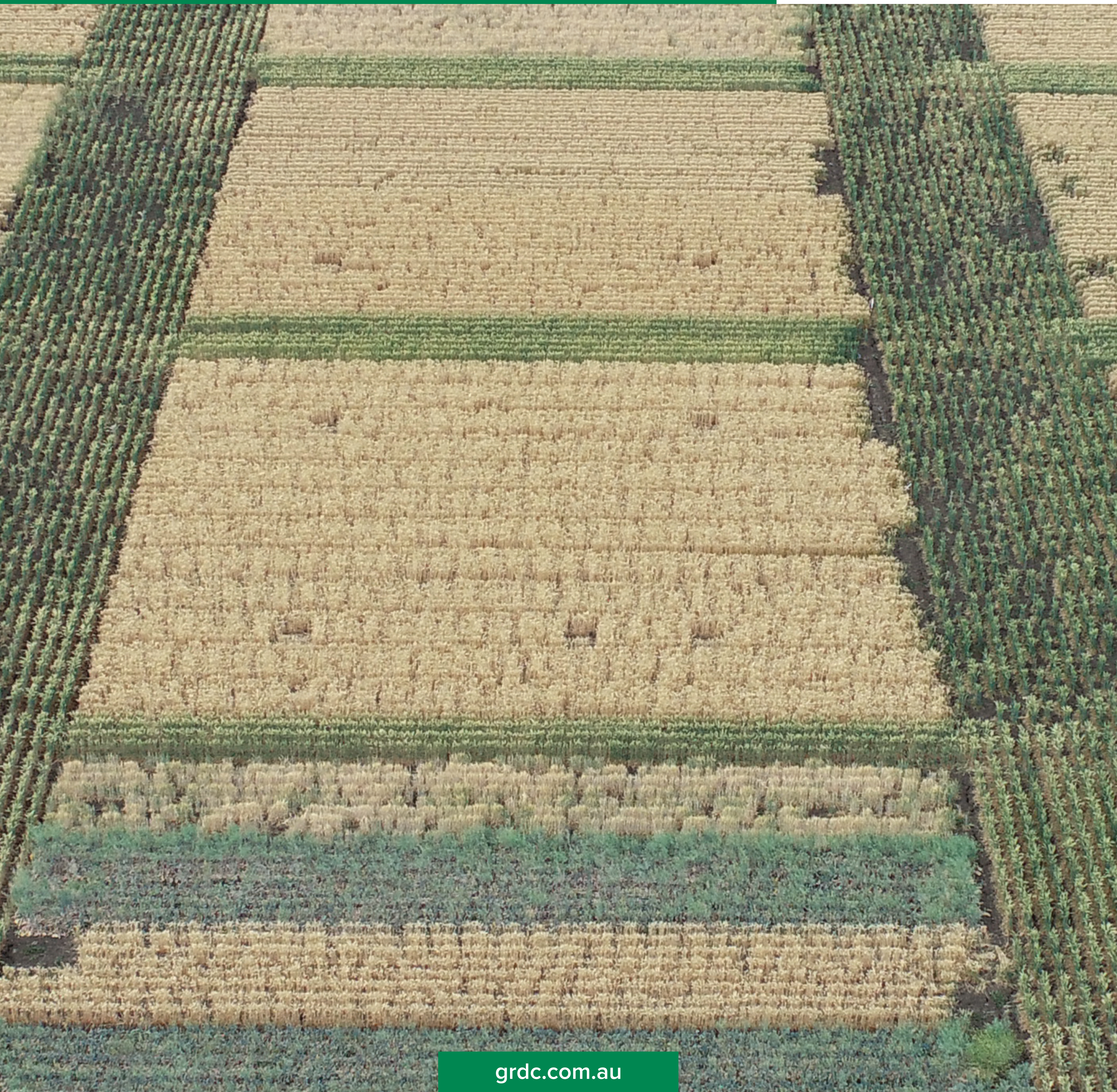
EMERALD QLD
TUESDAY 29

MOURA QLD
WEDNESDAY 30
NOVEMBER 2023

GRAINS RESEARCH UPDATE

DRIVING PROFIT THROUGH RESEARCH

GRDC™
GRAINS RESEARCH & DEVELOPMENT CORPORATION



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GRDC 2023 Grains Research Update Welcome

Welcome to the summer northern GRDC Grains Research Updates for 2023.

We are pleased to bring growers and advisers a series of events tailored to deliver the latest grains research, development and extension (RD&E) aimed at enhancing their businesses and profitability.

This year has been a testing year for many of our growers, with the forecast for below average rainfall playing out across much of Queensland and into northern New South Wales.

In challenging seasons, such as this, it can be valuable to reflect on how far we have come; thanks to progressive RD&E and the innovation and tenacity of grain growers we are better equipped to manage challenging conditions and produce crops with a higher yield than we would have achieved in decades previous.

Sustainability continues to be front of mind for our sector and an important consideration when it comes to farming enterprises. One quarter of GRDC's current RD&E investment portfolio has been identified as having direct environmental outcomes with a significant portion contributing indirect environmental research outcomes. GRDC's Sustainability Initiative articulates our focus on sustainability, and we look forward to sharing further results from these investments at future Grains Research Updates.

This year has also been a big one for GRDC. We announced our RD&E 2023-28 plan and a commitment to invest more than a billion dollars in research, development and extension to deliver significant gains for Australian grain growers.

In the northern region, this strategic investment revolves around addressing critical concerns highlighted through the National Grower Network (NGN) and RiskWi$e forums.

In central Queensland, we are investing in strategies to maintain consistent ground cover, in the north we are actioning requests to quantify phosphorus (P) use efficiency in vertosols, and in central and southwest Queensland we are investing deep-placed P projects on behalf of growers wanting to understand more about enduring residual benefits.

These represent just a few of the investments originating directly from Queensland growers. To ensure investments answer the most pressing profitability and productivity questions from the paddock, it is critical the GRDC is engaged with and listening to growers, agronomists and advisers so I encourage you to look out for opportunities to participate in regional NGN forum opportunities.

While we're pleased to be able to facilitate plenty of face-to-face networking opportunities across this Updates series, we have also committed to continuing to livestream and record some of the events for anyone who is unable to attend in person.

For more than a quarter of a century the GRDC has been driving grains research capability and capacity with the understanding that high quality, effective RD&E is vital to the continued viability of our grains industry.

Sharing the results from this research is a key role of the annual GRDC Updates, which bring together some of Australia's leading grains research scientists and expert consultants. We trust they will help guide your on-farm decisions this season and into the future.

We would like to take this opportunity to thank our many research partners who have gone above and beyond this season to extend the significant outcomes their work has achieved to growers and advisers.

If you have concerns, questions or feedback please contact our team directly (details on the back of these proceedings) or email northern@grdc.com.au. Please enjoy the Update and we look forward to seeing you again next year.

Gillian Meppem
Senior Regional Manager – North

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GRDC Grains Research Update
EMERALD & MOURA

Wednesday 29 November 2023 - McIndoe Function Centre, Emerald
Thursday 30 November 2023 - Kianga Memorial Hall, Moura

Registration: 12.30pm for a 1pm start, finish 5.30pm followed by a BBQ dinner

Time	AGENDA	Speaker(s)
1:00 PM	**GRDC welcome**	
1:10 PM	**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.**	Lindsay Bell (CSIRO) & Darren Aisthorpe (DAF Qld)
1:55 PM	**Water - making the most of our greatest and most often yield limiting asset** ○ Fallow efficiency and the impact of cover in different rainfall situations ○ Water use efficiency in different crops and farming systems and impacts on yield	Lindsay Bell (CSIRO) & Darren Aisthorpe (DAF Qld)
2:40 PM	**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	David Lester (DAF Qld) & Doug Sands (DAF Qld)
3:25 PM	**Afternoon Tea**	
3:55 PM	**The role of legumes in CQ farming systems** ○ How much N do they use and leave for subsequent crops? ○ Soil disease impacts and soil health issues in the crop sequence ○ Water use and ground cover impacts for fallow efficiency	Doug Sands (DAF Qld) & Darren Aisthorpe (DAF Qld)
4:40 PM	**Panel discussion: Key farming system decision points for profit in CQ farming systems** ○ Managing cropping opportunities and responding to seasonal variability ○ Factors driving cropping opportunities for 2024 ○ Nitrogen strategies - getting N on in a timely manner; spreading vs incorporation; use of manure ○ Factors driving N decision making for summer 2023/24.	Darren Aisthorpe (DAF Qld) David Lester (DAF Qld) Doug Sands (DAF Qld) Lindsay Bell (CSIRO) Plus **Emerald** Belinda Chase (Iker Ag) Josh Bell (JB Ag Services) **Moura** Stuart Olsson (AGnVet)
5:30-7:30 PM	**BBQ dinner & close**	

Contents

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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.

Darren Aisthorpe, DAF Queensland

Key words

northern farming systems, water use efficiency (WUE), fallow efficiency (FE), fertility, nutrition, economics, Emerald

GRDC code

DAQ00192

Take home message

- **Systems matter** – At Emerald, 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.
- **Nutrition** – No system on the medium/standard crop intensity and higher nutrition plan have fallen behind the baseline system with respect to system economics. The additional nitrogen (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.
- **Water use efficiency (WUE) and fallow efficiency (FE)** - The variation between systems, and also across crops within a system for WUE and FE indicate that there is room for improvement for both indices. With early indications from the Integrated weed management (IWM) plus nutrition split looking positive, a move back to narrower row spacings on an increased nutrition plan could be a positive move, so long as the logistical challenges can be overcome.

Background

The Queensland Department of Agriculture and Fisheries (DAF), CSIRO and the New South Wales Department of Primary Industries (NSW DPI) are collaborating to conduct an extensive field-based farming systems research program. This program focuses on developing farming systems to better use the available rainfall to increase productivity and profitability.

The Northern Farming Systems (NFS) projects are investigating how several modifications to farming systems will affect the performance of the cropping system. This involves 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 the following:

- **Crop intensity** – the proportion of time that crops are growing which impacts on the proportion of rainfall transpired by crops and unproductive water losses. This is being altered by changing soil water thresholds that trigger planting opportunities.
- **Increased legume frequency** – aim to have every second crop a legume over the crop sequence, assessing if required fertiliser N inputs can be reduced.
- **Nutrient supply strategy** – by increasing the fertiliser budget to achieve 90% of yield potential for that crop compared with 50% of yield potential, with the aim of boosting background soil fertility, increasing N cycling and maximising yields in favourable years.
- **Increased crop diversity** – crop choice aims to achieve 50% of crops resistant to root lesion nematodes (preferably two in a row) and crops with similar in-crop herbicide mode of action

cannot follow each other. The aim is to test systems where the mix and sequence of crops are altered to manage soil-borne pathogens and weeds in the cropping system.

This range of system modifications are being tested across six locations as part of this project: Emerald, Billa Billa, Mungindi, Spring Ridge, Narrabri and Trangie (red and grey soils). The core experimental site (CSA00050), located near Pampas on the eastern Darling Downs, aims to explore the interactions between these modifications to the cropping systems across a range of crop sequences that occur across the northern grains region. The core site is comparing 34 different systems.

Central Queensland site - Emerald

The site is located at the DAF Central Queensland Smart Cropping Centre (CQSCC) facility, 4 km east of Emerald (-23.528550, 148.207907). Elevation is approximately 189 m above sea level. The crop history in the field prior to the trial commencing was chickpea sown in 2012, followed by sorghum in summer 12/13, fallowed for winter 2013 and then irrigated cotton in summer 13/14.

In late 2014 forage sorghum was grown until early March 2015 when it was sprayed out and preparation began for the trial's first crops. The site then had 200 kg/ha of mono-ammonium phosphate (MAP) 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, likely due to the pervious cropping history and nutrient management (Table 1). Estimated water holding capacity is 240 mm to 1.5 m, but it is likely additional water may be available at deeper depths in this soil.

Table 1. Starting comprehensive analysis of the of Emerald Northern Farming Systems site in 2015.

Depth (cm)	BD (g/cm^3)	DUL (%)	Total porosity	Organic C (%)	Colwell-P (mg/kg)	BSES-P (mg/kg)	PBI	Colwell-K (mg/kg)	Sulphur (mg/kg)	Cond. (dS/m)	pH (CaCl$_2$)	pH (H$_2$O)	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 is 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 risks of germination damage. Starter fertilisers were applied in the seed row.

Trial design and management

Consultation began with local growers and agronomists in 2014 to identify the key limitations, consequences, and economic drivers of farming systems in the northern region. In April 2015, the farming systems were implemented at the Emerald site, relevant to Central Queensland (CQ), but consistent with the Northern Farming Systems Initiative and core site at Pampas.

A range of rules and protocols were developed around agronomic practices, crop types, planting triggers, and nutrition. These were adopted to preserve the integrity of each of the six initial systems.

1. *Baseline* (M01) - 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* (M07) - 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 on cereals targeting median (50th percentile) seasonal yield potential. Aligned with the *+intensity* system at the Pampas core site.
3. *Higher legume* (M03) - 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 *+legume* system at the Pampas core site.
4. *Higher nutrient supply* (M02) - N and phosphorus rates of the *Baseline* system is increased targeting 90th percentile of yield potential based on soil moisture in an environment of variable climate. The crops and other practices are the same as the *Baseline* system. Aligned with the *+nutrient* system at the Pampas core site.
5. *Higher soil fertility* (M02b) – 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 *+fertility* system at the Pampas core site.
6. *Integrated weed management* (IWM) (X01) - This minimum tillage system is focused on one crop/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 N rates on cereals targeting median (50th percentile) seasonal yield potential.

These six systems were maintained until after the winter crop of 2020. At that point the project was extended by GRDC and after consultation with the local reference committee and by request from the GRDC project manager, an additional four systems were implemented from December 2021.

1. *Baseline + Higher diversity (M04)* - How does a moderate intensity (*Baseline*) system using a diverse crop selection compare with the other systems?
2. *Higher legume + Nutrition (M30)* - Higher legume system + Pre-crop nutrition calculations now performed to target a 90th percentile yield instead of a 50th percentile. Stratification of N at sowing has been a significant issue for CQ systems. It is expected that the crop which has the N side banded may not see the N applied, rather we are fertilizing for the following crop, not the current crop.
3. *Lower intensity + Nutrition (M14)* - How does a low intensity, high nutrition system using a diverse crop selection compare against the other systems?
4. *IWM + Nutrition (X01b)* - Standard IWM system + pre-crop nutrition calculations now performed to target a 90th percentile. The standard IWM system was demonstrating a consistent decline in baseline fertility relevant to other systems, by increasing the nutrition levels, will this lead to improved production and system benefits.

Crop sequences to date

The Emerald trial has now been operating for nine years, with most systems now producing 10 different crops (Table 2). All the systems added in 2021 were applied onto existing system plots (as per description above) 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.

Table 2. Cropping sequence for Emerald Northern Farming systems experiment. 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

Results

Climate observations

Comprehensive climatic observations are kept for the Emerald NFS site including both daily summary data and 15-minute observations. While not a core focus of the overall trial program, being able to differentiate and understand 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, it is not raw maximum temperatures which drive the higher average temperatures. Rather the difference comes from the warmer minimum temperatures. These warmer temperatures can have a significant effect on plant physiology and ultimately cropping systems. Nights tend to be warmer (Figure 1) with overnight lows in the low to mid-20’s common place during the warmer months.

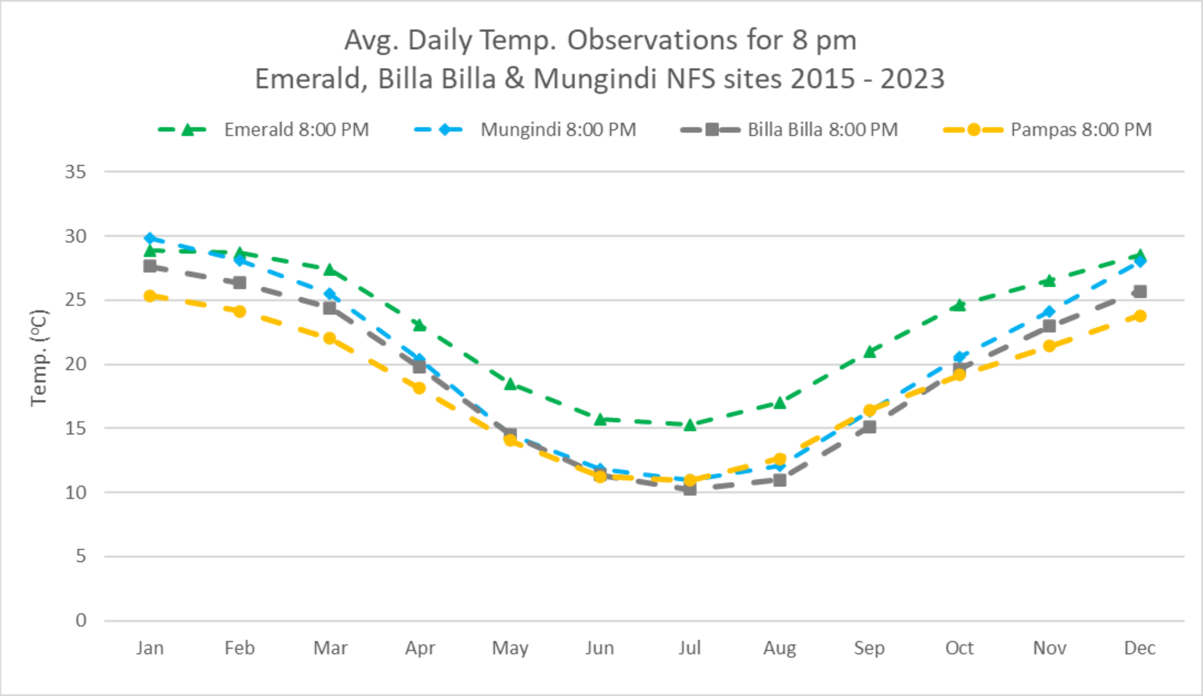

Figure 1. Average monthly temperature at 8 pm for the four QLD based Northern Farming Systems sites. From March to November, at 8 pm, for the past nine years, the Emerald site is consistently warmer later into the evening. Only the Mungindi site achieves higher 8 pm temperatures in December and January.

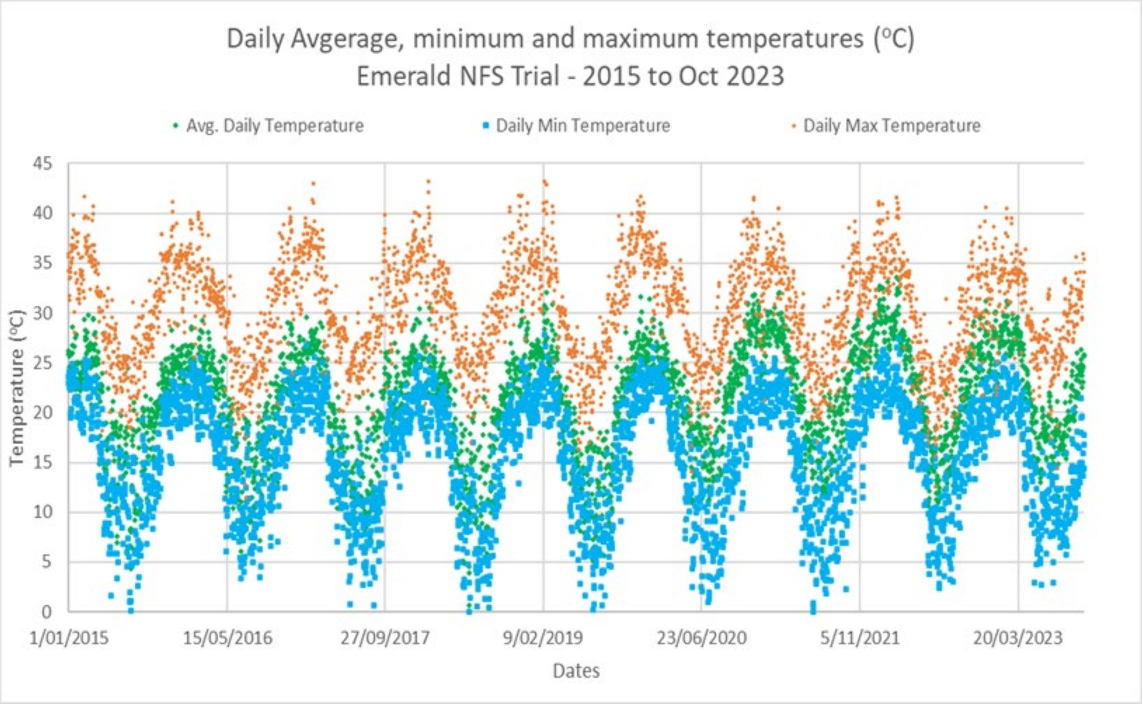

Figure 2. Daily minimum (blue/darker), maximum (orange/lighter) and calculated average daily temperature (green) for the duration of the Emerald Northern Farming systems trial. Temperatures have ranged from 0 °C to 44 °C. Frost risk at the Emerald site is much lower than the southern sites, or other locations in CQ, however as the figure shows, they certainly are possible.

Rainfall

Emerald’s long-term average annual rainfall is approx. 600 mm with a summer dominant distribution. Climate data from the Emerald site (Figures 3 & 4) agrees with the summer dominance of the rainfall over the nine-year life of the trial however the cropping sequence (Table 2) indicates something quite different, as seven of the last 10 crops grown have been winter crops.

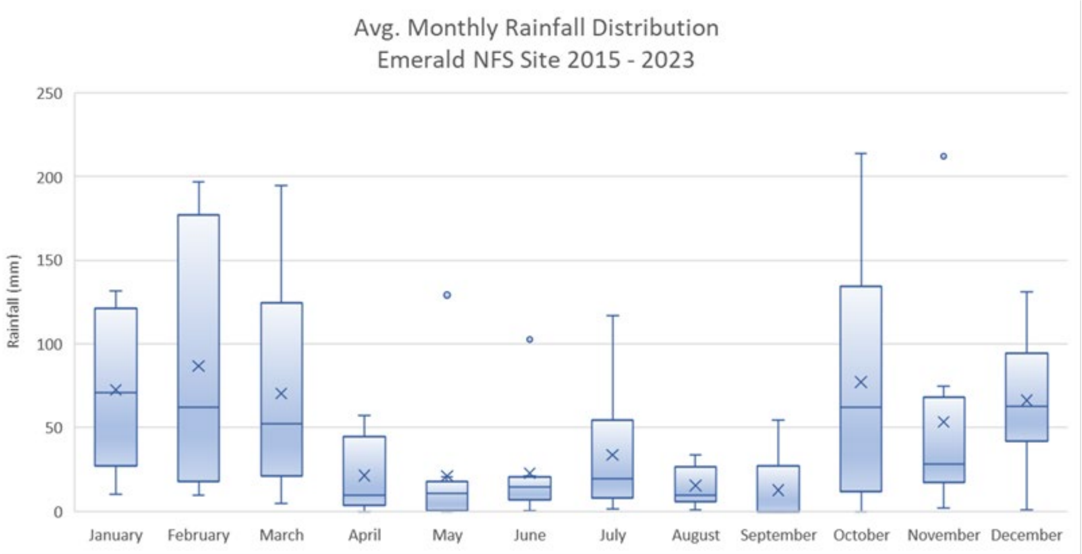

Figure 3. Box and Whisker Graph depicting monthly average rainfall distribution 2015–2023. The x marker indicates the mean monthly rainfall for the period, the middle line is the median, top and bottom error bars indicate the variation in average rainfall, while the individual points indicate outlier rainfall events when compared to all other falls over that period.

The box and whisker plot (Figure 3) shows the variability of the monthly rainfall over the duration of the trial program. 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 (however significant rainfall during that period has occurred). The graph shows monthly rainfall of more than 100 mm occurred in the 9 year period in every month except April, August and September. Conversely, every month except for January (10.2 mm) and February (9.6 mm) had a “less than 5 mm” total rainfall over the duration of the trial.

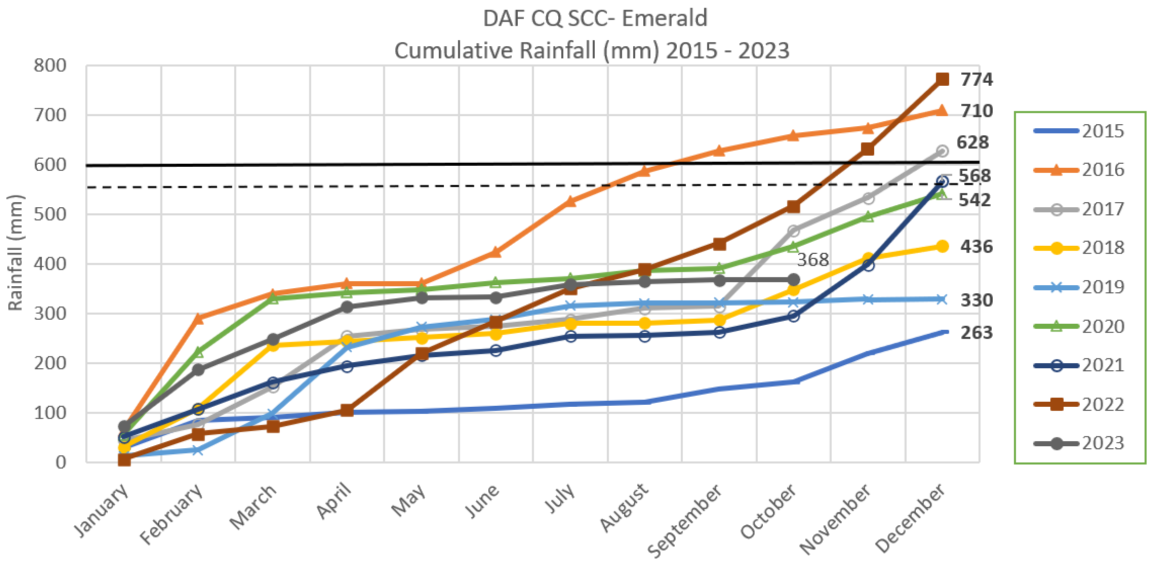

Figure 4. Cumulative rainfall for the nine years at the Emerald Northern Farming Systems trial. The horizontal dotted line indicates what the average rainfall has been for the period (560 mm), the thick line above it indicates the long-term average rainfall for Emerald (600 mm).

Figure 4 shows the variability of annual rainfall for the site (264 mm in 2015, 774 mm in 2022) but also when the rainfall fell. Consistent with Figure 3, cumulative rainfall in the period from April to September is typically the lowest of the year, 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 (562 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 indicators of predicted crop performance. A crop's ability to access stored soil water when required enables those crops (within reason) to handle higher temperatures or prolonged periods 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 (using sunlight) into oxygen and glucose. If a plant experiences higher than ideal temperature or low relative humidity, it 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, which takes more energy, the amount of water lost to transpiration is greater than the water it 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 during the growing season (or at least during critical periods like flowering and grain fill). Indices like vapour pressure deficit (VPD) are very useful in identifying when such periods exist. VPD is the difference between how much moisture the air can hold at any given point in time, and how much moisture the air is currently holding. The lower the deficit, the lower the chance of stress inducing conditions for any given crop.

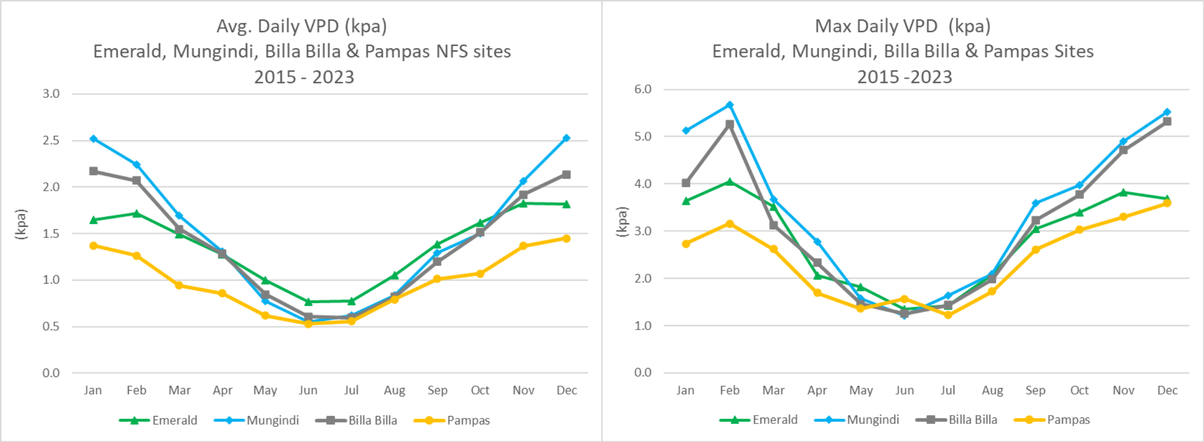

Figure 5. Daily average and maximum monthly VPD (kpa) observations for 2015–2023 for the Northern Farming Systems sites at Emerald, Mungindi, Billa Billa and the Pampas core site. For winter cereals, the target range (0.6 – 1.0 kpa) is much narrower for the Emerald site, relative to the other three sites, 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.

For the Emerald site, VPD monthly average can range between 0.8 to 1.8 kpa, (Figure 5) however daily figures can range between 0.1 to 4.0 kpa depending on relative humidity and temperature at the time. In a completely controlled environment, a target VPD of 0.6 - 0.8 kpa is 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

Over the duration of the trial to date, the Emerald site's average time in crop (for the six core systems) has been approximately 40%. The percentage of the cumulative rainfall for the past nine years (4861 mm) which has fallen in crop is approximately 30% or 1461 mm. Of the 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 between 18% to 23%, or a conversion rate of 623 mm for the 18% systems, up to 789 mm for the 23% system (*Higher fertility*) over the past nine years.

The long-term average WUE for the Emerald site (six original systems) is 12.9 kg of grain produced for every mm of rainfall per ha utilized by the crop (Table 3). That figure ranges from 9.5 kg for the *Higher intensity* system, up to 15.1 kg/mm/ha for the *Higher fertility* system.

Table 3. Fallow efficiency (%) and water use efficiency (WUE) kg/mm/ha of all 10 systems since commencement of that system. Please note the systems shaded blue commenced in early 2022.

	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)	t/ha /year
Baseline	4861	40%	29%	71%	18%	623	1410	2033	13.2	3.0
Higher Crop Int.	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 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 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 Intensity	**1991**	45%	30%	70%	18%	249	597	846	12.6	3.5
IWM + N	**1991**	48%	41%	59%	21%	244	816	1061	13.9	4.9

In isolation, the Fallow Efficiency (FE) across the systems looks less than ideal, with significant improvement needed given how much water we are missing out on, particularly considering the economic consequences of that. However, it should be considered:

- 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 Fertility* system
- nor was the *Higher crop intensity* system which was designed to increase the % of time in-crop
- and finally, the rainfall intensity and inconsistency over the duration of the trial.

If maximum raw tonnage/ha is the goal, perhaps turning attention to improving the average Water Use Efficiency (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 the systems 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 have yielded on average 300 kg/ha/year more than they have. Improve both WUE and FE 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.

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. White columns are current values, light yellow columns show 10% improvement in FE, blue columns show 10% improvement in WUE, and the green column shows the production uplift if both FE and WUE were increased by 10%.

Systems	**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 Int.	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 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**

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).

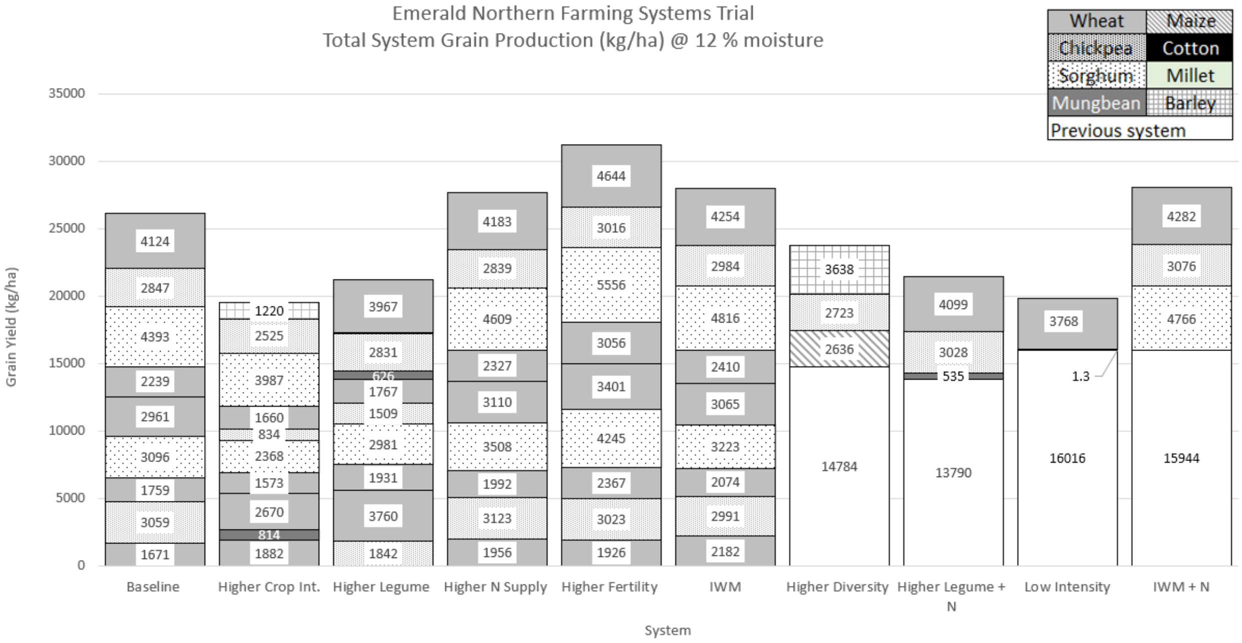

Figure 6. Cumulative grain production (kg/ha) for all 10 systems since 2015. For systems which started in 21/22, the cumulative total of the parent system prior to commencement has been added to the base of that column. On raw production volume, after nine grain crops, the *Higher fertility* system has produced 31 t/ha, which is 5 t/ha more than the *Baseline* system, with an identical cropping rotation.

The best performing system with respect to total grain production has been the *Higher Fertility* system, which has accumulated 31 t/ha from nine grain producing crops (Figure 6). The *IWM + N* system marginally out performed the *IWM* system by 71 kg/ha. The *Baseline system* ranked 5th with a cumulative deficit of 5 t/ha lower than the *Higher fertility* system.

Biomass production

The biomass production is correlated with yield, the difference between *Higher fertility* (86.3 t/ha) and *IWM + N* is minimal at 68 kg/ha after 10 crops over nine years (Figure 7). Comparing the biomass production between the *Baseline* and *Higher N* systems shows 1 t/ha difference despite the additional N fertiliser applied to the *Higher N*.

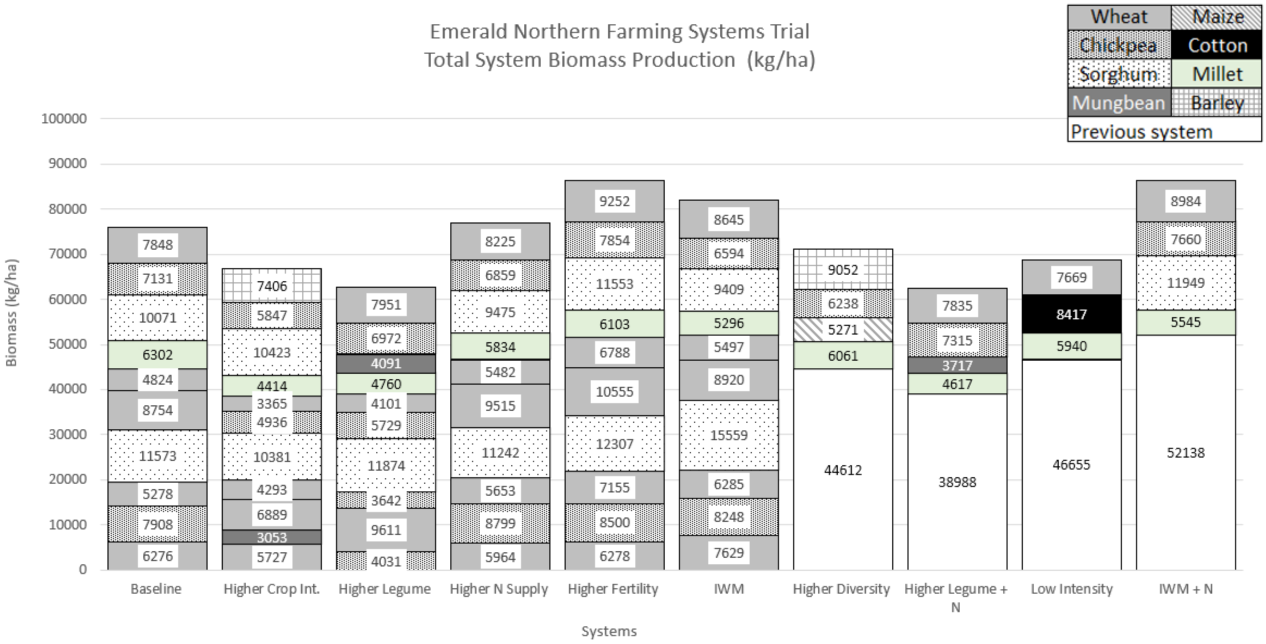

Figure 7. Cumulative biomass production (kg/ha) for all 10 systems since 2015. For systems which started in 21/22, the cumulative total of the parent system prior to commencement has been added to the base of the that system column.

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 QLD and NSW sites . The Emerald GM data shows that the *Higher fertility* system has been the best performing system for the past nine years with $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 next highest GM with $7602/ha and *Higher Nutrient* supply system at $7327/ha.

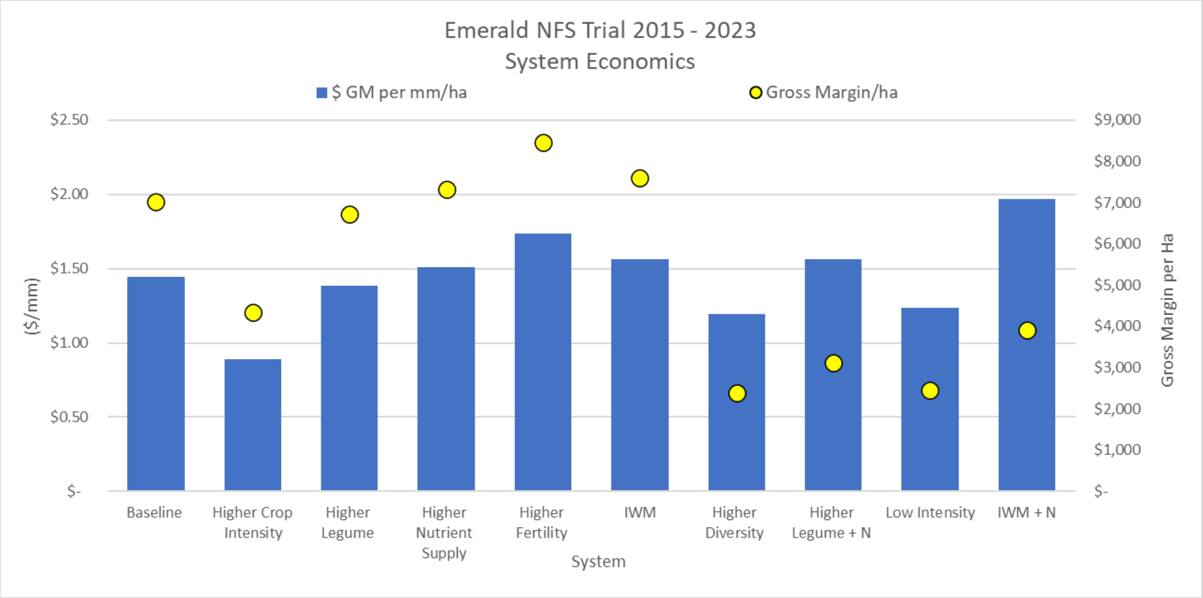

Figure 8. GM (circles) and GM/mm/ha (columns) for the duration of system for each system at the Emerald Northern Farming System site.

The cost of the manure application was not factored into the *Higher fertility* system as it was never intended to be a "manure" system, rather the manure was applied as 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 is to help maintain fertility levels. The input costs of applying manure was calculated on a purchase price of $15/t plus $20/t transport plus $3/t to spread (based on an application rate of 60 t/ha). On a per ha basis this equates to $2280/ha.

The system with the highest GM/mm was *IWM + Nutrition* at $1.97/mm/ha since its commencement in late 2021. *Higher fertility* sits second at $1.74/mm/ha while *Baseline* returned $1.44/mm/ha to date.

Nutrition

System available N is 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 fertility* system which sits consistently above all other systems, the increase in soil N became obvious post the second manure application in late 2016.

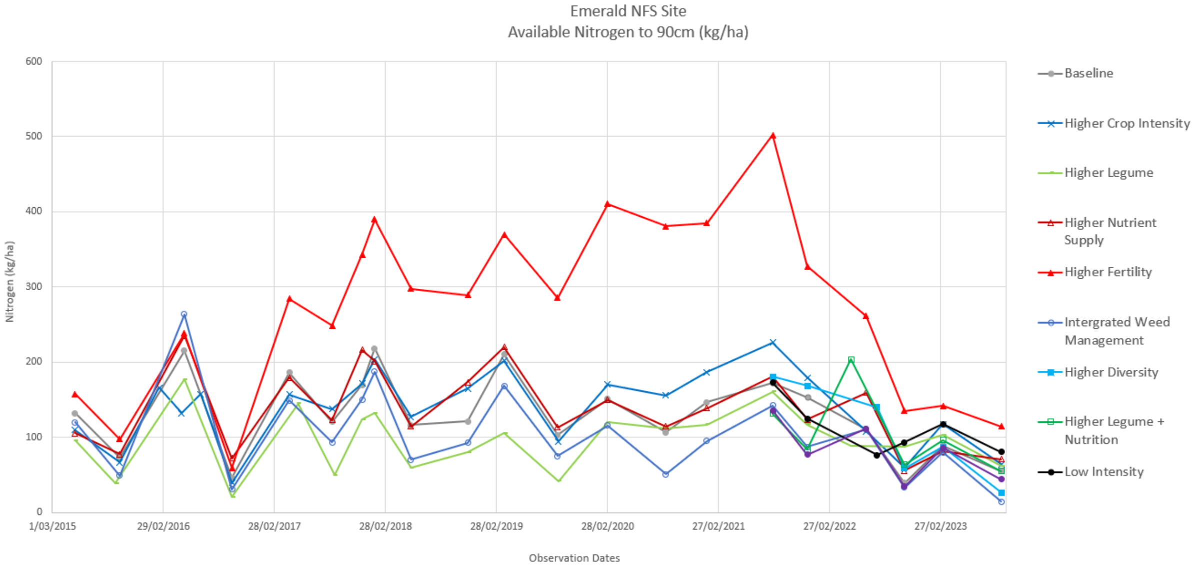

Figure 9. Profile average available N for all ten systems down to 90 cm since 2015. The graph shows the average available N for each of the systems when tested pre plant and post-harvest.

The *High 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 a concern that high N levels like these will produce lots of biomass and run out of water to fill if the season goes against you.

Yet when you compare the screenings, protein and yield of crops grown between 2017 and 2020 for *Higher Fertility* and the *Baseline* system (Table 5), the *Higher fertility* system consistently out yielded *Baseline*, had similar or higher grain protein, but most importantly, had lower screenings, three years out of the four. 2018 started wet and ended in very hot dry conditions during flowering and grain fill, while 2019 started well, but the rain stopped after July leading to another hard dry finish.

Table 5. Grain yield, quality and protein comparison between *Higher Fertility* and *Baseline* systems

		Higher 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

The second most notable observation is just how quickly the N levels have declined post 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 2023 still seems acceptable, when you consider the N levels for systems like the two IWM systems, however it's not until you look at where that N lies in the profile that you see how dramatic the decline has been.

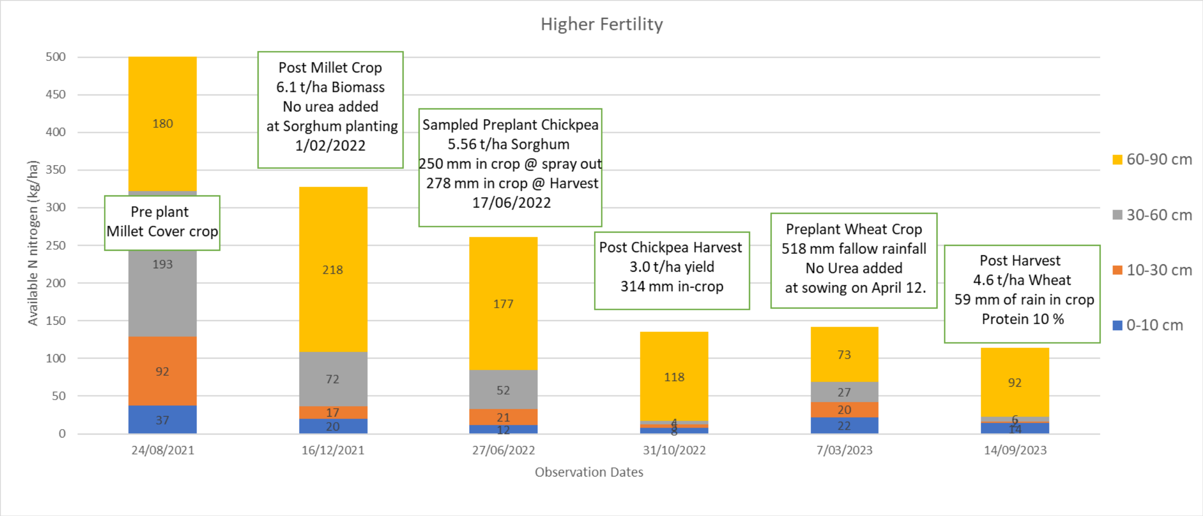

Figure 10. *Higher Fertility* profile N down to 90 cm from August 2021 to October 2023. Each stacked bar indicates available N for any given sampling date in increments

Anecdotally, the 2021 millet cover crop used 175 kg N/ha to produce 6.1 t/ha of biomass, the majority of which was drawn from 0-60 cm. The millet was terminated at flowering and residues remained. That system was then 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 of N. 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) and 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 of that 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 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 going to be 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, which meant no additional N was required. Of that total figure indicated, 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 10)

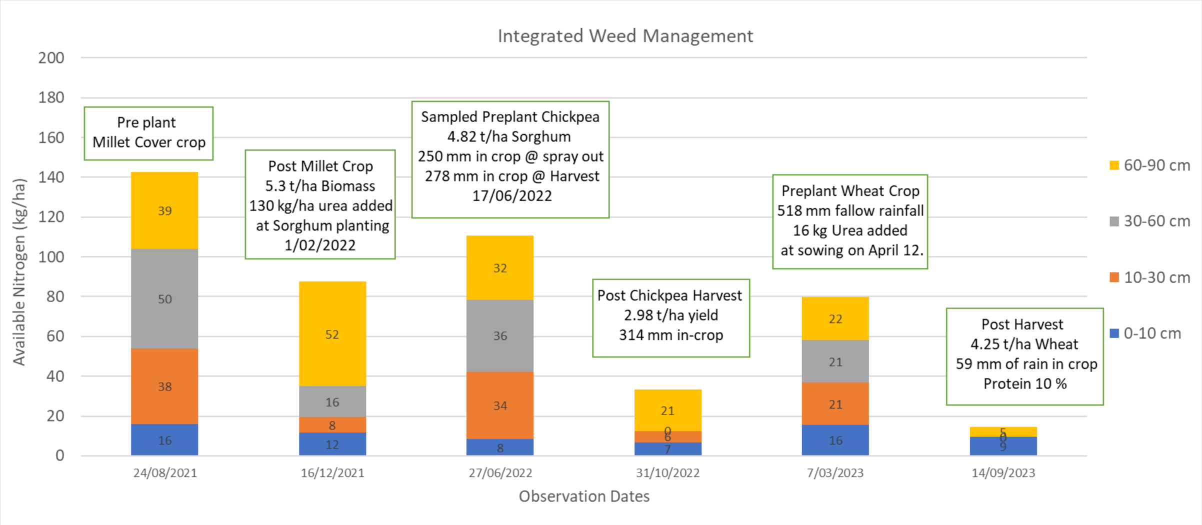

Figure 11. Integrated Weed Management (IWM) profile available N down to 90 cm from August 2021 to October 2023. Each stacked bar indicates available N for any given sampling date in increments

As a point of contrast, I have included the same depth increment graphs for both the *IWM* system and the *Higher Nutrient Supply* systems. Both systems have had identical cropping cycles to the *Higher 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 fertility* system (and *Baseline*).

The first and most important thing to note about these two system graphs is the Y axis scale. The *Higher fertility* system (Figure 10) went up to 500 kg/ha, these two systems (Figures 11 & 12) only go up to 200 kg/ha. Like the *Higher 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 nutrition* 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 sorghum, and yields were 4.8 t/ha for *IWM* and 4.6 t/ha for *Higher nutrition*.

Here we see the first diversion from the *Higher 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 over the same period. 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 breaking down millet residue did contribute additional N to the crop.

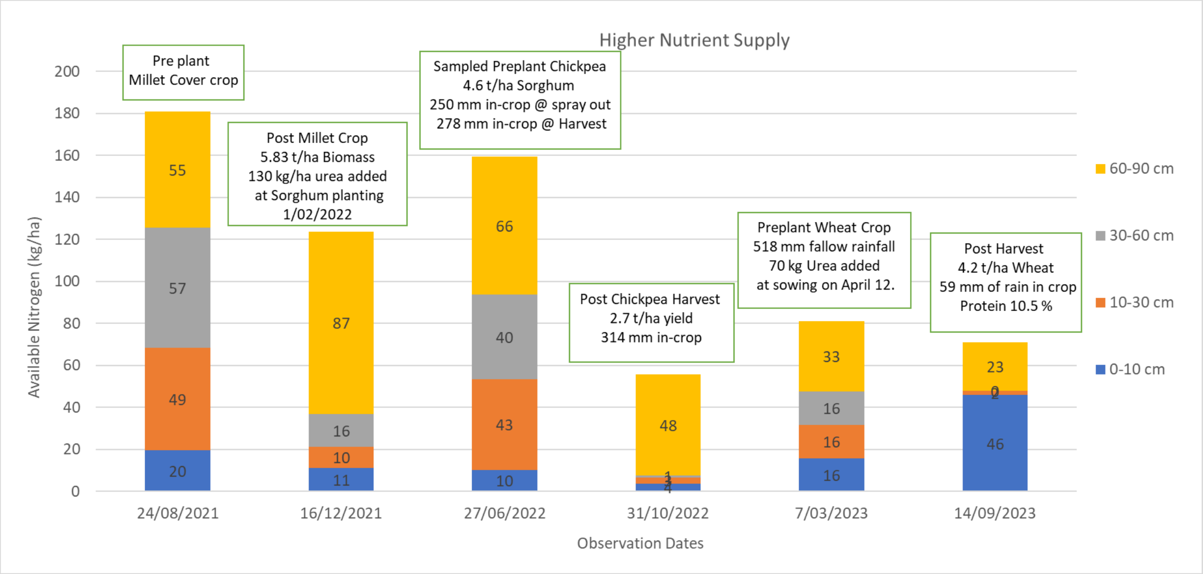

Figure 12. *Higher Nutrient Supply* profile of available N down to 90 cm from August 2021 to October 2023. Each stacked bar indicates available N for any given sampling date in increments.

Post chickpea, like the *Higher 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 of those values, only 13 kg was available above 60 cm for the *IWM* system and 8 kg for the *Higher nutrition* system.

N mineralisation post chickpea was 47 kg/ha for the *IWM* system and 25 kg/ha of N for the *Higher nutrition* 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 fertility* at only 7 kg/ha, a long way short of the 100 kg/ha plus mineralisation observed between 2016 – 2021.

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 + N	Chickpea	34	86	52
Baseline	Chickpea	40	89	50
IWM	Chickpea	33	80	47
Higher Legume + N	Chickpea	64	97	33
Higher Diversity	Chickpea	59	87	28
Higher Nutrient Supply	Chickpea	56	81	25
Low Intensity	Fallow	93	118	24
Higher Legume	Chickpea	88	103	15
Higher Fertility	Chickpea	135	142	7

At planting, 35 kg N/ha was applied to the *Higher nutrition* 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 nutrition* system. Grain protein for the *Higher nutrition* 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 between the two systems 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 system had 71 kg N/ha remaining in the profile, but unlike the *Higher fertility* system, which had 92 of its 114 kg N/ha at depth, the *Higher nutrition* 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 fertility* system has been the standout of the systems in place in Emerald, 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 in place has failed to maintain its fertility levels post 2021.

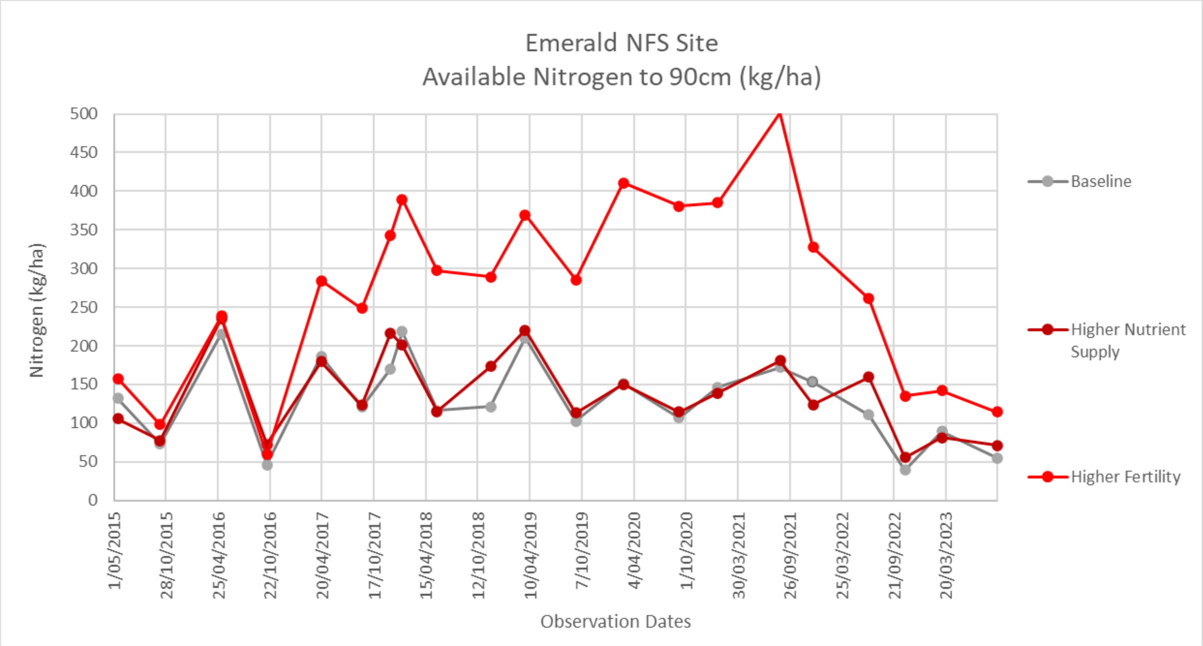

Figure 13. Available N in the profile down to 90 cm from 2015 to harvest 2023. The graph compares the *Baseline* (grey), *Higher Nutrient* supply (dark red) and *Higher Fertility* (bright red) systems. All three systems have had an identical crop sequence since 2015. *Baseline* uses a 50th percentile nutrition target while *Higher Nutrient* supply and *Higher fertility* use a 90th percentile nutrition target.

Both the *Higher nutrient* supply system and *Higher 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 being that if additional water became available during the season, these systems would not be lacking 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).

Table 7. Estimated Nutrients applied based on lab analysis of the Manure applied to the *Higher 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

For the *Higher fertility* system, because of the 'just in time' nutrition strategy, we have seen an excellent example of what can happen when a system is effectively mined. No N has been applied to that system post 2016, and while the 60 t/ha manure from the additional 10 t/ha of organic carbon (OC) lasted (Table 7), its performance was (and still is) stellar.

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 more N than all others going into this year's (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 (OC) 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 to it 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* mineralised 108 kg N/ha and *Higher fertility* mineralised 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.

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 12) 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 intensity* system and the *Higher legume + N* system.

Stratification is well understood and is common, particularly in winter crops in CQ which are grown on sub soil 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 + N* system which had its N applied at the end of March instead of at planting in April. That system received 35 mm of rainfall between application and planting which 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 in cashflow. In the WUE section (Tables 3 & 4) I broke 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, they don't highlight the variation between the systems which 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 obviously don't change, however now they have been 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. 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.

System	Cropping Area	Annual Rainfall	$ GM per mm/ha	Enterprise $/mm of rainfall	Enterprise Annual $ GM
Baseline	2000	560	$ 1.44	$ 2,889	$ 1,617,906
Higher Crop Intensity	2000	560	$ 0.89	$ 1,783	$ 998,346
Higher Legume	2000	560	$ 1.38	$ 2,769	$ 1,550,397
Higher Nutrient Supply	2000	560	$ 1.51	$ 3,015	$ 1,688,179
Higher Fertility	2000	560	$ 1.74	$ 3,477	$ 1,946,925
IWM	2000	560	$ 1.56	$ 3,128	$ 1,751,541
9-year average			**$ 1.42**	**$ 2,843**	**$ 1,592,216**
Higher Diversity	2000	560	$ 1.20	$ 2,392	$ 1,339,387
Higher Legume + N	2000	560	$ 1.57	$ 3,132	$ 1,753,973
Low Intensity	2000	560	$ 1.23	$ 2,466	$ 1,381,015
IWM + N	2000	560	$ 1.97	$ 3,934	$ 2,202,873
2-year average			**$ 1.49**	**$ 2,981**	**$ 1,669,312**

The annual difference between the best (*Higher fertility*) and the worst (*Higher crop intensity*) was $948,000 per year across the 2000 ha enterprise. Even the gap between *Higher 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 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* system and the *Higher Legume* systems had outperformed *Baseline* consistently up until recent times, but at what cost to soil fertility.

Even the *Higher nutrient supply* and *Higher 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.

Call to action

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 long-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 plan 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 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 GM 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.

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Capturing and using water most efficiently: how much do crop system choices matter?

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Key words

fallow, water-use-efficiency, gross margin, grain legumes, cereals, soil water

GRDC code

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Take home message

- Fallowing to reach critical thresholds of plant available soil water (wheat >110 mm, chickpea >80 mm and sorghum >140 mm) is required to maximise crop water use efficiency
- Fallows are relatively inefficient, capturing on average 22% ± 4% of rainfall
- Large variation in fallow efficiency (FE) exists due to climatic conditions, residual soil water, crop residues and fallow length – hence, tools to predict this can be useful
- Lower fallow efficiencies can be expected under longer fallows, where more water remains at harvest, and following crops leaving residues with less quantity and persistence (i.e., legumes or cotton)
- Higher fallow efficiencies occur: over shorter fallows, with drier soil profiles, and following crops with high levels of ground cover (e.g., winter cereals)
- Higher intensity cropping systems with more time in crop use more of the rainfall but achieve lower crop water use efficiency (WUE), while lower intensity systems use less rainfall but turn this into grain more effectively, and
- Balancing time in fallow and crop WUE by applying thresholds is critical to maximise system water use efficiency and overall returns per mm.

Introduction

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. A range of factors can influence the efficiency of fallows (i.e., the proportion of rain that accumulates in the soil profile) 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. Further, while accumulating more soil water prior to sowing a crop is always preferable, this often requires longer fallow periods, resulting in additional costs for maintaining that fallow and the number of crops grown declines. However, crops with higher starting water are often more efficient and less reliant on in-crop rainfall to drive their final yield. Hence, 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 (crop water use efficiency (WUE)). Here we look at how different farming systems have impacted on these factors. We use data collected from farming systems experiments over the past seven years to explore these questions.

Crop water use efficiency and influence of soil water

Crop water use efficiency 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 our farming systems experimental data; the average WUE (kg grain per mm) for wheat was 17.3, for chickpea was 8.2 and for sorghum was 20.8. However, there is always significant variability in this 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 in this dataset achieved a WUE of 23.2 for wheat, 11.8 for chickpea and 25.1 for sorghum.

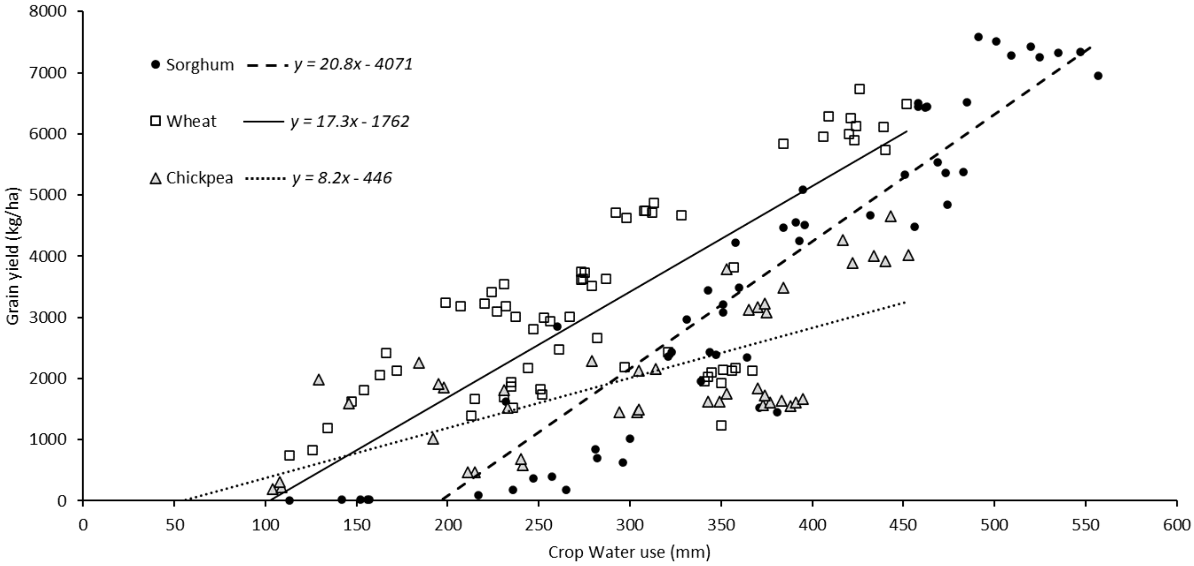

Figure 1. Relationship between crop water use (i.e., soil water extraction plus rainfall) and grain yield (*i.e.,* crop WUE) across crops monitored in northern farming systems experiments. The slope of the line indicates WUE of each crop and the X-intercept the estimate of the minimum water available to produce grain for each crop.

Figure 1 also clearly shows that there is a minimum amount of water required before a crop will produce yield. This is the amount of water required to grow sufficient biomass to produce grain. 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.

Using this data, we looked at the relationship between crop WUE and available soil water at the start of the sowing window (Figure 2). Across all crops, those with lower soil water achieved lower crop WUE, that is they were less able to convert the available water into grain yield. This indicates that these crops were likely to have encountered water stress which meant they were not able to convert biomass into grain yield. Equally crop WUE often declines at higher water availability, when surplus rainfall does not become available to the plant due to runoff, or is lost via higher evaporation.

The boxes in Figure 2 indicate those crops that achieved the best WUE, which corresponds with the peak of the curve. 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 PAW for chickpea and >140 mm for sorghum. While the outcome for each crop is going to be 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.

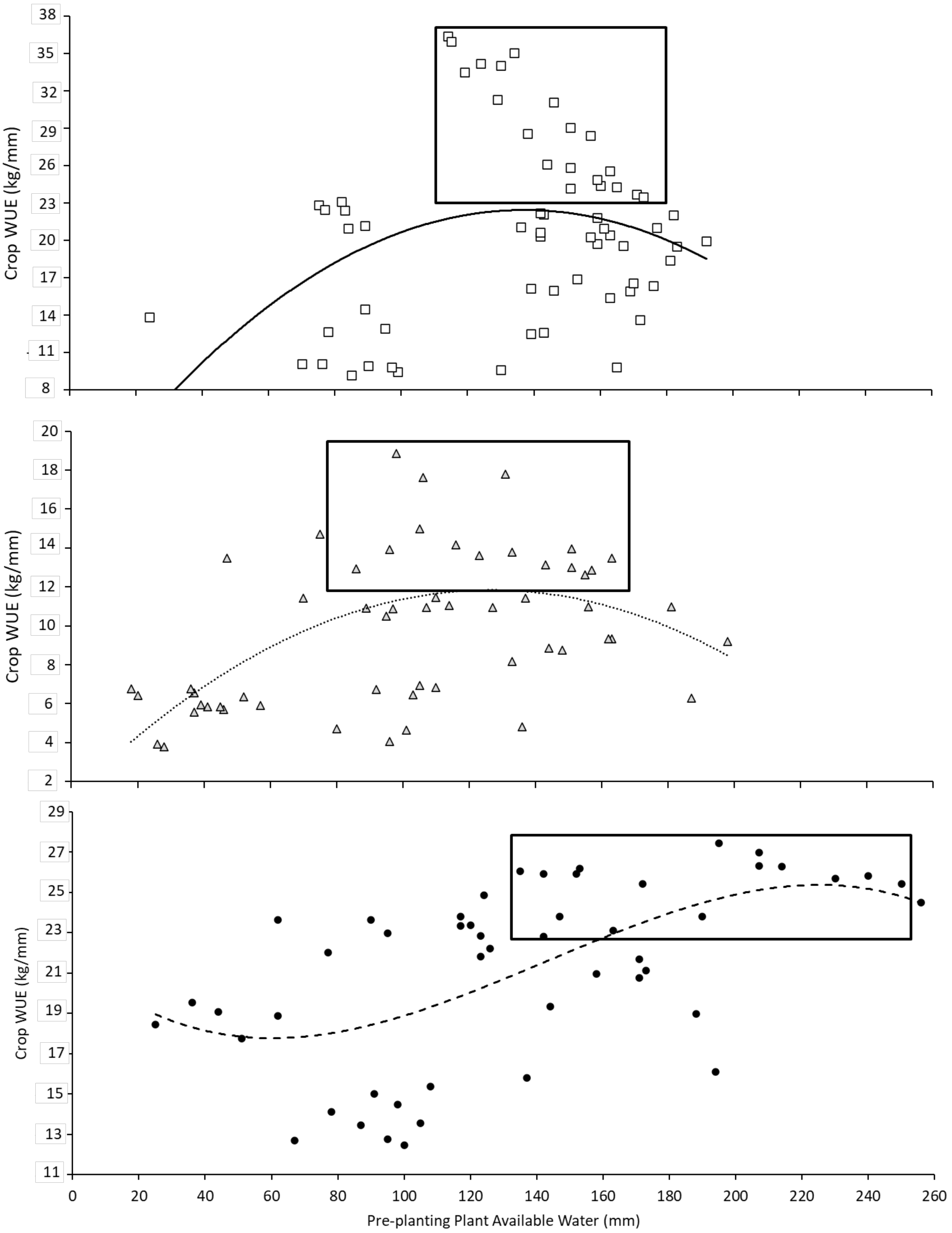

Figure 2. Relationship between crop WUE and plant available soil water (PAW, mm) sampled at the start of the sowing window for wheat (top, open squares), chickpea (middle, grey triangles) and sorghum (bottom, black circles) across farming systems experiments.

Fallow water accumulation - what can influence it?

Two main factors drive the amount of water that is available at sowing – the amount of water that accumulates over the prior fallow period and any residual moisture left from the previous crop. Fallow efficiency is the proportion of rainfall during a fallow that accumulates in the soil profile. Hence, achieving a higher fallow efficiency can significantly increase the available water for subsequent crops. For example, 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.

Environmental conditions such as the timing of rainfall events greatly influences the efficiency of fallows, which can vary dramatically from season to season. Overall, most of our 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, such as Robinson & Freebairn (2017) that report fallow efficiencies of 25-30% under no-till. Past research mostly examined systems where winter cereals were a larger component of the farming system, compared with cropping systems used now which include a higher proportion of legumes and summer crops, which are likely to achieve lower fallow efficiencies (see further results below). Our data suggests that using a generic 30% fallow efficiency may over-estimate fallow water accumulation in most cases, at least where cropping systems are not dominated by winter cereal crops.

Over our experimental years, environments with more winter-dominant rainfall had lower fallow efficiencies over summer fallows – this is likely due to smaller and less frequent rainfall events occurring during summer fallows meaning that soil water accumulates less efficiently.

1. ***How much do different crop residues (legume vs cereal or other) and fallow lengths impact fallow water accumulation?***

Across the farming systems sites we monitored fallow water accumulation following a range of different crops which includes residual soil water and final soil water for over 350 previous crops. Here we have collated this data in order to compare how different crop types impact subsequent fallow efficiencies (Figure 3). This data highlights the large variability in fallow efficiency that occurs and demonstrates some clear crop type effects on subsequent fallow efficiencies.

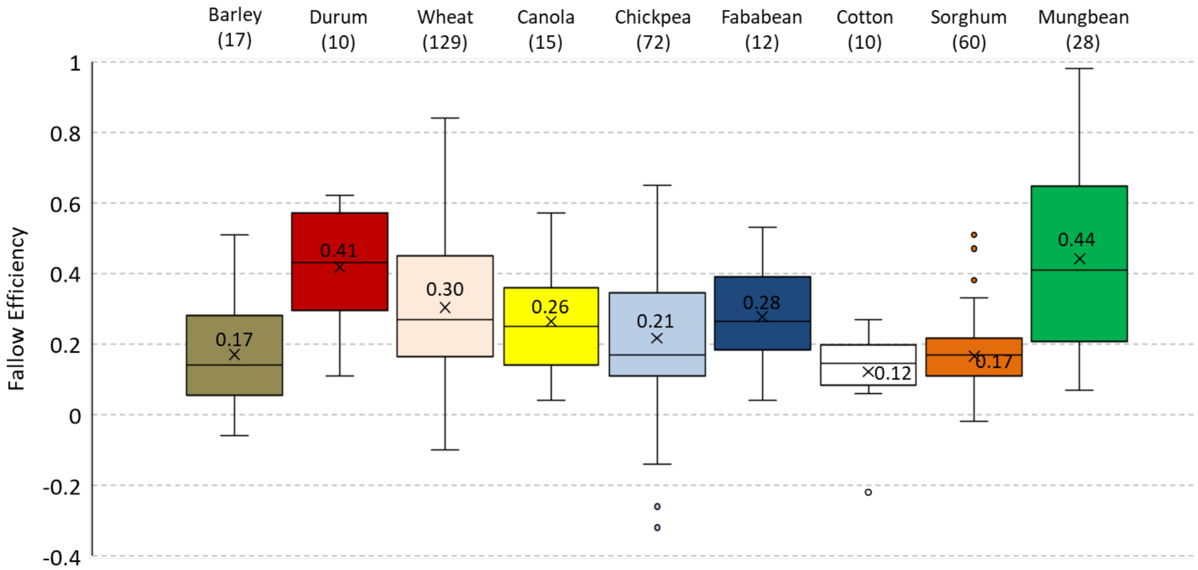

Figure 3. Summary of observed fallow efficiencies following different crop types across all farming systems sites between 2015 and 2022; only crops with 10 or more fallows are included. Boxes indicate 50% of all observations with the line the median and the x the average; the bars indicate the 10th and 90th percentile of all observations. Numbers in brackets indicate the number of fallows included for each crop type.

This data clearly shows the following effects of different crops:

- After winter cereal crops, fallow efficiencies are higher than after winter grain legumes and to a lesser degree, canola. The median fallow efficiency following all winter cereals was 0.27 (includes wheat, barley and durum), while following chickpea and other grain legumes was 0.19, with canola intermediate (0.23).
- After sorghum, fallow efficiencies are typically lower than after winter cereals (median of 0.17)this is due to a combination of more long fallows after sorghum. Short fallows after sorghum are generally higher efficiency than long fallows (i.e. 0.21 compared with 0.16).
- Fallows after cotton are the lowest efficiency (0.12) due to often being longer, with less residue and/or tillage for pupae control.
- Fallow efficiencies following mungbean were highly variable and while the data indicates high fallow efficiencies this is likely due to the residues remaining from previous cereal crops, as the mungbeans are often double cropped following wheat.

Fallow length also impacts on fallow efficiencies. Across our dataset longer fallows are generally less efficient – long fallows of >9 months have a median efficiency of 0.16, short fallows (4-9 months) have a median efficiency of 0.23, while fallows involving a double crop (*i.e.,* <4 months) have a median efficiency of 0.33.

2. *Residual water contribution to water availability for subsequent crops*

Fallow efficiency is also affected by residual soil water at harvest, with drier soils resulting in typically more efficient fallows than situations with more residual moisture. Hence, lower fallow efficiencies don’t always translate into less soil water at sowing of the next crop.

For example, legume crops often (but not always) leave soil water at harvest and despite lower fallow efficiency following grain legumes they may have similar water available for the next crop. In Table 1 we have compiled cases where chickpeas and wheat have been grown in the same season.

On numerous occasions we observed higher residual soil water at harvest after pulse crops (chickpeas, fababeans or field peas) compared to after wheat, on average this has been 41 mm more soil water post-harvest compared to wheat. This was often associated with rainfall later in the crops development where the winter cereals were able to extract this water while the pulses were maturing and did not utilise this additional water. However, at the end of the subsequent fallow this difference was greatly reduced so that on average only 10 mm more water remained in the soil profile after chickpea compared to wheat or barley. What this means, is that you shouldn't bank on the additional moisture after a grain legume translating into additional soil water available for subsequent crops, but equally fallow efficiency is not the only contributor to soil water in the next crop.

Table 1. Residual soil water at harvest and subsequent fallow water accumulation after chickpea and wheat compared across 7 sites/years

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

3. How much does fallow efficiency vary amongst farming systems approaches?

We have analysed the efficiencies of all fallows within different farming systems 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 are also found between different farming systems treatments tested across the sites. Key findings are:

- *Higher crop intensity* increased fallow efficiencies at most sites. This is due to less time in fallows and fallows having lower soil water content meaning less water is lost to evaporation.
- Conversely, systems with *lower crop intensity* had lower fallow efficiencies due to longer fallows and a greater proportion of rain and time in fallows meaning evaporative losses are higher.
- Systems with *higher legume* frequencies had lower fallow efficiencies (5% lower), particularly where they were reliant on summer rain accumulation. At several locations this effect was large, particularly where legumes were followed by a long-fallow period. This is due to the lower residue cover which breaks down faster following grain legume crops compared to cereals.

- On average, systems aimed at increasing *crop diversity* achieved similar fallow efficiencies to the baseline systems (regional baseline or reference system). However, there was large site-by-site variability, half the sites had a higher and half had a lower fallow efficiency. There were significant differences in how increasing crop diversity was achieved across the various locations (e.g., some involved alternative winter break crops, some involved long fallows to sorghum or cotton), which is likely to bring about these variable results.

Table 2. Comparison of fallow efficiency (i.e., change in soil water/fallow rainfall) for different cropping system strategies at 7 locations across the northern grains region. Colouring of numbers indicate the difference from the regional baseline or reference system – black = reduction, light grey = increase.

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		0.16	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**

*Crop system does not yet vary from the baseline in this regard

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 time in fallow required to accumulate sufficient water to maximise crop WUE, while at the same time not dramatically reducing overall system water capture.

Firstly, lets look at how much the overall system water capture and water use can vary between farming systems. Table 3 shows the proportion of total rain that was used by crops for the various farming systems at each location. Crop choice, like introducing more legumes or more diversity, have small positive or negative effects 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 on the counter, *Lower intensity* systems reduced the total water use.

To illustrate this with an example, let’s 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, 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 year would fall in-crop – resulting in a total crop water use of 390 mm (65% of rainfall). This means a crop grown after a longer fallow in a lower intensity system to be equally profitable must generate 1.6-times the grain/gross margin per mm of water used.

Table 3. Comparison of total water use as a percentage of total rainfall between different cropping system strategies at 7 locations across the northern grains region. Colouring of numbers indicate the difference from the regional baseline or reference system – black = reduction, light grey = increase.

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

*Crop system does not yet vary from the baseline in this regard

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, we have 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 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 once the efficiency of fallow water accumulation is considered then in most cases 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 2017/18.

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.

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

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	100	2.35	8.3	5.3	512	1.15
	Short fallow	177	3.36	9.9	4.2	678	0.85
Billa Billa 2017	Double crop	65	1.13	5.6	4.2	211	0.78
	Short fallow	125	1.49	6.7	4.5	278	0.84
Pampas 2017	Double crop	53	1.56	3.4	3.4	258	0.56
	Short fallow	169	1.83	5.2	3.5	424	0.81
Sorghum							
Billa Billa 2016/17	Short fallow	131	0.62	2.3	1.7	-138	-0.37
	Long fallow	212	1.31	3.8	2.3	34	0.06
Pampas 2016/17	Short fallow	147	4.51	10.8	8.2	1033	1.88
	Long fallow	238	5.66	10.6	6.8	1082	1.30
Pampas 2017/18	Double crop	96	0.65	2.2	2.2	30	0.10
	Short fallow	146	4.02	8.4	7.2	775	1.39
Chickpea							
Pampas 2017	Double crop	45	1.30	3.6	3.6	455	1.26
	Short fallow	169	1.68	6.4	3.8	651	1.47
	Long fallow	162	1.80	6.6	1.6	547	0.49
Billa Billa 2018	Double crop	163	0.82	4.5	2.7	209	0.69
	Short fallow	203	1.48	6.8	3.1	628	1.31

Conclusions

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 to sow your 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.

Further reading

Water use and accumulation

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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

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Key words

nitrogen budgeting, nitrogen fixation, fertiliser timing, nitrogen movement, denitrification, volatilisation, nitrogen recovery, 4R

GRDC codes

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

Take home message

The nitrogen (N) fertiliser demand for cereal cropping systems can increase due to two factors:

1. A reduction in the amount of soil organic N mineralised due to the continued decline of natural capital (soil organic carbon and total nitrogen) that occurs under cropping; and
2. An increased crop N demand due to higher yield potentials resulting from optimising other components of the cropping system.

The amount of biological N fixation by pulse crops (chickpea/mungbean) is related to the crop yield and biomass and the availability of soil mineral N from mineralisation or carry-over of residual fertiliser. Where deep phosphorus (P) and potassium (K) application increases chickpea biomass (and grain yield), there is generally more N fixed. While some of this is re-exported in grain, the greater residue return means more N is carried forward to the next crop.

Growers have a selection of fertiliser N management practices that 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 Qld.

Introduction

Cropping soils of the northern region are declining in natural fertility as the time since conversion to cropping from previous land uses increases. At the same time, 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, requires evolution of soil fertility management, including nitrogen.

The N cycle

There are many authors that 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.

DAF 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, with that understanding used to improve decision support tools and systems models, like APSIM. This research uses a stable isotope of N (^{15}N) to track movement, recovery, recycling and loss of fertiliser N for up to three consecutive crop seasons. The movement of fertiliser N down the soil profile during the recharge of soil water during a summer fallow, and the implications for N availability to a following winter cereal crop, is being investigated simultaneously through a project funded by federal Department of Agriculture, Water and Environment. Both projects are led by Prof. Mike Bell at the University of Queensland, with the Qld research occurring at Gatton, Kingsthorpe, Pampas and Mungindi. The objective of both studies is to better understand fertiliser N dynamics once applied to soil, and how recovery and use of that fertiliser can be optimised.

The ^{15}N 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). By having an unfertilised non-fixing reference plant in the same paddock during growth of the pulse crop, we can use the differences in abundance of ^{15}N in the tissues of the reference crop (soil N only) from that of the legume crop (soil N and atmospheric N) to determine how much N was fixed from the atmosphere by the legume. By doing similar calculations on the grain removed from the field, the amount of soil N removed from the field can be compared to the amount of fixed N returned in residues, and a N balance calculated 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.

N in CQ farming systems research

Since 2014 the CQ smart cropping centre (formerly the Emerald Agricultural College) has been part of a DAF-led and GRDC-supported project evaluating different cropping parameters around fertility management, crop choice for pathogen/weed management, and cropping intensity across the northern region. Another update on the results in CQ and the broader project are presented in this update (Bell and Aisthorpe 2023).

A component of the 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. This gives an insight into the behaviour of the immediately available plant N pool in the soil. It is only a partial story because the bigger picture includes N that is exported in grain, N remaining in stover and roots after harvest, N which has been incorporated into the soil organic matter pool, or lost off-farm via gaseous (denitrification, volatilisation) or aquatic (leaching, runoff) pathways.

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

5. Mixed baseline (M01)
6. High nutrient (M02)
7. High fertility (M02b)
8. High legume (M03)

Let’s start with the baseline system (M01), a wheat-chickpea-sorghum opportunity cropping system with fertiliser N inputs designed to meet the demands of crops achieving a median target yield. There have been 9 crops harvested (Table 1), including 7 cereal and 2 chickpea. The 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.

In ’Managing Legume and Fertiliser N for Northern Grains Cropping’ by David Herridge (2011), there are a series of equations that allow the estimation of 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. Using that framework, the N fixed at the Emerald experiment has been calculated, and those values used as part of evaluation of system N balances.

It is suggesting that ~260 kg N/ha was fixed by two chickpea crops in the baseline treatment. The 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 (Win22), when the starting soil mineral N (110 kg N/ha) was half that of the 2016 season. Cumulative N exported has been 571 kg N/ha in 26,148 kg of grain, which means this system has run up a deficit of 201 kg N/ha, i.e., there’s been 200 kg/ha more N exported than added into the system through fertiliser and fixed N. This N has to have been supplied by a rundown of the soil organic matter and N.

Table 1. CQSSC farming system mixed baseline running N balances

Code	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)
M01	Win15	wheat	132	102	16		38	6276	1671	-22	-22
M01	Win16	chickpea	215		3	112/40%	95	7908	3059	20	-2
M01	Win17	wheat	175	98	26		37	5278	1759	-11	-13
M01	Sum17	sorghum	218	119	4		53	11573	3096	-49	-62
M01	Win19	wheat	210	98	2		59	8512	2961	-57	-119
M01	Win20	wheat	151	76	1		48	4638	2239	-46	-166
M01	Sum21	sorghum	153	220	48		66	10071	4393	-18	-184
M01	Win22	chickpea	110		2	149/56%	84	7131	2847	66	-118
M01	Win23	wheat	89	95	7		91	7848	4124	-83	-201
M01 Total					**110**	**261**	**571**	**69234**	**26148**	-201	

* simulated modelled values using (Herridge 2011)

In the high nutrient M02 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 such that only an additional 55 kg N/ha more than the *baseline* has been applied over the entire sequence (Table 2). Grain yields for the *baseline* and *high nutrient* systems are equivalent (69,200 vs 70,000 kg/ha, respectively), but that higher fertiliser N input has resulted in slightly lower total N fixed. Collectively then, it is not surprising that the slightly higher fertiliser N input is balanced by higher grain N export, with the cumulative N balance (Table 2) being similar to that of the baseline system (i.e., -198 kg N/ha).

Table 2. CQSSC farming system high nutrient tunning N balances

Code	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)
M02 Total	165	235	597	70030	27648	-198

*simulated modelled values using Herridge (2011)

When the experiment was commenced a treatment (M02b) attempting to re-establish a high natural fertility status through addition of a large amount of organic matter was established. This was achieved through applying 50 t/ha of (dry equivalent) feedlot manure in two applications. These manure additions have resulted in large increases in the soil mineral N and annual fertiliser N applications have not been applied, with the exception of the N in the starter fertiliser (i.e., 2–6 kg N/ha as MAP, Table 3). Grain production has increased by a cumulative ~5 t/ha more than the M01 and M02 treatments, while an additional ~80–100 kg N/ha being removed in grain (672 kg N/ha, Table 3). The amount of Ndfa% is slightly lower, consistent with the higher soil mineral N supply.

Using the manure application rates and chemical analysis, an estimate of the addition of carbon (C), N, phosphorus (P) and potassium(K) was done correcting to 0% moisture. Total inputs are 10,480 kg C/ha (equivalent to 1% C), 1,110 kg N/ha, 416 kg P/ha and 1,000 kg K/ha. If we include the N addition from the two manure applications with the N fertiliser applied, an apparent surplus of 730 kg N/ha exists.

Table 3. CQSSC farming system high fertility (M02b) running N balances

Code	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)
M02b	Win15	wheat	157	140	281		45	6278	1926	237	237
M02b	Win16	chickpea	238		3	103/37%	96	8500	3023	10	247
M02b	Win17	wheat	266	132	890		51	7155	2367	839	1086
M02b	Sum17	sorghum	389	170	6		69	12307	4245	-63	1023
M02b	Win19	wheat	369	132	3		70	10419	3402	-68	955
M02b	Win20	wheat	410	113	3		65	6194	3056	-62	894
M02b	Sum21	sorghum	327	242	2		82	11553	5556	-80	813
M02b	Win22	chickpea	261		6	102/36%	92	7854	3016	16	829
M02b	Win23	wheat	141	113	5		102	9252	4644	-97	732
M02b Total					1199	205	672	79511	31233	732	

*simulated modelled values using Herridge (2011)

All three of these systems (M01, M02 and M02b) have been cereal dominated. The *high legume* treatment (M03) attempts to have 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 are 5 t/ha less than the mixed baseline system, reflecting the typically lower yields of grain legumes compared to cereals in the same seasonal conditions. Dry matter production and crop residue return to the soil is also less in this system, but grain N export is not that much 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 starter fertiliser applications. Simulated total N fixed by the system is ≈360 kg N/ha. These are modelled numbers so 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.

Table 4. CQSSC farming system high legume (M03) running N balances

Code	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)
M03	Win15	chickpea	96		2	77/44%	55	4031	1842	23	23
M03	Win16	wheat	176	79	3		77	9611	3761	-74	-50
M03	Win17	chickpea	144		3	65/35%	62	3642	1931	6	-44
M03	Sum17	sorghum	132	119	4		51	11874	2982	-47	-91
M03	Win19	chickpea	105		2	52/36%	54	5729	1509	1	-91
M03	Win20	wheat	120	76	1		37	3893	1767	-35	-126
M03	Sum21	mungbean	117		2	6/10%	23	4091	627	-15	-141
M03	Win22	chickpea	88		2	163/62%	87	6972	2831	101	-40
M03	Win23	wheat	103	95	2		87	7951	3967	-85	-147
M03 Total					22	362	531	57795	21215	-147	

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, the more N that is likely to 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, with those responses accompanied by substantial increases in crop biomass production. By applying the assumptions and model of Herridge (2011) to the Dysart deep P trial site, an estimate of total N fixed across a range of deep P treatment scenarios can be determined (Table 5). The experiment had two deep P applications during the research phase. Initial treatments had untreated control or 'Farmer Reference' treatment, then increasing subsurface P rates (0, 10, 20 or 40 kg P/ha) applied as MAP in 2014. In 2019, those original plots (apart from the FR) where split with a reapplication of 30 kg P/ha (as MAP). In Table 5 a treatment of 20P was the original P rate without reapplication, while the 20+30P represents an initial application of 20P and a reapplication of 30P.

These modelled 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%, comparing the farmer reference to two deep P applications. Even with increasing grain N removal, the estimated residual N carried forward was increased nearly 3-fold, from 66 to 190 kg N/ha. Of course, the release rate of N from the residues would be seasonally dependant, and recovery by future crops would be related to residue decomposition and movement of mineralised nitrate-N into the soil profile.

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

Chickpea N fixation in Queensland in 2023

This last winter season (2023) DAF has been measuring on-farm N fixation by chickpea across 25 sites in Central and Southern Queensland, using the previously described ^{15}N natural abundance method. After the analytical processes are completed, we'll be able to give another update early in the new year. The project is monitoring fallow water and mineral N changes between harvest and sowing of the next crop. DAF is also part of a new national consortium (led by University of Adelaide) investigating the understanding and effectiveness of N fixation in pulses. We will be following up with more information about N fixation in the new year.

Conclusions

Growers and advisers have a range of tools and techniques to fine-tune N management on their properties.

There are many factors that come together into a successful cropping N management strategy. Using a crop model such as ArmOnline to generate a range of yield potentials allows an estimation of different crop N demands and the likely amount of N which will be exported from the field. Soil sampling for mineral N can provide a good starting point as to how much plant available N is present before sowing. Higher soil mineral N backgrounds can reduce the reliance on recovery of fertiliser N in that year. Having an indication of the soil mineral N status also allows some estimating of likely soil N recovery by a pulse crop.

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Distribution of nitrates and its effect on plant uptake efficiency in Central Queensland farming systems

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GRDC code

Mungbean agronomy project (DAQ 1806-003RTX)
Companion cropping project (DAQ2104-006RTX)

Take home message

- Crops such as wheat, chickpea and mungbean can utilise up to 85% of the nitrates contained in the 10 – 60cm of the soil profile under Central Queensland cropping conditions.
- 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.
- 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.

Introduction

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

This paper will examine the relationship between water uptake and nitrate uptake in the crop and give practical examples of what has been observed in typical Central Queensland (CQ) cropping scenarios.

Background

The data presented in this paper has been taken from two GRDC funded field trial projects, the Companion Cropping project (DAQ2104-006RTX) and the Mungbean Agronomy project (DAQ2104-006RTX).

There were two experiments conducted in the companion cropping project and the results of the first experiment which ran from May of 2021 to October of 2022 have been used in this paper.

This experiment was designed to test the production outcomes of planting two crops (wheat and chickpeas) together at the same time either in alternate rows or mixed together in the same row. Other outcomes tested included what the fallow efficiency of the companion treatments were and whether there were any impacts on the uptake or cycling of soil nitrates. There were 12 treatments in this experiment including a wheat monocrop and a chickpea monocrop to act as benchmark controls for the other 10 companion crop treatments. It is the soil water and soil nitrate data from these two monocrop treatments that will be presented in this paper.

Sampling included taking soil cores in:

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

The main companion cropping experiment was planted and harvest in 2020 but a cover crop of wheat was planted in the following year across all the original plots. This was done 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 (five reps) from the wheat monocrop and chickpea monocrop treatments only, is presented in this paper.

The mungbean agronomy project had two experiments designed around testing mungbean yield response to nitrogen fertiliser application (mungbean N response). These experiments were conducted in the 2019-20 and 2020-2021 summer seasons. In these experiments there was a common range of applied nitrogen treatments which started at 30 kg N/ha up to 150 kg N/ha. These treatments were applied directly as a banded application after wheat harvest in late October of the previous year and were left fallow until mungbean planting in February of the following year.

The second experiment in 2020-2021 had two additional treatments that explored the impact of a much longer fallow on the soil nitrate profile. These long fallow treatments had no wheat planted in the previous winter which ensured an eight-month fallow as opposed to a three-month fallow for all the other treatments. 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 around testing for nitrogen fixation levels in the crop when planted on increasing levels of soil nitrate, some interesting data has been extracted from these trials 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 extracted nitrates 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 then 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 (CQSCC) 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 (Figure 1 and 2). These profiles were tested in increments of 0-10cm, 10-30cm, 30-60cm, 60-90cm and 90-120cm. There are several points that can be highlighted from this data.

Firstly, both crops extracted water down to 60cm very efficiently with less than 8mm of plant available water capacity (PAWC) left in those layers after harvest (Figure 1 and 2). Extraction from the 60-90cm layer was also significant for both crops but in the bottom layer (90-120cm) wheat had a much higher extraction rate (Figure 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 as an indicator of the efficiency of soil extraction for each profile layer. It is clear from the data (Figure 3) that the extraction rate from the top 60cm of the profile is consistently 80-85% regardless of crop type.

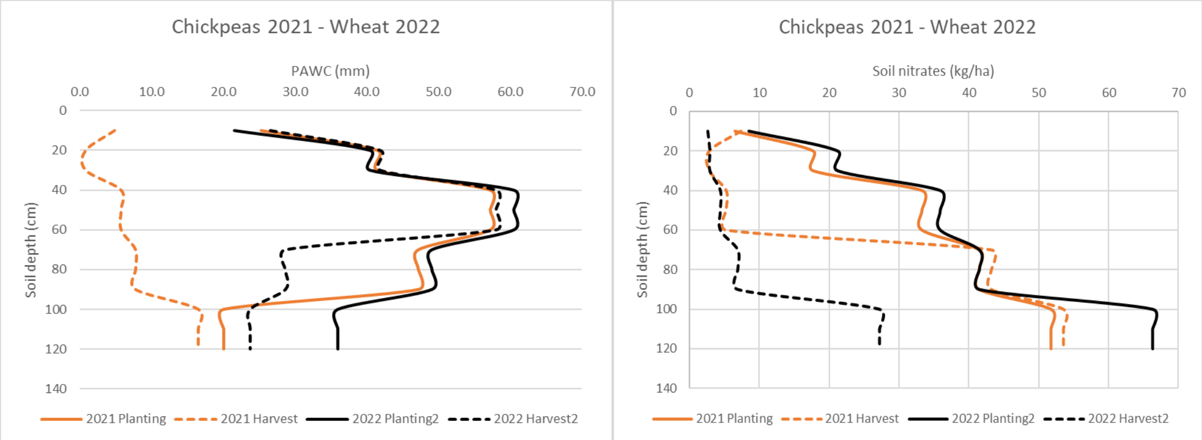

Figure 1. Mean soil water (left) and soil nitrate (right) of the 2021 chickpea and the following wheat crop in 2022 at planting and harvest. This data was extracted from the first companion cropping trial in 2021-2022.

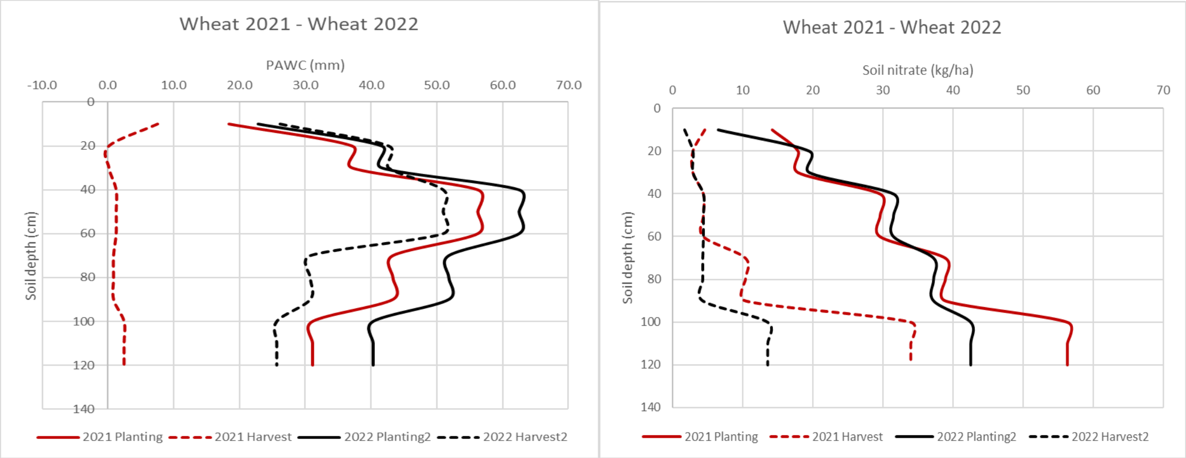

Figure 2. Mean soil water (left) and soil nitrate (right) of the 2021 wheat plots and the following wheat cover crop in 2022 for planting and harvest. This data was extracted from the first companion cropping trial in 2021-2022.

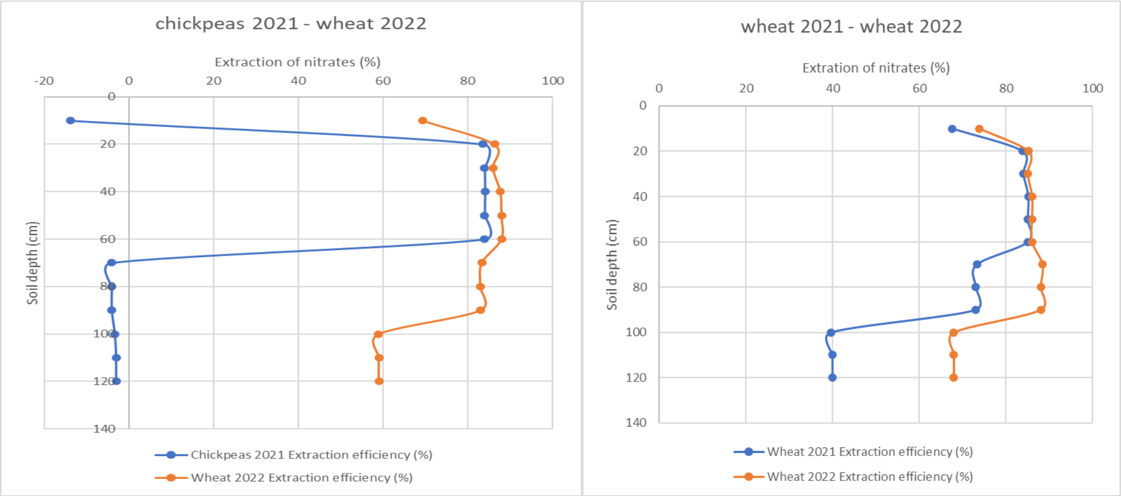

Figure 3. Soil nitrate extraction efficiency from soil profile presented as a % of the total soil nitrates present at planting for both the chickpea (left) and wheat (right) in 2021 and the following wheat cover crop in 2022. Data calculated from the first companion cropping trial (2021-2022)

The top 10cm layer can have 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 90-120cm) is 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 over 80% of the nitrates contained in this layer being extracted by the crop. This conclusion is supported by data extracted from the mungbean N response trials located on the CQSCC in summer of 2020-21.

In this experiment soil cores were taken in June 2020 (in fallow) and then remeasured at the planting of a mungbean crop in February 2021. This data subset compares three treatments:

9. LF0N – long fallow with no N applied.
10. LF60N – long fallow with 60 kg N/ha applied.
11. SF0N – short fallow with no N applied.

They 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.

The soil nitrate data extracted from the mungbean N response trial (Figure 4) shows three distinct levels of nitrate supply. Both long fallow treatments (LF0N, LF60N) have accumulated their highest N level in the 30-60cm zone after 8 months of fallow and 381mm of rainfall. The short fallow treatment has a different pattern of N distribution which incrementally increases with depth, much like a descending staircase, with the largest amount of nitrate being accumulated at the deepest layer.

For comparison, at the time of planting (Figure 4), the top 60cm of the profile contains; 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.

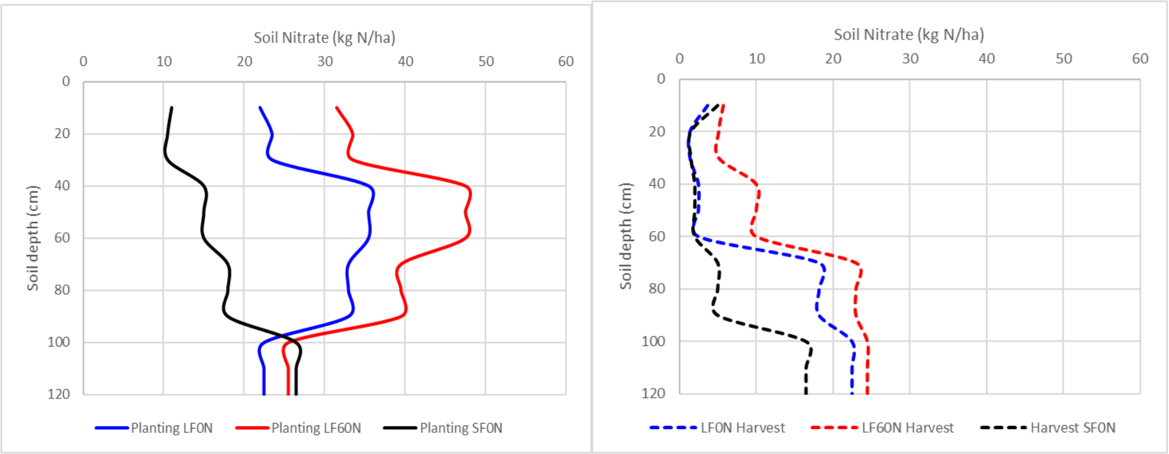

Figure 4. Nitrate levels measured at planting (left) and after harvest (right) of mungbeans grown in 2020-2021. This is a comparison between short and long fallows without N applied and a long fallow treatment with N applied.

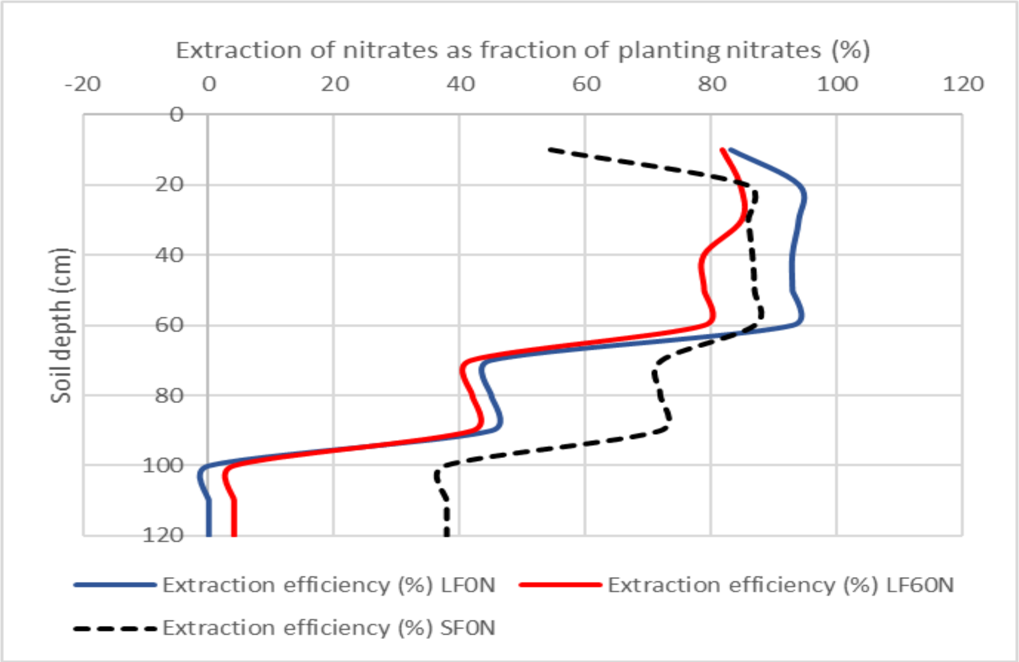

Figure 5. Comparison of the nitrate extraction efficiency of mungbean planted into short and long fallow treatments in the 2020-2021 mungbean N response trial by soil layer.

Overall, the long fallow treatments have 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 one of the long fallow treatments has made the biggest difference in the amount of nitrate accumulated in the 30-60cm layer although most layers down to 90cm benefited from the applied fertiliser compared to the long fallow treatment without any fertiliser applied (LF0N).

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

At the deeper soil layers the long fallow treatments have a similar pattern of extraction by layer with ~45% in the 60-90cm zone and almost nothing from the 90-120cm layer (Figure 5). Comparatively, the short fallow treatment shows ~70% extraction from the 60-90cm layer and ~40% extraction from the 90-120cm layer (Figure 5). All these 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 and the amount of soil nitrate that was extracted from the top 60cm of the profile (Table 1). The change (Δ) in soil nitrate levels in the top 60cm from planting to harvest shows a big difference between the long fallow distribution and the short fallow distribution (Table 1) and consequently there is a big difference in the amount of soil nitrate that has ended up in plant biomass.

Table 1. Summary data of key nitrate measurements for the short and long fallow treatments including N in the total biomass of the crop. This data is extracted from the mungbean N response trial in 2020-2021.

Treatment	Fallow length (days)	Fallow mineralised N (kg/ha)	∆ soil profile N (plant to harvest) kg N/ha	Total N in biomass*	∆ soil nitrates in top 60cm (plant to harvest) kg N/ha	Contribution of top 60cm 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* ^{15}*N.*

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 that was extracted from the top 60cm 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 60cm of the soil profile. These numbers have been generated from a mungbean crop that has a shallow root system, however chickpeas and wheat have also shown the same efficiency levels for nitrates existing in the 10-60cm layer of the profile (Figure 3).

The N fixation levels for these treatments (Ndfa%) measured by the natural abundance method were as follows; SF0N – 45%, LF0N – 10%, LF60N – 4% (not shown). Clearly the short fallow treatment fixed the most N from atmosphere and this maybe a result of not having as easy 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 QLD and NNSW which suggest that 70-80% of total nitrate uptake is through soil nitrate pools existing in the top 60cm (Figure 6) in unfertilised crops (Bell et al., 2016).

It makes sense that a long-term management program around N nutrition would be built around trying to maintain an adequate level of nitrate in the 10-60cm 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 then is to understand how the application rate, timing and placement of N based fertilisers relates to maintaining this ‘N bank’ in the 10-60cm soil profile.

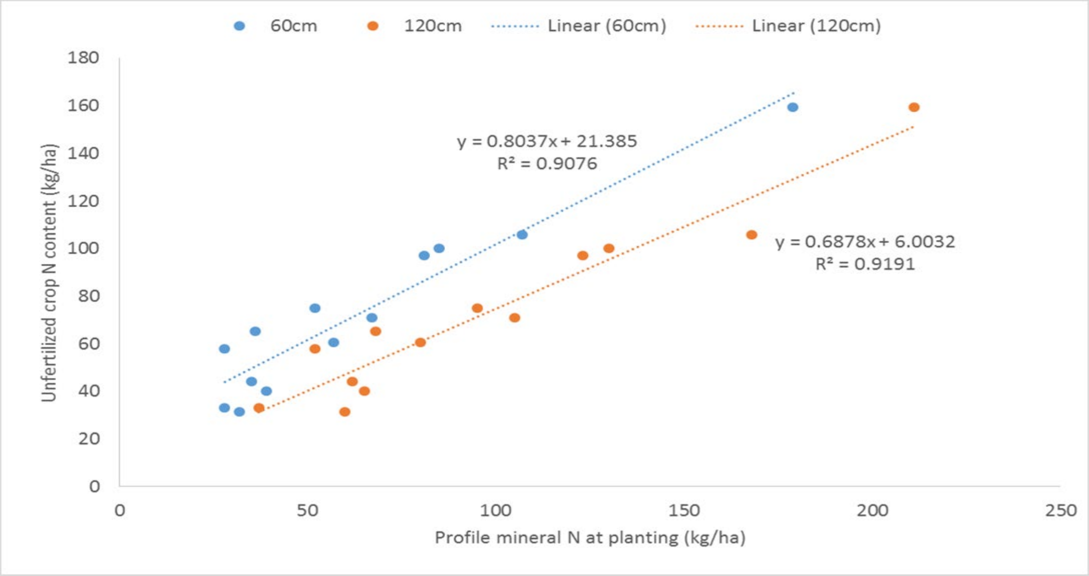

Figure 6. Mean data from a range of Queensland sorghum x nitrogen experiments where the points represent the amount of profile mineral N at planting in the unfertilized control treatments and their relationship to total N in biomass. Blue dots represent the top 60cm profile and the orange dots represent the 120cm profile.

Source: Bell M et al, (2016) Summer grains conference.

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 10cm. The movement of this N is reliant on water movement once it is in the nitrate form (plant available form) and this movement 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 is met between wet soil and dry soil. When rain falls on already wet soil this pressure gradient is not as strong and so the movement of water through the profile is slower and does not move as far.

Decisions around applying N fertiliser need to consider how long it is going to take for the nitrate to move through the profile and redistribute in those key zones of root uptake (10-60cm). The data extracted 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-month fallow, between harvest in 2021 and planting of 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 PAWC 207mm) and the wheat by 207mm (total PAWC 218mm). Based on the total PAWC numbers, both treatments had a full profile at planting of 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 has come from the mineralisation of organic matter since no fertiliser was added to these plots. The distribution of nitrates down the profile (Figures 7 and 8) shows that the amounts held within each measured layer does not necessarily reflect the same pattern as the PAWC pattern.

The PAWC data (Figure 7 and 8) predictably shows peak water holding capacity in the 30-60cm 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 90-120cm having the highest levels of nitrate (Table 2).

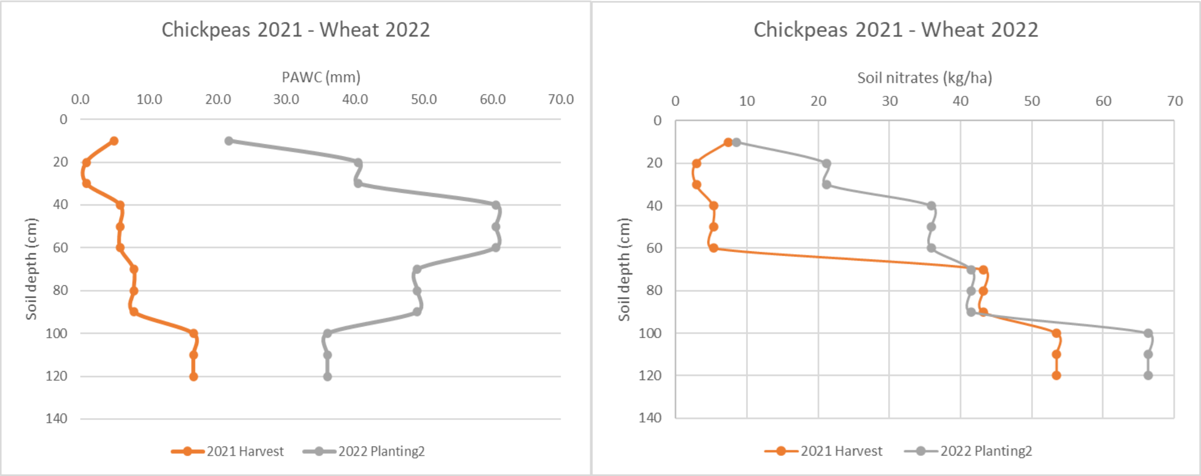

Figure 7. Mean PAWC and soil nitrates at chickpea harvest 2021 and wheat planting in 2022. Profile measurements are taken at 0-10, 10-30, 30-60, 60-90 and 90-120cm increments.

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 90-120cm increments.

From this data there is no way of knowing the proportion of nitrate that has been 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 (0-10cm) where crop residues are being broken down and in the 10-30cm zone where the largest root mass will also be broken down.

The distribution of N in the profile shows that the 0-10cm and 10-30cm zone contains 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 90-120cm zone and not in the 30-60cm zone where the highest water holding capacity is (Figure 7 and 8).

Table 2. Proportional distribution of nitrates down the soil profile after eight month fallow following wheat and chickpea crops. These nitrate levels are derived from the mineralisation of organic matter 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

Further data on the redistribution of soil nitrates in the profile can be extracted from the N response trials in mungbeans carried out in 2019-20 and 2020-21 at CQSCC. 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 distribution of nitrates through the profile at the start of the fallow period and when the crop was planted shows the long fallow treatments (8 months) have accumulated more nitrate in the 30-60cm zone than the short fallow treatment (3 months) (Figure 9). The distribution of nitrates at the start of the long fallow period is very similar to the pattern of distribution at planting.

The short fallow treatment has accumulated more N in the 30-60cm layer than the other layers but not to the same concentration as the long fallow treatments. It is notable that the nitrates in the 90-120cm layer have hardly moved in both short and long fallow treatments. This is not surprising given PAWC data (Figure 9) for these treatments shows almost no wetting of the 90-120cm layer which means there are few opportunities for the nitrate to be moved by water into this zone.

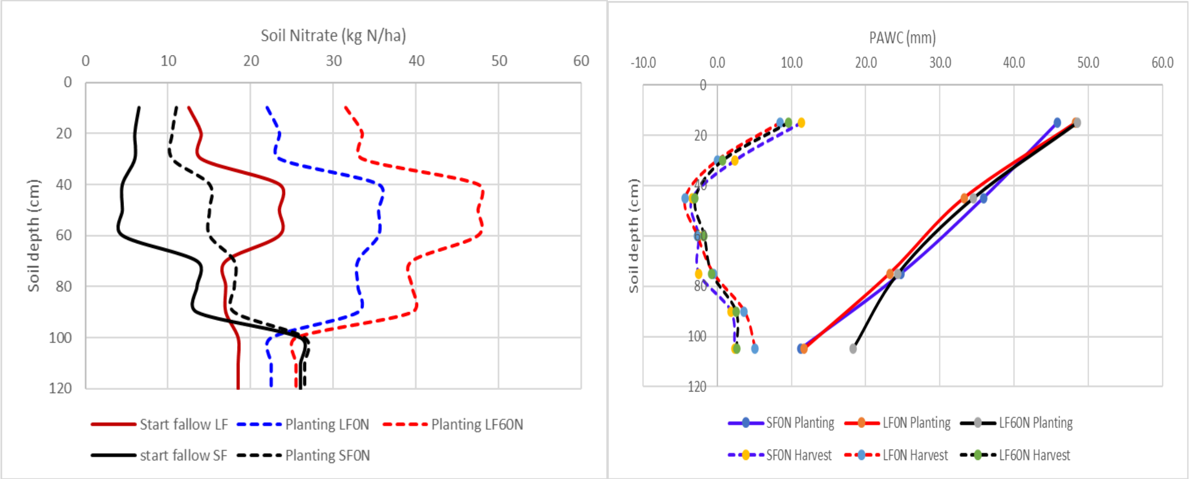

Figure 9. Mean nitrate distribution (left) between the start of fallow and planting for the short and long fallow treatments in the 2020-2021 mungbean N response trial. PAWC distribution (right) at planting and harvest for the short and long fallow treatments in the 2020-2021 mungbean N response trial.

The surprising factor in this data (Figure 9) is that the long fallow treatments had 381 mm of rainfall in the fallow period leading up to planting while the short fallow treatment had 240mm of rainfall.

Both fallows also received 100mm of irrigation in the summer period leading up to planting. The differing rainfall totals made little difference in the starting water profile (116mm *cf*. 125mm) of the two fallow periods. All three treatments had similar PAWC at planting (Figure 9) and those profiles were only ~65% full which explains 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 60kg N/ha in the long fallow treatment has increased the concentration of nitrates down the profile under these fallow conditions.

A useful comparison to this data from 2020-21 is the N response in mungbean experiment conducted in the previous summer 2019-20 at the CQSCC. In this experiment all treatments were applied after a wheat harvest at the end of October 2019 with several rates of N applied to the surface soil on the 25 November 2019 before being left fallow through to planting on 14 February 2020 (81 days). This site received no rainfall to mid-December, so a 100mm irrigation was applied on the 16 December 2019. After Christmas there was 303 mm of rainfall in 7 events prior to planting.

Soil cores samples were taken after wheat harvest but before N application and then again at planting. The soil nitrate and PAWC data extracted from this trial show three treatments (Table 3):

12. 0N control (no N applied)
13. 60N (60 kg N/ha applied)
14. 150N (150 kg N/ha applied).

Under these short fallow conditions over summer, the profile mineralised 68 kg N/ha with no fertiliser added (Table 3), which is relatively high in comparison to published data (Cox H, 2009). In comparison to this mineralisation rate, the fertiliser treatments added 51 kg N/ha (60N) and 175 kg N/ha (150N) which aligns well with the application rates (Table 3).

The distribution of these nitrates down the profile (Figure 10) shows a very similar pattern for each treatment with the 30-60cm layer accumulating the largest amount of nitrate and the 90-120cm layer not changing at all (Figure 10). The PAWC data (Figure 10) shows that very little soil water accumulated in the 90-120cm layer by planting time, which would explain why the nitrate levels did not change.

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

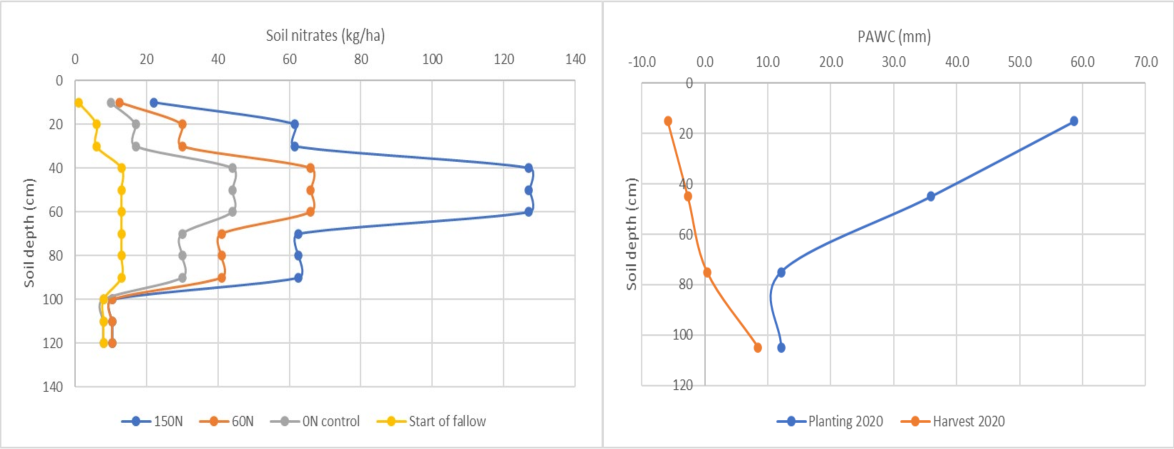

Figure 10. Mean distribution of soil nitrates (left) by soil layer under three N application treatments during an 81-day fallow over the summer period (2019-2020). PAWC distribution (right) by soil layer at planting and harvest in 2019 – 2020 summer mungbean crop.

The PAWC data (Figure 10) also suggests that the soil profile was not full at planting time with PAWC values averaging 119mm (not shown) which is about 65% of a full profile for this soil type.

The nitrate distribution in the profile (Figure 10) indicates rainfall has the key impact on depth of N and the rate of applied N has the biggest impact on concentration in each soil layer. Where there was no N applied, the soil nitrate level is more dependent on the 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 are only small amounts of nitrate being released at any one time and is available to move with a wetted front.

When N is applied to the surface soil there is a high concentration of nitrate formed in the surface layer and each successive rainfall event can move a larger concentration of nitrate down the profile. This will ensure that there is adequate nitrate available in this key zone for plant uptake that has been proven to have a high level of efficiency for plant access.

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 60cm 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 60cm above the natural mineralisation rate during a fallow period of 259 days. While these data sets are treated as being mutually exclusive because of the differing seasons it does give an indication that the length of fallow is not critical to getting soil nitrates distributed into the key uptake zones.

Key outcomes for growers

The two concepts that should underpin any nitrogen fertiliser program is that maximum efficiency of plant uptake of nitrates occurs in the 10-60cm 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 10-60cm 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 60cm 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 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 (0-10cm) 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 (10-60cm), then this rainfall period needs to be utilised as much as possible.

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

There are limitations to the scope of this data and one of these 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 their 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 10-60cm soil zone which in turn promotes the highest efficiency of uptake for the following crop.

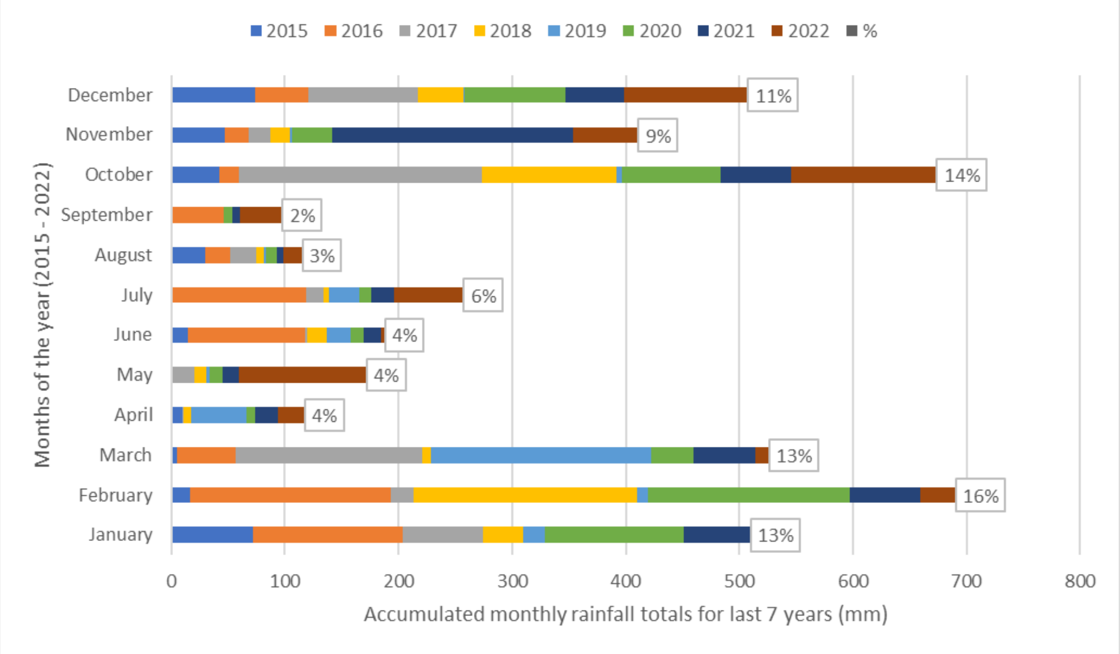

Figure 11. Monthly rainfall totals accumulated over the last seven years (2015 – 2022) at the CQSCC weather station. These accumulated monthly totals are presented as a proportion of the total rainfall that has occurred in this seven-year period (%).

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

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Key words

N_2 fixation, nitrate, ^{15}N natural abundance, nitrogen harvest index, chickpeas, mungbeans, mineralisation.

GRDC codes

Northern farming systems – DAQ2007-002RTX
Mungbean Agronomy – DAQ2104-006RTX

Take home message

- 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 60cm of the profile.
- Mungbean and chickpea crops can access and utilise soil nitrate N in the top 60cm as efficiently as cereal crops. This raises implications for nitrate N supply in crops following these pulse crops.
- 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.

Introduction

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 which 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 grain legumes 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.

Background

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 season. In these experiments there was a common range of applied fertiliser N treatments which started at 30 kg N/ha up to 150 kg N/ha (Table 1). These fertiliser treatments were band applied directly after wheat harvest in late October of the previous year (cover crop) and then were left fallow (wheat stubble) until the planting of mungbeans in February.

The second experiment in 2020-21 had two added treatments that explored the impact of a much longer fallow on the soil nitrate N profile. These long fallow treatments had no wheat planted over the winter resulting in an eight-month fallow as opposed to a three-month fallow for all the other treatments (Table 1).

Within each of these trials an assessment of N_2 fixation was carried using the ^{15}N isotopic natural abundance process on every plot using a non-nodulating soybean variety. From this process the proportion (%) of nitrogen derived from the atmosphere (Ndfa) in the plant could 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 harvesting. Further details of these experiments can be found in a previous GRDC update paper ‘What contributions do mungbeans make to soil nitrogen’ (2022).

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

2020 trials – treatment list **Irrigated and dryland trial**	**Treatment name**	**2021 trials – treatment list** **Irrigated and dryland trial**	**Treatment Name**
Short fallow + cover crop +zero N applied	0N	Short fallow + cover crop + zero N applied	0N
Short fallow + cover crop + zero N applied, no inoculant	0N-IN	Short fallow + cover crop + zero N applied , no inoculant	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	Short fallow + cover crop + 30 kg N/ha	30N
Short fallow + cover crop + 60 kg N/ha	60N	Short fallow + cover crop + 60 kg N/ha	60N
Short fallow + cover crop + 90 kg N/ha	90N	Short fallow + cover crop + 90 kg N/ha	90N
Short fallow + cover crop + 120 kg N/ha	120N	Short fallow + cover crop + 120 kg N/ha	120N
Short fallow + cover crop + 150 kg N/ha	150N	Long fallow + 60 kg N/ha	LF60N

The other project data that this report will draw on is the Northern Farming Systems project (DAQ2007-002RTX) which is a long-term experiment that has been running since 2015 at the CQSCC and involves collecting a range of data across six different farming system. Those farming systems include:

15. *Baseline* (M01) –- 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 (50th percentile) seasonal yield potential.
16. *Higher crop intensity* (M07) – 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 (50th percentile) seasonal yield potential.
17. *Higher legume* (M03) – 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 (50th percentile) seasonal yield potential.
18. *Higher nutrient supply* (M02) – Fertiliser N and phosphorus (P) rates of the *Baseline* system increased targeting 90th 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.
19. *Higher soil fertility* (M02b) – 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).
20. *Integrated weed management* (IWM) (X01) – 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 (50th Percentile) seasonal yield potential.

Sourced: Aisthorpe D (2023) unpublished

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 have been no assessments made in this trial on Ndfa% for the pulse crops grown across the various cropping sequences; however extensive soil measurements have been taken before and after each crop which 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).

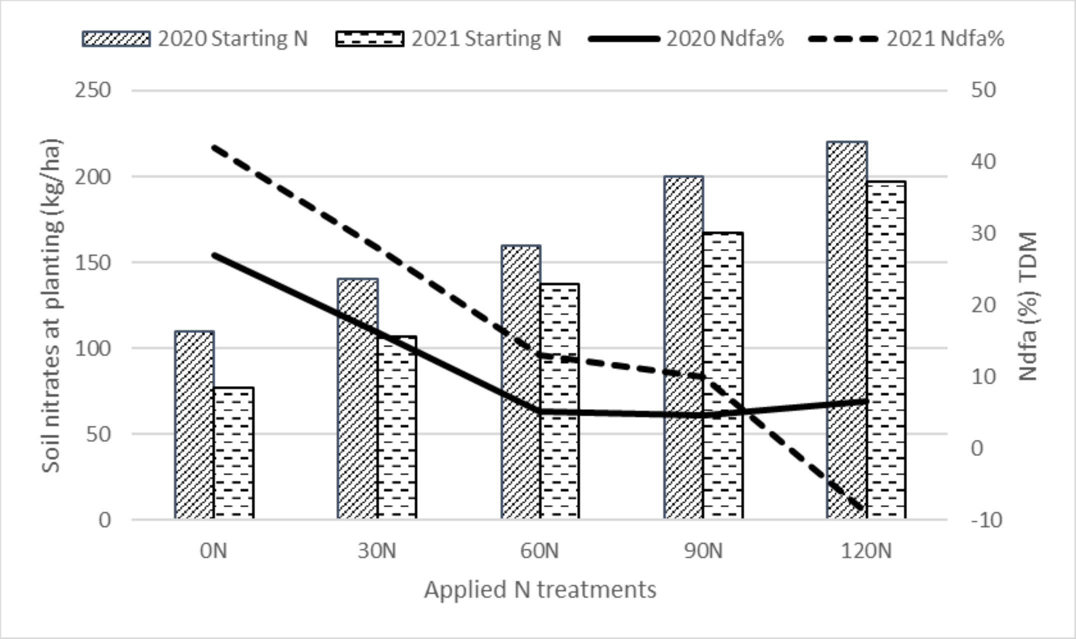

Figure 1. Nitrogen derived from the atmosphere (Ndfa%) in plant material in comparison to measured profile soil nitrate N at planting time to a depth of 120cm. Data is an average of irrigated and dryland trials located at the CQSCC in 2020 and 2021 summer seasons.

In addition to the Ndfa% data (Figure 1) grain samples were analysed for grain N. This grain N was divided by the total N recorded at peak biomass to calculate the N harvest index (NHI) for the crop. The NHI (Figure 2) represents the proportion of total N being exported from the paddock in grain. The lowest NHI was 0.6 (60%) in the 2020 trial while the upper end of the range was 0.9 (90%) in the 2021 trial.

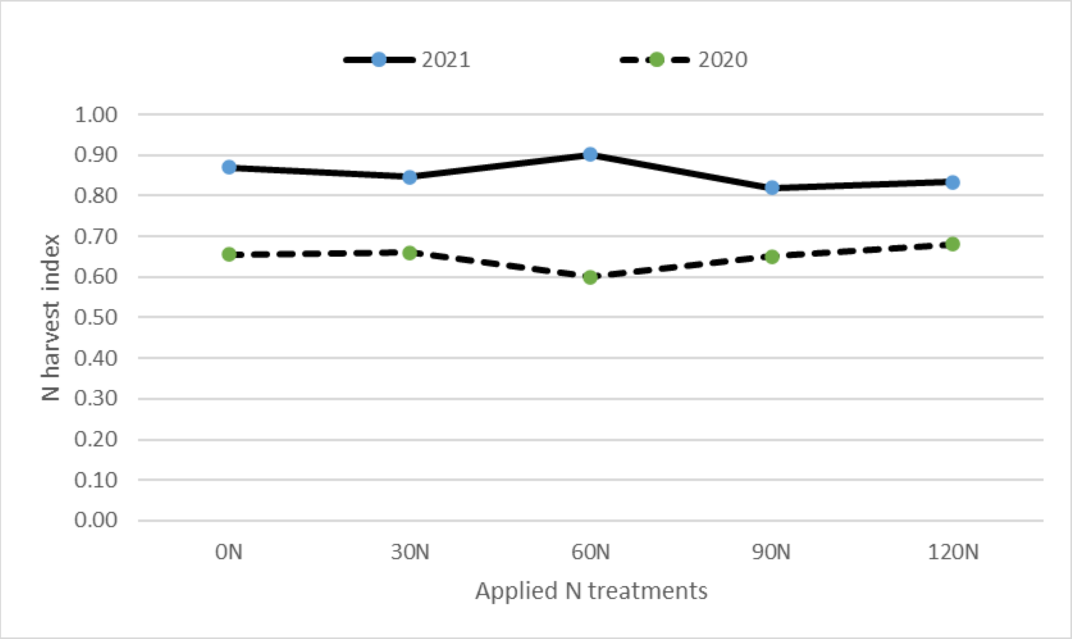

Figure 2. Calculated N harvest index based on total N in biomass data and total N in grain data. This data was derived from laboratory analysis.

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. 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) will 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 replace by N_2 fixation, then the soil nitrate N balance will be negative (Table 2).

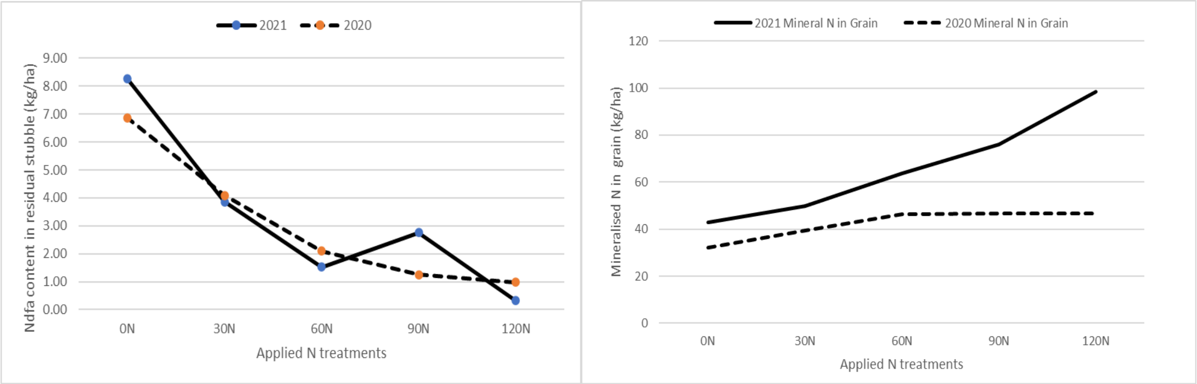

Figure 3. Calculated Ndfa% contained in stubble (left) based on Ndfa% in biomass and NHI. Calculated soil mineral nitrate N content in grain (right) based on Ndfa% in biomass and total N in grain.

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.

Table 2. Summary of N calculations in crop across increasing rates of N fertiliser treatments. Values from lab analysis include Ndfa(%) and total N in total dry matter (TDM), and grain N. Other figures are calculated from biomass and grain analysis. Data is an average of 2020 and 20221 trial data.

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*

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).

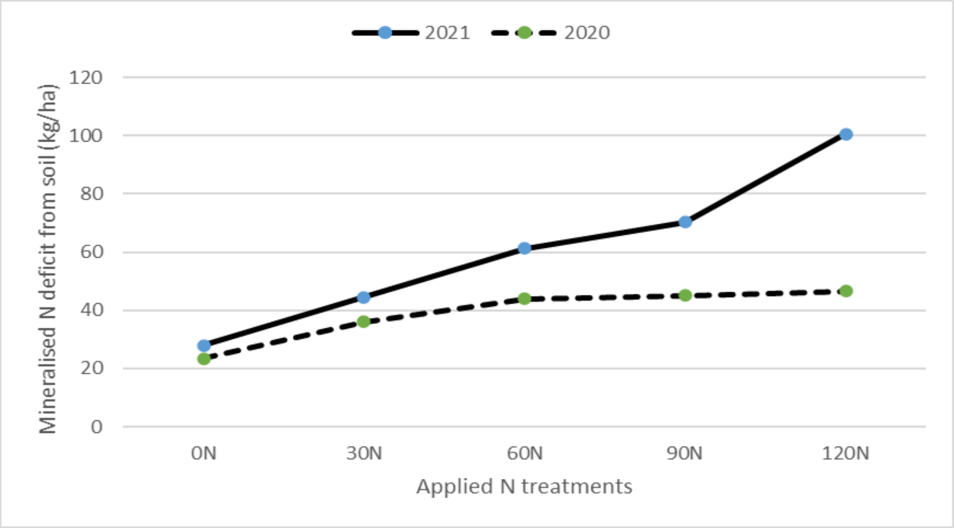

Figure 4. Calculated differences between mineral soil nitrate N contained in grain versus Ndfa contained in residual stubble. These differences create either a surplus or deficit in soil nitrate N pool.

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.

General 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 around how much of the root N is derived from atmosphere. This proportion of root N 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).

The recalculated data for soil nitrate N deficit (Figure 5), 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.

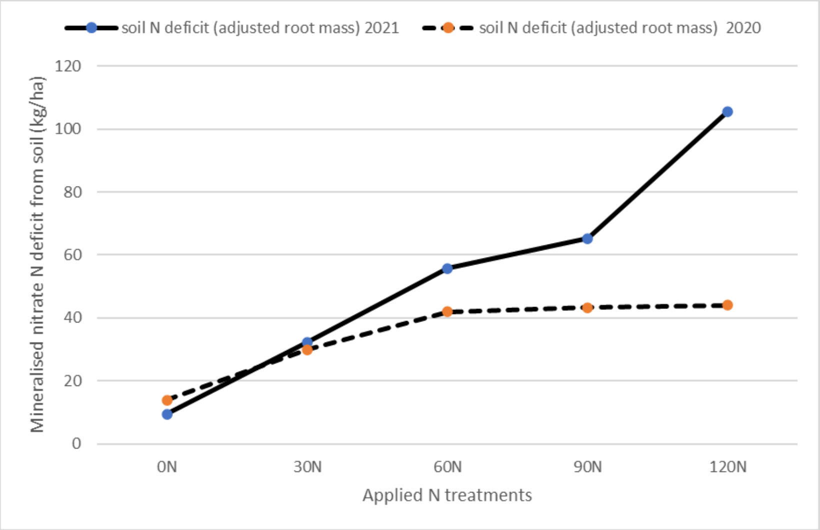

Figure 5. Recalculation of soil nitrate N deficits using the contribution of root mass to total Ndfa% content of the residual stubble. This data is based on a theoretical calculation that assumes that total nitrate N contained in the root mass of a pulse crop is 50% of the above ground biomass.

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.

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 extra treatments were used 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. Subsequently this has led to a lower Ndfa% (not shown) and a higher soil nitrate N deficit after the crop is harvested, using the same calculation process as previously described.

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

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 60cm 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 (Figure 6) shows that nearly 90% of the nitrates in the top 60cm 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 60cm 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 60cm (Figure 6) for the following crop. This long fallow situation (eight months) is not unusual in most CQ cropping systems.

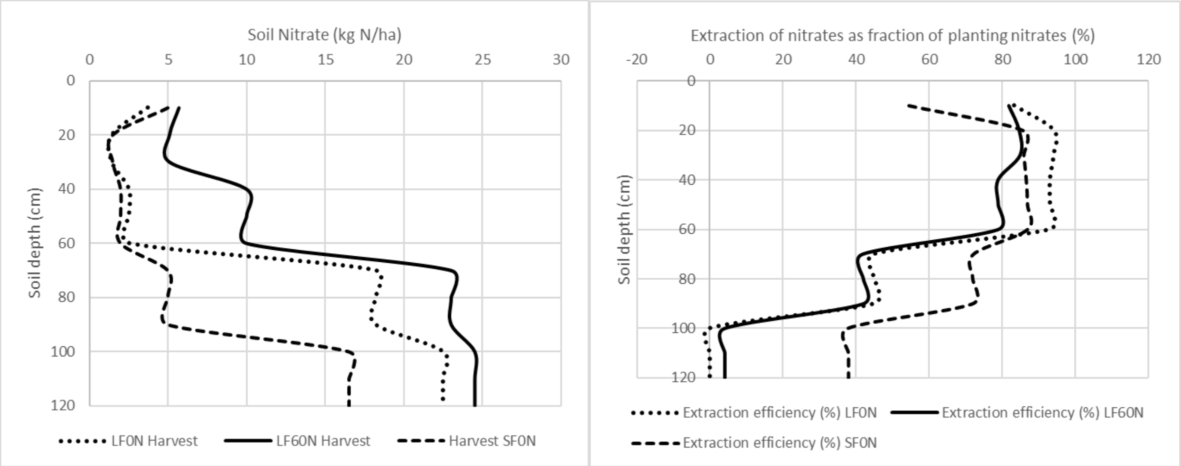

Figure 6. Soil nitrate N measured after harvest (left) and the proportion of soil nitrate N extracted from each layer between planting and harvest (right) of mungbeans in 2021 N response trial, comparing length of fallow.

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 ^{15}N 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 paper will concentrate on a confined data set.

Data extracted from the 24 August 2021 to 14 September 2023 in the *Higher nutrient supply* (see background description) has six soil testing intervals for soil nitrate N down to 90cm (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) in the space of 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 (60–90cm) is being underutilised until the wheat crop in 2023. It is therefore more useful to look at the changes on soil nitrate N in the top 60cm 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.

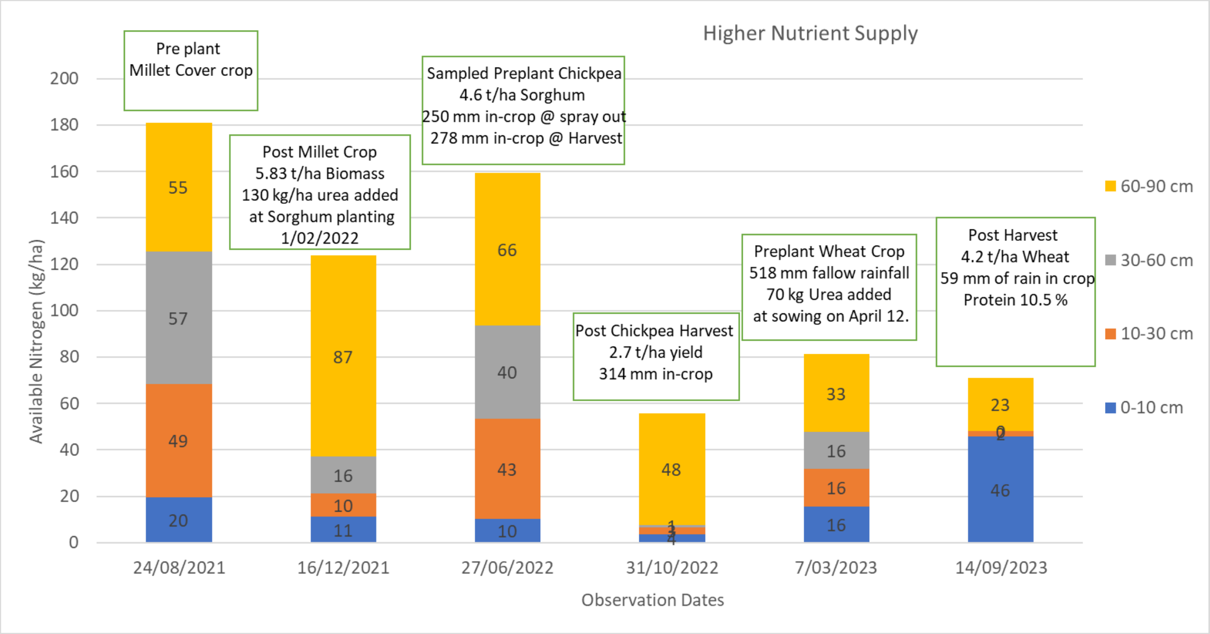

Figure 7. Soil nitrate N for the *Higher nutrient supply* treatment (M02) recorded by depth layer for each observation date. Included are details of urea application at planting, planting dates and rainfall totals. (*Source: Aisthorpe D (2023) unpublished.*)

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 0-90cm (kg/ha)	181	124	+60	159	56	81	+32	71
Accumulated Nitrate N 0-60cm (kg/ha)	126	37	+60	94	8	48	+32	48

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

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 60cm 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 60cm 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.

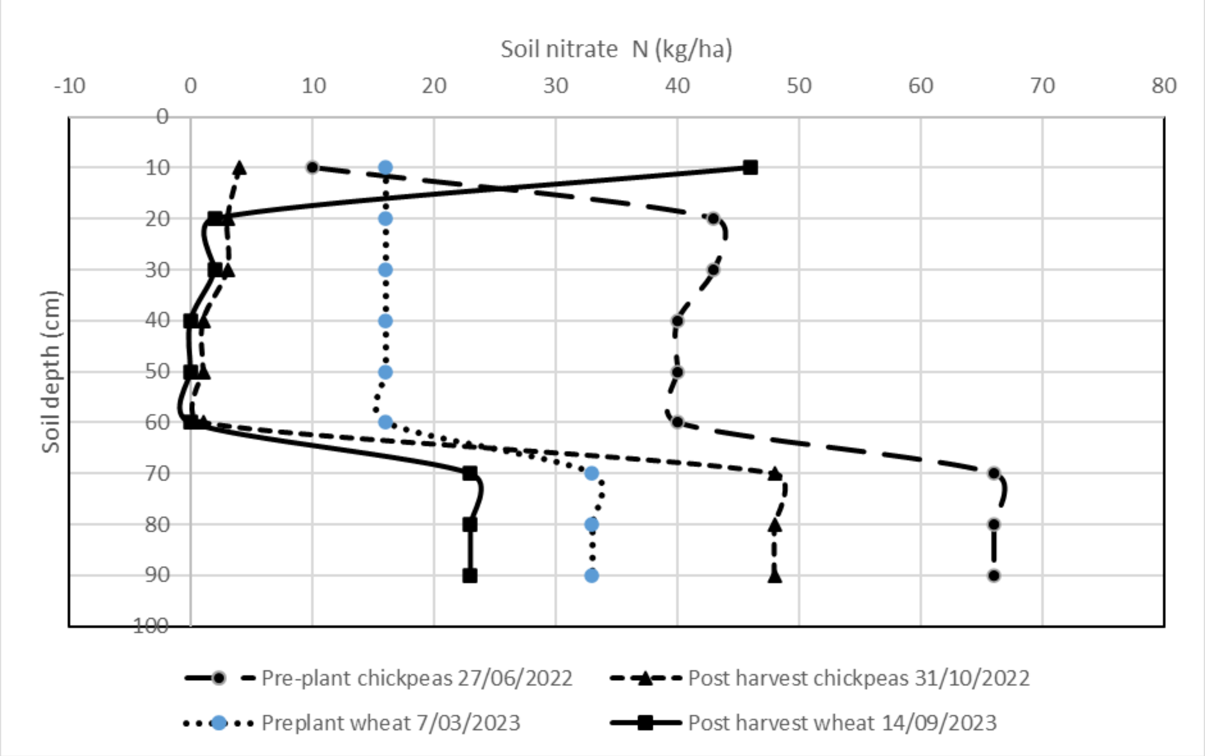

Figure 8. Comparison of the distribution of soil nitrate N in the profile at planting and harvest of chickpeas in 2022 and wheat in 2023.

The 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 518mm 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.

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 60cm of the profile.

Key outcomes 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 60cm of the profile before it 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 ^{15}N 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 60cm 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 in this paper 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.

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