Queensland grains research 2021-23

Queensland Government

This publication has been compiled by David Lawrence and Tonia Grundy on behalf of Crop and Food Science, Department of Primary Industries (DPI).

Plant Breeder's Rights

⍉ denotes that a variety is protected by Plant Breeder's Rights (PBR) and unauthorised commercial propagation or any sale of propagating material of this variety is an infringement under the *Plant Breeder's Rights Act 1994*.

Queensland grains research 2021-23

Foreword

Welcome to the seventh edition of Department of Primary Industries' (DPI) Queensland grains research that summarises the research, development and extension (RDE) of DPI's Broadacre Cropping Group across the grain growing regions of Queensland.

The research has been led and delivered by 26 research agronomists, extension officers and technical support staff based in Goondiwindi, Emerald, Kingaroy and Toowoomba. They continue to 'get their hands dirty' conducting RDE within local farming systems and so ensure the results are both rigorous and relevant to grain growers and agronomists, and lead to more informed decisions for productive, profitable and sustainable farming systems.

This year's edition provides the usual results of annual trials, but also contains summaries of work to date across some longer-term initiatives, such as the Northern farming systems project that is now in its eleventh year, assessments of soil health and soil organic matter, and the use of deep-placed phosphorus fertiliser to maintain the productive capacity of our aging soils. These insights and the agronomic advances from the team's targeted RDE and on-farm innovation has delivered, and will continue to support, better practices that advance our agriculture.

The projects reported here have co-investment from the Queensland Government, Grains Research and Development Corporation (GRDC), the federal Department of Agriculture, Fisheries and Forestry and collaboration with several universities, CSIRO and other interstate RDE agencies. Of course, none of this RDE would be possible without the support of these collaborators and the growers, agronomists and agribusinesses that have provided support along the way. We thank them for this ongoing support.

Our team hopes that these RDE summaries will help all readers in the grains industry and the wider Queensland community to remain profitable and productive into the future.

Dr Vino Rajandran
General Manager
Crop and Food Science
Department of Primary Industries

Contents

Broadacre cropping group

Emerald

Peter Agius
Technical Officer

Darren Aisthorpe
Senior Research Agronomist

Jane Auer
Technical Officer

Harry Gaston
Research Scientist

Katie Hullock
Technical Officer

Doug Sands
Senior Research Agronomist

Gail Spargo
Technical Officer

Sawtenterpreet Singh
Technical Officer

Cassandra Donaldson
Technical Officer

Goondiwindi

Andrew Erbacher
Senior Research Agronomist

Isabella MacPherson
Technical Officer

Cameron Silburn
Research Agronomist

Research facilities and biometry support

The regional research trials reported here would not have been possible without the support of dedicated technical and operational officers at the Department of Primary Industries' 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 Emerald Smart Cropping Centre (formerly the Emerald agricultural college) for their operation of heavy plant and research machinery.

The DPI biometry team and Analytics for the Australian Grains Industry (AAGI—co-funded by GRDC) have provided statistical analysis of the data presented in these reports when identified in the acknowledgement section.

Toowoomba


Trish Balzer
Research assistant


Henry Baskerville
Extension Officer


Julie Boddington
Technical Officer


Ian Broad
Technical Officer

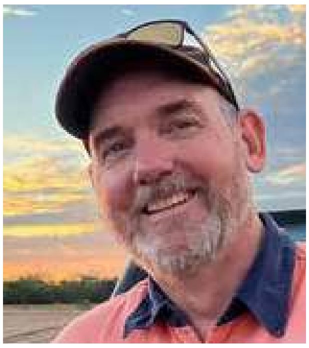

Jordan Davis
Research Agronomist


Jayne Gentry
Principal Development Extension Officer


Tonia Grundy
Senior Extension Officer


Megan Hunter
Extension Officer


Dr David Lawrence
Principal Development Extension Officer


Dr David Lester
Senior Research Scientist


Andrew McLean
Senior Technical Officer


Chinaza Onwuchekwa-Henry
Research Scientist


Hamed Zakikhani
Technical Officer

Kingaroy


Peter Want
Senior Experimentalist

Deep sowing of long coleoptile wheat in heavy vertosol soils—Condamine 2021

Cameron Silburn and Christabel Webber
Queensland Department of Primary Industries

***Research question**: What benefit can deep sowing with long coleoptile wheat (LCW) lines have on cropping systems in southern Queensland?*

Key findings

1. Seed quality (size, seed weight, germination percentage (%) and vigour) is essential for optimising emergence, particularly in deep sowing conditions.
2. Long coleoptile wheat varieties planted with lower quality seed (low vigour and germination) will not outperform standard wheat varieties with high seed quality.
3. The deep treatment redcued plant establishment but produced more tillers per plant than the shallow treatment.

Background

Long coleoptile wheat (LCW) has the potential to enable growers to plant into subsoil moisture in the optimum window to maximise yield potential. Across many parts of Southern Queensland growers are often faced with limited surface moisture which can delay planting. Deep sowing with LCW varieties can allow growers to take advantage of the subsoil moisture in the optimum planting window. Deep planting necessitates longer coleoptiles to avoid reduced emergence which would otherwise occur when planting standard varieties at deeper depths.

This research is building on trials conducted under laboratory conditions and field testing in southern and western grain regions by Dr. Greg Rebetzke. That research showed that when temperatures and soil texture/density are favourable, the substitution of the Rht-B1b and Rht-D1b dwarfing genes for alternative Rht8 and Rht18 genes can significantly increase the length and diameter of the coleoptile without dramatically increasing the overall height of the plant. It was observed through Dr Rebetzke's work (G. J. Rebetzke et al. 2004), that when conditions were less favourable (such as soil temperatures well above 19°C during emergence), coleoptile length could be almost halved for both modified and unmodified lines. LCW varieties haven't been validated in Queensland's heavier and warmer clay vertosol soils that require coleoptiles to have more resilience when establishing from depth.

These modified LCW wheat genetics can double the length of a conventional coleoptile. Validating planting LCW varieties at depth (more than 100 mm) will provide growers with increased confidence to deep plant into summer stored fallow moisture early in the planting window (rather than waiting for late autumn planting rains that could be better utilised to establish secondary roots and increase early tillering).

What was done?

The aim of the trial was to compare establishment under traditional (shallow) and deep planting conditions to validate suitability of long coleoptile varieties in Northern growing regions. These validations include deep plantings impact on time and ability to establish, tillering, flowering, and yield. The trial was a single sowing date timed to optimise yield potential of the selected varieties as well as managing frost risk for the region.

The trial was conducted with modified LCW genotypes in southern Queensland, against both commercial and pre-release lines of wheat and barley, that were recognised as having coleoptile lengths longer than the average commercial line. The Condamine trial was conducted on grey Vertosol clay soil, and 15 lines were selected, including modified Rht8 and Rht18 genotypes (known long coleoptile varieties), commercially available standard coleoptile varieties and one barley variety.

Seed was sourced from LongReach seeds, AGT, Intergrain, CSIRO and commercially sourced. Shallow planting depth was 30–50 mm soil over seed, and deep planting depth targeting 90–110 mm. The 15 varieties were replicated three times in a randomised plot design with two planting depths (deep and shallow). The plots were 2 m wide and

12 m long. The trial was planted into full moisture profile on 19 May 2021 on 50 cm row spacings. Urea was applied to all plots at planting 25 cm offset from the planting rows, at a rate of 100 kg N/ha.

Table 1. Varieties used in 2021 trial.

Source	Varieties
LongReach Seeds	LPB19-1337 LPB19-1492 LPB19-2962
AGT	V13121-156 V13121-020 RAC2721 (now Calibre⁽ᶁ⁾)
Intergrain	IGW6794 *16Y466-023 *16Y452-012
CSIRO	Mace⁽ᶁ⁾ *LCW Mace 18 *LCW M70-1+ (Magenta) Scepter⁽ᶁ⁾
Commercially sourced	LongReach Flanker⁽ᶁ⁾ Seednet Leabrook⁽ᶁ⁾ barley

* long coleoptile varieties

Various measurements were taken throughout the growing season, including several emergence counts over a three-week period, shallow and deep soil temperatures as well as ambient temperature, tiller counts at GS55 to GS65 for Zadok development scores, viable head counts at harvest, grain yield and yield components. Soil cores were taken at planting and harvest to assess water use efficiency and starting nutrient levels, along with EM surveys.

Results

Establishment

Target establishment for each variety was 100 plants/m². Shallow planting establishment (93 plants/m²) was significantly higher than the deep planting (67 plants/m²) (Table 2). Variety played an important role in establishment but there were no significant interactions between variety and depth (Figure 1).

Modified Rht8 and Rht18 long coleoptile varieties did not improve establishment over other known long coleoptile and standard coleoptile varieties (Figure 1). Leabrook⁽ᶁ⁾ barely had the best establishment at 96 plants/m².

Table 2. Average establishment for deep and shallow treatments of all varieties.

Planting depth	Plants/m²
Shallow	93 (a)
Deep	67 (b)
Average s.e.d.	2.8

Target establishment was 100 plants/m². Means with the same letters are not significantly different at the 5% level.

Soil temperatures for the trial did not reach a threshold that would have had a negative impact on coleoptile length or diameter (Figure 2). The deep-sown treatments were on average 1.4°C warmer than shallow planted treatments.

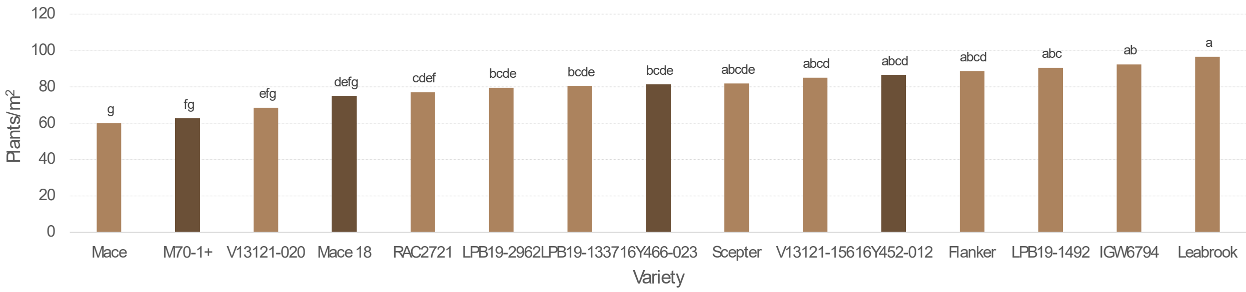


Figure 1. Average plants per m² of established (target establishment was 100 plants/m²).
Dark bars represent long coleoptile varieties. Means with the same letters are not significantly different at P(0.05).

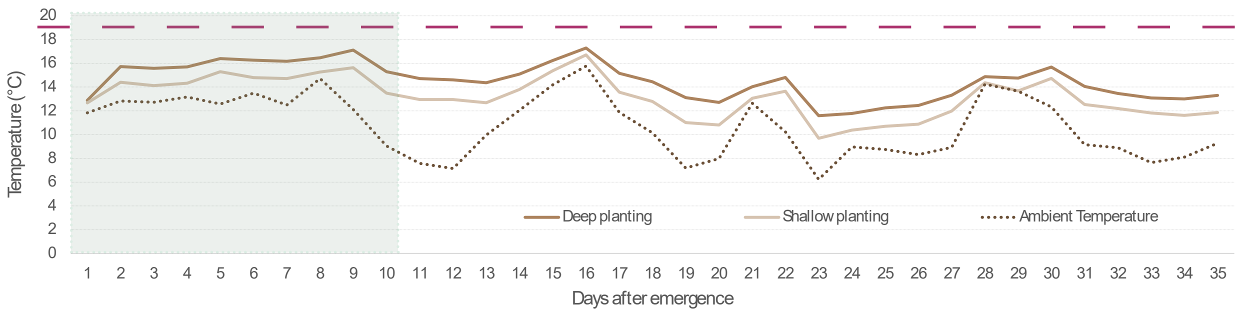


Figure 2.Soil temperatures measured at both shallow and deep planted treatments during plant establishment.
Dotted line indicates ambient air temperature, the shaded box indicates the key 10-day emergence period post planting while the dashed line indicates the 19°C threshold for soil temperatures where significant reductions in coleoptile length and diameter can begin to occur for some genotypes.

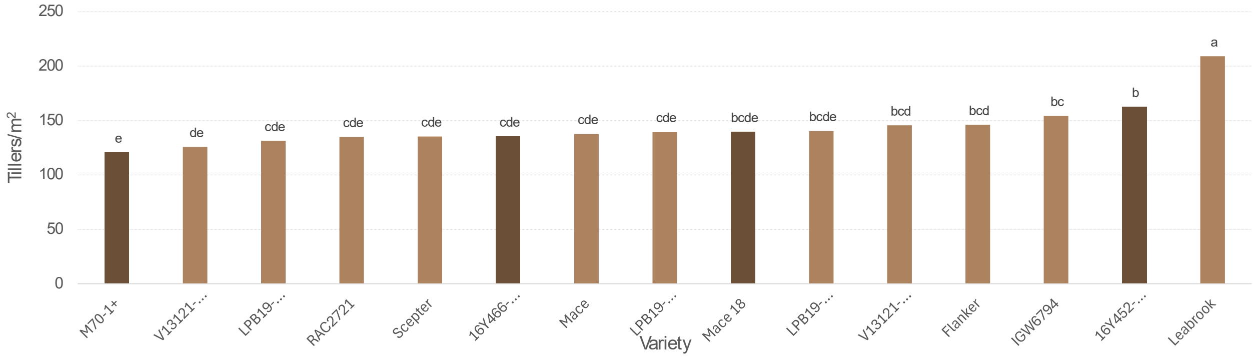


Figure 3. Average tillers/m² at flowering for each variety.
Dark bars indicate long coleoptile varieties. Means with the same letters are not significantly different at P(0.05).

Tillering

Sowing depth had no effect on the number of tillers produced at flowering. On average for all varieties there were 148 and 140 tillers/m² for shallow and deep sowing respectively. Tillering at flowering had a significant influence between variety at planting however, Leabrook⁽ᴰ⁾ barely had the highest (209 tiller/m²) followed by 16Y452-012 (163 tillers/m²) (Figure 3). Furthermore, there was an extra 5.2 tillers/m² for each additional 10 plants/m² that emerged.

Yield components

Shallow planted varieties resulted in 405 kg/ha increase in grain yield compared to deep planted treatments (significant result) (Table 3). There was no other significant result for other key metrics measured. Although the increased shallow sowing yield was a significant result, wheat's ability to compensate from a lower establishment to yield similarly is still remarkable, and highlights wheat's ability to compensate extremely well from poorer establishments if there are relatively low levels of stress on the plant during the growing period, particularly from GS30 to grain fill. There was also a significant relationship between the establishment (% target population achieved) and yield: as the (%) target population rose by 10% there was a 78 kg/ha decrease in yield, highlighting the importance of targeting the correct sowing rate.

Grain yield ranged between 3519 to 4144 kg/ha, with no significant differences detected. The LCW modified varieties 'book-ended' the yield results as two of the varieties were potentially heat-affected during storage and were unable to match other commercially available lines. The two pre-release LCW lines topped the yield charts. (Figure 4)

Implications for growers

Establishment in the deep planted treatment was poorer than the shallow planted treatments, as expected. However, while some lines failed to achieve over 70% of the target population, those with the worst emergence were still able to compensate and produce just over 3000 kg/ha. This was lower than the 4100 kg/ha achieved by the best-established lines but demonstrates the value of getting a crop planted in the optimum window compared to not planting at all if subsequent planting rains do not eventuate.

Seed quality was a significant issue for the three trials conducted by DPI across Queensland. The poor establishment of some lines was the result of storage in hot conditions over the previous summer. The conditions reduced germination, but more importantly seed vigour, as a result impacted establishment, particularly from depth.

The trial emphasises the importance of planting in the optimum window for yield potential in each region. The data highlight that even poorly-established crops (in this case as much as 20% below the target establishment) were able to compensate and yield similarly to crops that established well. This suggests that deep planting offers real potential to ensure crops take advantage

Table 3. Yield components of all varieties planted either deep or shallow at harvest.

Depth	Yield (kg/ha) @12% moisture	Tillers/m²	Tillers/plant	Protein (%)	Test weight (g)	Screenings (%)	300 seed weight (g)
Shallow	4000 (a)	141	1.8	14.1	78	4.3	10.44
Deep	3595 (b)	135	1.7	14.0	77	4.6	10.39
Average s.e.d.	144						

Means with the same letters are not significantly different at the 5% level.

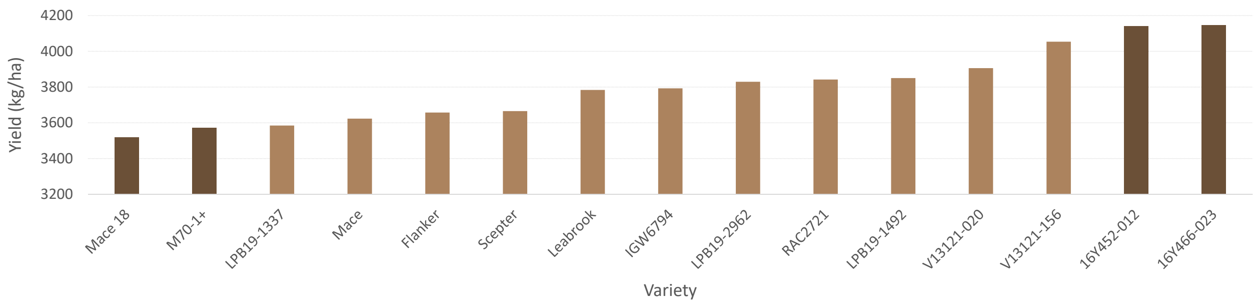


Figure 4. Average yield for each variety planted in both deep and shallow treatments.
Dark bars indicate long coleoptile varieties.

of the best planting time in most seasons. LCW varieties can only increase confidence in deep planting and their performance will continue to be studied over the coming years.

Acknowledgements

We would like to thank the grower at Condamine for their support and allowing us onto their property to conduct the trial. We would like to thank all farm and field staff contributing to the implementation and management of these experiments and trial collaborators.

The research team would like to acknowledge and thank AGT, LongReach Seeds and Intergrain for their support over the past 2 years; Dr. Greg Rebetzke for being so generous with his time, his guidance and support; and the Grains Research and Development Corporation for investing in the research.

References

G. J. Rebetzke, R.A. Richards, X. R. R. Sirault and A. D. Morrision (2004) Genetic analysis of coleoptile length and diameter in wheat, *Australian Journal of Agricultural Research* 55, 733–743.

Trial details

Location:	Condamine
Crop:	Wheat and barley
Soil type:	Grey Vertosol
In-crop rainfall:	200 mm
Fertiliser:	At-planting 35 kg/ha of Granulock® Z and 100 kg N/ha.

Deep sowing of longer coleoptile wheat in heavy vertosol soils—Lundavra 2021

Cameron Silburn and Christabel Webber
Queensland Department of Primary Industries

***Research question**: What benefits can deep sowing with long coleoptile wheat (LCW) lines have on cropping systems in southern Queensland?*

Key findings

1. Seed quality (size, seed weight, germination percentage and vigour) is essential to optimise emergence, particularly for deep-sown conditions.
2. Lower quality, long coleoptile wheat emerged better than high seed quality standard coleoptile wheat planted under stressed conditions.
3. Plant establishment was lower in deep planted treatments, but more tillers per plant were produced than the shallow treatment.

Background

Southern Queensland growers are often faced with limited surface moisture that can delay planting and reduce the yield potential of their crops. Long coleoptile wheat (LCW) may enable growers to maximise their yield potential by deep planting into subsoil moisture in the optimum planting window for their area. Deep planting necessitates longer coleoptiles to avoid reduced emergence that would otherwise occur when planting standard varieties at deeper depths.

This research builds on trials conducted under laboratory conditions and field testing in southern and western grain regions by Dr. Greg Rebetzke. That research showed that when temperatures and soil texture/density are favourable, the introduction of Rht-B1b and Rht-D1b dwarfing genes can double the length of the coleoptile and significantly increase its diameter without dramatically increasing the overall height of the plant, and that in less favourable conditions (such as soil temperatures well above 19°C during emergence), coleoptile length could be almost halved for both modified LCW varieties and unmodified lines.

However, these LCW varieties haven't been validated in Queensland's heavier and warmer clay Vertosol soils, which require coleoptiles to have more resilience when establishing from depth. Validating planting of LCW varieties at depth (more than 100 mm) in Queensland will increase growers' confidence to deep plant into summer stored fallow moisture early in the planting window rather than waiting for late autumn planting rains that could be better utilised to establish secondary roots and increase early tillering.

What was done

The aim of the trial was to compare establishment under traditional (shallow) and deep planting conditions of long coleoptile varieties in northern growing regions. Assessments included the impact of deep planting on the time and ability to establish, tillering, flowering, and yield. The trial was sown on a date chosen to optimise yield potential of the selected varieties while managing frost risk for the region. The modified LCW genotypes were compared to both commercial and pre-release lines of wheat and barley that were recognised as having longer than average coleoptile lengths.

The trial reported here was conducted on grey Vertosol clay soil in the Lundavra district. Fifteen lines were selected from the modified Rht8 and Rht18 genotypes, known long coleoptile varieties, commercially available standard coleoptile varieties and one barley variety (Table 1). Three replications were used in a randomised plot design with two planting depths (deep and shallow). The shallow planting depth was 30–50 mm soil over seed, and the deep planting depth targeted 90–110 mm. The plots were 2 m wide and 12 m long.

The trial was planted into a full moisture profile on 18 May 2021 on 50 cm row spacings. Urea was applied to all plots at planting 25 cm offset from the planting rows, at a rate of 100 kg N/ha.

Measurements taken throughout the growing season included emergences counts over a three-week period, soil temperature at both depths, ambient temperature, tiller counts at GS55 to GS65 for Zadok development scores, and viable head counts at harvest, grain yield and yield components.

Table 1. Varieties and seed source in 2021 trial.

Source	Varieties
LongReach Seeds	LPB19-1337 LPB19-1492 LPB19-2962
AGT	V13121-156 V13121-020 RAC2721 (now Calibre(D))
Intergrain	IGW6794 *16Y466-023 *16Y452-012
CSIRO	Mace(D) *LCW Mace 18 *LCW M70-1+ (Magenta) Scepter(D)
Commercially sourced	LongReach Flanker(D) Seednet Leabrook(D) barley

* long coleoptile varieties

Results

Establishment

The target establishment for each variety was 100 plants/m². Establishment for shallow planting was significantly higher than the deep planting (Table 2). Variety played an important role (Figure 1) but there was no significant interaction between variety and planting depth.

Table 2. Ten-day average soil temperatures post-planting and average establishment for deep and shallow treatments of all varieties.

	10-day average soil temp (°C) @ 8am	Plants/m²
Shallow	14	93.9 (a)
Deep	13.8	73.1 (b)
Average s.e.d		3.2

Planting occurred on 18 May 2021. Means with the same letters are not significantly different at the 5% level. Target establishment was 100 plants/m².

There was no difference between deep and shallow soil temperatures post planting (Table 2). Typically, May and June plantings at the trial location would not experience the higher soil temperatures that could threaten coleoptile length.

Modified Rht8 and Rht18 long coleoptile varieties did not improve establishment over other known long coleoptile and standard coleoptile varieties (Figure 2). The Leabrook barely had the best establishment of 115 plants/m².

Tillering

Planting depth had a significant effect on tiller number per metre. Planting shallow resulted in approximately 34 more tillers/m² at flowering

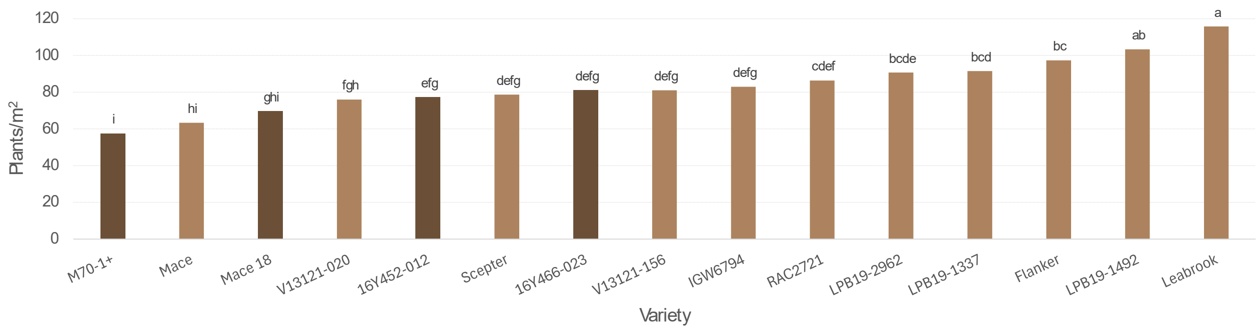


Figure 1. Average plants per m² of deep and shallow varieties. Target plant establishment was 100 plants/m².
Dark bars represent modified Rht8 and Rht18 long coleoptile varieties. Means with the same letters are not significantly different at P(0.05).

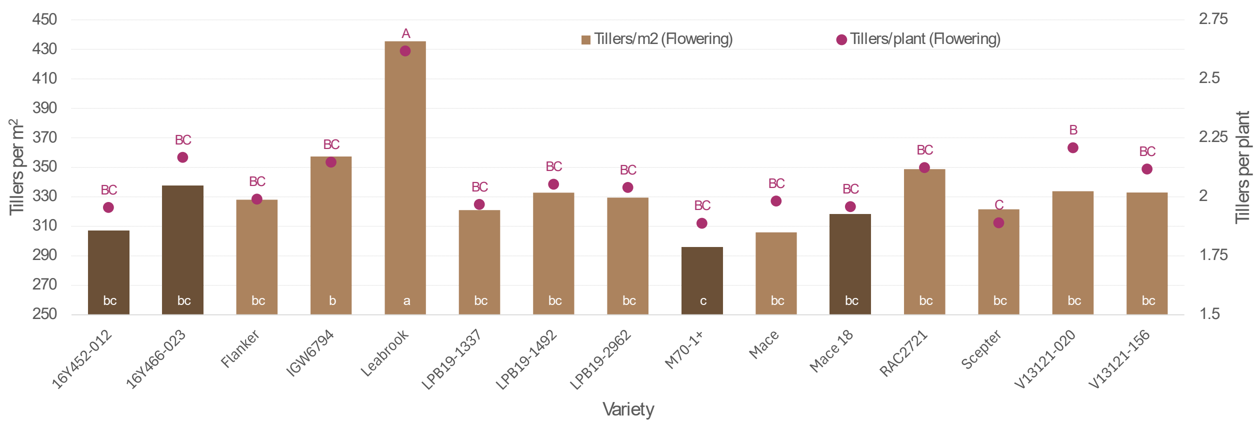


Figure 2. Average tillers per m² (bars) and tillers per plant (dots) of each variety at flowering.
Dark bars represent modified Rht8 and Rht18 long coleoptile varieties. Means with the same letters are not significantly different at P(0.05).

Table 3. Average tillering and days to flowering of all varieties by planting depth.

	Days to Flowering	Tillers/m²	Tillers/plant
Shallow	100.4	350.9	2.20
Deep	101	316.6	1.95
Average s.e.d	0.4	13.6	0.08

compared to planting deep (Table 3). Furthermore, when target population is expressed as a percentage, for every 10% increase in establishment resulted in 8.9 more tillers/m².

However, there was 0.2 less tillers/plant at flowering for each additional 10 emerged plants/m². There were also varietal influences as Leabrook$^{\phi}$ barley was the most prolific tiller of all varieties at flowering (435 tillers/m²) (Figure 2).

Yield components

Shallow planting resulted in a 280 kg/ha increase in grain yield compared to deep-planted treatments (not significant) (Table 4). Shallow planting increased the number of tillers per square metre, deep planting increased the tillers per plant (1.73 versus 1.58; Table 4) at harvest, although the differences were not significant.

Modified varieties M70-1+ and Mace 18 had the lowest establishment but were able to compensate by harvest to have similar numbers to other varieties that had better establishment. Leabrook$^{\phi}$ barley aborted significant numbers of heads between flowering and harvest, reducing from 435 to 306 tillers/m². Overall, all varieties had reduced heads at harvest compared to flowering indicating that head abortion did occur (Figure 2 versus Figure 3).

Grain yield ranged between 2745 to 4587 kg/ha and averaged 3785 kg/ha for all varieties. The Mace 18 modified LCW variety was able to compensate very well from poor establishment to yield 3845 kg/ha. M70-1+ however was the lowest yielding in the trial at 2745 kg/ha (Figure 4).

Implications for growers

As expected, establishment in the deep-planted treatment was poorer than the shallow-planted treatment. However, the worst emerged lines (~60% of target numbers) were still able to compensate and produce just under 3 t/ha. While lower than the 4.5 t/ha of the best performing line, it is still a respectable yield compared to not planting at all if waiting for rain to come.

Seed quality was an issue for the three LCW trials conducted by DPI across Queensland. The poor establishment of some lines was the result of storage in hot conditions over the previous summer before the seed was acquired. These conditions reduced germination, but more importantly seed vigour, which impacted establishment, particularly from depth.

By sowing at an optimum time for the region, lower established varieties were able to compensate by generating more tillers per plant in the deep treatments compared to shallow as there was less competition between plants for resources. These data highlight that poor establishments, in this case as much as 20% less that the target, will be able to compensate and reach similar yields to crops with good establishment if conditions allow. The modified LCW varieties and known long coleoptile

Table 4. Yield components of all varieties planted either deep or shallow at harvest.

	Yield (kg/ha) @ 12.5% moisture	Tillers/m²	Tillers/plant	Protein (%)	Test weight (g)	Screenings (%)	300 seed weight (g)
Shallow	3924	276	1.58	14.06	79	3.4 (a)	10.1
Deep	3645	254	1.73	13.95	79.3	2.8 (b)	10.2

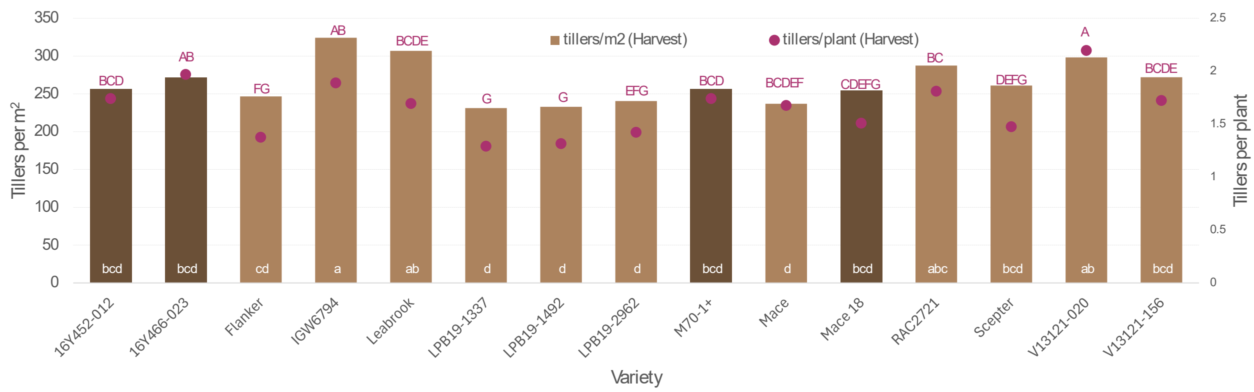


Figure 3. Average tillers per m² (bars) and tillers per plant (dots) of each variety at harvest.
Dark bars epresent modified Rht8 and Rht18 long coleoptile varieties. Means with the same letters are not significantly different at P(0.05).

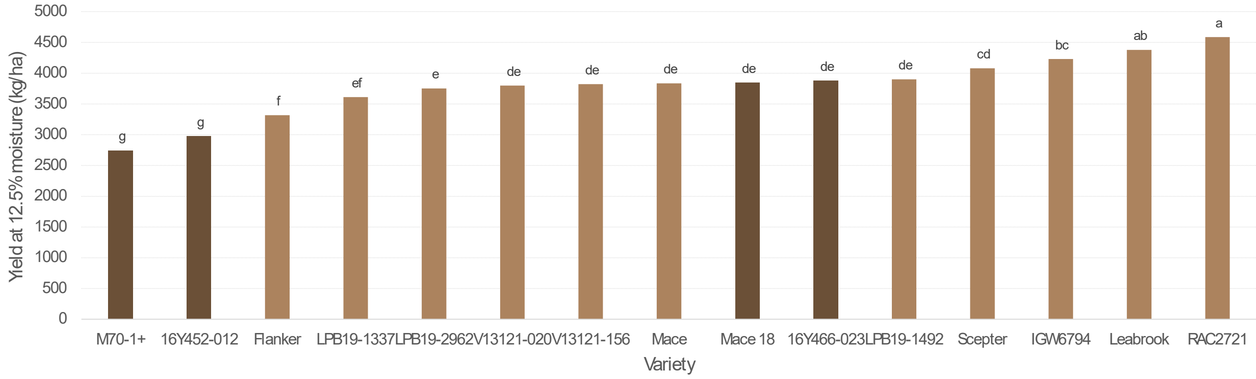


Figure 4. Yield corrected to 12.5% moisture (kg/ha) of each variety.
Dark bars represent modified Rht8 and Rht18 long coleoptile varieties. Means with the same letters are not significantly different at P(0.05).

varieties that established poorly in the trial due to storage conditions were also able to compensate reasonably well.

Acknowledgements

The research team would like to thank the collaborating family, local growers and consultants for their ongoing support and contribution to the project. Thanks also to the Grains Research and Development Corporation and the Queensland Department of Primary Industries for funding the project. We would like to thank all farm and field staff contributing to the implementation and management of these experiments and trial collaborators and host farmers.

Trial details

Location:	70 km NW of Goondiwindi
Crop:	Wheat and barley
Soil type:	Grey Vertosol
In-crop rainfall:	140 mm
Fertiliser:	35 kg/ha of Granulock® Z and 100 kg N/ha at planting.

Deep sowing of longer coleoptile wheat in heavy Vertosol soils—Lundavra 2022

Cameron Silburn
Queensland Department of Primary Industries

***Research question**: What benefit can the practice of deep sowing and the use of long coleoptile wheat (LCW) lines have on cropping systems in southern Queensland?*

Key findings

1. Under cool, mild and damp conditions, no significant difference in emergence was observed between the modified LCW lines and the longer conventional coleoptile lines.
2. Early sowing (TOS 1) allowed poorly-established lines sown deep to compensate and match the yield of TOS 1 shallow and TOS 2 shallow.
3. In damp high clay content Vertosols, press wheel downforce may need to be adjusted to improve emergence.

Background

The ability of long coleoptile wheat (LCW) genetics to almost double the length of a coleoptile could provide growers with increased confidence to deep sow into summer stored fallow moisture earlier in the sowing window.

The project aimed to assess the field performance of modified LCW genotypes in central and southwest Queensland, against both commercial and pre-release lines of wheat and barley that are recognised to have above average coleoptile lengths. The research was on heavier Black/Grey Vertosol soil types and assessed the performance of genotypes at both a shallow (traditional) sowing and deep sowing depths.

This report is on the 2022 component of the LCW research in southern Queensland; a single site, multi sowing date trial approximately 70 km northwest of Goondiwindi. The trial builds upon 2021 research from single sowing date trials around Billa Billa and Condamine in southern Queensland, and a multi-sowing date trial at Emerald in central Queensland.

What was done

The trial was planted into a full profile of moisture with 130 mm of plant available water (PAW) down to 120 cm. There was 180 kg N/ha available in the soil profile down to 90 cm. During the trial there was 280 mm of in-crop rain.

The first time of sowing (TOS 1) was planted on 21 April 2022 and second planting (TOS 2) occurred on 21 June 2022, after a planned May treatment couldn't be planted due to wet conditions (Figure 1).

Wet conditions also had a significant impact on the deeply planted seeds of TOS 2, which had very poor emergence (less than 10 plants/m^2); this treatment has been excluded from the results reported here.

The 2022 cropping year in southern Queensland continued to be very wet with mild conditions (Figure 1). As a result, the average yield for the trial was 3500 kg/ha, which was representative of the wider growing region.

Soil temperatures at TOS 1 were above the 19°C threshold that reduces coleoptile length and diameter for several days after planting (Figure 2). However, by mid-May soil temperatures rapidly declined to well below the threshold with an average temperature at 9 am of 8.4°C for TOS 2. Identified as a key issue for deep planting wheat in Queensland soils, soil temperatures are of particular importance when deep planting early. This was reinforced by the 2022 plant establishment results.

Results

Emergence

TOS 1 shallow planting had an establishment of 65 plants/m^2 compared to 71 plants/m^2 for TOS 2 shallow (Table 1); both below the target establishment of 100 plants/m^2. The best performing variety across both depths and planting dates was Flanker$^{\text{(D)}}$ (69 plants/m^2) and the worst performing variety was 16Y466-023 (50 plants/m^2; Figure 3). Overall, long-coleoptile varieties did not provide an advantage to establishment when planted deep (P = 0.588).

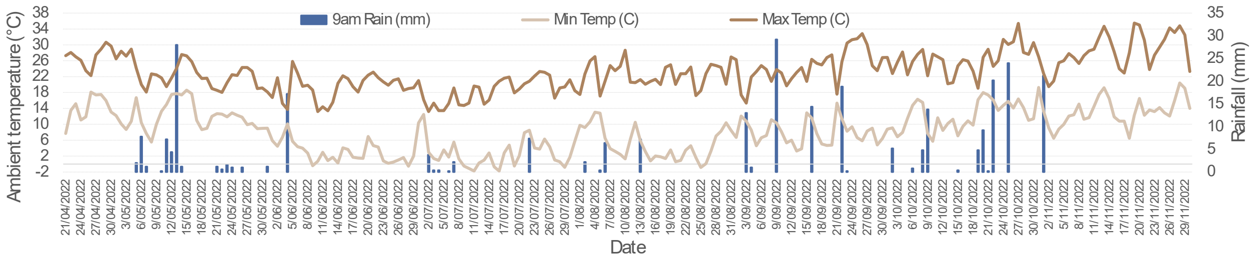


Figure 1. Minimum and maximum daily temperatures and daily in-crop rainfall during the 2022 winter cropping season.

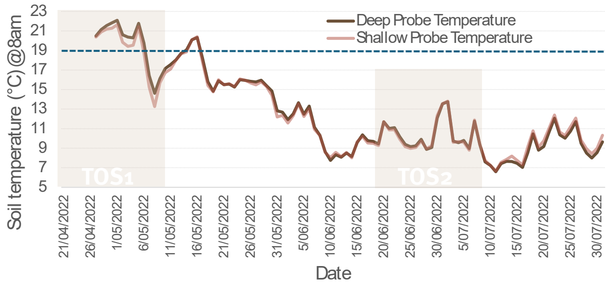


Figure 2. Daily soil temperatures @ 9am for the two sowing depths. Deep sown and shallow temperatures mirror each other very closely throughout the growing season.

Shaded boxes indicate the emergence period for the two TOS and dashed line indicates the 19°C threshold for significant temperature effect on coleoptile length and diameter.

Table 1. Average establishment of wheat planted at two times of sowing and two depths (deep and shallow).

TOS / Depth	Plants/m²	
TOS 1 – Shallow	65.0	a
TOS 1 – Deep	36.0	b
TOS 2 – Shallow	71.8	a

Means not followed by a common letter are significantly different at P(0.05).

Days to flowering

The deep planted TOS 1 took 6 days longer (115 days) to reach 50% flowering compared to TOS 1 shallow (108 days). The Days to Flowering (DTF) for the TOS 2 shallow planting was 97 DTF, due to the shorter growing season. This is consistent with observations from other trials and planting dates (Figure 4).

Yield response

Planting early appeared to provide a small benefit in terms of overall yield, but this gain was not statistically significant, and most likely due to the milder finish to the season and significant rainfall which allowed TOS 2 shallow to perform similarly to TOS 1. There were also no differences between shallow and deep-planted treatments for TOS 1 (3622 versus 3551 kg/ha; Figure 5).

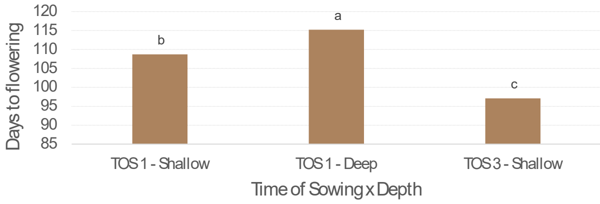


Figure 4. Days to flowering for all varieties in the trial. Deep sown seed in TOS 1 took 6.5 days longer to flower than shallow sown seed in TOS 1, which took 11.6 days longer than shallow sown seed in TOS 2 (P<0.001)

Error bars represent average sed. All commercially available varieties are subject to PBR (⦶) * Suspected, actual variety to be confirmed.

When comparing coleoptile type there was no difference between TOS 1 deep and shallow plantings. However, there was a significant yield penalty for TOS 2 LCW shallow-planted varieties (Figure 6) that appeared to be driven by susceptibility to disease, largely due to the age of the parent material. Sunchaser⦶ was the best performing variety when establishing from the deep-planted treatment.

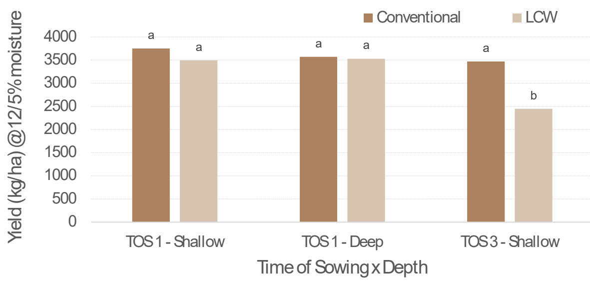


Figure 5. Yield (kg/ha) corrected to 12.5% moisture time of sowing x coleoptile type x depth interaction.

Means not followed by a common letter are significantly different (P = 0.05) average lsd 492 kg/ha. Despite the much lower establishment of TOS 1, deep planted treatments was able to statistically match TOS 1 and TOS 3 shallow average yields, TOS 3 deep's yield was significantly lower than all other sowing dates and depths.

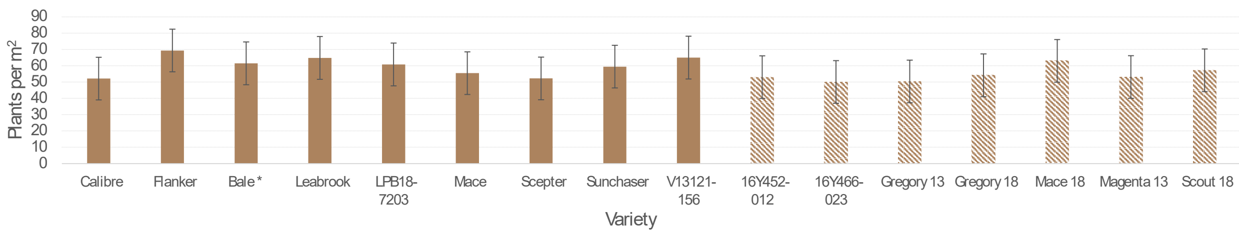


Figure 3. Varietal average emergence across sowing dates and depths. Conventional lines are solid, LCW lines are hashed.

Error bar indicates average lsd of 13.1. There was no significant difference between varieties (P=0.080) nor when comparing the two groupings at depth. (P = 0.588).

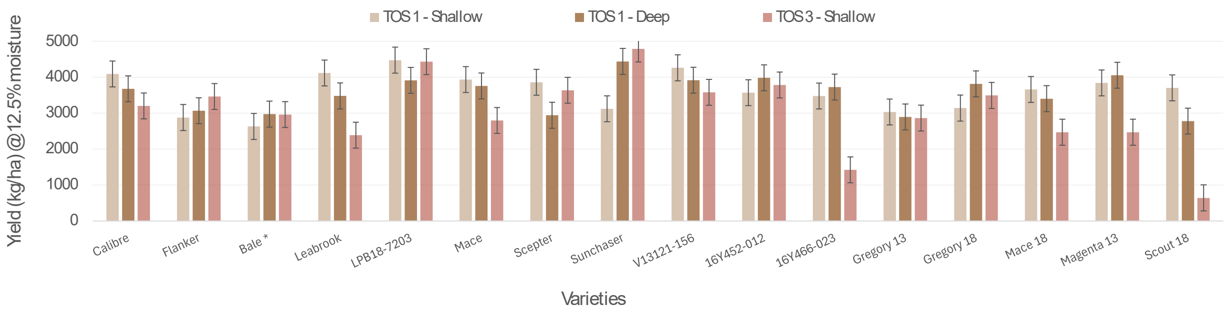


Figure 6. Yield (corrected to 12.5% moisture) x Variety for the two sowing dates and two depths measured.
Error bars represent average sed. Varieties from 16Y452-012 to Scout 18 all have either the Rht13 or Rht18 LCW substitution. Important to note, there is a wide range of genotypes and maturities and most importantly seed sources in this trial. Direct yield comparisons between varieties are unwise and should not be a basis for deep sowing genotype selection. All commercially available varieties are subject to PBR (⒫).
* Suspected; actual variety to be confirmed.

Implications for growers

The results of this year's trial show that LCW varieties performed similarly to already commercially available varieties but did not provide an advantage to establishment when deep planted. The past two years of research have been carried out in very wet years, which hasn't enabled any true deep plantings to show the benefit of deep planting into moisture.

It is important to note that this trial compares some of the best and most recent lines developed for this region, with modified LCW lines whose parents were originally commercially released as early as 2004 (EGA Gregory⒫) and as such does not compare 'apples with apples'. Also, the trial included a number of commercially unavailable (developmental) lines from at least eight different seed sources that ranged from high-quality seed direct from breeders, seed bought over the counter at local resellers, through to sample seed from the rain-affected trials in 2021. As such seed size, germination and vigour varied immensely, all factors with a direct effect on emergence numbers, particularly from depth in high stress scenarios.

Results to date (in above-average growing conditions) show that the modified lines offered no advantage to already commercially-available varieties when sown deep in SQ conditions. Another consideration is that the disease resistance of older varieties that were modified with LCW genetics is very limited, especially to yellow spot disease.

Long coleoptile wheat still needs further development to be suitable to Queensland conditions. Further research is important and will seek a single source for all seed used to remove the impact of inherent seed quality on establishment.

While not discussed in this report, the very low establishment in TOS 2 deep sowing appears to have been due to excess down pressure and compression of soil from press wheels mounted on a fixed bar behind the planter. While the pressed soil was pliable and the seed was easily accessible at planting, the soil became 'rock-like' across the top of the deep-sown treatments by the time of establishment counts, trapping the germinated seedlings below.

While commercial plantings would not include deep sowing into wet soils, questions remain about the optimum downforce pressure on cereals in high clay content soils, given the difference in emergence between TOS 1 (19°C soil) and TOS 2 (8.4°C soil) with the same planter and configuration setup.

Acknowledgement

We would like to thank the property owners for their support in allowing us access to conduct the trial.

The research team would like to acknowledge and thank AGT, LongReach Seeds and Intergrain for their support over the past 2 years. Our team would like to thank Dr. Greg Rebetzke for being so generous with his time, guidance and support.

DPI would like to thank the GRDC for investing in this preliminary research.

Trial details

Location:	70 km NW of Goondiwindi
Crop:	Wheat
Soil type:	Cracking Grey Vertosol with a plant available water capacity of more than 200 mm.
In-crop rainfall:	280 mm
Fertiliser:	35 kg/ha of Granulock® Z was applied with the seed.

Deep sowing of longer coleoptile wheat in heavy Vertosol soils—Emerald 2021

Darren Aisthorpe, Jane Auer and Ellie Parkinson
Queensland Department of Primary Industries

Research question*: What benefit can long coleoptile wheat (LCW) lines and deep sowing have on cropping systems in central Queensland?*

Key findings

1. Seed quality is paramount for improved establishment both in deep and shallow sowing conditions.
2. Sowing date can have a significant effect on a poorly established crop's ability to compensate for yield.
3. Growers need to be conscious of soil temperature and the negative effect it can have on crop emergence.

Background

The ability of long coleoptile wheat (LCW) genetics to almost double the length of a coleoptile could provide growers with increased confidence to deep sow into summer stored fallow moisture earlier in the sowing window, if proven successful.

This trial aimed to field validate modified LCW genotypes in central Queensland against commercial and selected pre-release lines of wheat and barley that are recognised to have longer than the average coleoptile lengths. The trial was conducted on heavier Black/Grey Vertosol soil types to assess the LCW genotypes' performance at both a shallow (traditional) sowing depth and a deep sowing depth.

What was done?

The Emerald Smart Cropping Centre experiment compared modified and standard genotypes sown at two depths (3–5 cm and 10–12 cm of soil over the seed) to assess establishment under 'typical' and deep sowing scenarios. The trial had three sowing dates in a split-plot design with a minimum of three replicates.

Sowing dates were mid-April, mid-May, and mid-June (Table 1) to assess the impact of soil temperature on emergence and establishment at the two nominated depths on Queensland's heavy grey cracking Vertosols. The trial block was irrigated pre-plant to ensure a suitable moisture profile, but was then treated as dryland after sowing.

Results

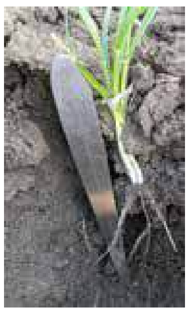
Average plant available water across the sowing dates was 187 mm to a depth of 1.5 m.

Table 1. Sowing dates and 10-day average soil temperatures during emergence for deep and shallow sown lines.

Date	Time of Sowing	10 day average soil temperature @ 8 am	
		Shallow	Deep
19/04/2021	TOS 1	21.6°C	22.7°C
19/05/2021	TOS 2	17.9°C	19.2°C
17/06/2021	TOS 3	17.3°C	15.7°C

TOS 1 average temperature was 4.3°C warmer than TOS 3 for shallow and 7°C for deep-sown lines.

Soil and air temperatures were monitored over the growing season to provide insight into emergence conditions over the three sowing dates. Temperatures did vary between the three emergence periods. Deep sowing at the first Time of sowing (TOS 1) had the warmest conditions with average temperatures at seed depth of almost 23°C at 8 am over the ten-day period (Table 1). The coolest conditions were experienced by the shallow sown seed in TOS 3, with an emergence temperature of 15.4°C at 8 am (Figure 1).



All three sowing dates were planted into good moisture within the specified depth ranges.

Figure 1. Soil temperature @ sowing depth observed at 8 am for each sowing date. Deep soil temperatures were consistently warmer than the shallow sowing depth seed.

TOS 1, TOS 2 & (TOS 3 boxes indicate the critical 10-day emergence period post the sowing date. The blue (deep) and orange (shallow) trend lines show that across the emergence periods, temperatures at depth were consistently warmer.

Establishment

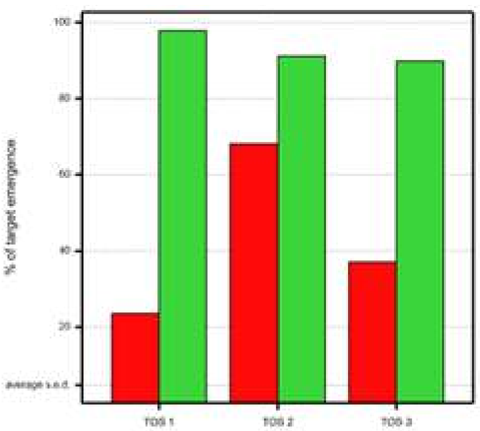
Seed was sourced from several suppliers (Table 2) making the comparison of the different lines difficult. It was later confirmed that the quality of the supplied LCW genotype seed was compromised due to storage conditions over the previous summer.

Table 2. Varieties used and seed sources.

Seed source	Varieties
Longreach Seeds	LPB19-1337 LPB19-1492 LPB19-2962
AGT	V13121-156 V13121-020 Calibre⍉
Intergrain	IGW6794 *16Y466-023 *16Y452-012
CSIRO	Mace⍉ *LCW Mace 18 *LCW M70-1+ (Magenta) Scepter⍉
Commercially Sourced	LongReach Flanker⍉ Seednet Leabrook⍉ barley

* long coleoptile varieties

Average shallow establishment across the sowing dates was typically within 10% of target populations (Figure 2), however, average establishment for each of the three sowing dates for the deep sown treatments ranged between 24% (TOS 1) to 70% (TOS 2) and down again to 37% (TOS 3).



Depth	TOS 1 19/04/2021		TOS 2 20/05/2021		TOS 3 17/06/2021	
Shallow	97.9	a	91.1	a	89.9	a
Deep	23.6	c	68.1	b	37.1	c
ave. lsd w/i TOS	11.1					
ave. lsd	13.0					
ave. sed w/i TOS	4.02					
ave. sed	4.68					
t-val (5%)	2.77					

Shallow establishment was significantly better than the deep sowing for all sowing dates. TOS 2 deep was significantly better than TOS 1 and 3 deep at P(0.05).

Figure 2. TOS x Depth interaction with related statistical analysis.

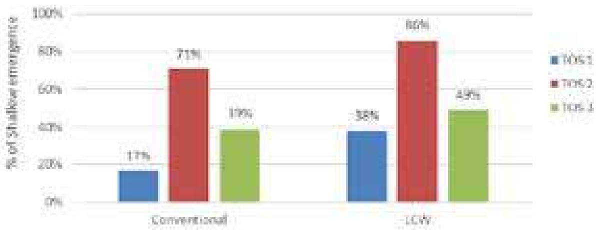


Figure 3. Percentage (%) of shallow establishment for both the LCW lines and conventional lines across the three sowing dates in at Emerald. The LCW lines' emergence was between 21% to 45% better than the conventional lines planted under the same conditions.

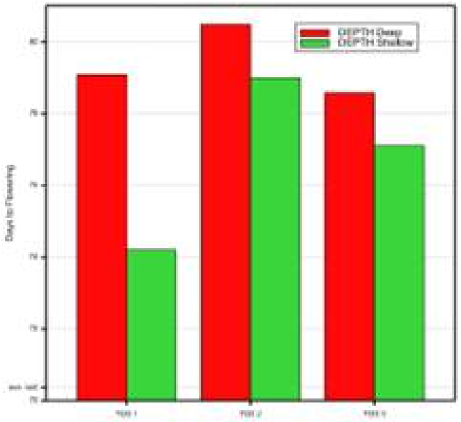
Re-analysis of this data for emergence (%) from depth compared to the same lines in shallow sowing highlighted differences between the conventional lines and the modified lines of 21% and 25% respectively (Figure 3). For TOS 1 the difference was 44.7% better than the conventional lines. Average temperatures during emergence for TOS 1 were 4 and 6°C warmer than TOS 2 and 3 respectively, possibly indicating that the LCW lines, despite their compromised quality, did establish better than the conventional lines.

In-crop phenology

Basic in-crop observations were made during the growing season for all three sowing dates, including flowering dates, tiller counts and grain yield and quality observations.

Days to flowering

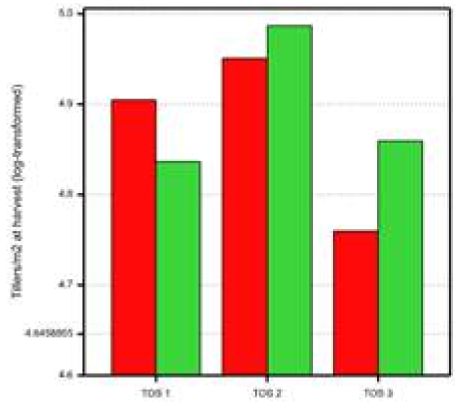
Average days to flowering (Figure 4) across the three sowing dates was significantly different, as was the difference between depths for each sowing date. TOS 1 had the largest average difference between the two sowing depths; the shallow-sown treatments were always the quickest. However, the average gap closed significantly between shallow and deep for the latter two sowing dates.



Depth	TOS 1 19/04/2021		TOS 2 20/05/2021		TOS 3 17/06/2021	
Shallow	74.2	d	79.0	b	77.1	c
Deep	79.1	b	80.5	a	78.6	b
ave. lsd w/i TOS	0.86					
ave. lsd	0.88					
ave. sed w/i TOS	0.35					
ave. sed	0.36					
t-val (5%)	2.45					

Means not followed by a common letter are significantly different at P(0.05).

Figure 4. Average days to flowering with related statistical analysis.



Depth	TOS 1 19/04/2021			TOS 2 19/05/2021			TOS 3 17/06/2021		
	Logt	Tillers		Logt	Tillers		Logt	Tillers	
Shallow	4.84	(125)	cd	4.99	(145)	a	4.86	(128)	bcd
Deep	4.91	(134)	abc	4.95	(140)	ab	4.76	(116)	d
ave. lsd w/i TOS	0.11								
ave. lsd	0.11								
ave. sed w/i TOS	0.047								
ave. sed	0.046								
t-val (5%)	2.45								

Means not followed by a common letter are significantly different at P(0.05).

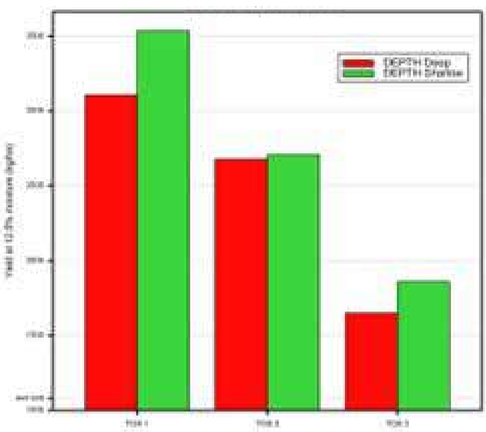
Figure 5. Harvest viable tiller counts with related statistical analysis.

Tiller counts at harvest

Average tiller counts per m² in TOS 1 deep and shallow treatments were not significantly different, nor were they different for TOS 2 or TOS 3. These numbers, when put into context with the emergence difference between deep and shallow sowing depths for TOS 1 and TOS 3 (Figure 5), show that remarkable compensation occurred in the deep-sown treatment for the number of plants emerged. Though not significantly different, the deep-sown treatment for TOS 1 had more tillers per m² than the shallow-planted treatments. TOS 2 and TOS 3 average tiller counts were higher for shallow than they were for deep.

Grain yields

Yield responses across the two depths and three sowing dates showed the benefit of early planting to maximise yield potential (Figure 6). TOS 1 shallow achieved the highest average yield at 3.5 t/ha for all sowing depths and dates. The deep sown TOS 1 had an average yield of just over 3 t/ha. This treatment out-yielded all later sown treatments regardless of sowing depth and emergence. The TOS 2 average yields were not statistically different, regardless of depth and establishment. TOS 3 shallow average yield managed to outperform the deep-sown treatments by almost 200 kg/ha.



Depth	TOS 1 19/04/2021		TOS 2 19/05/2021		TOS 3 17/06/2021	
Shallow (kg/ha)	3536	a	2708	c	1861	d
Deep (kg/ha)	3107	b	2677	c	1652	e
ave. lsd w/i TOS	157.1					
ave. lsd	166.6					
ave. sed w/i TOS	76.6					
ave. sed	81.3					
t-val (5%)	2.05					

Means not followed by a common letter are significantly different at P(0.05).

Figure 6. Yield response to TOS x Depth of sowing with related statistical analysis.

Table 3. Statistical analysis of average screenings (%) for each sowing depth and TOS for the Emerald trial.

Depth	TOS 1 19/04/2021			TOS 2 20/05/2021			TOS 3 17/06/2021		
	Logt	Screenings (%)		Logt	Screenings (%)		Logt	Screenings (%)	
Shallow	1.3	(2.7)	c	2.1	(7.1)	b	2.4	(10.1)	a
Deep	1.1	(2.0)	d	2.0	(6.7)	b	2.4	(9.8)	a
ave. lsd w/i TOS	0.07								
ave. lsd	0.07								
ave. sed w/i TOS	0.036								
ave. sed	0.036								
t-val (5%)	1.97								

Table shows both Log transformed (logt) and mean screenings (%) values. Means not followed by a common letter are significantly different (P=0.05).

Screenings

Average screenings across the three sowing dates and depths give an indication of conditions experienced by the treatments from head emergence to the end of grain fill (Table 3). For TOS 1 there was a small but significant difference in screenings between the two depths, with the deep sown treatment having the lowest average screenings of all treatments and dates at 2%. The shallow treatment screenings were 0.7% higher, indicating slightly higher water stress was experienced compared to the deep sown crop. TOS 2 screenings were significantly higher than TOS 1 at 6.7% (deep) and 7.1% (shallow). Statistically, there was no significant difference between the depths. TOS 3 had the highest screening at 9.8% (deep) and 10.1% for the shallow treatment.

Implications for growers

Data collected from the 2021 trials identified key issues growers need to deal with on a regular basis: the need for high-quality seed, and the importance of sowing date. The seed wheat that was stored in less-than-ideal conditions had lower germination and lower vigour and failed to perform to expectations in these trials. Despite their proven capacity to produce a coleoptile length well in excess 140+ mm, these compromised lines struggled even at shallow depths to reach acceptable populations and were worse when planted at depth.

It was not until seed was put under pressure (deep sown), we can begin to understand the full ramifications storage temperatures can have on wheat seed, particularly in warmer climates. Add into the mix; 10-day average soil temperatures still exceeding 22°C at 8 am in the latter half of April, and it's easy to understand why TOS 1 deep sown performed so poorly and did not meet target populations.

Soil temperature alone doesn't answer all the questions about poor emergence, especially for TOS 3. Based on the work of Dr. Rebetzke et al., coleoptile length should lengthen and increase in diameter to enable better emergence at cooler temperatures. By TOS 2, average soil temperatures at depth had come back to 19.2°C in Emerald, while at sister sites in southern Queensland, temperatures of 13.8°C near Westmar and 15.8°C at Condamine achieved significantly better establishment than TOS 1 in Emerald.

For TOS 3, despite average soil temperatures at depth now being 2°C cooler than TOS 2 in Emerald, emergence at depth fell away again, to be only 13% better than TOS 1 deep.

There is a common link between TOS 1 and 3 when comparing rainfall post sowing at Emerald; they both had approximately 30 mm of rainfall during the emergence period, whereas TOS 2 with the best emergence from depth had negligible rainfall. The soil at the trial site is a heavy Grey Vertosol, and with organic carbon levels down to 0.6% in the top 10 cm is prone to crusting on bare soil after short sharp rainfall events.

A final factor which may also have contributed was the effect of seed treatment applied to trial seed prior to TOS 1. All seed was treated with a product to protect from disease and insect attack during emergence and early crop stages. However, a warning on the label was discovered after sowing:

> "RESTRAINTS: DO NOT carry over treated seed from one season to the next as seedling emergence may be reduced or slowed in the following season. CRITICAL COMMENTS: Reduced emergence may occur if seed is … sown to a depth greater than 5 cm or into soil at a temperature less than 5°C or greater than 20°C."

All seed was treated just prior to TOS 1, so by TOS 3, some seed would have been treated for over three months. While not ideal, we still suspect seed quality, soil temperature, and rainfall were far more considerable limitations.

Table 4. Rainfall received 25 days after sowing.

DAS	TOS 1	TOS 2	TOS 3
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	15.1	0	0
6	0	0	0
7	0	0	1.1
8	0	0	6.3
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	1.1	0	0
14	0	0	10.7
15	0	0	8.4
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0.4
22	0	0.4	0
23	0	0	0
24	0.4	0	0
25	13.2	0	0
Total (mm)	29.8	0.4	26.9

Response to sowing date

The yield response to sowing date was a significant outcome for the 2021 TOS trials in Emerald. Despite TOS 1 deep only achieving an average target population of 23.6%, this treatment still managed to achieve the second highest yield of all sowing depths and dates. It had the lowest screenings of all treatments and the highest average test weight of all treatments. This outcome is quite remarkable, when commercially with such a low establishment it would have been at risk of being sprayed-out and re-sown.

Figure 7. Establishment for TOS 1, 24 days after sowing: deep sown (left) and shallow sown treatments (right).

While not the purpose of the trial, the data raises some significant questions about what is an optimum population for deep sowing in warmer climates and how poor an establishment can you get away with when sowing earlier in the season? Remote sensing data collected during the duration of the trial did provide some interesting insights. The box and whisker graph (Figure 8) shows the variance in surface temperature experienced for each sowing date over the duration of the trial.

TOS 2 experienced the narrowest variation from the mean surface temperature of the trial, however it was TOS 1 which experienced average temperatures 0.8°C cooler than the site mean, while TOS 3 experienced temperatures 1°C warmer than the site mean, peaking up to 4°C warmer than the site mean.

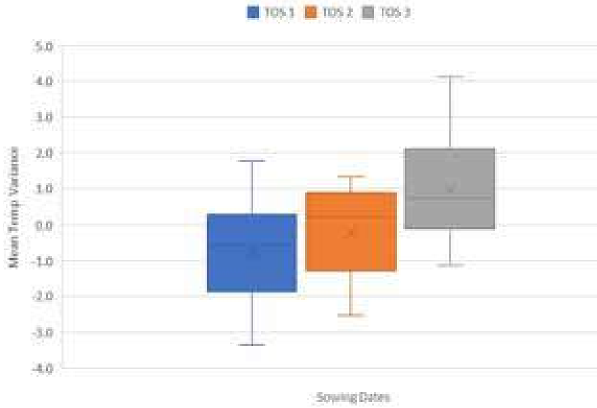


Figure 8. Mean site temperature variance across sowing dates. Graph shows the temperature variance from the mean temperature of the trial site over the trial period.

Acknowledgements

The research team would like the acknowledge and thank AGT, Longreach Seeds and Intergrain for all their support. Our team would also like thank Dr. Greg Rebetzke for being so generous with his time, his guidance and support. DPI also thanks the Grains Research and Development Corporation for investing in this preliminary research in central and southern Queensland.

Trial details

Location:	Emerald Smart Cropping Facility
Crop:	Wheat
Soil type:	Grey Cracking Vertosol soils down to a minimum of 150 cm.
In-crop rainfall:	TOS 1 – 70.9 mm TOS 2 – 71.4 mm TOS 3 – 64.3 mm. Please note: 30.3 mm fell between 20 September (TOS 1 harvest) and 10 October (TOS 2 & 3 Harvest date) which would not have benefited the two later sowing dates.
Fertiliser:	100 kg/ha of urea was applied 25 cm offset from the planting rows. Granular MAP was applied at 35 kg/ha with the seed at planting.

Deep sowing of longer coleoptile wheat in heavy Vertosol soils—Emerald 2022

Darren Aisthorpe and Jane Auer

Queensland Department of Primary Industries

***Research question**: What benefit can long coleoptile wheat (LCW) lines and deep sowing have on cropping systems in central Queensland?*

Key findings

1. If you have a full profile at depth after summer fallows, plant as soon as you are comfortable that the crop will be able to flower within your optimum flowering period.
2. Excellent seed quality (size, weight, germination percentage) is essential for optimising emergence, particularly in tougher conditions. Do not assume that because a variety has a longer coleoptile it will always have better emergence and will overcome low seed vigour or germination.
3. Soil temperature can have a significant impact on establishment, but not as significant as sowing date will have on yield. The LCW lines appear to handle higher soil temperatures better than non-LCW lines, however more work is needed to verify this.

Background

The ability of long coleoptile wheat (LCW) genetics to almost double the length of a coleoptile could provide growers with increased confidence to deep sow into summer stored fallow moisture earlier in the sowing window.

The laboratory and field testing conducted in southern and western grain regions of Australia by Dr. Greg Rebetzke et. al. shows that when temperatures and soil texture/density are favourable, the substitution of the Rht-B1b and Rht-D1b dwarfing genes for alternative (Rht13 and Rht18) genes can significantly increase the length and diameter of the coleoptile without increasing the overall height of the plant. However, Dr Rebetzke's work (G. J. Rebetzke et al. 2004) also found when conditions are less favourable (soil temperatures well above 19°C during emergence) coleoptile length can be almost halved for both modified and unmodified lines.

This project aimed to field-validate the value of modified LCW genotypes in central and southwest Queensland by comparing them against commercial and pre-release lines of wheat and barley that are recognised as having longer than the average coleoptile lengths. The research was done on heavier black / grey vertosol soil types to assess their relative performance at both a shallow (traditional) sowing depth and a deep sowing depth.

What was done?

The 2022 trial site came out of sorghum from early 2021 and had PAW of 200 mm down to 1.5 m; it was pre-irrigated in March due to continued hot and dry conditions in 2022.

Table 1. Sowing dates for 2022 and average soil temperature post sowing for the 2021 and 2022 trials.

Sowing date	10 day average soil temp @ 8am			
	Shallow		Deep	
	2021	2022	2021	2022
12/04/2022 (TOS 1)	21.6 °C	24.5 °C	22.7 °C	26.1 °C
9/05/2022 (TOS 2)	17.9 °C	20.9 °C	19.2 °C	22 °C
17/06/2022 (TOS 3)	17.3 °C	14.5 °C	15.7 °C	16.8 °C

Soil temperatures at time of sowing (TOS) 1 were markedly higher than the previous year at Emerald, with a ten-day average of 26.1°C for deep sown seed and 24.5°C for the shallow sown lines (Table 1). The coolest soil temperatures were experienced by TOS 3 Shallow (10-day average temperatures of 14.5°C).

Rainfall during the trial in 2022 was significant (Figure 1). A total of 357 mm of rainfall was received between the first sowing date (12 April) and the first harvest date (29 September). Ultimately, the trial received 530 mm of rainfall before TOS 3 was finally able to be attempted. While yields were recorded, the seed was not captured for quality testing due to significant sprouting and grain loss prior to harvest.

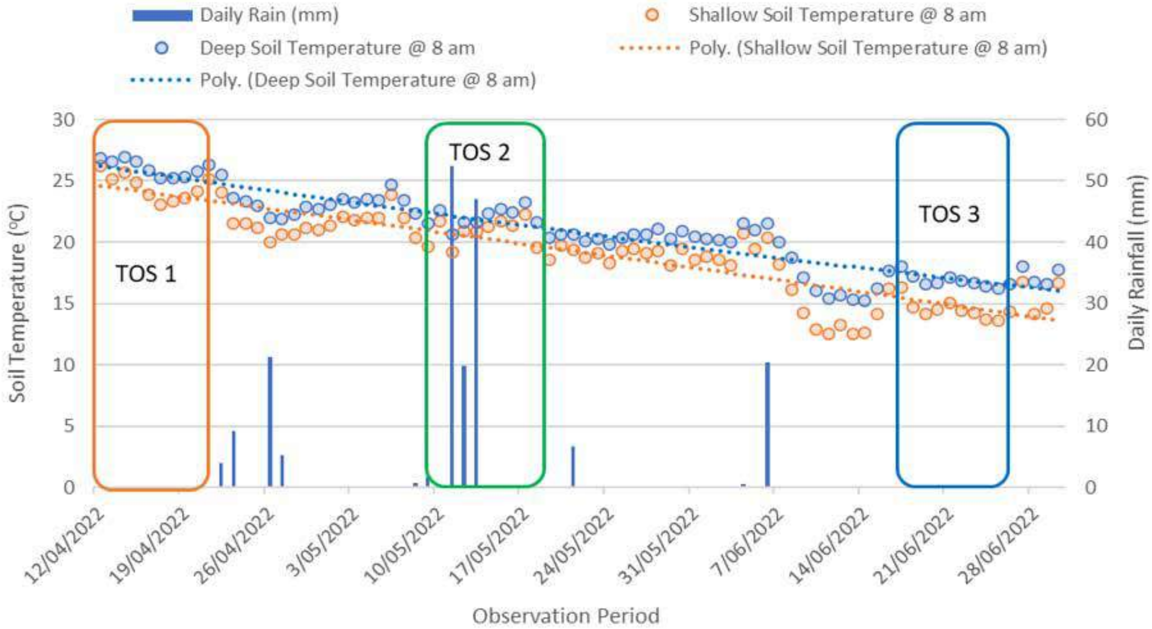


Figure 1. Daily soil temperatures (°C) @ 8 am and daily rainfall over the emergence periods for all attempted sowing dates. Blue circles indicate the soil temperature at seed depth for the deep-sown treatments and the orange dots indicate soil temperature as seed depth for the shallow sown treatments. The blue dotted trend line shows the estimated temperature curve for the deep treatments, the orange dotted line shows the estimated temperature curve for the shallow soil temperatures for the observation period. Daily rainfall is shown on the secondary vertical axis and clearly shows the significant rainfall received after planting TOS 2.

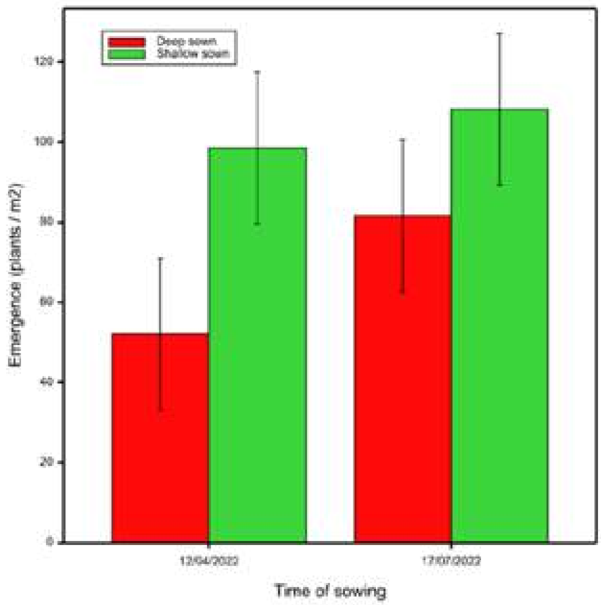
Results

Establishment

The 'shallow' sowing depth treatment in the trial aimed to have 30-50 mm of soil above the seed, while the 'deep' sowing depth targeted 95-110 mm of soil above the seed. This soil depth included both pressed soil and subsidence into the furrow on top of the seed. All treatments were planted into good consistent moisture with a tine opener on 50 cm row spacings.

Emergence in TOS 1 was significantly different between the two depths (Figure 2) The deep-sown treatments averaged 52 plants/m² while the shallow treatments averaged 98.5 plants/m². TOS 2 was compromised by heavy rainfall in May, receiving over 100 mm on the already wet soil over two days just after sowing (Figure 1). The sowing date was 'written-off' with no official counts completed. However, plots that managed to establish were allowed to continue to maturity with the rest of the trial.

TOS 3's average emergence (82 plants/m²) from depth was significantly better than TOS 1 (52 plants/m²) and was not significantly different to TOS 1 shallow emergence (Figure 2). The TOS 3 shallow emergence (108 plants/m²) was significantly better than the deep emergence.



Depth		TOS 1 12/04/2022		TOS 3 17/06/2022	
Shallow		98.5	ab	108.2	a
Deep		52.1	c	81.6	b
ave. lsd w/i TOS	11.6				
ave. lsd	18.8				
ave. sed w/i TOS	4.2				
ave. sed	6.8				
t-val (5%)	2.77				

Figure 2. TOS x Depth analysis conducted on TOS 1 and TOS 3 datasets. Deep sown treatments on a whole had a significantly lower emergence than the shallow sowing for TOS 1, or either of the 2 sowing depths in TOS 3. TOS 3 deep was not significantly different to shallow sowing in TOS 1. TOS 3 shallow had the best emergence of the 2 sowing dates.

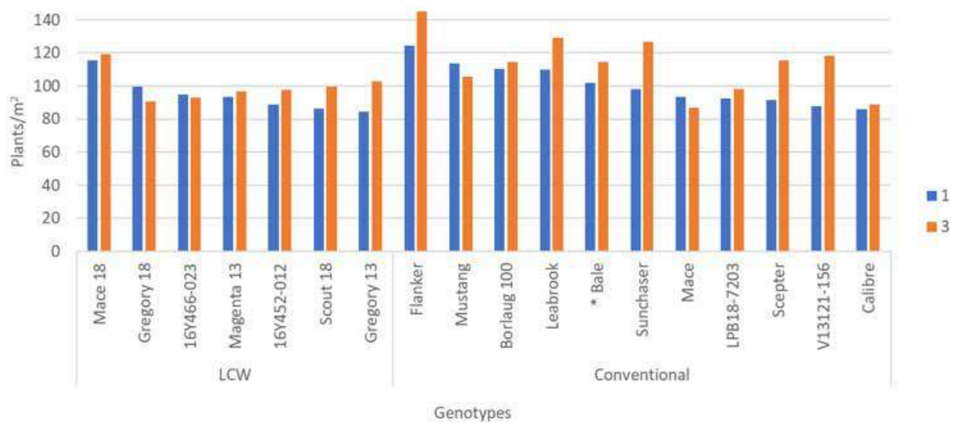


Figure 3. Shallow sown varietal emergence comparing TOS 1 & 3.
There were no statistical differences observed between sowing dates, nor between conventional or LCW lines, however the graph does highlight the emergence difference between the shallow sown treatments in this graph and deep sown treatments in Figure 4. Please note that all commercially available varieties are subject to PBR (* variety to be confirmed).

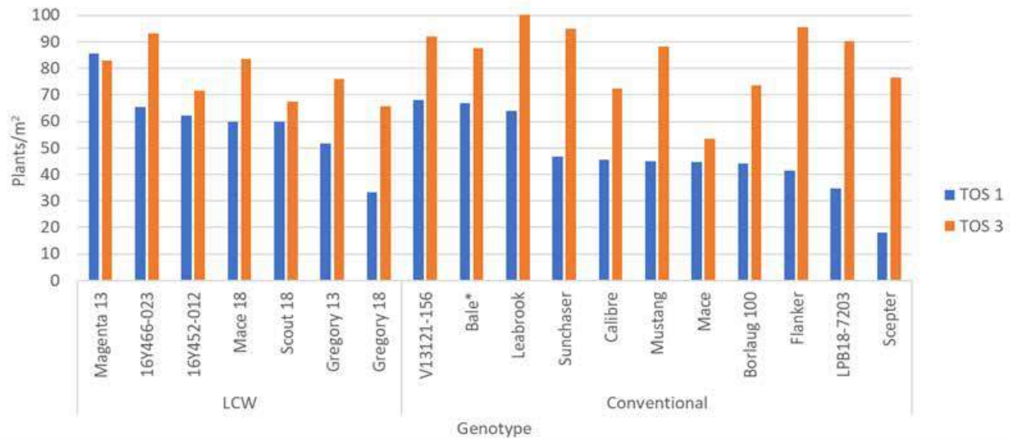


Figure 4. Deep sown varietal emergence comparing TOS 1 & 3.
For the LCW lines there was not a statistical difference between TOS 1 and TOS 3, however for the conventional lines there was (p=0.05) There was not a statistically significant difference between LCW lines and conventional lines used in this trial. Please note that all commercially available varieties are subject to PBR (* variety to be confirmed).

There were minimal statistically significant differences between the LCW lines and the conventional coleoptile lines. There was a significant 40-plant difference between the deep and shallow sowing depths for conventional lines across the two sowing dates (107 vs 67 plants/m^2). Equally, there was a significant difference in the LCW lines (97 vs 69 plants/m^2), but the difference was 11 plants/m^2 less at 29 plants/m^2. Details of specific varieties are summarised in Figures 3 & 4.

The 10-day average soil temperature post sowing for TOS 1 was 9°C hotter than TOS 3, and 7°C above the 19°C (Table 1) threshold that can compromise coleoptile development. There was not a significant difference between conventional and LCW lines for either of the two sowing dates assessed, nor was there a significant difference between sowing dates for the LCW lines.

A significant difference was identified between the emergence of the conventional lines in TOS 1 (74 plants/m^2 average across the 2 depths) compared to TOS 3 (99 plants/m^2); an improvement of 25 plants/m^2.

Crop development of the deep sown conventional lines in TOS 1 & 3 (Figure 5) were mapped using a crop health index generated from drone-based assessments of the trial over the growing season. These flights allowed assessment of crop health using a standard index such as NDVI and are used to map crop growth and distribution as a percentage (%) of a known healthy plot area. This index allows the quantification of crop establishment, vigour, and general development over a growing season, especially in systems where wider 50 cm row spacings are used.

In TOS 3, the deep-sown conventional lines' index values peaked at 0.6 to 0.95 (i.e. 60% and 95% of the known healthy area) at 60 days after sowing (DAS). TOS 1 peak levels of 0.47 to 0.9 were not reached until 85 DAS. The TOS 1 deep sowing had almost half the plants of TOS 3 (52 vs 82 m^2) on average. The health index values achieved at 60 DAS, saw most lines struggling to achieve 0.25 to 0.6, well behind TOS 3 after the same period post sowing.

Grain yield results were consistent with data from previous TOS x population datasets collected in Central Queensland. Despite emerged populations

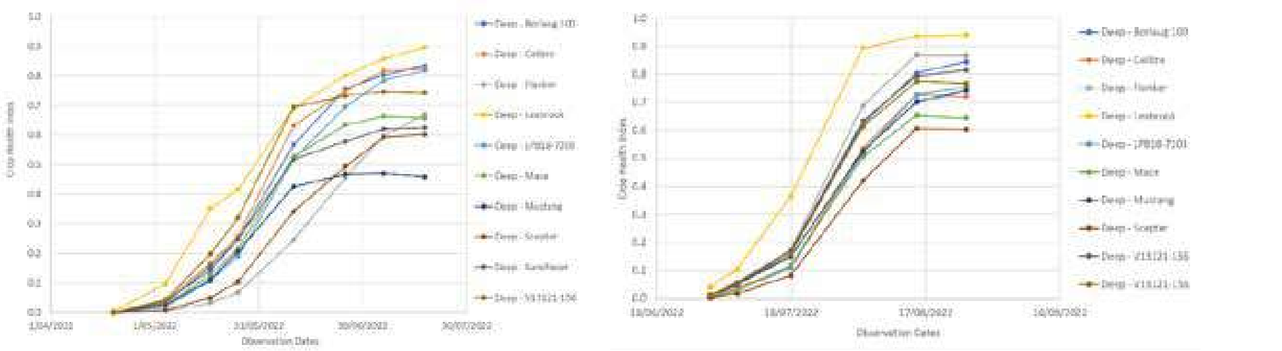


Figure 5. Crop development comparison of TOS 1 and TOS 3 for the deep sown conventional lines using a crop health index. The index assesses NDVI levels and biomass distribution over a known plot area. The TOS 1 graph shows a wider spread of the crop health index relative to TOS 3 for deep emergence. All the lines also hit peak index levels in TOS 3 significantly quicker than they do in TOS 1.

being almost half of the shallow-sown systems, the average yield of the deep-sown lines in TOS 1 (5106 kg/ha) was not significantly different to those of the shallow sown lines in TOS 1 (5135 kg/ha). Nor was the average yield of TOS 3 shallow significantly different to deep sown lines in TOS 1 (Figure 6).

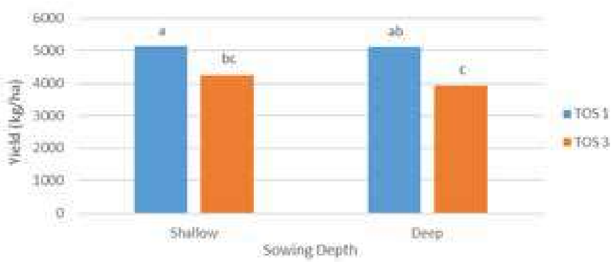


Figure 6. Depth x TOS Yield response in (kg/ha).
The graph shows average deep and shallow treatment grain yields. TOS 1 - Shallow had the highest yield of 5135 kg/ha, however TOS 1 Deep's yield was not significantly different at 5106 kg/ha. TOS 3 Deep had the lowest yield average yield at 3934 kg/ha. Columns without a common letter are significantly different (P=0.05).

Rainfall during the growing season did have a significant effect on the trial data collected. While grain was harvested from all 3 sowing dates, TOS 2 was heavily skewed by the very poor emergence from depth for multiple genotypes. Equally, TOS 3 received significant rain just before harvest, lodging many lines and reducing grain quality so much it was not deemed worthwhile performing quality tests upon it (Figure 7).

Figure 7. TOS 3 after receiving 140 mm in mid-October.

Implications for growers

Plant establishment when chasing soil moisture deeper than the standard sowing depth has always been a challenge for both winter and summer cereals. Growing winter cereals on and above the Tropic of Capricorn also brings with it some additional challenges, most notably being soil temperature. Soil temperatures over the past two years for our TOS 1 period (mid-April) have been significantly higher than the 19°C threshold (Table 1) identified as detrimental to coleoptile length and diameter. (G. J. Rebetzke et al. 2004).

Data from the past two years at Emerald show that soil temperatures remain, on average, 1.3°C warmer at depth. This exacerbates the challenge for deep-sown coleoptiles trying to push through 10 cm rather than 3-4 cm of soil in a conventional plant. The effect of this temperature can be seen in the emergence data from TOS 1 (Figure 2).

Seed quality matters

It is important to note that in this trial we are comparing some of the best and most recent lines developed for this region, with LCW lines whose parents were originally released in 2004 (EGA Gregory); as such we are not necessarily comparing apple with apples. Additionally, the number of commercially unavailable lines meant there were at least eight different sources for seed, which ranged from high-quality seed direct from breeders and seed bought over the counter at a local reseller, to seed sampled from rain-affected trials in 2021. As such, seed size, germination and vigour varied immensely; all factors that directly affect emergence, particularly from depth in high stress scenarios.

The statistical analysis failed to identify a significant difference in emergence between the LCW lines and the conventional lines in this data set. Apparent visual differences the results may have been masked by having so many different seed sources and their variable seed quality. Despite this, Magenta 13 appears to be a 'stand-out' of the LCW grouping. Its 300 seed weight at planting was 15 grams, while the rest of the LCW lines only had a 300 seed weight just over 11 grams, which showed in emergence counts (Figure 4).

Unlike the LCW lines, there was a statistical difference between average emergence for the conventional lines in TOS 1 vs TOS 3. This suggests that the LCW lines may have handled the hotter conditions better than conventional lines (Figure 4). TOS 3 was 9°C cooler at depth and the emergence response is stark in the conventional lines.

The response seen in the sister site in southern Queensland backs up the data from the Emerald site. The emergence in these cooler soils north west of Goondiwindi was significantly better for the conventional lines than what was seen in the Emerald TOS 1 data for the same lines.

Figure 8. Deep sown Magenta 13 taken in TOS 1.

The elephant in the room…

You could be excused for drawing the conclusion, that it might be best to wait and plant deep later into cooler soil, job done. While that will assist your emergence population, it is not recommended as long as you have good quality seed.

This trial reinforces past research and again showed the importance of sowing to ensure your flowering and grain fill is occurring during a period of least stress for the plant (lower temperatures and higher humidity). The greater the vapour pressure deficit (VPD), the harder the plant needs to work to replace water lost by transpiration and the less water/energy it has available to generate yield. VPD is a relationship calculation using temperature and relative humidity to assess how much water the air can hold.

Planting time is absolutely critical to maximise yields. On average, the TOS 1 deep-sown lines almost matched the shallow-sown TOS 1 lines and appeared to out-yield (although not statistically different at P=0.05) the shallow-sown TOS 3 despite the later sowing having almost twice the plants established, higher net crop health index levels, more consistent populations, and higher head/tiller counts/m^2 (Figure 6). The TOS 1 established plants could take advantage of the exceptionally low VPD level in the period (Figure 9) from the setting of tillers through to the completion of grain fill. And while the VPD levels remained below the 1 KPA level for much longer than average in 2022, TOS 3 still didn't reach 50% flowering until mid to late August, when temperatures and the VPD levels were already starting to creep back up again.

Key messages and implications

The 2022 winter season was well outside an average or typical year. As such, any data presented here it should be viewed carefully. Despite receiving more than 4 times our average in-crop rainfall, the core fundamentals of understanding farming systems and/or agronomic changes to maximise profitability of the long coleoptile trait in wheat held true.

1. **Sowing date** – if you have an accessible profile at depth to grow a crop, don't wait. In fact, you can start earlier if deep sowing. Identify and target an optimum flowering period for the maturity of wheat you are growing. This will maximise yield while minimising heat stress (and frost risk). Deep sowing can add up to 10 days to flowering date; the 'clock' starts from emergence, not sowing date.
2. **Seed quality** – Most commercially available wheat lines have an average coleoptile length between 6.5–7.5 cm, however we have seen lines emerge from significantly deeper in these trials. The CSIRO developed LCW lines do have the ability to develop coleoptile lengths of 15 cm plus. However, high-quality seed is essential if you want to take advantage of that attribute, particularly under the increased stress of additional depth and higher soil temps.

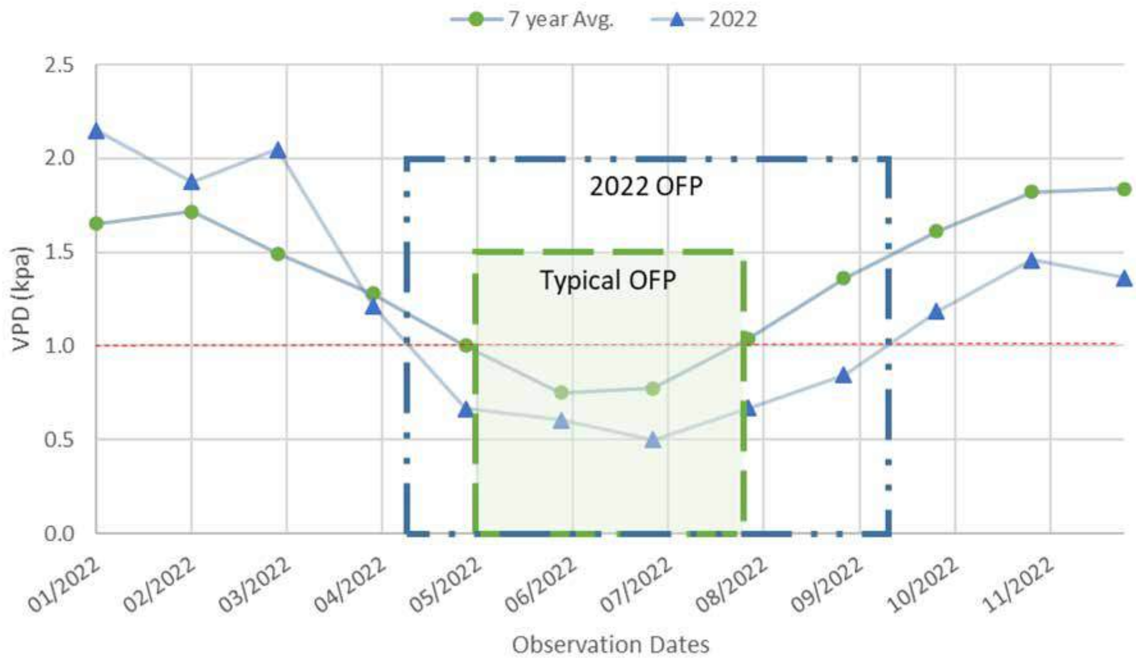


Figure 9. Emerald average monthly Vapour Pressure Deficit (VPD) for 2022 and the average value over the past 7 years at the Emerald Smart Cropping Centre.

2022 saw higher than average levels for the first 3 months of the year, but from May onwards the period below a VPD value of 1 kpa or below (or the optimum flowering period (OFP) was significantly longer and lower than the 7-year average (highlighted by the green box), extending well into September.

3. **Soil temperatures** – Temperatures over 21°C can have a significant effect on emergence, particularly from depth. Our data has shown that conventional lines, even with recognised longer coleoptiles still struggle more in hotter soils than the CSIRO LCW lines. As temperatures drop below 19°C, this becomes less of an issue.

Acknowledgements

The research team would like the acknowledge and thank AGT, LongReach Seeds and Intergrain for all their support over the past 2 years. Our team would like thank Dr. Greg Rebetzke for being so generous with his time, his guidance and support. DPI would like the thank Grains Research and Development Corporation for investing in this preliminary research in central and southern Queensland.

References

G. J. Rebetzke, R.A. Richards, X. R. R. Sirault and A. D. Morrision (2004) Genetic analysis of coleoptile length and diameter in wheat, Australian Journal of Agricultural Research 55, 733-743.

Trial details

Location:	Emerald Smart Cropping Centre
Crop:	Wheat
Soil type:	Cracking grey vertosol with a plant available water capacity of more than 200 mm
In-crop rainfall:	Total rainfall from 1 April to 1 November on site was 508 mm. Daily temperature ranges are shown in Figure 10.
Fertiliser:	35 kg of Granulock® Z was applied with the seed, 100 kg/ha of nitrogen (217 kg of urea) was applied between the rows using double disc openers.

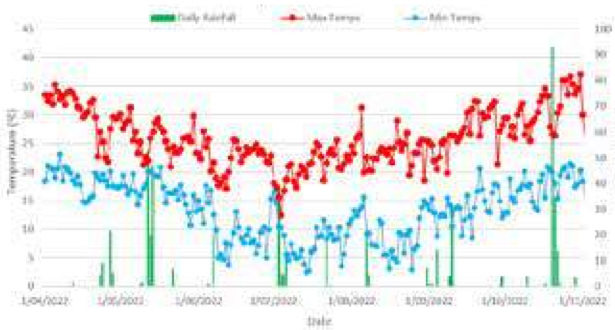


Figure 10. Daily minimum and maximum temperatures shown as the blue and red line graphs. The vertical green columns indicate daily rainfall over the period from 1 April to 1 November 2022.

Long coleoptile wheats – for deep seeding and optimising sowing window options

Darren Aisthorpe
Queensland Department of Primary Industries

Key findings from LCW research

1. Ensure high seed quality (seed weight, gemination % and vigour) to maximise emergence in adverse conditions.
2. Sowing deep early in the optimum sowing window will out-yield sowing shallow or deep late in the window in almost all scenarios.
3. Ensure press wheel pressure does not further exacerbate emerging seedling stress.
4. Soil temperatures above 19°C can have a negative effect on coleoptile length and need to be considered when timing sowing early in the planting window.

Background

Since the green revolution when dwarfing genes were introduced into wheat varieties to increase grain yield, there has been unintended selection for shorter coleoptile length, reducing the plants' ability to emerge from deep sowing or in unfavourable conditions. Long coleoptile genes have long been investigated as a possible solution to increase coleoptile length. However, in recent times this trait is being investigated to assist with changing autumn rainfall patterns to achieve more timely sowing opportunities.

Extensive laboratory and field testing conducted in southern and western grain regions of Australia showed that the substitution of the Rht-B1b and Rht-D1b dwarfing genes for alternative Rht13 and Rht18 genes can significantly increase the length and diameter of the coleoptile without increasing the overall height of the plant, however coleoptile length can be almost halved in warm soils (>19°C) for short and long coleoptile wheats alike (Rebetzke et al. 2004).

The work reported here aimed to compare the ability of LCW (which have coleoptiles nearly double the length of traditional dwarf wheats) against shorter coleoptile wheat to emerge from deep sowing in the heavy Vertosol soils of central and south-western Queensland.

All trials were planted on 50 cm row spacings, at two depths (including subsidence). Shallow sowing aimed to represent standard sowing practice, with no more than 3-5 cm of soil over the seed post plant. The deep sowing treatments were targeted to have 9-11 cm of soil over the seed.

Despite many positive anecdotal observations across the five trials, the two-year project was not able to statistically conclude that the LCW lines improved emergence in southern and central Queensland compared with shorter coleptile wheat.

Significant benefits were identified around optimising deep sowing results regardless of coleoptile type.

Possible emergence limitations

1. Soil temperature

Soil temperature has been proven to limit/reduce coleoptile length and diameter, particularly when soil temperatures exceed 19°C. Trials conducted since 2021, actively measuring soil temperatures at 3-5 and 9-11 cm, demonstrated that temperatures of >20°C are often experienced (Figure 1).

The data in Figure 1 (Emerald) and Figure 2 (southern Queensland) represent the range, mean and median of air and soil temperature at both standard and deep sowing depths, observed during the first 20 days post sowing for six trials over three years. The temperatures experienced at the Emerald Central Queensland Smart Cropping Centre location were significantly warmer (Figure 1) than the southern Queensland (SQ) sites (Figure 2). But it is important to note that the late April sown SQ site in 2022 did experience soil temperatures above the 19°C threshold found to significantly limit coleoptile length and diameter (Figure 2).

2. Seed quality

The quality of seed wheat can be assessed in a multitude of ways, and often influences emergence.

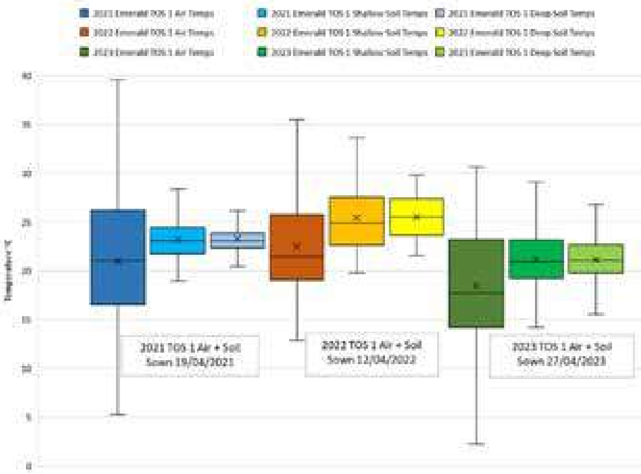


Figure 1. Air and soil temperature for two sowing depths at the Central Queensland Smart Cropping Centre, Emerald based on 15 minute observations (TOS 1 only).
The box shaded area represents 50% of all observations, the line across the box represents the median temperature observed and the X marker represents the mean temperature for the 20-day period. The graph shows soil temperatures, while variable over the 24 hour, 20-day period, averaged greater than 20°C, with the 2022 TOS 1 treatment averaging soil temperatures above 25°C, both shallow and deep.

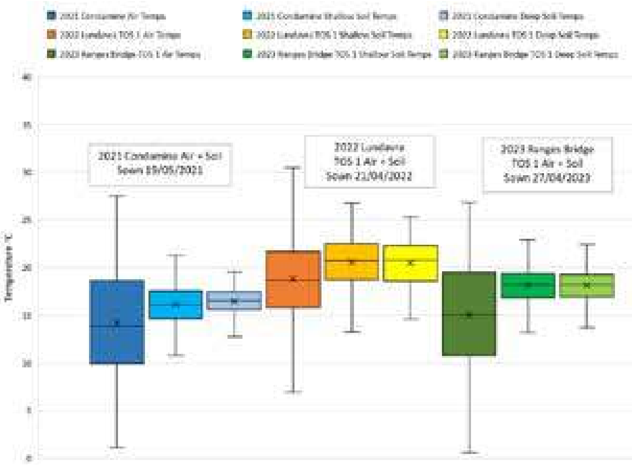


Figure 2. Air and soil temperature for two sowing depths at the southern Queensland trial sites (TOS 1 only).
The shaded box area represents 50% of all observations, the line across the box represents the median temperature observed and the X marker represents the mean temperature for the 20-day period. The graph shows soil temperatures, while variable over the 24 hour, 20-day period, were significantly cooler than the CQ site, though the late April sowing at both Lundavra and Ranges Bridge (Macalister) show these sites did experience average soil temperatures at or above the 19°C threshold discussed.

Factors that impact seed quality include:

- Climatic conditions during grain fill
- Indications of disease on seed
- Colouring/appearance/protein content
- Time since harvest
- Storage temperature and moisture post-harvest
- Insect damage in storage
- Seed treatments applied (and when).

When trying to compare one seed lot with another, typically it will come down to three key attributes:

1. **Germination (%)** – the percentage (%) of seeds that will germinate, given suitable moisture conditions, within a defined period, typically seven to ten days.
2. **Seed size** – Presented as the weight of a representative number of seeds. Often presented as grams per 300 or 1000 seeds.
3. **Seed vigour** – Generally understood in concept, but poorly/inconsistently assessed. At its most basic level, it is an assessment of the seedling's ability to germinate and then emerge from defined a seedbed environment in a timely manner.

Each of these seed attributes are key to identifying the expected performance of planting seed, and all three are linked. Ideally, when deep sowing, growers should source the very best quality seed available. All seed should be tested for all three of these attributes prior to planting, and the following calculations conducted to optimise crop establishment.

Example of sowing rate calculation to optimise crop establishment

1. Extract representative wheat seed sample from silo after seed is cleaned and graded.
2. Conduct germination test on 100 seeds over 7 days.
3. Count out 300 seeds and weigh them.
    - Germination (%) = 92% (within 7 days)
    - 300 seed weight = 12 grams
    - Target plant population is 1 million plants/ha
4. Calculate the germination adjust target plant population.
    - Target population ÷ germination (%) x 100 = germination adjusted population
    - 1,000,000 ÷ 92 x 100 = 1,086,957 seeds/ha
5. Adjust germination-adjusted population to allow for establishment losses*.
    - Germination-adjusted population ÷ establishment (%) x 100 = seeds required/ha
    - 1,086,957 ÷ 85 x 100 = 1,278,772 seeds/ha
6. Calculate sowing rate required to achieve target population.
    - Seeds/ha ÷ no. of seeds counted x seed weight (g) ÷ 1000 = sowing rate (kg/ha)
    - 1,278,772 ÷ 300 x 12 ÷ 1,000 = 51.2 kg/ha

*This value will vary (influenced by insect damage, seed bounce, compaction, planter configuration etc), but 85% is a reasonable establishment value to use in most planting scenarios. **Please note: these are example values; use your own testing to calculate sowing rate for each seed lot.**

High germination test counts, based on testing completed in a damp chux™ cloth on the kitchen table, or excessively large wheat seed do not guarantee that seed will be able to emerge when sown deep into heavy warm Vertosol soils at commercially-acceptable populations.

3. Soil strength

An increase in soil strength will impede emergence of the developing coleoptile. Inherently, soils with higher clay content (such as Vertosols) tend to have a higher density, while softer scrub soils (with lower clay content) tend to have a lower density and consequently faster emergence. At just over double the sowing depth, there is a significant increase in the energy required for a seedling to push through to the surface. Soil density or soil strength can also be exacerbated by excessive press wheel down pressure, particularly in damp soils. In some worse-case scenarios the seed trench can set like rock as it dries or following rain can create anaerobic conditions leading to seedling death.

Observations

Data from the 2022 TOS 1 Emerald and Lundavra trials (Figure 3) indicate that genotype emergence from deep sowing ranged from 20-90% of the shallow-sown treatments for the first sowing date at each site. These two sites and sowing dates experienced the highest average temperatures during the initial 20-day emergence period.

The response from most genotypes was remarkably similar across the two sites, given the cooler (and wetter) conditions experienced at the Lundavra site. There were some notable exceptions, the first being Sunchaser⊕ which performed exceptionally well in southern Queensland relative to the Emerald site, something it has repeated in other trials in southern Queensland in other years. It had the third largest seed in the trial and tested seed germination was excellent (Table 1), yet at the Emerald site, its emergence was middle of the pack. Gregory⊕ 18 and Scepter⊕ also emerged better at the Lundavra site compared to Emerald.

The most likely reason for the difference in emergence (relative to shallow) between sites for these three lines is being driven by the 5°C cooler soil temperature in southern Queensland over the emergence period. But if so, why did Magenta⊕ 13 and the pre-release line 16Y466-012 perform better from deep sowing in the hotter central Queensland conditions (Figure 3)? Testing showed both seed lines had acceptable quality seed, Magenta⊕ 13 had the largest seed of all the lines and the pre-release line 16Y466-012 had tested germination of 95% (Table 1).

As background, the shallow/overall emergence at the Lundavra site was lower than the Emerald site, despite using the same seed. It was later found that the press-wheel down-force of the southern Queensland planter (coil spring type rather than a solid or semi pneumatic type) was higher than first expected. While appearing to be satisfactory at planting, as the soil in the furrow dried post plant, it set very hard.

Time of sowing 1 (April) conditions were conducive to a good planting however after significant rain TOS 2 (May) did not occur due to wet conditions.

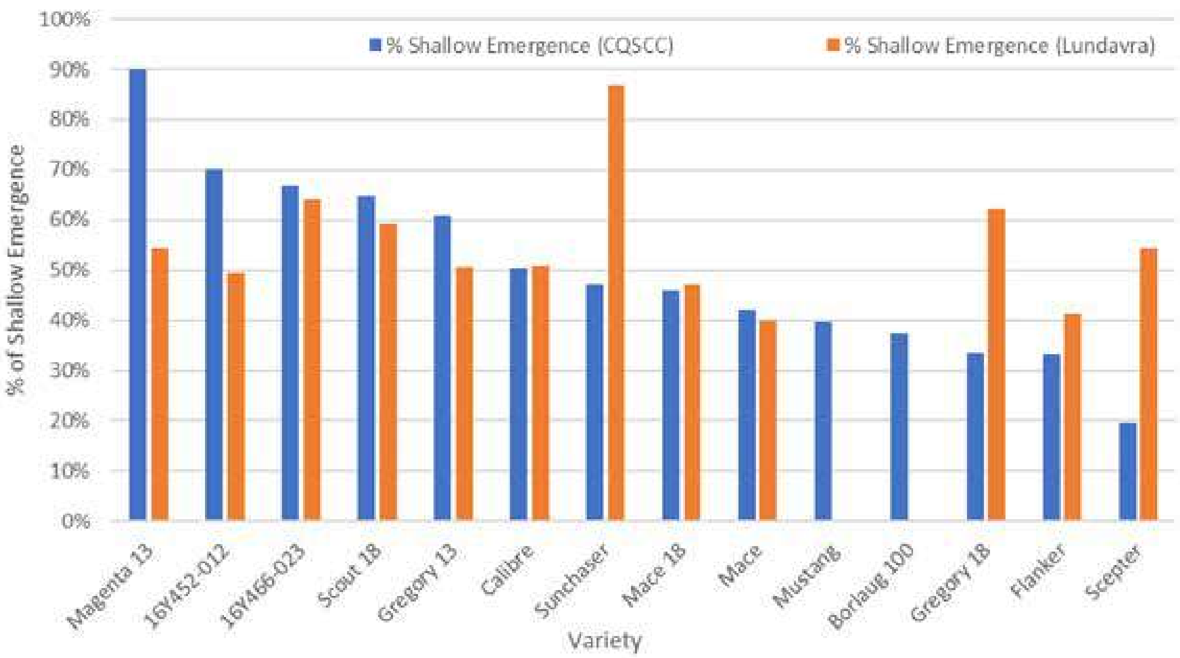


Figure 3. Emergence from deep sowing for each genotype, presented as a percentage of shallow sown emergence at Emerald CQSCC and Lundavra sites in 2022. The response was quite consistent across sites, with some outliers that could be explained by either temperature or reduced vigour. Magenta 13, LRPB Scout 18, Gregory 13, Calibre, Sunchaser, Mace 18, Mace, LRPB Mustang, Borlaug 100, Gregory 18, LRPB Flanker & Scepter are protected under the *Plant Breeders Rights Act 1994*.

Table 1. Seed quality attributes and sowing rate for the 2022 LCW trial program.

Variety	Seed size (g/300 seeds)	Seed size (seeds/ kg)	Seed germination (%)	Sowing rate (kg/ha)
Magenta⏀ 13	15.0	20000	92	63.9
Calibre⏀	13.6	22075	99	53.8
Sunchaser⏀	13.3	22556	98	53.2
LRPB Flanker⏀	12.7	23604	95	52.5
Gregory⏀ 13	12.7	23622	92	54.1
Borlaug⏀ 100	12.7	23622	97	51.3
Gregory⏀ 18	12.6	23810	99	49.9
Mace⏀	12.4	24194	98	49.6
Scepter⏀	12.2	24590	94	50.9
LRPB Mustang⏀	11.8	25424	90	51.4
16Y466-023	11.2	26786	95	46.2
16Y452-012	10.9	27523	95	45.0
Scout⏀ 18	10.8	27778	93	45.5
Mace⏀ 18	10.8	27778	97	43.7

Bold text indicates LCW lines.

It was only just dry enough to plant TOS 3 (June) and the deep sown treatment had to be written off due to almost zero emergence. This was caused by compaction from excessive press wheel pressure on wet soil which resulted in hard setting surface.

Despite the extra compaction described above, the data seemed to indicate that while the germination and seed size numbers for both Magenta⏀ 13 and 16Y466-012 looked sufficient, it was likely that seed vigour may not have been as good as other genotypes in the trial, leading to the reduced emergence compared to shallow sowing at the southern Queensalnd site.

It is important to note that these observations are all 'relative' to each other, not absolute, and that the genotypes in this trial have a range of coleoptile lengths that would also factor into performance from depth. To that point, the final observation from Figure 3 is when looking at the ranking of genotypes on the X-axis (Figure 3), of the 14 lines listed, only two of the top eight lines were not equipped with the alternative Rht13 and Rht18 genes. There is also a strong suspicion that the Gregory⏀ 18 seed had compromised vigour, given how much better the Gregory⏀ 13 performed.

Grower experience – timing of deep sowing

An important component of the project was understanding what experience growers have had with deep sowing winter cereals. While most were confident deep sowing chickpea, the feedback was quite different for deep sowing cereals. A cohort of growers had the equipment and felt reasonably comfortable being able to chase moisture down to depths of 10 to 15 cm, without getting too much soil back over the seed. But even within this cohort, the experience had been at best neutral to negative relative to their chickpea experience.

Of those who indicated that the experience had been less than ideal for them, (and ignoring any seed quality issues), the majority had only tried deep planting at the later end of their traditional planting window. They typically had moisture at depth late in the fallow, however it was out of reach at the beginning of the sowing window for a traditional planting.

By late May, expected rain hadn't come, or insufficient rain had fallen – more than 30+ mm was needed to join up the profile. Deep planting was attempted however seeders struggled to maintain a consistent sowing depth (keeping the tine in the moisture) and the moist layer was now deeper. They were also using varieties that would normally be planted a month earlier as they were not prepared to purchase new seed for this type of high-risk scenario.

As a result, emergence was well down and generally patchy. The established plants developed well, but flowering and grain fill were delayed due to reduced competition for resources, resulting in heat stress during this period that significantly reduced yield potential.

Optimum flowering dates

A large body of research shows flowering date will have a significant effect on yield of any given genotype. For Queensland conditions, aim for flowering in the coolest, lowest stress conditions possible for the crop while being mindful of frost risk at flowering and/or heat stress during grain fill. Across the LCW trial programs, wherever there has been a multi-date sowing, we have consistently seen a reduction in yield the later the sowing date, a response which is exacerbated when deep sowing (Figure 4).

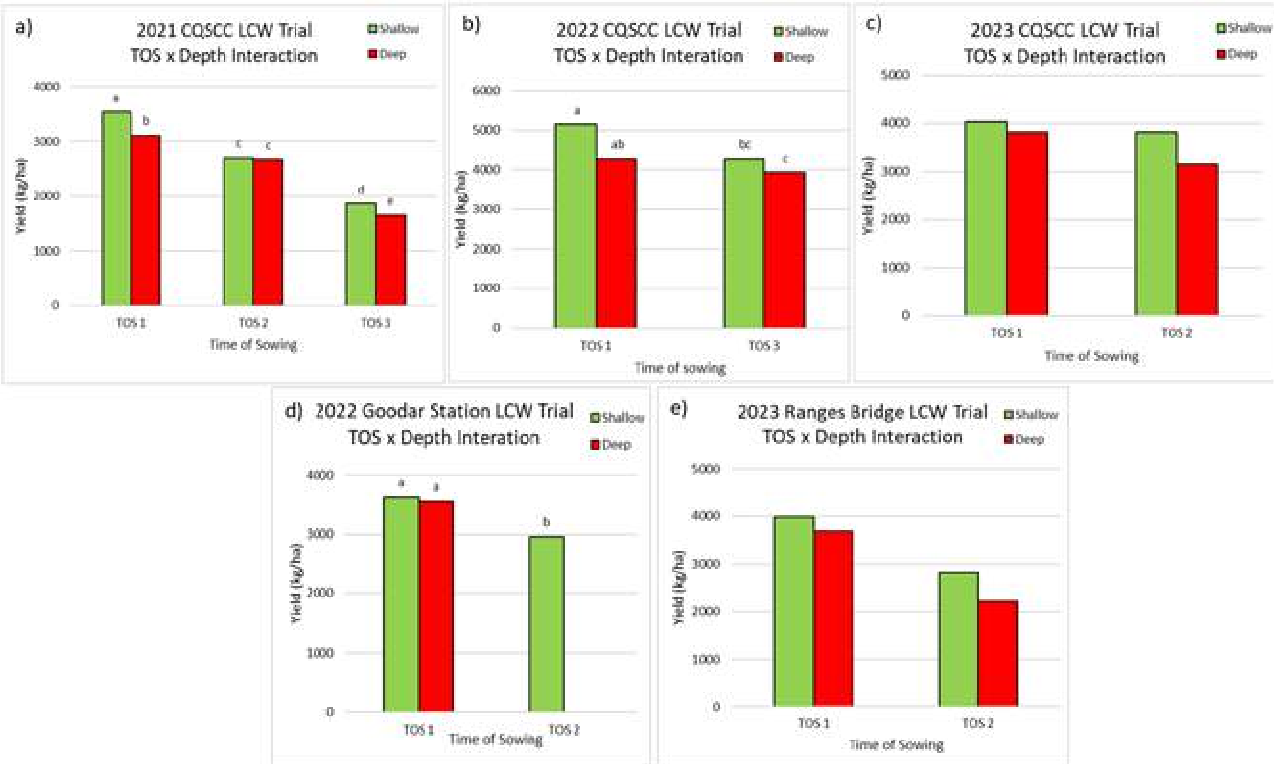


Figure 4. Yield response to TOS x sowing depth at all trials from 2021 - 2023 which included multiple sowing dates.
For 2021, the interval between sowing dates was 1 month, for 2022 the interval was 2 months due to wet conditions, for 2023 the interval was 3 weeks for CQ and 5 weeks for the SQ site (Ranges Bridge). Columns within each graph not labelled by a common letter are significantly different (P = 0.05). The 2023 data is still being analysed so only average difference is shown, any significant differences have yet to be determined.

The emergence from deep sowing for TOS 1 dates has been relatively consistent across the program, when compared to shallow emergence. In addition to the 2022 trials discussed above, the emergence for the 2021 Emerald trial was worse at depth (Figure 4a), with average emergence across all lines being 25% of shallow. Figure 4a shows that despite this low emergence, the early (TOS 1) deep-sown treatment significantly out-yielded the May and June shallow and deep sown treatments. When sown early, the ability of low population, deep-sown wheat to compensate is considerable. Late-sown wheat simply does not have sufficient time to recover, as temperatures rapidly begin rising from GS 55 onwards.

Implications

Both soil strength/density and soil temperature can have a significant effect on emergence, no matter what depth you are planting. To try and counter issues around soil strength, be very mindful of press wheel down pressure. Soil seed contact is essential, but don't put any more strain on the emerging seedling than necessary. Equally, if planting early, try to avoid any forecast high temperature periods during the 10-20 day emergence period.

Sowing to target a variety's optimum flowering window for a given location will pay dividends. Any emerging coleoptiles need to be able to drive up and out of the ground as quickly as possible to begin photosynthesis before the 'tank is empty'. Seed with high germination, large seed size and excellent vigour (ideally tested in conditions to replicate a deep sowing environment) is essential to maximise returns from any deep sowing opportunity.

References

Rebetzke GJ, Richards RA, Fischer VM, Mickelson BJ (1999) Breeding long coleoptile, reduced height wheats. Euphytica 106, 159–168.

Rebetzke GJ, Richards RA, Sirault XRR, Morrison AD (2004) Genetic analysis of coleoptile length and diameter in wheat. Australian Journal of Agricultural Research 55, 733-743.

Table 2. Pros and cons of shallow and deep sowing and sowing timing.

Timing	Depth	Pros	Cons
Early	Shallow	• Highest yield potential and the preferred option if available. • Best chance to get early in crop rainfall to establish secondary tillers. • Wider selection of varieties/maturities. • Improved grain quality over late sown lines.	• Soil temperature could reduce emergence in extreme conditions. • Frost risk.
	Deep	• Second highest yield potential of the four, but not preferred if shallow is an option. • Best chance to get early in crop rainfall to establish secondary tillers. • Wider selection of varieties/maturities. • Improved grain quality over late sown lines.	• Soil temperature typically higher at depth over 24 hour period. • Risk of heavy rain post plant/pre-emergence impacting establishment. • Lower emergence will extend flowering date. • Frost risk if too early.
Late	Shallow	• Typically, the best establishment in trials.	• Higher temperatures at flowering/grain fill. • Limited variety choices to maximise yield. • Limited opportunity to compensate yield loss if establishment is below expectation. • Greater chance of weather damage at harvest.
	Deep	• Usually better establishment than the early deep sown treatment.	• Higher temperatures at flowering/grain fill. • Limited variety choices to maximise yield. • Lower emergence than shallow will extend flowering date. • Greater chance of weather damage at harvest. • Less opportunity to compensate for lower establishment.

Acknowledgements

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

I would like to thank AGT, Longreach and Intergrain for their generosity in providing seed lines, both current and pre-release, for testing in these projects. Also, the feedback from key personnel within each of these businesses for their invaluable feedback.

I would like to acknowledge Dr. Greg Rebetzke and CSIRO for all the background support they gave the original project and their ongoing support within the current national project. Finally, I would like to acknowledge the significant effort put in by other DPI staff who have contributed to the work.

This article was originally published as a GRDC Update paper in March 2024 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2024/03/long-coleoptile-wheats-for-deep-seeding-and-optimising-sowing-window-options

Desiccating mungbean: is windrowing an alternative?

Jayne Gentry[1], Cameron Silburn[1], Paul McIntosh[2], James Hagan[1] and Rod O'Connor[1]
[1]Queensland Department of Primary Industries
[2]Pulse Australia/Australian Herbicide Resistance Initiative

Research question: *Is windrowing an alternative to desiccate mungbean?*

Key findings

1. Windrowing mungbean can be a viable alternative to chemical desiccation with no serious yield impact, less overall harvest losses and improved grain quality.
2. Situations where windrowing may be suitable include: multiple pod flushes, vigorous hard to kill plants, pending wet weather, heavy powdery mildew infestations, accessing markets with low glyphosate MRLs, or growing for seed and/or sprouting.
3. Avoid windrowing if there is limited access to appropriate machinery, uneven ground, very wet soil, or large amounts of rainfall are predicted.

Background

Currently Australian mungbean crops are chemically desiccated prior to harvest to aid 'dry-down' of the crop and facilitate mechanical harvest. An estimated 90–95% of the crop is desiccated with glyphosate, which is recommended for application when pods are black or brown (depending on individual product labels). Timing is critical to ensure maximum dry-down whilst minimising chemical residue in the seed. Improved mungbean varieties have led to more vigorous plants and desiccation has become increasingly problematic. One issue growers often struggle with is moisture remaining in the stem after desiccation that can cause seed coat staining resulting in downgraded grain quality. As a result, many growers have resorted to increasing herbicide rates.

The mungbean industry must be ready to adapt and meet market specifications if required, especially as export markets becoming increasingly sensitive to pesticide maximum residue limits (MRLs). Furthermore, international markets are amending their MRLs in very short time frames – often too quickly for the industry to respond. Consequently, residues of glyphosate in mungbean are already affecting the acceptance of Australian mungbean in some export markets. With over 90% of Australian mungbean exported, alternative harvest practices that do not use crop protection products were deemed a priority in the current strategic plan of the national industry body, the Australian Mungbean Association (AMA).

The Mungbean Agronomy Project (DAQ1806-003RTX – led by the Queensland Department of Primary Industries and supported by the Grains Research and Development Corporation and the Australian Mungbean Association) undertook research assessing the potential of mechanical desiccation of mungbean as an alternative to chemical desiccation. Windrowing is the mechanical process of swathing or cutting the crop and forming the cut crop into a strip (windrow) of biomass on the ground. Several days later the windrow is harvested by a header with a specialised pick-up front. Initial small plot experiments in 2021 successfully showed that mechanical desiccation of mungbean was a viable harvest option. This report explores the results from the 2022 commercial-scale trials.

What was done

Fifteen trials were implemented across southern Queensland and northern New South Wales, however only 12 had complete data sets due to rain. Two treatments were used in each trial: windrowing (Figure 1) and glyphosate desiccation (Figure 2).

The trials established on each grower's property were unique and designed to match the paddock layout and machinery configuration (controlled traffic systems). As a result, each trial varied in size and sample quantities. A range of assessment parameters including grain yield, plant moisture at desiccation and harvest, and grain losses were used.

Figure 1. Windrowed mungbean.

Figure 2. Chemically desiccated mungbean.

Grain losses were measured using a variety of techniques at each stage of the treatments:

- **Pre-harvest losses** (dessication only). Prior to dessication, hessian bags were placed around the base of mungbean plants to capture seed and assess shattering losses during dry-down.
- **Swathing losses** were measured at swathing (cutting) using 50 x 50 cm quadrats randomly placed in the swathed area. Collected mungbean seeds were weighed to measure the losses resulting from the swathing (such as shattering at the comb).
- **Header losses** were measured at harvest using a 'Bushels Plus' harvest loss system from Primary Sales Australia. A tray on the rear axle assessed seed loss out of the rear of the header during harvest.
- **Comb losses** (dessication only). Hessian bags were placed in the paddock under the path of the header. Seed on the bags after harvest was collected and weighed to assess losses such as shattering at the reel.
- **Total losses** were independantly measured after harvest using 50 x 50 cm quadrats placed directly where the windrow was harvested (and in a similar paddock position for glyphosate desiccation) to assess overall losses for both treatments throughout the whole period of the crop.

As these losses were difficult to measure and extremely variable across the paddock due to diferences in growers' harvesting machinery and set-up, the data presented should only be considered to be indicative of commercial performance.

Grain quality and glyphosate residue levels in the seed were also assessed.

Results

The results (Table 1) reinforce that windrowing is potentially a viable method for harvesting mungbean crops.

Table 1. Summary of results from 12 growers that had complete datasets of seed losses for the respective treatments.

	Glyphosate			Windrow		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Days to harvest from desiccation	8	16	11	5	16	9
Plant moisture at harvest (%)	19	47	31	13	27	19
Pre-harvest losses (kg/ha)	7	52	22	-	-	-
Swathing losses (kg/ha)	-	-	-	1	212	58
Yield (t/ha @12% moisture)	1.00	4.2	2.13	1.2	4.1	1.95
Header losses (kg/ha)	1	28	10	6	67	18
Comb losses (kg/ha)	15	161	100	-	-	-
Total losses (kg/ha)*	74	328	153	14	192	67

*Measured as an independent variable.

Yield

Windrowed mungbean showed a small yield penalty compared to glyphosate-desiccated mungbean with an average yield across trials of 1.95 t/ha versus 2.13 t/ha (Table 1). However, this was not consistent across all trials. Some crops achieved higher yields when windrowed, which may indicate different skills and timing in how the desiccation treatments were implemented. Crop yields across these trials varied widely, from 1 to 4 t/ha, although even the lowest-yielding crop still had a relatively high biomass.

Days to harvest from desiccation

Across the 12 grower sites with complete data sets, windrowing mungbean had the benefit of a shorter period to harvest by at least three days (Table 1). Trial logistics and access to harvest equipment meant the harvesting of windrow didn't occur at the optimal time in several cases.

Most of the windrows could have been harvested within the 4–7-day window, potentially halving the time to harvest compared to glyphosate desiccation. The earlier harvest with windrowing was possible due to the rapid dry down of plant material. Windrowed plant moisture was 19% at harvest compared to glyphosate which was 31% (Table 1) and followed a similar trend from the 2021 small trials at DPI's Hermitage research station (data not shown). Three days post-windrowing the plant moisture had almost halved and continued a rapid decline. It wasn't until 14 days after desiccation that glyphosate treatments reached a similar plant moisture level compared to windrowed treatments.

Grain losses

Total losses (measured as an independent variable) were lower in windrowed mungbean compared to glyphosate-desiccated mungbean (Table 1, Figures 3 and 4).

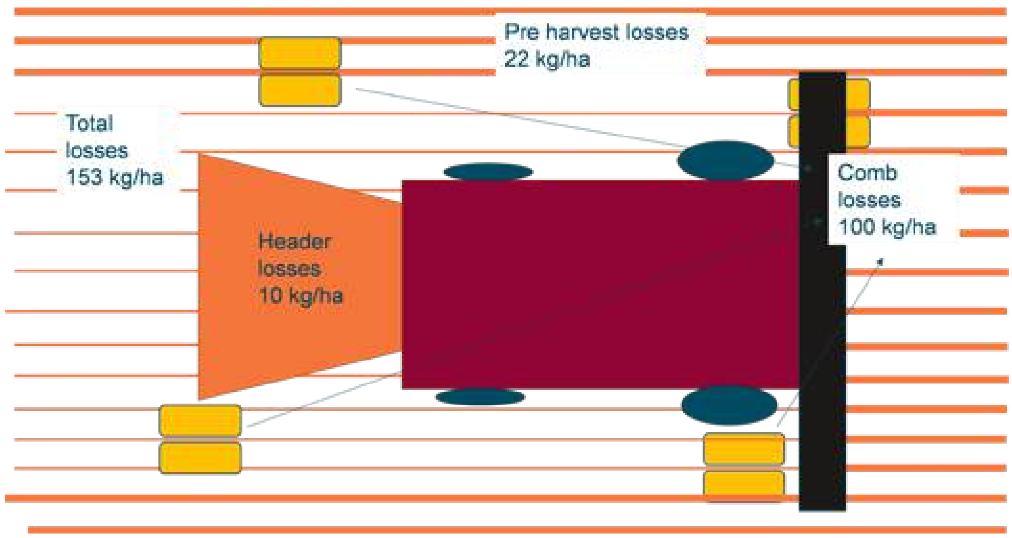


Figure 3. Diagram of harvest losses when harvesting glyphosate desiccated mungbean.

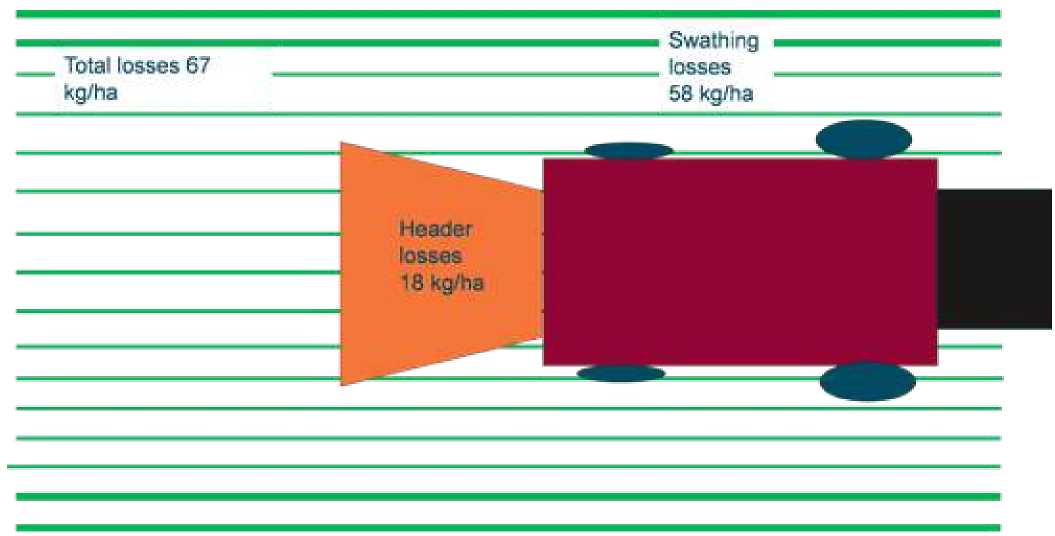


Figure 4. Diagram of harvest losses when harvesting windrowed mungbean.

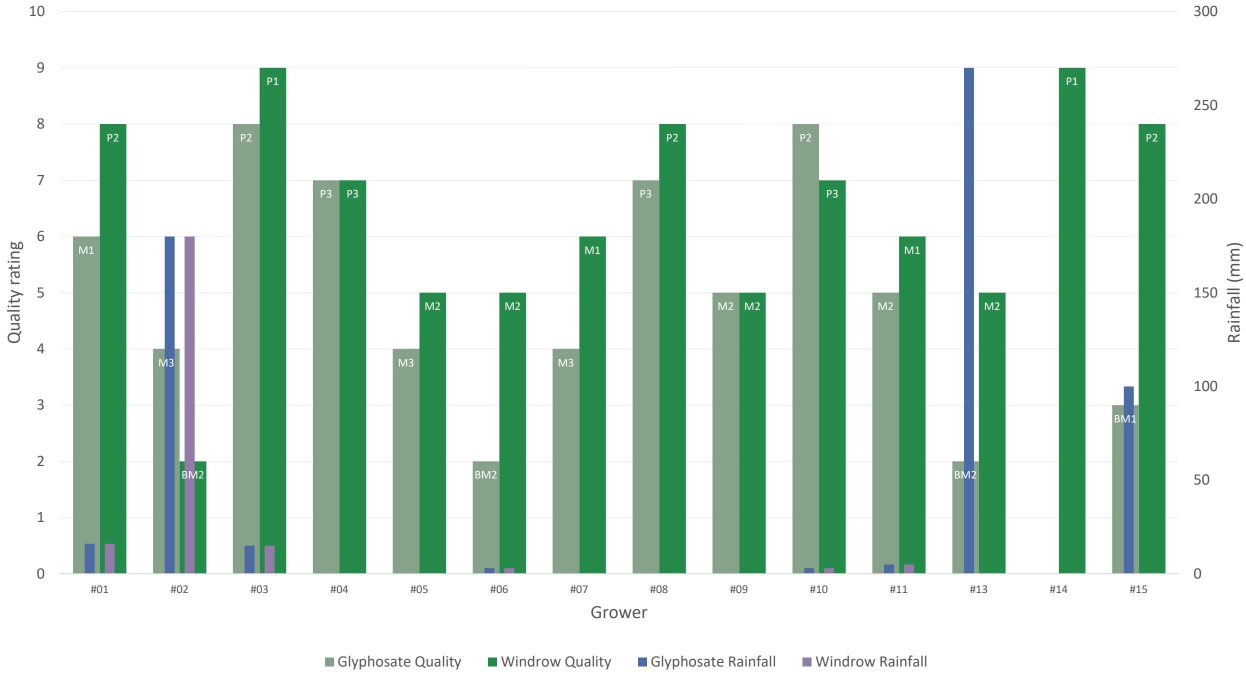


Figure 5. Quality rating for glyphosate and windrowed mungbean. Thin bars represent rainfall between desiccation and harvest. Letters and number near top of bar represent grain quality rating.

Average loss for windrowed treatments was 67 kg/ha compared to 153 kg/ha for glyphosate-desiccated mungbean. The highest loss of 328 kg/ha for glyphosate desiccation was a result of delayed harvest due to rain.

Swathing losses for windrowed treatments measured the loss which occurred during the swathing process (Figure 4). Results showed a loss of 58 kg/ha on average (range of 1 to 212 kg/ha; Table 1). The swathing losses between sites varied due to weather conditions and swathing machinery. The trials with lower swathing losses were achieved by swathing when the mungbean pods were still slightly soft in hand. When these conditions were met, swathing losses were below 30 kg/ha. The highest swathing loss of 212 kg/ha was recorded in a flood irrigated furrow system. The mungbean plants were leaning over into the furrow and the swather wasn't set up with crop lifters to capture pods below the machine's sickle bar. If this site is excluded from the results, average swathing losses reduce from 58 to 43 kg/ha.

Table 2. Grain quality rating scale conversion table from commercial code to number code.

Classification	Commercial rating scale	Number rating scale
Processing	P1	9
	P2	8
	P3	7
Manufacturing	M1	6
	M2	5
	M3	4
Below manufacturing	BM1	3
	BM2	2
	BM3	1

Grain quality

Mungbean grain quality was variable, however most trials achieved manufacturing grade and above (Figure 5, Table 2). Windrowed crops generally achieved higher quality levels (10 out of 14 had higher quality, 2 out of 14 were the same).

These trials showed that moderate falls of rain (from 25 to 50 mm) on the windrowed treatments had no serious impact on mungbean quality and harvestability. Two crops (#01, #03) had approximately 15 mm of rain and in both cases the windrowed treatment had better quality mungbean than the traditional glyphosate treatment. However, an extreme weather event of over 100 mm for grower #02 resulted in the complete loss of the windrowed mungbean and severe quality downgrades for both treatments. In the cases of growers #13, #14 and #15, windrowing enabled the crop to be harvested before rain due to faster dry-down and no withholding period to observe, resulting in a large quality advantage (Figure 5). Mungbean deemed below manufacturing (BM) occurred with large amounts of rain (>100 mm) post desiccation.

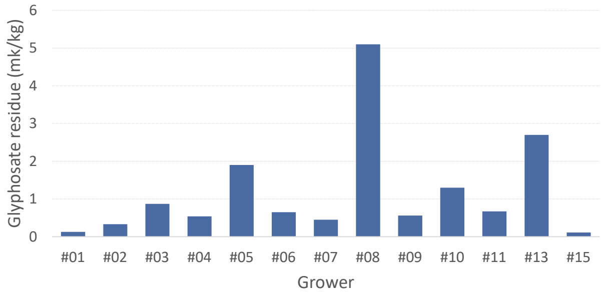


Figure 6. Residue levels (mg/kg) for mungbean grain desiccated with glyphosate.

The harvested seed in the glyphosate-desiccated treatments was tested for glyphosate residue. All samples recorded glyphosate, but were under the Australian maximum reside level (MRL) of 10 mg/kg (Figure 6). However, individual countries set their own MRLs.

Taiwan currently has the lowest MRL of 2 mg/kg. Two crops recorded over this MRL; 2.7 mg/kg for grower #13 and 5 mg/kg for grower #08. It is likely that Grower #08 had a higher percentage of green and immature pods at the time of glyphosate desiccation resulting in translocation of the chemical into immature seeds.

Gross margins

Partial gross margins were calculated comparing the cost of implementation of the treatments (Table 3):

- Glyphosate @ 570 g/L (highest label rate is 1.7 L/ha)
- Windrowing
- Diquat @ 200 g/L (highest label rate is 3 L/ha) included as a higher cost alternative chemical desiccant that is used for seed crops and sprouting markets.

These calculations indicate that windrowing mungbean costs approximately $13/ha more than glyphosate desiccation, but half the cost of a full label rate of diquat. Seed crops and crops for the sprouting market are recommended to be desiccated with diquat due to glyphosate being known to reduce germination. These comparisons suggest windrowing may be a viable option purely based on profitability.

Table 3. Cost estimates for mungbean desiccation.

Treatment	Costs 2022
Glyphosate @ 1.7 L/ha	$29.20
Windrowing	$42.05
Diquat @ 3 L/ha	$83.40

2022 assumptions: 12 m swath, 7 km/hr swathing speed, $14/L glyphosate, $26/L diquat, 36 m boomspray, 15 km/hr spraying speed, $1.80/L fuel.

Further, an increase in quality of the mungbean from manufacturing to processing would increase the price paid by marketers by $50 to $100/t. As these crops were on average over 2 t/ha, this represents a large increase in gross margin that more than covers the extra cost of windrowing.

Implications for growers

Growers have the option of harvesting their mungbean crops by windrowing, which has two major benefits over glyphosate desiccation; faster dry-down and no risk of glyphosate residue. Other benefits of windrowing include potential for earlier desiccation and harvest, easier threshing, no sap staining, and better grain quality. The on-farm commercial strip trials also showed fewer overall losses from windrowed mungbean, while yield was similar to the glyphosate-desiccated mungbean.

However, windrowing mungbean involves more costly operations with two slower passes (swather and header). It also requires specialised machinery. Swathers and pickup fronts are not common in Queensland, and machinery accessability is therefore likely to be the state's biggest barrier to the adoption of mungbean windrowing. It is expected to be less of an issue in NSW where there is greater availability of this specialised machinery as it is also used to harvest canola.

Mungbean regrowth post windrowing may result in an additional herbicide spray, adding to the cost, but this is highly dependent on rainfall. Interestingly, participating growers said they would rather spray regrowth post windrow harvest compared to desiccating mungbean with glyphosate to avoid any risk of chemical translocation to the seed. Spraying regrowth mungbean also gives far greater flexibility to use herbicides with various modes of action.

Timing of harvest operations and harvester set-up is important to minimise harvest losses across both techniques. Windrowing timing is not as critical as it is for chemical desiccation as there is no risk of chemical translocation. However, it is recommended to occur when ~90% of the pods have reached physiological maturity. Harvest losses may be reduced by picking-up early in the morning while there is still moisture on the crop. If the crop is too dry, harvest losses can be significant.

Growers need to be aware of the rapid dry-down of windrowed mungbean and time pickup accordingly. This research was carried out in relatively mild conditions from April to June. If mungbean were windrowed in the hotter summer conditions of

January and February (30°C plus days), dry-down could be as short as 2-3 days, which is much faster than glyphosate-desiccated mungbean with a 7-day withholding period before harvesting can occur.

Once the mungbean crop has been swathed and windrowed, it can tolerate small amounts of rain, up to ~50 mm, but ground surface moisture can result in the swather or pick-up front also harvesting smalls clumps of dirt that will impact grain quality.

Growers must ensure they discuss plans with their marketer prior to desiccation. Minimise glyphosate seed residue by accurately assessing physiological maturity and avoid desiccating immature crops, as spraying earlier than the recommended physiological maturity may result in translocation of the chemical to the seed. This translocation is likely to result in detectable levels in these seeds leading to implications for marketing.

It is still uncertain how successful windrowing would be in low biomass crops, as this research was conducted on crops with high biomass.

Mechanical desiccation may be an option in situations where:

- there are multiple flushes of pods.
- hard to kill vigorous plants are present.
- wet weather is forecast (i.e. in 7-14 days).
- heavy powdery mildew infestation is present and glyphosate can't be taken up by the plants.
- the crop is destined for a market with low glyphosate MRLs (e.g. Taiwan).
- crops are targetting the seed &/or sprouting market.

Mechanical desiccation is not an option in situations where:

- uneven ground is present (e.g., flood irrigated mungbean with large furrows) as this can result in very high losses).
- very large amounts of rainfall are predicted.
- appropriate machinery is not available.
- the soil is very wet (as this will result in wheel tracks and compaction).

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC (DAQ1806-003RTX), the author would like to thank them for their continued support. Further thanks to the Australian Mungbean Association for both their funding and support of this research. Finally, this research would not be possible without a team of dedicated research and technical staff.

This article has been adapted from a GRDC paper oroginally published in February 2023 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/02/desiccating-mungbeans-is-windrowing-an-alternative

Mungbean varietal differences to fusarium wilt—southern Queensland

Lisa Kelly, Jayne Gentry, Cameron Silburn, Doug Sands, Andrew McLean and Peter Agius
Queensland Department of Primary Industries

***Research question**: What is the susceptibility of cultivars Jade-AU⦶, Opal-AU⦶, Crystal⦶ and Onyx-AU⦶ to the mungbean Fusarium wilt pathogens?*

Key findings

1. The relative resistance rankings to fusarium wilt for the four cultivars tested are: Onyx-AU⦶ (most tolerant) › Opal-AU⦶ › Jade-AU⦶ › Crystal⦶ (most susceptible).
2. Prior to harvest, fusarium wilt impacted up to 80% of Crystal⦶ plants compared to only 22% of Onyx-AU⦶.

Background

Fusarium wilt has become a significant issue over recent years to many mungbean growers, particularly those across southern Queensland. It is estimated that the disease caused somewhere in the vicinity of $4.8M losses in the 2020-21 season with yield losses of up to 80% occurring in severely diseased paddocks.

Plants may be infected at any stage of growth, however symptoms are more frequently seen on maturing plants after flowering. Surviving plants that are infected early will remain stunted. Leaves of affected plants turn yellow and then wilt. The taproot of affected plants often rots, resulting in poor growth. When the stem and root of affected plants is split open longitudinally there is a brown discolouration of the vascular tissues.

Fusarium wilt in mungbean is caused by fungi within the *F. oxysporum* and *F. solani* species complexes, which both produce resistant spore structures (chlamydospores) that can survive in soils for many years. The pathogens may spread to unaffected paddocks on soil and crop debris attached to machinery, and through the movement of irrigation and flood water. Successive plantings of mungbean will increase the population of *Fusarium* innoculum in the soil and make disease more likely in subsequent mungbean crops unless a suitable crop rotation is used.

Research has confirmed that the two species infecting mungbean are capable of surviving in the roots of other hosts, including sorghum, cotton, barley, soybean and chickpea and recent glasshouse studies have indicated that the disease may be more severe in the presence of root lesion nematodes (*Pratylenchus* sp.). Studies have also indicated cultivar differences to the mungbean *Fusarium* spp. pathogens. In glasshouse studies, both Crystal⦶ and Jade-AU⦶ were highly susceptible, and Onyx-AU⦶ (a black gram) was moderately resistant to both *F. oxysporum* and *F. solani*. The newly-released cultivar Opal-AU⦶ was not tested in glasshouse studies, although anecdotal reports by growers and advisors during the 2021 cropping season suggested that Opal-AU⦶ had greater tolerance to the *Fusarium* spp. pathogens than Jade-AU⦶ and Crystal⦶. Prior to this study, the relative resistance to the fusarium wilt pathogens of these four cultivars had not been tested in the field.

What was done

Three field experiments were conducted in 2022 in paddocks with a history of mungbean fusarium wilt at Cambooya and Kingsthorpe in southern Queensland, and Rolleston in central Queensland. Each experiment consisted of 32 plots x 4 cultivars (Jade-AU⦶, Crystal⦶, Opal-AU⦶, Onyx-AU⦶) x 8 replicates planted in a randomised block design. Each plot was 2 m wide x 10 m long with 4 rows per plot. Rows were planted 50 cm apart with 250,000 plants/ha, or approximately 12.5 plants/m. The Kingsthorpe and Cambooya experiments were planted on 5 and 6 January 2022 respectively, while the Rolleston experiment was planted on 2 March.

Soil sampling was undertaken at each site (0-30 cm depth) prior to planting and again after harvest and submitted to the South Australian Research and Development Institute (SARDI) for PREDICTA® B testing. Additional samples were taken prior to planting at each site to determine soil water and the nutrient content at 0-10, 10-30, 30–60, 60–90, and 90-120 cm increments. Weather stations were set up at each field experiment to capture temperature, relative humidity and rainfall data.

Initial establishment counts of seedlings in the middle two rows of each plot were assessed approximately 20 days after sowing. Disease incidence was assessed 14 days later by counting the number of healthy plants in these middle two rows. These disease incidence counts were repeated approximately every 14 days (or when accessible) until harvest. Six plant counts were made at the Cambooya site (25/1, 8/2, 22/2, 9/3, 11/3 and 6/4 2022). Five plant counts were made at the Kingsthorpe site (24/1, 8/2, 22/2, 16/3 and 6/4 2022). Three plant counts were made at the Rolleston site (21/3, 31/3 and 11/4 2022).

Approximately ten randomly-selected symptomatic plants were collected from each field experiment and submitted to the DPI plant pathology laboratory. Isolations were made from the symptomatic stem and root tissues to confirm the *Fusarium* species present. Field staff followed the biosecurity guidelines of 'Come clean. Go clean' after each field visit to minimise the spread of disease.

The Kingsthorpe site in southern Queensland was harvested 20/4/22. Unfortunately, the Cambooya site could not be harvested due to flood and hare damage, while the Rolleston site was not harvested after significant damage from wild pigs.

Results

Cambooya

Fusarium wilt was detected in plants at the Cambooya site as early as the second plant count, at 33 days after sowing (Figure 1). Symptomatic seedlings were wilted with yellow or brown leaves that defoliated and progressed to plant death.

Figure 1. Symptoms of fusarium wilt detected in an Opal-AU⌀ seedling at the Cambooya field experiment on 8 February 2022. Symptomatic seedlings were wilted with yellow or brown leaves.

Fusarium wilt continued to impact plant growth in the trial throughout the season, with the whole trial showing some fusarium wilt symptoms of leaf chlorosis, stunting and unthrifty growth. Only plants with clear wilting and yellowing symptoms were counted as not healthy. Isolations from symptomatic plants revealed that both *F. oxysporum* and *F. solani* were responsible for the crop symptoms.

A comparison of final counts of healthy plants provided the resistance rankings for each cultivar; Onyx-AU⌀ (most tolerant) > Opal-AU⌀ > Jade-AU⌀ > Crystal⌀ (most susceptible) (Figure 2).

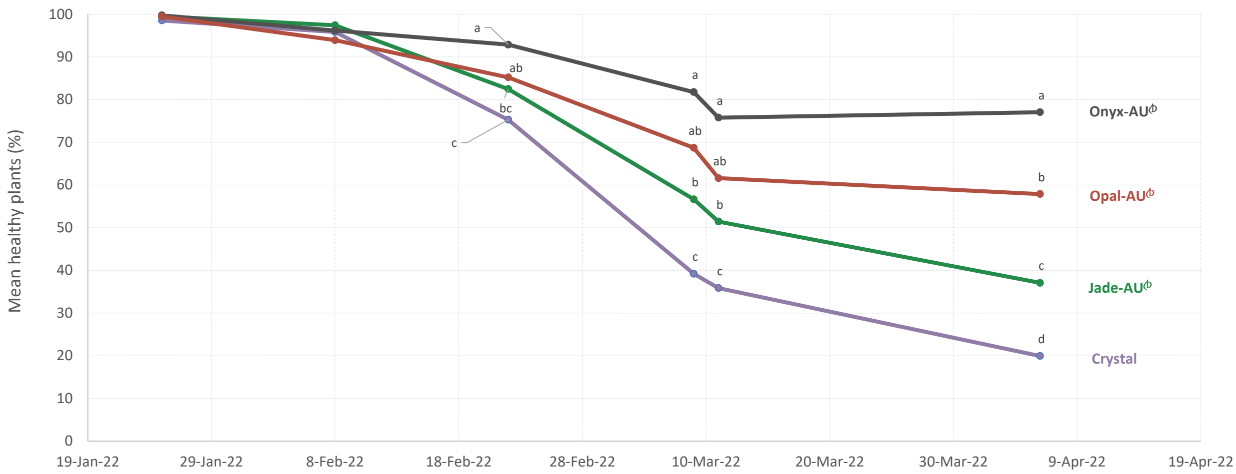


Figure 2. Mean percentage of healthy mungbean plants over time for each cultivar grown in the fusarium wilt trial at Cambooya in 2022. The proportion of healthy plants is reduced as the incidence of fusarium wilt increases.

Red arrow indicates flowering. Plant counts for cultivars at the given date are significantly different to one another when designated a different subscript, P(0.001).

Figures 3 and 4. Fusarium wilt in Crystal$^{\phi}$ (left) and Jade-AU$^{\phi}$ (right) caused poor growth and plant death in mungbean plots.

Plant counts showed a significant interaction of cultivar x time (P<0.001), in particular at flowering (22 February 2022) and the following three counts. The black gram cultivar, Onyx-AU$^{\phi}$, had a significantly lower incidence of fusarium wilt from flowering onwards compared to the three mungbean cultivars. Opal-AU$^{\phi}$ had significantly lower incidence of disease from flowering onwards compared to Crystal$^{\phi}$, and at the final plant count was also significantly different to Jade-AU$^{\phi}$. By the last plant count, in April 2022, there were obvious visual differences in the distribution of fusarium wilt symptoms for each cultivar 9 March 2022 (Figures 3 and 4).

From flowering onwards, a significant increase in disease incidence coincided with a significant increase in rainfall and a drop in maximum temperature.

A high level of *Pratylenchus thornei* (23 nematodes/g soil) was detected in the Cambooya field site prior to planting the mungbean trial. No other pathogens were detected in high numbers.

Kingsthorpe

A low incidence of fusarium wilt was present in the Kingsthorpe trial. While large patches of fusarium wilt-affected plants were present in the mungbean crop surrounding the trial, only scattered plants growing within the trial were symptomatic (Figure 5). Isolations from symptomatic plants revealed that both *F. oxysporum* and *F. solani* were responsible for the crop symptoms.

Despite little obvious disease, there was a significant interaction of date x cultivar for plant counts (P<0.05). At the timing of the last plant counts in April 2022, an average of 97.8% of Crystal$^{\phi}$ plants remained healthy (Table 1). Fusarium wilt occurred at a significantly higher incidence in Crystal$^{\phi}$ compared to Onyx-AU$^{\phi}$ and Jade-AU$^{\phi}$. Despite this, disease levels remained low across the entire trial with most cultivars establishing a higher

Figure 5. Whole plant wilting with Fusarium wilt in scattered plants growing at the Kingsthorpe site in April 2022.

number of plants than the initial counts by the end of the season. An analysis of grain yields collected from the Kingsthorpe site revealed a significant difference between cultivars (Table 1). Jade-AU⊕ and Crystal⊕ yielded the poorest of the cultivars and yielded significantly lower than Opal-AU⊕ and Onyx-AU⊕. Onyx-AU⊕ yields were significantly higher than the three mungbean cultivars.

Table 1. Incidence of fusarium wilt and yields for each cultivar growing at the Kingsthorpe site.

Cultivar	Mean healthy plants (%)* at final count	Grain yields (t/ha)
Crystal⊕	97.8c	1.017c
Jade-AU⊕	101.9ab	0.968c
Opal-AU⊕	100.8bc	1.253b
Onyx-AU⊕	105.2a	1.629a

* Means with same subscript are not significantly different at P(0.05).

A low level of *P. thornei* (2 nematodes/g soil) was detected in the Kingsthorpe field site prior to planting. No other pathogens were detected in high numbers.

Rolleston

A comparison of final counts of healthy plants in the Rolleston trial found the same cultivar resistance rankings as Cambooya; Onyx-AU⊕ (most tolerant) > Opal-AU⊕ > Jade-AU⊕ > Crystal⊕ (most susceptible) (Figure 6). Unfortunately, the trial was abandoned at the final plant count date when plants were flowering (11 April), due to pig damage to the trial. Disease symptoms at this point were becoming more obvious and it is likely that the difference between cultivars would have become more pronounced if the trial was continued until harvest.

Implications for growers

Fusarium wilt continues to cause significant damage to the mungbean industry, particularly crops grown in southern Queensland. This research demonstrates the improved tolerance of the newly released cultivar, Opal-AU⊕ to fusarium wilt compared to Jade-AU⊕ and Crystal⊕, with the black gram cultivar, Onyx-AU⊕, showing the highest tolerance level. However, with no commercially available varieties resistant to this disease, growers are urged to implement the following management steps to minimise disease impact:

- Avoid planting all mungbean varieties including Opal-AU⊕ in paddocks with a history of fusarium wilt.
- Avoid planting mungbean in the same paddock for at least three years. Growing successive plantings of mungbean, including Opal-AU⊕, in a paddock will increase pathogen populations over time.
- Effectively manage volunteer mungbean and weeds that may host the disease.
- Manage the crop to avoid stresses such as root damage and waterlogging. Additional stress from levels above 15 *P. thornei*/g soil will not only reduce yield potential but may exacerbated the severity of fusarium wilt.
- Practise good farm hygiene and use the 'Come Clean. Go Clean' strategy to minimise the spread of disease.

Further information

More information can be found in the *Minimising the risk of Fusarium wilt in the northern region* factsheet from GRDC.
grdc.com.au/resources-and-publications/all-publications/factsheets/2022/fusarium-wilt-in-mungbean.

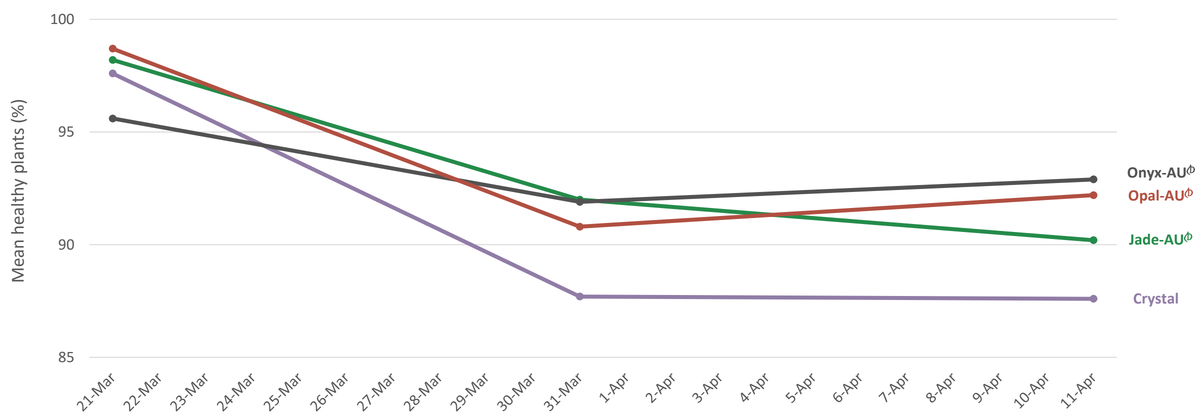


Figure 6. Mean percentage of healthy mungbean plants over time for each cultivar grown in the fusarium wilt trial at Rolleston in 2022. The proportion of healthy plants is reduced as the incidence of fusarium wilt increases.
Plant counts for cultivars at the final count date are significantly different to one another when designated a different subscript P(0.05).

Can planting chickpea in summer increase yield?

Christabel Webber and Andrew Erbacher
Queensland Department of Primary Industries

***Research questions**: Are there productivity gains in planting chickpea in late summer to avoid chilling effects at time of flowering? | How does varietal maturity influence yield?*

Key findings

1. Planting in June produced higher yields compared to planting in February.
2. Chickpea planted in late summer (February) set flowers and pods in autumn but did not hold them through winter.
3. There was no varietal difference for the two planting dates in this trial.

Background

Chickpea provides several benefits for farming systems in the northern region and has become an important crop with an estimated export value of $392 million. The benefits of chickpea include providing a break crop option for cereal root diseases such as crown rot, they can be planted later than cereals with the added benefit of being able to be planted deeply into soil moisture for a long period after rain, and they fix their own nitrogen. However, chickpea yields can be seriously impacted by chilling effects at flowering, reducing pod set.

Chilling effects on chickpea at flowering has been a major constraint for maximising yields, particularly in southern Queensland and northern New South Wales. Temperature at flowering is critical for chickpea yield, as flowers won't set pods when average daily temperatures are below 14°C. In addition, pods and seeds can continue to be aborted if minimum temperatures drop below 5°C.

Current practice based on past research around Goondiwindi identified June as the optimal planting date for chickpea, allowing the crop to flower after the cold periods that prevent flower retention and pod set. However, an alternative being explored by some growers is to plant chickpea in late summer so that the crop flowers and set pods before it gets cold. The hypothesis is that planting chickpea as early as March could allow the plant to set a higher yield potential by flowering and setting pods when conditions are more favourable, and avoiding the chilling effects.

What was done

The trial took place in 2021 on a property at Billa Billa, 50 km north of Goondiwindi on a brigalow/belah Grey Vertosol soil.

Seven commercial chickpea varieties were used: Boundary$^{\phi}$, PBA HatTrick$^{\phi}$, Kyabra$^{\phi}$, PBA Monarch$^{\phi}$, PBA Seamer$^{\phi}$, PBA Drummond$^{\phi}$, and PBA Pistol$^{\phi}$. All varieties were inoculated with peat slurry and planted on 50 cm rows with Granulock® Z added at planting.

This trial compared two times of sowing (TOS); 'early' (23 February) and at the 'traditional' time (30 June).

Measurements taken throughout the growing season included emergence plant counts, date of 50% first flowering, date of 50% brown pods, biomass cuts, grain yield and yield components. Soil cores were taken at planting and harvest to assess water use efficiency and starting nutrient levels.

February TOS 1 (left) and June TOS 2 (right); pink dots indicate the border between the two treatments.

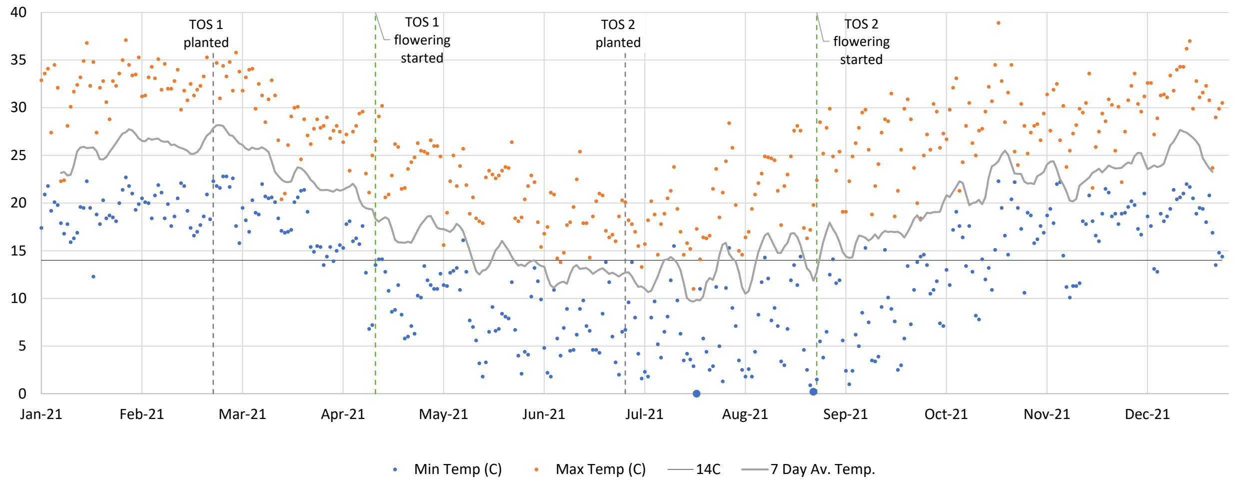


Figure 1. Minimum, maximum and average daily temperatures in 2021. Chickpea require an average daily temperature greater than 14°C for a flower to form a pod. Minimum temperature reached 0°C on 22 July and 27 August.

Results

Established populations for all varieties were within an acceptable range that would not limit yields, that is, 25 plants/m² established in the Febraury TOS and 28 plants/m² in the June TOS.

The February-planted chickpea was five days faster to flower on average than the June planting. There was also greater varietal difference in days to first flower for the Feburary TOS than the June TOS. In the early planting, the quickest varieties (PBA Pistol⒫ and PBA Seamer⒫) took 50 days to first flower (14 April), and the slowest (PBA Boundary⒫ and Kyabra⒫) took 77 days (6 May). In the traditional planting, the quick varieties took 62 days (28 August) and the slowest 72 days (5 September).

The weather was sufficiently warm for the early planting to set and hold pods for a month after flowering commenced (Figure 1). However, the February TOS aborted all its pods in July when the temperatures were low, then flowered again and set new pods when the weather warmed in August. In contrast, planting in June allowed the chickpea to start flowering in warmer temperatures in September. Despite the four-month difference in planting date, the February TOS matured less than one month before the June TOS.

The most noticeable result from the trial was the significant difference in biomass and grain yield between the times of sowing. The February TOS produced significantly more dry matter than the June TOS (Figure 2), however the traditional planting produced significantly more grain yield (Figure 3).

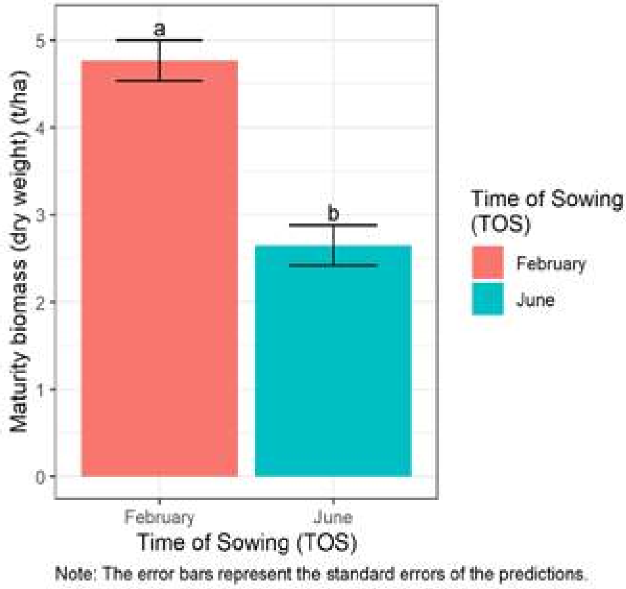


Figure 2. Biomass produced by the two times of sowing.

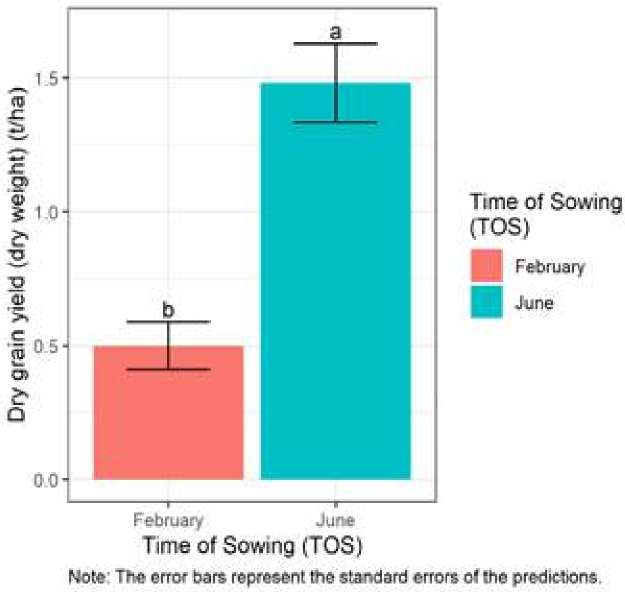


Figure 3. Grain yield produced by the two times of sowing, threshed out of the biomass cuts in Figure 1.

Chickpea needs to grow a branch to set a pod, so more biomass indicates more potential pods, unless flowers and pods are not retained through to yield. In this case, the early planting produced biomass for flowers and pods that were lost in winter. These plants then grew more biomass in spring for the yield that was harvested, with pods only near the ends of long branches after other pods had been lost. On the other hand, the traditional planting had pods right along the branch because it held most of the flowers as pods, and ultimately produced more yield from less biomass.

Implications for growers

Further research is required before recommending summer-planted chickpea in southern Queensland.

This trial showed that summer-planted chickpea can establish, flower, and set pods before average daily temperatures drop below 14°C. However, in this season the pods set did not survive cold days in July. The resulting large biomass chickpea crop was a response to cold weather causing a loss of flowers and regrowth to create new flowering positions. Similar crops are often seen commercially when chickpea is planted too early in the season.

The loss of flowers and yield effects was consistent across varieties. However, there may be potential for quicker varieties (such as PBA Seamer⁽ᵖ⁾, PBA Drummond⁽ᵖ⁾ or PBA Pistol⁽ᵖ⁾) to set more pods and mature before the cold sets in, or for cold-tolerant varieties (such as PBA Boundary⁽ᵖ⁾) to hold pods through colder temperatures. Further research is needed before the potential for summer planted chickpea is known. Further research could also compare performance of alternative pulse crops, such as mungbean, pigeon pea and faba bean, for the same planting window.

Reflowering after frost damage

Acknowledgements

The early chickpea project was funded solely by the Queensland Department of Primary Industries. The technical management, data collection and monitoring of this trial was carried out by the technical staff at Goondiwindi, Queensland. Thank you to the grower for hosting this trial.

Trial details

Location:	Billa Billa, Queensland
Crop:	Chickpea
Soil type:	Belah, Duplex
In-crop rainfall:	February TOS 340 mm June TOS 175 mm
Fertiliser:	35 kg/ha of Granulock® Z at planting

What do pulses contribute to the nitrogen balance in Central Queensland farming systems?

Douglas Sands and Darren Aisthorpe
Queensland Department of Primary Industries

Key findings

1. Nitrogen derived from atmosphere (Ndfa) in mungbean crops is strongly influenced by the amount of mineral soil nitrates that are available at planting. There is an almost linear decline in N_2 fixation as soil nitrates increase in the top 60 cm of the profile.
2. Mungbean and chickpea crops can access and utilise soil nitrate N in the top 60 cm as efficiently as cereal crops. This raises implications for nitrate N supply in crops following these pulse crops.
3. Mungbeans planted in long fallow situations will create a soil nitrate N deficit as N_2 fixation rates cannot replace the amount of soil nitrate being exported in grain. Circumstantial evidence suggests that chickpeas may be similar.

Background

There are many references in the literature over the last five decades relating to the benefit of pulse crops to the global agroecosystem with biologically fixed nitrogen (N) estimated to contribute 50 million tonnes of N annually to the global agricultural production system (Unkovich et al. 2008). This estimate is about half of the global application of mineral fertiliser N on agricultural land (Unkovich et al, 2008).

Pulse crops in Australia have become a more prominent part of our crop rotation to take advantage of expanding niche markets that offer good gross margins but also in the belief that they contribute to the N resources in our soils. There is no doubt that inoculated pulse crops will fix N_2 from the atmosphere that then can be incorporated into the amino acid components of the plant. What is less certain is the quantification of how much total plant N in any one season has been derived from atmosphere (Ndfa) and how much is derived from soil mineralisation.

There is a general recognition that there has been a wide range of data recorded for the amount of N_2 fixation that can occur in any one crop or season. There are environmental factors and management practices that can greatly affect the rate of N_2 fixation, hence the variable amounts of N_2 fixation that have been recorded. One of the biggest influences on the rate of N_2 fixation is the level of soil nitrate N available whereby fixation rates progressively decline in the presence of increasing levels of soil nitrate N.

It is this ability of pulses to take up soil mineral N in preference to N_2 fixation that has impacts on the N management of our broadacre farming systems. The ability to quantify the level of N_2 fixation against the level of soil nitrate N by crop species has become more important as industry takes a more detailed focus on long term N management in relation to sustainably increasing grain production.

This report will examine data that has been extracted from Central Queensland (CQ) regional trials relating to both mungbeans and chickpeas in order to be more definitive about the contribution that N_2 fixation makes to our soil N resources and comment on the implications that these results have on our N management decisions.

The extracted data relates to two GRDC-funded projects that have locally-based experiments at the Central Queensland Smart Cropping Centre (CQSCC). The Mungbean Agronomy project (DAQ2104-006RTX) had two experiments designed around testing mungbean yield response to N fertiliser application (mungbean N response).

These experiments were conducted in the 2019-20 and 2020-21 summer seasons, where there was a common range of applied fertiliser N treatments from 30 kg N/ha to 150 kg N/ha (Table 1) that were band applied directly after wheat harvest in late October (cover crop) and then were left fallow (wheat stubble) until the planting of mungbeans in February.

Table 1. Summary of treatments applied across mungbean N response trials in 2020 and 2021.

Treatment list 2020	2020 name	Change to 2020 treatments	2021 name
Short fallow + cover crop +zero N applied	0N	none	0N
Short fallow + cover crop + zero N applied, no inoculant	0N-Nil Inoc	none	0N-Nil Inoc
Short fallow + cover crop + zero N applied + double starter rate	0N+2ST	Long fallow + zero N applied	LF0N
Short fallow + cover crop + 30 kg N/ha	30N	none	30N
Short fallow + cover crop + 60 kg N/ha	60N	none	60N
Short fallow + cover crop + 90 kg N/ha	90N	none	90N
Short fallow + cover crop + 120 kg N/ha	120N	none	120N
Short fallow + cover crop + 150 kg N/ha	150N	Long fallow + 60 kg N/ha	LF60N

The second experiment had two added treatments that explored the impact of a much longer fallow on the soil nitrate N profile. The long fallow treatments had no wheat planted over the winter resulting in an eight-month fallow as opposed to a three-month fallow for the other treatments (Table 1).

Within these trials N_2 fixation was assessed using the 15N isotopic natural abundance process on non-nodulating soybean variety plots, allowing the proportion of nitrogen derived from the atmosphere (Ndfa) in the plant to be quantified. Other measurements included soil water and soil nitrates at the start of fallow before the application of the fertiliser N treatments, at planting and at harvesting. Further details can be found in a previous GRDC update paper 'What contributions do mungbeans make to soil nitrogen' (2022).

This report also draws on the Northern Farming Systems project (DAQ2007-002RTX), a long-term experiment that has been running since 2015 at the CQSCC and involves collecting a range of data across six different farming systems:

1. **Baseline** – A conservative zero tillage system targeting one crop per year. Crops are limited to wheat, barley, chickpea and sorghum, with nutrient application rates on cereals targeting median (50^{th} percentile) seasonal yield potential.
2. **Higher crop intensity** – Focused on increasing the cropping intensity to 1.5 crops per year when water allows. Crops include wheat, chickpea, sorghum, mungbean and forage crops/legumes, with fertiliser N rates on cereals targeting median (50^{th} percentile) seasonal yield potential.
3. **Higher legume** – The frequency of pulses in the *Baseline* system is increased to one pulse crop every 2 years to assess the impact of more legumes on profitability, soil fertility, disease and weeds. Fertiliser N rates on cereals targeting median (50^{th} percentile) seasonal yield potential.
4. **Higher nutrient supply** – Fertiliser N and phosphorus (P) rates of the *Baseline* system increased targeting 90^{th} percentile yield potential based on soil moisture in an environment of variable climate. The crops and other practices are the same as the *Baseline* system.
5. **Higher soil fertility** – Based on the *Higher nutrient supply* system, an additional 60 t/ha of manure (wet weight) was applied to change the starting soil fertility level. This system is designed to see if higher initial soil fertility can be maintained with greater nutrient inputs (90^{th} percentile).
6. **Integrated weed management (IWM)** – This minimum tillage system is focused on one crop per year but employs a wide range of practices to reduce the reliance on traditional knockdown herbicides in CQ farming systems. Crops include wheat, chickpea, sorghum and mungbean with fertiliser N rates on cereals targeting median (50^{th} percentile) seasonal yield potential.

A range of assessments are made on an annual basis across these treatments, including water use efficiency, nutrient balance, nutrient use efficiency, changes in weed populations, changes in disease pathogens, changes in soil health and profitability. Further details on this experiment can be found in another GRDC update paper 'Farming systems research in the Northern Grains Region and implication for key decisions driving risk and profit in Central Queensland' (2023).

There were no assessments made in this trial on Ndfa% for the pulse crops grown across the various cropping sequences; however extensive soil measurements were taken before and after each crop that shows some interesting results around profile soil nitrate N distribution, N mineralisation rates and the impact of pulses on soil nitrate N levels.

Discussion

Mungbeans

The Ndfa% data extracted from the mungbean N response trials in 2020 and 2021 (Figure 1) shows the effect that increasing soil nitrate N at planting had on the proportion of N in total dry matter (TDM) being derived from N_2 fixation. This trend is consistent with the general understanding that increasing soil nitrate N availability at planting will decrease the rate of N_2 fixation and this trend can be linear in most cases. This mungbean data (Figure 1) would suggest that the Ndfa% can go from a high of 45% (0N) to basically zero (90N and 120N).

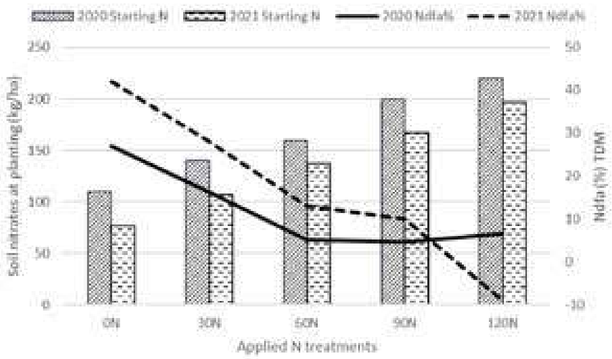


Figure 1. Nitrogen derived from the atmosphere (Ndfa%) in plant material in comparison to measured profile soil nitrate N at planting time to a depth of 120 cm.
Data is an average of irrigated and dryland trials located at the CQSCC in 2020 and 2021 summer seasons.

Grain samples were also analysed for grain N, which was divided by the total N recorded at peak biomass to calculate the N harvest index (NHI) for the crop (Figure 2), representing the proportion of total N being exported from the paddock in grain. The lowest NHI was 0.6 (60%) in the 2020 trial and the highest 0.9 (90%) in the 2021 trial. This means that 60–90% of the total N taken up by the crop from both soil nitrate N and N_2 fixation was ending up in the grain.

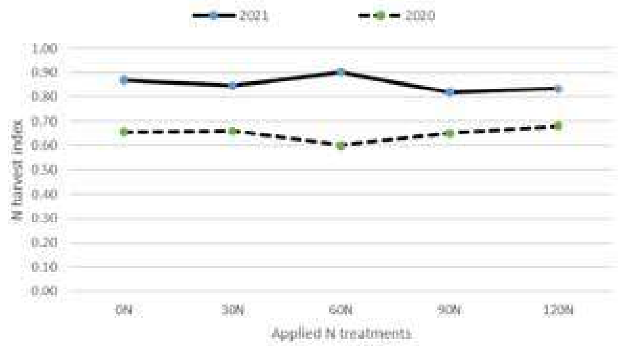


Figure 2. Calculated N harvest index based on total N in biomass data and total N in grain data.
Data derived from laboratory analysis.

It is unclear why the NHI in 2021 was consistently higher than 2020, although it may be related to yield, as the 2021 season had much higher yields (1.7 t/ha trial mean) than the 2020 trial (0.8 t/ha) due to seasonal constraints.

The NHI (Figure 2) combined with the Ndfa% (Figure 1) can be used to calculate whether the amount of Ndfa% in the stubble (Figure 3) would offset the amount of soil nitrate N in the grain (Figure 3). This calculation is important because it has direct impact on the soil nitrate N balance for the following crop. If there is more soil nitrate N being exported off the paddock than is being replaced by N_2 fixation, then the soil nitrate N balance will be negative (Table 2).

The mungbean N response trials had lower than expected N_2 fixation rates, represented by the Ndfa% recorded in both trials (Figure 1). In addition, the NHI showed a much higher proportion of total N uptake being exported from the field (Figure 2) than expected. These two data sets are used to calculate the amount of Ndfa% remaining in stubble compared to the soil mineralised nitrate N that is contained in the grain (Figure 3), to determine if the pulse crop is resulting in a deficit or surplus to the soil nitrate N pool.

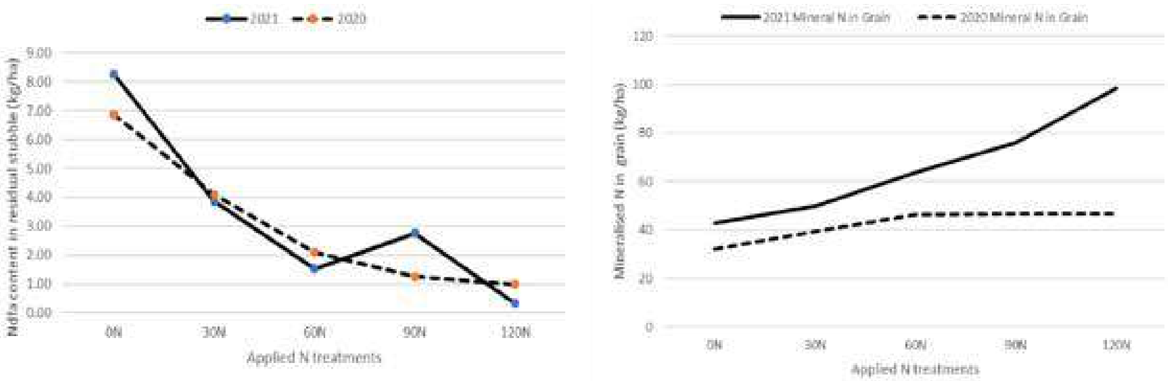


Figure 3. Calculated Ndfa% contained in stubble (left) based on Ndfa% in biomass and NHI. Calculated soil mineral nitrate N content in grain (right) based on Ndfa% in biomass and total N in grain.

Table 2. Summary of N calculations in crop across increasing rates of N fertiliser treatments.

Applied N treatments	Ndfa in TDM (%) *	N in TDM (kg/ha) *	N harvest index	Grain N (kg/ha) *	Stubble N (kg/ha)	Ndfa in stubble (kg/ha)	mineral N in grain (kg/ha)	Soil N balance (kg/ha)
0N	42	80	0.76	59	20	9	34	-26
30N	28	80	0.75	58	22	6	42	-36
60N	13	83	0.75	61	22	3	53	-50
90N	10	89	0.74	67	22	2	60	-58
120N	-9	91	0.76	70	21	-2	77	-78

* Derived from lab analysis data. Other figures are calculated from biomass and grain analysis. Data is an average of 2020 and 2021 trial data.

This surplus or deficit to soil nitrate N can be plotted for each fertiliser applied N treatment in both trials (Figure 4). This highlights that all treatments had a soil nitrate N deficit, ranging from 26 kg N/ha to 78 kg N/ha (Figure 4).

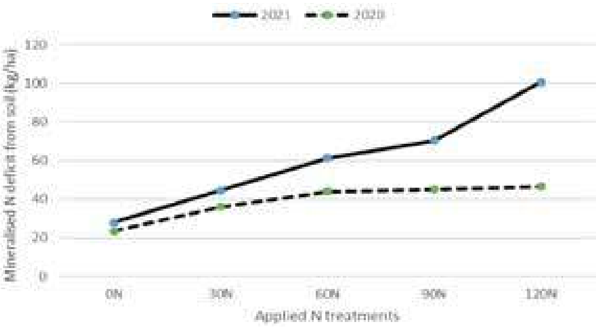


Figure 4. Calculated differences between mineral soil nitrate N contained in grain versus Ndfa contained in residual stubble. These differences create either a surplus or deficit in soil nitrate N pool.

There are two qualifications to these results (Figure 4). Firstly, the amount of Ndfa held in the root system has not been measured and will reduce this deficit by contributing more Ndfa to the soil pool. Estimates in the literature suggest that root reserves can contribute another 25–50% of the above ground N contained in biomass to the soil profile (Unkovich et al, 2008). Considering the measured Ndfa% (Figure 1), a calculation can be made of how much of the root N is derived from atmosphere, which can then be used to reduce the soil nitrate N deficit that was calculated (Table 2) and adjusted across the applied N treatments for a theoretical mineralised soil nitrate N deficit (Figure 5).

This recalculated data for soil nitrate N deficit, taking into account a theoretical contribution from the break-down of the root mass, has changed the 0N and 30N treatment deficits by ~15 kg N/ha and the rest of the treatments by less than 5 kg N/ha (Figure 4). This is largely because the proportion of Ndfa in the higher fertiliser N treatments was originally small so their root mass contribution to the soil nitrate N deficits is also small.

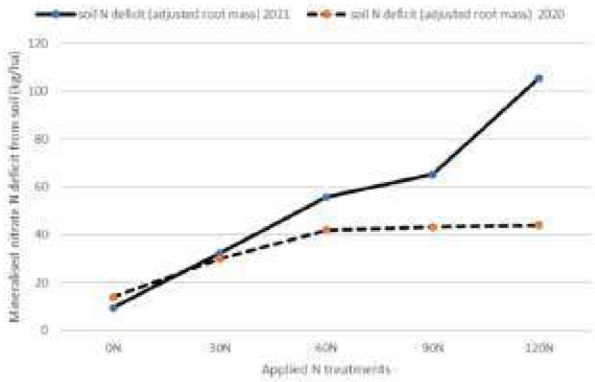


Figure 5. Recalculation of soil nitrate N deficits using the contribution of root mass to total Ndfa% content of the residual stubble.

This data is based on a theoretical calculation that assumes that total nitrate N contained in the root mass of a pulse crop is 50% of the above ground biomass.

The second qualification is that the amount of applied N fertiliser used to set up these different concentrations of mineralised soil nitrate N did not exceed extraction by the mungbean crop, except in the 0N treatment (Figure 5), which amounts to 10–15 kg N/ha. The downside of these N fertiliser applications is that the grain yield responses (<200 kg/ha, not shown) were small and could not justify the cost of the fertiliser application from the gross margin return (Sands et al, 2022). This makes the justification for applying fertiliser N to mungbeans more complicated even though the evidence would suggest that the crop will use it.

Table 3. Comparison of different fallow length on measured soil nitrate N at planting and calculated soil nitrate deficits based on measured Ndfa and grain N content.

Treatment category	Year	Fallow length (days)	Mineral soil nitrate N at planting (kg/ha)	Mineral soil nitrate N deficit (kg/ha)
Short fallow 0N	2020	94	110	24
Short fallow 0N	2021	81	77	28
Long fallow 0N	2021	246	134	76
Long fallow 60N	2021	246	196	83

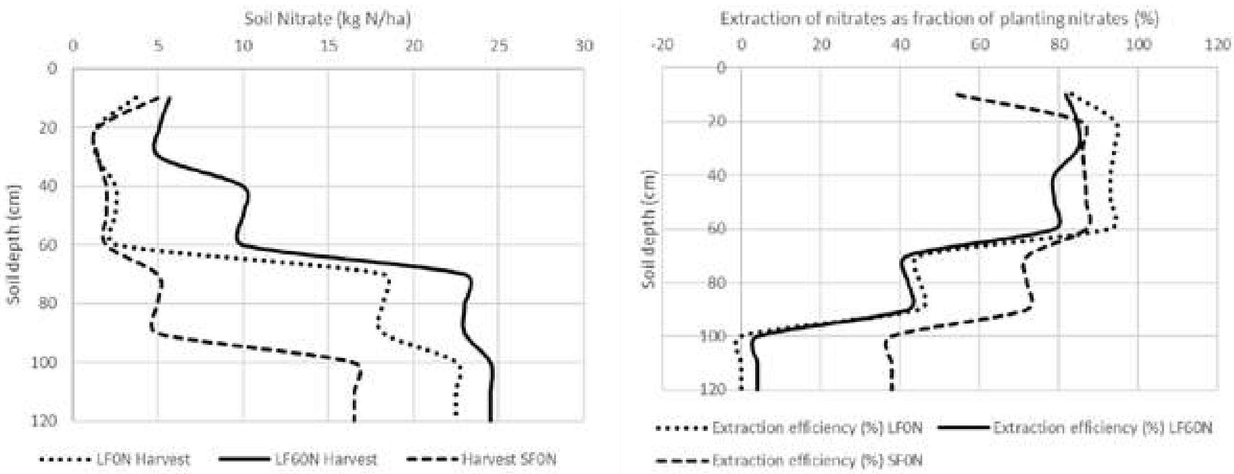


Figure 6. Soil nitrate N measured after harvest (left) and the proportion of soil nitrate N extracted from each layer between planting and harvest (right) of mungbeans in 2021 N response trial, comparing length of fallow.

The management implications of pulse crops that will use soil nitrate N before fixing N_2 become more relevant when mungbeans are planted into a longer fallow situation without any applied N fertiliser. In the 2021 mungbean N response trial two treatments were changed to test the impact of a much longer fallow period on the level of soil nitrate N at planting.

The 2021 long fallow treatments were split between no N applied (LF0N) and 60 kg N/ha applied at the start of the fallow in June the previous year (2020). A comparison between the 0N short fallow treatments and the two long fallow treatments in 2021 (Table 3) shows a distinct difference in the level of soil nitrate N at planting, which has subsequently led to a lower Ndfa% (not shown) and a higher soil nitrate N deficit post-harvest, using the same calculation process as previously described.

The important part of this data is that the long fallow treatment with no N applied (LF0N) has a deficit of 76 kg N/ha that has ultimately come from mineralisation of organic matter in the soil and has not been replaced by fertiliser N. This not only has impacts for the following crop but also for the long-term maintenance of nitrate N fertility and organic matter in the soil profile.

The short-term practical implications of the soil nitrate N deficits are that most of this is taken from the top 60 cm of the soil profile (Figure 6), which is the key area of uptake for most crops (Sands et al, 2023). The soil nitrate data for these short fallow and long fallow treatments shows that nearly 90% of the nitrates in the top 60 cm of the profile were utilised by the mungbean crop in both fallow lengths where no N was applied (Figure 6). This means that the top 60 cm of the profile needs to be resupplied with nitrate N before the next crop is planted to avoid N limitations to production.

The advantage of applying 60 kg N/ha of fertiliser in the other long fallow treatments is that some of that nitrate is still available in the top 60 cm (Figure 6) for the following crop. This long fallow situation (eight months) is not unusual in CQ cropping systems.

Chickpeas

The deficits in soil nitrate N left by a mungbean crop may also apply to chickpeas. Currently there is no N_2 fixation data collected locally for chickpeas but new projects in 2023 have started to collect this information by using the 15N natural abundance method in commercial chickpea crops. Long term soil monitoring in the Northern farming systems project does offer some insight into the impact of chickpeas on the soil nitrate N levels within a cereal/legume rotation.

Data extracted from one of the six treatments in this long-term project is a good example of the typical changes in soil nitrate N over time that have been seen in the other treatments over the last eight years but in the interest of brevity, this article focusses on data from the 24 August 2021 to 14 September 2023 in the *Higher nutrient supply* (see background description), which had six soil testing intervals for soil nitrate N down to 90 cm (Figure 7). The timing of those soil testing events are described in relation to the planting and harvest of four crops (millet, sorghum, chickpeas and wheat) over two years.

Stored soil nitrate N was highest at the start of the sequence before the millet crop was planted, at 186 kg N/ha, after an 11-month fallow (Table 4). This was also the most uniformly distributed soil nitrate N through the profile, with all layers having significant amounts of soil nitrate N (Figure 7). Following the millet crop there is a trend where the deepest layer (60–90 cm) is being underutilised

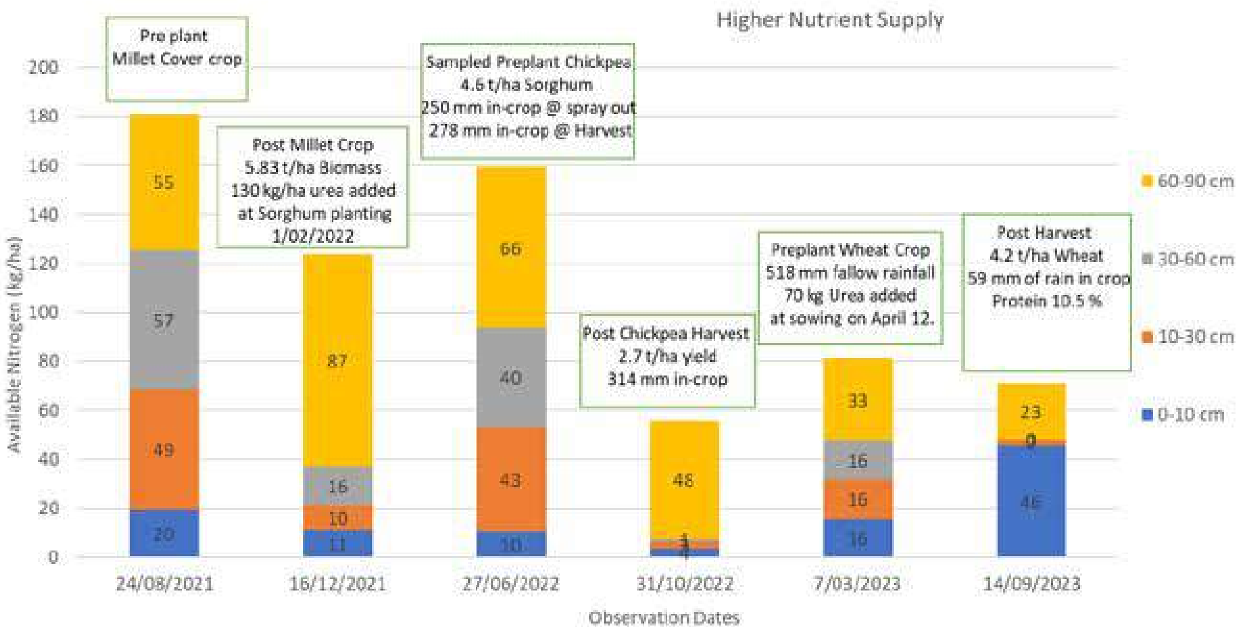


Figure 7. Soil nitrate N for the *Higher nutrient supply* treatment recorded by depth layer for each observation date. Included are details of urea application at planting, planting dates and rainfall totals (Source: Aisthorpe D (2023) unpublished).

until the wheat crop in 2023. It is therefore more useful to look at changes in soil nitrate N in the top 60 cm of the profile (Table 4), particularly as there is good evidence from other projects that this is the most efficient zone of N uptake for most crop types.

The soil nitrate N levels from the top 60cm of the profile (Table 4) shows a more distinctive change in soil nitrate N during each crop rotation. The most obvious change is in the chickpea crop grown in 2022 where it has depleted the top 60cm of soil nitrate N effectively from 94 kg N/ha to 8 kg N/ha.

Mineralisation following this chickpea crop, over a four-month fallow, has added 40 kg N/ha and another 32 kg N/ha has been added through a urea application (70 kg/ha) at planting of the wheat crop. Most of this urea appears to have been trapped in the top 10cm (Figure 8). This is most likely due to the fact there was only 59mm of in-crop rainfall (Figure 7) after planting. This wheat crop has been forced to drag as much soil nitrate N out of the 10 to 60 cm layers and access some of the nitrate N held in the deeper layers to meet its requirements for a 4.2 t/ha grain yield with 10.5% protein.

This scenario demonstrates the capacity of chickpeas to utilise soil nitrate N efficiently from the top 60 cm of the profile (Figure 8). The fallow mineralisation following the chickpea crop has not been able to refill the top 60cm profile to the same level as at the planting of the chickpea crop, even though chickpea residual stubble and roots were being broken down in the top 30cm of the profile with a low carbon to nitrogen ratio (C : N), so it would have released N quickly.

The application of urea at planting of the wheat crop was not utilised by the wheat crop. This may be because after this application there was not enough rainfall to redistribute this fertiliser derived nitrate N deeper into the profile where it could be used effectively. If this fertiliser had been added at the start of the fallow it would have had 518 mm of rainfall to help redistribute and may have been better utilised by the wheat crop.

Regardless of the timing of fertiliser application it is clear that chickpeas are utilising soil nitrate N as effectively as any cereal crop much like the observations made in mungbeans.

Table 4. Summary of soil nitrate N and fertiliser N applications by date and profile depth for *Higher nutrient supply* treatment.

Event	Pre-plant millet (soil test)	Post millet (soil test)	Plant sorghum plus 60 kg N/ha*	Pre-plant chickpeas (soil test)	Post harvest chickpeas (soil test)	End of fallow (127 days) (soil test)	Plant wheat plus 32 kg N/ha*	Post harvest wheat (soil test)
Event date	24/08/2021	16/12/2021	1/02/2022	27/06/2022	31/10/2022	7/03/2023	12/04/2023	14/09/2023
Accumulated nitrate N 0-90 cm (kg/ha)	181	124	+60	159	56	81	+32	71
Accumulated nitrate N 0-60 cm (kg/ha)	126	37	+60	94	8	48	+32	48

* Denotes planting date and application of urea. No soil test measurements.

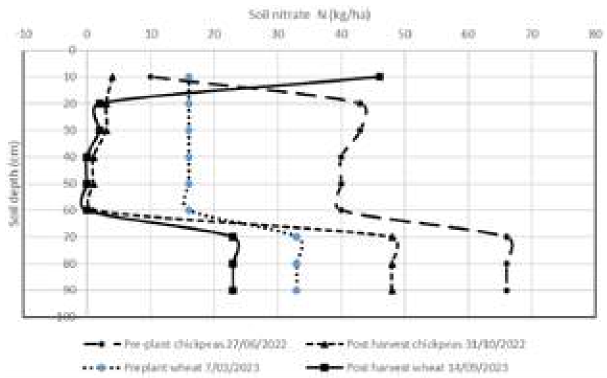


Figure 8. Comparison of the distribution of soil nitrate N in the profile at planting and harvest of chickpeas in 2022 and wheat in 2023.

The soil nitrate N profile of 94 kg N/ha available to the chickpea crop at planting was well distributed following the sorghum crop harvest which is unexpected considering the sorghum crop should have used ~120 kg N/ha.

The lack of a soil nitrate N deficit after sorghum harvest may be because 60 kg N/ha was applied (130 kg/ha of urea) at planting of the sorghum crop and there was 528 mm of in-crop rainfall to help with distribution and access. In addition to this fertiliser N application, it is assumed that the N that was locked up in the millet crop residue (~91 kg N/ha) was also released during this time and contributed to the 4.6 t/ha sorghum crop.

It should be noted that the millet crop was not harvested for grain but was instead terminated (sprayed out) and left to breakdown on the surface of the soil. Most of this crop residue had broken down by the time the sorghum was harvested.

This scenario leading up to the chickpea planting demonstrates how important rainfall is to incorporate and distributing nitrate N effectively into the profile. The timing of fertiliser application following the chickpea crop also demonstrates how important it is to maintain a consistent supply of N in the surface soil prior to rainfall to effectively refill the top 60 cm of the profile.

Implications for growers

Based on the evidence presented in this paper and previous papers it is clear that both chickpeas and mungbeans will take up nearly all the soil nitrate N in the top 60 cm of the profile before they will start fixing N_2. This has an immediate impact on the availability of soil nitrate N for the following crop.

Both mungbean and chickpea crop residues break down at a faster rate than cereal stubble because of the lower C:N ratio. Based on the evidence given in this paper the amount of N released from this residual stubble is not replacing the amount of soil nitrate N that is being exported in grain. This means that there is a reliance on the mineralisation of organic matter to provide enough nitrate N to cover the short fall in the soil nitrate N pool after a mungbean or chickpea crop has been harvested.

The reasoning for this is based on the 15N natural abundance measurements taken in mungbean trials where N_2 fixation levels were in general lower than expected, and the fixation level reduces as soil nitrate N levels increased. The NHI is also high which means that 60–90% of the N is being exported in grain rather than being returned in stubble residue. It is these two key factors that dictate the ability for a mungbean crop to replace the soil nitrate N that it uses.

The data for chickpeas does not include an analysis of its ability to fix N_2 in this paper, however it does show evidence that it sources its N in a similar manner to mungbeans. This is based on the measured extraction of soil nitrate N in the top 60 cm of the profile.

The characteristics highlighted in this paper do not change the fact that pulses are grown chiefly because of the gross margin they can generate for the grower and their capacity to provide their own N when soils are limited in nitrate N. This still provides a unique advantage over the production of cereals.

The data simply highlights the fact that soil nitrate N levels following a legume crop such as chickpeas or mungbeans will be just as low as following a cereal crop and that the pulse crop residue may not be able to replace the amount of nitrate N that has been exported in grain. This is dependent on several factors with the chief of these being the level of soil nitrate N that the crop gets planted into.

In a dryland cropping system where there is a heavy reliance on fallow periods to recharge stored soil water, this also provides a period for N mineralisation from existing soil organic matter. Mineralisation occurs naturally and is largely controlled by environmental factors (temperature, water, organic matter levels) without any grower input.

For example, fallow periods often allow for the mineralisation of 30-50 kg N/ha in most Vertosol soils which in turn means that at planting time, pulse crops can have 70-80 kg N/ha available (assuming about 30 kg N/ha left after most crops). At this moderate level of soil nitrate N, it has been shown by the mungbean data that it will impede N_2 fixation to the point that Ndfa% will be less than 50% depending on the biomass production of the crop. At this level the crop is not fixing enough N to replace what is being taken off in grain.

Future long-term management of N fertility in our broadacre cropping systems will need to account for the potential deficits that can result from growing pulses such as mungbeans and chickpeas. Replacement of soil nitrate N needs to be considered after pulse crops to reduce the pressure on the mineralisation of soil organic matter reserves and providing adequate N supply for the following crop to meet its yield potential.

References

Unkovich M, Herridge D, Peoples M, Cadisch G, Boddey B, Giller K, Alves B and Chalk P (2008) Measuring plant-associated nitrogen fixation in agricultural systems. ACIAR Monograph No. 136, 258 pp.

Sands D, Gentry J, Silburn C (2022) What contribution do mungbeans make to soil nitrogen? GRDC Update paper, Biloela 2022.

Aisthorpe D (2023) Farming systems research in the Northern Grains region and implications for key decisions driving risk and profit in Central Queensland. GRDC Update papers, Emerald 2023.

Sands D (2023) Distribution of nitrates and its effect on plant uptake efficiency in Central Queensland farming systems. GRDC update papers, Emerald 2023.

Acknowledgements

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

The authors would like to acknowledge the efforts of the technical officers involved in collecting the data that has been presented in this article.

This article has been adapted from a GRDC update paper originally published in November 2023 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/11/what-do-pulses-contribute-to-the-nitrogen-balance-in-central-queensland-farming-systems

Summary of fertiliser phosphorus (P) and potassium (K) deep-placement from 2009 to 2021

David Lester[1], Douglas Sands[1] and Michael Bell[2]

[1] Queensland Department of Primary Industries
[2] University of Queensland

***Research questions**: Does placing phosphorus and potassium (both immobile nutrients) in the soil at 15-20 cm deep increase grain yields? | How does altering the fertiliser band spacing or application rate change crop response to subsurface applications? | Does the choice or form of high-analysis fertiliser change crop response to subsurface applications?*

Key findings

1. Stratifying soil samples to measure chemical fertility differences between 0-10 and 10-30 cm layers provides better understanding of immobile nutrient access.
2. Putting high-analysis P and K fertilisers at 20-25 cm depth on low P and/or K sites significantly increased grain yield in Central Queensland across a range of crops. In southern Queensalnd, winter cereals are generally also responding positively, while responses in chickpeas and sorghum have ranged from positive to no effect.
3. The relationships with crop phosphorus uptake and grain yield for chickpea, wheat and sorghum are robust: as you get more P into the plant, yields are increasing.
4. Potassium is potentially a limiting factor, but data sets are not yet as extensive as for P.

Background

Research into phosphorus (P), potassium (K) and sulfur (S) started in 2009 in DAQ00148 (Bell 2012) with a re-evaluation of the critical soil test values measuring the fertility status of soils across the northern grains region (NGR), identifying a consistent negative nutrient balance of macronutrients (NPKS) and a decline in soil fertility across the NGR. The review also confirmed that low levels of P in the subsoil (below 10 cm) remained, or were declining, despite fertiliser P additions to the surface layers, leading to increased stratification of P (and other immobile nutrients) in topsoils across the region as approximately 50% of the net P removal occurred from below the top 10 cm, mostly from the 10-30 cm depth.

Table 1. Critical P values (mg/kg) to determine likely response or drivers of P availability in northern Vertosols.

	Surface (0-10 cm)		Subsoil (10-30 cm)	
Colwell P	<25	Likely to get starter response	<10	Likely to get response to subsurface P placement
Colwell P	>60	Ensure good groundcover to limit erosion loss	>100	Unlikely to see P deficiency
BSES P	<25	Limited evidence of residual P fertiliser	<30	Limited reserves of slowly available P. Consider replacement of removed P very 5 years
BSES P	>100	High residual P fertiliser load or natural P fertility	>100	Potential to slowly replace Colwell P reserves

Strategies to assess soil P fertility of both the 0-10 cm and 10-30 cm layers started to evolve. The BSES-P method (a dilute sulfuric acid extractant) now provides an indication of a soil's capacity to recharge the plant available P pool (as indicated by the Colwell-P test), through dissolution of slower release P minerals (McLaren et al. 2014). The combination of these 'tests' and the phosphorus buffer index (PBI) was proposed to determine likely fertiliser P responsiveness, and guide P application strategies (e.g. banding v dispersed P) (Table 1).

Values for suggested soil K levels were also estimated with much less certainty (Table 2), with a hypothesis that clay content/clay activity (indicated by CEC) as well as mineralogy were likely to influence potential fertiliser K responsiveness (Guppy et al. 2012).

Table 2. Critical K values used to determine likely response or drivers of K availability in northern Vertosols.

	Surface (0-10 cm)		Subsoil (10-30 cm)	
CEC (cmol/kg)	ExK (cmol/kg)	High Mg (>30% CEC) or Na (>6% CEC)	ExK (cmol/kg)	High Mg (>30% CEC) or Na (>6% CEC)
<30	0.2	0.4	0.1	0.2
30-60	0.4	0.7	0.3	0.5
>60	0.6	1.0	0.5	0.8

Field work in DAQ00148 included the preliminary proof-of-concept installation of a series of strip-trials on the Darling Downs where P and K fertilisers were applied into the subsoil (Bell 2012), and evolved into a range of nutrition omission experiments examining surface and subsurface addition of P, K and S both singly and in factorial combinations. These omission experiments assisted in validating the suggested 'responsive' end of the critical concentrations (Tables 1 & 2) by measuring consistent large, single nutrient responses to applied P in both the surface and subsurface across sites from Moree to Emerald (Bell and Lester 2012).

Having consistently generated positive responses to the application of some subsurface nutrition, the research then switched gear into much more regionally spread experiments (UQ00063), targeting subsurface P application and exploring K at sites that met the estimated criteria for K responsiveness based on the critical soil test values. For P, the research focussed on plant responses to increasing subsurface fertiliser application rates, typically with or without a starter application. Following the DAQ0148 work that highlighted the interaction between P and K responses on soils where low soil concentrations of both nutrients were recorded, K research explored increasing fertiliser K rates (at 20-25 cm depth) with a basal P application and a contrast set of treatments without P to explore a K-only effect.

The regional subsurface fertiliser placement in UQ00063 was conducted at a constant band spacing distance (roughly 50 cm). Both P and K uptake by roots are diffusion-driven processes meaning banding is the most efficient option for applying these less mobile nutrients, as bands create a strong concentration gradient along which nutrients can move to adjacent root systems (Lester et al. 2018a). Derivate research in UQ00078, UQ00086, UOQ1805 and UOQ1905 then explored other factors influencing the effectiveness of subsurface banding of P and K fertiliser applications. This included laboratory, glasshouse and field experiments examining rate by band spacing interactions (varying the band frequency and the in-band concentration), the fertiliser products and form of fertiliser (granular or liquid) used to deliver nutrients, the pH of the soil environment the fertiliser is placed into, and what happens when P and K fertiliser are applied together into the same band (Meyer et al. 2020). Also examined were interactions between root systems, water and P distributions and their impacts on plant P uptake (van der Bom, et al. 2022 updates). This research attempted to improve our understanding of the diversity of P dynamics that occur in different Vertosols in the NGR (i.e. the relative importance of absorption/de-sorption typical of acidic pH soils compared to precipitation/dissolution reactions more common on calcareous soils) and incorporating that understanding into APSIM P module parameters (Raymond et al. 2021a).

The following results section attempts to distill this broad history of research projects into the current understanding on soil and plant P and K nutrition: the good, the bad and the ugly. However, it is worth recapping how nutrients behave in soil and how soil nutrient supply meets crop demands, as these characteristics will have a large impact on the effectiveness of any fertiliser program.

How nutrients are acquired by plants

Before devising an effective fertiliser application strategy for any nutrient, we need to understand how that nutrient behaves in soil and is acquired by plant roots.

Nutrients are generalised into two groups related to their behaviour in soils (and particularly their response to water movement through soil profiles): mobile and immobile. Plant roots have three main mechanisms to gather nutrient from soils: mass flow, diffusion and root interception (Barber 1995). All three mechanisms are used for every nutrient, but the proportion acquired through each varies.

Nitrogen (N) is predominantly present in soil organic forms (associated with carbon) that need to be converted to mineral nitrogen (ammonium and nitrate) by microbial activity before plants can uptake. Once in those mineral forms, particularly as nitrate, the concentration of N in the soil water increases and N becomes very mobile. Mass flow uptake means as the plant takes up soil water it accumulates nitrate-N dissolved in that water at the same time. As roots deplete the water (and N) close to them, water moves to the root from undepleted soil further away, bringing nitrate with it. The most efficient nitrogen recovery occurs when the majority of available nitrate is distributed within the plant available water.

Phosphorus is the opposite of N in many ways, with most P in cropped soils present in inorganic forms of varying solubility. The fraction that is readily available for plant uptake is either in the soil water at very low concentrations or held (sorbed) onto clay and organic matter particles. The sorption and desorption processes can occur rapidly, but the net effect is that at any time there is a low concentration of P in the soil water. This means P resupply from water movement from other parts of the soil profile is limited, and P is considered an immobile element in clay soils or 'where you put it is where it stays'. For roots to access P they have to grow into undepleted soil, or be very close to a concentrated P supply like a fertiliser band.

Effective P uptake therefore requires either low P concentrations across large soil volumes, with roots always able to grow into soil with available P or concentrated patches of high P availability (i.e. bands or slots) which stay moist and where roots can concentrate in large numbers. Once you are relying on P fertilisers, placement is a critical success factor.

Potassium is an interesting blend of these contrasting characteristics. It is still held on clay and organic matter surfaces and occurs in relatively low concentrations in soil water. This means in our high clay soils it also is effectively immobile. What is challenging, though, is that roots don't congregate around a patch of high K like they do with P, and so it is harder to get rapid uptake of K from a band – unless you put some P with K, to act as an incentive for roots to congregate in that area.

Results

Deep fertiliser P and K - the 'good'

One of the strengths of the UQ00063 project was the extensive geographic distribution of approximately 30 experiments, with the majority extending from Moree to Kilcummin (Figure 1). They generally involved variable rates of P applied at ~20-25 cm deep in bands spaced roughly 50 cm apart. At sites where K was likely to be marginal based on soil testing (primarily in CQ), variable rates of K on the same band spacing as P were made. The K rates were contrasted between P applied with the K, and not. Most Queensland experiments included an untreated control, acting as a 'Farmer Reference' (FR) treatment to gauge baseline production without tillage or other nutrient inputs. They represent the baseline 'as-is, where-is' yield. Against this benchmark, the effects of ripping and application of basal nutrients (N, S, Zn) or the addition of various rates of fertiliser P and/or K in addition to the basal nutrients, were assessed. Table 1 provides an example of the treatment combinations used in the later years of the experimental program. All main deep-placed P plots were then split to 'with' and 'without' starter P fertilizer applications at planting, to assess whether effects of starter P and deep P were complementary.

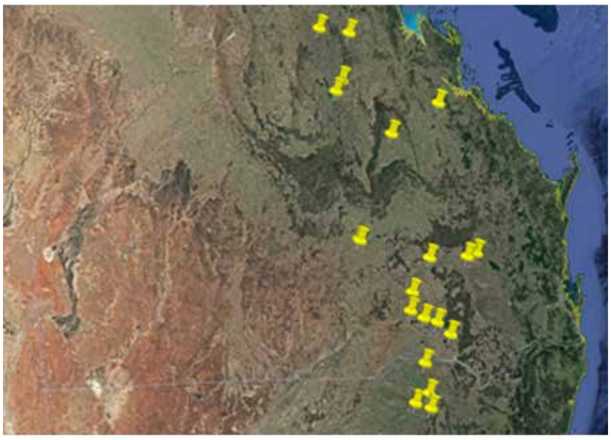


Figure 1. Location of the 30 P trials established from 2012-2017 under UQ00063.

Crop choice at each site was dependant on the local rotation of the cooperating grower, and the residual benefit of the different rates of applied P was tracked through subsequent growing seasons.

Table 3. Experimental treatments (application rates) for Mt Bindango deep-placed P sites.

Treatment	1	2	3	4	5	6	7
P rate (as mono ammonium phosphate)	FR	0	10	20	30	40	60
N rate (kg N/ha from MAP and urea)	-	40	40	40	40	40	40
Zn rate (kg Zn/ha from zinc chelate)	-	2.0	2.0	2.0	2.0	2.0	2.0

Field research under UQ00063 concluded in June 2021. Not every crop responded in every year, however, our general conclusions from the starter x deep P rate experiments are that starter applications are beneficial for cereal crops across the study region, with P application with seed at sowing ticking the box for early vigour and setting up of the crop. Overall, starter applications on most winter cereal crops increased yields compared to equivalents without starter application, while starter responses in both chickpea and sorghum were more variable.

Further research is needed in the potential role of liquid starter P applications to apply low rates of starter P uniformly – particularly in summer cereals grown in wide rows, where the number of granules/m of crop row is small. Research has shown the P uptake from starter applications is typically small (only an additional 1-2 kg), so there is potential to 'save' on the rate of starter P and divert elsewhere in the profile where crop recovery is more efficient (e.g. deep bands). Low-rate P applications are sufficient to stimulate root/shoot vigour, set potential grain number and reduce the variability in time to flowering / maturity.

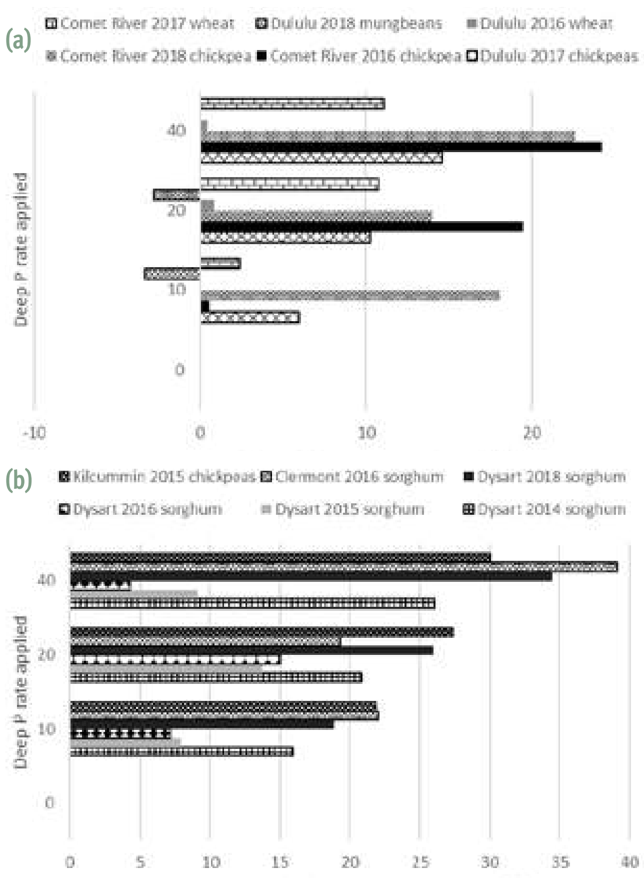


Figure 2. Mean relative grain yield responses to deep applied P treatments as a % of the zero P treatment for sites with (a) relatively high Colwell P concentrations (22 mg/kg) or (b) low Colwell P concentrations (<8 mg/kg) in the top 10 cm of soil.

Responses to deep P bands

Central Queensland

Grain yield responses to subsurface P banding in CQ for chickpea crops are typically very strong, while wheat and sorghum responses (where N isn't limiting for cereals) are more seasonally and site dependent (Sands et al. 2021a).

The relative yield responses in those sites with relatively high surface P (Figure 2a) showed a maximum response of ~25%, with a significant amount of variability across the crop years. More than half the yield responses to the 20 kg P/ha and 40 kg P/ha rates represented yield increases of 10% or lower (Figure 2a). This contrasts with the relative response to 20 kg P/ha and 40 kg P/ha rates in those sites that had much lower surface P concentrations (Figure 2b), in which 75% of the responses produced yield increases of 15% or more. The maximum relative response was also higher, with close to a 40% increase in grain yield (Figure 2b).

At Dysart there was even more upside chickpea yield with reapplied P increasing yields further (Figure 3). There were similar yields recorded for the FR treatment and the re-ripped 0P treatments with or without extra K and S applications, ranging from 1200-1400 kg/ha. The lack of response to ripping and basal nutrients (N, or N and K) suggest that P was the primary nutrient limit to productivity.

There were significant yield increases of 750-1250 kg/ha with the residual deep bands applied at 20 kg P and 40 kg P/ha with background KS, respectively – despite the original application being made back in 2013, and after five crop seasons. If no K had been applied in the original deep bands with the 40 P treatment, yields were reduced by 300 kg/ha – a small but statistically significant drop that suggests availability of K was a secondary limitation to yields at this site, evident only when P availability had been improved first.

The reapplication of 30 kg P/ha (as monoammonium phosphate plus zinc) prior to the 2019 season saw a further increase in potential yields to 2700-2800 kg/ha without background K, and to 3400-3500 kg/ha when K was also reapplied (Figure 3a). These responses support the primacy of the P limitation but also indicate a growing importance of K limitations once adequate P was available to meet crop demands. The 300-350 kg/ha drop in yields without K seen in the residual P treatments had now increased to 700-800 kg/ha with the improved P availability arising from the fresh reapplication (Figure 3b). The strong P responses at this site were consistent with results from the previous five crops grown on the site (2014, 2015 and 2016 sorghum, 2017 chickpeas and 2018 sorghum), but the magnitude of the response to the reapplication was a little surprising given the strong residual effects that were still evident from the original applications – especially the 40P treatment.

The response to increasing original P rates has changed with time after application. In the first three sorghum crops there was no difference in yields between the 20 and 40 kg P/ha applications, but in subsequent crop years a better relative response was increasingly evident with 40P rather than 20P and yields effectively increased in a linear response to increased P rate. While this linear response is still evident in the sixth crop season, it is clear that crops could respond to more P than was available from the residual bands and that further P from a reapplication was needed. The relative increase in yield response in relation to the residual bands raises the question of whether an earlier reapplication could have been economically beneficial, and this can only be answered by future research. However, the cost to reapply 30 kg/ha of P, along with the 50 kg/ha K and 90 kg/ha N in the background fertiliser, was roughly $260/ha. It is very

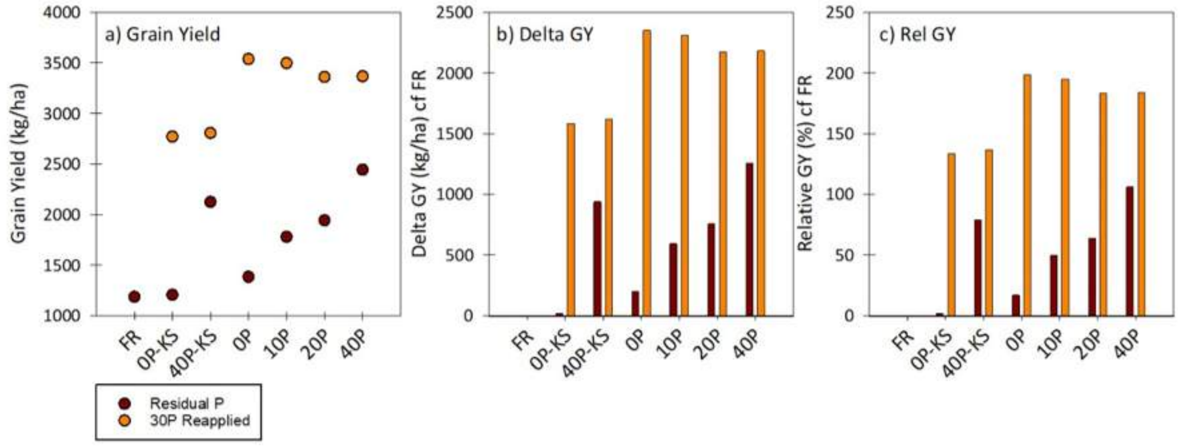


Figure 3. Dysart 2019 chickpea of the sixth crop on residual P versus the first crop on 30 kg P/ha reapplied for a) grain yield, b) change in yield from the untreated reference, c) change in yield as a relative measure.

clear that the reapplication at the Dysart site has paid for itself and delivered a profit in the year of application (assuming $650/t on-farm price).

Southern Queensland

Winter cereals throughout southern Queensland have generally reliably increased grain yields in a range of seasons by about 15% at the 30 kg P/ha treatment (Figure 4a) – with exceptions in droughted years.

Responses with chickpea are mixed (Figure 4b). There were usually significant dry matter increases measured (data not shown) but they do not always translate into increased grain yields. The yield effects appear muted when the 0P treatment (tillage and basal nutrient) had about a 10% increase without any additional P. Chickpea gave the largest relative yield increase (nearly 120%) at Condamine in 2014 (first crop at site). Excluding the huge response, grain yield increased by 13% with the 30 kg deep P/ha compared to the untreated control.

Sorghum has contrasting yield responses with rainfall post-flowering likely the major driver of yield (Figure 4c). Two of the five harvested crops delivered responses >15% in yield, but the remaining three were only 4-7%. One notable negative effect (the 0P Mt Carmel site) is possibly due to tillage effects on crop establishment with treatments established in May prior to sowing in October.

We have confidence in the responses from examining the underlying agronomic drivers measured: dry matter, grain yield and P uptake in each of those studies. Relationships between dry matter (DM) and grain yield (GY) have reasonable correlations (Figure 5 a-c). Subsurface P can increase soil supply of plant available P. That can increase dry matter produced which influences both the P uptake by the plant and concurrently can also influence grain yield. The next question is how to 'best' increase plant P supply?

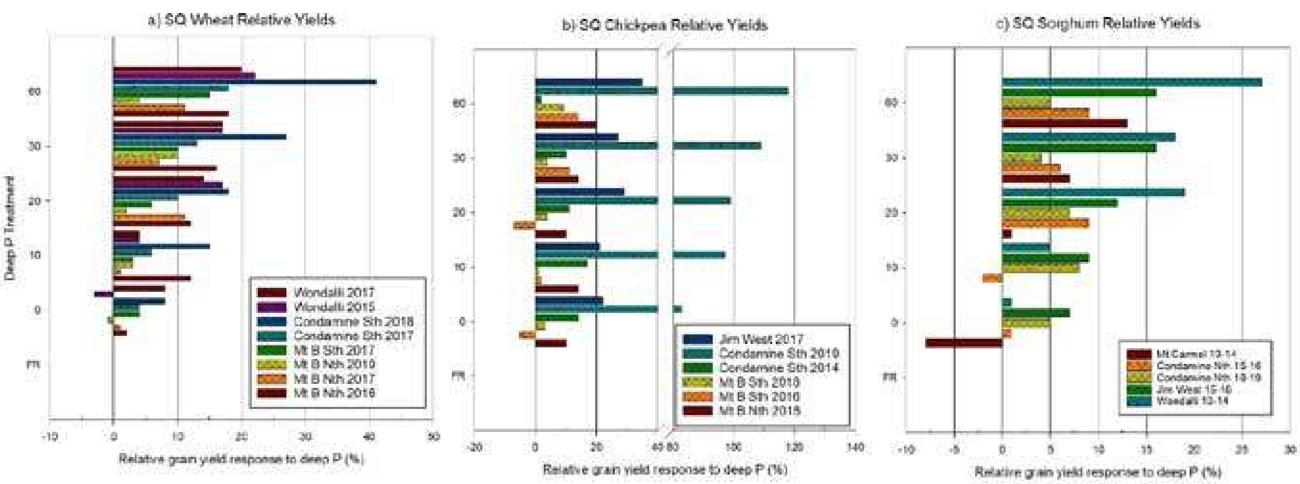


Figure 4. Relative yield responses to deep applied P treatments as a % of the untreated control for a) wheat, b) chickpea and c) sorghum in Southern Queensland (note different scales on the X axis).

Responses to deep K bands

Review of the potassium data from experiments is still in a preliminary phase as phosphorus has been a more widespread nutrient across the program. A case study site is presented showing some potential responses, but further investigation of the data will be forthcoming as final reports are prepared.

Central Queensland

Dululu's trial site has had four crops planted and harvested since it was first treated with deep banded fertiliser in November 2015: wheat (2016), chickpea (2017), mungbean (2017/18) and chickpea (2019). Full details are contained in Sands et al. (2021b).

The original soil test indicated adequate levels of P and K in the top 0–10 cm but low levels in the deeper layers (Table 4). Deep K responses at this site were more consistent than for P. Wheat was the only crop that did not respond to the highest rate of K application when background P was applied. Only mungbean responded to the highest K rate when no background P was applied; it is unclear if this is a particular characteristic of mungbean, or due to seasonal variation. Accumulated grain yield responses to K were greater than those in the P trial (data not shown). The highest K rate (100 kg K/ha) provided ~800 kg/ha more than the 0K treatment, and the highest rate of P (40P) in the P trial provided a ~600 kg/ha gain. While the reapplication of 50 kg K/ha to the 25K treatment produced the same accumulated production as the 100K treatment, the 50K treatment was almost 500 kg/ha behind both these treatments. It appears that the K at this site was used at a faster rate than the P, and reapplication will be needed sooner than normally expected for P responsive sites.

This trial site shows the need for subtle differences in management when soils are more restricted by K than P, and perhaps when higher topsoil P accentuates the differences in P supply between wetter and drier seasons. Plant uptake of K (36 kg K/ha) was much higher than P (7 kg P/ha) when the K and P were reapplied for the 2019 season. This five-fold difference presents a challenge regarding how much K should be applied and how long it will last. In the K trial in 2019, the reapplied treatment used up 15 kg of K more per hectare then the 100K residual treatment. This means that of the 50 kg K/ha that was reapplied in 2019, almost a third has been taken up by the 2019 chickpea crop.

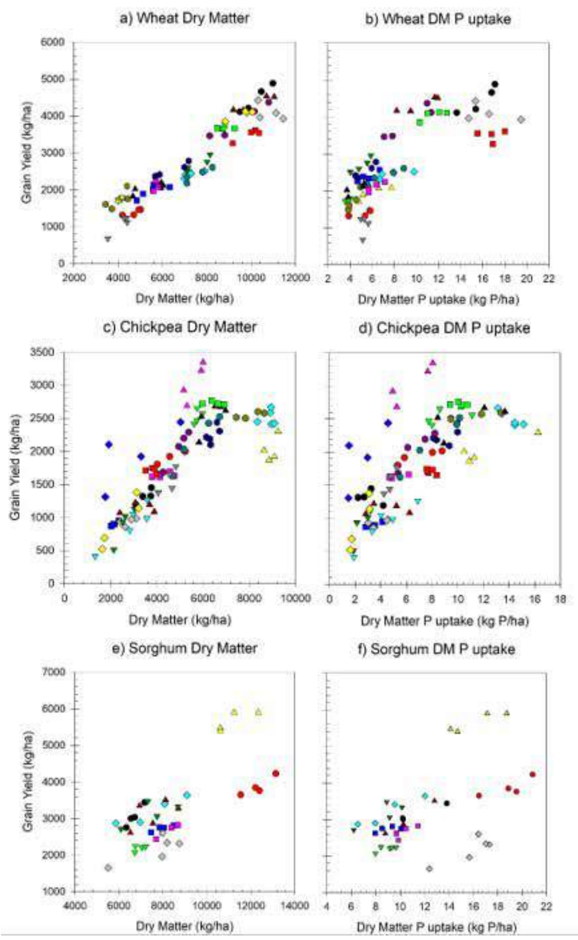


Figure 5. Scatter plot matrices of dry matter versus grain yield, and dry matter P uptake versus grain yield for a-b) wheat, c-d) chickpea and e-f) sorghum at deep P sites in Queensland.

Increasing plant nutrient uptake from fertilisers, including P and K

Acquisition of immobile nutrients applied into the subsurface by plant roots is an exercise in probability – fertiliser needs to be placed such that the roots are more likely to find those nutrients early enough in the plant life cycle to make a difference in growth, and that placement zone has to be wet enough for long enough for roots to be active and acquire enough nutrient.

Table 4. Soil analysis for the Dululu site.

Depth (cm)	Nitrate N (mg/kg)	P Colwell (mg/kg)	S (KCl-40) (mg/kg)	Exc. K (meq/100g)	BSES P (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

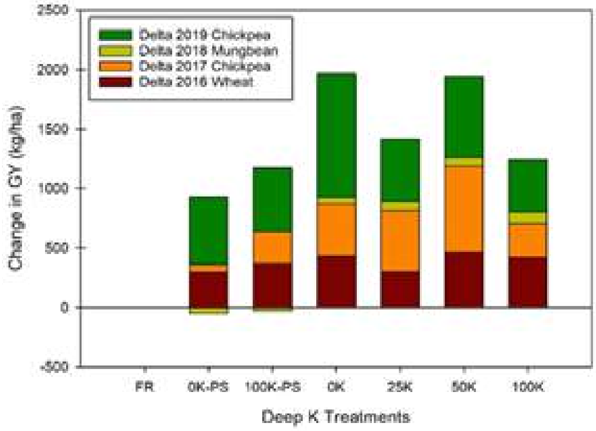


Figure 6. Accumulated grain yield increases over FR treatment for deep K treatments across four crops.
(25K treatment data includes the extra application of 50 kg K/ha in 2019).

The placement effects of P and K fertiliser applications on crop uptake and yield responses have been examined using field experiments in two projects. Early research in DAQ00148 compared applying into the topsoil, or subsoil, or both on three fertiliser band spacings (Figure 7), at one constant application rate of 40 kg P/ha as MAP. Research in UQ00078 evolved to explore the diffusion gradients created by a range of P rates (0, 10, 20, 40 or 80 kg P/ha) or K rates (0, 25, 50 or 100 kg K/ha) at each of the three band spacings at depth. The research outcome suggests that while band spacings are important (narrower is better – 25 cm & 50 cm give better nutrient access than 100 cm), it is the rate of application that has the greatest impact on crop recovery.

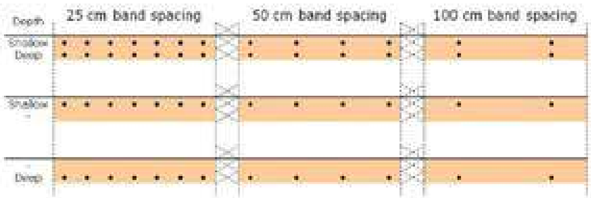


Figure 7. Fertiliser band and depth placement strategies for P and K application in DAQ00148.

Above ground dry matter at maturity was increased with increasing P rate in 3 of 6 seasons across the two sites (data not shown). Briefly, responses were approximately 10% greater than the 0P treatment, with the effect not really detectable until application rates were >20 kg P/ha. In several years, distinct visual growth responses were observed in the stages up to flowering. Full details are reported in Lester, Weir et al. (2018b) and Lester and Bell (2020).

Chickpea grown in 2017 and sorghum in two fields (2018-19) allowed drone platforms to capture NDVI to assess the relative influence of application rate and band spacing. In general, the rate of P applied appeared to be a more dominant contributor to NDVI than band spacing (Figure 8).

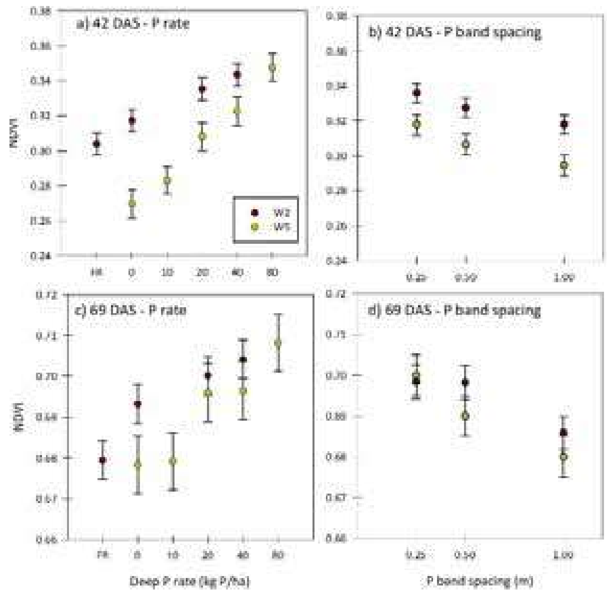


Figure 8. NDVI of sorghum at 42 and 69 DAS for deep P rate x band spacing experiments conducted in W2 and W5 fields growing sorghum in 2018-19.

Product choice investigations

In most northern region cropping soils, granular ammonium phosphates should be the first product choice for application in a subsurface program. Field experiments in UQ00078 at two sites in Queensland over two growing seasons compared no P application with applying rates of ammonium phosphates as granular and fluid forms (MAP, DAP, FlowPhos) or calcium phosphates (TSP) without any clear cut result (Lester et al. 2018b), due to the inherent variability in field sites and challenging seasonal conditions where a lack of water/heat stress limited potential yields.

Laboratory and glasshouse research conducted at University of Queensland (Meyer et al. 2020) examined P products and the interaction with coapplied K on fertiliser bands in a variety of soils. Findings suggest for non-calcareous soils, the pH of the soil and the pH of the P product as it dissolved influenced soil P availability. In general, ammonium phosphate fertilisers are the preferred delivery mechanism for band applications but there was little evidence of any advantage of MAP over DAP, with similar findings reported in Raymond et al. (2022 updates) for dispersed P.

Increased crop growth when comparing untreated controls to the 0 kg P/ha plots is common in the crop seasons post-application, suggesting that tillage associated with subsurface nutrient placement is providing some benefit, although these trials were not designed to separate tillage effects from the background nutrients that were added at the time. The soil disturbance needs to be disruptive enough to break up legacy compaction, and early enough to allow reconsolidation of soil, to enable successful establishment of the next crop.

Economic ROI from deep P and/or K

Fertilising with deep P and K are longer term decisions, with significant upfront costs (Table 4) and returns expected to be recouped over 5 years or more. Analysis of the 8 longest running trial sites in southern and central Queensland, where P was applied as MAP, show promising returns from deep P application, with cumulative yield benefits ranging from 1% to 42% at 20 kg P/ha (Table 5).

Table 5. Treatment cost by P rate with basal N.

Treatment (P kg/ha)	Application ($/ha)	Urea ($/ha)	MAP ($/ha)	P treatment cost ($/ha)
0	$30	$69	$0.00	$99
10	$30	$61	$73	$164
20	$30	$57	$109	$196
40	$30	$52	$145	$227
60	$30	$43	$218	$291

Note: Using long term average MAP ($800/t) and Urea ($450/t) prices.

Using 5-year average prices these yield benefits have largely transferred through to significantly improved profitability, with 20 kg/ha P generating up to $1586/ha in additional gross margin above farmer reference treatments (Table 6). Return on investment averages 2.7 across the 8 sites, meaning for every $1 spent on deep-P, profit has increased by $2.70.

Unresponsive sites highlight some of the uncertainty still surrounding the practice of deep P and K fertilisers. For example, the Warra site suffered a significant yield penalty due to deep placement in the year 1 sorghum crop (presumably due to lingering tillage effects on soil moisture), which was not overcome by deep P addition due to a strong K deficiency that was observed across the site. This occurred despite soil tests suggesting K was marginal-adequate. Following a background K application, all subsequent (grain) crops showed positive responses to deep-P, but these benefits were not enough to meet the treatment costs and the first year yield penalty in the high value chickpea crop to break even.

Where Colwell P concentrations in subsoils are low (<10 mg/kg), deep-P appears to offer strong economic returns in many situations, although there were several sites where other constraints, particularly N and K deficiencies, have limited P responses across the trial program. This means growers need to take into account all-nutrient requirements of crops, as well as the constraint status of their soils, and apply nutrition in line with the improved 'non-P-limited' yield potentials.

Deep P and K banding - the 'bad'

Potentially negative results include:

- There is a 'goldilocks' soil moisture for putting treatments in. Too dry and you break your gear up trying to work hard ground and you can't get your bands deep enough. Too wet and you don't get the disturbance you need to break up the upper 20-25 cm profile.
- Doing deep placement without sufficient rainfall for reconsolidation doesn't allow successful crop establishment and/or good access to the deep bands. There needs to be good soil-band contact in moist soil for roots to access these nutrients, and fertiliser sitting in air gaps/voids created by tillage will not result in nutrient uptake. The solution is timing deep banding earlier in the fallow once there has been enough rainfall to soften the profile in the tilled zone. The longer the period post-ripping, the more rainfall events (hopefully) and the better the profile reconsolidation.
- Growing season conditions will influence the crop's response to subsurface-applied nutrients – especially when the topsoil layers are quite fertile. The length of time the crop root system has access to different soil layers (i.e. the top 0-10 cm versus the subsoil), how enriched each layer is for the nutrient in question, and how often each layer rewets during a growing season, will all influence the response to deep banded nutrients. This uncertainty is overcome to some extent by the good residual value obtained from these deep bands, especially for deep P, so a lack of response in a good season can see responses deferred to subsequent growing seasons.
- Meaningful data from northern New South Wales is sparse, due to a combination of extended very adverse drought conditions and logistical challenges associated with operating over a large geographic area from a single research base.
- Translation from research experiments to grower practice is mixed. There are reports deep P bands are not always working for every grower who does it. A more thorough

Table 6. Cumulative yield benefit vs farmer reference.

	Central Queensland				Southern Queensland			
P rate (kg/ha)	Comet River (4)	Emerald (5)	Dysart (6)	Dululu (4)	Mt Bindago (4)	Warra (4)	Condamine South (5)	Jimbour West (6)
0	21%	7%	13%	12%	1%	-8%	6%	9%
20	36%	5%	42%	19%	10%	1%	14%	18%
30					13%	0%	16%	19%
40	39%	7%	41%	19%				
60					14%	4%	19%	24%
Colwell-P (mg/kg at 10-30 cm)	6	6	1	3	3	3	4	8

Note: numbers in brackets following site names are the number of crops that have been harvested at these sites. It is expected that the benefits of higher rates of P will become more pronounced the longer each site is cropped.

Table 7. Cumulative gross margin benefit and ROI of 20P vs FR ($/ha).

	Central Queensland				Southern Queensland			
	Comet River (4)	Emerald (5)	Dysart (6)	Dululu (4)	Mt Bindago (4)	Warra (4)	Condamine South (5)	Jimbour West (6)
Gross margin benefit	$770	$27	$1586	$767	$60	-$94	$392	$673
Return on investment	3.9	0.1	8.1	3.9	0.3	-0.5	2.0	3.4

investigation of these situations (soil characteristics, application method and timing and rate, seasonal conditions etc) is needed to determine whether these effects are related to soil types or other factors.

Deep P and K - the 'ugly'

Unknowns relating to deep P banding include:

- We can't track uptake directly from fertiliser P bands over multiple crop sequences. The estimates are based on the difference between P uptake from untreated and treated plots, assuming the change in P uptake is all that is being acquired from the fertiliser band. There may well be greater P uptake from the deep P bands and some sparing of background P from the rest of the soil profile; but we don't know if this occurring, and if so, how big these effects may be.
- Getting good estimates of differences in nutrient uptake by crops using the differences between banded treatments is challenging due to variability in measurement of the above ground dry matter from a small sample area, and the homogenising of bulky plant samples containing both vegetative material and immature grains into a representative plant sample of <1 g for acid digestion. Grain yields and grain nutrient concentrations provide a more robust estimate of P/K leaving the paddock but this fraction varies with crop nutrient status and indeed the nutrient itself. A lack of grain nutrient removal may still mean a lot of the deep-banded nutrient has been taken up by the plant but returned to the relatively enriched topsoil, which is particularly the case for K.
- Understanding of P behaviour across diverse cropping soils is limited. There are sites (e.g. Central Queensland Smart Cropping Centre) where crops are obtaining substantially more phosphorus than current soil tests suggest they should. We still don't know where that P is coming from, which highlights that our understanding of P dynamics in Vertosols still has a way to go.
- The longevity of P from undisturbed fertiliser P bands (the 'fertosphere') in soils is variable, with work being conducted in UQ00063 by Chelsea Janke following up the banding studies reported by Meyer et al. (2020; 2021) over longer aging periods. Other lab work is being undertaken to assess behaviour of P dispersed through the soil (Raymond et al. 2021b); this work is linked to field studies in Qld and NNSW conducted in UQ00082. The laboratory studies are showing that for the same rate of P application, some soils allow a much greater proportion of applied P to enter the plant available soil P pools (measured by Colwell P) than others (Raymond et al. 2022), consistent with results from field sites at Gindie, Hopeland and Ningadoo; the reasons are still being assessed.
- Our knowledge of interactions between soil moisture, root activity and P acquisition for different species is limited (van der Bom et

al. 2020). These interactions have significant implications for plant growth and phenology, as well as for breeding programs selecting for specific root morphologies to improve deep water extraction.

- The interaction between plant P uptake, growth and phenology responses, soil water extraction and transpiration is also uncertain. Are crops extracting more water because they have larger root systems, or respiring more efficiently because of better P status?
- Lastly, potassium is a major nutritional challenge in cropped Vertosols and, given the relative immobility of K and the amounts taken up by crops, is going to provide a significant long-term challenge to fertiliser management programs. There has been less research on K management in clay soils nationally and internationally, as K infertility has not traditionally been a problem due to adequate initial reserves. As those reserves are eroded, the imperative to better understand K dynamics in Vertosols is increasing and research in this space is breaking new ground.

Implications for growers

There is a strong likelihood of having to manage P and potentially K simultaneously in many broad acre cropping sites across the NGR in coming years, to optimise the efficient use of available water. In relation to soil K supplies, this is already reality in significant areas of CQ (especially on the open downs soils) and we are probably approaching these conditions in the northwest slopes of NSW and on some box/upland soils in southern Queensland.

Most of the research reported here has involved a single application of deep P/K bands into low P subsoils. Data suggests that while responses are profitable in most situations, these single bands are not completely overcoming the problem of P/K infertility. The strong residual value of banded P in particular, combined with periodic reapplications enriching 'new' soil on each occasion, are a way to rebuild soil fertility banks.

Grain yield increases in response to fertiliser K applications in Vertosols have been limited to sites in CQ and the inland Burnett, where subsoil K reserves are very low. Trials on soils with marginal K status in southern Qld have also been able to provide insights into crop K acquisition from fertilisers, but at this stage yield responses have been small and inconsistent. This situation will change as the crop removal continues, and so we need to continue to develop both short- and long-term responses to K decline.

An important consideration is how often these re-applications are needed, with the data suggesting there will be a need to reapply subsurface K much sooner than subsurface P. Crop K uptakes are typically ten times greater than P, so the residual amount of deep K after consecutive cereal/sorghum crops will rapidly decline. Most of this K won't be leaving field in grain. It won't be where you put it in the subsoil as it will instead be released from stubbles into the topsoil where it will not be available to roots deeper in the soil. How long deep K applications last, and how you manage subsoil P and K will be important, as deep K bands alone are not effectively utilised by plants - an 'entrée' of P with the K is needed to give roots a reason to proliferate around the bands. Identifying appropriate P/K blends for different situations and application frequencies will occupy nutrition researchers for some time to come.

Acknowledgements

Delivery of these research findings would not be possible without the conscientious efforts of DPI technical and operational staff to collect and process the soil and plant samples needed.

The research undertaken has been made possible by the significant contributions of growers through both trial cooperation, and the support of the Queensland Department of Primary Industries, the University of Queensland and the GRDC. The authors would like to thank them for their support.

This article has been adapted from a GRDC paper originally published in March 2022 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/03/deep-p-and-k-outcomes-from-8-years-of-research-the-good,-the-bad-and-the-ugly

References

Barber, SA (1995) 'Soil nutrient bioavailability: A mechanistic approach.' (John Wiley & Sons: New York)

Bell, MJ (2012) DAQ00148: Defining critical soil nutrient concentrations in soils supporting grains and cotton in Northern NSW and Queensland - See more at: www.grdc.com.au/Research-and-Development/DAQ00148#sthash.4s5IE3bU.dpuf. Grains Research and Development Corporation Available at www.grdc.com.au/Research-and-Development/DAQ00148.

Bell, MJ, Lester, DW (2012) Multiple nutrient deficiencies in northern grains cropping – latest results and management responses for system profitability. In 'Grains Research Updates. Goondiwindi', March 2012. (GRDC. Available at www.youtube.com/watch?v=xAuwg3b1xQQ

Bell, MJ, Lester, DW, Sands, D (2019) Nutritional strategies to support productive farming systems. In 'GRDC Grains Research Update (Dalby). Dalby Qld', 2 August 2019. Available at grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/07/nutritional-strategies-to-support-productive-farming-systems

Guppy, CN, Bell, MJ, Moody, PW (2012) Interpreting soil tests in the light of P, K and S research. In 'GRDC Adviser Update - 2012. Goondiwindi'. Grains Research and Development Corporation. Available at www.grdc.com.au/Research-and-Development/GRDC-Update-Papers/2012/04/Interpreting-soil-tests-in-the-light-of-P-K-and-S-research

Lester, DW, Bell, MJ (2020) Phosphorus: Rate was more important than band spacing for uptake by summer crops in 2018-19. In 'Queensland Grains Research 2019-20 Regional agronomy (research).' (Eds DN Lawrence, T Grundy.) pp. 61-64. (Department of Primary Industries, Brisbane, Qld)

Lester, DW, Bell, MJ, Weir, DJ, Lush, D (2018a) Deep-placing phosphorus in NE Australian grain soils: 2. Influence of P rate x band spacing (and form) on crop yield. In '6th Symposium on Phosphorus in Soils and Plants. 'From Molecular to EcoSystems'. Leuven, Belgium', 10-13 September 2018. pp. 251. (Katholieke Universiteit Leuven (KUL). Available at kuleuvencongres.be/PSP6/articles/documents/psp6-abstracts.pdf

Lester, DW, Weir, D, Lush, D, Bell, MJ (2018b) How can you get more deep-placed phosphorus into crops to boost grain yield? In 'Queensland Grains Research - 2017-18 Regional Agronomy.' (Eds J Gentry, T Grundy.) Vol. 2017-18 pp. 94-99. (Department of Primary Industries, Brisbane, Qld)

McLaren, TI, Guppy, CN, Tighe, MK, Moody, P, Bell, M (2014) Dilute Acid Extraction is a useful Indicator of the Supply of Slowly Available Phosphorus in Vertisols. Soil Science Society of America Journal 78, 139-146.

Meyer, G, Bell, MJ, Doolette, CL, Brunetti, G, Zhang, Y, Lombi, E, Kopittke, PM (2020) Plant-Available Phosphorus in Highly Concentrated Fertilizer Bands: Effects of Soil Type, Phosphorus Form, and Coapplied Potassium. Journal of Agricultural and Food Chemistry

Meyer, G, Bell, MJ, Lombi, E, Doolette, CL, Brunetti, G, Novotny, EH, Klysubun, W, Zhang, Y, Kopittke, PM (2021) Phosphorus speciation in the fertosphere of highly concentrated fertilizer bands. Geoderma 403,

Raymond, N, Kopittke, PM, Wang, E, Lester, D, Bell, MJ (2021a) Does the APSIM model capture soil phosphorus dynamics? A case study with Vertisols. Field Crops Research 273, 108302.

Raymond, N, Lester, DW, Bell, MJ (2021b). Boosting deep-phosphorus availability in vertosols. GRDC Groundcover supplement - Nutrient management for enduring profitability. GRDC, North.

Raymond, NS, Kopittke, PM, Van der Bom, F, Lester, D, Wang, E, Bell, MJ (2022) Phosphorus dynamics in Vertosols: improving fertilizer management. In '20th Australian Agronomy Conference - Agronomy System Solutions for Complex Problems. Toowoomba Qld', September 2022.

Sands, D, Bell, MJ, Lester, DW (2021a) What have we learnt from the deep banding of phosphorus in Central Queensland? In 'GRDC Grower Update 2021. Theodore Qld'. (GRDC. Available at grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2021/11/what-have-we-learnt-from-the-deep-banding-of-phosphorus-in-central-queensland

Sands, D, Lester, DW, Hagan, JM, Bell, MJ (2021b) Re-applying deep phosphorus and potassium after three years further boosted chickpea yields—Dululu. In 'Queensland Grains Research 2020-21 Regional agronomy (research).' (Eds DN Lawrence, T Grundy.) pp. 26-32. (Department of Primary Industries, Brisbane, Qld)

van der Bom, FJT, Williams, A, Bell, MJ (2020) Root architecture for improved resource capture: trade-offs in complex environments. Journal of Experimental Botany 71, 5752-5763.

Wang, X, Lester, DW, Guppy, CN, Lockwood, PV, Tang, C (2007) Changes in phosphorus fractions at various soil depths following long-term P fertiliser application on a Black Vertosol from south-eastern Queensland. Australian Journal of Soil Research 45, 524-532.

Nitrogen cycling and management decision making—Central Queensland

David Lester[1], Darren Aisthorpe[1], Lindsay Bell[2], Doug Sands[1], David Lawrence[1], Michael Bell[3]

[1] Queensland Department of Primary Industries
[2] CSIRO
[3] The University of Queensland

***Research question**: How do different fertiliser strategies affect the nitrogen balance of farming systems in Central Queensland?*

Key findings

1. Increased nitrogen (N) fertiliser demand by cereal cropping systems is caused by either a reduction in the amount of soil organic N mineralised due to the continued decline of natural capital (soil organic carbon and total nitrogen) under cropping, or higher yield potentials resulting from optimising other cropping system components.
2. The amount of biological N fixed by pulse crops (chickpea/mungbean) relates to crop yield/biomass and the availability of soil mineral N from mineralisation or residual fertiliser. Where deep phosphorus and potassium application increases chickpea biomass (and grain yield), there is generally more N fixed. While some is re-exported in grain, greater residue return means more N is carried forward to the next crop.
3. Fertiliser N management practices have differing strengths and weaknesses – it is not a one-size-fits-all model for CQ (or northern region) farming systems. The 4R framework allows choice of rate, source, time and place for any nutrient applied to be implemented suiting each growers' preferences, with on-going research addressing several themes in regional Queensland.

Background

Natural fertility of northern region cropping soils is declining as the time since conversion to cropping from previous land uses increases. Meanwhile, improved agronomic practices continue to increase grain yield of both cereal and pulse cropping systems. Collectively therefore, the nutrient cycle is changing with increasing plant demands and potentially diminishing soil reserves. These transfers of nutrients within soil profiles, and off farm as product export, require evolution of soil fertility management, including nitrogen.

The N cycle

Many authors have described the fundamentals of the N cycle in cropping systems for Australian (Barton et al. 2022), northern region (Herridge 2011, Cox and Strong 2017) and central Queensland (CQ) specific scales (Cox and Strong 2017). They all outline the potential flows of N between different soil pools and to plants and the atmosphere.

DPI is investing with GRDC and other partners in a new national project (UQ2204-010RTX) to develop a better understanding of fertiliser N cycling and loss in grain production systems, and improve decision support tools and systems models, like APSIM. This research uses a stable isotope of N (15N) to track movement, recovery, recycling and loss of fertiliser N for up to three consecutive crop seasons. Simultaneously the movement of fertiliser N down the soil profile during water recharge in summer fallows, and the implications for N availability to a following winter cereal crop, is being investigated through a project funded by the federal Department of Agriculture, Fisheries and Forestry. Both projects aim to better understand the post-application dynamics of fertiliser N, and optomise recovery and use of that fertiliser, with the Queensland research occurring at Gatton, Kingsthorpe, Pampas and Mungindi.

The 15N isotope can also be used to measure how much N is being fixed from the atmosphere by pulse crops through a method called 'natural abundance' (Unkovich et al. 2008). Comparing 15N abundance in the tissues of an unfertilised non-fixing reference plant in the same paddock as the pulse crop, can help determine how much N was fixed from the atmosphere by the legume. Similar calculations on the grain removed from the field can compare the amount of soil N removed from the field to the amount of fixed N returned in residues, to calculate

N balance for the crop. Of course, all the N in legume residues is potentially available to following crops, so the total amounts of residue and their rates of breakdown have to be estimated if we are to finesse the fertiliser N estimate for the following crop. This is where well calibrated system models can really help refine our N management.

Results

N in CQ farming systems research

Since 2014 the CQ smart cropping centre (formerly the Emerald Agricultural College) has been part of a DPI-led project evaluating different cropping parameters around fertility management, crop choice for pathogen/weed management, and cropping intensity. Some of the results in CQ and the broader project are presented in Bell and Aisthorpe (2023).

A component of monitoring of N dynamics between different cropping sequences involves measuring the soil mineral N (nitrate and ammonium) within the soil profile pre-sowing and post-harvest for all crops to give an insight into the behaviour of the immediately available plant N pool in the soil. The bigger picture also includes N that remains in the field in plant residues or incorporated into the soil organic matter pool, is exported in grain, or lost off-farm via gaseous (denitrification, volatilisation) or aquatic (leaching, runoff) pathways.

This article looks at apparent N balances in four of the management systems in the experiment:

1. Mixed baseline
2. High nutrient
3. High fertility
4. High legume

Let's start with the *Mixed baseline* system, a wheat-chickpea-sorghum opportunity cropping system with fertiliser N inputs designed to meet the demands of crops achieving a median target yield. Nine crops have been harvested (7 cereal and 2 chickpea; Table 1). Soil mineral N content at sowing has typically been higher than crop N demand, so fertiliser N applications have been minimal, totalling 110 kg N/ha since 2015.

'Managing Legume and Fertiliser N for Northern Grains Cropping' by David Herridge (2011) contains a series of equations for estimating how much N a pulse crop might have fixed. It works backwards using a harvested grain yield, and some starting mineral N levels to give a modelled estimate. The N fixed at the Emerald experiment was calculated using that framework, and the values used as part of the evaluation of system N balances.

It suggested that ~260 kg N/ha was fixed by the two chickpea crops in the baseline treatment. Higher mineral N (215 kg N/ha) in winter 2016 (Win16) (prior to sowing the 2016 chickpea crop) would have contributed to the relatively low proportion of N derived from atmospheric fixation (Ndfa% of only 40%) compared to that achieved in the chickpea crop in 2022, when there was half the starting soil mineral N. A cumulative N export of 571 kg N/ha in 26,148 kg of grain means this system has exported 200 kg/ha more N than was added into the system through fertiliser and fixed N. This N has to have been supplied by a rundown of soil N and organic matter.

In the *High nutrient* system, the starting mineral N levels have been consistently high pre-sowing (data not shown), reducing the amount of fertiliser needed to meet a 90% yield target – only an additional 55 kg N/ha more than the baseline has been applied over the entire sequence (Table 2).

Table 1. CQSSC farming system *Mixed baseline* running N balances.

Chron Year	Crop	Min N to 0.9m (kg/ha)	Crop N budget (kg/ha)	Fert N app (kg/ha)	Sim Tot N fixed / Ndfa%*	Grain N exp (kg/ha)	Dry matter (kg/ha)	Grain yield (kg/ha)	(Fert N + TNF) – grain N (kg/ha)	Cum (Fert N + TFN) - grain N (kg/ha)
Win15	wheat	132	102	16		38	6276	1671	-22	-22
Win16	chickpea	215		3	112/40%	95	7908	3059	20	-2
Win17	wheat	175	98	26		37	5278	1759	-11	-13
Sum17	sorghum	218	119	4		53	11573	3096	-49	-62
Win19	wheat	210	98	2		59	8512	2961	-57	-119
Win20	wheat	151	76	1		48	4638	2239	-46	-166
Sum21	sorghum	153	220	48		66	10071	4393	-18	-184
Win22	chickpea	110		2	149/56%	84	7131	2847	66	-118
Win23	wheat	89	95	7		91	7848	4124	-83	-201
Total				110	261	571	69234	26148	-201	

* simulated modelled values using (Herridge 2011).

Table 2. CQSSC farming system *High nutrient supply* running N balances.

Fert N app (kg/ha)	Sim Tot N Fixed* (kg/ha)	Grain N exported (kg/ha)	DM (kg/ha)	Grain yield (kg/ha)	(Fert N + Tot N Fixed) - Grain N (kg/ha)
165	235	597	70030	27648	-198

*simulated modelled values using Herridge (2011).

Grain yields for the baseline and nutrient systems are equivalent (69,200 vs 70,000 kg/ha, respectively), but the higher fertiliser N input has resulted in slightly lower total N fixed. Collectively, it is not surprising that the slightly higher fertiliser N input is balanced by higher grain N export, with the cumulative N balance (-198 kg N/ha; Table 2) being similar to that of the baseline system.

When the experiment commenced, a *High fertility* treatment was established that attempted to restore a high natural soil fertility status through addition of a large amount of organic matter. A total of 50 t/ha of (dry equivalent) feedlot manure was added in two applications, resulting in large increases in the soil mineral N and annual fertiliser N applications were not applied, with the exception of the N in the starter fertiliser (i.e. 2–6 kg N/ha as MAP; Table 3). Grain production increased by a cumulative ~5 t/ha more than the baseline and nutrient treatments, while an additional ~80–100 kg N/ha was removed in grain (672 kg N/ha; Table 3). The amount of Ndfa% was slightly lower, consistent with the higher soil mineral N supply.

Using the manure application rates and chemical analysis, an estimate of the addition of N, carbon (C), phosphorus (P) and potassium(K) was done correcting to 0% moisture. Total inputs were 1110 kg N/ha, 10,480 kg C/ha (equivalent to 1% C), 416 kg P/ha and 1000 kg K/ha. Including the additional N from the two manure applications, an apparent surplus of 730 kg N/ha exists.

These first three systems were cereal-dominated. The *High legume* treatment aimed for a 50:50 cereal:pulse ratio over time, and in the system so far, 5 of 9 crops have been pulses. This doubling of the number of pulse crops has altered several results.

Cumulative grain yields were 5 t/ha less than the baseline system, reflecting the typically lower yields of pulses compared to cereals in the same seasonal conditions. Dry matter production and crop residue return to the soil was also less in the legume system, but grain N export was only slightly lower than the baseline system (531 vs 571 kg N/ha) due to the typically higher N concentrations in the legume grain.

Having a higher legume intensity is altering the N input dynamics of that system. Fertiliser N input is negligible (22 kg N/ha), essentially coming from starter fertiliser applications. Simulated total N fixed by the system is ≈360 kg N/ha. These modelled numbers do have a larger uncertainty, but suggest the potential for pulse crops to make reasonable system N inputs. Cumulatively the system is still in net deficit of ≈150 kg N/ha.

Other factors that will affect fixed N inputs in cropping systems

While the percentage of crop N derived from fixation is influenced by the soil mineral N, as shown in the rotation sequences, the amount of N fixed by pulse crops is ultimately determined by the amount of biomass grown in that season. The more biomass that is grown (even at the same %Ndfa),

Table 3. CQSSC farming system *High fertility* running N balances.

Chron Year	Crop	Min N to 0.9m (kg/ha)	Crop N budget (kg/ha)	Fert + Manure N app (kg/ha)	Tot N Fixed / Ndfa%*	Grain N exp (kg/ha)	Dry matter (kg/ha)	Grain yield (kg/ha)	(Fert N + Tot N Fixed) - grain N (kg/ha)	Cum (fert N + TFN) - grain N (kg/ha)
Win15	wheat	157	140	281		45	6278	1926	237	237
Win16	chickpea	238		3	103/37%	96	8500	3023	10	247
Win17	wheat	266	132	890		51	7155	2367	839	1086
Sum17	sorghum	389	170	6		69	12307	4245	-63	1023
Win19	wheat	369	132	3		70	10419	3402	-68	955
Win20	wheat	410	113	3		65	6194	3056	-62	894
Sum21	sorghum	327	242	2		82	11553	5556	-80	813
Win22	chickpea	261		6	102/36%	92	7854	3016	16	829
Win23	wheat	141	113	5		102	9252	4644	-97	732
Total				1199	205	672	79511	31233	732	

*simulated modelled values using Herridge (2011).

Table 4. CQSSC farming system *High legume* running N balances.

Chron Year	Crop	Min N to 0.9m (kg/ha)	Crop N budget (kg/ha)	Fert N app (kg/ha)	Sim Tot N fixed / Ndfa%*	Grain N exp (kg/ha)	DM (kg/ha)	Grain yield (kg/ha)	(Fert N + TNF) - grain N (kg/ha)	Cum (fert N + TFN) - grain N (kg/ha)
Win15	chickpea	96		2	77/44%	55	4031	1842	23	23
Win16	wheat	176	79	3		77	9611	3761	-74	-50
Win17	chickpea	144		3	65/35%	62	3642	1931	6	-44
Sum17	sorghum	132	119	4		51	11874	2982	-47	-91
Win19	chickpea	105		2	52/36%	54	5729	1509	1	-91
Win20	wheat	120	76	1		37	3893	1767	-35	-126
Sum21	mungbean	117		2	6/10%	23	4091	627	-15	-141
Win22	chickpea	88		2	163/62%	87	6972	2831	101	-40
Win23	wheat	103	95	2		87	7951	3967	-85	-147
Total				22	362	531	57795	21215	-147	

the more likely that N will be added to that system through fixation. In sites that have been strongly responsive to deep P applications (e.g. Sands et al. 2022), substantial yield (and profit) responses to subsurface P applications have been recorded, accompanied by substantial increases in crop biomass production. By applying the assumptions and model of Herridge (2011) to the Dysart deep P trial site, estimates of total N fixed across the deep P treatment scenarios were determined (Table 5).

The experiment had two deep P applications during the research phase, with increasing subsurface P rates (0, 10, 20 or 40 kg P/ha) applied as MAP in 2014 and an untreated control or 'Farmer Reference' (FR). In 2019, the original plots (except the FR) were split with a reapplication of 30 kg P/ha (as MAP). In Table 5, 20P is the original P rate without reapplication, while the 20+30P represents an initial application of 20P and a reapplication of 30P.

Themodelled estimates suggest that improving plant P access could increase total N fixation from 50 to 230 kg N/ha, and Ndfa% from 45 to 76%. Even with increasing grain N removal, the estimated residual N carried forward increased nearly 3-fold, from 66 to 190 kg N/ha. Of course, the release rate of N from the residues would be seasonally

Table 5. Estimated %Ndfa and simulated total N fixation with deep P treatments at Dysart in 2019.

Treatment	Farmer Reference	20P	20+30P	40P	40+30P
Grain yield (12%)	1.16	1.92	3.34	2.44	3.36
Grain N (kg N/ha)	36	59.6	103.7	75.7	104.3
%Ndfa	45.3	59.9	76	66.9	76.2
Total N fixed (kg N/ha)	50	107.1	230.2	150.6	232.9
Residue N (kg N/ha)	66	110	190	139	192

dependant, and recovery by future crops would be related to residue decomposition and movement of mineralised nitrate-N into the soil profile.

Chickpea N fixation in Queensland in 2023

In the 2023 winter season DPI measured on-farm N fixation by chickpea across 25 sites in Central and Southern Queensland, using the previously described 15N natural abundance method. Along with a new national project on N Fixation, this will provide a greater insight into chickpea and mungbena N fixation across Queensland and how to manage it in out farming systems.

Implications for growers

Soil organic matter loss during long-term cropping and improved agronomy leading to increased yields means all growers and agronomists need to review their nitrogen management strategies to achieve their full yield potential and profitability.

Use of manures to lift soil organic matter levels has demonstrated a higher yield potential on healthier soils that have more soil organic matter and can supply more nutrients, especially nitrogen, to crops.

Nitrogen fertiliser must be used at the right rate, with the right product/source, applied at the right time and in the right place to maximise its value for productivity and the farming system.

If deep-placed phosphorus is used to improve yield potential, an increase in nitrogen rates is likely to be required to ensure the new yield potential from the phosphorus application can be achieved.

Legumes can fix large amounts of atmospheric nitrogen in line with their needs for the seasons, but will only do so on soils with insufficient available soil nitrogen for them to use. If enough soil nitrogen is available, legumes will use it and may not fix much nitrogen at all. Consequently, to maximise the nitrogen contribution of legumes to the farming system they are best used when available soil nitrogen levels are low.

Acknowledgements

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

In addition, federal Department of Agriculture, Fisheries and Forestry funding through the University of Queensland for Project 4-H4T03F0 'Understanding impacts of contrasting cropping systems on soil organic matter and the dynamics of soil water and nitrogen in rainfed cropping systems on Vertosols in northeast Australia' for research at Mungindi and Pampas farming systems experiments is greatly appreciated.

The authors thank the dedication and diligence of the technical and operational staff in each of their respective organisations that allows this research to be delivered. Projects included:

- DAQ2007-002RTX – Northern Farming Systems
- UQ2204-010RTX – Predicting N Cycling & Losses In Aust Cropping Systems
- DAQ2303-006RTX – Understanding the nitrogen contribution of chickpea in Qld
- UQ00063 MPCNII – Regional soil testing guidelines for the northern grains region
- DAQ2307-001RTX NGN – Understanding the long-term residual benefit of deep placed P in south-west and central Queensland
- UOA2312-008RTX – Improving the understanding and the effectiveness of N fixation in pulses in Australia.

This article has been adapted from a GRDC paper originally published in November 2023. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/11/nitrogen-cycling-and-management-decision-making-in-central-queensland-farming-systems-n-availability-and-recovery-across-the-farming-system-n-impacts-on-productivity-implications-for-management-in-cq

References

Barton, L., F. C. Hoyle, P. R. Grace, G. D. Schwenke, C. A. Scanlan, R. D. Armstrong and M. J. Bell (2022). Chapter One – Soil nitrogen supply and N fertilizer losses from Australian dryland grain cropping systems. Advances in Agronomy. D. L. Sparks, Academic Press. 174: 1-52.

Bell, L. W. and D. Aisthorpe (2023). Farming systems research in the Northern Grains Region and implications for key decisions driving risk and profit in Central Queensland. Yield, economics and seasonal risk. GRDC Grains Research Update. Emerald, Qld, GRDC.

Bruulsema, T. W., J. L. Lemunyon and B. Herz (2009). Know your fertilizer rights. Crops & Soils, John Wiley & Sons, Ltd. 42: 13-16.

Cox, H. W. and W. M. Strong (2017). The Nitrogen book : principles of soil nitrogen fertility management in central Queensland farming systems : includes easy-to-use electronic N fertiliser calculator, State of Queensland.

Cox, H. W. and W. M. Strong (2017). The Nitrogen book : principles of soil nitrogen fertility management in northern NSW and southern Queensland farming systems : includes easy-to-use electronic N fertiliser calculator, State of Queensland.

Herridge, D. F. (2011). Managing Legume and Fertiliser N for Northern Grains Cropping. Canberra, ACT, Grains Research and Development Corporation.

Sands, D., M. J. Bell and D. W. Lester (2022). Deep applied phosphorus and potassium: Reapplication of deep bands, timing, and economics. GRDC Grains Research Update, Capella, Qld, Grains Research and Development Corporation.

Unkovich, M., D. F. Herridge, M. B. Peoples, G. Cadisch, R. M. Boddey, K. E. Giller, B. J. R. Alves and P. M. Chalk (2008).

Measuring plant-associated nitrogen fixation in agricultural systems. Canberra, Australian Centre for International Agricultural Research.

Distribution of nitrates and the effect on plant uptake efficiency—Central Queensland

Douglas Sands, David Lester & Darren Aisthorpe
Queensland Department of Primary Industries

Key findings

1. Crops such as wheat, chickpea and mungbean can utilise up to 85% of the nitrates contained in the 10–60 cm portion of the soil profile under Central Queensland cropping conditions.
2. Rates of nitrogen fertiliser applied, and intensity of rainfall (number of events x amount x timing) are the key criteria in the distribution of nitrates in the soil profile.
3. Fallow length is not as critical to distribution of fertiliser nitrogen as application rate and rainfall but does increase mineralisation and distribution of nitrates derived from organic matter.

Background

Over the last decade, it has become clear that there are several factors influencing efficient nitrogen (N) uptake by dryland crops grown on high clay-content Vertosol soils. These factors have been consolidated into four major categories: rate, timing, source and placement. Uptake efficiency by plants is intrinsically tied to soil water capacity. Furthermore, the distribution and concentration of nitrates in the soil profile depends on the accumulation of soil water in the profile.

This article examines the relationship between water uptake and nitrate uptake in the crop, giving practical examples of what has been observed in typical Central Queensland (CQ) cropping scenarios. The data presented is from two GRDC-funded field trial projects, the Companion Cropping project (DAQ2104-006RTX) and the Mungbean Agronomy project (DAQ2104-006RTX).

An experiment conducted in the Companion Cropping project ran from May 2021 to October 2022, designed to test the production outcomes, fallow efficiencies and nutrition impacts of planting wheat and chickpeas together at the same time either in alternate rows or mixed together in the same row. Soil cores were sampled in:

- May/June 2020 (planting)
- November 2020 (start of fallow)
- June 2021 (planting and end of fallow)
- November 2021 (after harvest).

The main companion cropping experiment was planted/harvested in 2020 but a cover crop of wheat was planted in the following year across all original plots to assess the yield impacts of the preceding companion cropping treatments and the efficiency of the intermediate fallow period on both stored water and soil nitrates. The mean data from the wheat monocrop and chickpea monocrop treatments is presented here.

The Mungbean Agronomy project's two experiments were conducted in the 2019-20 and 2020-2021 summer seasons, testing mungbean yield response to banded nitrogen fertiliser application (from 30 to 150 kg N/ha). The treatments were applied directly after wheat harvest in late October of the previous year and were left fallow until mungbean planting in February.

Two additional treatments in the second experiment explored the impact of a much longer (8 versus 3 months) fallow on the soil nitrate profile. These long fallow treatments had no wheat planted in the previous winter. Soil cores were taken at the start and end of each of these fallow periods to assess both soil water and soil nitrate accumulation.

While these experiments were primarily designed to test for nitrogen fixation levels in the crop when planted on increasing levels of soil nitrate, some interesting data has been extracted showing the change in soil nitrate levels down the profile over different fallow periods and N application rates.

The data from both projects shows some contrast in the level of nitrates extracted from the profile between a shallow rooted crop (mungbeans) and deeper more robust root systems (such as chickpea and wheat).

Key criteria for soil nitrate uptake in-crop

There are many examples of the relationship between soil water and soil nitrates in the literature and this is underpinned by the concept that the mechanism of nitrate uptake in the plant is through mass flow. Nitrate is a mobile compound that dissolves in water and consequently is moved by water. As the plant root absorbs water it also absorbs nitrate in whatever concentration that nitrate happens to be in the soil water at the time. As the plant root depletes the water immediately around itself more water moves into that zone from the surrounding bulk soil. In clay soils there is a particularly strong concentration gradient that underpins the capillary action so the plant can effectively draw water from a relatively large soil area and with this comes dissolved nitrates.

This means that the efficiency of water uptake by the plant is intrinsically linked to the efficiency of nitrate uptake. There are modifying factors to this concept in relation to root mass and root depth as well as whether the plant is a legume and can derive some of its N from the atmosphere through rhizobial N fixation.

The first companion cropping experiment conducted at the Central Queensland Smart Cropping Centre in 2021 and 2022 illustrates this point well when examining the soil profiles in the wheat and chickpea. Analysis of soil cores taken at planting and harvest show the levels of plant available water (PAW) and nitrate down the profile during the 2021 and 2022 winter seasons (Figures 1 and 2). These profiles were tested in increments of 0–10 cm, 10–30 cm, 30–60 cm, 60–90 cm and 90–120 cm.

Several points that can be highlighted from this data. Firstly, both crops extracted water down to 60 cm very efficiently with less than 8 mm of plant available water capacity (PAWC) left after harvest (Figure 1 and 2). Extraction from the 60–90 cm layer was also significant for both crops but wheat had a much higher extraction rate in the 90–120 cm layer (Figures 1 and 2).

Similarly, the nitrate extraction rate follows a similar pattern with less than 5 kg N/ha remaining in the top 60cm of the soil profile for both crops. The extraction of soil nitrates by layer can be converted into a percentage of the total nitrates that existed at planting (Figure 3). This calculated data can be used

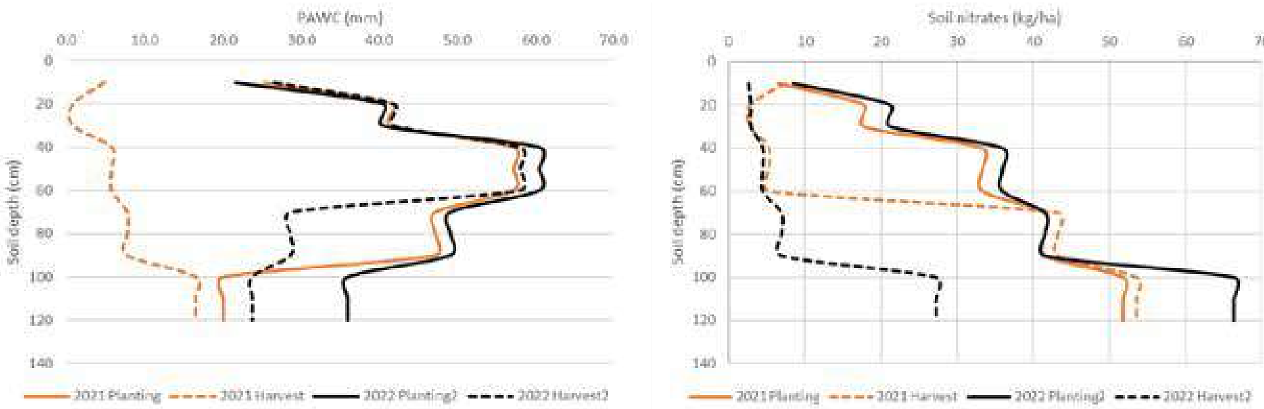


Figure 1. Mean soil water (left) and soil nitrate (right) of the 2021 chickpea and the following wheat crop in 2022 at planting and harvest.

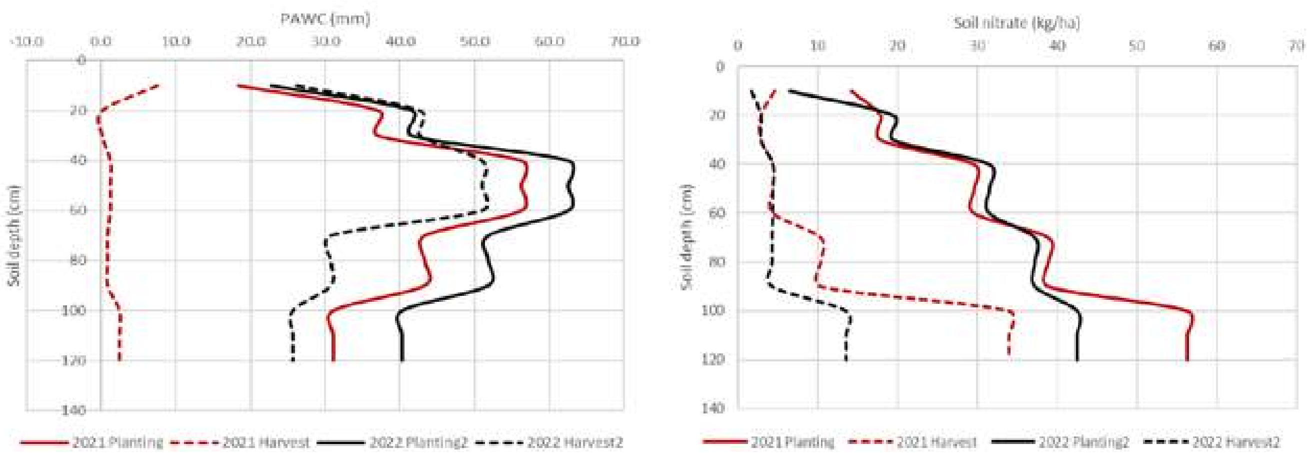


Figure 2. Mean soil water (left) and soil nitrate (right) of the 2021 wheat plots and the following wheat cover crop in 2022 for planting and harvest.

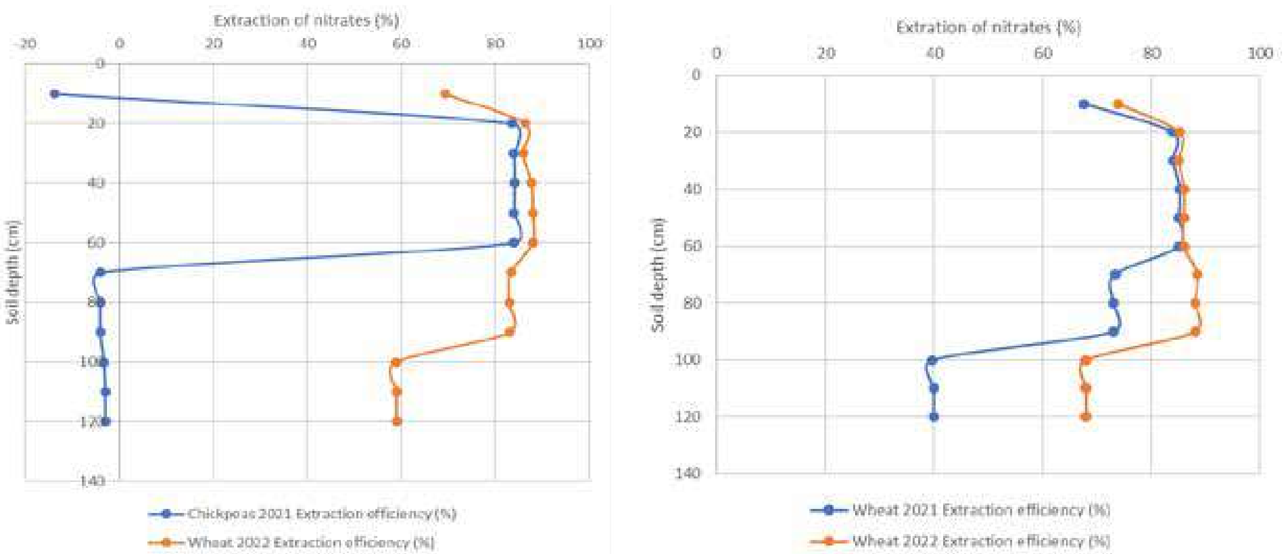


Figure 3. Soil nitrate extraction efficiency from soil profile presented as a percentage of the total soil nitrates present at planting for both the chickpea (left) and wheat (right) in 2021 and the following wheat cover crop in 2022.

as an indicator of the efficiency of soil extraction for each profile layer. The extraction rate from the top 60 cm of the profile was consistently 80-85% regardless of crop type (Figure 3).

The top 10 cm layer had a variable extraction rate; from a negative extraction level (nitrates increased) up to 65%. This is not surprising given the many environmental variables that can impact the surface soil (evaporation and rainfall). Nitrate extraction from the deeper layers (60-90 cm and 90-120 cm) was also quite variable, depending on crop type, with efficiency ranging from negative single digits (chickpeas) to over 80% (wheat; Figure 3).

It is clear from the nitrate extraction data (Figure 3) across four separate crops that the 10–60 cm zone is the most efficient supplier of nitrates to the plant with extraction of over 80% of the nitrates contained in this layer. This conclusion is supported by data collected from the mungbean N response trial in the summer of 2020-21.

Soil cores were taken in June 2020 (in fallow) and remeasured when planting mungbeans in February 2021. This data subset compares three treatments:

1. LF0N – long fallow with no N.
2. LF60N – long fallow with 60 kg N/ha.
3. SF0N – short fallow with no N.

Treatments were assessed in the first week of November 2020 (after a cover crop of wheat was harvested) and then again at planting of the mungbean crop in February 2021.

There were three distinct levels of nitrate supply in the data from the mungbean N response trial (Figure 4). Both long fallow treatments (LF0N, LF60N) accumulated their highest N level in the 30-60 cm zone after 8 months of fallow and 381 mm of rainfall, while the short fallow treatment's N distribution incrementally increased with depth, with the largest amount of nitrate being accumulated at the deepest layer.

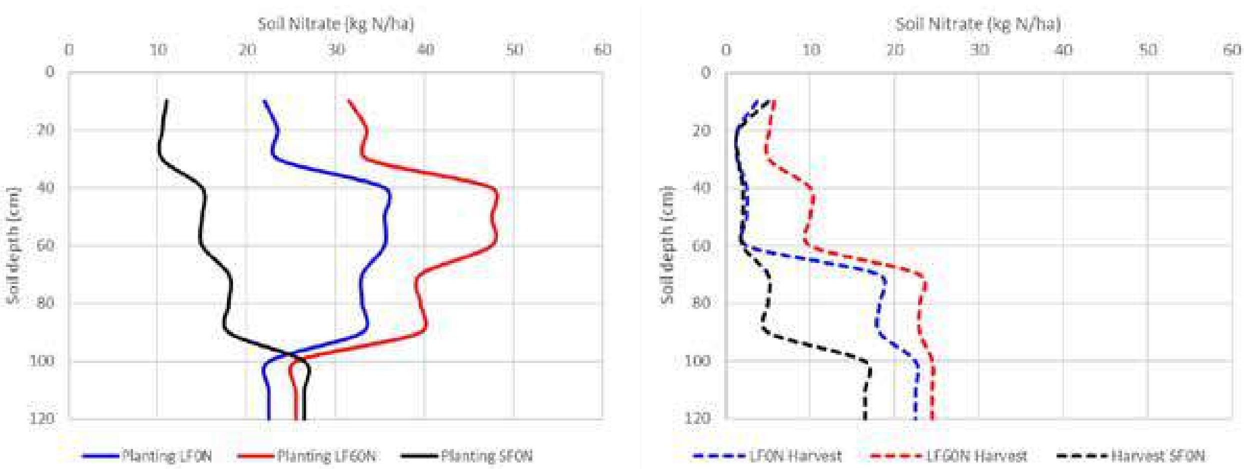


Figure 4. Nitrate levels measured at planting (left) and after harvest (right) of mungbeans grown in 2020-2021. This is a comparison between short and long fallows without N applied and a long fallow treatment with N applied.

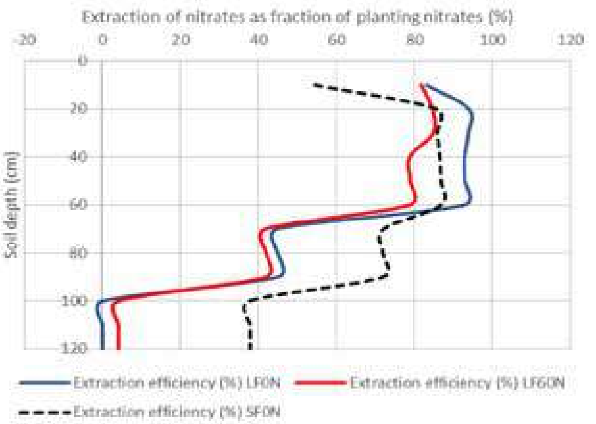


Figure 5. Comparison of the nitrate extraction efficiency of mungbean planted into short and long fallow treatments in the 2020-2021 mungbean N response trial by soil layer.

At the time of planting, the top 60 cm of the profile contained 37 kg N/ha in the SF0N treatment, 81 kg N/ha in the LF0N treatment and 113 kg N/ha in the LF60N treatment (Figure 4).

Overall, the long fallow treatments accumulated far more nitrate in the profile than the short fallow treatments (as would be expected from a longer period of mineralisation). The addition of 60 kg N/ha at the start of the LF60N treatment made the biggest difference in the amount of nitrate accumulated in the 30-60 cm layer, although most layers down to 90 cm benefited from the applied fertiliser compared to the long fallow treatment without any fertiliser applied (LF0N).

The soil core measurements taken at harvest showed the top 60 cm of the profile was again the key area of draw-down for soil nitrates by the crop in all three treatments (Figure 4). Calculations of extraction efficiency by soil layer (Figure 5) reinforce this with the 10-60 cm zone showing 80-90% reduction in soil nitrates (compared to planting levels).

At the deeper soil layers the long fallow treatments had a similar pattern of extraction by layer with ~45% in the 60-90 cm zone and almost nothing from the 90-120 cm layer (Figure 5). Comparatively, the short fallow treatment showed ~70% extraction from the 60-90 cm layer and ~40% extraction from the 90-120 cm layer (Figure 5). All treatments were part of the same trial and had similar grain yields (±10%; data not shown). It is unclear why the short fallow treatment had more nitrate extraction from the deeper layers than the long fallow treatments, as it was expected that the plant would fix its own N if soil extraction became too difficult.

It is useful to compare the amount of soil nitrate in the plant biomass against the amount of soil nitrate that was extracted from the top 60 cm of the profile (Table 1). The change (Δ) in soil nitrate levels in the top 60 cm from planting to harvest showed a big difference between the long and short fallow distributions (Table 1) and consequently there was a large difference in the amount of soil nitrate that ended up in plant biomass.

The crop grown on the long fallow treatment had almost double the crop biomass N compared to the short fallow, which equates to 80-90% of the nitrate extracted from the top 60 cm of the soil profile. This would suggest that the key to getting more N into the crop is to have more nitrate in the top 60 cm of the soil profile. While these numbers were generated from a shallow rooted mungbean crop, chickpeas and wheat have also shown the same efficiency levels for nitrates existing in the 10-60 cm layer of the profile (Figure 3).

The N fixation levels for these treatments (Ndfa%; data not shown) measured by the natural abundance method were: 45% (SF0N), 10% (LF0N), and 4% (LF60N). The short fallow treatment fixing the most N from the atmosphere may have been a result of having less access to nitrates in the top half of the profile as the long fallow treatments did.

The mungbean, wheat and chickpea data complements previous sorghum research in Queensland and northern NSW suggesting that 70-80% of total nitrate uptake is through soil nitrate pools existing in the top 60 cm (Figure 6) in unfertilised crops (Bell et al. 2016).

It makes sense that a long-term management program for N nutrition would be built around

Table 1. Summary data of key nitrate measurements in the mungbean N response trial fallow treatments, including nitrogen in the total crop biomass.

Treatment	Fallow length (days)	Fallow mineralised N (kg/ha)	Δ soil profile N (plant to harvest) kg N/ha	Total N in biomass*	Δ soil nitrates in top 60 cm (plant to harvest) kg N/ha	Contribution of top 60 cm of profile N to crop N uptake (%)
Short fallow + 0N	94	25	-51	52	- 28	54
Long fallow + 0N	259	51	- 88	91	- 73	80
Long fallow + 60N	259	92	- 109	99	- 92	93

* The total N in biomass figures do not include the Ndfa that was measured in this biomass from natural abundance assessment of 15N.

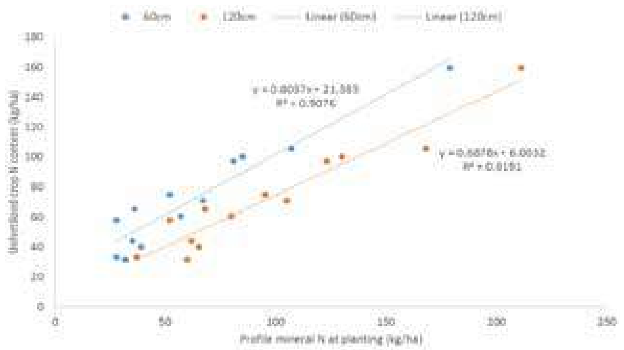


Figure 6. Mean data from a range of Queensland sorghum x nitrogen experiments where the points represent the amount of profile mineral N at planting in the unfertilized control treatments and their relationship to total N in biomass. Blue dots represent the top 60 cm profile and the orange dots represent the 120 cm profile.
Source: Bell M et al, (2016) Summer grains conference.

maintaining adequate nitrate in the 10-60 cm zone as there is good evidence that most crops can access nitrates in this part of the profile with a high degree of efficiency. The next step is to understand how the application rate, timing and placement of N-based fertilisers relates to maintaining this 'N bank' in the 10-60 cm soil profile.

Delivery of N into key zones

Most of the N applied in our current farming system is applied either on the surface of the soil or banded in the top 10 cm. This N is reliant (once it is in the nitrate or plant-available form) on water movement that can be enhanced by a strong soil moisture gradient between wet soil and dry soil (otherwise known as a wetting front). There is strong evidence that the first significant rainfall event after harvest promotes the deepest wetted front, although this is dependent on the amount of rainfall. The capillary action apparent in most cracking clay soils will continually move water into dry soil until an equilibrium occurs between wet and dry soil. When rain falls on already wet soil the pressure gradient is not as strong, the movement of water through the profile is slower and the N does not move as far.

Decisions regarding N fertiliser application need to consider how long it will take for the nitrate to move through the profile and redistribute in the key zone of root uptake (10-60 cm). Data from the chickpea and wheat treatments in the 2021 companion trials (Figure 7 and 8) show the level of replenishment that occurred down the profile over the eight-

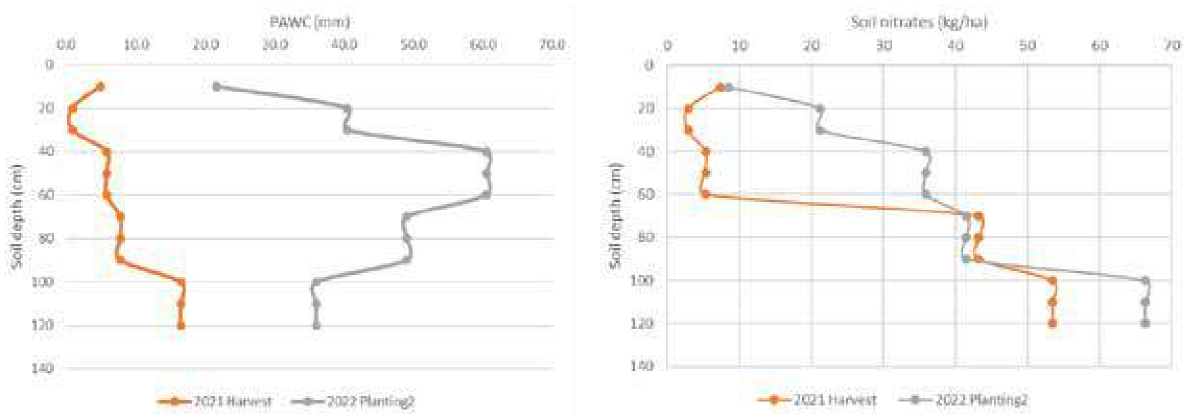


Figure 7. Mean PAWC and soil nitrates at chickpea harvest 2021 and wheat planting in 2022. Profile measurements are taken at 0-10, 10-30, 30-60, 60-90 and 90-120 cm increments.

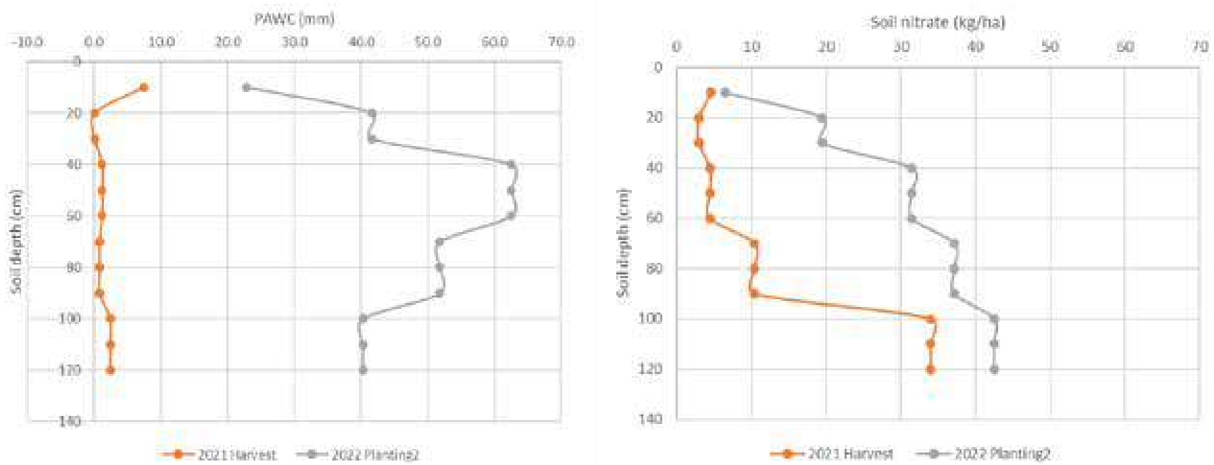


Figure 8. Mean PAWC and soil nitrates at wheat harvest 2021 and wheat planting in 2022. Profile measurements are taken at 0-10, 10-30, 30-60, 60-90 and 90-120 cm increments.

Table 2. Proportional distribution of nitrates down the soil profile after eight month fallow following wheat and chickpea crops. These levels are derived from organic matter mineralisation with no N fertiliser applied.

Depth layer (cm)	Soil nitrate expressed as a % of total profile nitrates	
	Wheat, end of fallow	Chickpea, end of fallow
0–10	5	5
10–30	14	12
30–60	23	21
60–90	27	24
90–120	31	38

month fallow (between harvest in 2021 and planting the wheat cover crop in 2022). This fallow period had 625 mm of rainfall over the summer period and no additional N was applied.

The chickpeas increased PAWC by 171 mm (total 207 mm) and the wheat by 207 mm (total 218 mm). Based on the total PAWC numbers, both treatments had a full profile when planting the 2022 wheat cover crop. Over the same fallow period nitrate levels increased by 61 kg N/ha in the chickpeas and 81 kg N/ha in the wheat. It is assumed that this came from the mineralisation of organic matter since no fertiliser was added to these plots. The nitrate distribution down the profile (Figures 7 and 8) shows that the amount held within each measured layer does not necessarily reflect the PAWC pattern.

The PAWC data (Figures 7 and 8) predictably show peak water holding capacity in the 30–60 cm zone in both the wheat and chickpea plots (28% and 26% of the total profile respectively). The nitrate distribution shows nitrates accumulating down the profile with the highest levels of nitrate within 90–120 cm (Table 2).

From this data there is no way of knowing the proportion of nitrate that has moved with a wetted front (redistributed) down the profile versus nitrate that has been mineralised in-situ in the different layers (Table 2). It is assumed that most of the mineralisation occurs in the surface soil (0–10 cm) where crop residues are being broken down and in the 10–30 cm zone where the largest root mass will also be broken down.

The distribution of N in the profile shows that the 0–10 cm and 10–30 cm zones contain the lowest amount of nitrates (Table 2), therefore it is assumed that much of this mineralised N has been moved down the profile by successive rainfall events. What is not clear is why the nitrates are accumulating in the 90–120 cm zone and not in the 30–60 cm zone where the highest water holding capacity is (Figures 7 and 8).

Further data on the redistribution of soil nitrates in the profile comes from N response trials in mungbeans carried out in 2019–20 and 2020–21. The 2020–21 trial data (Figure 9) shows the comparison between long fallow and short fallow distribution of nitrates at the start of each respective fallow period and at planting. It also shows the comparison between long fallow with and without additional N fertiliser.

The pattern of nitrate distribution through the profile at the start of the fallow period and when the crop was planted shows the long fallow (8 month) treatments accumulated more nitrate in the 30–60 cm zone than the short (3 month) fallow treatment (Figure 9). The distribution of nitrates at the start of the long fallow period was very similar to the pattern of distribution at planting.

The short fallow treatment had accumulated more N in the 30–60 cm layer than the other layers but not to the same concentration as the long fallow

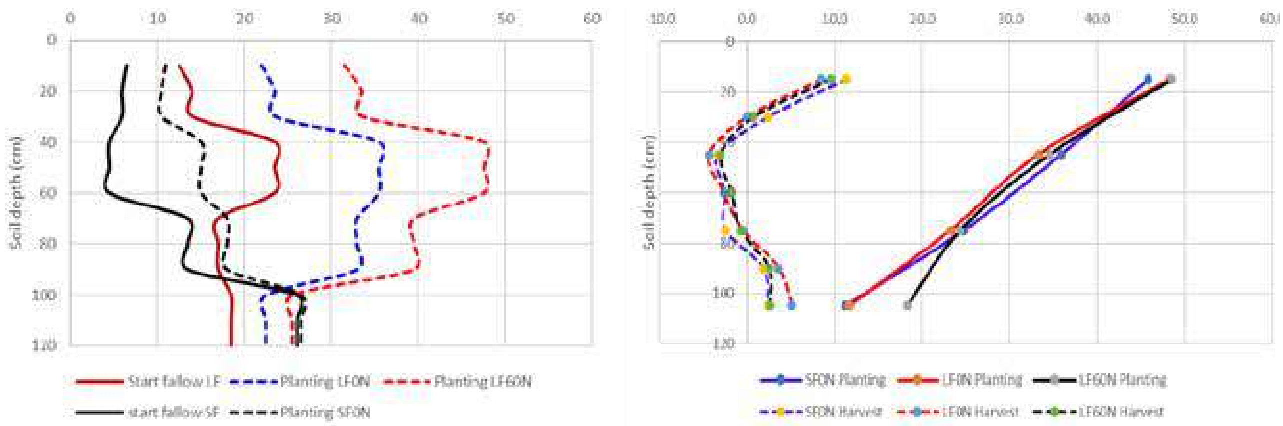


Figure 9. Mean nitrate distribution (left) between the start of fallow and planting for the short and long fallow treatments in the 2020-2021 mungbean N response trial. PAWC distribution (right) at planting and harvest for the short and long fallow treatments in the 2020-2021 mungbean N response trial.

Table 3. Summary of key nitrate measurements for selected treatments in 2019-2020 mungbean N response trial.

Treatment	Start of fallow N (kg/ha)	Applied N (kg/ha)	Planting N (kg/ha)	Δ soil N over fallow (kg/ha)	Difference to 0N control (kg/ha)
0N control	41	0	109	68	0
60N	41	60	160	119	51
150N	41	150	284	243	175

treatments. It is notable that the nitrates in the 90-120 cm layer had hardly moved in both short and long fallow treatments. PAWC data (Figure 9) for these treatments shows almost no wetting of the 90-120 cm layer, meaning there were few opportunities for the nitrate to be moved by water into this zone.

A surprising factor in the data presented in Figure 9 is that 381 mm of rainfall fell in the long fallow period while the short fallow treatment had 240 mm of rainfall (both fallows also received 100 mm of irrigation in the summer period). Yet these rainfall totals made little difference in the starting water profile (116 mm compared with 125 mm) of the two fallow periods. All three treatments had similar PAWC at planting (Figure 9) and those profiles were only ~65% full, explaining why the lower layers had not wet up properly.

Despite there being little difference in the PAWC between the long fallow and short fallow treatments, the distribution of nitrates in the profile benefited from a longer period of fallow with more rainfall events (8 events SF, 14 events LF) and this contributed to the movement of nitrates down the profile. The addition of 60 kg N/ha in the long fallow treatment increased the concentration of nitrates down the profile under these fallow conditions.

A useful comparison to this 2020-21 data is the N response in a mungbean experiment conducted the previous summer, where all treatments were applied after a wheat harvest at the end of October 2019. Several rates of N were applied to the surface on the 25 November 2019 and the treatments were fallowed through to planting on 14 February 2020 (81 days). This site received no rainfall to mid-December, so a 100 mm irrigation was applied on the 16 December 2019. After Christmas there was 303 mm of rainfall in 7 events prior to planting mungbeans.

Soil cores samples were taken after wheat harvest but before N application and then again at planting. There were three treatments:

1. 0N control (no N applied)
2. 60N (60 kg N/ha applied)
3. 150N (150 kg N/ha applied).

Under short fallow conditions over summer, the profile mineralised 68 kg N/ha with no added fertiliser, which is relatively high compared with published data (Cox H, 2009). The fertiliser treatments added 51 kg N/ha (60N) and 175 kg N/ha (150N), aligning well with the application rates (Table 3).

The distribution of these nitrates down the profile shows a very similar pattern for each treatment with the 30-60 cm layer accumulating the largest amount of nitrate and the 90-120 cm layer not changing at all (Figure 10). The PAWC data shows

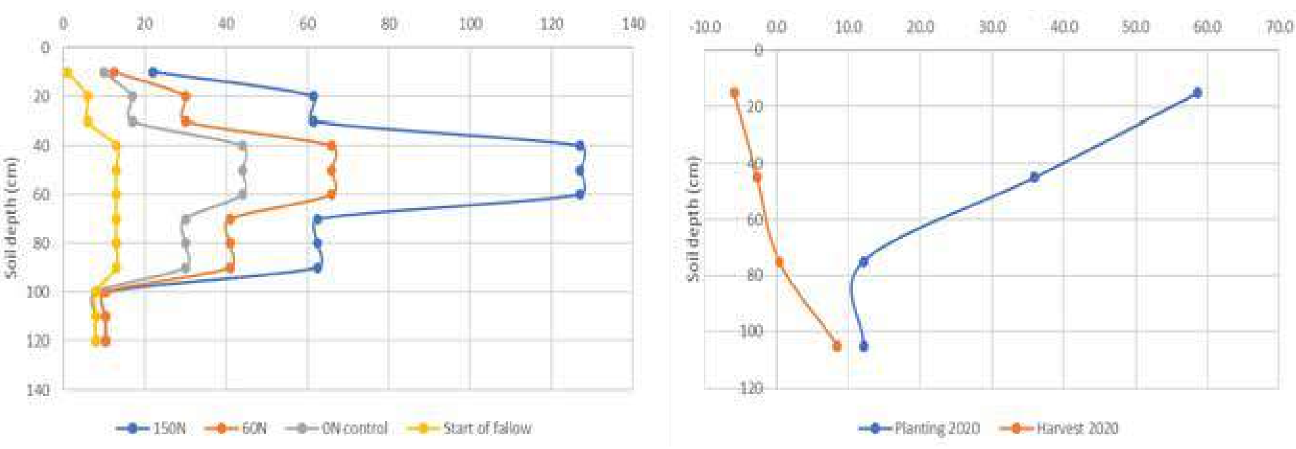


Figure 10. Mean distribution of soil nitrates (left) by soil layer under three N application treatments during an 81-day fallow over the summer period (2019-2020). PAWC distribution (right) by soil layer at planting and harvest in the 2019–2020 summer mungbean crop.

that very little soil water accumulated in the 90-120 cm layer by planting time, which would explain why the nitrate levels did not change. The PAWC data also suggests that the soil profile was not full at planting time with PAWC values averaging 119 mm (not shown) which is about 65% of a full profile for this soil type.

The nitrate distribution in the profile (Figure 10) indicates rainfall had a key impact on depth of N and the rate of applied N had the biggest impact on the concentration in each soil layer. Where there was no N applied, the soil nitrate level was more dependent on mineralisation from organic matter, which is a slow-release process and can only happen when there is adequate soil moisture. Hence when rainfall occurs there were only small amounts of nitrate being released and thus available to move with a wetted front.

When N is applied to the surface soil a high concentration of nitrate forms in the surface layer and each successive rainfall event can move a larger concentration of nitrate down the profile. Sufficient rainfall events can ensure that there is adequate nitrate available in the key zone for plant uptake.

Length of fallow may not be as critical to maintaining nitrate fertility in the most accessible zones of the soil profile as the rate of application and the intensity of rainfall events. The two N response mungbean experiments conducted over a two-year period showed that adequate levels of nitrate were distributed through the profile under a short fallow scenario when adequate rainfall or irrigation occurred after application.

In the 2019-20 experiment the 60N treatment accumulated an additional 38 kg N/ha in the top 60 cm above the natural mineralisation rate during a fallow period of 81 days. In the 2020-21 trial the 60N treatment in a long fallow situation accumulated an additional 32 kg N/ha in the top 60 cm above the natural mineralisation rate during a fallow period of 259 days. While these data sets come from differing seasons, they indicate that the length of fallow is not critical to getting soil nitrates distributed into the key uptake zones.

Implications for growers

The two concepts that should underpin any nitrogen fertiliser program is that maximum efficiency of plant uptake of nitrates occurs in the 10-60 cm zone of the soil profile and that movement of nitrates down the profile is governed by both rainfall and application rate. In farming systems where in-crop rainfall is limited or sporadic at best, then nitrates that are stored in the 10-60 cm zone are going to deliver the most consistent nitrate supply.

Data presented in this paper has shown that regardless of crop type (cereal or legume) the nitrates in the top 60 cm are always drawn down to low levels (<5 kg N/ha). This means that there needs to be a consistency of supply of fertiliser N at the surface layer to ensure the best chance of being distributed with the rainfall during the fallow

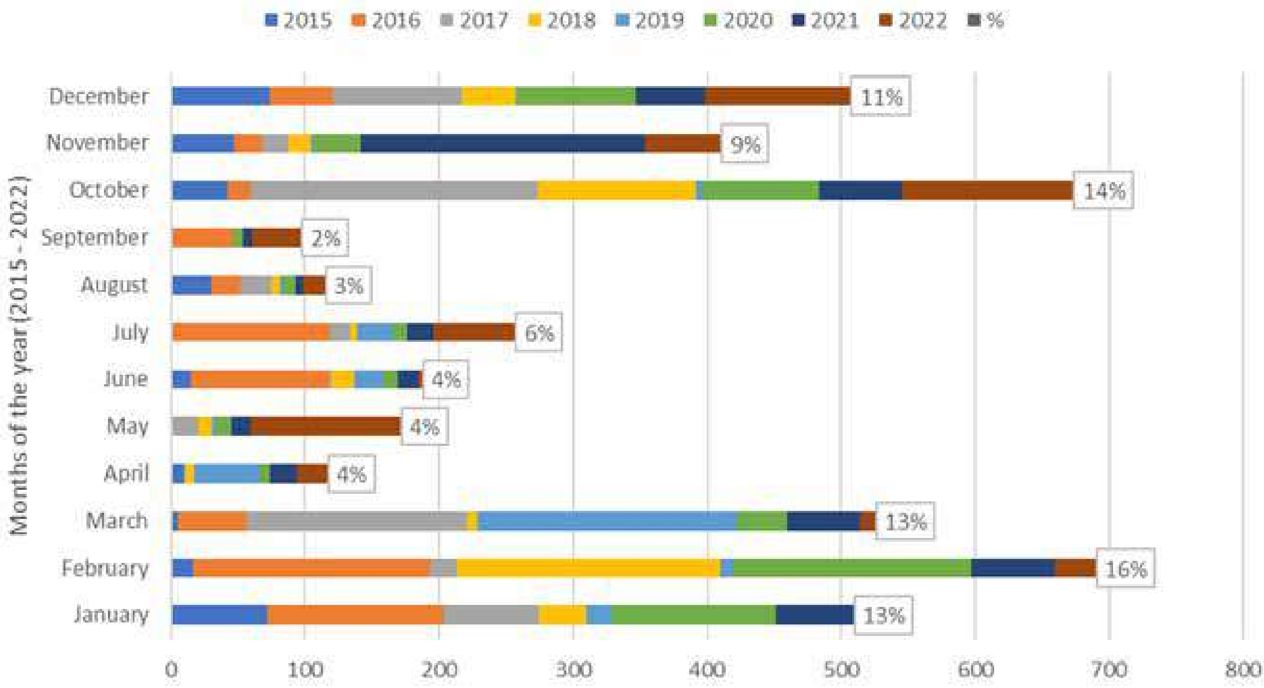


Figure 11. Monthly rainfall totals accumulated over the last seven years (2015–2022) at the CQSCC weather station. These accumulated monthly totals are presented as a proportion of the total rainfall that has occurred in this seven-year period (%).

period. These fallow rainfall events will eventually ensure enough PAWC for the next crop. Applying N fertiliser before the fallow rainfall will ensure that the N fertiliser is not stranded in the surface profile (0-10 cm) for a long period of time and has the greatest chance to be redistributed before the next crop.

In a CQ dryland crop system the most reliable rainfall period is summer and more particularly the months of January, February and March (Figure 11). To continually maintain a 'bank' of nitrate in the most accessible part of the profile (10-60 cm), then this rainfall period needs to be utilised as much as possible.

Data presented in this article suggests that a short fallow over the summer period is all that is required to redistribute the surface applied N throughout the top 60 cm of the profile provided that enough rainfall is received during the summer months. Included are examples where the redistribution of soil nitrate was adequate in the 10-60 cm zone with only enough rainfall to fill the profile to two thirds full, while the 90-120 cm layer remained dry.

One of the limitations to the scope of this data is that in nearly all the examples given, the N fertiliser was applied to very dry soil profiles where PAWC was below crop lower limits. It is expected that this provides the best rate of nitrate distribution compared to situations where N fertiliser is applied after significant rainfall events have changed fallow conditions.

For CQ growers, the most effective N management strategy is to apply N fertiliser prior to the wettest three months of the year, and this should be done every year, regardless of crop type (legume, cereal or oilseed). This will maintain a continual supply into the 10-60 cm soil zone which in turn promotes the highest efficiency of uptake for the following crop.

References

Bell MJ, Lester DW, Sands DN, Graham R, Rowlings D and Grace P (2016). Recovery of soil and fertiliser N in sorghum. 3rd Australian Summer Grains Conference. Gold Coast, Australia.

Cox H (2009) The Nitrogen Book – Principles of soil nitrogen fertility management in Central Queensland farming systems. Queensland Government publishing, Brisbane. www.publications.qld.gov.au/dataset/the-nitrogen-books/resource/1a11d889-e77f-4d13-8f5e-0eab129b9809

Acknowledgements

The experiments in this article were conducted at the Central Queensland Smart Cropping Centre. The research undertaken was made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, the author would like to thank them for their continued support.

The author also thanks the research teams's technical officers who worked diligently on these projects.

This article has been adapted From a GRDC paper originally published in November 2023 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/11/distribution-of-nitrates-and-its-effect-on-plant-uptake-efficiency-in-central-queensland-farming-systems

Soil health stocktake—Queensland

Jayne Gentry, Henry Baskerville, David Lester, Doug Sands and David Lawrence
Queensland Department of Primary Industries

***Research question**: What is the soil health status of Queensland cropping paddocks based on indicators of their physical, chemical and biological properties?*

Key findings

1. **The total organic carbon average across all locations was 1.21% (0–10 cm) and 0.89% (10–30 cm).**
2. **Out of 270 paddocks, 155 (57%) recorded low levels of phosphorus, indicating a potential response to the application of deep phosphorus.**
3. **Out of 270 paddocks, 95 (35%) recorded low levels of potassium, indicating a potential response to the application of deep potassium.**

Background

Soil health can be defined as 'the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans' (USDA nd). Soil health is complex as it is driven by physical, chemical and biological properties, processes and their interactions with farming practices. Hence, soil health and the impacts of management on it are best considered holistically.

Reduced soil organic matter and soil fertility where native vegetation has been removed are key indicators of soil health decline in Australia. This decline is most significant on soils that are under long-term cultivation (Dalal & Mayer 1986) and is becoming a major constraint to the productivity and sustainability of Australian farms.

Soil sampling is one way of investigating soil properties. This is often conducted by an agronomist who provides a recommendation to the grower that outlines the required fertiliser application for the subsequent crop. Without an understanding of the soil analysis and/or its connection to soil health, growers cannot make informed management decisions. Consequently, the *Healthier soils through better soil testing* project was funded in February 2022 by the Queensland Department of Primary Industries and the Australian Government's National Landcare Program to improve management of soil health.

What was done

Delivered across 2022–2024, the project had three main activities: soil testing, action learning workshops and participatory action (on-farm) research. This article covers the soil testing results.

The key functions of soil health and the indicators assessed were:

1. The soil's ability to maintain soil organic matter (measured by soil organic carbon).
2. The soil's ability to supply nutrients for plant growth (measured by available nitrogen, phosphorus and potassium).
3. Good soil structure (measured by dispersion and exchangeable sodium percentage).
4. Freedom from toxicities (measured by salinity and chlorides).
5. Freedom from pathogens (measured by Predicta®B).
6. Levels of arbuscular mycorrhizal fungi (AMF) (measured Predicta®B).

Ninety cropping properties were identified by the project team across southern and central Queensland. Three paddocks on each of these properties (a total of 270 paddocks) were sampled (Figure 1). The three paddocks were identified via a one-on-one semi-structured interviews with the growers (and their agronomists where appropriate). These interviews also allowed targeted soil sampling to investigate grower-specific questions and so maximise their learning. Paddocks compared the impact of different scenarios such as differences in management practices, soil type, or length of cultivation on soil properties.

The project team conducted soil sampling with rigorous protocols to ensure scientific integrity of the data. Where possible soil sampling was done with the grower in their own paddocks, so they could see and feel their own soil beyond the surface.

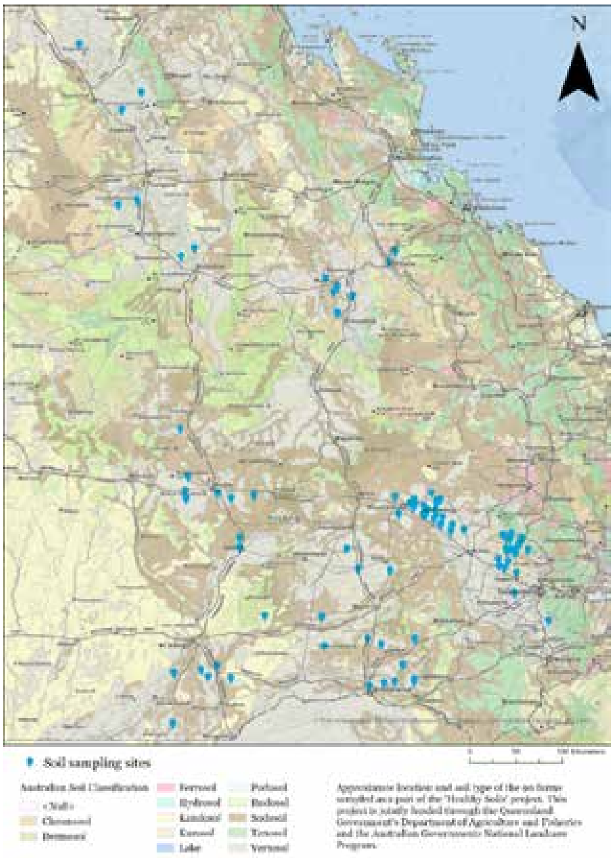


Figure 1. Map of participating properties.

Six cores were taken from each paddock and segmented into 0-10, 10-30, 30-60, 60-90, 90-120 (if possible) cm layers, with each layer from the six cores bulked. The 0–10 cm and 10–30 cm layers were analysed for pH (H_2O), pH ($CaCl_2$), total organic carbon (method 6B1 – Heanes wet oxidation), electrical conductivity, chloride, nitrate nitrogen (N), ammonium N, dispersion, exchangeable cations, total N, Colwell phosphorus, phosphorus buffering index and BSES phosphorus. The 30-60, 60-90, 90-120 cm layers were analysed for pH (H_2O), pH ($CaCl_2$), electrical conductivity, chloride, nitrate nitrogen (N), ammonium N, dispersion and exchangeable cations. A further sample (0–15 cm) from each paddock was analysed using Predicta®B DNA-based soil testing service.

Results

The data collected from this activity provided a comprehensive benchmark of soil physical, chemical and biological properties of Queensland cropping paddocks. Several key insights could be made from the cumulative data.

1. **Total organic carbon** (TOC) levels varied across geographical locations. The western locations recorded lower TOC. Within the 0-10 cm layer, the lowest TOC (0.37%) was recorded at St George, and the highest (4.44%) at Toowoomba. The average across all locations was 1.21% in the 0–10 cm layer and 0.89% in the 10–30 cm layer (Figure 2).
2. **Plant available nitrogen** (kg/ha) (measured as nitrate N and calculated using a bulk density of 1.3) indicated that 204 of the 270 paddocks (76%) had less than 100 kg N/ha in the 0–90 cm part of the soil profile that grain crops typically access, and 143 paddocks (53%) had very low levels (50 kg N/ha or less). This is important because ~45 kg N/ha is required to grow 1 t wheat/ha at 13% protein, and many of the growers were targeting 2-3 t/ha.
3. **Colwell phosphorus** levels (considered to indicate plant-available phosphorus) were lowest in the Goondiwindi, Roma and St George regions and highest in the Toowoomba and Banana regions (Figure 3).
4. **BSES phosphorus** levels (considered to indicate P reserves that slowly become

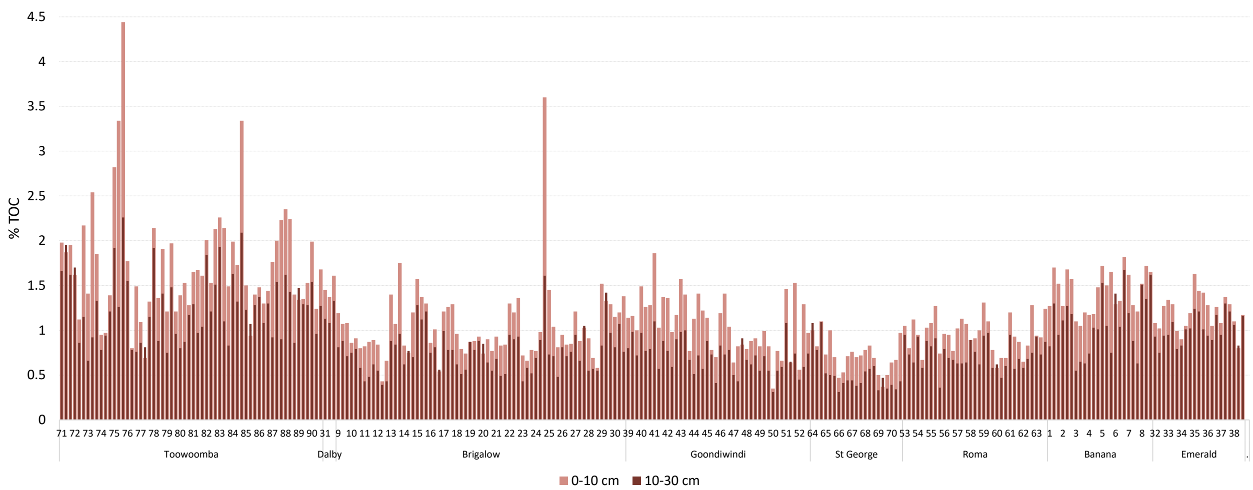


Figure 2. Total organic carbon (%): 0–10 cm and 10-30 cm for each paddock (listed 1–270) by location.

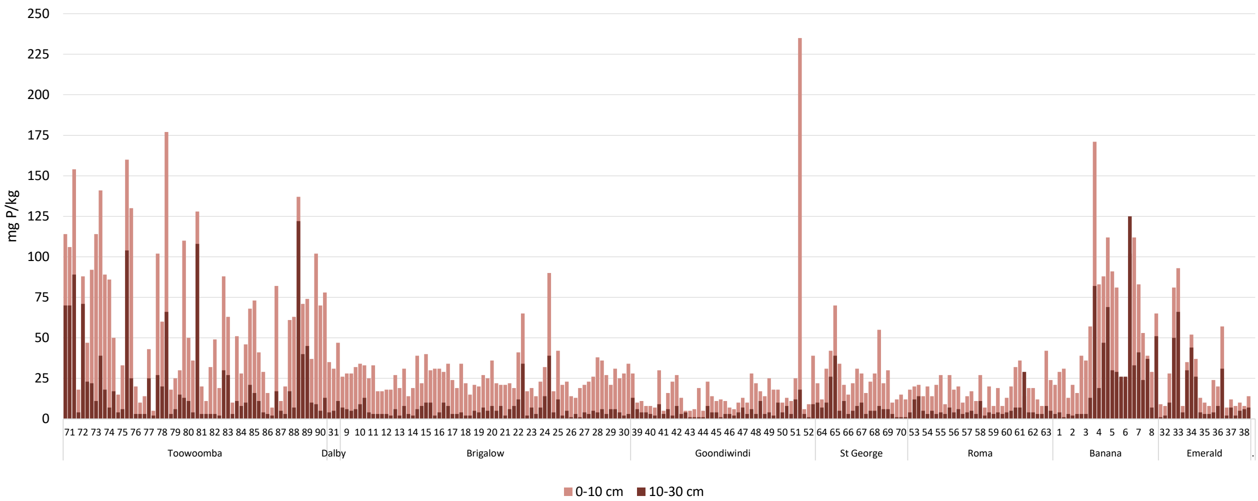


Figure 3. Colwell phosphorus (mg/kg): 0–10 cm and 10-30 cm for each paddock (listed 1–270) by location.

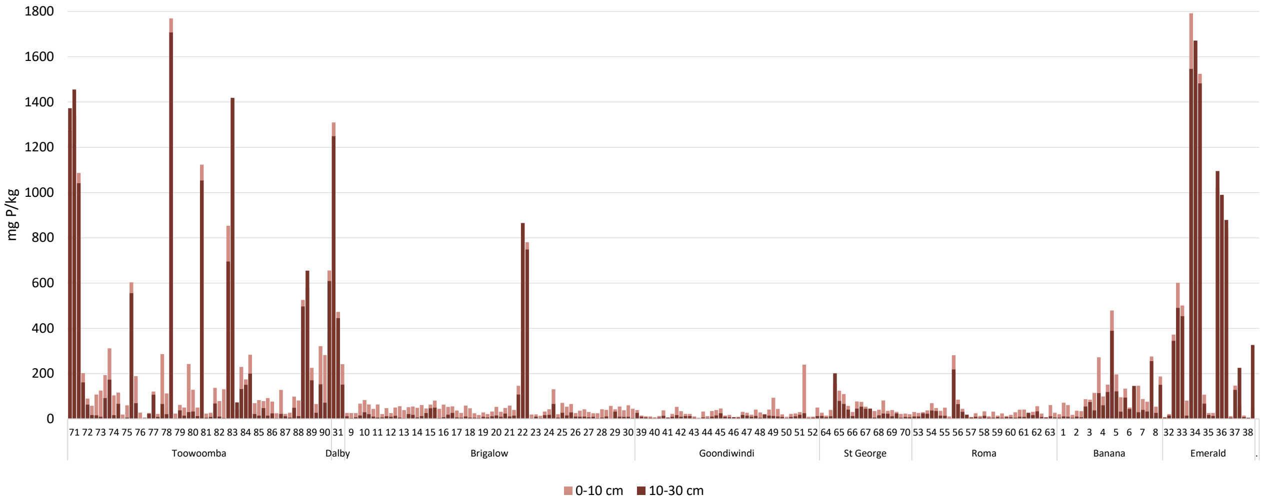


Figure 4. BSES phosphorus (mg/kg): 0–10 cm and 10-30 cm for each paddock (listed 1–270) by location.

available) were low (below 50 mg P/kg in the 10-30 cm layer) in 206 paddocks with the lowest levels detected in the Brigalow, Goondiwindi, St George and Roma regions (Figure 4). The lowest result was 5 mg P/kg in the 0–10 cm layer and <1 mg P/kg in the 10–30 cm layer. These extremely low levels would be severely limiting plant growth. Responses to the application of deep P are likely if levels in the 10–30 cm layer are 7 mg Colwell P/kg and below, and 50 mg BSES P/kg and below (Bell 2023). Of the 270 paddocks tested, 155 paddocks (57%) fell into this category.

5. **Potassium** (measured as exchangeable potassium) was consistently low in the Brigalow region and in some of the soils in the Goondiwindi region (Figure 5). Responses to the application of deep K are likely if levels in the 10–30 cm layer are 0.2 cmol K/kg and below for <10 cmol/kg cation exchange capacity (CEC), 0.25 cmol K/kg and below for CEC 10–30 cmol/kg and 0.35 cmol K/kg and below for >30 cmol/kg (Bell 2023). Of the 270 paddocks tested, 95 paddocks (35%) fell into this category (35%).
6. **Salinity** (measured as electrical conductivity dS/m) increased down the profile, often with moderate levels of salinity seen below 30 cm. Some very high levels (1.5+ ds/M) were detected in the Roma region and to a lesser extent in the St George and Banana regions (data not shown). These very high levels would be limiting plant growth.
7. **Chloride** levels were generally low for most paddocks, with levels increasing further down the profile. However, there were paddocks with chlorides above 300 mg/kg below 30 cm in the Goondiwindi, St George, Roma and Banana regions (data not shown), which is considered to impair root growth of intolerant crops.

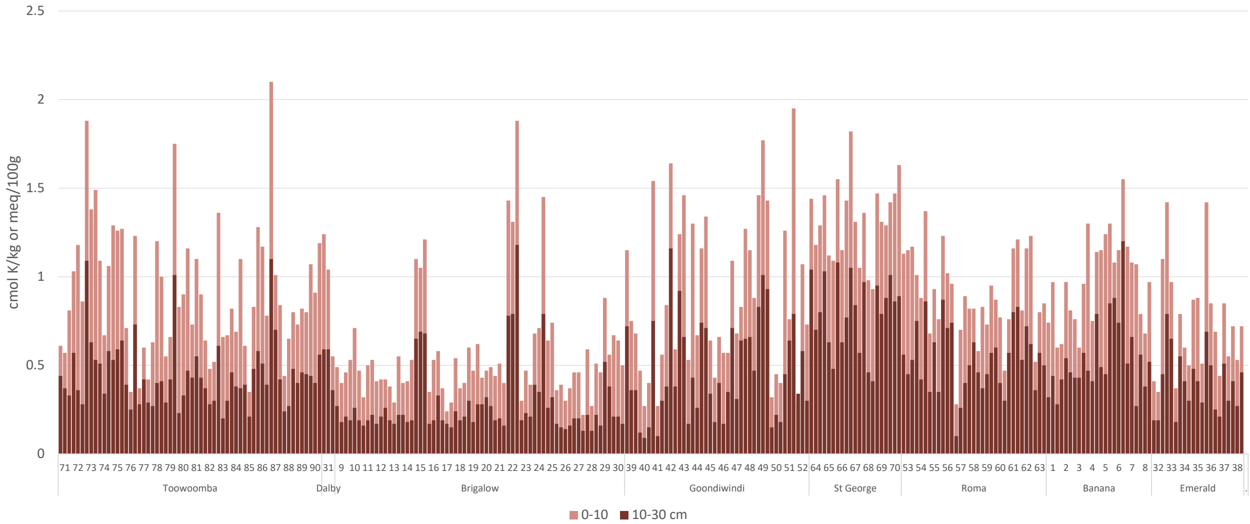


Figure 5. Exchangeable potassium (cmol K/kg): 0–10 cm and 10-30 cm for each paddock (listed 1 – 270) by location.

8. **Sodicity** was detected in many of the paddocks (measured as exchangeable sodium percentage (ESP)), with levels increasing down the soil profile. Sodicity is assumed when ESP in the surface (0-20 cm) is greater than 6%, with ESP >15% indicating a strongly sodic soil (levels over 20% below 20 cm can cause severe problems). Sodic soils cause dispersion, limiting a plant's ability to extract water. The Goondiwindi, St George and Brigalow regions had the highest ESPs.
9. **Soil physical characteristics**. The Emerson dispersion method showed poor structured (dispersive) soils occurred at varying rates across all geographical regions. St. George, Goondiwindi and Brigalow had high rates of dispersive soil (58%, 54%, and 49% respectively) while Emerald was dominated by non-dispersive soils (94%) (data not shown). Dispersion was detected at different locations within the soil profile. As dispersion limits root growth, it is important to identify where it is occurring in the profile to help understand the rooting depth of crops and from where soil water and nutrients can be accessed.
10. **Soil biological data** (measured via Predicta®B analysis, data not shown) indicated the most common pathogens to be crown rot, common root rot, white grain disorder, take-all, pythium root rot and charcoal rot. Arbuscular mycorrhizal fungi (AMF) varied greatly across paddocks with <1 kcopies DNA/g soil being detected in five paddocks through to the highest reading of 634 kcopies DNA/g soil.

One grower (Brigalow) was interested in comparing their long-term cropping soil (50+ years) to bordering remnant vegetation to understand the change in soil health over time. Some very interesting results were seen:

- Total organic carbon: 0–10 cm was 0.77% in the cropping versus 3.6% in the remnant vegetation, indicating a loss of ~3% TOC.
- Phosphorus: Colwell P levels decreased under cropping from 90 mg to 23 mg P/kg in the 0-10 cm layer and from 39 to 7 mg P/ha

Soil sampling.

Sampling remnant vegetation - Brigalow.

in the 10–30 cm layer. The BSES P similarly declined from 131 to 33 mg P/kg 0-10 cm and from 66 to 16 mg P/kg 10-30 cm.

- Chloride: levels massively decreased under cropping, from 1674 mg/kg under remnant vegetation in the 30–60 cm layer down to 13 mg/kg after 50+ years cropping.

Implications for growers

Comprehensive soil testing and analysis is a useful tool to determine soil health. It is important to take deep cores and analyse them incrementally in line with dryland cropping critical levels. However, once a paddock has been tested and analysed, changes other than nitrogen and soil biology will be slow. Future testing may only be worthwhile every five to 10 years. Additionally, by comparing paddocks and considering their differences, a deeper understanding of how soil health is affected can be gained.

Total organic carbon levels are quite low in Queensland cropping soils. This data set confirms past research findings that levels decrease under cropping. These lower levels reduce the overall resilience of soils, particularly the amount of nitrogen and phosphorus that can be mineralised and become available to support crop growth.

This means that higher levels of fertiliser are required to continue to maximise crop production. To maintain carbon levels growers need to boost biomass production, i.e. grow the biggest crops as often as possible. This can be achieved by implementing the best possible agronomy.

A large proportion of soils have low levels of immobile nutrients, such as P and K, that may be impacting crop production. Continuing to remove P and K from subsoil (i.e. 10-30 cm) without replacement will exacerbate this situation. Growers should consider replacing P & K in this subsoil when levels drop below critical levels.

Past research shows that applying deep P fertiliser can be highly profitable in depleted soils, although responses can vary. Further research is underway to assess the risk/reward trade-off with farm data. Potassium on the other hand is a different story. There has been very little research focused on potassium to accurately determine critical levels and develop clear recommendations to rectify deficiencies. More research is required. Current recommendations suggest applying test strips to identify responses.

Acknowledgements

The research presented within this paper would not have been possible without the support of growers and agronomists and investment from the Australian Government Landcare Fund and the Queensland Department of Primary Industries.

This soil sampling was undertaken during the extraordinarily wet winter of 2022. It was all-hands -on-deck from the research team to take advantage of the very small windows of 'dry weather' to take these soil cores. But the whole team's perseverance and never-say-die attitude paid off. Not only did we get VERY good at taking soil cores from wet soil we have produced an exceptional dataset of grain cropping soils in Queensland.

References

Bell, M (2023). Fertiliser deep banding. Grains Research and Development Corporation.

USDA. (n.d.). Soil health. Natural Resources Conservation Service. www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health

The impacts of cropping on soil organic matter and carbon: Data from 10 years of grains research in Queensland

David Lawrence[1], Michael Bell[2] and Jayne Gentry[1]

[1] Queensland Department of Primary Industries
[2] University of Queensland

Research questions:

How do soil organic matter and carbon levels change when land is developed for cropping?
What is the value of soil organic matter and carbon for grain production in Queensland?
What practices best protect and improve soil organic matter and carbon levels?

Key findings

1. Grain production can reduce the original soil organic matter levels by up to 70%.
2. Soil organic matter is ~60% carbon. The rest includes nutrients that have far more value than soil carbon itself.
3. Land use changes, such as clearing land for cropping or returning land to pastures, have much larger impacts on soil organic matter levels than in-crop agronomy.
4. Modern farming practices that maximise dry matter production such as improved water-use-efficiency, additional crops, higher yields, pasture rotations and not burning or baling, are key to maximising soil organic matter in cropping situations.
5. Well-grown pastures can make major improvements in old croplands. Soil organic carbon levels under pastures can be up to 1.0 t/ha/year higher than with continued cropping.

Background

Soil organic matter is critical for healthy soils and sustainable agricultural production. This is not 'news' to growers, agronomists, or indeed anyone with a vegetable garden or compost heap at home. We all know that healthy soils with high organic matter levels grow better crops that are easier to manage. However, we also know that soil organic matter (SOM) and soil organic carbon (SOC) levels are declining, meaning continued grain production and healthy crops are needing more fertiliser, especially nitrogen (N).

To make sensible decisions on how best to manage SOM and SOC on-farm, we need to understand how SOM and SOC work, why their levels are declining, the implications for enduring profitability, and what we can realistically do to combat the decline.

Soil organic carbon – an indicator of soil organic matter

SOM is what's important to agricultural production. However, SOC is a reliable indicator (~60% of organic matter) that we can measure, meaning a soil with 1.0% SOC has ~1.7% organic matter by weight. Over time SOC has become a key indicator of soil health, the sustainability of long-term crop production, and the need for nutrient input to maintain productivity.

Forms and dynamics of soil organic matter and carbon

SOM is 'everything in the soil that is of biological origin, whether it's alive or dead'. It includes live plant roots and litter (not shoots), humus, charcoal, and other recalcitrant charcoal-like residues of organic matter decomposition. It also includes organisms that live in the soil (collectively called the soil biota), such as centipedes, ants, earthworms, mites, fungi and bacteria). One thing all these materials and organisms have in common is that they all contain carbon.

The measured SOC is derived from decomposing plant material as the soil biota feed on it for energy and nutrients. Soil biota populations wax and wane with the supply of their preferred foods and predation by other organisms. Similarly, the amount and age of the different SOC 'fractions' will fluctuate in response to the quality and quantity of inputs (i.e. residue type and frequency of addition) and the influence of moisture and temperature on the decomposing organisms (Figure 1).

Microbial respiration during decomposition releases carbon dioxide, or methane in anaerobic conditions, and any nutrients surplus to the biota's needs are released (mineralised) in inorganic forms for use by other microbes and plants.

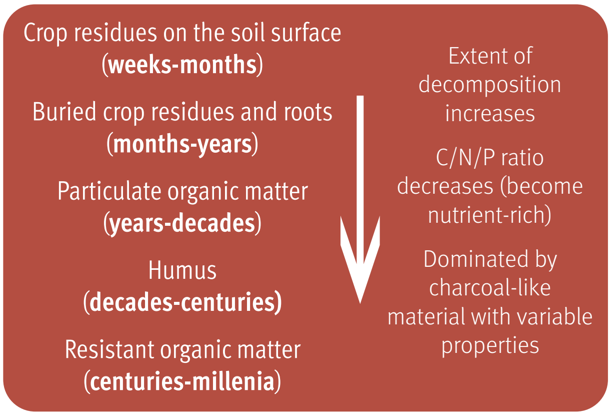


Figure 1. Forms of soil organic matter and carbon and their indicative 'half-life' in the soil that indicates how long formation of the next 'fraction' takes.

However, soils are often nutrient-poor environments so as organic materials age and decompose in the soil, generally more carbon is released as CO_2 than surplus nutrients. For example, fungi need a C:N ratio of ~8:1 (8 C atoms for every N atom) available to grow more hyphal threads, but can digest poor quality crop residue with C:N ratios up to ~100:1. In this scenario, surplus C is respired while the N is conserved, and the soil organic material becomes increasingly nutrient-rich as it ages.

Microbes generally need a C:N ratio of ~25:1. Legume residues can have lower C:N ratios and may release excess N into the soil when they decompose, while cereal stubble have very high C:N ratios and will immobilise available N from the soil as they decompose. The humus that eventually forms from decomposition of these crop residues will have C:N ratios of approximately 12:1. After many cycles of digestion and excretion, these humic materials are less readily decomposed than the initial plant residues, but the nutrients they contain ensure that they remain a valuable contribution to soil fertility.

Benefits of soil organic matter

While SOM contains ~60% organic carbon, it is the decomposition of organic matter with its associated materials that drives most physical, chemical, and biological soil processes, supplying a range of nutrients needed by both plants and soil biota. Organic matter helps major soil functions:

1. **Physically** by improving structure, infiltration, and water holding capacity,
2. **Chemically** by improving nutrient supplies and buffering pH; and
3. **Biologically** by maintaining a food supply for microbes and the microbial activity that supplies available nutrients for plants and competes with soil-borne pathogens.

The impact of these functions varies with soil type, and the forms or fractions of SOC that we measure. The width of the lines in Figure 2 represents the impact of soil carbon on that function, and the colour represents the fraction of the carbon that provides that function in the soil. For example, the relative contribution of organic matter/carbon to cation exchange capacity (CEC) and water holding capacity is large on sandy soils but small on heavy clays that already have high CECs and water holding capacities. On all soil types the bulk of nutrients come from the humus fraction, while the particulate fraction provides much of the energy for microbial activity.

What is the value of SOM to grain growers?

For many of these soil functions, the economic value is hard to quantify, yet it's clearly higher than the value of soil carbon alone. For example, each tonne of SOC is associated with ~100 kg organic N, so when the SOC levels in the 0-10 cm layer of a brigalow/belah soil decline by 1% (10-13 t/ha), it

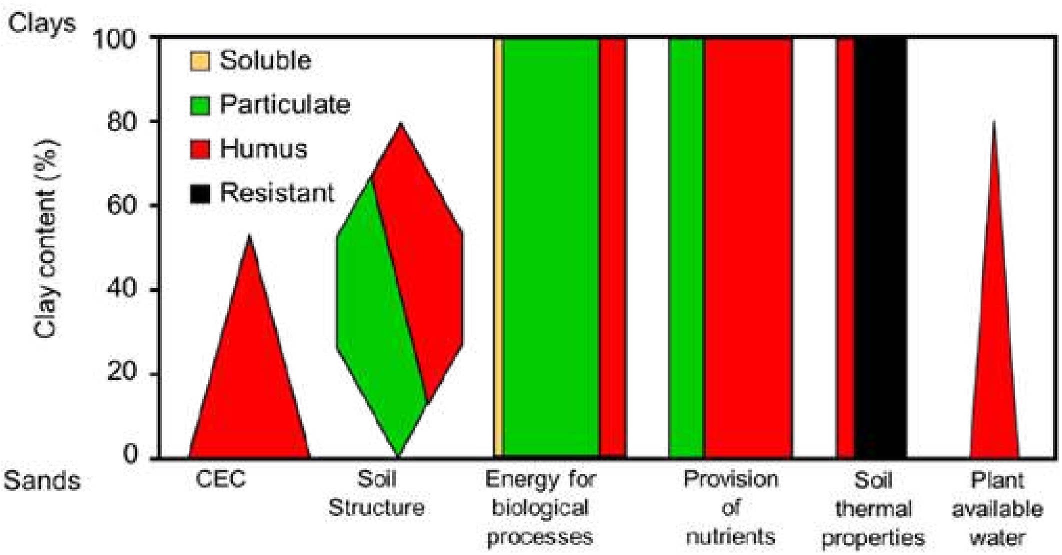


Figure 2. Soil organic carbon fractions and clay content impact on soil function (Hoyle, 2014).

means up to $1,500/ha of N has been released for use by crops over time (based on the long-term urea cost of $550/t at 46% N). For all nutrients, including phosphorus and sulfur, this figure may be as high as $2,000/ha using long-term prices. Using 2022 urea prices of $1,300/t, the decline in SOM's nutrient capital climbs to $3,500/ha for N alone and >$4,000 /ha for all nutrients with each 1% decline in SOC in the top 10 cm.

These nutrients were not wasted. Decomposing SOM reserves enabled cropping for 30+ years with little or no fertiliser, but fertiliser use is now increasing as the supply of N and other nutrients from SOM decline, along with soil mineral reserves of phosphorus and potassium. Profitability will clearly change as fertiliser costs increase to supply more nutrients in older degraded cropping soils.

What was done

Natural soil organic matter levels vary with each location's soil type, rainfall and vegetation. The SOC level for each farming system is a result of the balance between inputs (e.g. plant residues, other organic inputs) and losses (e.g. erosion, decomposition, harvested material) (Figure 3).

A series of 500 paired-site comparisons were taken from 2008 to 2017 to assess the impact of land-use and farming practices on SOC levels across the northern grain region.

Soil organic carbon under remnant vegetation

Total organic carbon (TOC) in the top 10 cm of the soil under remnant vegetation varied from 0.7 at Walgett to 3.8-5.0% on brigalow soils at Condamine and Central Queensland (Figures 4 and 5). Critical levels for each soil/location are not defined because the varied functions of organic matter are difficult to match with crop productivity. Basically, more organic matter is better.

Declines in soil organic carbon under long-term cropping

There was a consistent decline in SOC associated with land clearing and cultivation across all soil types (Figure 5a). Total organic carbon declines

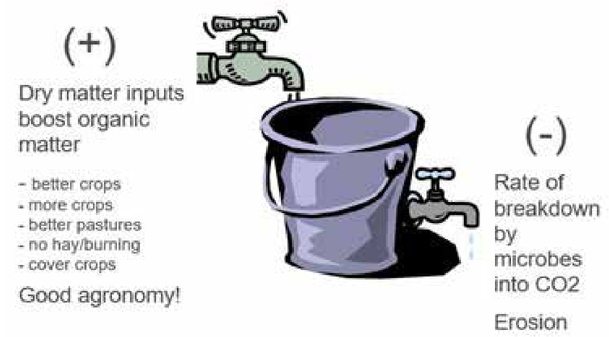


Figure 3. Soil organic carbon levels: a balance between dry matter (organic) inputs, losses and decomposition.

varied with location but were most dramatic on the highly fertile brigalow soils. For example, the Central Queensland brigalow soils had naturally higher levels of SOC than the open downs soils (Figure 5b, 5c). They also had higher declines under cropping, but still maintained higher SOC levels than open downs soils after 20+ years of grain production. Over the very long-term (e.g. 100 years) it is expected that these differences in the final 'equilibrium' levels of SOC that could be expected on different soil types will be small.

Declines of 60-70% (i.e. >2-3% TOC) were common and there were similar declines in TOC in the 10-30 cm layers, representing total losses of natural nutrient reserves of up to $5,000-8,000/ha in the top 30 cm using long-term prices. At 2022 prices, this loss of nutrient reserves in the top 0-30 cm would take between $15,000 and $24,000/ha worth of fertilisers to replace.

This decline under cropping is driven by fallowing to store moisture. Unfortunately, fallow efficiencies in the northern grain region are typically between 20-30%, which means 70-80% of fallow rainfall is lost, mostly to evaporation. This rainfall is not transpired by plants to grow dry matter and replenish the organic matter that is continually decomposed by microbes in the moist soil.

Declines under pastures were less dramatic than cropping. Pastures do not have fallows and use most of their rainfall to grow dry matter that's ultimately returned to the soil. However, the total dry matter production under pasture is still typically lower than that of native vegetation.

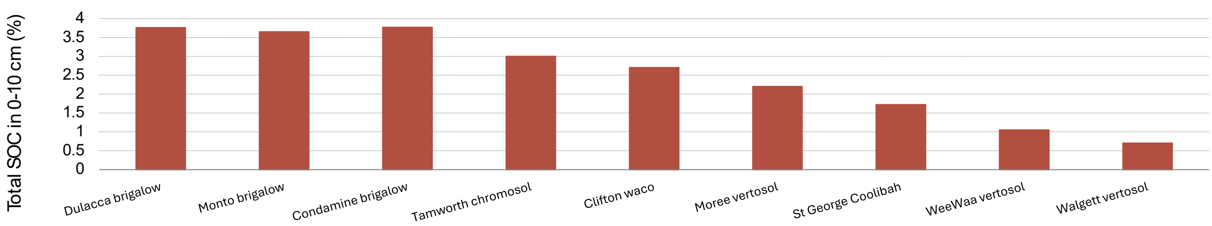


Figure 4. Location and remnant land type on soil organic carbon levels (0-10 cm).

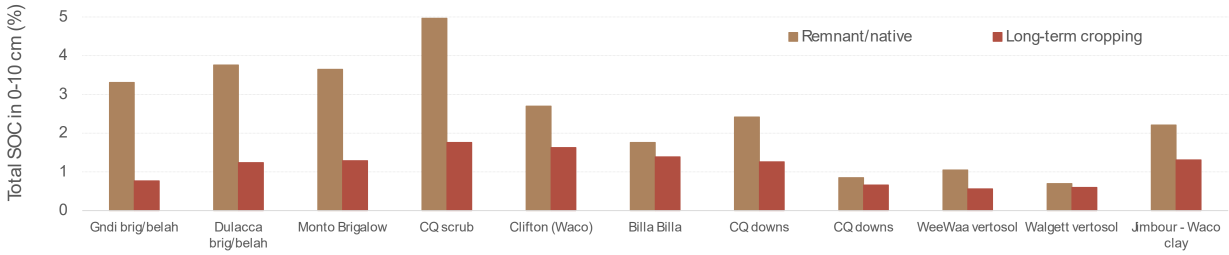


Figure 5a. Long-term cropping (20+ years) impacts on soil organic carbon levels.

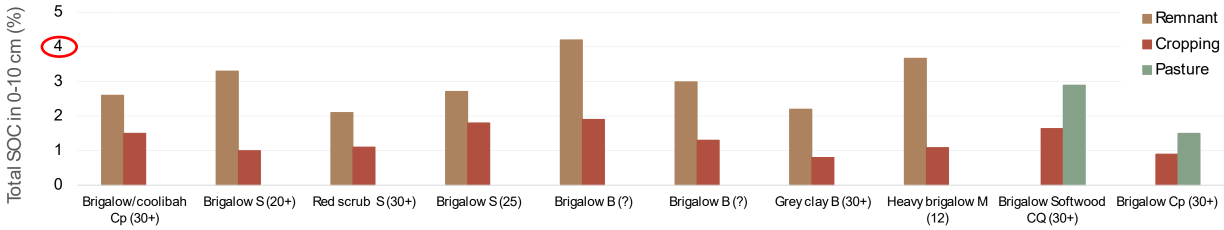


Figure 5b. Long-term cropping (20+ years) impacts on soil organic carbon levels of brigalow soils in Central Queensland.

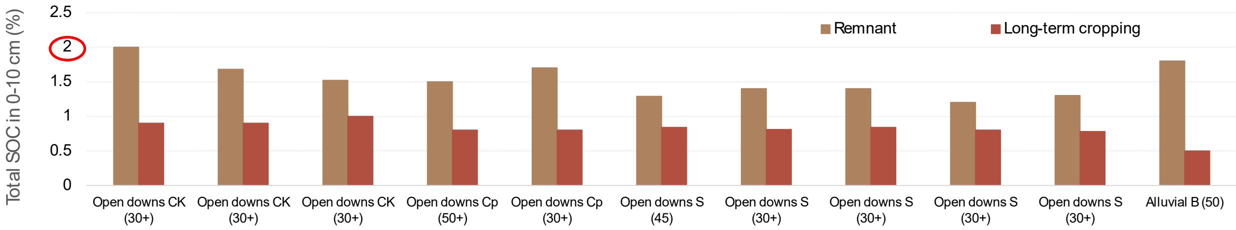


Figure 5c. Long-term cropping (20+ years) impacts on soil organic carbon levels of open downs soils in Central Queensland.

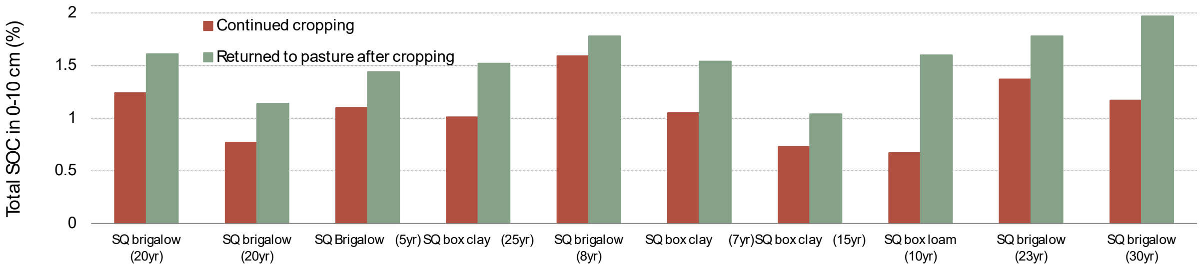


Figure 6a. Total organic carbon comparisons for croplands resown to pasture (Western Downs).

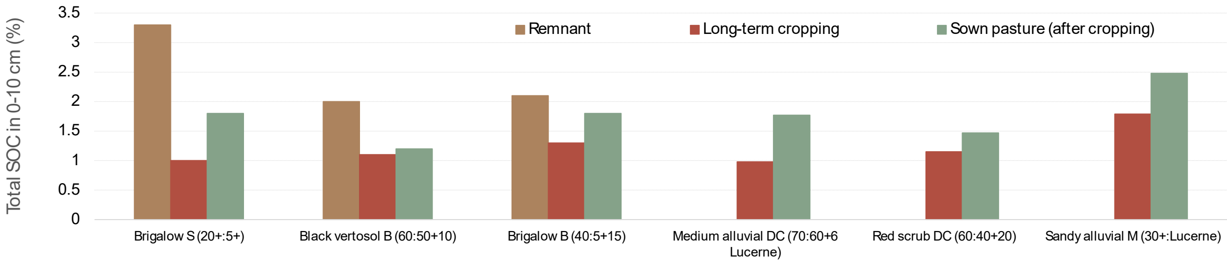


Figure 6b. Total organic carbon comparisons for croplands resown to pasture (Central Queensland).

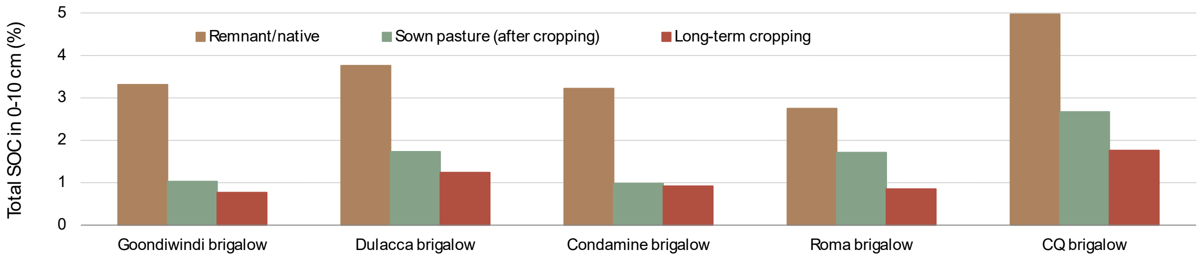


Figure 7. Three-way comparisons of the soil organic carbon under remnant vegetation, ongoing cropping versus cropland that had been resown to pastures.

Rebuilding soil organic carbon with pastures

SOC levels were generally lower in paddocks under continuous cropping than those returned to pastures for at least five years (Figure 6a, Figure 6b). The changes in carbon showed that the difference could be at least 1.0 t/ha/year in well-grown pastures (Table 1). Some pastures provided little if any increase in soil carbon stocks after many years. The determining factor appears to be the presence of legumes in the better-performing pastures.

Three-way comparisons between remnant vegetation, long-term cropping and long-term cropping land returned to pasture revealed the variable ability of pastures to build or maintain soil carbon levels (Figure 7 & 6b). Re-investigation of the soil test data suggests the soil carbon level recovery reflects the soils' phosphorus levels and the subsequent legume growth in the pastures (Table 1).

The best performing pasture for rebuilding soil carbon stocks (Roma), had high phosphorus levels and strong legume (medic) growth that could supply an extra 30 kg N/ha/year and produce 900-1200 kg extra dry matter each year for better productivity and higher soil carbon stocks.

In contrast, the pasture that had no impact on soil carbon levels (Condamine), was extremely deficient in phosphorus (3 mg/kg bicarbonate P 0-10 cm) and had no legume growth. This left the pasture with little dry matter production due to extreme N deficiency after a cropping phase. This pasture may never recover without remedial action and the farmer may have low dry matter levels, poor beef production and little increase in soil carbon stocks for the foreseeable future.

Highlighting the importance of soil phosphorus had a major impact on the project participants. It was the catalyst for many of the mixed farmers developing strategies to maintain soil phosphorus levels on their cropping country. This will support bigger and better crops with higher yields and maintain their flexibility to rebuild soil carbon and soil health levels with pastures into the future.

Growers using pasture phases to rebuild their SOM and SOC levels must also consider how long it takes for more stable SOM and SOC (e.g. humus) to develop. The half-life of particulate carbon indicates that humus takes 'years to decades' to form (Figure 1). This means a 5-to-10-year pasture phase will primarily increase the more easily decomposed (labile) particulate carbon and contribute far less to the nutrient-rich humus that had developed under remnant vegetation over centuries. Consequently, the rebuilt SOM and SOC levels will break down much faster when returned to cropping than when the country was initially developed (Figure 8).

Table 1. Examples of the change in carbon stocks when cropland was returned to pastures.

Location	Soil/vegetation	Years in crop	Years in pastures	Carbon stocks (t/ha)	Change in carbon (t/ha/yr)
Samples to 30 cm (0-10 cm + 10-30 cm) using conservative bulk densities of 0-10: 1.25 & 10-30: 1.3					
McCallister	Waco clay	60 50	0 10 (native grass)	44 54	+1
Jandowae	Brigalow clay	40+ (baled) 40+	0 40 (sown grass)	49 63	+0.4
Nindigully	Red box loam	40 30	0 10 (sown grass)	28 31	+0.3
Nindigully	Coolibah clay	25-30 25-30	0 10 (sown grass)	17 21	+0.4
Samples to 10 cm only using conservative bulk densities of 0-10: 1.25					
Warra	Brigalow clay	45 35	0 10 (sown grass/medic)	12 17	+0.5
Glenmorgan	Box wilga loam	25 15	0 10 (sown grass/medic)	8 20	+1.2
Condamine	Brigalow belah clay	40 30	0 10 (sown grass/medic)	15 25	+1
Talwood	Red clay	40 40	0 7 (sown grass/medic)	13 19	+0.9
Talwood	Brigalow clay	15 15	0 3 (sown grass)	14 18	+1.3
Talwood	Grey Clay	25 15	0 10 (sown grass)	9 13	+0.4
Goondiwindi	Brigalow belah clay	30 30	0 20 (sown grass)	16 20	+0.2
Condamine	Belah wilga clay	35 20	0 15 (native grass)	12 12	0

Rebuilding soil organic carbon levels i soils

While mixed farmers may be able to use pasture phases to manage their soil carbon levels, most grain farmers were interested in options for their permanent cropping paddocks.

A range of agronomic practices were assessed for their impacts on SOC in the paired-site comparisons, however these impacts were minor at best and appeared to be overwhelmed by the effect of fallowing.

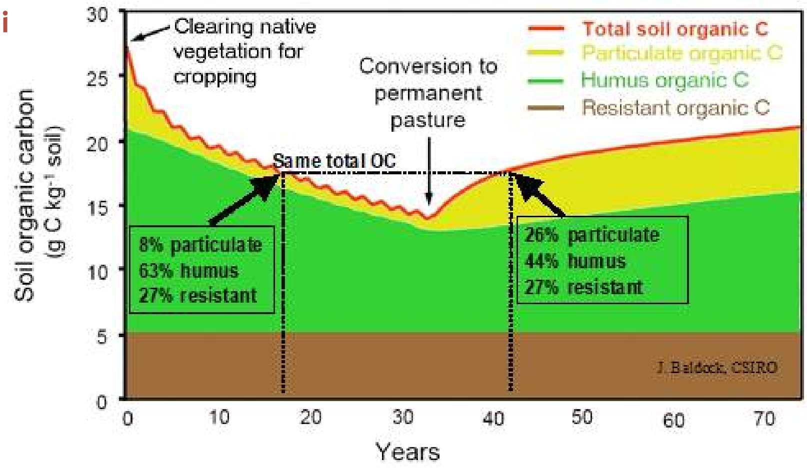


Figure 8. Model of changes in soil organic carbon fractions under cropping and a return to pastures (Hoyle et al. 2011).

The practices assessed included:

- **Crop choice:** Crops with different levels of dry matter (e.g. cotton vs grain) showed only minor differences, reinforcing the overall impact of a prolonged fallow in northern farming systems. This reassured some cotton growers who worried that cotton farming systems were further degrading their soils. Systems with increased use of legumes also had no clear impact on SOC.
- **Forage crops:** Forages have potential to produce more dry matter and maintain higher SOC levels than grain crops (Figure 9). However, these differences were minor at best, perhaps because many forage crops underperform on poorer soils with less management and fertilisers, and stock redistribute some residues via manure around watering points and shade lines.
- **Manures:** It is logical for grain-only producers to think that manures add dry matter and must therefore increase SOC. However, SOC levels showed no real benefit from the relatively low commercially-used rates (typically to supply phosphorus) and

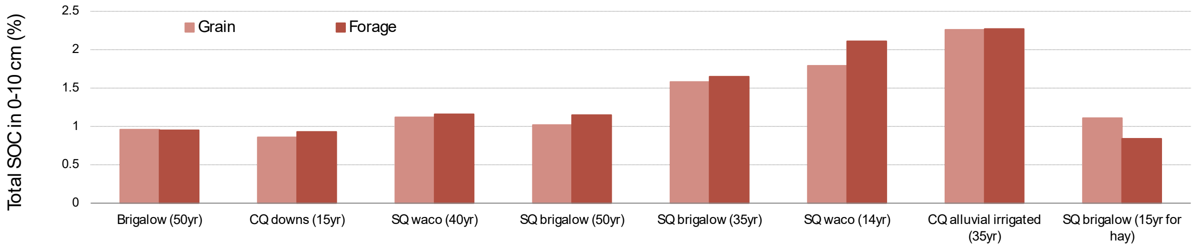


Figure 9. Total organic carbon levels under long-term grain and forage cropping.

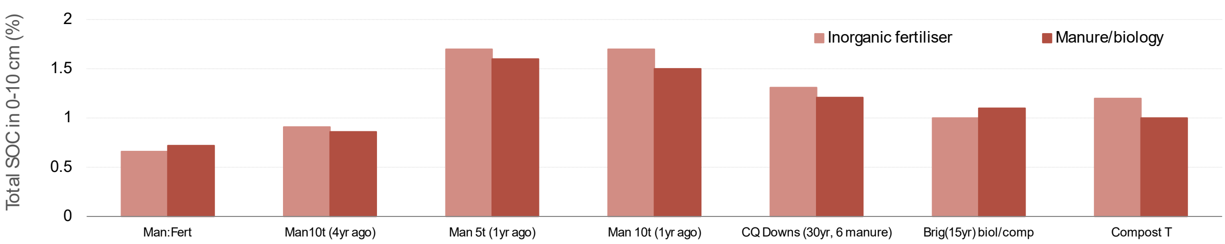


Figure 10. Total organic carbon levels under traditional fertiliser and manure/biology treatments.

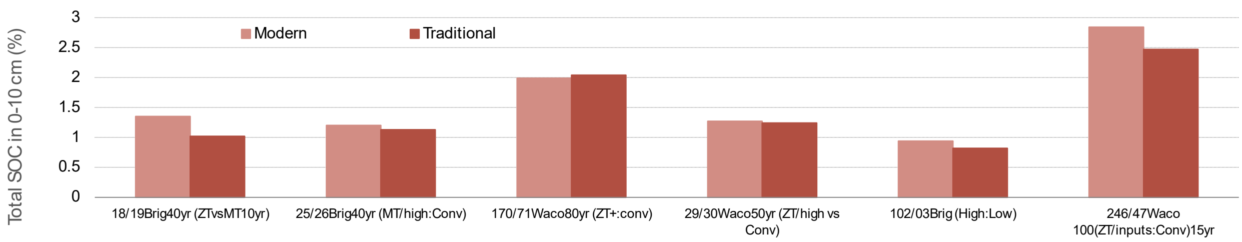


Figure 11. Total organic carbon levels under modern (less tillage, more fertiliser) compared to more traditional systems.

the rapid breakdown of the labile carbon in manures (Figure 10). No comparisons of repeated use of heavy manure rates were available, as farmers with feedlots spread manure on all their cropping paddocks. In some cases, SOC levels actually declined where manures and other biological products were used, perhaps due to people reducing the overall amount of nutrients being added. The key insight was to ensure that crop nutrient needs are met regardless of the inorganic or organic products being used.

- **Farming systems:** Modern farming systems with zero/reduced tillage and high nutrient replacement rates were compared to more traditional management practices. As farmers tend to change tillage practices and nutritional strategies across the whole farm, the project was unable to locate separate comparisons of different tillage practices and of high nutrient applications on paired paddocks. The data suggests potential for a small, if any, impact of modern practices on maintaining SOC levels, which would require further monitoring to confirm (Figure 11). DPI's ongoing research in the Northern Farming Systems project with NSW DPIRD and CSIRO also suggests that modern farming systems that maximise dry matter production by growing as many high-yielding crops as possible can maintain and even increase soil organic matter and carbon.

Implications

Long-term grain production clearly reduces soil organic carbon (and hence organic matter) levels. On well-structured soil this decline and the loss of soil nutrients such as nitrogen may be managed by increased rates of fertiliser. However, management must then be 'spot-on' as soils with lower soil organic matter are less resilient as they are less able to respond to seasonal changes by mineralising more nitrogen in good seasons. The soil will also be more prone to disease, so again, good agronomy and timely management will become increasingly important.

For grain-only producers, strategies to maintain soil organic carbon will need to use the best possible agronomy to grow the best crops that produce as much dry matter as possible, as often as possible; balanced with the need for each crop to be profitable. Cover crops and companion cropping to produce more dry matter with the same rain may also offer some improvements in soil organic matter and carbon.

Mixed farmers with the option to grow pastures have much greater potential to rebuild soil organic matter and carbon levels. The best results for rebuilding soil organic matter and carbon will be from growing the best, most productive, and profitable pastures for livestock.

Positive results will require both a good supply of nitrogen from fertiliser and/or legumes with an adequate phosphorus supply for good legume growth to support high levels of pasture dry matter production.

Ultimately, any practice that increases the return of dry matter from stubble and roots will help maintain, or at the very least, slow the decline of soil organic matter and carbon levels in our cropping lands. This includes using zero/reduced tillage to maximise water capture and grow more crops and higher yielding crops with adequate nutrition to meet their full potential; considering cover crops and companion crops if they can increase dry matter production without compromising grain yields; avoiding burning and baling that removes dry matter and nutrients from the paddock; and using pasture phases where practical.

Introducing the best 'profitable' practices as soon as possible and not waiting until soils suffer major declines will be important for both 'younger' country and following pasture phases to prolong the gains once they have rebuilt SOM and SOC levels.

Ultimately, all grain growers are going to need an informed soil organic matter strategy because it underpins their soil's resilience, nutrient supply, and general soil health.

Acknowledgements

This research was made possible by the significant contributions of collaborating growers and the financial support of the Grains Research and Development Corporation, Land & Water Australia and the Australian Department of Agriculture, Water, and the Environment; the authors would like to thank them for their continued support.

References

Hoyle, F (2014) Managing soil organic matter: A practical guide, Grains Research and Development Corporation. Canberra.

Ameliorating soil constraints with deep ripping, gypsum, and soil organic matter in Queensland

Cameron Silburn[1], David Lester[1], Jack Speedy[1], Richard Flavel[2], Craig Birchall[2], Chris Guppy[2]
[1]Queensland Department of Primary Industries
[2]University of New England

***Research question**: Can soils constrained by sodicity be ameliorated to increase grain yields?*

Key findings

1. **Improved crop nutrition (using phosphorus) has been the main driver to significantly increase grain yield, especially in wetter than average seasons.**
2. **Gypsum treatments are improving yield over time, particularly in drier years.**
3. **Ripping alone has not improved yields and could be detrimental to soil structure and crop yields long term.**

Background

Seventy-five percent of Australian soils have constraints that limit agricultural productivity, such as biological, chemical or a physical features of the soil that restrict root development and limit the crop's ability to utilise stored moisture and nutrients. The Queensland Department of Primary Industries, Grains Research Development Corporation, and the University of New England have been investigating ameliorating soil constraints in the Northern Grains Region to determine if dispersion caused by sodicity, compaction and soil nutrition can be ameliorated by utilising surface and/or subsoil gypsum, lime, organic matter (OM), phosphorus (P) and/or physical interventions (e.g. ripping).

What was done?

Six major trials (core sites) were established in 2019 from Dulacca in southern Queensland to Parkes in New South Wales. This article covers the Queensland sites (Millmerran, Dulacca and Talwood) up to 2023 (representing 12 cropping years). Trials were established on growers' properties in 75 m^2 plots with four replicates. Growers managed the treatments as part of their normal operations using commercial equipment. Various measurements were taken including yield, biomass, soil water and soil mineral nitrogen.

The results from an additional network of large-scale on-farm research (OFR) strip trials using commercial equipment are also reported here.

This 'proof-of-concept' research (at rates considerably higher than those likely to be economically viable) focused on ameliorating soil constraints, specifically reducing dispersion caused by sodium in the upper 50 cm and reducing compaction and immobile nutrient deficiencies in the top 20 cm of the soil profile. The effects on soil water storage and grain yield were examined to determine if the improved soil structure would result in improved production outcomes beyond the first year. The treatments (Table 1) included both physical and chemical ameliorants, and explored the options of shallow or deep tillage. Additives included banded fertiliser, gypsum to reduce exchangeable sodium percentage (ESP) to <3%, orgnanic matter (lucerne pellets or composted feedlot manure), and elemental sulfur to decrease soil pH.

Surface gypsum treatments were spread onto the soil, and then incorporated by ripping to 20 cm. Actual application rates varied with each site based on calculations that captured the required amount of calcium to lower the ESP below 3%. The subsurface gypsum placement was banded at 20 cm depth, with only 50% of the total gypsum needed to remediate the 20 to 50 cm layer of soil applied, due to the logistics of potentially needing to place upwards of 20 t of gypsum in that layer.

Organic matter limits aggregate dispersion and provides nutrients at depth, and while not reducing ESP, may also improve water-holding capacity and pore stability. Composted feedlot manure was applied to the subsoil at 10 t/ha. Elemental sulfur was tested to dissolve calcium carbonate to produce gypsum in-situ, while deep-banded nutrients (N and P) were included to compare with the organic matter.

Queensland core sites are presented individually. Detailed results and updates from the NSW core sites conducted in the project can be found online (see the link in the acknowledgements).

Table 1. Treatment structure for soil constraints core sites in southern Queensland.

Treatment		Rip	Banded nutrient (fertiliser)	Gypsum	Organic matter	Elemental sulfur
1	Control					
2	S-Rip	Shallow				
3	S-Rip + BN	Shallow	Band			
4	S-Rip + BN + Surf Gyp	Shallow	Band	Surface		
5	D-Rip + BN	Deep	Band			
6	S-Rip + BN + Deep Gyp	Shallow	Band	Deep		
7	S-Rip + BN + (Surf + Deep) Gyp	Shallow	Band	Surface + Deep		
8	D-Rip + BN + Surf Gyp	Deep	Band	Surface		
9	S-Rip + BN + ES + Surf Gyp	Shallow	Band	Surface		Deep
10	D-Rip + High BN	Deep	High-rate band			
11	D-Rip + Deep OM	Deep			Deep	
12	D-Rip + Deep OM + ES	Deep			Surface	Deep
13	D-Rip + All	Deep		Surface + Deep	Deep	Deep

Note: S-Rip = shallow rip to 20 cm; D-Rip = deep rip to 40 cm; Banded nutrients (BN) @ 30 kg P/ha; High BN = 100 kg P/ha; Organic matter = composted manure @ 10 t/ha.

Results

Millmerran

High intensity cropping (Table 2) has enabled invaluable insights into the yield benefits of amelioration strategies (Table 3). The 2020/21 sorghum crop was unable to be harvested due to wet conditions followed by severe mouse damage, so was excluded from the analysis.

Above-ground biomass cut at crop maturity indicated >10% increases (data not shown) with several treatments (3, 4, 7, 10) consistent with yield gains of harvested crops.

The application of banded nutrients (BN) resulted in the most consistent yield benefit (Table 3). Shallow ripping did not significantly change yield from the control so it can be assumed that it was the applied P that increased yield. Including surface gypsum resulted in an additional 0.78 t/ha of grain grown compared to *S-Rip + BN*. The additional surface gypsum is most likely increasing infiltration and improving plant establishment. Deep gypsum applications have had no effect on yields.

The high nutrition treatment (*D-rip + High BN*) is increasing yields the most (2.87 t/ha) compared to the *Control*, indicating that P is most likely the biggest constraint to improving yields (Table 3).

The organic matter treatments have performed close to the high inorganic nutrition treatment however low yields from the 2022 wheat crop impacted the cumulative yield results.

Table 2. Millmerran core site cropping sequence.

Season	Rotation
2019 winter	Treatments implemented
2019/20 summer	Sorghum
2020 winter	X
2020/21 summer	Sorghum (results excluded due to mouse damage)
2021 winter	Barley
2021/22 summer	X
2022 winter	Wheat
2022/23 summer	X
2023 winter	Wheat

Table 3. Millmerran cumulative grain yield for 4/5 crops.

Treatment		Yield (t/ha)	Delta (t/ha)	se	*
1	Control	11.6	0.00	0.283	f
2	S-Rip	11.7	0.03	0.283	f
3	S-Rip + BN	13.2	1.58	0.283	de
4	S-Rip + BN + Surf Gyp	14.0	2.36	0.283	abc
5	D-Rip + BN	13.1	1.51	0.283	e
6	S-Rip + BN + Deep Gyp	13.3	1.69	0.283	cde
7	S-Rip + BN + (Surf + Deep) Gyp	13.9	2.26	0.283	abcd
8	D-Rip + BN + Surf Gyp	14.2	2.55	0.200	ab
9	S-Rip + BN + ES + Surf Gyp	13.6	1.94	0.283	bcde
10	D-Rip + High BN	14.5	2.87	0.283	a
11	D-Rip + Deep OM	13.3	1.71	0.200	cde
12	D-Rip + Deep OM + ES	13.5	1.84	0.283	bcde
13	D-Rip + All	13.5	1.85	0.283	bcde

Note: Colour gradient indicates highest (green) and lowest (red) yielding treatments. Sorghum 2020/21 was not harvested and wasn't included in this analysis. Delta is difference from untreated Control. Means with the same letters are not significantly different at P = 0.05.

Dulacca

The Dulacca site has had a very intensive cropping rotation. In the last 18 months due to increased rain, three crops were grown in two years (Table 4).

The most recent crops (sorghum 2022/23 and wheat 2023), were very low yielding due to seasonal factors, preventing the trial from truly expressing treatment responses. No single treatment factor (such as BN, OM or D-Rip) provided the main yield benefit, however there are indications that treatments with deep gypsum are helping to increase yield. *D-rip + All* is the highest-yielding, at 2.72 t/ha more than the *Control* (Table 5).

Talwood

The Talwood site has had a low cropping intensity with only two crops grown since trial establishment (Table 6), creating less confidence in yield trends, however results to date are promising. Including BN appears to be the main driver of yield, increasing yield by at least 1.62 t/ha (Table 7).

Table 4. Dulacca core site cropping sequence.

Season	Rotation
2019 winter	Treatments implemented
2019/20 summer	X
2020 winter	Wheat
2020/21 summer	X
2021 winter	Wheat
2021/22 summer	X
2022 winter	Barley
2022/23 summer	Sorghum
2023 winter	Wheat

Table 5. Dulacca cumulative grain yield over 5 crops.

	Treatment	Yield (t/ha)	Delta (t/ha)	se	*
1	Control	11.43	0.00	0.23	e
2	S-Rip	11.86	0.43	0.46	de
3	S-Rip + BN	11.39	-0.04	0.46	e
4	S-Rip + BN + Surf Gyp	11.68	0.25	0.46	de
5	D-Rip + BN	12.22	0.79	0.46	bcde
6	S-Rip + BN + Deep Gyp	12.56	1.13	0.46	bcd
7	S-Rip + BN + (Surf + Deep) Gyp	12.05	0.62	0.46	cde
8	D-Rip + BN + Surf Gyp	13.26	1.83	0.46	abc
9	S-Rip + BN + ES + Surf Gyp	12.22	0.79	0.46	bcde
10	D-Rip + High BN	12.42	0.99	0.46	bcde
11	D-Rip + Deep OM	12.18	0.75	0.46	bcde
12	D-Rip + Deep OM + ES	13.38	1.95	0.46	ab
13	D-Rip + All	14.15	2.72	0.46	a

Note: Colour gradient indicates highest (green) and lowest (red) yielding treatments. Delta is difference from untreated Control. Means with the same letters are not significantly different at P(0.05).

Table 6. Talwood core site cropping sequence.

Season	Rotation
2019 winter	Treatments implemented
2019/20 summer	X
2020 winter	X
2020/21 summer	Sorghum
2021 winter	X
2021/22 summer	Sorghum cover crop
2022 winter	Wheat
2022/23 summer	X
2023 winter	X

Table 7. Talwood cumulative grain yield over 2 crops.

	Treatment	Yield (t/ha)	Delta (t/ha)	se	*
1	Control	7.23	0.00	0.165	c
2	S-Rip	7.58	0.35	0.285	bc
3	S-Rip + BN	8.85	1.62	0.285	a
4	S-Rip + BN + Surf Gyp	8.57	1.34	0.329	a
5	D-Rip + BN	8.95	1.72	0.285	a
6	S-Rip + BN + Deep Gyp	8.27	1.04	0.285	ab
7	S-Rip + BN + (Surf + Deep) Gyp	8.53	1.30	0.285	a
8	D-Rip + BN + Surf Gyp	9.01	1.78	0.285	a
9	S-Rip + BN + ES + Surf Gyp	8.42	1.19	0.285	a
10	D-Rip + High BN	8.99	1.76	0.285	a
11	D-Rip + Deep OM	6.88	-0.35	0.285	c
12	D-Rip + Deep OM + ES	5.58	-1.65	0.285	d
13	D-Rip + All	5.32	-1.91	0.285	d

Note: Colour gradient indicates highest (green) and lowest (red) yielding treatments. Delta is difference from untreated Control. Means with the same letters are not significantly different at P(0.05).

The addition of gypsum hasn't provided any clear yield benefits to date, most likely due to the low cropping intensity. OM treatments have performed poorly due to early flowering caused by high available nutrition in the sorghum 2020/21 crop. In addition, these plots were heavily infested with midge and suffered mouse damage, resulting in reduced cumulative yields.

Economics

When examining the economics of subsoil intervention, sensible economic assumptions have been made: treatment costs were estimated from a combination of previous studies, grower estimates, expert opinion, and average market price of inputs, but growers will need to consider and adjust for their individual economic situation.

Application costs include amendment material costs at farm gate (product prices, transport and handling) and costs associated with applying amendments including labour (paid or imputed) and all machinery costs (operation and depreciation), derived from grower estimates and/or contract machinery operation prices. Updated crop variable running costs were based on a generalised agricultural management plan (using practicing agronomists) per crop for a model area in the centre of the northern region (Moree) and applied globally throughout all sites. Cumulative net return has been calculated for each intervention at all three sites, and the payback period for each intervention at each site (Table 8).

Millmerran

Over four years (four crops) the cumulative income of some treatments was $550–$1000/ha higher than the *Control* (Figure 1). This site responded strongly to deep applications of banded nutrients that replaced the depleted subsoil P but required ripping interventions to incorporate. A response to OM amendments and surface gypsum application was also achieved. It is worth noting that the availability of relatively cheaper composted manure at this location made the payback period much shorter for the OM treatment (Table 8).

Dulacca

Over four years (five crops) the cumulative income of some treatments was up to $762 return per ha higher than the *Control* treatments (Figure 2).

Talwood

With only two crops over the four years, returns ranged from a net cost of $300/ha for some of the high-rate treatments where yields were depressed, to a net benefit of $667/ha over the *Control* (Figure 3). The deep and surface applied gypsum and deep P treatments also performed quite well, with higher yields compared to the control treatments.

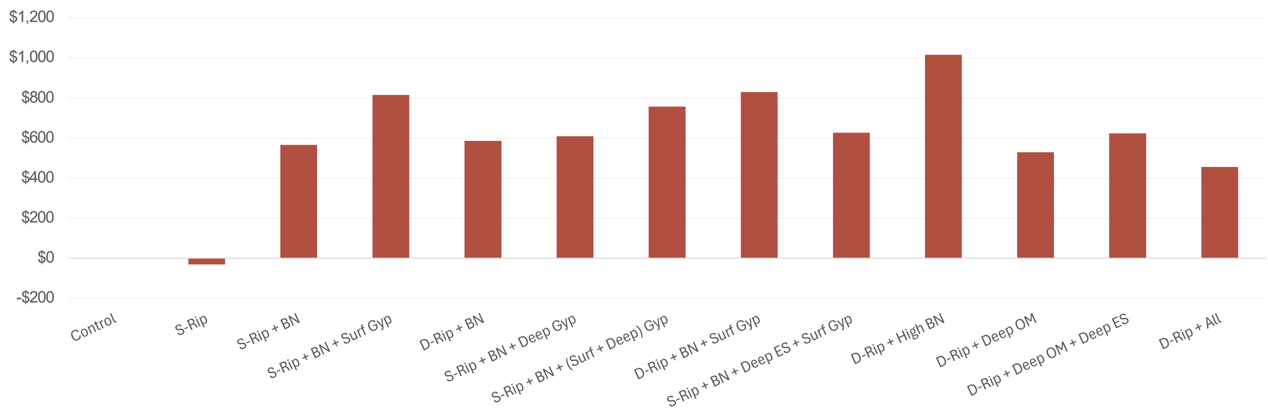


Figure 1. Millmerran cumulative net returns from crops grown between 2020 and 2023 for subsoil amelioration treatments.

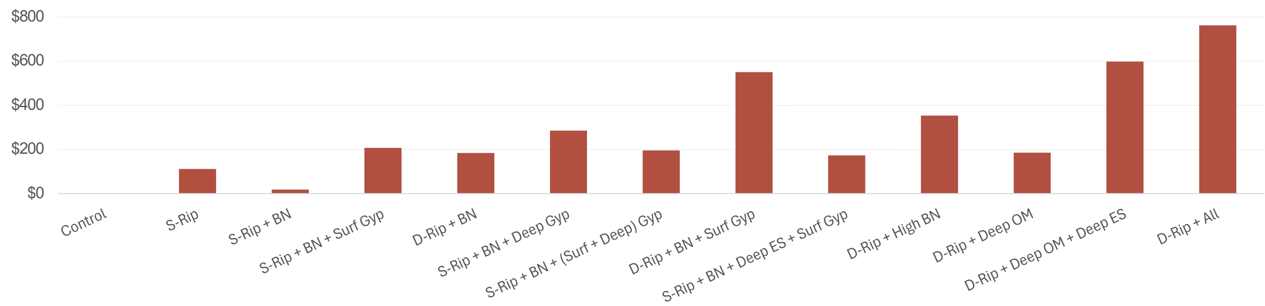


Figure 2. Dulacca cumulative net returns from crops grown between 2020 and 2023 for subsoil amelioration treatments.

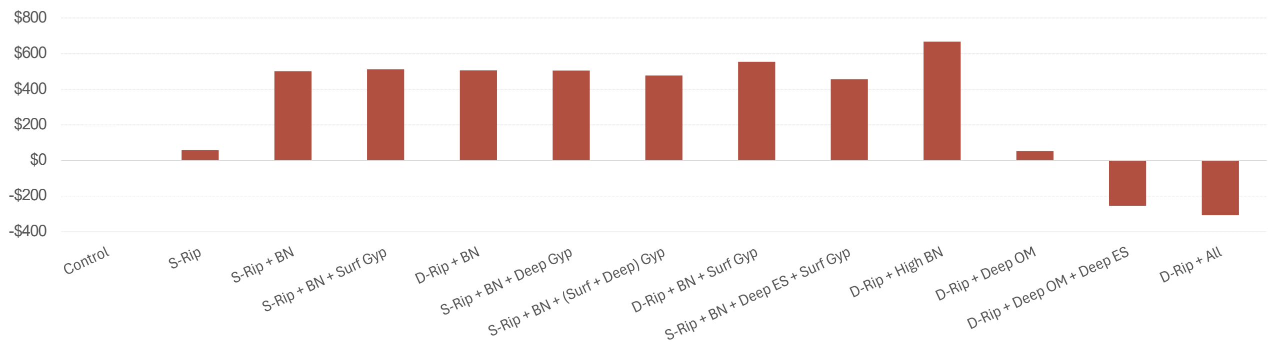


Figure 3. Talwood cumuative net returns from crops grown between 2020 and 2023 for subsoil amelioration treatments.

Combinations of ripping and additional nutrition (deep) in the form of fertiliser appear to be having benefits at this site.

Payback period

The payback period is strongly linked to the potential productivity of each environment. In areas with lower yield potential, the relative benefits are lower and payback periods correspondingly longer. Soils with higher buffering capacity also require a longer payback time, reflecting the higher inputs required to significantly change the soil properties.

Based on the last four years, the most economically viable management strategies involve low capital expenses on inputs with some returns suggesting tillage and nutrient treatments are paying the bills (Table 8). It is subsequently worth considering that the cost in diesel to rip to depth without adding the necessary amendment is unlikely to be recovered. Similarly, repeated smaller gypsum/OM applications coupled with deep ripping is cost-prohibitive. Hence, a single, large addition may ultimately be best practice.

Table 8. Payback period (years) of initial amelioration investment based on the average net return following the first four years following application.

Treatment	Millmerran	Dulacca	Talwood
Control	–	–	–
S-Rip	-6	2	3
S-Rip + BN	1	43	2
S-Rip + BN + Surf Gyp	4	19	8
D-Rip + BN	2	6	2
S-Rip + BN + Deep Gyp	10	25	12
S-Rip + BN + (Surf + Deep) Gyp	5	22	8
D-Rip + BN + (Deep + Surf) Gyp	10	19	18
S-Rip + BN + ES + Surf Gyp	13	52	19
D-Rip + High BN	3	9	4
D-Rip + Deep OM	6	17	60
D-Rip + Deep OM + ES	12	13	-31
D-Rip + All	33	23	-55

Variable expenses are generalised and based on commonly recommended inputs. Returns are relative to the yield and quality of harvested grain.

On farm research (OFR) sites

The use of amendments on most (83%) of the OFR sites sampled using a plot header resulted in yield increases. These increases ranged from 20 to 83%, with an average 41% increase for the best performing treatment at each site. These results are drawn from the drier 2023 season where there were some poor yields, so small yield gains led to large percentage increases. An initial review of results to date shows the best treatments varied with the individual sites. Key constraints for each soil are outlined in Table 9.

Table 9. Brief soil type description for responsive on-farm research sites in 2023.

Site	Description
Parkes	Red Sodosol with moderately sodic, non-dispersive topsoil, neutral pH and high bulk density over a sodic, dispersive and alkaline subsoil with high bulk density. P availability (Colwell) is 32 mg/kg in the surface (0–10 cm) and 6 mg/kg at depth (10–20 cm).
Armatree	Red Sodosol with moderately sodic and dispersive topsoil, acid pH and high bulk density over a sodic, dispersive and alkaline subsoil with high bulk density. P availability (Colwell) is 40 mg/kg in the surface (0–10 cm) and 8 mg/kg at depth (10–20 cm). Moderate salinity throughout the profile.
Millmerran	Grey/brown Vertosol with sodic, non-dispersive topsoil, neutral pH. Sodic at depth with dispersion increasing with alkaline pH. P availability (Colwell) is 28 mg/kg in the surface (0–10 cm) and 6 mg/kg at depth (10–20 cm).
North Star	Red Chromosol with non-dispersive soil throughout the profile. The profile is generally not sodic with an increase in patches at depth. pH is generally neutral but alkaline at depth. P availability (Colwell) is 28 mg/kg in the surface (0–10 cm) and 8 mg/kg at depth (10–20 cm).
Croppa Creek	Red/grey soil (variable site) with a non-sodic surface increasing to sodic at depth but generally not dispersive. Neutral pH in the surface increasing to highly alkaline at depth with some salinity (EC).

At Millmerran, the addition of surface lime and gypsum with ripping increased yield by 33% compared with deep ripping alone, while at Armatree, lime increased yield by 28% while gypsum was less effective. Both sites were highly compacted and the addition of calcium as lime to lower pH surface soils seems to have improved the maintenance of soil structure following disturbance.

At North Star, deep P with ripping resulted in an 83% yield benefit. This is consistent with the generally low levels of available P at depth and the reliance on stored moisture during the season.

At Parkes, the best treatments in a season with cool and moist grain filling conditions had a 40% increase in yield compared with controls. The largest responses were to high rates of OM (manure, biosolids etc.) when combined with lime or gypsum, all without ripping. These treatments appear to have had significant positive influence on the structure and nutrition in this lighter but compacted red soil.

Deep ripping alone, with no amendment, also provided substantial benefits at some sites (e.g. Parkes, Millmerran and Armatree). However, core site data indicates that these treatments may be

Soil constraints field day at Millmerran.

short-lived, so care should be taken if considering this practice, as there are potential implications for long term soil structural decline and loss of soil organic carbon.

For the five sites measured with hand harvests in strips, two produced statistically significant results. At Croppa Creek, the manure, gypsum and deep fertiliser in combination provided the greatest benefits for yield with an 114% increase (more than double) for canola. Gypsum by itself and manure by itself had little benefit but the combination was important. This suggests that where deep constraints occur, improving structure can help with plant access of water but nutrition must support any increased yield potential. The North Star site was variable but had a trend to increased yield with added P and gypsum.

Several OFRs that demonstrated yield responses required a combination of amendments (e.g. extra nutrition and gypsum together), with little response to individual amendments. If looking at amending a strip or paddock, consider including combinations of amendments depending on your site.

Finally, it is important to note that improving available water through structural improvement isn't worth much if you don't have the nutrition to support additional growth. Core site experiments that responded to structural treatments all had additional nutrition supplied.

Implications for growers

The results to date suggest that nutrition is the main driver for yield improvement at two of the three major Queensland sites (Millmerran and Talwood). Growers need to ensure that crops are provided with sufficient nutrition and that they review those nutrition needs once other ameliorants are used to increase yield potential.

It is also evident that ripping by itself provides little to no long-term benefit. At some sites ripping has increased yield in the crop following the ripping event, however this benefit is usually short-lived and core site data is beginning to show negative crop responses two to three years later. Ripping should be avoided unless it is used to introduce a longer-term ameliorant.

The most common and perhaps most economical strategy is likely to be deep P due to ease of application compared to gypsum or manure. However, if there is capacity to apply gypsum or manure deep and the soil test indicates it could be responsive then this option should be explored further because there may be additional benefits.

Each site is different, and so there is no single recipe to follow. Soils with a high buffering capacity or CEC will need higher rates of amendments to make a significant change; this higher cost may not be reflected in greater gains in grain yield. This therefore needs to be taken into consideration when deciding to use amendments in a paddock.

For growers beginning their soil amelioration journey, soil testing should be the first step to determining possible constraints and consequently amendment options. Ameliorants can have a high cost and appear to work best in combinations, such as deep P and gypsum. So, once ameliorant options have been identified from the soil test results, test strips should be used for several growing seasons to assess their impacts.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contribution of growers through both trial cooperation and the support of the Grains Research and Development Corporation; the authors would like to thank them for their support.

This article has been adapted from a GRDC paper first publihed in August 2024 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2024/08/ameliorating-soil-constraints-with-deep-ripping,-gypsum,-and-soil-organic-matter-queensland

Further reading

Dispersive soil manual - Managing dispersive soils: practicalities and economics – northern region. grdc.com.au/resources-and-publications/all-publications/publications/2023/dispersive-soil-manual

GRDC Grains Research Update paper - Soil constraints project - an update on the economic response of long term soil amelioration strategies – February 2024 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2024/02/soil-constraints-project-an-update-on-the-economic-response-of-long-term-soil-amelioration-strategies

GRDC Grains Research Update paper - Ameliorating sodicity; what did we learn about ameliorating sodicity constraints with a range of treatments? Yield responses to ripping, gypsum and OM placement in constrained soils – March 2022 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/03/ameliorating-sodicity-what-did-we-learn-about-ameliorating-sodicity-constraints-with-a-range-of-treatments-yield-responses-to-ripping,-gypsum-and-om-placement-in-constrained-soils

GRDC Grains Research Update, online (recording) - Ameliorating sodicity – Central & Northern NSW & Qld - March 2022. grdc.com.au/events/past-events/2022/march/grdc-grains-research-update,-online-ameliorating-sodicity-central-and-northern-nsw-and-qld

GRDC Grains Research Update paper - Amelioration for sodicity - deep ripping and soil amendment addition across NSW and Qld. Engineering challenges. Yield responses to ripping, gypsum and OM placement in constrained soils – February 2021. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2021/02/amelioration-for-sodicity-deep-ripping-and-soil-amendment-addition-across-nsw-and-qld.-engineering-challenges.-yield-responses-to-ripping,-gypsum--and-om-placement-in-constrained-soils

Trial details

Location: Dulacca

Soil type: Grey/Brown Vertosol, surface soils not spontaneously dispersive but subsurface highly dispersive.

Depth (cm)	pH (H2O)	pH (CaCl2)	EC (1:5)	ECEC (cmol/kg)	ESP %	Cl (mg/kg)	P (mg/kg)
0-10	8.5	7.7	0.21	29.8	9	43	9
10-20	8.8	7.8	0.25	30.3	13	53	14
30-40	8.1	7.3	0.46	35.3	20	102	4
60-70	6.8	6.7	0.66	34.1	26	275	8

Location: Millmerran

Soil type: Grey/Brown Vertosol, surface and subsurface soils not spontaneously dispersive, very compact soil through the profile.

Depth (cm)	pH (H2O)	pH (CaCl2)	EC (1:5)	ECEC (cmol/kg)	ESP %	Cl (mg/kg)	P (mg/kg)
0-10	6.6	6.3	0.15	17.7	13	153	38
10-20	8.7	7.4	0.24	23.2	14	330	5
30-40	6.9	6.2	0.38	31.4	22	428	3
60-70	6.4	5.5	0.43	35.5	25	457	2

Location: Talwood

Soil type: Red/Brown Vertosol with surface soils not spontaneously dispersive, subsurface highly dispersive at 60-70 cm.

Depth (cm)	pH (H2O)	pH (CaCl2)	EC (1:5)	ECEC (cmol/kg)	ESP %	Cl (mg/kg)	P (mg/kg)
0-10	8.3	7.6	0.17	35.5	11	22	18
10-20	8.7	7.9	0.23	39.3	10	26	3
30-40	8.9	7.8	0.36	39.4	18	73	2
60-70	9.2	7.9	0.44	40.7	24	163	2

Scan the QR code to find out more:

SCAN ME

Northern Farming Systems site—Billa Billa

Andrew Erbacher, Christabel Webber and Isabella Macpherson
Queensland Department of Primary Industries

***Research questions**: Can systems performance be improved by modifying farming systems in the northern grains region? | What have been the implications of these system modifications since 2015? | What are the trends that are expected in our farming systems? | How will these changes impact on the performance and status of our farming systems?*

Key findings

1. Ground cover from the last crop impacted chickpea yield in 2021.
2. Rainfall in January provided good mungbean and sorghum yields, but high mouse pressure made accurate yield assessment difficult.
3. The wet spring summer of 2020/21 produced strong yield increases for added nitrogen in the Bambatsi grass pasture.

Background

Grain production systems at Goondiwindi are based on winter cropping and most farms use zero or minimum tillage systems, with a strong reliance on stored fallow moisture from summer rains. While summer crops are primarily grown as a disease break, they are still an important part of the system, and are typically planted after a long fallow in spring when there is a greater water profile than winter crops to insure against hot growing seasons with variable rainfall.

Billa Billa, one of six sites in the Northern Farming Systems project (DAQ00192, extended to 2025 as DAQ2007-002RTX), is located ~50 km north of Goondiwindi on the Leichhardt Highway on a Duplex soil with a plant available water capacity of 180 mm. The site is constrained by increasing levels of sodicity and chlorides at depth. 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.

This report investigates the activities and draws insights from the Billa Billa site in the 2020-21 summer to winter 2022 seasons. Previous activities and insights can be found in past editions of *Queensland grains research*.

What was done

Consultation meetings in late 2014 and early 2015 resulted in the development of nine locally relevant systems to be trialled at Billa Billa. These were implemented from 2015 until 2020, when these systems were refined by a local reference group to ensure relevance. The systems remained largely unchanged, although both of the pasture systems were split, with half reverting to a *Baseline* system in 2019 and the other half continuing as a ley pasture for another 3-5 years.

1. ***Baseline*** is typical of local zero tillage farming systems with ~one crop per year grown based on moderate planting moisture triggers of 90 mm plant available water (PAW) for winter crops and 120 mm PAW for summer crops. Crops grown in this system are limited to wheat/barley, chickpea and sorghum. These crops are fertilised with nitrogen (N) and phosphorus (P) to achieve average seasonal yield potential for the PAW measured prior to planting.
2. ***Lower crop intensity*** reflects a more conservative approach that accumulates at least 150 mm PAW prior to planting the next crop. Long fallows are used to achieve a cropping frequency of 2 crops in 3 years (0.7/year), with the same nutrient management as the *Baseline* system.
3. ***Higher crop intensity*** aims to minimise the fallow periods within the system and grow 3 crops every 2 years. Crops are planted on lower PAW (50 mm for winter crops

and 70 mm for summer crops) 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 again fertilised with N and P to achieve average seasonal yield potential for the PAW measured prior to planting.

4. ***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 (ranging from 90 mm to 120 mm) have been identified to manage individual crop risk and to target 1 crop per year. These crops are fertilised to achieve the average seasonal yield potential. The unique rules for this system focus on managing root lesion nematodes, with 50% of the selected crops to be resistant to *Pratylenchus thornei*, and 1 in 4 crops resistant to *Pratlenchus neglectus*. To manage herbicide resistance, two crops of the same herbicide mode-of-action cannot follow each other. Crops grown in this system include wheat/barley, chickpea, sorghum, mungbean, faba bean, field pea, canola/mustard, millet, cotton, safflower, linseed and sunflower. These crops are fertilised with N and P to achieve average seasonal yield potential for the PAW measured prior to planting.
5. ***Higher legume*** aims to minimise the use of nitrogen fertiliser by growing every second crop as a pulse (legume) crop. Legume crops are selected with a preference for those producing greater biomass and greater carry-over nitrogen benefits. Crops grown in this system are similar to the *Baseline* (wheat/barley, chickpea, sorghum) with additional pulse options (faba bean & mungbean). Moderate planting triggers of 90 mm to 120 mm PAW are used. Crops are again fertilised with N and P to achieve average yield potential for the PAW however, nitrogen is only applied to the cereal crops.
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 (creating a risk that crops may be over fertilised in years where water supply is limited). This system is planted to the same crop sequences as the *Baseline* each year; the only difference is the amount of nutrients applied.
7. ***Higher soil fertility*** was treated the same as the *Higher nutrient supply* system. However, it had an additional 10 t/ha organic carbon (70 t/ha compost) applied in 2015 to raise the inherent fertility of the site to see if a higher 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, and simulates grazing with a forage harvester to utilise a pre-determined amount of biomass. In 2019 half the pasture was removed (after 4 years) and returned to the *Baseline* cropping system to quantify the benefits gained by the pasture phase while the remaining half was left as pasture.
9. ***Grass ley pasture + nitrogen fertiliser*** is identical to the *Grass ley pasture* (including the split in 2019), but with 100 kg N/ha (217 kg/ha urea) applied to the pasture each year over the growing season to boost dry matter production, which is nearly always constrained by nitrogen deficiency in grass-based pastures, and so increase the rate of soil carbon sequestration.

Results

Lower crop intensity was fallowed since winter 2019 and planted on the first opportunity in spring with single skip 1 m sorghum planted on 29 December 2020 with 150 mm plant available water (PAW).

After a dry spring, Billa Billa had a wet summer, which saw *Higher crop intensity* double cropped to sorghum on 15 January with 100 mm PAW and *Higher crop diversity* planted to mungbean on 4 February with 120 mm PAW (Figure 1). Both were wheat in 2020, so had good levels of standing stubble that was maintained by inter-row planting. The *Higher crop intensity* sorghum was on solid 1 m rows and mungbean on the same row spacing as the previous wheat (40 cm).

There was considerable mouse pressure in the district that season and this trial was not exempt. The earlier planted sorghum in *Lower crop intensity* was completely stripped by mice, so biomass was assessed using hand cuts and the crop sprayed out. With consistent baiting and netting for birds, the later planted sorghum in *Higher crop intensity* suffered less crop damage. The baiting was sufficient to protect the mungbean from noticeable crop losses.

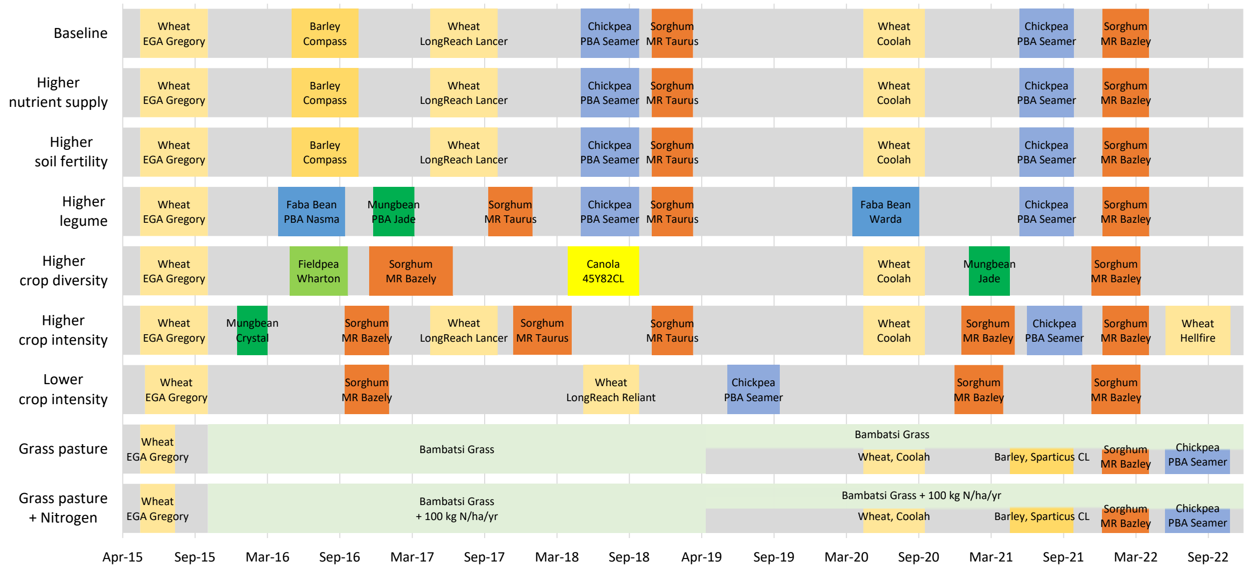


Figure 1. Crops grown at Billa Billa in the nine farming systems.

Timing of the *Lower crop intensity* sorghum spray-out was matched to a commercial paddock of sorghum near the trial that had a similar fallow length and was planted on the same day. Hand cuts were also taken from that commercial area to estimate the yield of the sorghum lost to vermin. A double cropped sorghum paddock planted on the same day as our *Higher crop intensity* on the adjoining farm was also hand-cut as a yield check for our later planted sorghum.

A wet autumn provided sufficient moisture for the remaining six fallowed systems to be planted to winter crops in 2021. The two ex-grass pasture systems were planted to Sparticus CL⁽ᶦ⁾ barley on 18 May with 150 mm PAW. *Baseline*, *Higher nutrient supply*, and *Higher soil fertility* were planted to chickpea on 11 June with 140 mm PAW. *Higher legume* was also planted to chickpea at this time, but with less ground cover provided by the faba bean stubble, this system had 50 mm less PAW (90 mm) than the three systems that had wheat stubble. This stored water difference was despite the 2020 faba bean leaving 20 mm more PAW at harvest than the 2020 wheat.

With a wet June and moisture in profile after harvesting sorghum, *Higher crop intensity* had enough PAW to plant chickpea on 30 June (70 mm).

Rainfall in December provided an opportunity to plant *Higher crop diversity* and *Lower crop intensity* to sorghum on 16 December 2021 with 150 mm PAW. Further rain in December and January allowed an opportunity to double crop the remaining seven systems to sorghum on 6 January with 100 to 150 mm PAW.

The *Higher crop intensity* system double cropped again in winter with Hellfire wheat planted on 14 June with 100 mm PAW. The two ex-pastures also accumulated enough PAW (140 mm) to be planted to PBA Seamer⁽ᶦ⁾ chickpea on the same date. Interestingly the *Baseline* had the same planting PAW triggers as the ex-pastures but did not accumulate enough PAW to have a winter crop planted after the sorghum.

Nitrogen

All systems had sufficient nitrogen to meet the demands of the cereal crops in 2021, albeit six of the ten crops grown were legumes. At soil sampling (May 2021) there were three distinct levels of soil mineral nitrogen: *Lower crop intensity*, *Higher legume* and *Higher soil fertility* had 300-400 kg N/ha; *Baseline*, *Higher nutrient supply* and ex-fertilised grass pasture had 200-250 kg N/ha; and *Higher crop intensity*, *Higher crop diversity* and ex-grass pasture had ~100kg N/ha.

The sorghum in 2021-22 also had sufficient nitrogen in eight of the nine systems. *Lower crop intensity* and *Higher legume* had 300 kg N/ha, *Higher soil fertility* had 260 kg N/ha, *Higher nutrient supply* had 150 kg N/ha and *Baseline*, *Higher crop diversity*, *Higher crop intensity* and ex-fertilised pasture had 80–120 kg N/ha. The ex-pasture (without N) had only 11 kg N/ha when this sorghum was planted, so 67 kg N/ha (150 kg urea) was broadcast ahead of rain after crop emergence on this system.

Higher crop intensity had 36 kg N/ha after the sorghum, so had 21 kg N/ha (46 kg urea) applied in front of the planter. The two ex-pasture systems were equally low in N at planting but were planted to a legume, so no extra N was applied.

Crop performance

The 2020/21 sorghum crop was severely affected by mice, so estimated grain yields were based on biomass production and the harvest index of nearby commercial sorghum crops where hand cuts were taken at spray-out. These hand-cut estimates matched modelled yields for the season.

The 2020/21 sorghum plots received over 300 mm of in-crop rainfall. The December-planted sorghum in *Lower crop intensity* had an estimated yield of 3 t/ha while the January-planted sorghum in *Higher crop intensity* was estimated at 3.5 t/ha. The mungbean in *Higher crop diversity* was planted a fortnight after *Higher crop intensity* but sprayed out on the same day for a grain yield of 2 t/ha.

The chickpea in *Baseline*, *Higher nutrient supply* and *Higher soil fertility* yielded 2.0 t/ha, while *Higher legume* had 50 mm less PAW at planting which reduced yields by 0.7 t/ha (yielded 1.3 t/ha). In *Higher crop intensity* the chickpea was planted later with less PAW and only yielded 0.6 t/ha, but this is in addition to the 3.5 t/ha of sorghum grown over the *Baseline*'s fallow period.

The barley in the two ex-pasture systems had similar yields of 3.5 t/ha, although the ex-fertilised pasture had slightly higher biomass (7.8 t/ha versus 7.4 t/ha) and grain protein (13% versus 11.5%).

In the following summer the December-planted sorghum in *Lower crop intensity* and *Higher crop diversity* had the most PAW and produced the highest yield (3.9 t/ha). In the January-planted sorghum, *Higher soil fertility* had the highest grain yield and protein (3.5 t/ha at 14% protein). *Baseline*, *Higher nutrient supply*, *Higher legume*, *Higher crop diversity* and *Higher crop intensity* all yielded about 3 t/ha with 13.4% protein. The ex-ley grass pasture had the least nitrogen at planting. With urea added to match the budgeted yield expectations, it also yielded 3 t/ha, but with 11.3% protein. The ex-fertilised grass pasture had 20 mm less PAW than the ex-grass ley pasture and yielded 0.6 t/ha less (2.4 t/ha at 12.1% protein).

Grass ley pasture

The pastures have typically been cut twice per year when the Bambatsi flowered; a spring growth cut around Christmas, and an autumn cut as the grass goes dormant. The top two thirds by height (one third by weight) are removed to simulate grazing. In 2021 these cuts were 28 May and 16 December. The wet summer in 2022 provided an extra cut on 22 February and the traditional autumn cut on 5 July. There was no spring cut in 2022. The 2021 autumn cut had 7.3 t/ha of dry matter in the unfertilised plots and 9.3 t/ha in the nitrogen fertilised pasture. This translated to 3.1 t/ha at 4.9% protein and 4.5 t/ha at 6.7% protein as the removed portions in the unfertilised and fertilised pastures respectively. The spring cut had similar differences in yield and protein (albeit higher) between the two pastures. The unfertilised pasture had 9.0 t/ha of dry matter for 3.6 t/ha removed at 6.9% protein and the pasture with added nitrogen grew 11.7 t/ha dry matter with 5.6 t/ha removed at 8.8% protein.

In 2022 the February cut grew 8.8 t/ha for a harvested portion of 2.7 t/ha in the unfertilised pasture, and 12.1 t/ha for a harvested portion of 3.7 t/ha in the fertilised pasture. The final cut in 2022 was taken after the grass was frosted and had stopped growing for the season. This grew 4.6 t/ha and 9.5 t/ha without and with 106 kg urea/ha (50 kg N/ha) respectively, for harvested portions of 1.8 t/ha and 2.4 t/ha.

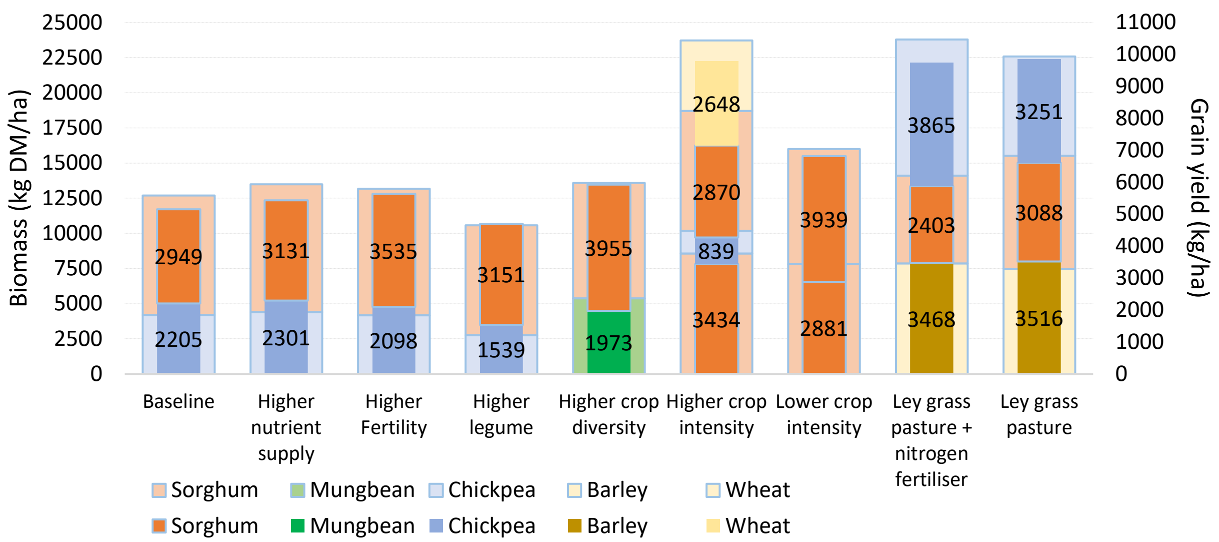


Figure 2. Biomass and grain yields of crops at Billa Billa harvested in 2021.

Over the 2021-2022 season there was an extra 10.9 t/ha grown and 3.6 t/ha of a higher quality feed harvested from the application of 100 kg N/ha, that is 36 kg extra dry matter for each kilogram of N applied. This also represents a potential to grow an extra 250 kg of beef per hectare in that season.

Bambatsi pasture prior to harvest in April 2021 (fertilised with urea on the left and unfertilised on the right).

Implications for growers

This season demonstrated the value of maintaining ground cover over the fallow. Despite the high rainfall in 2021, the soil profile was not full for the winter crop and stubble cover had a big impact on fallow efficiency over the summer. At this site low cover after faba bean in 2020 captured 70 mm less rainfall than the systems with wheat stubble, resulting in a 35% reduction in chickpea yield.

There were dramatic differences in biomass (and grain yield) produced by the different crop types grown in 2021. For example, chickpea in *Baseline* grew half as much biomass as barley in ex-ley pasture; and mungbean in *Higher crop diversity* grew much less biomass than the sorghum in *Higher crop intensity*. This difference in biomass will have an impact on ground cover left after harvest, and the higher nitrogen content of the legume stubble will allow them to break-down faster, thus reducing cover more over the fallow and impacting the ability to capture rainfall for the next crop.

Nitrogen left by pulse crops should also be considered. A rule of thumb is that N in legumes is approximately 3% of dry matter. Pulse crops with high harvest index (ratio between biomass and grain yield) will often remove a lot of the nitrogen they fix with their rhizobia. In these crops N was 2-2.6% of dry matter in the chickpea and mungbean and 3.5-4% in the grain. In contrast the cereals (sorghum or barley) had 1.2-1.7% N in dry matter and grain concentrations of 1.7-2.2%. Therefore, *Baseline*, *Higher crop diversity* and ex-ley pasture had 100 kg N/ha in the biomass of chickpea, mungbean and barley respectively and *Higher crop intensity* sorghum slightly higher at 150 kg N/ha, but N removal in the grain was 75 kg N/ha in the respective chickpea and mungbean, versus 50 kg N/ha in the sorghum and barley. Counter-intuitively, this means only 25 kg N/ha was returned by the legume crops, while the cereals returned 50-100 kg N/ha. The other consideration is that the nitrogen in the stubble will become available as the stubble is broken down, so the N in the chickpea and mungbean stubble will likely be available over the next year, whereas barley and sorghum stubble can remain on the surface for multiple years along with the associated nutrients.

The application of 100 kg N/ha/yr to our grass-only Bambatsi pasture has produced an extra 5000 kg of 'utilised' (simulated grazing) biomass per hectare (from 13,000 kg DM/ha extra growth) over two wet summers. This equates to 30 kg DM per kg of nitrogen, which has the potential to produce an extra 3.5 kg beef per kg of N (700 kg/ha). This nitrogen effect on grass production and quality is only emerging now as the site had 400 kg of mineral N/ha when the pasture was planted and several dry seasons that limited potential grass growth. We have now depleted the available mineral nitrogen and are relying on mineralisation to supply nitrogen for growth. It appears that mineralisation over winter is providing N for spring growth but without a legume, the pastures become nitrogen deficient later in the summer, especially with good rains. This demonstrates the production gains possible over summer in grass pastures by applying nitrogen after the spring flush.

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 Primary Industries for funding the project (DAQ00192).

Trial details

Location:	Billa Billa
Crops:	Bambatsi grass, barley, wheat, chickpea, sorghum, mungbean
Soil type:	Belah, Duplex
Rainfall:	644 mm (2021) 699 mm (2022)

Northern Farming Systems site—Mungindi

Andrew Erbacher, Christabel Webber and Isabella Macpherson
Queensland Department of Primary Industries

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

Key findings

1. Ground cover had limited impact on fallow efficiency when all the rain fell in the month prior to planting.
2. The *Higher nutrient supply* system has produced more wheat biomass, but it did not translate to improved grain yield for the third time in this trial.
3. Chickpea yield was increased in the 2022 *Lower crop intensity* system by past crop rotations reducing root lesion nematodes.

Background

Dryland farming in western Queensland is typically based on winter cropping under a zero or minimum tillage system. Most farms in the region operate on a sequence of cereal crops (wheat and barley) rotated to pulses (chickpea). There is limited summer cropping (dryland cotton and sorghum) which is chiefly grown for disease control.

Availability of water to the crop is the key determinant of yield in the region where rainfall is relatively low and unreliable, so maintaining a profitable farming system is challenging. There is generally only enough rainfall to support a cropping frequency of one crop per year. This severely limits double cropping opportunities and results in long fallows when rotating between summer and winter crops. Winter cropping relies heavily on stored soil moisture from late summer rain and increasingly less reliable summer rainfall has further reduced growers' confidence to grow dryland summer crops.

The Farm Practices Research project (DAQ00192) was established in 2014 with the first crops planted winter 2015 and was extended to 2025 as the Northern Farming Systems (DAQ2007-002RTX). Mungindi is one of the eight sites in the project and is located 22 km north-west of Mungindi on a Grey Vertosol with a plant available water capacity (PAWC) of 180 mm. The Mungindi site has been cropped for over 30 years and is representative of cropping in this dryland western region. This site is well known for high root lesion nematode populations.

What was done

Consultation meetings in late 2014 and early 2015 developed five locally relevant systems to investigate at Mungindi, which expanded to six systems in 2016. These six farming systems were implemented until 2020, when the project received renewed funding and the systems were reviewed and refined by a local reference group to ensure continued relevance for the next five years. The six systems are:

- ***Baseline*** – represents an aggressive (high intensity) winter-dominant cropping system used in the Mungindi region with three main crops on a fairly set rotation of wheat/barely/chickpea. Aggressive moisture triggers of 50 mm plant available water (PAW) are employed for all crops, aiming to grow a crop every year. A nitrogen (N) budget is calculated on a median yield potential and applied to cereal crops as required. Phosphorus (P) is applied as starter to all crops at 4 kg of P per hectare.
- ***Moderate crop intensity*** – similar to the *Baseline* (focussing on wheat, barley and chickpea), but only planting when the soil profile is at least ½ full (90 mm PAW). Sorghum and cotton, with higher PAW triggers (150 mm), are included as options in a wet spring/summer. This system investigates a middle ground between the *Baseline* and *Lower crop intensity* systems. Planting on 90 mm PAW reduces the number of 'failed crops' without having to wait for an almost full profile (as in *Lower crop intensity*) to plant. Nutrient management matches the *Baseline* system.

- ***Lower crop intensity*** – a conservative system that only plants when the soil profile is at least 80% full. This system allows wheat, barley, chickpea, sorghum, or cotton to be planted once 150 mm is accumulated in the soil profile. Crop choice is dictated by the most profitable option when the water trigger is met. Cover crops may be grown to manage low cover situations (<30%) and a wheat cover crop may be harvested if above average yields are expected. Nutrient management matches the *Baseline* system.
- ***Higher crop diversity*** – investigates alternative crop options to help manage and reduce root lesion nematode populations, other soil-borne diseases, and herbicide resistance. The profitability of these alternative systems will be critical. A wider range of crops may enable growers to maintain soil health and sustainability as the 'age of cultivation' increases. Unique rules for this system are: (i) 50% of the selected crops are resistant to *Pratylenchus thornei*, and (ii) one in four crops are resistant to *Pratylenchus neglectus*. To manage herbicide resistance, two crops requiring the same herbicide mode-of-action cannot follow each other. Crop options for this system include wheat/barley, chickpea, sorghum, maize, sunflowers, canola/mustard, field pea, faba bean, mungbean and cotton. Nutrient strategies are similar to the *Baseline* with PAW triggers adapted to suit the individual crop's risk.
- ***Higher legume*** – is focused on improving soil fertility and reducing the amount of fertiliser N required by growing more pulse (legume) crops that can fix atmospheric N as required. One in every two crops is a legume and the suite of crops available for this treatment are wheat/barley, chickpea and faba beans. The *Higher legume* strategy is based on a *Baseline* moisture trigger and nutrient strategy. Nitrogen is only applied to cereal crops.
- ***Higher nutrient supply*** – assesses the impact of fertilising for a higher yield potential in this declining nutrient environment by applying a N budget calculated for 90% of yield potential and a 100% replacement of P removed. Increasing nutrient supply is currently viewed very conservatively in the Mungindi region. The same crops as in the *Moderate crop intensity* system are grown each year so that it is possible to compare the nutrient effect on the two systems.

Higher legume chickpea on the left and *Moderate crop intensity* wheat on the right in 2021.

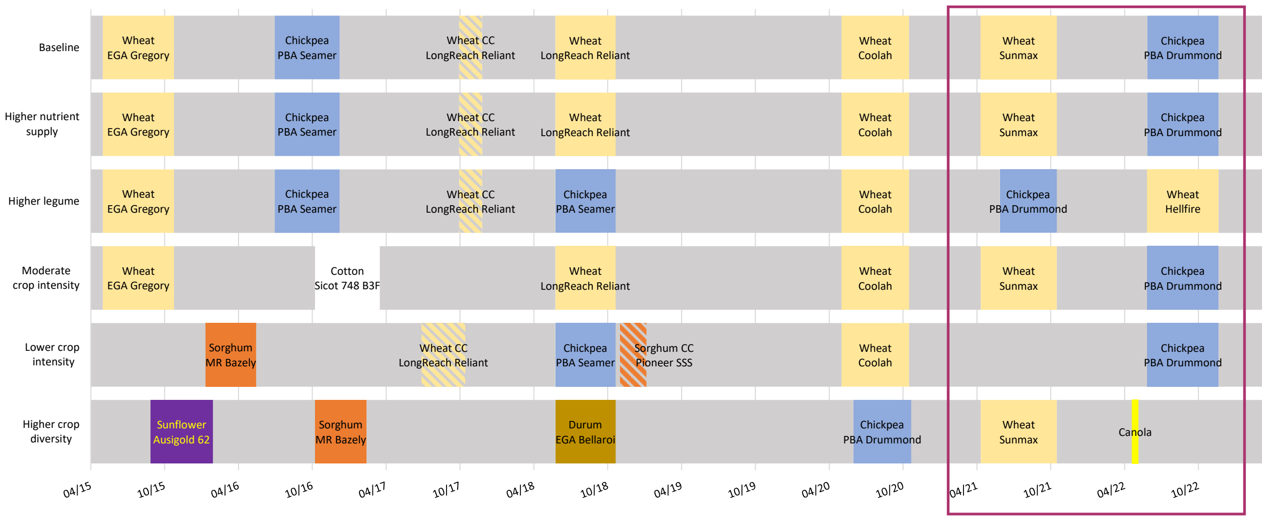


Figure 1. Crop sequences implemented at Mungindi. The box surrounds the crops reported here.

Results

2021

The site did not have enough plant available water (PAW) to plant any systems (i.e. <50 mm) when it was soil sampled on 9 March 2021. However, after 110 mm of rainfall in March, the *Baseline*, *Moderate crop intensity*, *Higher nutrient supply* and *Higher crop diversity* were planted to Sunmax⏀ wheat on 16 April with 125 mm PAW (Figure 1). *Higher crop diversity* was chickpea in 2020, so had the least ground cover (30%) but with all the effective rainfall received immediately prior to planting and on dry cracked soil, it had similar PAW to the systems with the wheat stubble (70% cover). An additional 121 mm of rainfall was received in-crop.

Higher nutrient supply grew the most biomass of the systems planted to wheat (8 t/ha versus 7 t/ha in the other three systems) but grain yield was the same for all four systems (Figure 2). Harvest index was quite low at 31% for the Sunmax⏀ wheat, but was consistent for all four systems planted to wheat that season to produce 2.3 t/ha of grain.

Nitrogen was not limiting in this crop. *Baseline*, *Moderate crop intensity* and *Higher crop diversity* had 14% grain protein and *Higher nutrient supply* was 18%. Surprisingly, screenings were low for all four systems at 2.5%, albeit *Higher nutrient supply* had a smaller seed size with 3.4 g per 100 seeds compared to 3.5 g per 100 seeds in the other three systems.

The previous crop in *Higher legume* was wheat, so was not planted to Sunmax⏀ with the other systems. Instead, PBA Drummond⏀ chickpea was planted on 8 June 2021 with 130 mm PAW at planting and 105 mm of in-crop rainfall. The chickpea produced 3.9 t/ha of biomass and 2.2 t/ha grain yield.

Lower crop intensity had good stubble cover from the 2020 wheat crop but did not accumulate enough PAW to plant a crop (150 mm), so remained fallow.

2022

The site was sampled on 15 March 2022 and the four systems that grew wheat in 2021 had 140-150 mm PAW. *Higher legume* had less stubble cover after chickpea in 2021 and had less PAW (116 mm). *Lower crop intensity* still had good ground cover from the 2020 wheat, and with the benefit of a long fallow had the most PAW (190 mm PAW).

Canola was established on 28 April in the *Higher crop diversity* and wheat was planted in *Higher legume* and *Lower crop intensity* systems on 9 May. Unfortunately, the Moonie River flooded across the site on 25 May and none of these crops survived.

Once the water receded, PBA Drummond⏀ chickpea was planted in *Baseline*, *Higher nutrient supply* and *Moderate crop intensity* as planned, albeit late on 29 June. *Lower crop intensity* was also planted to chickpea as the wheat planting window had closed. *Higher legume* grew chickpea in 2020, so a quick wheat (LPB Hellfire⏀) was planted. No crops were suitable for the rotation restrictions of *Higher crop diversity*, so it was left fallow for a spring plant.

It continued to rain and stay cool though spring, so crops matured a month later than usual for a 24 November harvest. The wheat yielded well, producing 9.5 t/ha biomass for 3.7 t/ha grain yield (Figure 2). With 280 mm of in-crop rain and a cool spring, the chickpea did not thrive, producing 2.5 t/ha biomass in the *Baseline* and 0.67 t/ha grain. The *Lower crop intensity* chickpea produced almost double this biomass (4.2 t/ha) and 30% more grain (0.9 t/ha). Despite the late planting date, the cool spring delayed pod set so there was 20 cm of lost pod positions before the first pod (see photo) in all systems. This was a major contributor to the harvest index being much lower than the 2021 chickpea (26% HI in 2022 versus 50% HI in 2021).

The yield difference between *Baseline* and *Lower crop intensity* systems is much harder to explain as they had the same variety planted on the

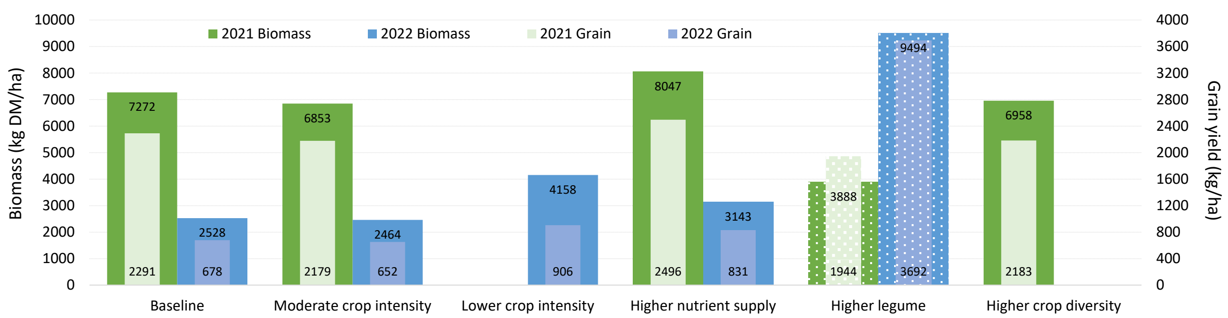


Figure 2. Biomass and grain yield in 2021 and 2022. In 2021 four systems had wheat, ***Higher legume*** had chickpea and ***Lower crop intensity*** was fallow; in 2022 four systems had chickpea, ***Higher legume*** was wheat and ***Higher crop diversity*** was fallow. Biomass is presented on the left axis and grain yield is presented on the right axis, so that a crops with bars of the same height for biomass and grain yield have a harvest index of 40%. Values at the base of the bar are grain yield, and at the top of the bar are biomass.

Chickpea interrow planted into 2020 wheat stubble flowering and producing pods.

same day with similar soil water and nitrogen levels at both planting and harvest. However, the most notable difference was the number of root lesion nematodes (*Pratylenchus thornei*) – *Baseline* had damaging levels (2.3 nematodes/g soil) at planting, whereas *Lower crop intensity* had low levels (0.3 nematodes/g soil), and it's likely that the level of nematodes in the *Baseline* system was the key driver of the system's yield loss.

After the May flood, the four systems planted to chickpea in 2022 into wheat stubble from 2021 or 2020 were above plant available water capacity (PAWC) of the soil. The *Higher legume* planted after chickpea in 2021 was 30-50 mm drier at 90% PAWC. The chickpea crop reduced the water profile by 10 mm at harvest, while the wheat was 30 mm drier. However, all systems still had enough soil water to double crop on the next planting opportunity.

Implications for growers

2021 saw the fourth wheat crop grown in the *Higher nutrient supply* and *Baseline* systems. In each of these crops the *Higher nutrient supply* strategy has grown more crop biomass and grain protein, but 2021 was the first improvement in grain yield. In fact, two of the previous crops had 'hayed off' with reduced grain yield compared to the *Baseline* system. Haying-off is often attributed to a higher biomass crop using more soil water in vegetative growth and having less water available for grain fill. However, the *Higher nutrient supply* wheat crops are consistently flowering later than the same varieties and planting dates in the *Baseline* system, which places the crop under higher heat stress, a shorter grain fill period and contributes to the higher grain screenings observed in past seasons. This suggests that paddocks with high levels of plant available nitrogen in these western regions should be planted to wheat varieties that flower up to a week earlier than people are now using on older soils where soil fertility and N levels have declined.

The 2022 chickpea yields demonstrate the detrimental impact of root lesion nematodes. Indeed, the 30% reduction in yield could have been even greater if the season had a dry finish. This highlights the need to have periods without a host plant to reduce nematode levels. This can be done in two ways, by fallowing or using resistant crops. In the *Lower crop intensity* system, root lesion nematode populations were reduced and kept low through long cropless fallows, where root lesion nematodes could not reproduce. The experiment has had crops where the root lesion nematode population has doubled. If this increase is from a low base there may still only be a low population, which can then be managed and reduced by subsequent fallows. The *Higher crop diversity* systems also had similar low root lesion nematode populations despite growing two more crops. This system has increased the diversity of crops by including nematode-resistant crops that prevented increases in root lesion nematodes populations. These resulting populations will decrease further over subsequent fallows.

The first step to managing nematodes is to test your soil via Predicta® B to deteremine if root lesion nematodes (*Pratylenchus* sp.) are present. Then consider which strategy, fallowing, incorporating resistant crops, or a combination of both, will work best on your farm.

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, the Queensland Department of Primary Industries, CSIRO and New South Wales Department of Primary Industries and Regional Development for funding the project.

Trial details

Location:	Mungindi
Soil type:	Grey Vertosol
Rainfall:	2021: 497 mm 2022: 572 mm

Capturing and using water most efficiently: how much do crop system choices matter?

Lindsay Bell[1], Andrew Erbacher[2], David Lawrence[2], Andrew Verrell[3], Jon Baird[3], Darren Aisthorpe[2], Andrew Zull[2], Jayne Gentry[2], Greg Brooke[3] & Kaara Klepper[4]

[1] CSIRO Agriculture and Food
[2] Queensland Department of Primary Industries
[3] New South Wales Department of Primary Industries and Regional Development
[4] GRDC

Key findings

1. **Maximising crop water efficiency requires fallowing to reach critical thresholds of plant available soil water, however fallows are relatively inefficient, usually capturing only around one fifth to one quarter of rainfall.**
2. **Fallow efficiency can be highly variable depending on fallow length, soil profile moisture and levels of ground cover, hence tools to predict this can be useful.**
3. **Higher intensity cropping systems with more time in-crop use more of the rainfall but achieve lower crop WUE; lower intensity systems turn rain into grain more effectively.**
4. **Balancing time in fallow and crop water use efficiency by applying thresholds is critical to maximise system water use efficiency and overall returns per mm.**

Background

The efficiency that soil water accumulates during fallows and availability of that soil water for use by crops are key drivers of farming system productivity and profitability. Using fallows to accumulate soil water to buffer subsequent crops against the highly variable climate is critical in northern grain production systems. Fallow efficiency (i.e. the proportion of rain that accumulates in the soil profile) can be influenced by a range of factors, including ground cover, seasonality or timing of rainfall events, the length of the fallow, and residual water left at the end of the preceding crop.

Accumulating more soil water prior to sowing a crop is always preferable, as crops with higher starting water are often more efficient and less reliant on in-crop rainfall to drive their final yield. However, this often requires longer fallow periods, resulting in additional costs for maintaining that fallow and reducing the number of crops grown. Optimising water use efficiency of the farming system is a balancing act between maximising fallow water accumulation and the capacity of crops to convert available water into product. Here we look at data collected from farming systems experiments over the past seven years to examine how different farming systems have impacted on these factors

Crop water use efficiency and influence of soil water

Crop water use efficiency (WUE) is the amount of grain produced per mm of water available to the crop, including rainfall during the growing season plus soil water at sowing, minus the residual water left at harvest. Figure 1 shows this relationship for wheat, chickpea and sorghum across the farming systems experimental data; the average WUE (kg grain/mm) was 17.3 for wheat, 8.2 for chickpea and 20.8 for sorghum. However, there is always significant variability in WUE due to differences in growing season conditions, timing of rainfall and/or other factors that might reduce crop performance (e.g. nutrient deficiencies, disease). The best 20% of crops achieved a WUE of 23.2 (wheat), 11.8 (chickpea) and 25.1 (sorghum).

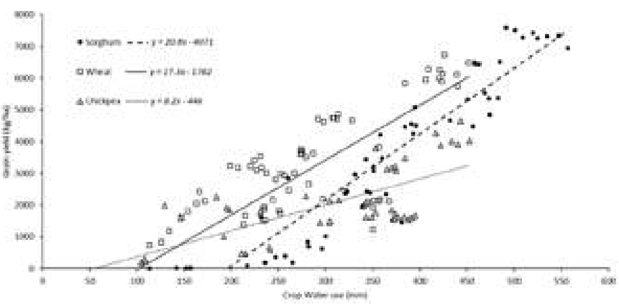


Figure 1. Relationship between crop water use (soil water extraction + rainfall) and grain yield (crop WUE) across crops monitored in northern farming systems experiments. The slope of the line indicates WUE of each crop and the X-intercept the estimate of the minimum water available to produce grain for each crop.

Figure 1 also clearly shows a minimum amount of water is required before a crop will produce yield (i.e. the amount of water required to grow sufficient biomass to produce grain) – about 60 mm for chickpea, 100 mm for wheat and 200 mm for sorghum, which grows during summer with a higher evaporative demand.

At the start of the sowing window, crops with lower soil water achieved lower crop WUE (they were less able to convert the available water into grain yield; Figure 2). These crops were likely to have encountered water stress, although crop WUE also often declines at higher water availability, when surplus rainfall is unavailable to the plant due to runoff, or lost via higher evaporation. The boxes in Figure 2 indicate crops that achieved the best WUE (where the curve peaks).

For each crop there are critical soil moisture levels where crops are more likely to maximise their WUE: 110-180 mm plant available water (PAW) for wheat, 80-160 mm for chickpea and >140 mm for sorghum. While the outcome for each crop is a result of subsequent seasonal conditions, these values indicate a trigger to sow these crops that enables them to use their water most effectively to produce grain.

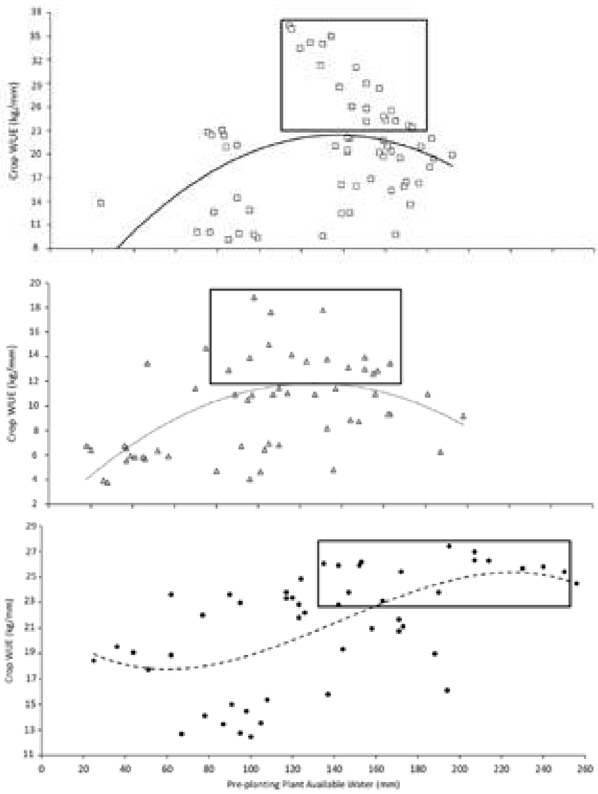


Figure 2. Relationship between crop WUE and plant available soil water (PAW, mm) sampled at the start of the sowing window for wheat (top, open squares), chickpea (middle, grey triangles) and sorghum (bottom, black circles) across farming systems experiments.

Fallow water accumulation

Two main factors drive the amount of water available at sowing:

1. accumulation over the prior fallow period
2. residual moisture from the previous crop.

Fallow efficiency is the proportion of fallow rainfall that accumulates in the soil profile. A higher fallow efficiency can significantly increase the available water for subsequent crops. A fallow receiving 400 mm of rain with an efficiency of 25% will have accumulated 100 mm of soil water at sowing while a fallow with an efficiency of 20% would have only accumulated 80 mm. This difference could have a significant impact on the opportunity to sow a crop and/or the gross margin of the following crop.

Fallow efficiency is significantly influenced by environmental conditions such as the timing of rainfall events, which can vary dramatically from season to season. Overall, most baseline systems (representing current district best practice) achieved fallow efficiencies of 22% ± 4% over the whole cropping sequence. This is consistent with long-term simulations which show fallow efficiencies of 21-24% for cropping systems with crop intensities of 0.75-1.0 crops per year (i.e. 66-75% time in fallow).

These values are lower than those calculated by others historically (e.g. Robinson & Freebairn's 2017 fallow efficiencies were 25-30% under no-till). Current cropping systems include a higher proportion of legumes and summer crops, which are more likely to achieve lower fallow efficiencies than winter cropping systems (see Figure 3) and using a generic 30% fallow efficiency may therefore over-estimate fallow water accumulation.

Environments with more winter-dominant rainfall had lower fallow efficiencies over summer fallows – likely due to smaller and less frequent rainfall events occurring meaning that soil water accumulated less efficiently.

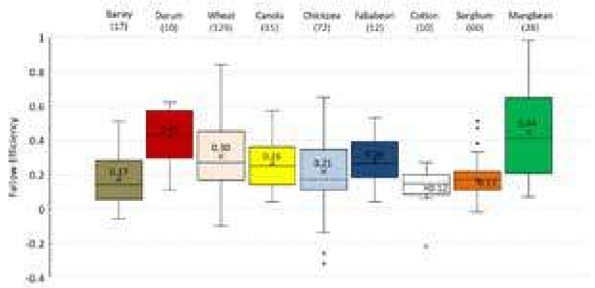


Figure 3. Summary of observed fallow efficiencies following different crop types between 2015 and 2022.

Boxes indicate 50% of all observations with the line the median and the x the average; the bars indicate the 10th and 90th percentile of all observations. Numbers in brackets indicate the number of fallows included for each crop type.

Influence of crop residues and fallow lengths

Fallow water accumulation (including residual soil water and final soil water) following a range of different crops was monitored for over 350 previous crops across the farming systems sites to compare how different crop types impact subsequent fallow efficiencies (Figure 3), highlighting the large variability in fallow efficiency that occurs and clearly showing the effects of different crops:

- Fallow efficiencies were higher after winter cereals than after winter pulses. The median fallow efficiency was 0.27 following winter cereals (wheat, barley and durum), and 0.19 following chickpea and other pulses, with canola intermediate (0.23).
- Lower fallow efficiencies after sorghum (median of 0.17) were due to a high proportion of long fallows. Short fallows after sorghum were generally higher efficiency (i.e. 0.21 compared with 0.16).
- Fallow efficiencies after cotton were the lowest (0.12). Usually longer, they often had tillage for pupae control and/or less residue.
- Fallow efficiencies following mungbean were highly variable. High efficiencies indicated by the data are likely due to carry-over residues from previous cereal crops, as mungbeans are often double cropped following wheat.

Fallow length also impacts on fallow efficiency. Longer fallows are generally less efficient – median efficiencies for long fallows (>9 months) was 0.16, short fallows (4-9 months) was 0.23, while those involving a double crop (<4 months) were 0.33.

Contribution of residual water at harvest

Lower fallow efficiencies don't always translate into less soil water at sowing of the next crop as drier soils typically result in more efficient fallows than situations with more residual moisture.

For example, legume crops often leave soil water at harvest and despite a lower fallow efficiency following pulses may have similar water available for the next crop. Table 1 lists cases where chickpea and wheat were grown in the same season. An average of 41 mm more residual soil water at harvest was present after pulse crops (chickpeas, fababeans or field peas) compared to after wheat. This was often associated with rainfall later in the crops' development that the winter cereals utilised but the maturing pulses did not. However, by the end of the subsequent fallow this difference had reduced to an average of 10 mm more water in the soil profile after chickpea compared to wheat or barley. Therefore fallow efficiency is not the only contributor to soil water in the next crop and you can't assume that the additional moisture after a pulse will mean additional soil water available for subsequent crops.

Variability in fallow efficiency amongst farming systems approaches

The efficiencies of all fallows within different farming systems were anaylsed by calculating the ratio of all rain falling during fallow periods to total accumulated soil water over these fallows across the whole crop sequence (not just individual crops). Significant differences in the efficiency of fallows were also found between different farming systems treatments tested across the sites.

Table 1. Residual soil water at harvest and subsequent fallow water accumulation after chickpea and wheat.

Site (season)	Crop	Residual water at harvest (mm PAW)	Fallow efficiency	Fallow rain (mm)	Final soil water (mm PAW)
Emerald (10/15 to 5/16)	Wheat Chickpea	44 71	0.20 0.19	525 568	150 177
Emerald (11/16 to 4/17)	Wheat Chickpea	93 89	0.16 0.20	341	147 158
Emerald (9/17 to 1/18)	Wheat Chickpea	56 76	0.33 0.23	364	177 157
Pampas (11/15 to 9/16)	Wheat Chickpea	61 106	0.38 0.26	459	238 198
Pampas (11/16 to 4/17)	Wheat Chickpea	41 47	0.47 0.41	299	182 167
Pampas (11/16 to 9/17)	Wheat Chickpea	9 91	0.25 0.11	344	96 129
Pampas (10/17 to 4/18)	Wheat Chickpea	28 141	0.18 0.00	228	69 139

Table 2. Comparison of fallow efficiency (i.e. change in soil water/fallow rainfall) for different cropping system strategies.

Crop system	Core - Pampas			Billa Billa	Narrabri	Spring Ridge	Emerald	Mungindi	Trangie (red soil)	Trangie (grey soil)	All site average
	Mix	Win	Sum								
Baseline	0.26	0.26	0.19	0.20	0.34	0.27	0.20	0.17	0.09	0.11	**0.21**
High nutrient	0.27	0.23	0.25	0.25	0.32	0.31	0.21	0.21	0.10	0.14	**0.23**
High diversity	0.27	0.25	0.13	0.22	0.29	0.24	–	0.28	0.06	0.16	**0.21**
High legume	0.20	0.24	0.16	0.11	0.29	0.18	0.17	0.15	0.08	0.14	**0.17**
High intensity	0.37	0.37	0.37	0.23	0.34	0.28	0.20	–	–	–	**0.31**
Low intensity	0.19	0.10	0.15	0.28	0.16	0.18	–	0.09	0.03	0.11	**0.14**

Colouring of numbers indicate the difference from the regional baseline or reference system – rust = reduction, blue = increase.

Key findings (see Table 2):

- *Higher crop intensity* increased fallow efficiencies at most sites due to less time in fallows and fallows having lower soil water content (less water is lost to evaporation).
- Systems with *lower crop intensity* had lower fallow efficiencies due to longer fallows and a greater proportion of rain and time in fallows (evaporative losses are higher).
- Systems with *higher legume* frequencies had lower fallow efficiencies (5% lower), particularly if reliant on summer rain accumulation. This effect can be large, particularly where legumes were followed by a long-fallow period, due to lower residue cover that broke down faster following pulse crops compared to cereals.
- On average, systems aimed at *increasing crop diversity* achieved similar fallow efficiencies to the baseline systems. However, there was large site-by-site variability, likely due to significant differences in how increasing crop diversity was achieved across the various locations (e.g. alternative winter break crops, or long fallows to sorghum or cotton).

Balancing fallow to achieve overall farming system water capture

The range of factors that affect fallow water accumulation and the balance of fallow and time in-crop drive differences in water use over the whole farming system. Hence, it is important to find the right balance between the length of fallow required to accumulate sufficient water to maximise crop WUE, while not dramatically reducing overall system water capture.

The overall system water capture and water use can vary significantly between farming systems. Table 3 shows the proportion of total rain used by crops for the various farming systems at each location.

Crop choice, like introducing more legumes or more diversity, has a small effect on total system water use, but big differences are driven by the cropping intensity (i.e. % of time in crop). *Higher intensity* systems almost always increased the proportion of total water use compared to the *Baseline*, and *Lower intensity* systems reduced the total water use.

Consider an environment receiving an average of 600 mm of rainfall per year. A lower intensity farming system where a crop is receiving 70% of rain in the fallow period (e.g. 0.6-0.7 crops per year) with fallow efficiencies of 0.16, would accumulate 67 mm in fallow per year and in-crop rain would be 180 mm per year – resulting in total crop water use of 247 mm per year (41% of rainfall). In contrast,

Table 3. Comparison of total water use as a percentage of total rainfall between different cropping system strategies.

Crop system	Core - Pampas			Billa Billa	Narrabri	Spring Ridge	Emerald	Mungindi	Trangie (red soil)	Trangie (grey soil)	All site average
	Mix	Win	Sum								
Baseline	69	57	78	42	57	51	45	31	57	59	**55**
High nutrient	70	57	80	42	57	51	45	31	57	59	**55**
High diversity	70	53	66	48	52	50		27	59	61	**54**
High legume	67	52	66	55	53	48	37	36	61	66	**54**
High intensity	83	83	83	67	71	51	45	–	–	–	**69**
Low intensity	51	49	45	43	27	31		18	57	55	**42**

Colouring of numbers indicate the difference from the regional baseline or reference system – rust = reduction, blue = increase.

Table 4. Comparison of yield and water use of crops with varying lengths of preceding fallow, for a range of crops and locations.

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

Double crop is 0-4 month fallow; short fallow is 4-8 month; long fallow is 9-18 months.

a farming system that captures 50% of the rain in fallows (1.2–1.4 crops per year) with fallow efficiencies of 0.30, would accumulate 90 mm of water per year and 300 mm per yr would fall in-crop – resulting in a total crop water use of 390 mm (65% of rainfall). This means for a crop grown after a longer fallow in a lower intensity system to be equally profitable it must generate 1.6 times the grain/gross margin per mm of water used.

So the question is: how much more productive or profitable are crops that are sown on a higher water threshold?

From the farming systems data, there are eight examples of where a common crop was sown at the end of fallows of varying length and different starting water (Table 4). In every comparison, higher PAW at planting resulted in increased grain yield, which in seven of the eight comparisons improved crop water use efficiency (WUE). However, 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 in most cases once the efficiency of fallow water accumulation is considered there was little difference in productivity of the systems in terms of kilograms grain produced per mm of rain. The only exceptions were a chickpea crop following an 18-month fallow at Pampas in 2017 and a sorghum double-crop at Pampas in 17/18).

However, there were more clear differences in system gross margin per mm of rain. Crops sown outside the optimal range of soil water (either too high or too low) converted rainfall ineffectively into profit in comparison to crops grown in the same season with optimal soil water at sowing. For example, in wheat, all the crops sown with pre-plant PAW <100 mm achieved lower $/mm returns. For sorghum, the two crops sown with <140 mm PAW achieved lower $/mm returns. Across these comparisons the marginal gain in profit per mm of additional water at sowing ranged from $0.50 to $14.90, but was mainly between $1.10/mm and $2.20/mm.

Implications for growers

Overall, these farming systems experiments have shown that systems with less time in fallow increase system water use and WUE through higher fallow efficiency. However, significantly higher returns for crops sown on higher plant available water more than compensates for the low efficiencies of fallow water accumulation. Crops sown on sub-optimal PAW at sowing did not achieve a higher conversion of water into profit and hence applying appropriate thresholds when sowing crops enables the system water use efficiency to be optimised. Though, this does mean that it is critical to optimise management and inputs for crops following long fallows in order to convert the extra water efficiently into yield outcomes.

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 GRDC, the authors would like to thank them for their continued support. 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.

This article has been adapted from the GRDC research paper published in November 2023 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/11/capturing-and-using-water-most-efficiently-how-much-do-crop-system-choices-matter

Further reading

Water use and accumulation

Lindsay Bell, Andrew Erbacher (2018). Water extraction, water-use and subsequent fallow water accumulation in summer crops. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/water-extraction-use-and-accumulation-in-summer-crops

David Freebairn (2016). Improving fallow efficiency. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/improving-fallow-efficiency

Kirsten Verberg, Jeremy Whish (2016). Drivers of fallow efficiency: effect of soil properties and rainfall patterns on evaporation and the effectiveness of stubble cover. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/drivers-of-fallow-efficiency

Local farming systems experiments

Andrew Erbacher, David Lawrence (2018). Can systems performance be improved by modifying farming systems? Farming systems research – Billa Billa, Queensland. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/can-systems-performance-be-improved-by-modifying-farming-systems

Darren Aisthorpe (2018). Farming systems: GM and $ return/mm water for farming systems in CQ. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/12/farming-systems-gm-and-$-returnmm-water-for-farming-systems-in-cq

Jon Baird, Gerard Lonergan (2018). Farming systems site report – Narrabri, north west NSW. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/farming-systems-site-report-narrabri

Andrew Verrell, Lindsay Bell, David Lawrence (2018). Farming systems – Spring Ridge, northern NSW. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/farming-systems-spring-ridge-northern-nsw

Lindsay Bell, Kaara Klepper, Jack Mairs, John Lawrence, Andrew Zull (2018). Farming system impact on nitrogen and water use efficiency, soil-borne disease and profit. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/03/farming-system-impact-on-nitrogen-and-water-use-efficiency-soil-borne-disease-and-profit

Lindsay Bell, Kaara Klepper, Jack Mairs, John Lawrence (2017). Improving productivity and sustainability of northern farming systems: what have we learnt so far from the Pampas systems experiment? grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2017/07/mproving-productivity-and-sustainability-of-northern-farming-systems-what-have-we-learnt-so-far-from-the-pampas-systems-experiment

Lindsay Bell, David Lawrence, Kaara Klepper, Jayne Gentry, Andrew Verrell, and Guy McMullen (2015). Improving northern farming systems performance. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2015/07/improving-northern-farming-systems-performance

References

Robinson JB, Freebairn DM (2017). Estimating changes in Plant Available Soil Water in broadacre cropping in Australia. In 'Proceedings of the 2017 Agronomy Australia Conference', 24 – 28 September 2016, Ballarat, Australia. www.agronomyconference.com

Modifying farming systems in northern grains region: legacies, profit and risk of pulse and nitrogen strategies

Jon Baird[1], Kathi Hertel[1], Lindsay Bell[2], Jayne Gentry[3], Andrew Erbacher[3], Darren Aisthorpe[3], David Lawrence[3], Branko Duric[1] & David Lester[3]

[1]New South Wales Department of Primary Industries and Regional Development
[2]CSIRO
[3]Queensland Department of Primary Industries

***Research question**: How do fertiliser strategies and increased use of pulse crops affect farming systems performance?*

Key findings

1. **Applying nitrogen fertiliser rates targeting high yields boosted long-term system productivity at several research sites, and 'banking' soil N can reduce reliance on tactical fertiliser applications.**
2. **Over the long term, including pulses can improve system profitability, however increasing their frequency will not necessarily reduce nitrogen fertiliser use because while legumes can fix nitrogen from the atmosphere, they can also extract soil mineral nitrogen if it is available. High-yielding legumes will export nitrogen at a far higher rate than similar yielding cereals, often negating any nitrogen benefit they have fixed.**
3. **Over the long-term, soil mineral nitrogen reserves and system nitrogen balances are declining regardless of different farming system strategies, except where high nitrogen replacement has been applied.**
4. **Crops are more efficient at sourcing nitrogen from soil sources than applied fertiliser, so soil monitoring is essential to determine fertility levels to match crop requirements.**

Background

Long-term sustainability and profitability of farming systems need to evolve to manage the challenges of climate variability, soil-borne pathogens, herbicide resistance in problem weeds, and declining soil fertility with increased reliance on costly fertiliser inputs. A major challenge is to match crop nutrient supply and demand under variable growing conditions and maintain the soil's underlying fertility into the future. The Northern Farming Systems Project is looking at the long-term implications of different fertiliser application strategies and using more legumes in the farming system.

Legume (pulse) crops represent just 10% of the total cropping area nationally (Pulse Australia 2023), with winter species predominating in the northern cropping region. Legume crops can fix nitrogen (N) via rhizobial symbiosis but also remove N from the system via plant residues and grain. This creates a different dynamic to the overall farming system compared to that of non-legume crops.

Given that N is a major variable cost in most farming systems with heavy reliance on off-farm sources (primarily urea), the effect of legumes on subsequent crops' N requirements, performance, and soil N balance can be significant. Understanding these impacts together with pulse profitability and risk are key to improving the future sustainability and profitability of farming systems.

What was done

The project commenced in 2014 with long-term experiments at seven locations: a core experimental site comparing 38 farming systems at Pampas near Toowoomba, and a further six regional sites with six to nine locally-relevant farming systems at Emerald, Billa Billa and Mungindi in Queensland and Narrabri, Spring Ridge and Trangie in NSW.

This report will focus on three farming systems treatments implemented across the experimental sites: the local regional '*Baseline*' or current best management system (the selection of crops and their management were designed in partnership with local grower panels), and systems with modified strategies that increased either nitrogen

(N) fertiliser rates (*Higher nutrient*) or legume crop frequency (*Higher legume*) across the system:

1. *Baseline* – analysed as the control treatment. Crops were planted at or above soil moisture of 50% plant available water (PAW) and fertiliser N and phosphorus (P) rates were applied to meet the demand of a 50^{th} percentile crop yield.
2. *Higher nutrient* — identical crop sequence to *Baseline* but with higher N and P fertiliser rates applied to meet the demands of a 90^{th} percentile crop yield.
3. *Higher legume* - at least 50% of planted crops are legumes, with crops planted at or above 50% PAW. Fertiliser N and P rates were applied to meet the demand of a 50^{th} percentile crop yield for non-leguminous crop. In pulse crops no N fertiliser was applied and P fertiliser rates were calculated to meet export rates.

Over seven years of cropping (2015 to 2021), seasonal conditions at regional experiment sites have varied, with extremes of drought and flooding, as well as 'average' and 'favourable' seasons.

Results

Grain productivity

Increased nutrients

Applying higher fertiliser rates across seasons maintained higher residual N levels in the soil. The legacy of this higher soil fertility within the system provided a strong foundation for future crops to optimise production, especially in average or above average rainfall seasons. At three of the seven regional sites, applying additional fertiliser in the *Higher nutrient* system increased grain productivity compared to the *Baseline* system. At these sites grain production increased on average by half a tonne per hectare over the seven seasons (Figure 1). The lack of positive rsponse at the other sites to additional N was mostly because the drier than average seasonal conditions meant that crop demand did not exceed supply provided in the *Baseline*, and hence the additional N was not required.

At one site (Trangie grey soil), grain yield was slightly lower in the *Higher nutrient* system than the *Baseline*. In this example a lower yield was obtained in one year. In other years, seasonal conditions prevented taking advantage of the extra soil N.

Increased legumes

Increased plantings of pulses in cropping systems over recent years has been driven in part by the profitable prices for pulses, along with an aim to reduce N fertiliser use and potentially improve soil health/fertility. However, the addition of legumes to the farming system had little to no influence on productivity over the seven years at most sites. We identified variability and a higher risk with the adoption of legumes at two sites (Pampas and Billa Billa) that had lower system grain yields than the *Baseline* system. Pulses often produce lower yields than cereals, but many have higher prices per tonne so the economic outcome may look quite different to non-leguminous crops (Figure 2).

System economics - profit/loss

Economic analyses of the farming systems used 10-year average grain prices (2011-2020) and general input/machinery/processing costs. System gross margins from the last six seasons show that while current growers' practices (*Baseline*) are performing well in their regions, several sites have improved returns by incorporating more legumes or applying more fertiliser for higher yield production (Figure 2).

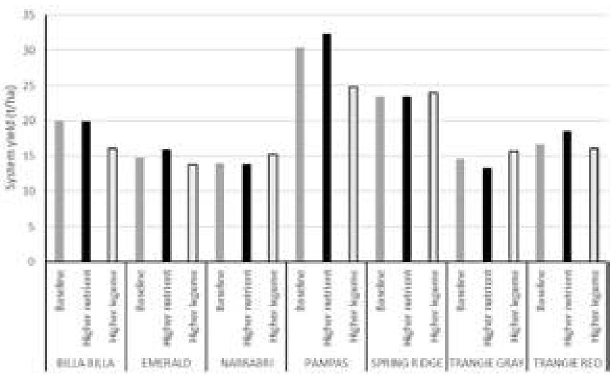


Figure 1. Grain production (t/ha) in the *Baseline*, *Higher nutrient*, and *Higher legume* systems over 7 years (2015–2021) at long-term farming systems experiments.

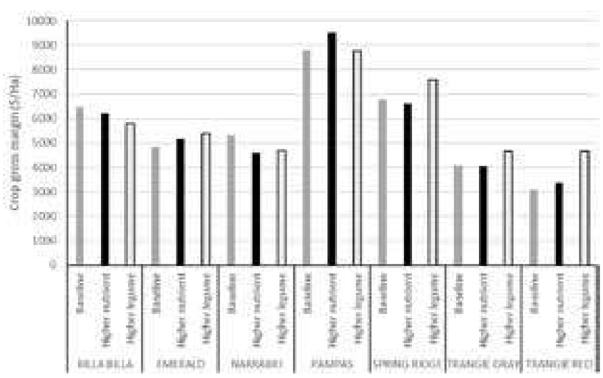


Figure 2. Cumulative crop gross margins over 7 years (excl. fallow costs) of the modified farming systems with additional fertiliser input and legume crops (2015–2021).

Increased legumes

Over the seven years, the *Higher legume* systems produced higher or equal returns at five of the seven sites compared to the *Baseline*, while there was a small penalty ($500/ha) at two sites. For example, at the Spring Ridge and the Trangie red soil site, systems gross margins were >$1000/ha higher in the *Higher legume* system (Figure 2). These higher gross margins are related to the higher grain price of legumes over this period, however these high prices can be variable and growers should be aware of current grain prices and understand the often-higher input costs associated with high-yielding legumes.

Increased nutrients

Higher grain yields with additional fertiliser application were achieved at three of the seven sites, however higher fertiliser input generated a greater cost to the *Higher nutrient* system, reducing long-term system profitability at the other sites where there was no grain yield response to the additional N applied.

While this analysis did not consider the value of N 'banked' in the soil, there were deficits to the gross margin compared to the *Baseline* system even if this added value was included (Bell et al. 2022). Nonetheless, the cost of this high nutrient strategy is relatively small (equating to around $20/ha/yr) compared to the upside that can be achieved when seasonal conditions are positive.

Legacy effects of legumes on crop yields and nitrogen use of following cereals

A closer investigation into the legacy of pulses in a farming system was conducted by examining particular crops and short-term sequences within the various systems across the experiments. This was done by comparing grain yield and crop N use of subsequent crops grown after either a winter legume or non-legume crop (Table 1). Of the seven comparisons, only two occasions saw an observable yield benefit following legumes compared to a non-legume crop. On all but one occasion the crop following the legumes also received a similar N application to meet the N budget predicted for that crop in that season. Typically crops grown after a legume crop had higher N use (i.e. the change in mineral N between sowing and harvesting plus applied fertiliser N). This was due to sourcing more N from the soil mineral pool and N derived from the legume's N fixation activity rather than applying higher fertiliser N rates.

Farming system influence on fertiliser nitrogen input requirements

Fertiliser prices were at record levels in 2023, highlighting how improving fertiliser recovery and efficiency can be crucial to maximising growers' return on investment. Here we examine the degree that different farming systems have altered the N inputs required and the balance of N applied and exported over the seven experimental years.

One aspect of the *Higher legume* system was to investigate whether additional legumes would maintain or improve soil fertility while at the same time reducing fertiliser input over the long term. At most sites, there was little if any change in the total fertiliser N required in the *Higher legume* system compared to the *Baseline* (Table 2).

On average across all sites, the *Higher legume* systems required 45 kg N/ha less over the 6 years than the *Baseline* (i.e. only 8kg N/ha/yr less) because the legumes exported much more N from the system (Table 2), leaving little additional N cycled to offset subsequent N applications in non-legume

Table 1. Legume crop influence on the following crop yield, N applied and used (applied fertiliser plus the change in soil mineral N) across various comparisons in farming systems experiments.

Site	Season	Crop	Previous crop	Grain yield (t/ha)	Applied N fertiliser (kg/ha)	Crop N use (kg N/ha)
Narrabri	2017	Wheat	Chickpea	2.4	76	129
			Fababean	2.2	76	112
			Canola	2.0	76	79
Spring Ridge	2017	Wheat	Chickpea	3.2	52	152
			Fababean	3.2	52	123
	2020	Wheat	Chickpea	4.8	27	139
			Canola	4.9	96	107
Trangie – grey soil	2018	Barley	Wheat	0.4	9	9
			Chickpea	0.1	9	9
	2020	Wheat	Canola	2.0	9	157
			Fababean	4.3	11	269
Emerald	2017	Wheat	Chickpea	1.8	26	93
			Wheat	1.6	26	43
	2020	Wheat	Chickpea	1.8	–	45
			Wheat	2.2	–	9

Table 2. Fertiliser N applied and grain N exported from *Baseline*, *Higher nutrient* and *Higher legume* systems across 6 farming systems sites over 7 experimental years (2015-2021).

Location	Fertiliser N applied (kg N/ha)			Exported N (kg N/ha)		
	Baseline	Higher nutrient	Higher legume	Baseline	Higher nutrient	Higher legume
Billa Billa	18	77	23	417	451	430
Emerald	49	55	11	330	347	335
Narrabri	206	447	208	345	350	468
Pampas	155	337	80	498	538	556
Spring Ridge	307	446	146	482	496	450
Trangie Grey	63	169	89	235	287	322
Trangie Red	137	395	105	263	344	300

crops. Spring Ridge is one site where the application of N fertiliser was significantly reduced under the *Higher legume* system compared to the *Baseline* system, indicating a potential saving in fertiliser use by growing more legumes in this region when background soil nitrate levels are low. However, soil N has also been extensively used during the same period (Figure 3), and therefore soil nutrients must be monitored to ensure native soil nitrogen use is not detrimental to long-term soil fertility.

A common theme across most farming system sites is that applying the higher fertiliser strategy clearly required additional N inputs (ranging from an additional 6 to 260 kg N/ha over the 6 years). However, the unused surplus N was retained in the soil and so maintained higher mineral N levels in the soil than the *Baseline* system, which then offset the required N in subsequent crops (Figure 3).

Maintaining a higher system N status via N banking is a potential management practice in northern farming systems to ensure greater yields can be achieved in high decile seasons. Lester et al (2021) found that fertiliser recovery can be improved when nitrogen is applied early in the fallow, and logistics improve for growers when they fertilise during lower labour demand period rather than at sowing or during the growing season.

Something growers need to be aware of when applying fertiliser early in a fallow period is the potential losses that could occur during the fallow before the crop can utilise the N. For example, a severe weather event at Spring Ridge caused high mineral N loss in late 2019 in the fallowed *Baseline* and *Higher nutrient* systems, with losses between 203 and 152 kg N/ha (Figure 3). These events may be rare, but they can cause significant losses, particularly in paddocks prone to waterlogging.

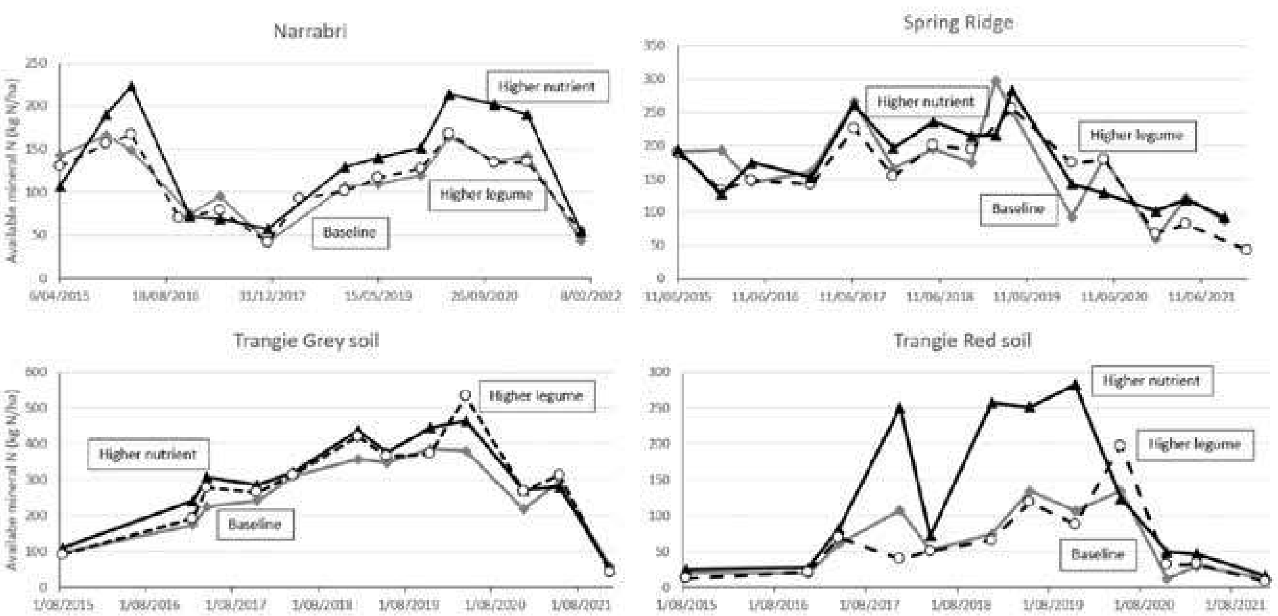


Figure 3. Mineral nitrogen long-term dynamics at Farming system sites in Northern NSW. The grey line and diamond marker are ***Baseline*** system; black line and triangle is the ***Higher nutrient*** system; and the dashed line with open circle is the ***Higher legume*** system. Note y axis scale varies at each site.

Source of crop nitrogen use

For the three modified cropping systems across the seven experimental sites – *Baseline* (triangle), *Higher nutrient* (square) and *Higher legume* (circle), the source of N was calculated over the experimental period (2015-2021), with Figure 4 showing the proportion derived from either the starting soil mineral pool, applied fertiliser, or nitrogen mineralised from the soil (i.e. accumulated during a fallow or the balance of crop uptake that was not sourced from fertiliser or soil mineral pools).

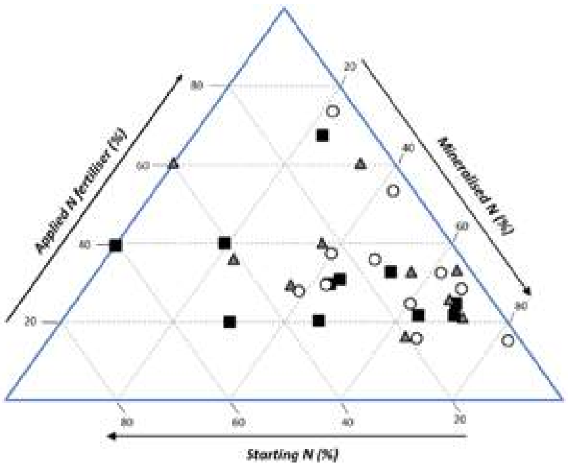


Figure 4. The source of N used by modified systems as a percentage of crop use.
Baseline is grey triangles; ***Higher nutrient*** is black squares and ***Higher legume*** is white circles. The dotted lines represent 20% levels of percentage for each N source.

This study highlights the importance of cropping systems' efficiency in utilising N from stored organic sources. Most systems and experimental sites sourced at least 40% of their nitrogen from mineralised organic or stored N rather than drawing down from starting N levels. This data supports findings from Daniel et al. (2019) where the efficiency of N grain recovery from soil N sources was ≈4 times greater than that of applied fertiliser N.

Including more pulses in the rotation resulted in crops utilising more N from mineralised N, attributable to the faster breakdown of legume residues. This meant there is generally a lower reliance on using background N (starting N) and synthetic fertilisers.

Effect of crop choice on nitrogen export from a farming system

Previous reports from the Northern Farming Systems Project have shown there is minor to no reduction in fertiliser application when pulse crop frequencies were increased (Baird et al. 2019). This article shows that pulses increase cropping systems' N balance compared to cereals, with the majority of N sourced from increased cycling of N.

Crop N export rates help us understand the gap between system N balance and fertiliser input between pulses and cereals. High-yielding pulses with a high harvest index will export N at a far higher rate than similar yielding cereals (Figure 5). The N export rate is significantly different for yields above 2.5 t/ha. For example, a pulse crop yielding 5 t/ha will on average export 174 kg N/ha while wheat will export 110 kg N/ha.

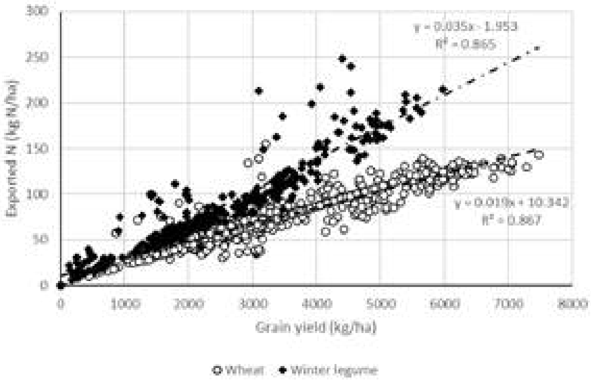


Figure 5. Crop export rates of wheat and winter pulses (including chickpea, faba bean and field pea) from the Northern Farming Systems Project (2015–2021).

Implications for growers

Long term, soil mineral nitrogen reserves and system nitrogen balances are declining regardless of different farming system strategies, except where high nitrogen replacement has been applied.

Modifying farming systems can provide growers with potential improvements in yield and gross margins, but legacies need to be monitored as every system will have pros and cons. Farming systems containing a high frequency of pulse crops do not necessarily reduce nitrogen fertiliser use.

Growers with farming systems that utilise more pulses should be mindful of their high use (and cycling) of N. While legumes can provide inputs of nitrogen via fixation from the atmosphere, they can extract soil mineral nitrogen if it is available. The high N removal and potential to extract mineral N may in fact mean that pulse crops have little or no direct benefit or on occasion lower mineral N than following non-pulse crops. The N balance outcome is largely dependent upon the grain yield (amount of N exported kg/ha) and peak biomass of the legume crop (directly related to the amount of N fixed kg/ha).

It's recommended that growers monitor their soil N levels to ensure their systems won't be yield limited due to low soil N which may happen if a high loss event occurs. It is important to know the current soil N status and not that legumes will have left excess N or contribute additional N to subsequent crops.

It is also clear that systems that include high application rates of N fertiliser do maintain higher levels of background N and reduce reliance on tactical fertiliser applications; much of the N is carried over to subsequent seasons. This strategy will ensure growers have sufficient N to reach their yield potential in most seasons. However, the economics of this system needs to be considered. It may cost more when fertiliser prices are high, but may also allow rates to be cut when prices are high if there is sufficient carry-over N to meet crop demands.

Acknowledgements

We thank the local growers and consultants who have actively supported and continue to contribute towards this project. We also thank the Grains Research and Development Corporation (DAQ00192; CSA00050; DAQ2007-004RMX) the Department of Primary Industries and Regional Development in New South Wales, the Department of Primary Industries in Queensland, and the CSIRO who have supported this long-term project. This article has been adapted from a GRDC paper published in February 2023.
grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/02/modifying-farming-systems-in-northern-grains-region-legacies-profit-and-risk-of-pulse-and-nitrogen-strategies

References

Baird J, Gentry J, Lawrence D, Bell L, Aisthorpe D, Brooke G, Erbacher A, Verrell A, Zull A and Klepper K (2019). The impact different farming systems have on soil nitrogen, phosphorus and potassium. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/03/the-impact-different-farming-systems-have-on-soil-nitrogen,-phosphorus-and-potassium

Bell L, Baird J, Lawrence D, Lester D, Gentry J, Aisthorpe D, Erbacher A, Hertel K and Anderson B (2022). Farming system nutrient legacies – impacts of N strategies on N inputs, cycling and recovery over multiple years. grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/03/farming-system-nutrient-legacies-impacts-of-n-strategies-on-n-inputs,-cycling-and-recovery-over-multiple-years

Daniel R, Norton R, Mitchell A, Bailey L, Kilby D, Duric B and Price L (2019). 5 years of nitrogen research – have we got the system right? grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/08/5-years-of-nitrogen-research-have-we-got-the-system-right-

Lester D, Bell M, Sands D (2021). (Possible) Nitrogen strategies, application timing and surface spreading in CQ (or, 'things I know that I don't know'). grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2021/11/nitrogen-strategies,-application-timing-and-surface-spreading-in-cq

Pulse Australia (2023). www.pulseaus.com.au/about/australian-pulse-industry#industryoverview

Greenhouse gas footprint of different farming systems in the northern grains region

Lindsay Bell[1], Dean Schrieke[1], Brook Burrett[1], Maartje Sevenster[1], Nazmul Islam[1], Andrew Erbacher[2], Darren Aisthorpe[2], Jon Baird[3], Branco Duric[3]

[1] CSIRO Agriculture and Food
[2] Queensland Department of Primary Industries
[3] NSW Department of Primary Industries and Regional Development

Key findings

1. More than half of emissions were soil nitrous oxide (N_2O) losses; pre-farm gate emissions were typically <20%.
2. Accounting for changes in soil carbon significantly altered the greenhouse gas footprint across sites and systems.
3. Despite higher inputs, higher intensity cropping systems generated lower total emissions, as drier soils and reduced time in fallow limited N_2O losses, and increased biomass inputs improved the soil carbon balance.
4. Higher nutrient input strategies led to higher emissions due to increased N_2O losses, as well as higher emissions associated with fertiliser production and use.
5. Changing the crop mix or increasing legume frequencies did not consistently impact total emissions; differences were site-specific.

Background

Reducing greenhouse gas (GHG) emissions is crucial for the environmental standing and global market access of Australia's agricultural sector. Identifying and implementing practices that reduce emissions or optimise GHG intensity (maximise productivity per unit of GHG emitted) is a key priority of the Australian grain industry. While national studies have been conducted to assess GHG footprints and mitigation options (see Grains Research and Development Corporation's Emissions Factsheet; grdc.com.au/__data/assets/pdf_file/0022/572350/Emissions-Factsheet-V7.pdf), the implications of local practices remains unclear. A localised approach is necessary to provide detailed insights and verify assumptions from broader assessments.

Farming systems experiments funded by GRDC offer a comprehensive dataset for evaluating the GHG impacts of different farming methods across the northern grains regions of New South Wales and Queensland. This dataset spans several years and includes multiple system variations, such as: increasing crop diversity (including legume frequency and alternative crops); altering cropping intensity (balance between fallow and active growth phases); strategies that influence fertiliser and chemical inputs; and the incorporation of regenerative practices such as ley pastures or cover crops. Each of these factors influence soil carbon (C) and nitrogen (N) balances, as well as input requirements. Consequently, this study aims to assess the potential of a diverse range of farming systems to mitigate or lower GHG emissions and intensity.

What was done

Farming systems experiments

Farming systems experiments have been underway at seven locations in central and southeast Queensland and northern New South Wales since 2015. These experiments capture data crucial for estimating GHG emissions and intensity (i.e. GHG per tonne of grain/product), including variables like crop biomass and grain yield, fertiliser and chemical inputs, and operations such as sowing, harvesting, and spraying. Due to intricacies and ambiguities in attributing emissions from livestock grazing, systems that incorporate rotations with ley pastures have been omitted from this analysis (but are likely to be included in the future). As a result, this report focusses exclusively on grain production systems.

The dataset comprises over 80 combinations of farming system treatments across 7 sites spanning eight years (March 2015 – April 2022). Each site features a *Baseline* system, embodying the prevailing understanding of a best-practice crop sequencing and management of the respective cropping region. Alternative systems modify the *Baseline* sequence in several ways: *Higher/lower crop intensity* – widening sowing windows and altering the soil water threshold to trigger sowing a crop and thus increasing/decreasing the proportion of time when crops are growing; *Higher legume* – incorporating at least 50% pulse crops; *Higher crop diversity* – increasing the range of crops available for use (e.g. canola, cotton) and forcing a two-break crop requirement before the same crop can be grown again; and *Higher nutrient supply* systems, which increase the annual nitrogen and phosphorus budget from a median crop yield (Decile 5) to a higher yield expectation (Decile 9). At most sites, individual treatments are applied, while combinations of these strategies were evaluated in a core experiment at Pampas on the Eastern Darling Downs.

Calculating GHG emissions

Drawing from farming systems experimental data, we employed a Tier 3 (i.e. locally specified calculations or modelling) approach to estimate GHG emissions over the experimental period, whereas Tier 2 or Tier 1 approaches use national or international emissions factors to estimate emissions using regional activity data. Emissions were separated into Scope 1 (on-farm), Scope 2 (associated with electricity use on farm) and Scope 3 (pre-farm gate emissions embedded in farm inputs like fertilisers and pesticides). Scope 2 emissions were negligible (<1% of total) and thus not included in this analysis. Scope 1 emissions occurring on-farm include sources such as N_2O emissions from the soil (including from decomposition of crop residues), and CO_2 emissions from diesel used by on-farm machinery and hydrolysis of urea fertilisers. Using activity data for each site and system we simulated experimental management in APSIM to predict direct N_2O emissions (from the soil), indirect N_2O emissions (from N lost in runoff or leaching) and changes in soil carbon (C) over the experimental period (Figure 1). Other emissions sources were estimated using emissions factors defined in the National Greenhouse Gas Inventory (NGGI) 2021 (National Inventory Report, 2023).

After compiling total GHG emissions from the various sources, we calculated the emissions intensity for each system, defined as the gross margin per kilogram of CO_2 emitted. While other analyses might measure emissions intensity per tonne of grain, this approach does not provide a fair comparison among systems due to variations in yield and values of the different crop types that make up these systems. This metric also aids in estimating potential abatement costs (the cost to implement a system that reduces net emissions). However, our calculations are based on assumptions about crop prices and inputs, making these figures specific to certain seasons and conditions and not universally applicable.

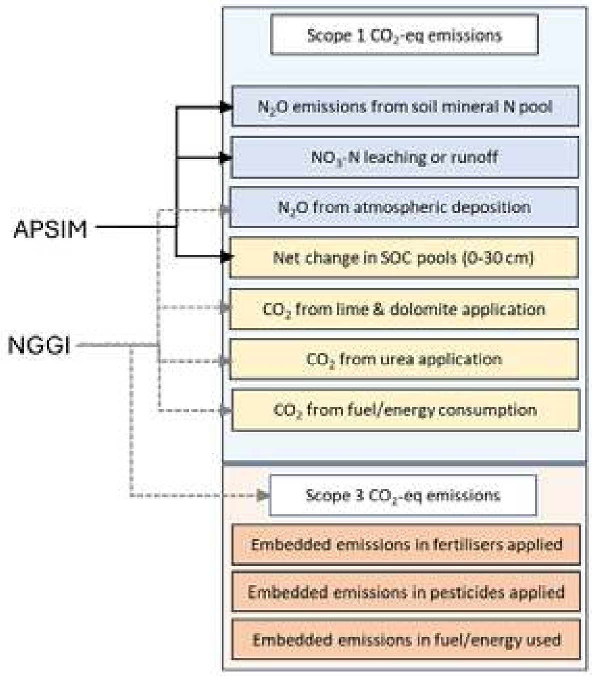


Figure 1. Various GHG sources calculated using activity data from farming systems experiments and those that were estimated from simulations using APSIM and those that used the National Inventory Report (2021) values.

Emissions sources from farming systems

Without considering soil C change, other emissions sources were estimated to average 830 kg CO_2-eq/ha/yr and vary amongst sites between 650 to 1400 kg CO_2-eq/ha/yr for the *Baseline* systems, except Mungindi which has a drier climate and hence was significantly lower (330 kg CO_2-eq/ha/yr).

Across all sites, emissions associated with direct N_2O losses from the soil were the largest contributor to the GHG footprint of the farming system (Figure 2). While N_2O losses are small, they have a large relative global warming potential, with each kg of N_2O has an impact equivalent to 298 kg of CO_2. It is worth noting that this estimated N_2O emission includes emissions from both applied fertilisers and N mineralised from soil organic matter (discussed below). Scope 3 emissions associated with inputs of fuel, fertiliser and pesticides were typically less than 20% of the total emissions at all sites, but the relative contribution of each varied depending on the use of

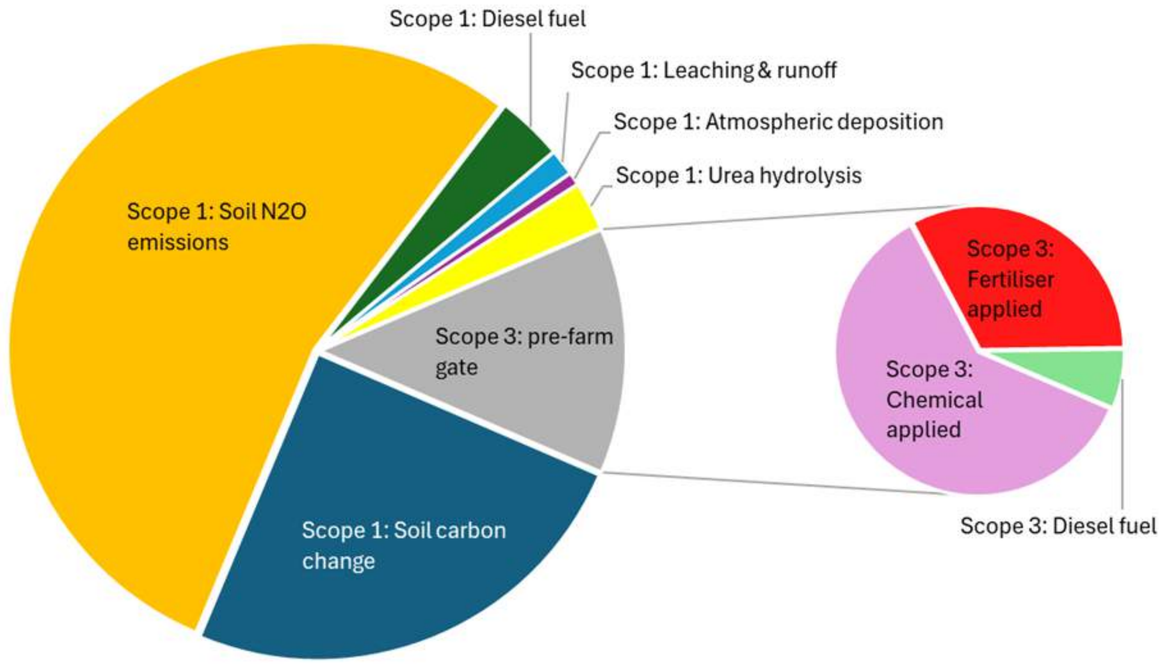


Figure 2. Contribution of different sources of GHG emissions to the net emissions from *Baseline* farming systems (kg CO_2-eq. per ha per year) averaged across all sites over the period 2015–2022.

these inputs (Figure 2). There was large variability in the estimated change in soil C between sites, but on average the soil C decline was estimated to contribute 25% of the total emissions.

Farming system impacts on GHG footprint

Emissions before including soil carbon change

There were some consistent trends in terms of relative emissions amongst systems across sites. The *Higher nutrient supply* strategies, where crops were fertilised to target a maximum grain yield potential, generated higher emissions than the *Baseline*, largely due to elevated N_2O emissions, but also due to slightly higher Scope 3 emissions from fertiliser production and from urea hydrolysis. On average these systems increased emissions by 300 kg CO_2-eq/ha/yr.

The *Higher crop intensity* farming systems, characterised by more frequent cropping had lower N_2O emissions than other systems, due to the system having less time in fallow and having drier soils that reduced the frequency and size of soil N loss events (e.g. denitrification). On average they had emissions 120 kg CO_2-eq/ha/yr lower than the *Baseline*. Conversely, *Lower crop intensity* systems, where crops are only grown when the soil profile is full, had longer fallow periods and consequently wetter soils, which led to increased net N_2O emissions compared to their higher-intensity counterparts. On average, these systems had emissions 140 kg CO_2-eq/ha/yr higher than the *Baseline*.

There was large between-site variability in response to changing the crop mix via increasing crop diversity or legume frequency. Compared to the *Baseline*, the N_2O emissions from the *Higher legume* system were similar or marginally higher at three sites, lower at one site (Emerald), and significantly higher at two sites; on average emissions were 200 kg CO_2-eq/ha/yr higher than the *Baseline*. This variation appeared to be driven by circumstances when legumes left higher mineral soil N which was then prone to losses (e.g. denitrification) over the subsequent fallow. The N_2O emissions from the *Higher crop diversity* systems were reduced at two sites, increased at two sites and similar at one site; with an overall neutral effect on GHG emissions compared to the *Baseline*. This variation appears to be related to the types of crops implemented to diversify the farming system across the experiments; some sites involved cereals like sorghum, while at others this was replaced by crops like canola or cotton.

Soil carbon change influences system GHG footprint

Incorporating simulated changes in soil C (0–30 cm depth) into the GHG emissions calculations significantly influences the estimated net emissions across sites and between systems. At the Billa Billa and Emerald sites, where simulations began with high measured levels of labile organic C, reductions in soil C contributed to 50–70% of the farming systems' GHG footprint (Figure 3). This corresponds to an annual decrease in soil C ranging from 250 to

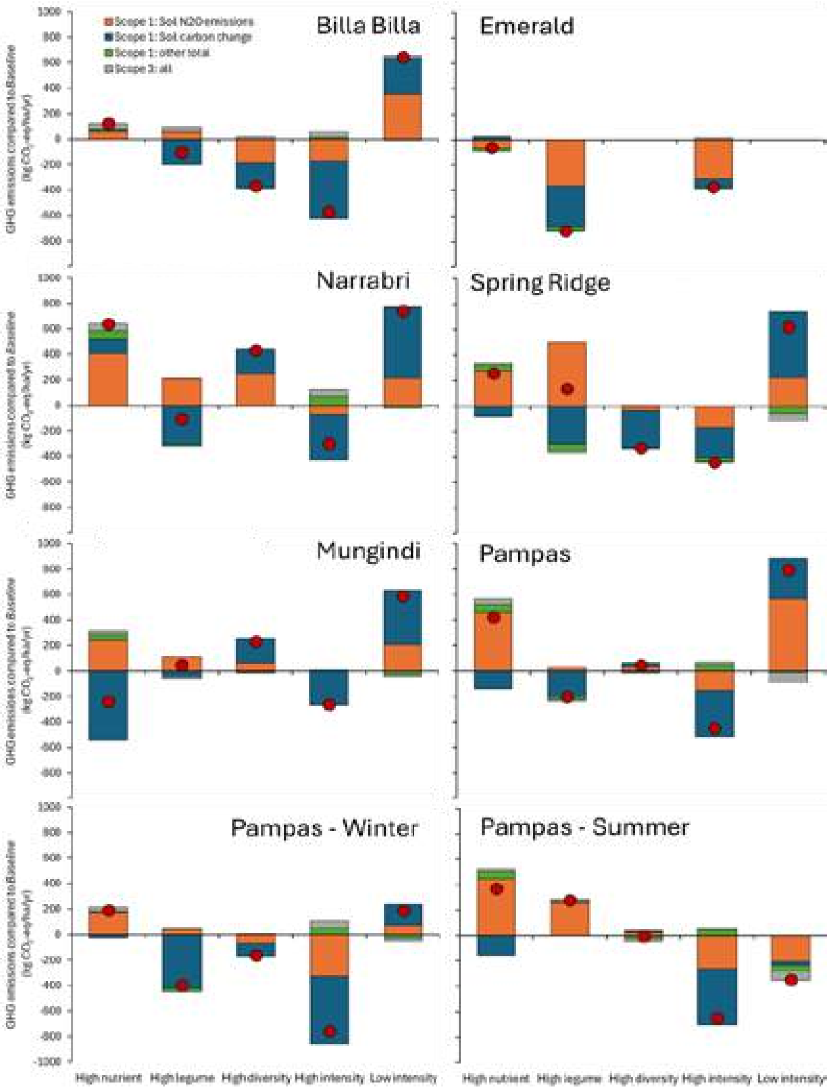


Figure 3. Estimated GHG emissions (kg CO_2-eq/ha/yr) and their sources amongst different farming systems compared to the Baseline system at each experimental location over 8-years. Bars indicate the magnitude of change (either positive – increasing emissions, or negative – decreasing emissions) and the red dot is the total change accounting for all computed sources. Sources estimated include on-farm (Scope 1) emissions from N_2O coming from the soil and crop residue decomposition, simulated increases or decreases in soil carbon over the life of the experiment, other Scope 1 emissions from fuel use, urea hydrolysis or leaching/runoff losses of N and pre-farm gate (Scope 3) emissions embedded in inputs of fertilisers, crop protection products and fuel.

450 kg/ha over the experimental period. Measured soil C at both sites has also trended down over the experimental phase. Other experimental sites had relatively stable or minor changes in soil C (150 kg of soil C/ha/year), and in several instances, there was a predicted net C sequestration, which could offset other emissions by up to 550 kg CO_2-equivalent/ha/yr. Notably, some of the higher intensity cropping systems at Pampas were predicted to result in a net C gain over the experimental period, making them GHG positive.

Consistent trends were observed across sites regarding the impact of farming systems on soil C change, which in turn affected the net GHG emissions. Across all sites, the *Higher crop intensity* farming systems demonstrated a more favourable soil C balance compared to the *Baseline*. This improvement is attributed to the higher biomass (and therefore C) inputs in these systems, resulting from more frequent cropping and reduced time in fallow over the same period. Increased biomass, combined with lower N_2O emissions, meant that these systems consistently recorded the lowest net GHG emissions. In contrast, the *Lower crop intensity* systems were predicted to have a negative soil C balance at all sites (significantly worse than other farming systems). This adverse outcome is linked to the lower crop frequency, reducing biomass (and C) inputs to counterbalance soil organic matter decomposition over time.

The *Higher legume* systems were estimated to have a more favourable soil C balance than the *Baseline* at most sites. The reasons for this are not entirely clear, but are thought to relate to the lower carbon-to-nitrogen (C:N) ratio of legume residues, which contribute positively to the soil C pools. Although the beneficial effect on soil C was somewhat offset by higher N_2O emissions, the *Higher legume* systems were generally predicted to have lower GHG emissions than the *Baseline* system.

The *Higher crop diversity* systems exhibited large site variability in their relative impact on soil C, with some sites showing a positive effect and others neutral or negative. Finally, the Higher nutrient strategies were simulated to have a neutral effect on soil C at three sites, and a positive effect at the other three; only at Mungindi was this positive effect large enough to offset the higher N_2O emissions associated with these systems.

System interactions

Within the core experiment at Pampas, which evaluated a combination of different farming systems strategies, it was evident that increasing the intensity of the farming system consistently reduced net emissions compared to the lower intensity counterparts (Table 1). Amongst these combinations, a system combining higher intensity cropping with higher crop diversity and higher legume frequency achieved a net C positive outcome over the experimental period of about 800 kg CO_2-eq/ha/yr. However, when higher nutrient input strategies were combined with higher diversity cropping, GHG emissions increased relative to the *Baseline*, and were higher than when these strategies were applied independently.

Emissions intensity

Using the total emissions data, which included simulated N_2O losses and accounted for differences in soil C changes among systems, led to distinct rankings in terms of emissions intensity (i.e. $/$CO_2$-eq). The estimated GHG intensities varied significantly across the different farming systems, with values ranging from $190 to $1900 per tonne of CO_2-eq/ha. No single system consistently emerged as the 'best' in terms of emissions intensity, and rankings varied across sites when comparing gross margin per emissions. However, the systems with the lowest projected total emissions nearly always displayed the highest productivity, both in terms of gross margin returns (Figure 4), indicating the existence of numerous 'win-win' scenarios, and that optimising for system profitability could also lead to optimised GHG emissions intensity.

The *Higher crop intensity* farming system generated the most favourable emissions intensity at four of the sites but was the least favourable system at Emerald, where the higher intensity system has shown to have much lower returns over the experimental period. On average, these systems

Table 1. Estimates of net change in annual GHG emissions (including soil C change) across the factorial of farming systems changes compared to the *Baseline* system implemented at the core experiment (Pampas) between 2015 and 2022.

	GHG emissions (kg CO_2-e/ha/yr)	
System	Moderate intensity	High intensity
Baseline	0	-481
Higher nutrient	+386	+55
Higher legume	**-208**	-333
Higher diversity	+49	-294
Higher diversity + Higher nutrient	**+606**	**+146**
Higher diversity + Higher legume	**+87**	**-797**

produced $1900 of gross margin return per tonne of CO_2-eq/ha. The *Higher legume* and *Higher crop diversity* farming systems generated the most favourable GHG intensity at Emerald and Billa Billa sites, respectively. Conversely, the *Lower crop intensity* systems consistently underperformed across all locations. These systems generated lower annual gross margins and had the highest GHG emissions, generating an average of $300 in gross margin per tonne of CO_2-eq/ha.

At the core experimental site, where factorial combinations of farming systems were evaluated, the *Higher crop intensity* systems demonstrated higher returns per kg CO_2 compared to their *Lower crop intensity* counterparts. The ranking amongst the systems was consistent with their total emissions, indicating that differences in accumulated gross margin did not significantly alter their relative GHG intensity rankings. This consistency suggests that the efficiency gains in terms of GHG emissions are directly correlated with the intensity of farming practices, independent of the economic performance measured by gross margin.

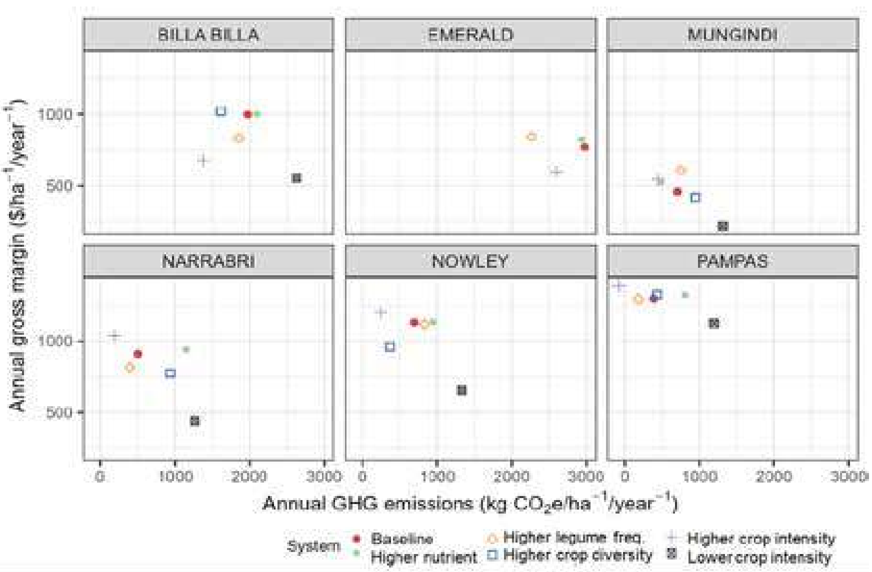


Figure 4. GHG emissions intensity, that is the relationship between estimated annual GHG emissions (Scope 1 & 3) and estimated gross margin of different farming systems over 8-years at the six experimental locations in Australia's northern grain-growing region.

Implications for growers

These findings highlight that the GHG footprints of farming systems can vary significantly, with up to a two-fold difference in the main sources of emissions and more than a four-fold difference in emissions per tonne of grain yield or revenue generated. This disparity expands further when changes in soil

C are factored into the GHG balance. Typically, farming systems that are more intensive and have fewer idle periods are associated with lower emissions. This is particularly true when accounting for changes in soil C and the reduction of N_2O emissions. In contrast, systems with longer fallows and less time in-crop tend to have the highest emissions. The impact of cropping intensity on emissions proved to be more significant than the choice of crops, which resulted in variable effects on overall GHG emissions across different locations.

This analysis underscores the importance of simulating N and C dynamics to accurately compare different farming systems, rather than relying on static emissions factors that primarily calculate emissions based on activity data, with a particular emphasis on fertiliser inputs. Utilising these more simplistic, yet less comprehensive approaches would have led to vastly different predictions, as they fail to account for impacts on soil moisture states and changes in soil C. The analysis further illustrates that even relatively minor annual changes in soil C can significantly influence the GHG footprint of the production system, acting either as contributors or mitigators. The scale of these predicted changes in soil C are modest enough to pose substantial challenges for measurement, even over decadal time periods. Therefore, alternative approaches are likely to be needed to evaluate the relative impact of different farming systems on soil C, capturing both positive and negative influences.

As farmers face the growing challenge of balancing the environmental footprint of production with the need to produce food, adopting a holistic approach to evaluating different production systems becomes increasingly important. The calculations presented here are one of a few multi-year studies, both nationally and internationally, that directly compare GHG emissions across a variety of farming systems. This research serves as a benchmark for grain production in eastern Australia and offers a detailed insight into how altering agronomic practices, such as crop rotation, nutrient inputs, and cultural methods, can impact GHG emissions and intensities. This analysis not only contributes to our understanding of the environmental aspects of agricultural production but also informs strategies aimed at reducing emissions while maintaining or increasing food production.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC, and the authors would like to thank them for their continued support.

We acknowledge the various collaborators involved with collecting the experimental data and farmer collaborators for hosting the farming systems experiments across the region.

This article has been adapted from a GRDC paper originally published in August 2024 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2024/08/greenhouse-gas-footprint-of-different-farming-systems-in-the-northern-grains-region

References

National Inventory Report 2021 (2023). Department of Climate Change, Energy, the Environment and Water. Commonwealth of Australia. www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2021-volume-1.pdf

Sevenster M, Bell L, Anderson B, Jamali H, Horan H, Simmons A, Cowie A, Hochman Z (2022). Australian Grains Baseline and Mitigation Assessment. GRDC Updates, February 2022. grdc.com.au/__data/assets/pdf_file/0031/572449/Paper-Sevenster-Maartje-GHG-footprint-Grains-February-2022.pdf

Northern farming systems – what's driving the profitability in western areas?

Andrew Erbacher[1], David Lawrence[1], Jayne Gentry[1], Lindsay Bell[2], Jon Baird[3], Darren Aisthorpe[1], David Lester[1], Branko Duric[3], Kathy Hertel[3]

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

***Research question**: Can systems performance be improved by modifying farming systems in the northern region?*

Key findings

1. Cropping intensity has had the biggest influence on system profitability.
2. *Higher legume* frequency has reduced nitrogen fertiliser inputs but has not improved profitability.
3. Applying nitrogen fertiliser to grass ley pastures produced more biomass in the pasture phase and returned more mineral nitrogen in the cropping phase.

Background

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.

In 2014 research began 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 develop systems with the most potential for use across the northern region. The Queensland Department of Primary Industries, CSIRO and New South Wales Department of Primary Industries and Regional Development established a field-based farming systems research program, focused on developing farming systems that could better use the available rainfall to increase productivity and profitability. The overarching research question was: *Can systems performance be improved by modifying farming systems in the northern region?*

What was done

This ongoing research question is being addressed at two levels by the Northern Farming Systems initiative; to look at the long-term 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.

To do this, trials were established at Emerald, Pampas, Billa Billa, Mungindi, Narrabri, Spring Ridge and Trangie, representing a range of climates and average rainfalls.

For each of these regions, typical grower practice (circa 2014) is represented in the '*Baseline*' system, then compared with modification of the system's strategies by the 'choices we make' with respect to

1. Which crops to plant
   - When to plant – *Higher crop intensity* and *Lower crop intensity*
   - What crop to choose – *Higher crop diversity* and *Higher legume*
2. How much fertiliser to apply.
   - Quantity of fertiliser - *Higher nutrient supply*
   - Alternative nutrient sources - *Higher soil fertility* and Pasture+/-N

We are now into the ninth year of running these systems; in this article we look at some of the impacts these choices have made, focusing on the Billa Billa and Mungindi sites and drawing on others as appropriate.

Economics in this project are calculated using a 10-year average price for commodities and fertiliser, standardised cost for machinery operations (plant, harvest, spray) and actual pesticide applications using a standardised quoted price.

Results

Which crops to plant?

When to plant – Crop intensity

In these experiments cropping intensity and fallow length is determined by how much plant available water (PAW) accumulates in the soil. In the *Baseline* system this is about 60% of PAWC (plant available water capacity); at Billa Billa it is 90 mm PAW for wheat and chickpea and 120 mm for sorghum. A *Higher crop intensity* system is planted with 40% PAWC (60 mm PAW) and *Lower crop intensity* with 80% PAWC (150 mm PAW).

We know that fallow efficiency (FE – the proportion of rainfall stored in the soil for later use) is highest on dry cracked soils and so it is not surprising to observe the highest fallow efficiencies achieved in the *Higher crop intensity* system. As the soil gets wetter, we have less cracks for mass flow of water into the soil and slower potential infiltration rates. Stubble loads also breakdown, reducing the groundcover that protects our soil from evaporation (among other things), so again it is not surprising that the *Lower crop intensity* system has the lowest fallow efficiency.

Averaged over all seven sites and seven years, the fallow efficiency was 21% in the *Baseline*, 31% in *Higher crop intensity*, and 14% in *Lower crop intensity*. Combine this with growing more crops and we see the proportion of rainfall used by crops (that is Fallow rain x FE + In-crop rain) again favours a *Higher crop intensity* system. The *Baseline* systems used 55% of rainfall, *Higher crop intensity* used 69% and *Lower crop intensity* used 42% of rainfall.

However, fallow efficiency and even the proportion of rainfall used does not automatically translate to more grain yield and profit. Looking at the performance of the 163 sorghum, wheat and chickpea crops in the first six years of the project we demonstrated that crop water use efficiency (WUE – kg of grain produced per mm of water used) was maximised by having a minimum amount of PAW stored prior to planting the crop. Based on our data this is about 60 mm for chickpea, 100 mm for wheat and 200 mm for sorghum. Sorghum is higher because it grows during summer with a higher evaporative demand.

If we put this all together and look at how the systems performed, we see that the *Baseline* had the best balance between storing enough PAW to improve WUE and shorter fallows to improve FE.

At Mungindi the *Baseline* has grown six crops in the first eight years of the project to January 2023, for a combined gross margin of $3032/ha ($378/ha/year), whereas *Lower crop intensity* grew four crops for a gross margin of $1128/ha ($141/ha/year).

At Billa Billa the *Baseline* grew nine crops in these first eight years to net $6535/ha ($817/ha/yr). Like Mungindi, *Lower crop intensity* grew less crops (six) in the same period to return $2627/ha ($328/ha/yr). *Higher crop intensity* grew an extra two crops (eleven in eight years) but produced less grain yield for each crop and in total; returning lower gross margins than the *Baseline* at $4426/ha ($553/ha/yr).

Across all seven sites, the average gross margin per crop is highest in the *Lower crop intensity* and the lowest average gross margin per crop is in *Higher crop intensity*. With less crops grown in *Lower crop intensity*, only two sites (Pampas and Emerald) successfully executed high enough valued crops to return a combined higher gross margin than the *Baseline* over the eight years. Similarly, the *Higher crop intensity* system only grew enough 'extra crops' to return a higher combined gross margin than *Baseline* at two sites (Pampas and Narrabri).

What crop to choose - Diversity

From the 1950s to the 1980s the most profitable crop across southern Queensland was wheat and the most profitable rotation was wheat followed by wheat. However, when zero-till farming was introduced, crops became more prone to stubble-borne diseases (particularly crown rot, caused by *Fusarium* sp.), so farmers were forced to diversify their rotation to manage this disease.

In the current farming systems experiments, the *Higher crop diversity* systems predominantly set out to improve the management of crown-rot, along with root lesion nematodes (RLN; *Pratylenchus* sp.) and herbicide resistance (particularly Group 1, formerly Group A) by forcing double-break crops and allowing more herbicide modes of action (MOA) options. In essence, the 'less-diverse' *Baseline* system had the crop options to achieve this objective with wheat, chickpea and sorghum, which poses the question, 'are we growing diversity for diversity's sake?' Only Pampas has increased profitability of the *Baseline* systems with *Higher crop diversity*, but there are some useful insights that can be drawn from this system.

At Mungindi, summer crops were considered 'high risk', particularly from heat stress at flowering from spring-planted crops. Without reliable summer 'break crops' the system has a high risk of RLN and

Group 1 herbicide resistance. A *Lower crop intensity* winter cropping system allows winter fallows to use alternative herbicide MOA for black oats and phalaris control while the long fallow is as effective as growing a resistant crop for reducing RLN. However, as previously discussed, the *Lower crop intensity* system has sacrificed a lot of profit in forgone opportunities compared to the *Baseline*. The alternative approach of using a *Higher crop diversity* system has successfully reduced the RLN population at Mungindi from very damaging levels (13/g soil) to a low of 0.3/g soil in 2021 by growing resistant crops – sorghum, sunflowers and durum. This *Higher crop diversity* returned a lower gross margin of $2595/ha ($325/ha/yr) than the *Baseline*, however it was still twice as profitable as the *Lower crop intensity* system.

At Billa Billa pathogens were low and have mostly remained low in all systems, so the *Higher crop diversity* system has had little opportunity to improve the biological outcomes of the system. Instead, all the crops grown to reduce our risk of crown rot and RLN were hosts to charcoal rot (*Macrophomina phaseolina*), which is now present at quite high levels in this system at the Billa Billa site.

What crop to choose - Legumes (pulses)

The other 'diversity' strategy in these experiments was to use a *Higher legume* system, included to reduce reliance on nitrogen fertiliser. At five of the seven sites there was a reduction in nitrogen fertiliser applied in the *Higher legume* compared to the *Baseline* (two were the same), for an average saving of 95 kg N/ha over eight years (a range of 0–170 kg N/ha).

Across all sites and seasons, the average variable cost for growing a cereal crop (wheat, barley, sorghum) was $155/ha, whereas the pulse crops (chickpea, fababean, mungbean) cost $220/ha due to higher seed costs and more in-crop sprays with fungicides and insecticides.

Despite the reduction in fertiliser applied, the higher cost of growing pulse crops meant total costs were similar for *Baseline* and *Higher legume* at five of the seven sites. The gross margin was only improved by *Higher legume* at one site, (Mungindi; $4360/ha, $545/ha/yr), which rather than any biological factors, can be attributed to *Higher legume* growing a 2.2 t/ha chickpea crop in 2021 followed by 3.5 t/ha wheat crop in 2022, whilst the *Baseline* grew the same two crops in reverse order for very different yield outcomes (2.6 t/ha wheat in 2021 and 0.7 t/ha chickpea in 2022).

The Billa Billa soil has high chloride and sodicity at depth, so pulses can only extract soil water from the top 50 cm of soil. This impact on yields has meant that income from pulses is less than cereals in most seasons. Consequently, the *Higher legume* system at Billa Billa had the lowest gross margin of any site in the project at $3916/ha ($490/ha/yr).

How much fertiliser to apply?

Quantity of fertiliser - Higher nutrient

The yield potential of crops for different planting dates and starting PAWs were modelled for all locations in the project. The modelling helped estimate the average (median or 50%) yield potential, do a nitrogen budget for that outcome and apply nitrogen fertiliser at planting as required in the *Baseline* system. The *Higher nutrient supply* system uses the yield potential for a 1 in 10 year season (90% yield potential) and applies enough nitrogen (N) fertiliser to achieve that yield. No N fertiliser is applied to pulse crops. The *Higher nutrient supply* system also applies a higher rate of starter phosphorus (P) but has not shown a yield difference in any sites.

Billa Billa is a 'newer paddock' with 1.2% organic carbon that was previously managed by the landowner as a higher nutrient farming system. The paddock had high available nitrogen levels (~350 kg N/ha) in the soil when the experiment started and has been able to supply sufficient nitrogen for the crops. Only 20 kg N/ha (43 kg urea/ha) has been applied to date in *Higher nutrient supply* so has had no significant impact.

At Mungindi we have applied 134 kg N/ha (290 kg urea) more in *Higher nutrient supply* (298 kg N/ha) than in *Baseline* (164 kg N/ha) over four wheat crops. Each wheat crop has produced more biomass in *Higher nutrient supply*, but the extra N delayed flowering into hotter times, leading to lower grain yield in two of the four years. The four wheat crops grew an extra 1.8 t/ha of biomass, but 0.4 t/ha less grain in *Higher nutrient supply* compared to *Baseline*. With the added cost of fertiliser, *Higher nutrient supply* returned $2935/ha ($367/ha/yr); $100/ha less than *Baseline*. All is not lost though, with an average additional 50 kg N/ha available at planting of each crop in *Higher nutrient supply*.

Alternative nutrient sources - Higher fertility

At Billa Billa and Emerald 50–70 t/ha compost/manure was added to a system to mimic a 'newer' paddock with a higher organic carbon. This system was then treated with the *Higher nutrient supply* strategy, aiming to hold that higher fertility.

At Billa Billa, the starting soil fertility has been sufficient to supply the demands of all crops in *Baseline* to date. *Higher soil fertility* had an extra 0.6 t/ha (3.6 t/ha versus 3.0 t/ha) in double-cropped sorghum after chickpea in 2022 but has not provided a yield benefit overall. That system has consistently mineralised more nitrogen in the fallow, so after eight crops in this experiment, it still has adequate mineral nitrogen to supply crop demand whereas the *Baseline* and *Higher nutrient supply* systems now need nitrogen fertiliser.

Organic carbon (OC) was measured at this site at in 2015 (before the compost was added), and again in 2019. In 2019 *Higher soil fertility* had more OC than *Baseline*, which maintained OC @ 1.2% over that period. However, the 0.2% increase in measured OC was less than half of what was added in the compost application. OC will be measured again in 2025, to see if that downward trend has continued or whether OC has stabilised at a higher level.

The Emerald site had lower starting fertility (0.8% OC), so has been more responsive to both the *Higher nutrient supply* and *Higher soil fertility* systems. In nine crops grown at Emerald, *Higher nutrient supply* has produced 1.5 t/ha more grain than *Baseline*, while *Higher soil fertility* with the large initial manure treatment and extra fertiliser has produced an extra 5.1 t/ha of grain.

Alternative nutrient sources - Pasture with and without nitrogen fertiliser

Grass ley pastures were established at both Billa Billa and Pampas in 2015, with the aim of increasing OC naturally, then returning to cropping with a higher fertility. These grass pastures had 1/3 of the bulk (2/3 height) cut and removed at anthesis, and 80% of nutrients (NPKS) returned (as fertiliser) as a surrogate to grazing in a small-plot cropping experiment. One half of the pasture plots had 50 kg N/ha (109 kg urea/ha) applied after each 'grazing event' (100 kg N/year).

In 2019, OC measurements showed that the pasture had indeed increased OC levels by 0.2% to 1.4% at Billa Billa. At this point (three years of grass), half the pasture replicates were returned to cropping and treated with the same management as *Baseline*, while half were retained as pasture for another three to five years.

Only small visual and measured responses to applied nitrogen were evident in the pasture up to 2019, so as expected the effect on OC was the same in these two pastures. Once returned to cropping, the areas that were previously fertilised pasture ('*ex-fertilised pasture*') had an extra 100 kg N/ha applied during the planting of each crop, to meet crop requirements. The areas of previously unfertilised pasture ('*ex-unfertilised pasture*') have needed 70 kg N/ha of nitrogen fertiliser in the third (sorghum) crop. Similar trends were observed at Pampas. While there was no fertiliser saving at Pampas, there was an extra 400 kg/ha of grain over four crops grown in the first three years after pasture removal.

These 'ex-pasture' systems also appear to have improved infiltration, meeting the planting PAW trigger to double crop twice in 2021-2022 at Billa Billa, while the long-term cropping *Baseline* was only double cropped once. Unfortunately, this increase in double cropping led to an unexpected downside to yields from the additional nitrogen. The barley in 2021 yielded 200 kg/ha more in the *ex-fertilised pasture* (3.2 t/ha) than the *ex-unfertilised pasture* (3.0 t/ha), and then the double-cropped sorghum after that was 400 kg/ha worse in the *ex-fertilised pasture*. This caused great initial confusion, but the higher-yielding barley crop extracted 20 mm more PAW at harvest, something commonly observed in past cover cropping research. Over a normal fallow this would typically recover and balance out, but in a double crop situation the moisture deficit was still evident at planting of the sorghum and led to the unexpected yield penalty.

The long-term pastures at Billa Billa have had clear visual and biomass responses to nitrogen since 2019. An extra 10 t/ha (dry weight) of biomass was produced from 550 kg N/ha applied since 2015. As previously mentioned, the grazing value of the pastures has only been estimated (not grazed and animals weighed), but the gross margin of the fertilised pasture is $3058/ha ($382/ha/yr) more than that of the unfertilised pasture ($11816/ha or $1477/ha/yr versus $8758/ha or $1095/ha/yr).

The longer-term pastures suffered severe pasture dieback in summer 2022-23 and were brought back into cropping, with similar trends emerging in the two crops since then (data not yet available).

Implications for growers

Cropping intensity and stored soil moisture levels on which crops are planted has had the greatest impact on the systems' gross margins.

While seasonal variability influences the success of individual crops, the project has shown a relationship between plant available water (PAW) at planting and the water use efficiency (WUE) of chickpea, wheat and sorghum. That is, fallowing for a minimum threshold of PAW prior to planting crops ensures the crops convert the available soil water and in-crop rain to grain yield efficiently.

The optimum PAW threshold (i.e. intensity of the system) is different for each of these crops. For chickpeas, maximum WUE is achieved with greater than 60 mm of PAW, but WUE declines above 160 mm PAW at planting. Similarly, wheat has maximum WUE when planted with greater than 100 mm and less than 180 mm of PAW at planting. Sorghum WUE is more influenced by heat or in-crop rainfall than wheat and chickpea, but this data showed consistently high WUEs were achieved when greater than 200 mm PAW was available at planting. This is not possible in many soils, however the worst WUEs occurred when sorghum was planted with less than 120 mm PAW, so 120 mm is recommended as the minimum PAW for planting sorghum unless you can be very confident about the in-crop rainfall of the coming season.

For growers considering a higher nutrient strategy, (from more fertiliser inputs or applying organic amendments such as manure or compost), be aware that the crops with an adequate supply of nitrogen may develop and flower later than those with low nitrogen. This may expose them to more heat in grain-fill and ultimately reduce grain-fill duration. Taking note of the likely flowering date will allow variety selection to be tailored to maintain the full yield potential while balancing heat stress and the frost risk of your farm.

The final note is for the mixed croppers. Rotating pasture phases in cropping country will build organic carbon in the soil and provide benefits to the crops after the pasture phase. To maximise organic carbon production in the pasture phase, nutrients and grazing management should be applied to maximise biomass production. A grass pasture can produce additional biomass with nitrogen fertiliser, or legumes can be established to fix nitrogen, but nitrogen fixation by legumes will be low if phosphorus is not readily available.

Acknowledgements

The research undertaken as part of this project is made possible by the significant contributions of growers through both trial cooperation and the support of the GRDC; the author would like to thank them for their continued support.

I would like to thank the property owners for their long-term support by providing the Mungindi and Billa Billa trial sites featured in this report.

I would also like to acknowledge and thank the technical officers and farm staff who supported the authors in managing the farming systems experiments.

Harvesting trial sites in 2022.

Farming system impacts on profitability and sustainability indicators—eastern Darling Downs

Lindsay Bell, Jeremy Whish and Heidi Horan
CSIRO

Key findings

1. Farming system decisions, particularly the soil water required for sowing, can have a large influence on system profitability over both the short and long-term; differences of >$100/ha/yr occur regularly.
2. Systems using a wider diversity of crops can not only help manage biotic threats (e.g. diseases and weeds) but also be profitable compared with conventional systems.
3. While the last 6 years have presented a diverse range of seasons, in general they have not favoured alternative farming systems compared to the *Baseline* system.
4. Simulated predictions (modelling) of relative system profitability generally correspond well with those calculated from experimental data over the same period.

Background

The Northern Farming Systems project has been examining how adjusting farming system strategies impacts various aspects of the farming system across a diverse range of production environments, including changing:

1. The **mix of crops grown** by increasing the frequency of legumes or diversifying crop choices to provide disease breaks.
2. The **intensity of the cropping system** by either increasing it by reducing the soil water threshold to sow more crops or by reducing it and only growing higher profit crops once the soil profile is full; and
3. The **supply of nutrients** provided to crops to target either average yields or to maximise yield potential in any season.

However, even with 9 years of data, the full range of climatic conditions that are experienced across the region have not been captured, and periods of extremely dry seasons or extremely wet seasons are likely to favour particular farming systems. Simulation modelling can provide a useful addition to the data collected by helping to explore how the different farming strategies might perform over the longer term and under a wider range of climatic conditions. In this article we compare APSIM predictions of system profitability and sustainability indicators over the long term (using simulations from 1957 to 2023) against observed data for the period 2015–2022 for the core farming systems site at Pampas on the Eastern Darling Downs (similar analysis has been completed for other sites across the region).

System simulations and estimates of profitability

The APSIM simulations used the soils characterised at each location and long-term climate data from the closest meteorological station. For each farming system, the simulation used a prioritised list of crops, their sowing window, and minimum soil water required to allow them to be sown, as per the rules in Table 1.

Revenue, costs and gross margin for each crop were calculated using predicted grain yields and estimates of crop protection, non-N fertilisers and operational costs (Table 2). Fertiliser inputs were simulated dynamically based on a crop budget targeting a median yield (N fertiliser was costed at $1.30/kg N), and fallow herbicide applications ($15/ha/spray) were predicted based on the number of germination events that occurred.

Given the dynamic nature and range of different crops across these simulations, only a single crop sequence was generated over the simulated period. System gross margins were aggregated over a sequential 6-year period (e.g. from 1957–1962, 1958–1963 and so on) to allow a comparison of the simulation's predictions for the experimental period of 2015–2021 at Pampas against more than 50 other 6-year periods. The simulations assumed a set crop input cost while experimental data used actual costs incurred, meaning there was always a difference in the actual gross margins estimated from the model compared to the actual costs attributed in the experiments, so the magnitude of the change compared to the *Baseline* system was used to indicate relative performance.

Table 1. Rules associated with crop priority, crop choice, crop frequency and the plant-available water threshold required to be sown applied in farming systems at Pampas and in long-term simulation analyses.

System	Crop choice rules	Crop choices	Crop priority (1 – lowest; 3 - highest)	Soil PAW required to trigger sowing	Crop freq. limits (crops in years)
Baseline	No more than 3 winter cereals or sorghum consecutively ≥2 yrs between chickpea	Wheat Chickpea Barley Sorghum Mungbean	2 3 1 2 1	150 150 150 150 100	2 in 3 1 in 3 1 in 3 3 in 4 1 in 3
High legume frequency	As above + Legume every second crop	As above + Faba bean Field pea Soybean	 2 1 3	 150 150 200	 1 in 3 1 in 3 1 in 3
Higher crop diversity	As in *Baseline* + ≥1 yr break after any crop ≥50% crops nematode resistant	As above + Canola Sunflower Millet Maize Cotton	 3 1 1 3 3	 200 150 120 200 200	 1 in 3 1 in 3 1 in 4 1 in 3 1 in 2
Higher crop intensity	As in *Baseline*	Wheat Chickpea Barley Sorghum Mungbean	2 3 1 2 1	100 100 100 100 70	2 in 3 1 in 3 1 in 3 3 in 4 1 in 3
Lower crop intensity	As in *Baseline*	Wheat Chickpea Sorghum Mungbean Cotton	2 3 1 3 3	200 200 200 150 200	2 in 3 1 in 3 3 in 4 1 in 3 1 in 2

Table 2. Assumed prices (10-year average, farm gate after grading/bagging/drying) and variable costs for inputs and operations (e.g. seed, pesticides, starter fertilisers, sowing, spraying) and harvest costs (for viable yields only) for each crop simulated.

Crop	Price ($/t product)	Variable crop costs ($/ha)	Harvest costs ($/ha)
Wheat	269	175	40
Durum	335	175	40
Barley	218	175	40
Chickpea	504	284	45
Sorghum	221	221	55
Mungbean	667	276	55
Faba bean	382	341	40
Field pea	382	341	40
Canola	503	351	70
Soybean	607	305	55
Sunflower	1052	365	55
Maize	250	218	55
Millet	564	350	70
Cotton	1800[A]	774	280

[A] Calculated on total harvest assuming 45% cotton lint turnout and 55% seed.

Experimental differences in system performance

After over 9 years of implementing the farming systems experiments at Pampas, the largest impacts on system profitability have been associated with changes in crop intensity – with these systems being both positive and negative compared to the *Baseline* over the life of the project depending on the season (Table 3). As of March 2024, the highest return has been produced by the *Low crop intensity* system – however, over one third of the income from this system came from a high yielding (8 bale/ha) dryland cotton crop in 2022-23. At the same point in time the *Higher crop intensity* system had produced a higher gross margin than *Baseline* by about $100/ha/yr. However, these systems have varied significantly in their relative profitability over the past 9 years (Figure 1). The *Lower crop intensity* system has been the lowest accumulated gross margin for over half the time, only recovering to exceed the others in summer 2022-23. Similarly, during the dry seasons of 2018-19, the relative profitability of the *Higher crop intensity* system declined, but this recovered again during the wetter period of 2021-2022.

Table 3. Total income, input costs and gross margin achieved over 9 years and the contributing individual GM of each crop amongst different farming system strategies at Pampas between April 2015 and January 2023.

System treatment	Baseline	High nutrient	High legume	High diversity	High intensity	Low intensity
Total crop income ($/ha)	11340	11500	11320	11080	12830	12780
Total input costs ($/ha)	2160	2520	2040	2120	2650	1780
Total gross margin ($/ha)	9180	8980	9280	8960	10180	11000
Annualised GM ($/ha/yr)	1020	1000	1030	1000	1130	1220
Season	**Crop by Crop GM ($/ha)**					
Win 15	Wt 1539	Wt 1305	Fb 1806	Cn 1427	Wt 1636	Wt 1458
Sum 15	X	X	X	X	Mg 52	X
Win 16	X -138	X -138	X -136	X -143	X -78	X -132
Sum 16	Sg 1459	Sg 1436	Sg 1437	Sg 1393	Sg 1256	Ct 1743
Win 17	Cp 725	Cp 27	Cp 757	Cp 722	Cp 748	Wt 164
Sum 17	X	X	X	X	Sg 36	X
Win 18	X 57	X -57	X -57	X -57	X	X
Sum 18	Sg 999	Sg 1129	Sg 989	Ct 1293	Sg 495	X
Win 19	X	X	X	X	X -20	X
Sum 19	X	X	X	X	Mg -67	X
Win 20	X -99	X -99	X -114	X -80	X -48	X -136
Sum 20	Sg 910	Sg 895	Mg 910	Sg 640	Sg 467	Ct 2334
Win 21	Cp 1074	Cp 875	Wt 1116	Cp 1019	Cp 1988	X -18
Sum 21	Sg 892	Sg 955	Mg 690	Sg 79	Sg 997	Sg 1050
Win 22	Wt 1460	Wt 1318	Cp 1449	Dr 1680	Wt 1498	X -85
Sum 22	X	X	X	X	X	Ct 4629
Win 23	Wt 427	Wt 426	Wt 437	X	By 1220	X

Costs incurred during fallows are attributed at the end of the fallow prior to sowing the next crop.
Crops: Wt – Wheat, Sg – Sorghum, Cp – Chickpea, Mg – Mungbean, Fb – Fababean, Cn – Canola, Ct – Cotton, Dr – Durum, By – Barley.

Systems that have changed the mix of crops by either increased frequency of legumes (pulses) or diversified crop choices, or where nutrient supply has been increased have changed the net gross margin little, with differences after 9 years of less than $40/ha/yr. After the initial years, these small differences have also been relatively stable and small (since 2017; Figure 1). During the first 3 years, the *High legume frequency* system had the highest gross margin but in later years this earlier advantage has been diminished. The *Higher crop diversity* system has also achieved similar gross margins over this period, but in the summer of 2023 (data not shown) a highly profitable sunflower crop elevated its relative profitability.

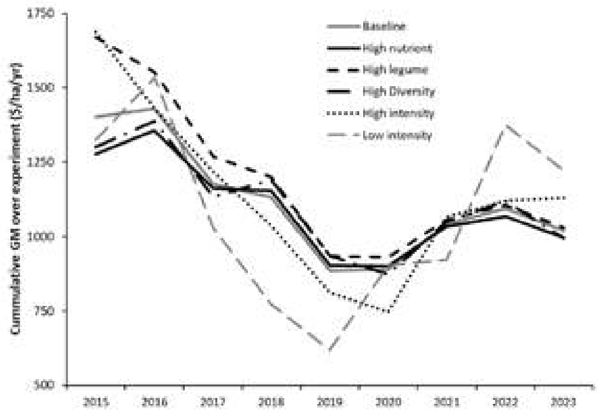


Figure 1. Cumulative gross margin (i.e. from April 2015 to April of each ensuing year) over 9 experimental seasons between different farming systems at Pampas.

Crop sequences & frequencies amongst long-term simulated systems

Long-term simulations of each of the experimental systems using the crop choices and rules described above resulted in quite distinct changes in the mix and intensity of crops grown over the long-term (Figure 2).

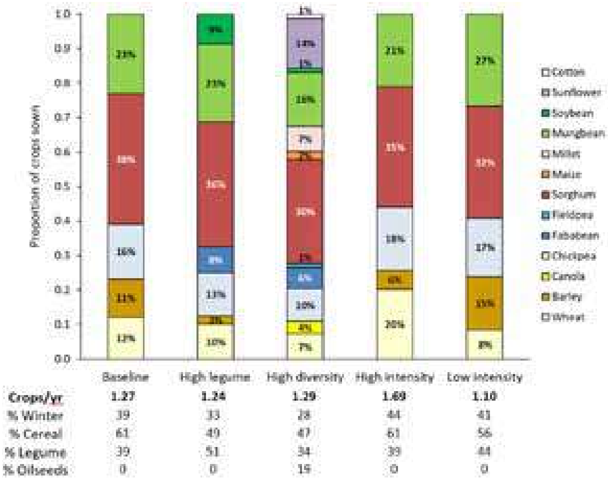


Figure 2. Cropping intensity (crops/yr) and the proportion of different crops under different farming system strategies at Pampas over the long-term (60 year) simulation.

Applying the *Baseline* farming system rules predicted a long-term crop intensity of around 1.25 crops per year, or 5 crops in 4 years, with a crop frequency of about 40% sorghum, 25% mungbean, 20% winter cereals and 15% chickpea.

Altering the system to apply the *Higher legume frequency* strategy resulted in a similar crop intensity but some additional soybean crops and faba bean replacing barley in the crop sequence (Figure 2).

The *Higher crop diversity* system saw a drop in both legume and cereal frequency and less winter crops. Oilseeds increased to 20% of the crops grown – canola replacing barley and sunflowers replacing sorghum. Millet was also often substituted for mungbean as a summer double-crop and maize occasionally replaced sorghum.

The *Higher crop intensity* strategy (i.e. lower soil water thresholds to sow crops) saw an increase in crop frequency by about 0.4 crops/yr (i.e. an additional 24 crops over the 60-year simulation), but the mix of crops was fairly similar to the *Baseline*.

The *Lower crop intensity* system (that had a higher soil water threshold to sow crops) saw the crop frequency drop by 0.2 crops/yr – less than might be expected; the proportion of different crops also remained fairly stable except early-sown barley often replaced wheat.

Long-term predictions of system profitability

Figure 3 shows the range in average annual gross margin predicted over all the 6-year periods between 1957 and 2020 amongst the various simulated farming systems. These are arranged from the lowest to the highest to show the distribution of these predictions – this variability is driven only by climatic conditions as crop prices are held constant at 10-year average values.

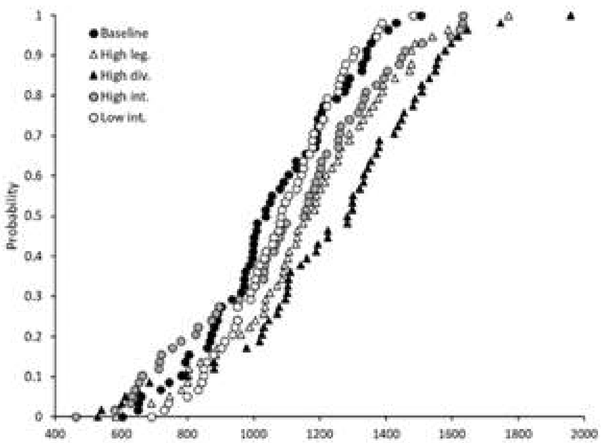


Figure 3. Distribution of simulated gross margin ($/ha, X-axis) (average of 6-years) over 60 years period (1957-2020) of different farming systems strategies at Pampas.

The simulations suggest that across the full range of 6-year periods the *Baseline* system simulated here was never the most profitable choice. The *Higher crop intensity* system (grey circles) exceeds the profit generated in either the *Baseline* or *Low crop intensity* systems about 50% of the time, particularly under more favourable conditions. However, the *Higher crop intensity* system produces the lowest returns about 25% of the time when the overall profit is lowest. On the other hand, the *Low crop intensity* system (white circles) performs relatively well compared to *Baseline* and *Higher crop intensity* systems under the lower production and profit periods, exceeding them around 30% of the time.

The systems that alter the mix of crop (either *Higher legume frequency* or *Higher crop diversity*) are predicted to generate higher profits over most periods. In general, they achieve similar potential profits to the other systems in the lower profitability periods, but potentially offer significant upside under more favourable conditions. In particular, these systems were able to offer a broader range of crop options to make use of seasonal rainfall and hence were more able to make use of additional crop opportunities when they occurred.

Short-term (experimental period) relative to the long-term

Comparing these long-term simulations with the experimental periods enables a comparison of observed differences in system profitability within a longer period. It also allows the comparison of differences in gross margin from both the experiments and the model predicted differences in gross profit. This article compares the gross profit generated over the 2015–2022 period, as simulations are yet to be run for the whole period as reported above.

Figure 4 presents similar results to those in Figure 3, but compares the predicted outcomes of each of the systems against the *Baseline* in each of the 6-year periods simulated, showing that the modified farming systems frequently produce higher average returns; the *Higher crop diversity* systems 85% of the time, *Higher legume frequency* systems 70% of the time, and *Higher/Lower crop intensity* systems about 60–70% of the time. However, the *Higher/Lower crop intensity* systems also had significantly lower profit in some periods compared to the *Baseline*.

Figure 4 also includes the model predictions of the difference in gross margin between the *Baseline* and the altered systems over the experimental period (indicated by the larger symbols), with the vertical lines indicating the experimental findings. The observed and model predicted differences in gross margin corresponded well for most systems, apart from *Higher crop intensity* system which the model predicted would be about $150/ha/yr behind, (corresponding to the lower quartile of outcomes), but in the experimental results generated around $60/ha/yr higher gross margin.

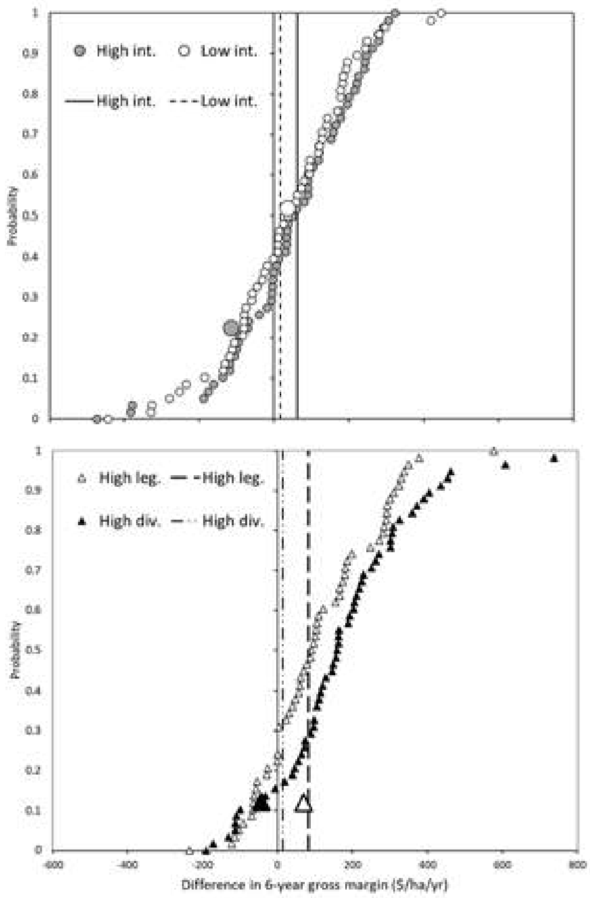


Figure 4. Difference in simulated 6-year gross margin between the *Baseline* and: (top) *Higher- or Lower crop intensity* systems; and (bottom) *Higher legume frequency* or *Higher crop diversity* systems at Pampas between 1957 and 2023. Small symbols show the difference in simulated annual returns between the systems over 54 different 6-year periods. Vertical lines indicate the experimentally determined differences in gross margin between each of the systems and the *Baseline* (2015–2022), large symbols indicates the simulated difference over the same period and where this would have sat on the wider distribution of simulated periods.

Over the experimental period the *Higher legume frequency* system was predicted to be $70/ha/yr ahead of the *Baseline*, but the model predicted that over 90% of other 6-year periods would have generated further higher profits from this system. The *Higher crop diversity* system was predicted to produce slightly lower gross margin than the *Baseline* over the experimental period, but again over 90% of other periods would have generated relatively higher gross margins from this system. On the other hand, the *Lower crop intensity* has performed similarly to the *Baseline* over the experimental period, however this was around the median of these results, indicating that the experimental period was probably more favourable to this strategy than to the other systems.

Implications for growers

Farming strategies or systems need to consider resilience and relative performance across the full range of likely climate variability. While this experimental work has captured a range of seasons, the modelling here adds further insight into how the various farming system strategies might perform over the long term. The modelling predictions of the relative differences over the past 6 years correspond well with the experimental data over the same period. While some of the alternative systems have not been advantageous over this experimental period, the long-term analysis suggests that making use of a greater diversity of crops could add significant upside under more favourable growing seasons. Further examination of the influence of price variability and risk on these findings is required to understand how robust different strategies are, and the key factors that might influence this.

Acknowledgements

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

We acknowledge the various collaborators involved with collecting the experimental data and farmer collaborators for hosting the farming systems experiments across the region.

This article has been adaped from a GRDC paper originally published in February 2023 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/02/short-and-long-term-profitability-of-different-farming-systems-southern-qld

Farming system impacts on yield, economics, and seasonal risk—Central Queensland

Darren Aisthorpe

Queensland Department of Primary Industries

Key findings

1. At Emerald, a more conservative cropping strategy (one crop per year) on a non-limiting nutrition plan has been the most consistent strategy to maximise returns.
2. No system on the medium/standard crop intensity and higher nutrition plan has fallen behind the *Baseline* system with respect to system economics.
3. There is scope for future nutrient strategies to include higher nitrogen rates and applications early in the fallow to improve availability to crops.
4. If logistical challenges can be overcome, changing to narrower row spacings on an increased nutrition plan could be a positive move.

Background

The Queensland Department of Primary Industries, CSIRO and the New South Wales Department of Primary Industries and Regional Development are collaborating in an extensive field-based farming systems research program focused on developing farming systems to better use the available rainfall to increase productivity and profitability.

The Northern Farming Systems project is investigating how several modifications to farming systems affect the cropping system's performance by assessing various aspects of these systems including: water use efficiency (WUE); nutrient balance and nutrient use efficiency (NUE); changes in pathogen and weed populations; changes in soil health; and profitability. The key system modifications being examined involve changes to:

- **Crop intensity** – adjustments to soil water thresholds that trigger planting opportunities.
- **Increased legume frequency** – aim for a legume every second crop, assessing if nitrogen fertiliser inputs can be reduced.
- **Nutrient supply strategy** – increase the fertiliser budget to achieve 90% of yield potential to boost background soil fertility, increase N cycling and maximise yields in favourable years.
- **Increased crop diversity** – 50% of crops are resistant to root lesion nematodes (preferably two in a row) and avoid consecutive crops with similar in-crop herbicide mode of action.

This range of system modifications are being tested across six locations: Emerald, Billa Billa, Mungindi, Spring Ridge, Narrabri and Trangie (red and grey soils). The core experimental site, located near Pampas on the eastern Darling Downs, aims to explore the interactions between these modifications in a range of crop sequences that occur across the northern grains region by comparing 34 different systems.

What was done

The Emerald site is located at the DPI Central Queensland (CQ) Smart Cropping Centre facility, 4 km east of Emerald (~189 m above sea level). The field history prior to the trial was chickpea in 2012, sorghum in summer 2012–13, fallowed for winter 2013 and then irrigated cotton in summer 2013–14.

Forage sorghum was then grown from late 2014 until early March 2015 and sprayed out in preparation for the trial. The site had 200 kg/ha of mono-ammonium phosphate applied as deep as possible (20–25 cm) on 50 cm row spacings. The first planting occurred May 2015.

Soil characteristics

The site is located on cracking, self-mulching, grey Vertosol soil, more than 1.5 m deep. The soil had moderate background fertility levels, particularly at the surface (Table 1), likely due to the previous cropping history and nutrient management. Estimated water holding capacity was 240 mm to 1.5 m, with the possibility of additional available water below that depth in this soil.

Table 1. Starting comprehensive analysis of the of Emerald Northern Farming Systems site in 2015.

Depth (cm)	BD (g/cm³)	DUL (%)	Total porosity	Organic C (%)	Colwell-P (mg/kg)	BSES-P (mg/kg)	PBI	Colwell-K (mg/kg)	Sulfur (mg/kg)	Cond. (dS/m)	pH ($CaCl_2$)	pH (H_2O)	Cl (2018) (mg/kg)
0–10	1.249	34.801	0.529	0.77	45.13	69.93	99.03	437.67	10.88	0.17	6.80	7.54	0.77
10–30	1.412	38.850	0.467	0.50	12.33	21.23	114.16	224.54	11.27	0.16	7.15	8.07	0.50
30–60	1.414	38.704	0.466	0.35	2.88			161.38	21.21	0.19	7.21	8.30	0.35
60–90	1.393	39.438	0.474	0.27	1.83			177.04	351.28	0.45	7.23	8.10	0.27
90–120	1.365	40.481	0.485	0.17	3.58			228.50	773.31	0.74	6.89	7.50	0.17
120–150	1.367	40.419	0.484	0.11	5.71			254.38	412.00	0.55	5.44	6.20	0.11

Depth (cm)	(meq/100g)					mg/kg	DTPA (mg/kg)			
	Exc. Na	Exc. Ca	Exc. K	Exc. Mg	Exc. Al	Boron ($CaCl_2$)	Cu	Fe	Mn	Zn
0–10	0.76	20.17	1.09	10.30	0.11	1.32	1.63	15.69	24.83	2.57
10–30	1.22	20.72	0.55	11.30	0.09	1.33	1.40	14.30	8.92	1.15
30–60	2.65	18.96	0.42	12.90	0.09					
60–90	4.22	18.36	0.45	13.32	0.11					
90–120	5.47	16.93	0.61	14.18	0.14					
120–150	5.38	15.47	0.66	13.95	0.09					

Nutrition calculations

Starter phosphorus (P) and nitrogen (N) fertilisers are applied at sowing. These applications are made in line with the yield potential (50th percentile or 90th percentile, according to the nutrient strategy) for each crop based on sowing date and available soil water at sowing as simulated by APSIM.

The nutrient strategy was determined at the commencement of each system and does not change.

- **50th percentile** – sufficient additional N or starter is applied at planting to ensure enough of these nutrients are available to the crop to achieve an 'average' yield based on the starting plant available water and APSIM's modelled yield expectations for that planting date
- **90th percentile** –sufficient additional N or starter is applied at planting to ensure enough of these nutrients are available to the crop to achieve a yield for the top 10% of years based on the starting plant available water and APSIM's modelled yield expectations for that planting date.

The crop N budget was calculated based on industry recommendations for each crop, and the shortfall from available mineral N (determined by soil testing at the start of the sowing window) was made up with an N application as urea at sowing. This is applied in the inter row between seeding rows to reduce the risk of germination damage. Starter fertilisers were applied in the seed row.

Trial design and management

Consultation with local growers and agronomists in 2014 identified the key limitations, consequences, and economic drivers of northern region farming systems. In April 2015, selected systems (relevant to CQ, but consistent with the Northern Farming Systems Initiative and core site at Pampas) were implemented at Emerald. Rules and protocols were developed regarding agronomic practices, crop types, planting triggers, and nutrition, to preserve the integrity of the six initial systems:

1. **Baseline** – A conservative zero tillage system targeting one crop/year. Crops are limited to wheat, barley, chickpea and sorghum, with nutrient application rates on cereals targeting median (50th percentile) seasonal yield potential. Aligned with the 'Baseline' system at the Pampas core site.
2. **Higher crop intensity** – Focused on increasing the cropping intensity to 1.5 crops/year when water allows. Crops include wheat, chickpea, sorghum, mungbean and forage crops/legumes, with N rates for cereals targeting median (50th percentile) seasonal yield potential. Aligned with the Pampus '+intensity' system.
3. **Higher legume** – The frequency of pulses in the *Baseline* system is increased (one pulse crop every 2 years) to assess the impact of more legumes on profitability, soil fertility, disease and weeds. N rates on cereals targeting median (50th percentile) seasonal yield potential. Aligned with the Pampas '+legume' system.

4. **Higher nutrient supply** – N and phosphorus rates of the *Baseline* system are increased targeting the 90th percentile of yield potential based on soil moisture in a variable climate environment, with crops and other practices the same as *Baseline*. Aligned with the Pampas '+nutrient' system.
5. **Higher soil fertility** – Based on the *Higher nutrient supply* system, an additional 60 t/ha of manure (wet weight) was applied to change the starting soil fertility level. This system is designed to see if higher initial soil fertility can be maintained with greater nutrient inputs (90th percentile). Aligned with the Pampas '+fertility' system.
6. **Integrated weed management (IWM)** – A minimum tillage system focused on one crop/year but employing a wide range of practices to reduce reliance on traditional knockdown herbicides in CQ farming systems. Crops include wheat, chickpea, sorghum and mungbean with N rates on cereals targeting median (50th percentile) seasonal yield potential.

These six systems were maintained until the 2020 winter crop, when the project was extended by GRDC. After consultation with the local reference committee and by request from the GRDC project manager, an additional four systems were implemented from December 2021:

7. **Higher crop diversity** – A moderate intensity (*Baseline*) system using diverse crop selection.
8. **Higher legume + Nutrition** – Higher legume system + pre-crop nutrition calculations targetting a 90th percentile yield instead of a 50th percentile. The side-banded nitrogen is expected to advantage the following crop, not the current crop.
9. **Lower intensity + Nutrition** – A low crop intensity, high nutrition system using a diverse crop selection.
10. **IWM + Nutrition** – IWM system + pre-crop nutrition calculations targetting a 90th percentile yield; aimed to combat the consistent decline in baseline fertility of the standard IWM system.

Table 2. Cropping sequence for the Emerald Northern Farming systems site. The struck-out letters for systems on the right-hand side indicate crops that were grown in that location prior to the system being split off the parent system.

Legend:	W = Wheat	Cp = Chickpea	S = Grain Sorghum	Mb = Mungbean	B= Barley	C = Dryland Cotton	Ma = Maize	Mi = Millet	F = Fallow	
Expanded CQ NFS Systems (system code)										
Crop Cycle	**Baseline (M01)**	**Higher Crop Intensity (M07)**	**Higher Legume (M03)**	**Higher Nutrient Supply (M02)**	**Higher Soil Fertility (M02b)**	**Integrated Weed Management (X01)**	**Higher Diversity (M05)**	**Higher Legume + Nutrition (M03b)**	**Lower intensity (M14)**	**IWM+ Nutrition (X01b)**
Winter 2015	W	W	Cp	W	W	W	~~W~~	~~Cp~~	~~W~~	~~W~~
Summer 2015/16	F	Mb	F	F	F	F	~~F~~	~~F~~	~~F~~	~~F~~
Winter 2016	CP	W	W	Cp	Cp	Cp	~~Cp~~	~~W~~	~~Cp~~	~~Cp~~
Summer 2016/17	F	F	F	F	F	F	~~F~~	~~F~~	~~F~~	~~F~~
Winter 2017	W	W	CP	W	W	W	~~W~~	~~CP~~	~~W~~	~~W~~
Summer 2017/18	S	S	S	S	S	S	~~S~~	~~S~~	~~S~~	~~S~~
Winter 2018	F	F	F	F	F	F	~~F~~	~~F~~	~~F~~	~~F~~
Summer 2018/19	F	F	F	F	F	F	~~F~~	~~F~~	~~F~~	~~F~~
Winter 2019	W	CP	CP	W	W	W	~~W~~	~~CP~~	~~W~~	~~W~~
Summer 2019/20	F	F	F	F	F	F	~~F~~	~~F~~	~~F~~	~~F~~
Winter 2020	W	W	W	W	W	W	~~W~~	~~W~~	~~W~~	~~W~~
Summer 2020/21	F	F	F	F	F	F	~~F~~	~~F~~	~~F~~	~~F~~
Winter 2021	F	F	F	F	F	F	~~F~~	~~F~~	~~F~~	~~F~~
Summer 21	Mi	Mi	Mi	Mi	Mi	Mi	~~Mi~~	~~Mi~~	~~Mi~~	~~Mi~~
Summer 22	S	S	Mb	S	S	S	Ma	Mb	C	S
Winter 22	CP	CP	CP	CP	CP	CP	CP	CP	F	CP
Summer 22/23	F	F	F	F	F	F	F	F	F	F
Winter 23	W	B	W	W	W	W	B	W	W	W

Crop sequences to date

After 9 years, most systems have now produced 10 different crops (Table 2). All systems added in 2021 were applied onto existing system plots (which were split in half), so any crop/system data shown for these four systems prior to summer 2022 was derived from the 'parent' system.

Results

Climate observations

Comprehensive climatic observations for the Emerald NFS site included daily summary data and 15-minute observations. While not a core focus of the trial program, differentiating and understanding how climatic events are driving agronomic responses across the very broad geographic spread of trials is important.

Temperature

Unsurprisingly, Emerald's average temperatures tend to be higher than the more southern sites. However, raw maximum temperatures are not driving the higher averages. The warmer minimum temperatures can have a significant effect on plant physiology. Nights tend to be warmer (Figure 1) with overnight lows in the low to mid-20s commonplace during the warmer months.

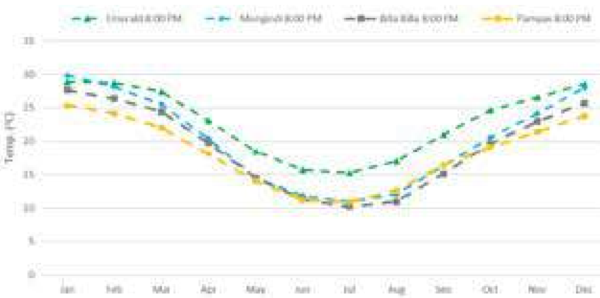


Figure 1. Average monthly temperature at 8 pm for the four Queensland- based Northern Farming Systems sites.
The Emerald site (green line) is consistently warmer later into the evening from March to November.

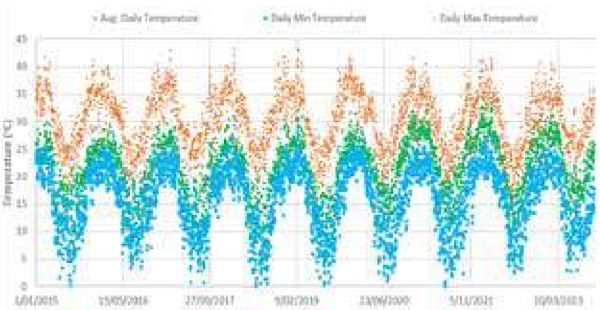


Figure 2. Daily minimum (blue), maximum (orange) and calculated average daily (green) temperatures for the Emerald Northern Farming systems trial (range 0 to 44°C).

Frosts are still possible at the Emerald site (Figure 2), although the risk is much lower than the southern sites (or other locations in CQ).

Rainfall

Emerald's long-term average annual rainfall is approx. 600 mm with a summer-dominant distribution. While climate data from the Emerald site (Figures 3 & 4) confirms the summer dominance of rainfall over the nine years, seven of the last ten crops grown have been winter crops (Table 2).

The box and whisker plot (Figure 3) shows the variability of the monthly rainfall. While the monthly average rainfall (marked as an x) is consistent with a summer-dominant rainfall pattern, the distribution of rainfall over the trial period points to a greater likelihood of rainfall later in summer rather than from October onwards (although significant early rainfall has occurred). The graph shows monthly rainfall of >100 mm occurred in every month except April, August and September. Conversely, every month except for January (10.2 mm) and February (9.6 mm) had a <5 mm total rainfall at some stage during the trial.

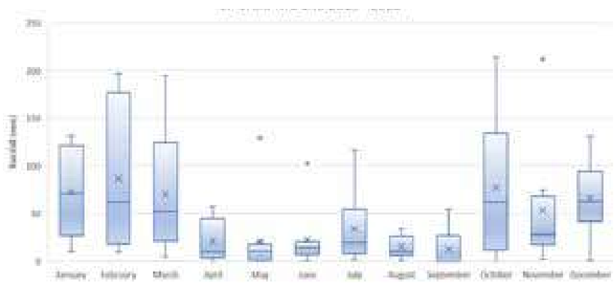


Figure 3. Monthly average rainfall distribution 2015–2023.
The 'x' marker indicates the mean monthly rainfall for the period, the middle line is the median, top and bottom error bars indicate the variation in average rainfall, while the individual points indicate outlier rainfall events when compared to all other falls over that period.

Figure 4 shows the variability of annual rainfall for the site (264 mm in 2015, 774 mm in 2022) but also when the rain fell. Consistent with Figure 3, cumulative rainfall in the period from April to September is typically the lowest, with most years showing only incremental rainfall accumulation at best over that period. Only 2016 and 2022 stand out as exceptions. The grey dotted line indicates the average rainfall received for the site over the past nine years (560 mm), 40 mm below the long-term average of 600 mm.

Climate-induced crop stress

While rainfall and temperature are drivers of crop growth, in isolation they are not strong predictors of crop performance. A crop's ability to access stored soil water when required enables it (within reason) to handle higher temperatures or prolonged periods

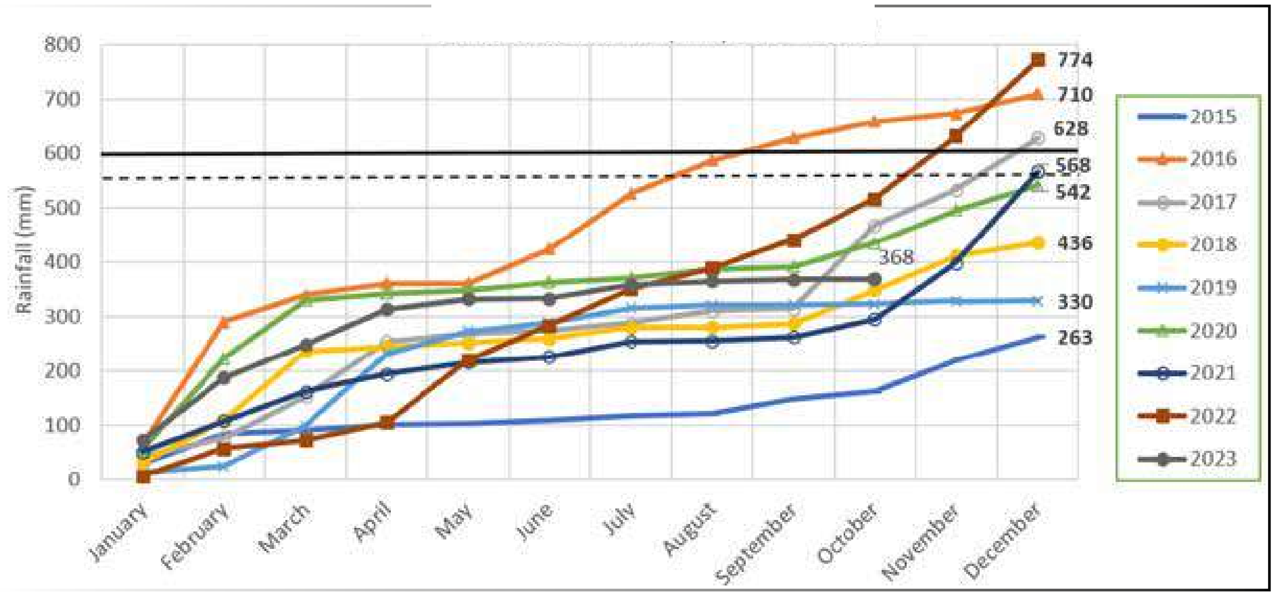


Figure 4. Cumulative rainfall for nine years at the Emerald Northern Farming Systems trial.

The horizontal dotted line indicates the average rainfall over the reported trial period (560 mm), the thick line above it indicates the long-term average rainfall for Emerald (600 mm).

of little to no rainfall. However, there are obviously limits to their capacity to do this, depending on the crop type and the time sown.

Photosynthesis is the process of converting carbon dioxide + water into oxygen and glucose, using sunlight. A plant experiencing higher than ideal temperatures or low relative humidity diverts water and energy from this process to try to cool/hydrate itself through transpiration, which isn't a significant issue if there is plenty of plant available water and is only for a short period of time. However, if water is limited or at depth, the amount lost to transpiration is greater than what the plant can extract. This is when crop stress can occur causing the plant to shut down to prevent excess water loss, which can have a significant effect on crop production and quality.

In an ideal situation, you would grow crops in periods when they would experience the least amount of stress (or at least during critical periods like flowering and grain fill). Indices like vapour pressure deficit (VPD; the difference between how much moisture the air can hold and how much it is currently holding) are very useful in identifying these periods. The lower the deficit, the lower the chance of stress-inducing conditions for a crop.

For the Emerald site, VPD monthly average ranges between 0.8 to 1.8 kpa (Figure 5), however daily figures vary between 0.1 to 4.0 kpa depending on relative humidity and temperature. A VPD of 0.6-0.8 kpa is usually deemed optimum for a range of crops. Commercially, indicative observations show a VPD of 0.7–0.9 seems ideal for flowering or grain filling winter cereals, while a VPD well below 2.0 kpa during flowering and grain fill would be preferred for summer cereal and pulse crops.

Water capture & use efficiency

During the trial to date, the Emerald site's average time in-crop (for the six core systems) has been approximately 40%. The in-crop percentage of the cumulative 4861 mm of rainfall over the past nine years is approximately 30%, or 1461 mm. Of the

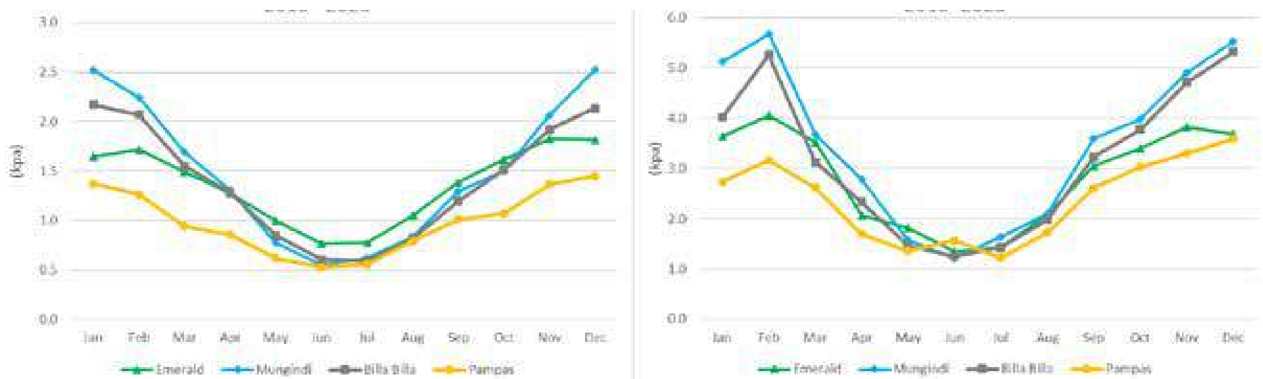


Figure 5. Daily average and maximum monthly VPD (kpa) observations for 2015–2023 for the Northern Farming Systems sites at Emerald, Mungindi, Billa Billa and the Pampas core site.

For winter cereals, the target range (0.6 – 1.0 kpa) is much narrower for the Emerald site, relative to the other three sites, however during January – March, conditions appear much milder on average in Emerald, relative to Billa Billa and Mungindi, hence the difference in sorghum cropping windows.

Table 3. Fallow efficiency (%) and water use efficiency (WUE) kg/mm/ha) since commencement of the system.

System	Total rainfall (mm)	Time in crop (%)	Rain in crop (%)	Fallow rainfall (%)	Fallow efficiency (%)	Available fallow moisture (mm)	In-crop rainfall (mm)	Total crop PAW (mm)	Long term grain WUE (kg/mm/ha)	Average yield (t/ha /year)
Baseline	4861	40%	29%	71%	18%	623	1410	2033	13.2	3.0
Higher crop intensity	4861	43%	30%	70%	21%	731	1458	2189	9.5	2.3
Higher legume	4861	35%	23%	77%	19%	724	1118	1842	12.4	2.5
Higher N supply	4861	40%	29%	71%	19%	672	1410	2082	13.5	3.1
Higher soil fertility	4861	40%	29%	71%	23%	789	1410	2199	15.1	3.7
IWM	4861	40%	29%	71%	20%	691	1410	2100	13.8	3.2
Higher crop diversity	1991	50%	37%	63%	18%	229	737	965	12.4	4.0
Higher legume + N	1991	42%	27%	73%	19%	270	538	808	12.5	3.4
Low crop intensity	1991	45%	30%	70%	18%	249	597	846	12.6	3.5
IWM+Nutrition	1991	48%	41%	59%	21%	244	816	1061	13.9	4.9

Note: The last 4 systems commenced in early 2022.

remainder (3400 mm), the fallow efficiency (FE) or the system's ability to convert fallow rainfall into plant available water (PAW) stored in the soil across the 10 systems has ranged from 623 mm (18% systems), up to 789 mm for the 23% system (*Higher soil fertility*).

The long-term average water use efficiency (WUE) for the Emerald site (six original systems) was 12.9 kg of grain produced for every mm of rainfall per ha utilised by the crop (Table 3). That figure ranges from 9.5 kg for the *Higher crop intensity* system, up to 15.1 kg/mm/ha for the *Higher soil fertility* system.

In isolation, the FE across the systems needs significant improvement given how much water we are missing out on, particularly considering the economic consequences. However, other factors to consider include:

- the inconsistency of rainfall intensity over the duration of the trial.
- all systems are operated under a zero till, controlled traffic regime.
- the fallow efficiency of the *IWM* systems with higher populations / narrow row spacings was no better than the *Higher soil fertility* systems, nor was the *Higher crop intensity* system (that was designed to increase the percentage of time in-crop).

If maximum raw tonnage/ha is the goal, perhaps improving the average WUE may offer a simpler solution to increase production.

If the six original systems had a 10% improvement in FE with no change to WUE, on average all would have achieved a grain yield gain (/ha/year) of 100 kg (Table 4). However, if we were able to improve WUE by 10% with no change to FE, the systems would

Table 4. A 'What if' scenario of improving fallow efficiency (FE, %) and water use efficiency (WUE, kg/mm/ha) comparing the benefits of improving either index by 10% on long term grain production.

System	System Fallow Efficiency %	System Fallow Efficiency + 10%*	System Grain WUE (kg/mm/ha)	Long Term Grain WUE + 10 % (kg/mm/ha)**	System avg. production (t/ha/year)	10 % FE improvement (t/ha/year)*	10% WUE Improvement (t/ha/year)**	10% for both *** (t/ha/year)
Baseline	18.1%	19.9%	13.2	14.5	3.0	0.09	0.30	0.40
Higher crop intensity	21.5%	23.6%	9.5	10.4	2.3	0.08	0.23	0.40
Higher legume	19.4%	21.3%	12.4	13.6	2.5	0.10	0.25	0.47
Higher N supply	19.5%	21.4%	13.5	14.9	3.1	0.10	0.31	0.54
Higher soil fertility	22.9%	25.1%	15.1	16.7	3.7	0.13	0.37	0.66
IWM	20.0%	22.0%	13.8	15.2	3.2	0.11	0.32	0.55
Site average (9 years)	20.2%	22%	12.92	14.21	2.98	0.10	0.30	0.50

* 10% improvement in FE, ** 10% improvement in WUE, *** production uplift if both FE and WUE were increased by 10%.

have yielded on average 300 kg/ha/year more than they have. Improve both WUE and FE, and the yield gain would be 500 kg/ha/year or an additional 4.5 t of grain/ha over nine years, for the same rainfall amount and seasonal distribution.

Production

Crop yield

Cumulative yield and biomass data over the duration of the trial were assessed for each system. For the systems that were added after splitting off from one of the six 'core' systems, to allow for a quick comparison, the cumulative quantity of grain or biomass produced prior to the split is added to the system graphs (Figure 6).

The best performing system with regard to total grain production has been *Higher soil fertility*, which has accumulated 31 t/ha from nine grain producing crops (Figure 6). The *IWM + N* system marginally outperformed the *IWM* system by 71 kg/ha. The *Baseline* system ranked fifth with a cumulative deficit of 5 t/ha lower than *Higher soil fertility*.

Biomass production

Biomass production is correlated with yield; the difference between *Higher soil fertility* (86.3 t/ha) and *IWM + N* is minimal at 68 kg/ha after ten crops over nine years (Figure 7). Comparing biomass production between the *Baseline* and *Higher nutrient supply* systems shows 1 t/ha difference despite the additional N fertiliser applied to the *Higher nutrient supply* system.

Economics

An economic analysis calculated the gross margin (GM, $/ha) and GM per mm ($/mm/ha) of all systems and their interactions across and within the Queensland and New South Wales sites. The Emerald data shows that the *Higher soil fertility* system has been the best performing system for the past nine years at $8450/ha, which is higher than the six original systems by $850/ha and the *Baseline* system by $1450/ha (Figure 8). The *IWM* system is the next highest with $7602/ha followed by *Higher nutrient supply* at $7327/ha.

Figure 8. GM (circles) and GM/mm/ha (columns) for the duration of each system at the Emerald site.

The cost of manure application was not factored into the *Higher soil fertility* system as it was never intended to be a 'manure' system, but a strategy to increase the level of soil fertility to levels when the site was first farmed. The strategy to apply nutrition to target the 90th percentile of crops was to help maintain fertility levels. Input costs of applying manure included a purchase price of $15/t plus $20/t transport plus $3/t to spread (based on an application rate of 60 t/ha), equating to $2280/ha.

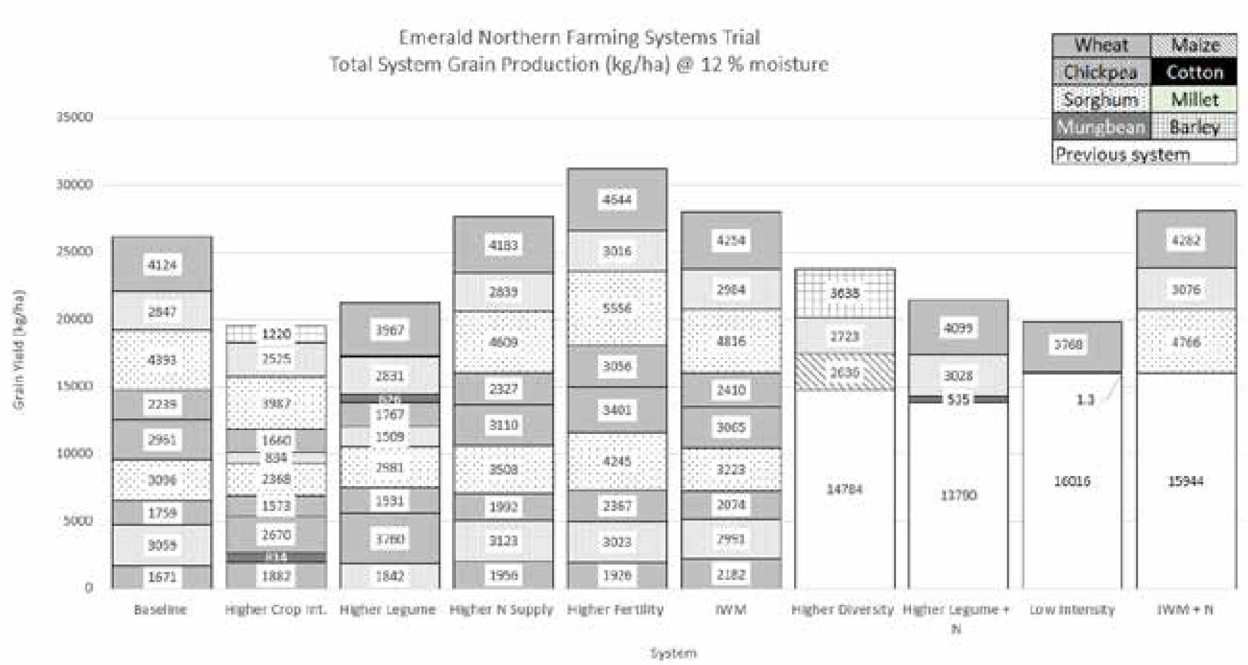


Figure 6. Cumulative grain production (kg/ha) for all 10 systems since 2015.

For systems which started in 21/22, the cumulative total of the parent system prior to commencement has been added to the base of that column. On raw production volume, after nine grain crops, the ***Higher soil fertility*** system has produced 31 t/ha, which is 5 t/ha more than the ***Baseline*** system, with an identical cropping rotation.

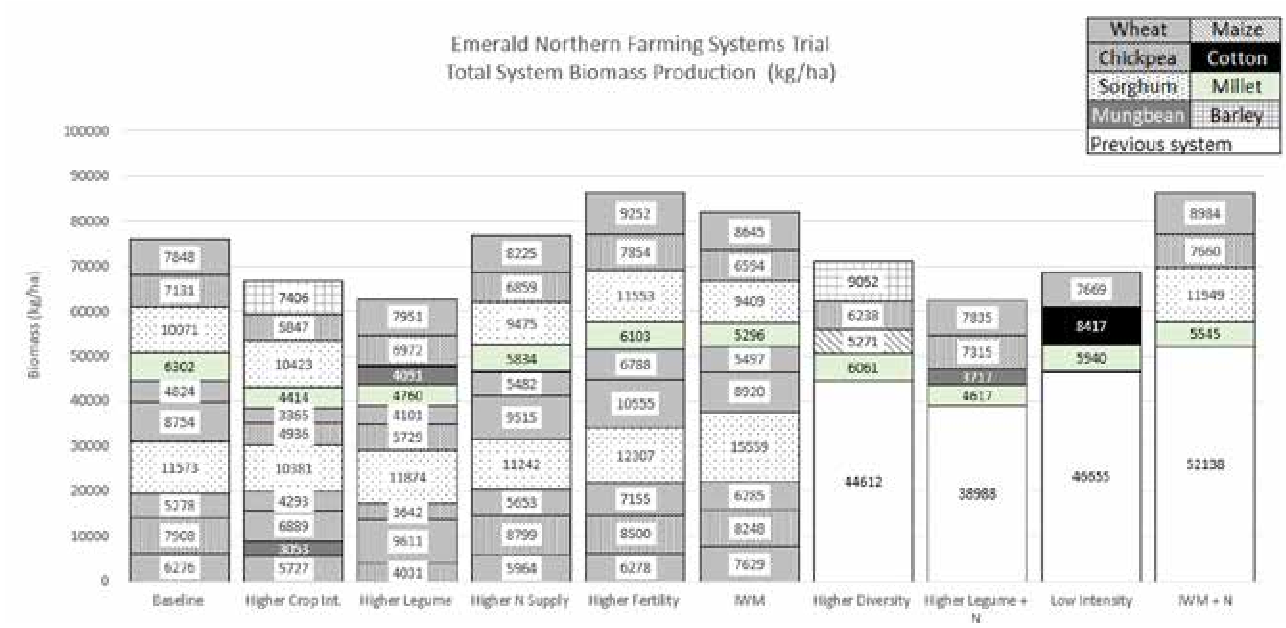


Figure 7. Cumulative biomass production (kg/ha) for all 10 systems since 2015. For systems which started in 21/22, the cumulative total of the parent system prior to commencement has been added to the base of the that system column.

The highest GM/mm was *IWM + Nutrition* at $1.97/mm/ha since its commencement in late 2021, folowed by *Higher soil fertility* at $1.74/mm/ha, while *Baseline* has returned $1.44/mm/ha to date.

Nutrition

System available N was measured both pre-plant and post-harvest for all crops to a depth of 90 cm (Figure 9) which enables the monitoring of total N cycling over time and monitor where the N is in the profile. As the trial progressed, N levels fluctuated from system to system and crop to crop relative to the *Baseline*. The most obvious deviation has been the *Higher soil fertility* system which sits consistently above all other systems, the increase in soil N became obvious after the second manure application in late 2016.

The *High soil fertility* system peaked at over 500 kg/ha of available N down to 90 cm in late August 2021, after an extended fallow period post the wheat crop in 2020. But it is important to note that it has maintained levels above 250 kg/ha since March 2017. For many, there is concern that plants with high N levels will produce lots of biomass and run out of water to fill if the season is unfavourable.

Yet when you compare the screenings, protein and yield of crops grown between 2017 and 2020 for the *Higher soil fertility* and *Baseline* systems (Table 5), the *Higher soil fertility* system consistently out-yielded Baseline, had similar or higher grain protein, but most importantly, had lower screenings, three years out of the four. The 2018 season started wet and ended in very hot dry conditions during flowering and grain fill, and 2019 started well, but the rain stopped after July leading to another hard dry finish.

Another observation is just how quickly the N levels declined after the millet cover crop – sorghum – chickpea – wheat crops between late 2021 and September 2023. To still have 114 kg/ha of N available post-harvest in 2023 seems acceptable, when you consider the N levels for systems like the two *IWM* strategies, however looking at where that N lies in the profile highlights how dramatic the decline has been.

Anecdotally, the 2021 millet cover crop used 175 kg N/ha to produce 6.1 t/ha of biomass, with the majority drawn from 0-60 cm. The millet was terminated at flowering and residues remained, and the system was planted to sorghum in early February, which received 250 mm prior to spray out and produced 5.56 t/ha of grain despite some very hot dry conditions in March – early April. The difference between planting and harvest N for that crop was –66 kg/ha. Such a small difference for that amount of grain would indicate that as the millet residue was breaking down (which it did quickly during that crop), some of the available N was being picked up by the developing sorghum crop.

The sorghum was harvested on the 17/06/2023, with almost a full moisture profile thanks to 180 mm of the 278 mm of rainfall from late April onwards. Profile N indicated there was 261 kg N/ha available at planting, however 177 kg N/ha was in the 60–90 cm profile area. The crop, though late sown and double cropped, yielded 3 t/ha thanks to the additional 314 mm of in-crop rain and the very mild spring temperatures. But N levels down to 60 cm

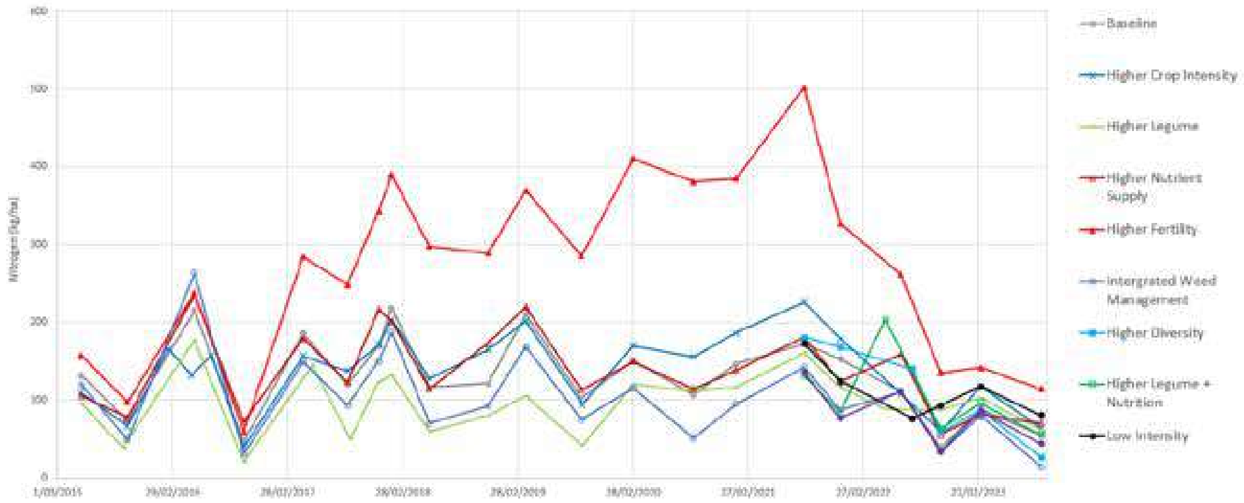


Figure 9. Profile average available N for all ten systems down to 90 cm since 2015. The graph shows the average available N for each of the systems when tested pre plant and post-harvest.

were exceptionally low post harvest. The full profile test indicated 135 kg/ha of N, but only 17 kg/ha of that was available above 60 cm.

The chickpea crop produced 7.85 t of biomass, and as the crop was harvested with a header equipped with a chopper, breakdown of that stubble was relatively quick.

An additional 518 mm of rainfall was received post the chickpea crop until the next crop was planted in April 2023. Water triggers were hit for a summer cereal crop, but because of the rainfall received during the planting window and significant wheel track issues from the previous two crops that needed to be corrected, a winter crop was targeted for 2023 instead.

Total N at planting was 142 kg/ha, meaning no additional N was required, however only 7 kg N/ha had mineralised post-harvest of the chickpea. There does however appear to have been a redistribution of N through the profile, with N below 60 cm down from 118 kg to 73 kg/ha, but N above 60 cm containing 69 kg/ha instead of 17 kg/ha.

The 2023 season was very dry but started with an almost full profile. Total in-crop rain was 59 mm for this system, 24 mm of which fell four days after sowing, 27 mm fell in early July and the sundry being made up of incidental showers of less than 2 mm. The wheat yielded beyond expectations for the season, producing 4.6 t/ha of grain, and 9.2 t/ha of biomass. Profile N down to 90 cm is 114 kg/ha, however only 23 kg/ha of that is above the 60 cm (Figure 10a).

As a point of contrast, the same depth increment graphs for both the *IWM* and *Higher nutrient supply* systems have been included. Both systems have had identical cropping cycles to the *Higher soil fertility* system, the difference being that the *IWM* system uses a 50th percentile nutrition program, but also plants on narrower row spacings. The *Higher nutrient supply* system uses a 90th percentile nutrition system, on the same row spacing as the *Higher soil fertility* system (and *Baseline*).

The most important thing to note about these two system graphs is the Y axis scale. The *Higher soil fertility* system (Figure 10a) went up to 500 kg/ha, these two systems (Figures 10b and 10c) only go up to 200 kg/ha. Like the *Higher soil fertility* system, both these systems started with adequate N levels distributed across the profile after the fallow in 2020–21. Post the millet crop, which produced 5.8 t for *Higher nutritient supply* and 6 t for *IWM*, we again saw a significant draw-down of N from the 0–60 cm part of the profile leading into the summer sorghum crop. At planting 60 kg N/ha was required and applied for both systems when planting

Table 5. Grain yield, quality and protein comparison between the *Higher soil fertility* and *Baseline* systems.

		Higher soil fertility				Baseline			
		Starting profile N (kg/ha)	Yield (t/ha)	Protein (%)	Screenings (%)	Starting profile N (kg/ha)	Yield (t/ha)	Protein (%)	Screenings (%)
2017	Wheat	239	2.37	13	2.5	187	1.76	13	2.7
2018	Sorghum	284	4.24	11.9	14	219	3.09	11.9	22.2
2019	Wheat	390	3.4	12.7	8.3	210	2.96	12.3	7.15
2020	Wheat	411	3.05	14.3	2.8	150	2.24	13.1	3.75

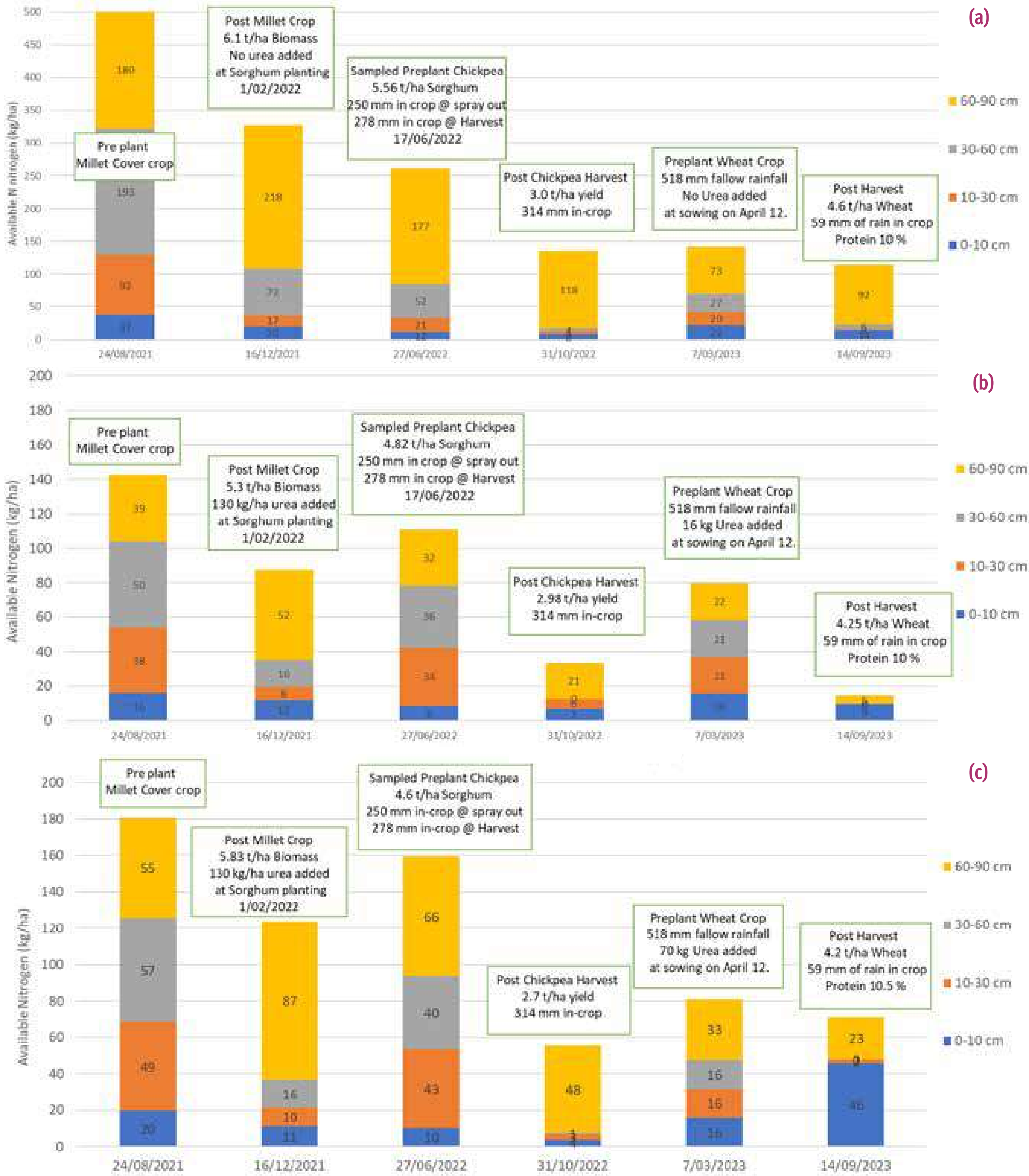


Figure 10. Comparison on of available N down to 90 cm from August 2021 to October 2023 for (a) *Higher soil fertility* (b) *Integrated weed management (IWM)* and (c) *Higher nutrient supply*. Each stacked bar indicates available N for any given sampling date in increments.

sorghum, and yields were 4.8 t/ha for *IWM* and 4.6 t/ha for *Higher nutritient supply*.

Here we see the first diversion from the *Higher soil fertility* system (which received no additional N). Available N levels were higher after harvest of the sorghum crop compared to preplant. *IWM* increased by 24 kg N/ha, while *Higher nutrient supply* increased by 35 kg N/ha. While less than the N applied at planting, considering that both systems had just produced over 4.5 t of grain and 9.4 t of total biomass, it appears that the rapidly decomposing millet residue contributed additional N to the crop.

Post chickpea, like the *Higher soil fertility* system, there was very little residual N left in these systems, particularly above 60 cm. Total N was higher for the *Higher nutrient supply* system, with a total of 56 kg/ha available down to 90 cm, compared to 33 kg/ha for the *IWM* system, however only 13 kg was available above 60 cm for the *IWM* system and 8 kg for the *Higher nutrient supply* system.

N mineralisation post-chickpea was 47 kg/ha for the *IWM* system and 25 kg/ha of N for the *Higher nutrient supply* system. It appears that for this fallow period, the lower the finishing post-harvest N, the greater the mineralisation (Table 6). Across the 10 systems (with *Higher crop intensity* as a notable exception) generally the lower the starting N post-harvest, the greater the fallow mineralisation, with IWM + N mineralising 52 kg/ha, down to *Higher soil fertility* at 7 kg/ha, a long way short of the 100 kg/ha plus mineralisation observed between 2016–2021.

At planting, 35 kg N/ha was applied to the *Higher nutrient supply* system and 16 kg N/ha should have also been applied to the *IWM* system, unfortunately due to a transcribing error, only 8 kg/ha was applied. Yields were well above expectation despite minimal in-crop rain, with both systems averaging just over 4.2 t/ha grain yield, while producing in excess of 8.6 tonne of biomass for the *IWM* system and 8.2 t/ha for the *Higher nutrient supply* system. Grain protein for the *Higher nutrient supply* system was 10.5% while the *IWM* system was 10%.

Both systems had almost identical N going onto the 2023 season, planted at the same time and despite the row spacing difference, produced almost identical amounts of grain. The biggest difference was residual N post-harvest. The *IWM* system had a total of 15 kg/ha of N remaining down to 90 cm. The *Higher nutrient supply* system had 71 kg N/ha remaining in the profile, but unlike the *Higher soil fertility* system, which had 92 of its 114 kg N/ha at depth, the *Higher nutrient supply* system had 46 of the 71 kg N/ha in the top 10 cm and 23 kg N/ha down below 60 cm with very little in between.

Summary

The *Higher soil fertility* system has been the standout of the Emerald systems, both in terms of how high the N profile got and the yield responses achieved relative to the *Baseline* system, but equally how poorly even the 90th percentile nutrient strategy has failed to maintain its fertility levels post 2021.

Both the *Higher nutrient supply* system and *Higher soil fertility* nutrition requirements are targeted at a 90th percentile crop yield or top 10% of yield predictions (based on starting PAW) and APSIM modelling for a given sowing date. The ambition is that if additional water became available during the season, these systems would not be lacking in available N or phosphorus.

For most of the trial, partly because of the inherent fertility and mineralisation qualities of the soil at the site, additional N application requirements have been minimal as available N in the profile was already above the crop needs (even at the 90th percentile level). Therefore, the variation between *Baseline* and *Higher nutrient supply* has been negligible, with no significant improvement in profile N compared to the *Baseline* system over the past nine years (Figure 13).

The *Higher soil fertility* system, because of the 'just in time' nutrition strategy, is an excellent example of what can happen when a system is effectively mined. No N has been applied to that system post 2016, and the performance of the 60 t/ha manure from the additional 10 t/ha of organic carbon (OC) has been stellar (Table 7).

However, the quantum of the decline in N levels post the cover crop (175 kg/ha of N), sorghum crop (66 kg/ha of N) and then chickpea (126 kg/ha of N) was surprising. The system still had significantly

Table 6. N mineralisation (kg/ha) post chickpea going into the 2023 winter cereal crop. Apart from *Higher crop intensity*, there appears to be almost a linear response to mineralisation base on how much N was available post-harvest.

System	Crop	Post harvest profile N (kg/ha) 31/10/2022	Pre-plant profile N (kg/ha) 07/03/2023	Mineralised N (kg/ha)
Higher crop intensity	Chickpea	60	118	58
IWM + Nutrition	Chickpea	34	86	52
Baseline	Chickpea	40	89	50
IWM	Chickpea	33	80	47
Higher legume + Nutrition	Chickpea	64	97	33
Higher crop diversity	Chickpea	59	87	28
Higher nutrient supply	Chickpea	56	81	25
Low crop intensity	Fallow	93	118	24
Higher legume	Chickpea	88	103	15
Higher soil fertility	Chickpea	135	142	7

Table 7. Estimated nutrients applied based on lab analysis of the manure applied to the *Higher soil fertility* system.

	Nutrient	est. applied (kg/ha)
Mar-15	Nitrate (N)	24
	Phosphorus (P)	110
	Carbon (OC)	1795
	Potassium (K)	233
Nov-16	Nitrate (N)	20
	Phosphorus (P)	313
	Carbon (OC)	8799
	Potassium (K)	478
	Total N applied (kg/ha)	43
	Total P applied (kg/ha)	422
	Total OC applied (kg/ha)	10594
	Total K applied (kg/ha)	711

more N than all others going into the 2023 wheat crop, but most of that was at depth, and net mineralisation had only produced 7 kg/ha during the fallow period (Table 6).

The 367 kg/ha reduction in N was not completely lost to the system. You only need to look at how little net N was removed post the 2022 sorghum crop across the systems, relative to the crop yields and biomass produced to understand that N tied up in the millet residue had already begun returning to the system. That residue broke down quicky post desiccation in early November 2021, and by chickpea planting in 2022, groundcover was limited.

It will be interesting to track this system moving forward. Even if the organic carbon boost has been used, the additional benefits of the significant amounts of P, K and other nutrients (Table 7) present in the manure at the time of application will still be present and may continue to offer an advantage for some time yet.

Chickpea in high N scenarios

Questions remain around what effect planting a chickpea crop into soil with plenty of available N would have. N levels across all systems (particularly those in sync with the *Baseline*) were at the lowest level they have been, after the 2022 chickpea, or at least since post-harvest of the last chickpea crop back in 2016 (which also happened to be grown in a wet year). While the crop yielded on average across the systems 2.9 t/ha and produced 6.9 t/ha of biomass, it also extracted an average 81 kg/ha of N to do so.

Despite a wet summer, and a profile with plenty of water and warm conditions over the fallow period, we did not see the levels of mineralisation in 2022–23 (Table 6) that we did in 2016–17. That fallow, post chickpea, the *Baseline* mineralised 141 kg/N/ha, *Higher nutrient supply* 108 kg N/ha and *Higher soil fertility* 224 kg/N/ha. Those crops averaged 3 t/ha grain yield and 8.3 t/ha biomass, however when the chickpeas were planted, there was an average of 238 kg/ha of N available. These were levels that weren't seen again until pre-sorghum 2018.

There are many significant benefits to growing chickpea within a cropping rotation, however, believing that you will be significantly adding N to a profile which may already have reasonable to good fertility, may not be one of them.

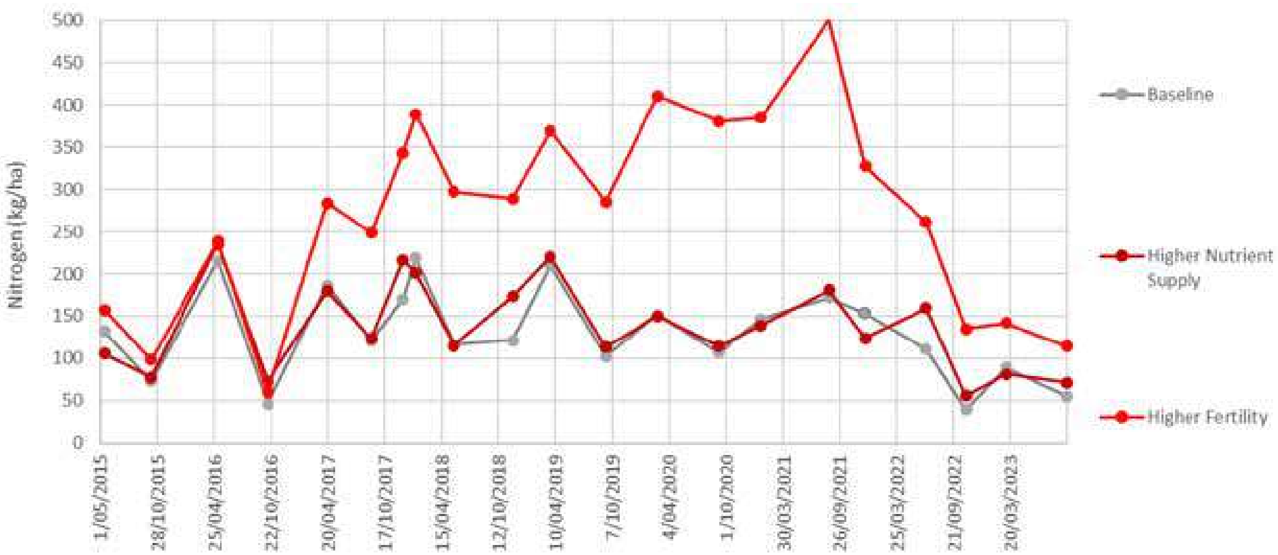


Figure 13. Available N in the profile down to 90 cm from 2015 to harvest 2023. The graph compares the *Baseline* (grey), *Higher nutrient supply* (dark red) and *Higher soil fertility* (bright red) systems. All three systems have had an identical crop sequence since 2015. *Baseline* uses a 50th percentile nutrition target while *Higher nutrient supply* and *Higher soil fertility* use a 90th percentile nutrition target.

Nutrient stratification

The *Higher nutrient supply* system in 2023 received 32 kg/ha of N at planting, 16 kg N/ha was present prior to application, and post harvest 46 kg N/ha was found in the top 10 cm (Figure 10c) yet the layers between 10 and 60 cm had little N remaining. Much of the N applied had become stratified due to application onto an already full moisture profile and the lack of significant rainfall later in the season to move the N down into the root zone. This effect was consistent for the *Lower crop intensity* and *Higher legume + N* systems.

Nutrient stratification is common and well understood, particularly in winter crops in CQ that are grown on subsoil moisture with minimal in-crop rainfall post-planting. The *Higher legume + N* system, when planted to a pulse crop, aims to leverage stratification so sufficient N to replace the expected N removal of a pulse crop will be available post-harvest for the next crop

The only system that didn't see as significant a case of stratification was the *IWM + Nutrient* system that had its N applied at the end of March instead of at planting in April. It received 35 mm of rainfall between application and planting that seems to have been sufficient to make it available to the crop.

mm to $

Ultimately as system managers, as much as we like to think the aim is produce more grain, more protein or more fibre, when it is all paired back to bare basics, what we are fundamentally doing is trying to convert rainfall into cashflow. The WUE section (Tables 3 & 4) breaks down the WUE and FE of the different systems to date. In summary, after nine years:

- Average rainfall: 560 mm
- Average time in crop: 40%
- Average rainfall in crop: 28%
- Fallow efficiency: 20% (soil PAW increase over fallow ÷ fallow rainfall)
- Water use efficiency: 12.9 kg/mm/ha

While interesting in isolation, these figures don't highlight the variation between the systems that have been in place at Emerald since 2015/2021, nor the financial repercussions of the system choices. In Table 8, there is a 'what if' scenario, showing annual returns per system for a 2000 ha cropping enterprise in CQ with an annual rainfall of 560 mm per year.

In the table, the GM/mm/ha values have been used from the economics section and extrapolated out to the value across the full enterprise. In addition, the average PAW used by the crop has been calculated, based on the crop water use percentage above for each system. Using this value, we can put a value to every mm of rainfall a crop uses and what that is worth to the enterprise.

Table 8. Case study showing what value per mm for each system would have provided annually for a 2000 ha enterprise with an annual rainfall of 560 mm per year.

System	$ GM per mm/ha	Enterprise $/mm of rainfall	Enterprise Annual $ GM
Baseline	$ 1.44	$ 2,889	$ 1,617,906
Higher crop intensity	$ 0.89	$ 1,783	$ 998,346
Higher legume	$ 1.38	$ 2,769	$ 1,550,397
Higher nutrient supply	$ 1.51	$ 3,015	$ 1,688,179
Higher soil fertility	$ 1.74	$ 3,477	$ 1,946,925
IWM	$ 1.56	$ 3,128	$ 1,751,541
9-year average	$ 1.42	$ 2,843	$ 1,592,216
Higher diversity	$ 1.20	$ 2,392	$ 1,339,387
Higher legume + N	$ 1.57	$ 3,132	$ 1,753,973
Low crop intensity	$ 1.23	$ 2,466	$ 1,381,015
IWM + N	$ 1.97	$ 3,934	$ 2,202,873
2-year average	$ 1.49	$ 2,981	$ 1,669,312

Enterprise $/mm of rainfall shows the system value per mm to the entire enterprise. Enterprise Annual $ GM extrapolates out the gross margin per ha across a commercial enterprise of 2000 ha.

The annual difference between the best (*Higher soil fertility*) and the worst (*Higher crop intensity*) was $948,000 per year across the 2000 ha enterprise. Even the gap between *Higher soil fertility* and the *Baseline* system was $330,000 per year, which is still significant.

However, these numbers do not necessarily tell the true story of the systems' performance. To replicate a manure-based solution like *Higher soil fertility*, if you could get sufficient product, as discussed, it could cost more than $2200 per ha, which would have reduced its ranking to below the *Higher legume* system to around $1.29 per ha over the 9 years. Equally the *IWM* and the *Higher legume* systems had outperformed *Baseline* consistently up until recent times, but at an unknown cost to soil fertility.

Even the *Higher nutrient supply* and *Higher soil fertility* systems may have looked quite different if the higher nutrient calculations had been a fixed value, vs a trigger level policy. Of the four split systems, *IWM + Nutrition* annual gross margin is certainly very impressive and a possible indication of what *IWM* could have been, however given how recent their introduction has been, I would still consider those values with scepticism.

Implications for growers

Systems matter

For the Emerald site, a more conservative cropping strategy (one crop per year) but on a non-limiting nutrition plan has been the most consistent strategy to maximise returns. It sounds basic, but planting into plenty of moisture, at an optimal sowing date for that crop to reduce stress risk, with non-limiting nutrition will always produce the best outcomes over the longer term. Any system that has been 'pushed' because of PAW/sowing date/sowing depth/crop choice or density, has at some point in time taken a hit, and rarely been able to catch that lost ground up.

Nutrition

No system on the medium/standard crop intensity and higher nutrition plans have fallen behind the *Baseline* system with respect to system economics. The additional N applications made at planting have always improved returns. However, after nine years and some high yielding crops, there is scope for future nutrient strategies to include higher N rates and applications early in the fallow to improve N availability to crops.

WUE and FE

The variation between systems, but also across crops within a system, for both indices indicate that there is room for improvement of both. Ignoring the *Higher soil fertility* system, of the other medium crop intensity systems, *IWM*'s FE% and WUE was as good or better than most other systems with a gross margin to match. With early indications from the plus nutrition split positive, a move back to narrower row spacings could be a positive move, so long as the logistical challenges can be overcome.

Acknowledgements

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

I would also like to acknowledge CSIRO, New South Wales Department of Primary Industries and Regional Development and the Queensland Department of Primary Industries for their management of and contribution to the trials across QLD and northern NSW.

Finally, I would like to recognise my DPI colleagues and local team members for all their efforts over many years assisting in pulling it all together.

This article has been adaped from a GRDC update paper originally published in December 2023 grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/11/farming-systems-research-in-the-northern-grains-region-and-implications-for-key-decisions-driving-risk-and-profit-in-central-queensland.-yield,-economics,-and-seasonal-risk.

Companion cropping wheat and chickpea—Billa Billa

Andrew Erbacher, Makhdum Ashrafi and Kerry Bell
Queensland Department of Primary Industries

***Research questions**: Can we increase ground cover and fallow efficiency after chickpea? | What is the yield impact of growing wheat and chickpea together as companion crops? | What impact will companion crops have on the yield of the following wheat crop?*

Key findings

1. Combined yields of companion crops were equivalent to those of monoculture crops.
2. Companion cropping wheat with chickpea provided more stubble cover.
3. Wheat following companion crops or chickpea had less crown rot than wheat monoculture.

Background

Chickpea is an important crop in Queensland. It is a highly profitable legume and provides a disease break. However, chickpea leaves the soil quite bare, and the reduction in fallow efficiency (amount of fallow rainfall captured for use by the next crop) is a big problem in areas that rely on stored soil water for yield.

A recent study in this region (Erbacher et al. 2021) examining the potential of cover crops to improve ground cover, reduce erosion and build soil water available to the next crop sparked interest in growing a cover crop with chickpeas in order to examine both chickpea performance and if sufficient stubble is created to improve water storage and to protect the subsequent fallow from erosion.

Companion cropping or intercropping is when two or more crops are grown in the paddock together. This is not a new or novel concept, it occurs in many home vegetable gardens (such as marigolds to keep the pests out of tomatoes, or flowers to attract pollinators into the pumpkin patch). What is unusual is doing this on a broadacre scale and with mechanically-harvested crops.

A review by CSIRO (Fletcher et al. 2016) showed potential to increase crop productivity by growing two crops together as intercrops, particularly 'peaola' (canola and field pea), which increased productivity by 50% in 24 of 34 studies reviewed. Cereal-legume intercrops also increased total productivity in 64% of studies.

The CSIRO review focused on temperate cropping areas in southern Australia and internationally, so the question remained whether companion systems would perform as well in a subtropical environment and a farming system reliant on stored soil water for reliable yields. Given the importance of good stubble levels to maximise stored soil water and maintain grain yield, this trial focussed on using wheat with chickpea to provide more stubble post-harvest.

What was done

With the objective of increasing ground cover after chickpeas, discussion with local growers and agronomists developed a treatment list to compare ways to prevent the chickpea being dominated by the wheat. A linseed-chickpea combination was also assessed, similar to the 'peaola' systems used in Canada, but better suited to a June planting window. The treatments were:

1. Wheat monoculture (control)
2. Chickpea monoculture (control)
3. Linseed monoculture (control)
4. Chickpea followed by sorghum cover crop
5. Chickpea/wheat, alternate rows
6. Chickpea/wheat, mixed within rows (50:50)
7. Chickpea/wheat, mixed within rows (67:33)
8. Chickpea/wheat, mixed; spray-out chickpea
9. Chickpea/wheat, mixed; spray-out wheat
10. Chickpea/linseed, alternate rows

Each species tested as a companion was also grown as a monoculture at recommended planting rates as a baseline comparison.

The trial was planted on 30 June 2021 using a twin-cone seven row plot planter, plumbed so one cone delivered to odd rows (1, 3, 5, 7) and the other cone to even rows (2, 4, 6) to allow planting of each treatment as a single pass operation.

Varieties selected were suitable for a June planting: LPB Hellfire⁽ᴰ⁾ wheat with a target of 1 million plants/ha; PBA Seamer⁽ᴰ⁾ chickpea with a target of 250,000 plants/ha; and Glenelg linseed at 25 kg/ha.

The treatments with both crops harvested had planting rates reduced to reflect an equivalent plant density; for alternate row treatments the in-row population was the same as the monoculture controls, and the 'mixed' treatments targeted 500,000 wheat plus 125,000 chickpea per hectare or 333,333 wheat plus 166,667 chickpea per hectare spread evenly across all seven rows.

The two 'spray-out' treatments were planted at a full rate of each crop mixed within the row, so that the harvested population was the same as the monocultures. MCPA plus Ally® was used to kill chickpea at flag leaf emergence of the wheat, and Verdict® plus oil to kill wheat at first flower of the chickpea. Both were applied in early September.

Hand cuts were taken at physiological maturity, separating the crops within each treatment. These were subsequently threshed to measure a hand cut grain yield. The trial was also desiccated at this time to ensure even dry-down of the treatments, and the trial was mechanically harvested two weeks later.

At harvest, a test strip was used to determine the optimum header set-up for the five crop combinations (wheat, chickpea, linseed, wheat & chickpea, linseed & chickpea), and adjustments were made between harvesting each plot. The header samples were cleaned post-harvest to separate the seed types, which were weighed individually.

As the monoculture crops had different yield potentials, the combined companion crop yields would be expected to total somewhere between the two monoculture crops, making it difficult to assess whether a benefit/penalty was achieved, so indiviual companion crop yields were converted to a percentage of their associated monoculture crop before being added together. This combined percentage is called land equivalent ratio (LER). An LER of 100% (e.g. 60% + 40%) suggests no interaction (the same grain yield would have been achieved by growing equivanlent unmixed areas of the crops). An LER of 80% indicates antagonism between the crops (resulting in a 20% reduction in overall yield), whereas an LER greater than 100% (e.g. 60% wheat plus 60% chickpea to make 120% LER) would indicate a positive interaction (20% more yield generated than land planted to monocultures).

For comparison, a sorghum cover crop was also planted after the chickpea monoculture on 12 December 2021 and sprayed out on 13 January 2022 (32 days later).

All plots were soil sampled on 6 May 2022 to measure fallow efficiency of the different stubble loads left by the 2021 companion crops, and Coolah wheat was planted on 10 May to measure the carry-over yield benefit from the previous crops.

Results

Companion crop yields

The maturity biomass, hand-cut grain yields and header yields all produced similar relative yields (LER) and proportions of crops' contribution to yield, so only header yields are presented (Table 1).

Grain yields indicate the wheat had a competitive advantage over the chickpea. This was most evident in the mixed 50:50 and two 'spray-out' treatments, where the established wheat population was high enough to limit the chickpea yield to ~10% of the monoculture chickpea (Table 1).

Table 1. Harvested grain yield in kg/ha and as percentage of the monoculture controls.

	Wheat	Chickpea	Linseed	Combined yield		Ground cover %	2022 Wheat
Wheat monoculture	2160 a				100% ab	73% abc	1506 c
Chickpea monoculture		1496 a			100% ab	18% d	2132 a
Linseed monoculture			778 a		100% ab	25% d	1958 a
Chickpea followed by cover crop		1646 a			110% a	84% a	2076 a
Chickpea/wheat, alternate rows	1216 b	477 c		1693	90% b	65% c	1516 c
Chickpea/wheat, mixed within rows, 50:50	1874 a	104 d		1978	96% ab	78% ab	1863 ab
Chickpea/wheat, mixed within rows, 67:33	1507 b	436 c		1943	99% ab	70% bc	1934 a
Chickpea/wheat (mixed), spray-out chickpea	1888 a			1888	89% b	79% ab	1522 bc
Chickpea/wheat (mixed), spray-out wheat		170 d		170	12% c	63% c	1899 a
Linseed /chickpea, alternate rows		925 b	314 b	1239	102% ab	23% d	1964 a
lsd	295	214	140			12%	346

Treatments with different letters are significantly different to other treatments within the same column at P(0.05).

Chickpea first flower coincided with flag leaf of the wheat, so both were sprayed out on 9 September. Spraying out at this stage produced the same yield (statistically) for the remaining crop as that crop's yield in the mixed 50:50 treatment, although this yield penalty was not suprising in an environment where crops frequently rely on stored water to set grain; the sprayed-out crop had been competing with the harvested crop for this valuable resource.

The two treatments with wheat and chickpea mixed in the rows achieved approximately 100% LER. The 50:50 split treatment was slightly lower (96%) in the header-harvested sample, but the hand cuts were 100% for both biomass and grain in that treatment.

Reducing the population of wheat relative to chickpea (67% chickpea: 33% wheat) lifted the yield of the chickpea to 30% of the monoculture chickpea, maintaining the 100% LER.

Separating the wheat and chickpea into an alternate row configuration had a similar impact on the chickpea yield, lifting it from 10% to 30% of the monoculture chickpea. However, this was at the expense of the wheat yield and overall LER. The reduction was small (10%), but consistent for total biomass, hand cut yield and header yield.

Impacts after companion crops

There was very little difference in plant available water (PAW) at planting or harvest of either the 2021 or 2022 crops (Figure 1). There was ~40 mm difference in PAW between chickpea fallow and the cover crop at sorghum termination in January 2022, but there was sufficient rain after the cover crop was terminated to recover that water deficit before the May planting. Ground cover ranged from 18% to 84% at the end of the fallow (Table 1). Typically this would result in different fallow efficiencies and therefore PAW, but there was sufficient fallow rainfall that all plots had a full profile when the 2022 wheat crop was planted.

Soil nitrates measured at this site were high enough to provide all of the needs of both 2021 and 2022 crops (Figure 2). With nitrogen and starting soil water unlimited, it was expected that wheat yields in 2022 would be the same in all treatments, however the 2022 wheat following wheat monoculture produced the lowest yield (Table 1) and highest screenings and had visual effects of stubble disease (crown rot).

The 2022 wheat after chickpea monoculture had the highest yield, with six other treatments similar (Table 1).

Wheat with chickpea sprayed out and alternate row wheat chickpea companion crops were the only treatments statistically similar to the low yields of the wheat monoculture. Where the chickpea was sprayed out (while the wheat was still vegetative), the stubble that remained was very wheat-dominant, acting as a potential disease bridge.

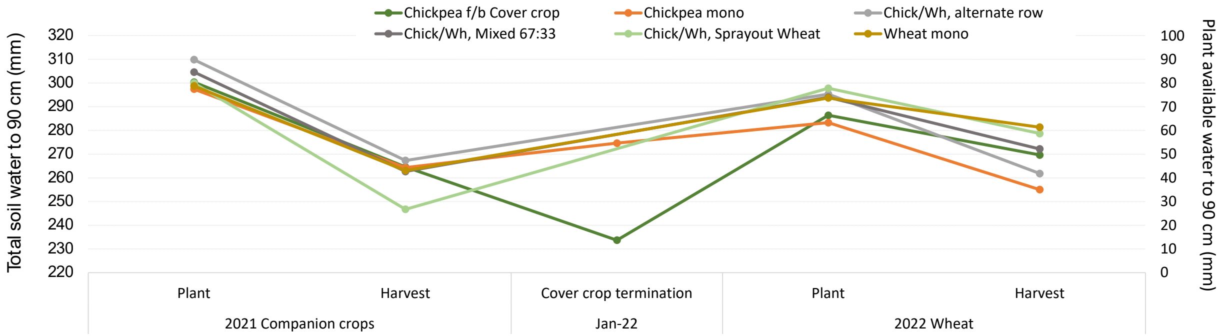


Figure 1. Total soil water measured in the top 90 cm of several treatments during the trial (measurements did not change between 90 and 120 cm).

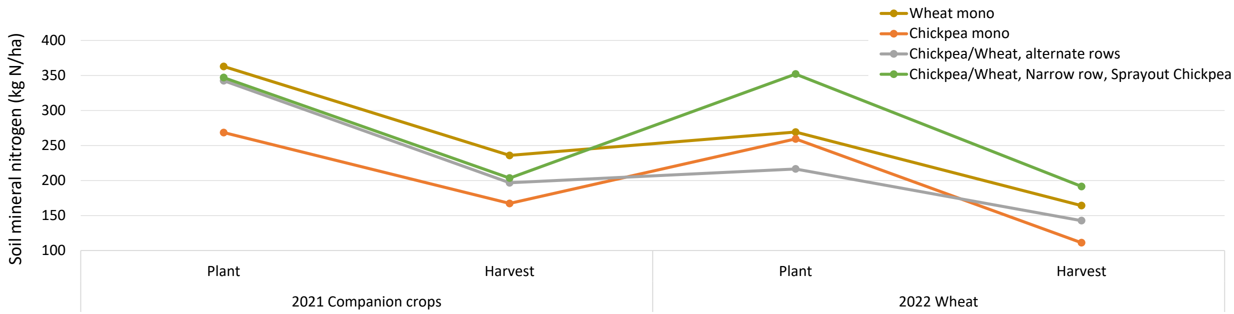


Figure 2. Nitrate and ammonium nitrogen, to a depth of 90 cm, measured at planting and harvest of selected companion crops and the following wheat crop.

While the alternate row companion crop result is less clear, the rows of 'monoculture wheat' in this configuration may have acted as a pathogen source.

Nitrogen (N)

With the high soil nitrogen (N) at this site it is unlikely the legumes fixed any N from the atmosphere. The reduction in soil N during the 2021 companion crops (Figure 2) was more than the N measured in the biomass (Table 2), supporting the assumption that the legumes derived all of their N from the soil.

What is interesting is that the sprayed-out chickpea companion crop mineralised the most N over the fallow period (Figure 2), despite the terminated chickpea biomass only having 6 kg N/ha. The chickpea monoculture had similar N uptake in biomass and removal in the grain to the wheat monoculture (Table 2), but also mineralised more N over the fallow than the wheat. This extra mineralisation far exceeds N returned by the previous crop, so is more likely a result of rapid cycling of nutrients from organic matter following chickpea, than the legumes providing extra N.

Implications for growers

It is possible to grow companion crops in Queensland on stored soil water without a yield penalty. However, a yield benefit (not achieved in this trial) would be required to offset additional grading and handling expenses.

The objective of growing the cereal with chickpea was to increase fallow efficiency after chickpea, increasing the yield potential of the next crop. The differences in ground cover achieved by the different crop combinations would normally affect fallow efficiency in this environment, but with an exceptionally wet summer all plots were equally wet. Further research in a wider range of seasons would be beneficial, and more work is needed on manipulating crop configurations to get the best mix of crop type in the harvested sample and looking at different crop combinations.

This trial demonstrated the value of good rotations in minimising stubble-borne disease; especially (but not limited to) crown rot, and showed the potential of companion crops to reduce disease pressure.

Table 2. Nitrogen content of four 2021 companion crop treatments and the following wheat crop (2022).

Above ground biomass kg N/ha	2021			2022
	Chickpea	Wheat	Total	Wheat
Wheat monoculture		81	81	92
Chickpea monoculture	80		80	99
Chickpea/wheat, alternate rows	24	50	74	88
Chickpea/wheat, spray-out chickpea	6	69	75	86
Grain kg N/ha removed				
Wheat monoculture		61	61	33
Chickpea monoculture	59		59	45
Chickpea/wheat, alternate rows	18	32	50	34
Chickpea/wheat, spray-out chickpea	0	50	50	31

Acknowledgements

This Queensland Department of Primary Industries research was supported by the Grain Research and Development Corporation funding (DAQ2104) and was made possible by the significant contributions of local growers and agronomists through both trial cooperation and interpretation of the results. We would also like to thank the host farmers and all the farm and field staff contributing to the implementation and management of these experiments.

References

Fletcher AL, Kirkegaard JA, Peoples MB, Robertson MJ, Whish J & Swan AD (2016). 'Prospects to utilise intercrops and crop mixtures in mechanised, rain-fed, temperate cropping systems', Crop & Pasture Science, vol. 67, pp 1252–1267.

Erbacher AJ, Lawrence DN, Anderson B, Huth N (2021). 'Growing cover crops for improved fallow effciciency – what have we learnt from three years of research?', Queensland Grains Research 2020–21, pp. 89–95.

Trial details

Location:	Billa Billa
Crop:	Wheat, chickpea, linseed
Soil type:	Duplex
Rainfall July 2021 to Nov 2022:	880 mm

Companion cropping different species—Kioma

Andrew Erbacher and Isabella Macpherson
Queensland Department of Primary Industries

***Research questions**: What is the yield impact of growing crops together as companion crops? | How does crop species and configuration (mixed together or separated into alternate rows) have an impact on companion crop performance?*

Key findings

1. All companion crops achieved similar total grain yields (approximately 100% land equivalent ratios or LER). However, the machine-harvested LER in field pea mixtures were higher due to companion crops holding the plants upright for better results.
2. Planting configuration had very little impact on yield in these trials.

Background

Companion crops are known to increase productivity, and are commonly used in home vegetable gardens (e.g. marigolds to keep pests out of tomatoes, or flowers to attract pollinators into the pumpkin patch). A review by Penny Roberts et. al. (2022) of Australian companion cropping research showed trials since 1977 had an average of 14% and 31% increase in productivity in cereal-legume and pea-canola intercrops, respectively. Despite these gains, the use of companion cropping in broadacre farming has remained low.

However, there is increasing interest in companion cropping for broadacre farming systems both internationally and in Australia. A growing number of trials are being undertaken, with research mostly in temperate cropping areas reliant on in-crop rainfall for yield. The question remains whether these systems will perform in a subtropical environment and farming systems that are reliant on stored soil water for yield stability.

The research reported here builds on previous cover crop research on the viability of companion cropping, examining crop yields, soil water, soil nitrogen and other crop impacts for wheat and chickpea planted in a range of configurations.

Recent discussion with growers and agronomists highlighted greater interest and potential for benefits with other crop combinations, given legumes such as chickpea provide relatively little ground cover after harvest. There was also increased focus on canola, linseed and field pea combinations in the scientific literature, with three broad categories of multi-species cropping and cover cropping options reported:

1. cereals/grasses that typically have fibrous root systems, are competitive and leave high levels of stubble cover.
2. legumes that are capable of fixing nitrogen from the air.
3. non-leguminous broadleaf crops (usually selected for their strong taproot and ability to access subsoil moisture and nutrients).

What was done

Two field trials were established to study different combinations of the three cropping options. Combinations were selected to match crops that could be planted and harvested on the same dates (Table 1).

The companion crop combination with the greatest reported benefits in the literature was 'peaola' (field pea and canola), so Hyola Equinox CL$^{\phi}$ canola and Wharton$^{\phi}$ field pea were paired with a long season wheat (Sunmax$^{\phi}$) that suited the preferred April planting date of canola. These combinations were planted on 21 April 2022 and harvested on 8 November 2022.

Table 1. Species in companion crop trials at Kioma.

	Early species	Late species
1	Wheat (Sunmax$^{\phi}$)	Wheat (LPB Hellfire$^{\phi}$)
2	Field pea (Wharton$^{\phi}$)	Chickpea (PBA Seamer$^{\phi}$)
3	Canola (Hyola Equinox CL$^{\phi}$)	Linseed (Glenelg)
4	Wheat/Canola; alternate row	Wheat/Linseed; alternate row
5	Wheat/Canola; mixed	Wheat/Linseed; mixed
6	Wheat/Field pea; alternate row	Wheat/Chickpea; alternate row
7	Wheat/Field pea; mixed	Wheat/Chickpea; mixed
8	Canola/Field pea; alternate row	Linseed/Chickpea; alternate row
9	Canola/Field pea; mixed	Linseed/Chickpea; mixed
10	(Wheat/Field pea)/Canola; alternate row	Wheat/Chickpea/Linseed; alternate row
11	Wheat/Field pea/Canola; mixed	Wheat/Chickpea/Linseed; mixed
12	Wheat/tillage radish; spray-out tillage radish	Wheat/tillage radish; spray-out tillage radish

A second combination of species was selected to suit later May/June plantings, to coincide with a complementary trial focused on plant available water impacts. The combinations for trials using the later planting date (13 June) were LPB Hellfire⦶ wheat and PBA Seamer⦶ chickpea that were paired with Glenelg linseed (the linseed and chickpea combination is commonly used in Canada). These crops were harvested on 9 December 2022. All treatments were replicated four times.

The spare plot in each 4x3 field layout was used for a wheat with 'spray-out' tillage radish treatment. Tillage radish is renowned for its strong tap root that can access deep nutrients early and bring them to the surface where the remaining crop(s) can utilise them once the sprayed-out radish decays. The tillage radish was planted as a 'sprinkling' (4 kg/ha or 1 plant/m^2) in a full rate of wheat and sprayed out at bud formation with 5 g/ha Ally® in a hand sprayer.

The three crops in each trial were planted as a monoculture and as two- and three-way combinations, either planted as a mixture in the same rows or separated into alternate rows. Monoculture target populations were 100 plants/m^2 for wheat (50 kg/ha) and linseed (25 kg/ha), 40 plants/m^2 for canola (3 kg/ha), and 30 plants/m^2 for both field pea and chickpea (75 kg/ha). Planting rates were reduced to half of each crop for the two-way combinations and a third of each in the three-way combinations.

The early trial was planted as two offset passes with a four row 50 cm planter to give 25 cm row spacings. The planter setup was not compatable with three alternate rows, so for the triple combination, wheat and field pea were mixed together, and canola was planted in the alternate row. The 'mixed' combinations were planted across all eight rows.

The late trial's planter had six (33 cm) rows, plumbed to plant alternate rows separately giving three rows of each crop in the alternate row combinations. For the three-way combination, the wheat and chickpea were separated across the six alternate rows and the linseed was planted through five inter-row fertiliser coulters.

Differences in maturity dates in the early trial prompted hand harvesting of heads from 1 m of each plot (as a precaution against shattering) before all crops matured and could be mechanically harvested together.

Monoculture crop species have different yield potentials, so it would be expected that combined yields of companion crops will be somewhere between the two monoculture crops being compared. The difficulty in assessing whether a benefit/penalty was achieved is circumvented by coverting crop yields to a percentage of the monoculture crop and adding the percentages together. This combined percentage is called a land equivalent ratio (LER).

An LER of 100% (e.g. 60% from crop 1 + 40% from crop 2) suggests the same grain yield would have been achieved by growing a paddock of each crop. An LER of 80% would mean there was antagonism between the crops resulting in a 20% reduction in total yield. The aim of companion cropping is to achieve an LER greater than 100%. For example, 60% wheat plus 60% chickpea equals 120% LER, which would require 20% more land planted with monocultures to harvest the same amount of grain.

Results

The field pea in the early trial was not suited to an April planting date. It flowered for about a month before it was warm enough to set pods, maturing three weeks earlier than the canola. The long season wheat matured three weeks after the canola.

Because the field pea had matured and lodged six weeks prior to harvest, it had weathered onto the ground and difficult to harvest (Image 1). Two of the four replicates were harvested normally and the other two were lifted so the header could collect the whole sample to evaluate total yield produced. Field pea yielded a total of 1.5 t/ha when harvested 'as is' and 2.4 t/ha when lifted, leading to quite different LERs for the harvestable compared to total yields for the companion crop combinations that included fieldpea (diamonds versus circles in Figure 1).

The LERs for field pea treatments were close to 100% when calculated using the 'total yield' for field pea. However, when the ‘as is’ harvest data was used there was up to 25% more grain (LER 125%) in canola/field pea mixed (Figure 1). The gains were due to the companion crops holding the field pea higher (Image 2) to be more easily harvested than the monoculture that had a lot of grain left in the paddock. These LER differences were smaller in the wheat/field pea companions because the wheat made-up a much larger portion of the total yield.

There were significant shattering losses in the canola while waiting for the wheat to mature. Canola’s header yield of 2.7 t/ha was 1 t/ha less than the hand-harvested yield. Shattering losses were consistent across all treatments, so LERs were the same for hand harvest and header yield despite 30% shattering losses.

The challenges in harvesting lodged field pea (Image 1) versus easy harvest with field pea suspended from canola branches (Image 2).

Wheat monoculture yielded 5.1 t/ha. There were patches of wheat with head pruning, mainly in the Wheat/Canola companion crop plots that produced an LER less than 100% (91–94%). There was some evidence of mouse activity in the trial, so it is likely that the canola provided a climbing frame that gave the mice greater access to the wheat heads.

In the early planting date, the tillage radish grew quite large before it was terminated and 'set back' patches of wheat, resulting in a 25% reduction in wheat yield despite the very low population of radish. The tillage radish planted in cooler weather (June) was much smaller at termination, so the wheat was not smothered and yielded the same as the monoculture wheat.

All of the crops grew well in the late species trial, and all treatments in this experiment achieved LER close to 100% (Figure 2). Of the monocultures, wheat yielded 3.1 t/ha, chickpea 2.9 t/ha, and linseed 2.1 t/ha.

This season suited linseed with much higher established populations and yields than expected. Indeed, yields were double the average yields suggested for the high rainfall zone of Victoria. This resulted in linseed suppressing chickpea more than would be expected. The wheat/chickpea yields were similar to those observed in the Kioma 2022-23 plant available water trial in the same paddock.

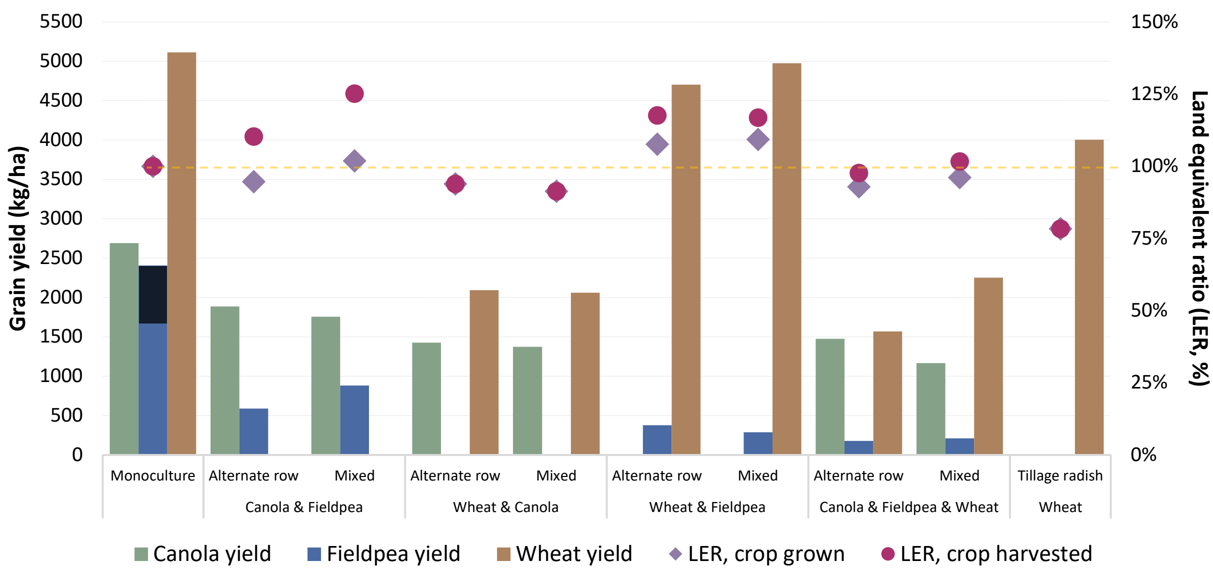


Figure 1. Grain yields and land equivalent ratio (LER) of wheat, field pea and canola in the early sown species trial. The darker bar on field pea monoculture represents the additional yield gained by assisting the crop into the header.

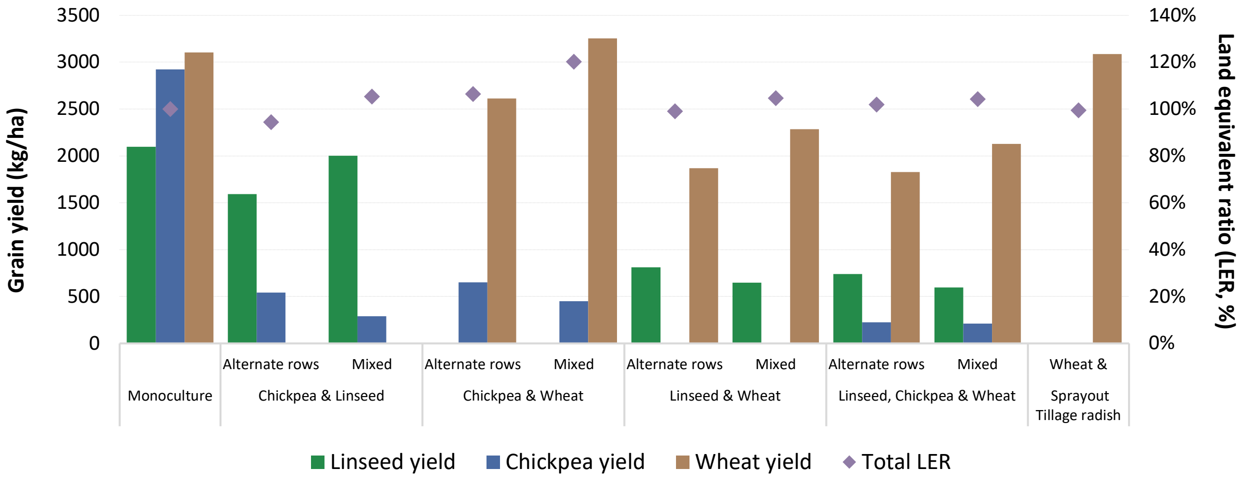


Figure 2. Grain yields and land equivalent ratio (LER) of wheat, chickpea and linseed in the later sown species trial.

Implications for growers

The implications of this research are limited by the seasonal conditions in which it was conducted. However, management of companion cropping systems is more difficult than managing monocultures. Different seasons, planting times and development of each crop and variety will impact on the ability of growers and agronomists to manage the crops and their results. The challenge then becomes to identify the likely constraints that will be encountered in that crop/season and include the companions most appropriate for that constraint.

All the crops in this research grew relatively unconstrained in this favourable season; the LERs of the crops were consistently about 100%. It appears that crops grown in ideal conditions will gain little or no benefit from a companion crop. However, companion crops can offer benefits to production challenges, such as the poor harvestability of the field pea monoculture in the early planted trial reported here. Research in Saskatchewan Canada (Granshaw, 2012) concluded “the absolute field pea yields were actually higher when intercropped with canola at this site, presumably a result of the relatively severe lodging observed in the monocrop field peas”. It is likely that any nitrogen benefit from companion cropping with legumes will also only be achieved when the crop would otherwise be nitrogen-limited (a constraint not encountered in any of our experiments).

Further research across a range of different seasons is needed to confirm and quantify the yield impacts of companion cropping, the best suited crops for each region, and the likely constraints and opportunities for companion cropping.

Acknowledgements

This Queensland Department of Primary Industries research was supported by the Grain Research and Development Corporation funding (DAQ2104) and was made possible by the significant contributions of local growers and agronomists through both trial cooperation and interpretation of the results. We would also like to thank the host farmers and all the farm and field staff contributing to the implementation and management of these experiments.

Further reading

Roberts P, Fletcher A, Kirkegaard J, O'Leary G and Dowling A (2022). 'The potential for intercropping in Australian farming systems and pathways to Adoption', Proceedings of the 20th Agronomy Australia Conference, 2022 Toowoomba Qld (www.agronomyaustraliaproceedings.org)

Granshaw B (2012). 'Intercropping, the growing of two different crops simultaneously', Nuffield scholarship report, Nuffield Farming Scholarships (nuffieldscholar.org)

Trial details

Location:	Kioma
Crop:	Wheat, field pea, canola, chickpea, linseed
Soil type:	Grey Vertosol
Rainfall in-crop:	450mm and 310 mm

Companion cropping with wheat and chickpea—Kioma

Andrew Erbacher and Isabella Macpherson
Queensland Department of Primary Industries

***Research questions**: Can companion cropping increase ground cover and fallow efficiency after chickpea? | What is the yield impact of growing wheat and chickpea together as companion crops? | What impact will companion crops have on the yield of the following wheat crop?*

Key findings

1. Companion cropping wheat and chickpea provided more ground cover than chickpea monocultures.
2. Companion crops provided from no benefit to 22% more yield than monocultures.
3. Reducing wheat populations in 'mixed' companion crops increased chickpea yield and therefore increased land equivalent ratio.

Background

Chickpea is important in Queensland as a profitable crop that provides a rotation break. However, it leaves the soil quite bare, which reduces fallow efficiency (i.e. the amount of fallow rainfall captured for use by the next crop). This is a big problem in an area that relies on stored soil water for yield.

The DPI research team recently completed a study growing cover crops in the fallow to improve ground cover and soil water available to the next crop (see 'Growing cover crops for improved fallow efficiency' in *Queensland Grains Research 2020-21*), which demonstrated the value of ground cover and raised questions about the viability of companion cropping to build ground cover after chickpea.

Companion crops are known to increase productivity, they are in every home vegetable garden (e.g. from marigolds to keep the pests out of tomatoes, or flowers to attract pollinators into the pumpkin patch). Australian companion cropping research has been conducted for nearly 50 years with an average of 14% and 31% increase in productivity in cereal-legume and pea-canola intercrops, respectively, but this approach not been widely used in broad-acre farming.

However, companion cropping is generating more interest and is being introduced to broadacre farming systems both internationally and in Australia, primarily in temperate cropping areas that rely on in-crop rainfall for yield. So, the question for the northern grains region was whether these systems would perform in a subtropical environment and a farming system that relies on stored soil water for yield stability.

Given this reliance on stored soil water to maintain grain yield and the cost of fallow efficiency when stubble levels are low following chickpea, the research reported here focused on wheat and chickpea.

What was done

The team, along with growers and advisors, reviewed the successes and learning opportunities from the 2021 Billa Billa trial (see page 150) to develop further companion cropping options to assess. Treatments in this 2022 trial had a stronger focus on allowing the chickpea to compete with the wheat.

The aim in companion planting wheat with chickpea was to increase ground cover, so the options included a cereal that was sprayed out as a cover crop, leaving only the chickpea for harvest. The treatments were:

1. Wheat (control)
2. Chickpea (control)
3. Chickpea followed by a cover crop
4. Chickpea/wheat, spray-out chickpea
5. Chickpea/wheat, spray-out wheat
6. Chickpea/wheat, spray-out wheat earlier
7. Chickpea/wheat, alternate narrow rows
8. Chickpea/wheat, alternate standard rows
9. Chickpea/wheat, mixed within rows, 50:50
10. Chickpea/wheat, mixed within rows, 67:33
11. Chickpea/wheat, mixed within rows, 80:20
12. Chickpea/wheat, mixed within rows, 90:10

Narrow alternate row wheat/chickpea beside standard alternate row wheat/chickpea.

Mixed 90:10 chickpea/wheat in front of wheat monoculture.

The trial was planted at Kioma on 13 June 2022 using a twin-cone six row plot planter plumbed to plant different crops in alternate rows in a single pass. In narrow row treatments the wheat was planted in the inter-rows as a second pass.

Each species tested as companions was also grown as a monoculture at recommended planting rates for comparison, using varieties suited to a June planting date. Hellfire⊕ wheat was planted with a target of 1 million plants per hectare and Seamer⊕ chickpea with a target of 250,000 plants per hectare.

The three 'spray-out' treatments were planted at a full rate of each crop, and separated into narrow alternate rows so that the harvested crop had the same row spacing and population as the monocultures.

Treatments harvesting both crops had planting rates reduced to reflect an equivalent plant density; i.e. for alternate row treatments the in-row population was the same as the monoculture controls, and the 'mixed' treatments were a percent of monocultures spread evenly across all six rows (50:50 was 125,000 chickpea and 500,000 wheat; 90:10 was 225,000 chickpea and 100,000 wheat).

In the spray-out treatments, MCPA plus Ally® was applied to kill chickpea at flag leaf emergence of the wheat. Verdict® plus oil was applied to kill wheat at two different growth stages: early at first node of the wheat and late at first flower of the chickpea.

Hand-cuts were taken at physiological maturity, separating the crops within each treatment. These were subsequently threshed to measure grain yield that could be compared to mechanically harvested yields. At harvest, both crops were taken together, then graded post-harvest to separate the seed types, which were then weighed individually.

The monoculture crops will have different yield potentials, so it would be expected that combined yields of companion crops will be between the two monoculture crops being compared. In that situation it is difficult to assess whether a benefit/penalty was achieved, so the crop yields were converted to a percentage of the monoculture crop then added together. This combined percentage is called the land equivalent ratio (LER).

An LER of 100% (e.g. 60% + 40%) suggests the same grain yield would have been achieved by growing a paddock of each crop. An LER of 80% would mean there was antagonism between the crops resulting in a 20% reduction in yield, whereas the hope is to achieve an LER greater than 100%. For example, 60% wheat plus 60% chickpea equals 120% LER, which would require 20% more land planted with monocultures to harvest the same amount of grain.

A sorghum cover crop was planned after the chickpea monoculture but there was no planting opportunity over the spring/summer. All plots were soil sampled on 3 May 2023 to measure fallow efficiency from the different stubble loads left by the 2022 companion crops, then wheat was planted as part of the wider paddock to measure the carryover yield benefit from the previous crops.

Results

Companion crop yields

Our maturity biomass, hand-cut grain yield and header yield all produced similar relative yields (LER) and proportions of crops' contribution to yield. As such only the header yields are presented in this report (Figure 1).

The alternate row companion crop yielded similarly to the monocultures. Widening the row spacing reduced the competition from the wheat and doubled the proportion of chickpea in the sample (up to 17%) but had no impact on total yield or LER.

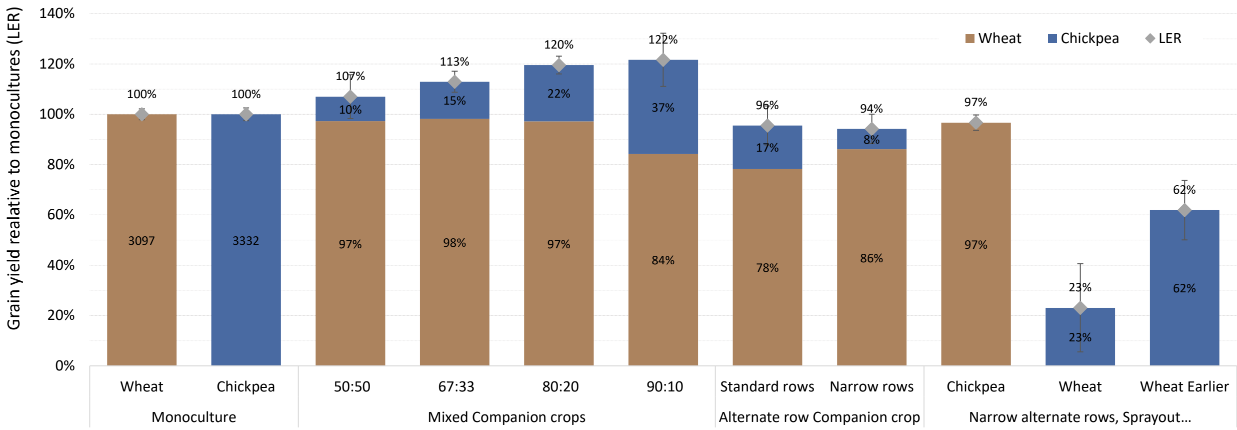


Figure 1. Grain yield of wheat and chickpea companion crops as a proportion of the equivalent monocultures.
Yields of wheat and chickpea monocultures are shown (in kg per ha) and combined relative yields is shown as LER (land equivalent ratio).

The three spray-out treatments were planted on the same configuration as the narrow alternate row companions. With a wet spring, the wheat left after the chickpea was sprayed out recovered to a similar yield as the wheat monoculture. The chickpea also recovered some yield after the wheat was sprayed out, yielding more than the chickpea portion of the narrow alternate row companion crops, but this still represented a 75% reduction in yield compared to monoculture chickpea. Spraying out the wheat earlier (at first node) had a smaller yield penalty (40% compared to monoculture), but the wheat provided less stubble cover for the fallow.

The mixed companion crops increased yields in this trial with total LER increasing when more chickpea and less wheat was planted in the population. For the 50:50, 67:33 and 80:20 (chickpea:wheat) populations the wheat portion yielded similarly to the wheat monoculture and chickpea yields increased, thus increasing the combined LER. The 80:20 combination had the same population of wheat and chickpea (200,000 per ha of each). At 90:10 the wheat yielded 16% less than monoculture wheat and the chickpea yield increased to 38% of chickpea monoculture for a 22% combined benefit.

The chickpea matured a month after the wheat in this trial. This allowed the chickpea to continue to set yield after the wheat had 'stopped competing' with it, so the treatments with stronger chickpea plants took greater advantage of this opportunity. Consequently, the chickpea continued to use soil water and the chickpea monoculture had less soil water than the wheat monoculture at harvest. If the rain had continued it may have caused shattering losses or quality downgrades in the wheat, while waiting for the chickpea to mature.

Impacts after companion crops

Ground cover was assessed prior to planting the wheat in 2022 (Figure 2); as expected, the wheat monoculture stubble provided much more ground cover than the chickpea monoculture stubble (which was higher than expected because there was not much rainfall in the fallow to encourage breakdown). The wheat grown with sprayed-out chickpea and narrow alternate row wheat-chickpea companions had the most cover because the 2022 wheat in these plots yielded similarly to the monoculture, and there was a little bit of extra cover provided by chickpea stubble in the inter-row.

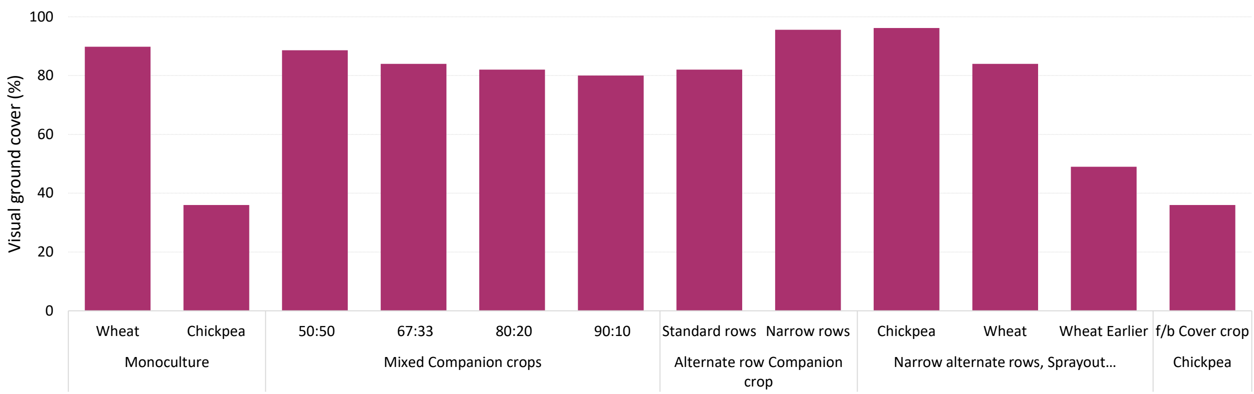


Figure 2. Visual estimate of stubble cover at the end of the fallow following companion crops.

Spraying out wheat at flag-leaf created resilient stubble that still provided good cover at the end of the fallow, but as previously mentioned this had a big impact on yield in 2022. The option of spraying out the wheat earlier reduced that yield impact, but only left slightly more cover than the chickpea monoculture at the end of the fallow. Unfortunately, there was not sufficient rain in this fallow to plant a cover crop as an alternative comparison.

Spraying out wheat companion treatments.

Reducing the proportion of wheat in mixed companion crops reduced ground cover, but not as much as expected. Rather, changing row spacing of the wheat had a much greater effect on ground cover; the 50:50 mixed and alternate row companions at both row spacings had the same wheat populations (Figure 2).

Differences in plant available soil water (PAW) can be mostly attributed to the chickpea growing for longer than the wheat in a cool wet spring. The chickpea monoculture was 45 mm drier than the wheat monoculture when the companion crops were harvested, and all the companion crop options had soil water between the two monoculture crops; those with more chickpea had the least water (i.e. 90:10 mixed and spray-out wheat earlier) and those with the least chickpea had the most water (i.e. chickpea/wheat narrow alternate rows) (Figure 3).

With very little rainfall over the fallow, there was little change in PAW and the ranking of wettest to driest treatments was unchanged, albeit the spread between wheat dominant companion crops and chickpea dominant companion crops increased.

Figure 3. Plant available water for a selection of treatments at planting of companion crops and the following wheat crop.
PAW was measured to 120 cm for all 12 treatments, but only six are shown representing highest proportions of wheat and chickpea.

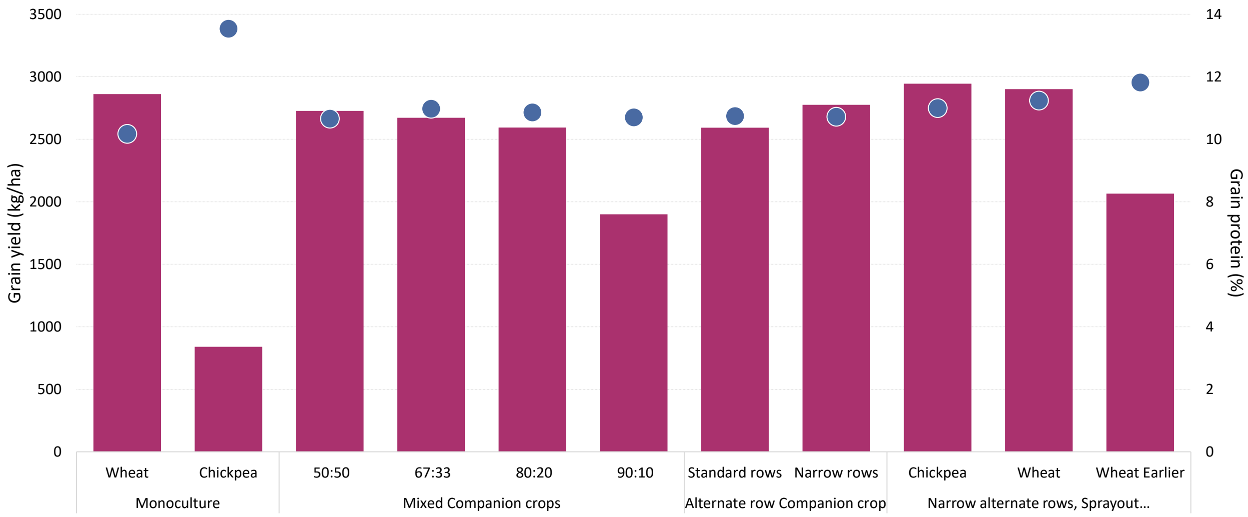


Figure 4. Grain yield and protein of wheat in the season following companion crops.
Yield is represented as bars (units on left axis), and protein is the blue dot (units on the right axis).

At harvest of the 2023 wheat crop, the treatments with the most PAW at planting had the highest grain yield and least soil water at harvest (Figure 3, Figure 4). This was due to higher-yielding crops having stronger root systems that were able to extract more soil water and so convert stored PAW to increased yield.

Grain proteins suggest yield could have increased with more nitrogen in all treatments except the chickpea monoculture (Figure 4). Grain proteins suggest the wheat after chickpea monoculture maximised yield for the water available to the crop.

Nitrogen

Nitrogen (N) uptake was measured in the biomass and removal of the grain in six selected treatments (wheat and chickpea monocultures, chickpea/wheat alternate narrow rows, chickpea/wheat alternate narrow rows with chickpea sprayed-out, chickpea/wheat mixed at 50:50 and 90:10).

Of the treatments sampled in 2022, nitrogen uptake in biomass was highest in chickpea monoculture, which also had the highest N removal in the grain (Table 1).

The mixed 90:10 companion crop was the next highest for nitrogen uptake in biomass and removal in grain, and also had the second highest chickpea yield behind the chickpea monoculture. Despite having the highest N content in biomass, these two treatments had the least N returned in stubble (18 and 27 kg N/ha) due to N removal in the grain.

The other four treatments measured (i.e. alternate narrow row and mixed 50:50 companion crops, spray-out chickpea and wheat monoculture) all had similar, but lower, N uptake and grain removal, resulting in more N (42–60 kg N/ha) returned in the stubble.

Table 1. Nitrogen content of selected treatments and the following wheat crop (2023) using above ground biomass (kg N/ha).

		2022			2023
	Treatment	Chickpea	Wheat	Total	Wheat*
Above ground biomass kg N/ha	Chickpea mono	144		144	
	Chickpea/wheat, alternate narrow rows	22	116	138	
	Chickpea/wheat, Mixed, 50:50	28	105	134	
	Chickpea/wheat, Mixed, 90:10	72	70	142	
	Chickpea/wheat, narrow row, spray-out chickpea	4	119	123	
	Wheat mono		132	132	
Grain kg N/ha removed	Chickpea mono	126		126	20
	Chickpea/wheat, alternate narrow rows	9	69	78	52
	Chickpea/wheat, mixed, 50:50	12	80	92	51
	Chickpea/wheat, mixed, 90:10	45	70	115	36
	Chickpea/wheat, narrow row, spray-out chickpea	0	79	79	57
	Wheat mono		80	80	51

*In 2022 N content was measured with 'wet chemistry'; in 2023 wheat grain protein was measured with NIR and N content of grain back-calculated.

Table 2. Nitrate and ammonium nitrogen, to a depth of 90 cm, measured at planting and harvest of selected companion crops and the planting of the following wheat crop and the change in mineral N in the companion crop phase and subsequent fallow.

	Plant 2022	Harvest 2022	Plant 2023	Change in-crop	Fallow change
Chickpea mono	92	12	69	-80	57
Chickpea/wheat, alternate narrow rows	98	7	51	-90	44
Chickpea/wheat, mixed, 50:50	87	13	51	-74	38
Chickpea/wheat, mixed, 90:10	93	15	60	-78	46
Chickpea/wheat, narrow row, spray-out chickpea	104	6	65	-98	59
Wheat mono	95	9	55	-85	46

Mineralisation, the change in N over the fallow, was highest after the chickpea monoculture and the companion planted to wheat and chickpea with chickpea sprayed-out. These options had more mineral nitrogen at planting of the 2023 wheat crop than the other four treatments measured (Table 2). Chickpea monoculture (and mixed 90:10) was not able to utilise the extra nitrogen to increase grain yield as yield was limited by the reduced water available to the 2023 wheat crop (Figure 3). Wheat grown with sprayed-out chickpea in 2022 had similar PAW to the monoculture wheat at planting of the 2023 crop, so was able to capitalise on the extra N at planting, producing an additional 100 kg/ha of grain at 0.8% higher protein (Figure 4).

Implications for growers

This experiment has demonstrated that wheat and chickpea can be grown together as companions without suffering a yield penalty.

Literature on companion cropping cereals and legumes suggests maximum benefit is achieved when the less competitive (legume) crop makes up >30% of the yield. This experiment supports that conclusion as chickpea yields and LER increased as crop configuration allowed the chickpea to better compete with the wheat. This was achieved in two ways: by widening the row spacing when wheat and chickpea are separated into alternate rows; and by adjusting the ratio of wheat and chickpea when mixed together. The optimum ratios in this experiment were when the chickpea population was the same (80:20) or greater (90:10) than the wheat population, with both treatments providing a 20% yield increase over monocultures.

Growing wheat with chickpea and spraying it out at flag-leaf to then only harvest chickpea increased ground cover after chickpea, but caused a large reduction in the yield of chickpea in that season. Based on this trial alone, the option is not recommended. Spraying out the wheat earlier at first node (GS31) reduced the impact on yield of the chickpea, but the stubble was not resilient enough to provide adequate protection over the fallow. Again, this option is not recommended.

While there were nitrogen differences measured was a result of chickpea in 2022 treatments; the greater impact on yield of the 2023 wheat crop was from the additional PAW extracted by chickpea in a cool wet spring, followed by a dry fallow with limited recharge. In that situation, the treatments that produced the more chickpea yield in 2022 had the less PAW at planting of the following crop and therefore grew less wheat in 2023.

Spraying out companion planted chickpea has provided more nitrogen mineralised over the fallow, with minimal reduction in 2022 wheat yield and a small yield benefit in the 2023 wheat. The nitrogen benefit was greater than the nitrogen measured in the sprayed-out chickpea, which could signal increased mining on nitrogen. Budgets would also need to consider the cost of chickpea seed, inoculant and in-crop spray-out of the chickpea, versus the cost of applying an additional 10 kg N fertiliser.

Acknowledgements

The research undertaken as part of this project (DAQ2104) was made possible by the significant contributions of growers through both trial cooperation and the support of the Grains Research and Development Corporation. We would also like to thank host farmers and all the farm and field staff contributing to the implementation and management of these experiments.

Trial details

Location:	Kioma
Crop:	Wheat, Chickpea
Soil type:	Brigalow, Grey Vertosol
Rainfall:	Jun 2022 to Nov 2023: 585 mm Jun to Nov 2022: 338 mm (in-crop) Nov 2022 to May 2023: 211 mm (fallow) May to Nov 2023: 36 mm (in-crop)

Notes:

For further information contact the lead author:

DPI staff

Andrew Erbacher (Goondiwindi)
Mobile: 0475 814 432

Jayne Gentry (Toowoomba)
Mobile: 0428 459 138

Dr David Lawrence (Toowoomba)
Mobile: 0429 001 759

Dr David Lester (Toowoomba)
Mobile: 0428 100 538

Douglas (Doug) Sands (Emerald)
Mobile: 0457 546 993

Cameron Silburn (Goondiwindi)
Mobile: 0428 879 900

Other contributors

Dr Lindsay Bell (CSIRO Toowoomba)
Mobile: 0409 881 988

For an electronic copy of this document, visit publications.qld.gov.au and search for 'Queensland grains research'.







Queensland's Broadacre Cropping Group 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.

For further information, please contact the relevant authors or the DPI Customer Service Centre on 13 25 23.