grain cropping region and Regional Research Agronomy residual herbicide trial sites.

Residual (pre-emergent) herbicides are applied to the soil and are absorbed by the germinating seedlings. They offer an alternative to knockdown chemistries and are often able to provide longer term control of weeds by controlling several flushes of emergence. However, the efficacy of residual herbicides are influenced by a wide range of external and environmental factors including run-off, volatilisation and decomposition (Figure 2). These factors will impact on the persistence and availability of residual herbicides. As such, the reliability of residual herbicides can be variable. In addition, they can potentially persist for a long time and cause damage and yield reduction in subsequent susceptible crops.

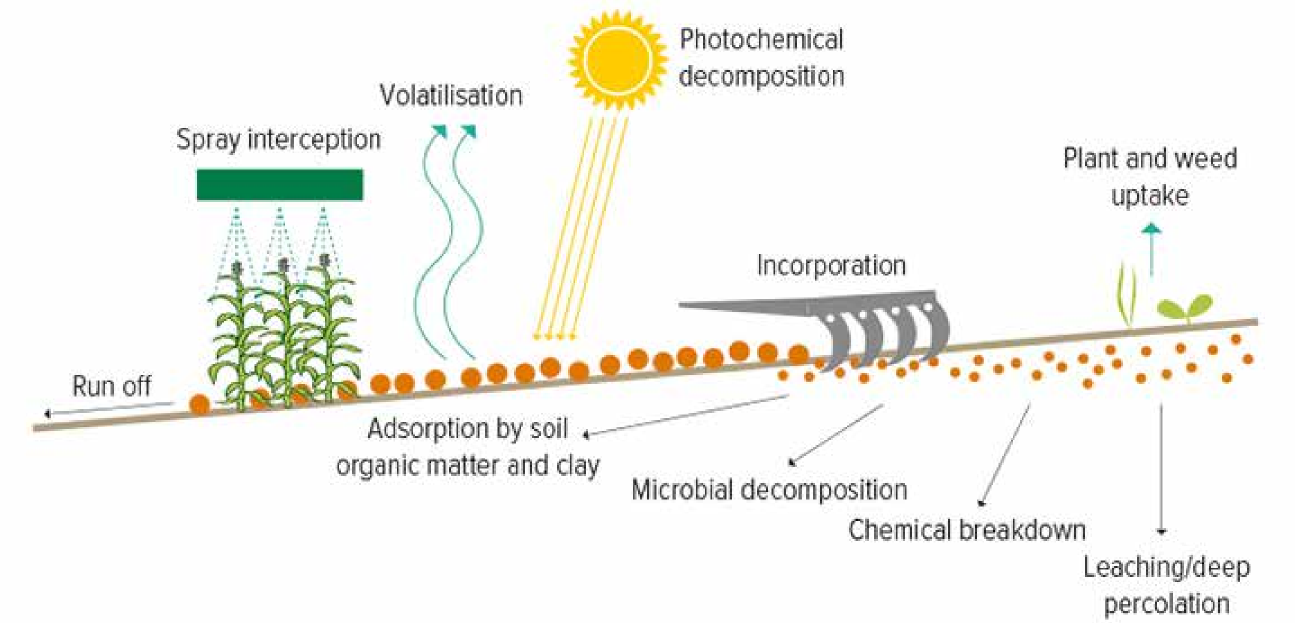

Figure 2. Factors that influence the persistence, availability and efficacy of residual herbicides (Source: Congreve and Cameron, 2018)

DAF's regional research agronomy and weed science teams worked together to conduct residual herbicide trials on a range of soil types and climates across Queensland (Figure 1). In the summer of 2015-16 a range of herbicides were tested, both alone and as a mixture, at nine sites spread throughout Queensland cropping regions.

These sites targeted five major weeds:

- sowthistle (*Sonchus oleraceus*)
- feathertop Rhodes grass (*Chloris virgata*)
- awnless barnyard grass (*Echinochloa colona*)
- sweet summer grass (*Brachiaria eruciformis*)
- stink grass (*Eragrostis cilianensis*)

In the summer of 2016-17, these trials were repeated with a greater focus on mixtures of herbicides and sowthistle.

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Residual herbicides—length of residual and efficacy: a summary of 18 trials across Queensland

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Key findings

1. Terbyne® Xtreme® and Valor® provided the best residual control of common sowthistle as stand-alone residual herbicides and as mix partners with 'grass active' herbicides.
2. Group K, Group D and Flame® provided the best residual control of grass weeds as stand-alone residual herbicides and as mix partners.
3. Herbicide mixtures provided improved control over individual products and are likely to provide more wide-spectrum control of a range of weed species.

Background

After many years of zero-till farming with chemical fallows, we are getting more pressure from weeds with resistance to the knock-down herbicides that were once effective. As such it is becoming more important to adopt other weed control tactics to stop seed set of our difficult to control weeds. Residual herbicides provide a range of different herbicide modes of action. When used in a rotation, residual herbicides can reduce the risk of herbicide resistance.

Many of these products are commonly used for in-crop weed control, but they can also offer an effective, alternative chemical approach for weed control in the fallow.

There are a range of environmental factors that affect the efficacy of residual herbicides. Therefore, residual herbicides should be applied in combination with other effective weed control tactics as part of an integrated approach, with the aim of zero weed seed set.

Recognising the increasing difficulty in effective fallow control of sowthistle and grasses and the potential role of residual herbicides, a series of field trials were established to compare efficacy of residual herbicide treatments across a range of environments and soil types.

NOTE: Products/combinations in this field experiment were tested FOR RESEARCH PURPOSES ONLY. Not all products used are registered for the purposes we have tested. Always read the label prior to use and only apply herbicides as approved in the label.

What we did

A series of nine fallow field trials were conducted across grain growing regions of Queensland (Border Rivers, Darling Downs and Central Queensland) (Table 1) during summer/autumn 2015/16 to evaluate the efficacy and persistence of a range of residual herbicides for the control of grass weeds (awnless barnyard grass (ABYG), feathertop Rhodes grass (FTR), sweet summer grass (SSG) and stink grass) or sowthistle in fallow (Table 2). The results from these trials were evaluated and treatment lists adjusted, for another nine field trials conducted in summer/autumn 2016/17 across the same geographic areas, but with a stronger emphasis on sowthistle.

In 2015/16, the trials targeted a range of difficult to control weeds, with treatments selected to target either grass weeds, broadleaf weeds, or a combination when both were expected. One site targeted sowthistle, one site targeted FTR and seven sites targeted mixed populations of sowthistle and grasses (one SSG, one FTR, one stink grass and four ABYG). After reviewing the 2015/16 results, 2016/17 treatments were determined, with a greater emphasis placed on evaluating mixtures of residual herbicides, and with a focus on establishing trial sites likely to grow sowthistle. One site (Callandoon) did not have any sowthistle emerge, and two sites (Mt McLaren and Gindie 1) had populations too low to measure significant differences. The site at Jondaryan 1 had additional split plots, with crop residue retained on half and removed from the other half of each plot.

Table 1. Location of trial sites and other details.

Site location	Soil type	Treatments applied	Weeds present
South-west Queensland			
Boomi	Black Vertosol	21 December 2015	ABYG
Toobeah 1	Brigalow	22 December 2015	ABYG
Toobeah 2	Poplar box duplex	22 December 2015	FTR
Callandoon	Alluvial box	27 October 2016	ABYG
Yagaburne	Brigalow	20 April 2017	Sowthistle
Mungindi	Grey coolibah	3 March 2017	Sowthistle
Darling Downs			
Kingaroy	Ferrosol	26 February 2016	ABYG, sowthistle
Warwick	Black Vertosol	25 February 2016	ABYG
Pampas	Black Vertosol	21 January 2016	Sowthistle ns.
Jondaryan 1	Black Vertosol	9 November 2016	Sowthistle (+/- stubble cover)
Jondaryan 2	Black Vertosol	27 April 2017	Sowthistle
Jandowae	Grey Vertosol	23 November 2016	ABYG, FTR, sowthistle
Central Queensland			
Gindie	Open downs	11 December 2015	SSG
Gindie	Poplar box duplex	10 December 2015	FTR
Goovigen	Callide alluvial silt	15 December 2015	Stink grass
Mount McLaren	Open downs	3 May 2017	Sowthistle ns.
Gindie 1	Open downs	5 April 2017	Sowthistle ns.
Gindie 2	Brigalow	27 April 2017	Sowthistle, SSG

Table 2. Residual herbicide treatments applied at up to 18 Queensland sites for the control of common sowthistle and difficult to control grasses.

Product/s*	Mode of action (MOA)	Rate (/ha)	Number of sites	Effective rate (trials with >90% reduction in weeds / trials with weed present)		Indicative price $/ha
				sowthistle	grass	
Untreated control	-		18			
Flame®	B	200 mL	17	3/8	9/11	4
Terbyne® Xtreme®	C	1.2 kg	18	6/8	2/11	35
Group $C_{triazine}$	C	3.3 kg	16	2/8	3/9	26
Group C2 (urea)	C	1 kg	8	0/2	3/7	14
Group D	D	3.3 L	18	0/8	9/11	53
Balance®	H	100 g	18	2/8	8/11	16
Group K	K	2 L	18	1/8	10/11	26
Valor®	G	280 g	9	4/6	2/3	53
Group B + Group H	B + H	200 mL + 100 g	17	6/8	10/11	20
Group B + Group K	B + K	200 mL + 2L	17	5/8	11/11	30
Group B + Group D	B + D	200 mL + 3.3 L	17	5/8	11/11	57
Group D + Group H	D + H	3.3 L + 100 g	17	3/8	11/11	70
Group C1 + Group D	C + D	1.2 kg + 3.3 L	9	5/6	2/3	88
Group C1 + Group B	C + B	1.2 kg + 200 mL	9	5/6	3/3	39
Group C1 + Group H	C + H	1.2 kg + 100 g	9	4/6	3/3	50
Group $C_{triazine}$ + Group K	C + K	2 kg + 2 L	9	2/5	3/3	42
Group H + Group K	H + K	100 g + 2 L	9	1/6	3/3	42
Group B + Group G	B + G	200 mL + 280 g	9	4/6	3/3	57
Group G + Group K	G + K	280 g + 2 L	9	5/6	3/3	80

*Chemical groups are used in place of product name where the product is not registered for use in fallow. Please note: Not all products tested are registered for use in fallow. Please check labels for use patterns and only apply as per label.

Residual herbicides were applied to small plots (ranging in size from 3x12 m to 6x20 m) along with unsprayed controls (Table 2). Herbicides were applied using a quad-bike at 100 L/ha of water with an air-inducted coarse (C) droplet size. Weed counts were made after each flush of emergence, following sufficient rain, and any emerged weeds were sprayed out with a knockdown herbicide to avoid double counting.

This report provides a summary of effective treatments across the 18 trial sites, with individual trial details previously reported in *Queensland grains research* 2016 and 2017/18. For the purpose of this report, a trial with effective control is defined as having one or more assessments where treatments were statistically different to the untreated control, and where greater than 90% reduction in weeds was achieved relative to the untreated control.

Results

Sowthistle

The efficacy of the residual herbicide treatments was variable across sites. However, there were some treatments that provided more consistent, effective suppression of sowthistle emergence (Table 2).

Terbyne® Xtreme® and Valor® provided the most consistent control of sowthistle when applied alone, being effective at six of eight and four of six trial sites respectively. Mixtures with these two herbicides also provided good control of sowthistle; when Terbyne® Xtreme® was mixed with Group B (5/6), Group D (5/6) or Group H (4/6) and when Valor was mixed with Group K (5/6) or Group B (4/6). Flame® provided less consistent control of sowthistle (3/8), but provided improved control as a mixture with Group H (6/8), Group K (5/8), or Group D (5/8). Interestingly, these three products provided poor control of sowthistle when applied alone (2/8, 0/8 and 1/8 respectively).

The duration of control differed between residual herbicide treatments. For example, at the Yagaburne site, all residual treatments initially provided a significant reduction in sowthistle emergence at 40 days after application (DAA). However, at 187 DAA, efficacy was greatly reduced in all but six of the treatments (Figure1). These treatments maintained control with sowthistle emergence not significantly different to 0 plants/m².

The duration of persistence will impact on the efficacy of weed control but can also impact on the potential damage to subsequent susceptible crops. Dry years generally increase the persistence of many residual herbicides beyond the time frames stated on labels.

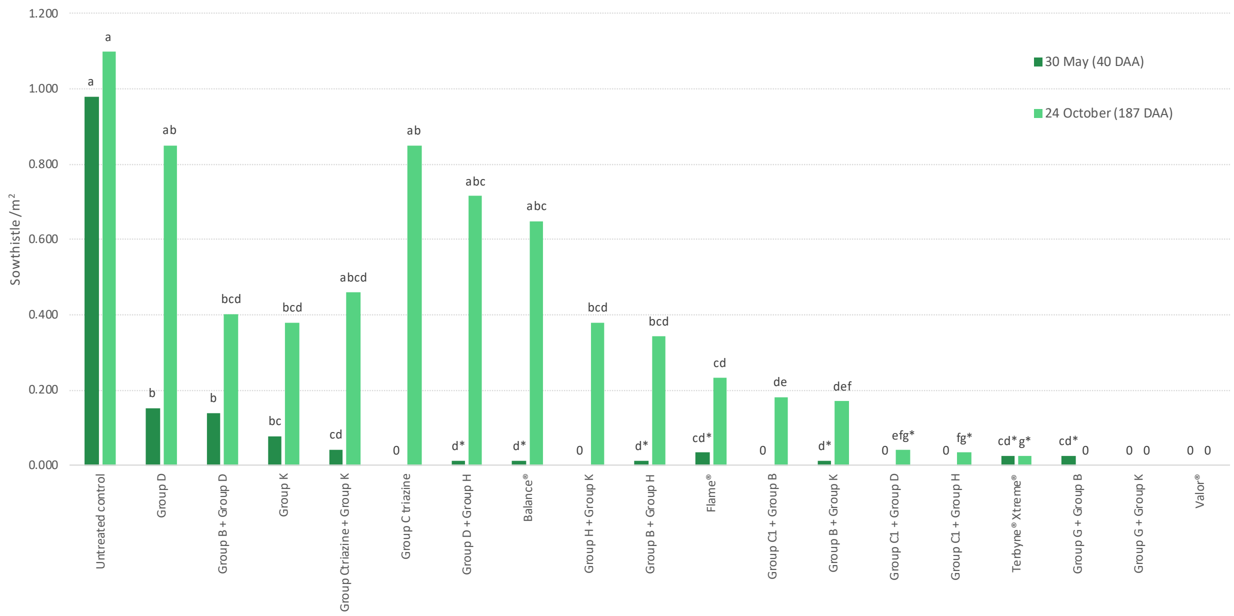

Figure 1. Sowthistle emergence (plants/m²) at Yagaburne following application of residual herbicides and counted 40 days after application (DAA) (30 May 2017) and 187 DAA (24 October 2017).
Columns within the same assessment date with similar letters are not significantly different. * = not significantly different to 0. P(0.05).

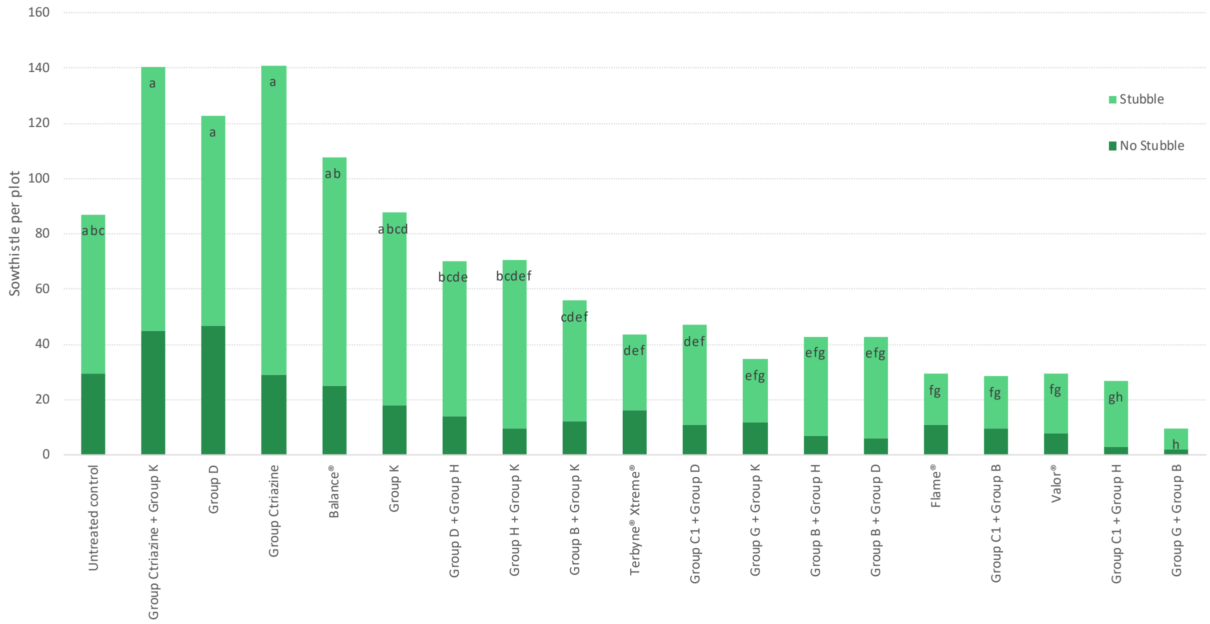

Figure 2. Sowthistle emergence (plants/m²) at Jondaryan 1 following application of residual herbicides in plots with crop stubble and without crop stubble. Counts were made 147 DAA (5 April 2017).
Columns with similar letters are not significantly different P(0.05).

Retaining crop stubble resulted in an increase in the emergence of sowthistle (Figure 2). Sowthistle requires an extended period (three days) of moisture to germinate and it is likely moisture was retained for longer under the crop stubble than in a bare fallow.

Previous research has shown crop residues can intercept a large proportion of residual herbicides, stopping them from getting to the soil target where they are activated. However, although the establishment of sowthistle was higher in the stubble plots, the presence of stubble did not reduce the efficacy of any herbicide treatments with a proportionate/equal reduction in emergence measured in both with and without stubble treatments (Figure 2).

Grasses

A range of grasses established over the 18 trials conducted over the two summers, with grass species varying between trials according to location and soil type. In 2015/16 eight sites measured significant herbicide treatment differences for grass weeds (four ABYG, two FTR, one SSG and one stink grass), as well as a further three sites with the revised treatments in 2016/17 (one SSG, one FTR and ABYG mixture and one ABYG).

Similar to sowthistle, these trials have demonstrated some treatments are able to provide more consistent reductions in grass weed establishment (Table 2). All three Group C products tested were not able to provide consistent control when applied alone (2/11, 3/9, 3/7), with effective grass control only achieved when rainfall was received within a few days of application. This is in spite of Terbyne® Xtreme® being the most consistently effective product applied alone for sowthistle control.

The other five mode of action groups (MOAs) performed well, (Group K 10/11, Group B 9/11, Group D 9/11, Group H 8/11 and Group G 2/3). Grass control was improved further by mixing multiple MOA. Nine of the eleven MOA combinations tested provided effective control of grasses at all of the sites, with the last two MOA combinations providing effective control at all but one site.

Similar to sowthistle control (Figure 1), herbicides varied in their ability to persist and provide continued control of multiple cohorts of grass weeds. Flame® and Valor® have demonstrated effective control beyond 180 days after application at a number of trials, with mixing partners often improving this control.

Implications for growers

Rotating weed control tactics is a key strategy in the management and prevention of herbicide resistance. Weed management shouldn't be prescriptive, but should take into account the environment (soil type, likely rainfall etc.) and future cropping aspirations. As such the results presented here are to help inform decision making and are not a recommendation for weed control.

Residual herbicides offer an opportunity for prolonged control of multiple flushes of weed emergence and for mode of action rotation. Our results show there are residual herbicide options for the effective suppression of sowthistle and grass emergence in fallows. Terbyne® Xtreme® and Valor® provided the best residual control of common sowthistle as stand-alone residual herbicides. Whereas Group K, Group D and Flame® provided the best stand-alone residual control of grass weeds.

Applying residual herbicides as a mixture, while more costly, has provided improved control compared to the individual products. Mixtures can also provide control of a broader spectrum of weeds, which is important when you consider 17 of the 18 trials in this series had both grass and broadleaf weeds germinating.

As residual herbicides can be variable in their control and efficacy, it is important to use them in combination with other weed management tactics. For example, if applying a residual for fallow weed control, make sure any weed escapes are controlled (either with knockdown herbicides, targeted tillage or manual removal), and consider following with a competitive crop to provide added control.

Many herbicides require moisture to break down. With our recent run of hot, dry seasons, be mindful that some residual herbicides can persist for longer than described on their labels.

Acknowledgements

We very much appreciate the support of the trial co-operator and consultants for their effort and contributions to the project, along with Department of Agriculture and Fisheries Weed Science and technical staff that supported these experiments. Thanks also to the Grains Research and Development Corporation and the Department of Agriculture and Fisheries (DAF) for funding the project.

The DAF biometry team and SAGI (co-funded by GRDC) have provided statistical analysis of the data presented.

Sowthistle seedling.

Treatments with and without stubble.

Seedling leaf pre- and post-spray.

Pathology research

Managing disease in mungbeans remains one of the major production challenges facing growers. Most mungbean varieties are moderately to very susceptible to all the main diseases. Powdery mildew (*Podosphaera xanthii*) is found wherever the crop is grown and can cause significant yield losses, particularly in late-planted crops where weather conditions are more favourable to disease development. Although newer varieties do have better plant disease resistance characteristics, most are still rated as 'susceptible' or 'very susceptible' to powdery mildew. Only Green Diamond⁽ᵖ⁾ and Jade-AU⁽ᵖ⁾ have a slightly higher rating of 'moderately susceptible'.

Plant resistance and the application of foliar fungicides are the only two viable options available for the management of powdery mildew in mungbeans. Recent trials indicate that the best level of control can be achieved when the first fungicide spray is applied between the first sign of the disease (normally found in the lower leaves of the vegetative crop) and when the disease can be found in the lower third of the canopy. The first spray should be followed by a second spray two weeks later.

Research into the management of powdery mildew in mungbeans has continued over the last twelve months. Research including that undertaken by the Queensland Department of Agriculture and Fisheries (DAF) is being used to create a mobile app for use on Android and iOS devices to help inform spray decisions. The app will provide a probability of return for a fungicide application and other information to help make an informed decision. The new app is being tested in 2019 for a public release in late 2019 or early 2020.

Preliminary scoping research into halo blight (*Pseudomonas savastanoi* pv. *Phaseolicola*) and tan spot (*Curtobacterium flaccumfaciens*) in mungbeans was also undertaken. Both these diseases can cause significant economic yield loss and only good cultural practices (for example using certified seed and crop rotations) offer any real management control at this stage.

Timing of fungicide application had the greatest impact on powdery mildew severity.

The impact of different management practices on the control of powdery mildew in mungbeans

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Research Question: *Does active ingredient, row spacing or plant population impact the effectiveness of fungicides on powdery mildew control in mungbeans?*

Key findings

1. All fungicide active ingredients used provided equivalent powdery mildew control.
2. Row spacing did not impact fungicide efficacy.

Background

Powdery mildew in mungbeans is caused by the fungus *Podosphaera xanthii* and is found wherever the crop is grown in Australia. The fungus requires a living host and is unable to survive on plant residues. Although there are several confirmed hosts which can carry over the disease from one season to another, infection can also originate from spores traveling long distances in the wind, given the right conditions. The disease is favoured by moderate temperatures (22-26 °C) with high relative humidity and tends to appear in late-planted summer crops maturing into cooler conditions.

Infected plants have a greyish-white powdery growth on the surface of leaves, stems and pods. Infection can appear at any growth stage, depending on weather conditions.

Yield losses due to powdery mildew vary from year to year but can be significant if disease development occurs before or at flowering. Yield losses most commonly range between 10 and 15%, however they can be as high as 46% depending on the variety, growth stage at infection and rate of disease development.

Plant resistance and foliar fungicides are the only two viable options available for the management of powdery mildew in mungbeans. Most varieties are rated 'susceptible', except for Green Diamond⊕ and Jade-AU⊕, which have a slightly higher rating of 'moderately susceptible'.

Previous research trials have demonstrated that the control of powdery mildew using fungicides is both financially viable and highly effective. Past trials indicate that best results are achieved when the first fungicide spray application is applied at the first sign of powdery mildew, normally found on the lower leaves of a vegetative crop, followed by a second spray two weeks later.

Plant row spacing has been shown to be very important in optimising crop yield. Recent research in agronomy practises has indicated that yield is optimised when row spacing is between 25 and 50 cm. However, there has been only limited research on the effect narrower row spacings have on the development of powdery mildew in the crop and how it impacts on control methods.

What was done

The trial was established at Wellcamp Research Station on 13 February 2018. A randomised block design was used consisting of three factorials (row spacing, fungicide treatment and plant population) and three replications. Plot size was two metres wide x 10 metres long, row spacing treatments were 0.25 m, 0.5 m and 1 m, and plant populations of 200 000 and 400 000 plants per hectare were targeted. Plots were planted with Jade-AU⊕ mungbean, the variety with the highest level of resistance and currently considered the industry standard. Spreader rows were planted with mungbean var. Berken (rated very susceptible to powdery mildew).

The trial was planted on 13 February 2018 and harvested on 31 May 2018. Powdery mildew was first observed on 21 March 2018 and developed rapidly in the crop. The first fungicide spray was applied on 28 March 2018 and the second application on 16 April 2018.

Fungicides applied were:

- Folicur SC® (430 g/L tebuconazole) at 145 mL/ha,
- Group 3 fungicide at 250 mL/ha
- Veritas® (200 g/l tebuconazole + 102 g/l azoxystrobin) at 300 mL/ha.

The Folicur SC® and Veritas® fungicides were used under the Australian Pesticides and Veterinary Medicines Authority (APVMA) permit numbers PER13979 and PER82104, respectively. Fungicide treatments were applied at the first sign of disease and then again 14 days later using a pressurised hand-held two metre boom sprayer delivering 134 L/ha at 5 km/h.

Treatment plots were regularly monitored and assessed for powdery mildew against incidence and severity (Tables 1 and 2). Plots were harvested and grain yield per hectare calculated.

Plots were rated on a whole plot basis on 23 March (31 days after emergence (DAE)), 5 April (44 DAE), 11 April (50 DAE), 18 April (57 DAE), 26 April (65 DAE) and 2 May (71 DAE).

Note: Products in this field experiment were tested FOR RESEARCH PURPOSES ONLY. Not all products used were registered for the purposes we tested. Always read the label prior to use and only apply fungicides as approved in the label.

Table 1. Powdery mildew incidence rating (IR) scale (developed by Sue Thompson USQ).

IR	Infection description
1	No powdery mildew colonies observed on any plants
2	Small colonies in lower 1/3 of canopy, up to 75% of plants affected
3	Colonies in the lower 1/2 canopy, >75% of plants affected
4	Colonies in the lower 2/3 of canopy, up to 75% of plants affected
5	Colonies in the lower 2/3 of canopy, >75% of plant affected
6	Colonies in the lower 2/3 of canopy, 100% of plants affected
7	Colonies in the lower 2/3 of canopy, 100% of plants affected, some plants with colonies in the top 1/3 of canopy
8	Colonies to top of plant with >75% of plants affected
9	Colonies to top of plant with 100% of plants affected and heavy leaf drop

Table 2. Powdery mildew severity rating (SR).

SR	Infection description
1	No powdery mildew colonies observed
2	Small colonies covering up to 10% of leaf area
3	Larger colonies covering up to 25% of leaf area
4	Heavy infection covering up to 75% of the leaf area
5	Severe infection covering more than 75% of leaf area

Powdery mildew mungbean trial showing different disease development between treatments and differences between row spacing treatments. Image taken 26 April 2018, 65 DAE.

Results

Powdery mildew developed rapidly in the crop reaching an average incidence level of 5, 44 DAE for all treatments. At the same time severity rating averaged 2.29. There was no significant difference between all treatments at this stage. At 57 DAE the control treatment had an incidence rating of 7.2 and a severity rating of 3.44 which was significantly different from the other three treatments. At 71 DAE the incidence rating for the control was 8.2 (Figure 1) and a severity rating of 4.88 (Figure 2), significantly different from all other treatments.

A significant difference in yield was recorded between the control (1275 kg/ha) and the other fungicide treatments (Group 3 yielded 1469 kg/ha, Veritas® yielded 1442 kg/ha, Folicur SC® yielded 1439 kg/ha) (Figure 3). There wasn't any significant difference in yield between the fungicide treatments. There was a significant difference in yield between row spacings with the 0.25 m row (1538 kg/ha) and 0.5 m row (1523 kg/ha) being significantly higher than the 1 m (1157 kg/ha) row spacing. There was also a significant difference in yield between plant populations with the 400K plants/ha (1464 kg/ha) being higher than the 200K plants/ha (1348 kg/ha).

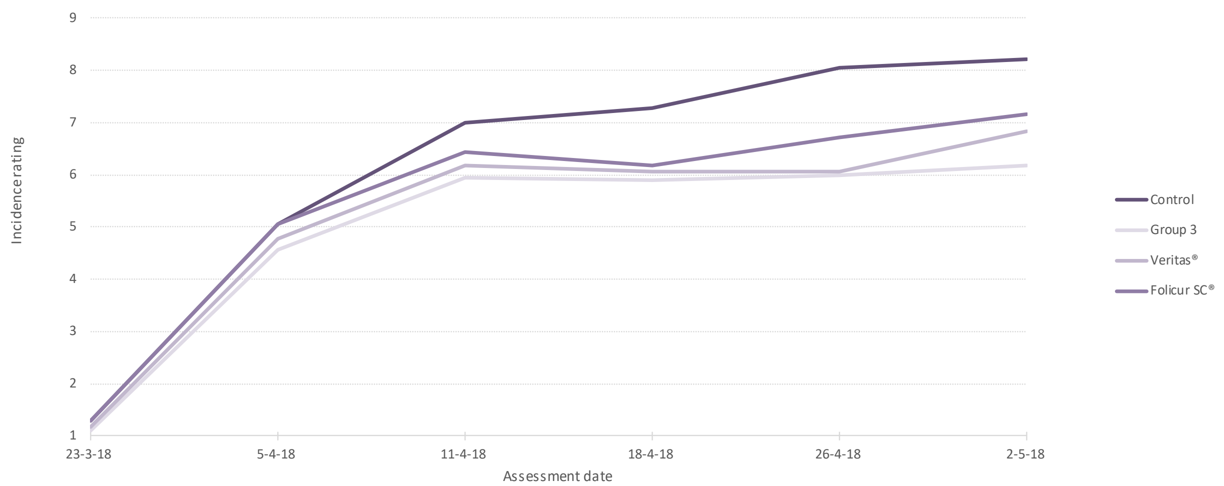

Figure 1. Incidence rating of powdery mildew in mungbeans at Wellcamp Research Station 2018. Points represent the mean of four replications at each respective assessment date.

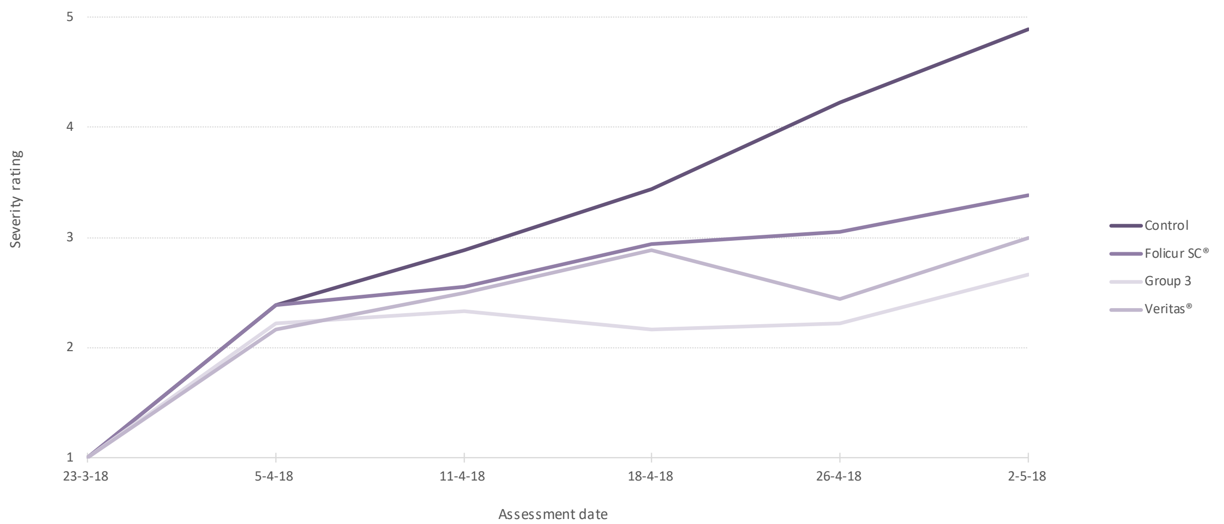

Figure 2. Severity rating of powdery mildew in mungbeans at Wellcamp Research Station 2018. Points represent the mean of four replications at each respective assessment date.

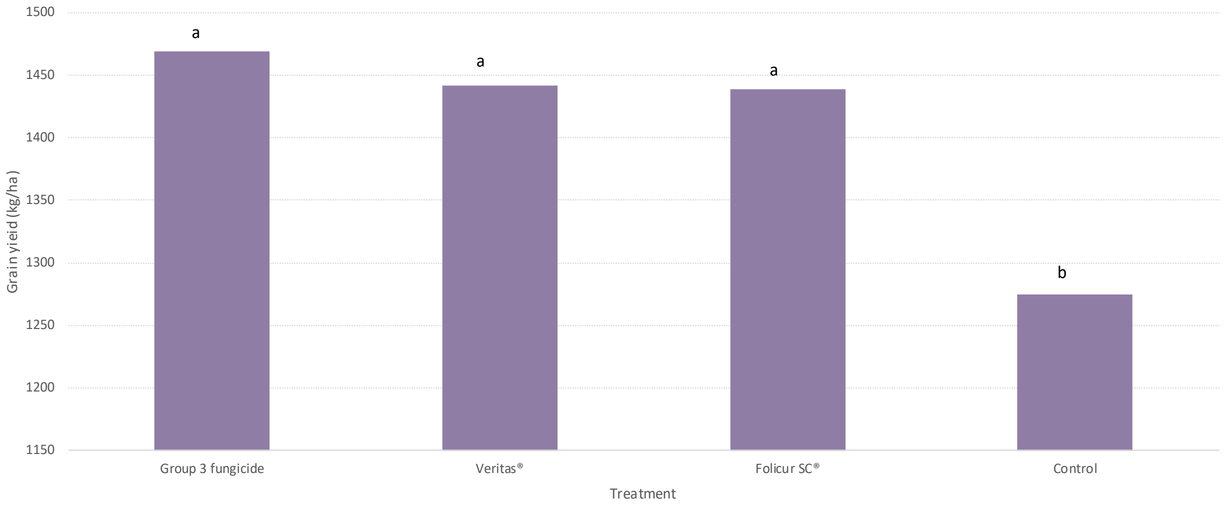

Figure 3. Average grain yield for treatments at Wellcamp 2018 (lsd = 136). Bars represent the mean of the four replications for each treatment.

No significant difference was measured for either disease severity or incidence between fungicide treatments from either the row spacing or plant population variables.

Implications for growers

Powdery mildew has been shown to cause significant yield reduction and economic impact when environmental conditions are suitable for the development of the disease in the crop. Well timed fungicide application is an effective, economic management practice in the control of this disease. Previous trial results indicate that best fungicide application efficacy is achieved when the first spray is applied at first sign of the disease followed by a second spray 14 days later. However, the first spray can be effectively applied up to 1/3 plant disease infection as long as it is followed by a second spray 14 days later. Timing of the first fungicide application appears to be more critical than the fungicide used. Results indicate that there is no difference in efficacy between the three fungicides trialled.

Row spacing configuration does not appear to impact on recommended powdery mildew management practices however row spacing has had significant impact on yield. Results confirm narrow row configurations (0.25 m to 0.5 m) can yield significantly more than wider rows (1 m), supporting the research from the Pulse Agronomy project (UQ000067).

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The DAF biometry team and SAGI (co-funded by GRDC) have provided statistical analysis of the data presented.

Trial details

Location:	Wellcamp Research Station
Crop:	Mungbean
Soil type:	Black Vertosol
Fertiliser:	Granulock® Z 40 kg/ha

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Queensland's Regional Research Agronomy team conducts experiments that support agronomists and grain growers to make the best decisions for their own farms. The research summaries in this publication provide rigorous data for industry-wide solutions and relevant information to refine local practices.

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