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

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Take home messages

- Most farming systems extract more nutrients than are supplied by common fertilisation strategies
- Increasing the frequency of legumes doesn't necessarily reduce N inputs required across the crop sequence and increases export of potassium
- High yielding legume crops export more N and extract soil mineral N to a similar extent to cereals, often resulting in little additional mineral N for subsequent crops
- We found little difference in soil N extraction or subsequent mineralisation between various grain legumes, challenging assumptions that fababean or field pea provide greater N benefits to the farming system
- The high fertiliser application in the *higher nutrient* system (fertilising to crop yield potential) has maintained higher soil mineral N levels but has rarely increased grain yield or total system N use. Around 50% of additional N applied has remained available in the mineral N pool for subsequent crops
- Increasing crop intensity did not greatly increase nutrient export, but did increase fertiliser inputs across the farming system.

Introduction

While advances in agronomy and the performance of individual crops have helped grain growers to maintain their profitability, current farming systems are underperforming; with only 30% of the crop sequences in the northern grains region achieving 75% of their water limited yield potential.

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

"Can systems performance be improved by modifying farming systems in the northern region?"

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

Experiments were established at seven locations; a large factorial experiment managed by CSIRO at Pampas near Toowoomba, and locally relevant systems being studied at six regional centres by DAF and the DPI NSW (Emerald, Billa Billa, Mungindi, Spring Ridge, Narrabri and Trangie (red & grey soils)).

One of the central aspects of this research was to examine how farming systems compared in terms of their requirements for nutrient inputs and their long-term impacts on soil nutrient status and cycling. Several system modifications (described below) explicitly targeted increasing the nutrient efficiency and overall nutrient supply in the farming system to see how these would impact on system productivity and nutrient balance and use-efficiencies. In this paper we examine some of these key system comparisons to explore the following questions:

1. Will increasing the frequency of grain legumes lower the N fertiliser requirements or improve N utilisation in the crop sequence? How does this impact on other important nutrients?
2. What are the consequences of increasing fertiliser inputs to ensure crops maximise their yield potentials? How does this influence system nutrient cycling and balances?
3. What are the implications of increasing crop intensity for nutrient use and requirements?
4. How do different crops (legumes, cereals, others) impact on N cycling and accumulation for subsequent crops?

Farming system descriptions

The following paper focussed on system comparisons between the following systems being implemented across the range of farming systems experimental sites. The systems varied in the following ways from a *baseline* system at each location:

- ***Baseline*** – an approximation of common farming system practice in each district: dominant crops only used; sowing crops on a moderate soil water threshold to approximate common crop intensities (often 0.75-0.8 crops per year); and fertilising to median crop yield potential
- ***High crop intensity*** – increasing the proportion of time that crops are growing by reducing the soil water threshold required to trigger a planting opportunity (e.g. 30% full profile)
- ***High legume frequency*** – crop choice aims to have every second crop as a legume across the crop sequence and uses high biomass legumes (e.g. fababean) when possible
- ***High nutrient supply -*** increasing the fertiliser budget for each crop based on a 90% of yield potential rather than the baseline of 50% of yield potential.

Trial details

Sites were selected to represent a range of climatic conditions, soil types, nutritional status and paddock history. Each site was comprehensively soil tested at the beginning of the project. There is a considerable range in soil fertility across the sites (Table 1) which dramatically influenced the requirements for inputs of N fertilisers in particular at some sites (e.g. Billa Billa and Pampas) where high levels were present at the start of the experimental period.

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

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

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

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

Grain legumes are integral in current farming systems with areas consistently increasing. This increase in frequency of legumes has been due to several factors including high grain prices but also a belief that they improve soil fertility and reduce overall N fertiliser input costs. Here we compare the impact of increasing the frequency of legumes on the N inputs, exports, and total system N use compared the baseline system. It is important to note here that as the project only has four years of data all these systems have only planted 1 or 2 extra legume crop compared to the baseline.

Higher legume systems exported more N from the system in grain than the baseline systems in 8 out of the 11 comparisons across the farming system sites (Table 2). On average across all sites the high legume sequences exported an additional 30 kg of N from the system (ranging from 78 to -7 kg/ha). The higher legume system showed mixed results in relation to reducing the amount of N fertiliser required for a cropping system (Table 2). For example, the higher legume system reduced nutrient inputs at some sites, such as Emerald which reduced the total N fertiliser requirement by 83 kg N/ha compared to the baseline system. While at Trangie (grey soil) and Pampas, the higher legume system actually increased N fertiliser required in subsequent crops by 25 kg N/ha compared to the local baseline system. Altogether across all sites there was little saving in the N inputs used in cropping systems employing higher frequencies of grain legumes. This was also reflected in the total system N use (soil mineral N depletion plus fertiliser N inputs) over the 3.5 years of cropping systems employed so far. Only 6 of the 11 higher legume systems reduced total N use compared to the baseline system, with the largest reduction of 88 kg at Emerald. However, the other sites recorded higher total N use from the legume system.

Overall these results indicate that across our farming systems experiments the implementation of additional legume crops in the crop sequence has had little positive benefit on reducing N fertiliser input needs or reducing soil N use. The legumes are utilising soil mineral N to the same extent as cereal crops and have higher N export which offsets N fixation inputs. Also notable is that this result is consistent across the full range of starting soil N conditions, from locations with very high starting mineral N status to locations with low mineral N status where legumes would require to fix N to meet their needs. These results significantly challenge the common held assumption that grain legumes will have benefits for reducing N fertiliser needs in the crop sequence. As our capacity to grow high yielding grain legumes has increased as has our harvest index and hence the ratio of N removed in grain to that left in biomass, thereby diminishing the contributions of residual N after the crop.

Table 2. Cumulative nitrogen dynamics for the *baseline and higher legume* systems at 11 sites (Northern grains region) between 2015 and 2018

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

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

How does increasing legume frequency impact on soil phosphorus and potassium export?

Phosphorous export has been variable across sites, with some higher legume systems exporting more and some less compared to baseline (Table 3). However, the higher legume system did increase the amount of potassium exported on average across all sites relative to the baseline system (14 kg K/ha). Pampas (mixed) had the greatest amount of exported potassium, a total of 31 kg K/ha from 2015 to 2018. Although this is not unexpected as legume seed has more than double the K content than cereal grains, K levels will need to be monitored to ensure the system does not cause deficiencies for future crops. In situations where K deficiency may be an emerging issue or where levels are marginal, this greater export under a higher legume system may mean that nutrients need to be replaced sooner or a higher level of replacement will be required.

Longer term trends of underlying fertility will be assessed with further collection of soils and benchmarking these results in 2019 against the initial baseline levels that were measured at the start of the project.

Table 3. Cumulative phosphorus and potassium removal of the higher legume systems at 11 sites in the northern grains region (2015 – 2018)

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

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

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

With declining soil fertility across the northern region there is increasing interest in identifying ways to either halt or reverse this trend. Past research suggests that maximising biomass production is one way to achieve this; more biomass will increase soil organic matter levels which will build the natural supply of nutrients such as N and P. To maximise biomass production, supplying adequate crop nutrition is critical, along with providing nutrients to promote soil microbial processes.

The capacity to address nutrient depletion and increase crop biomass and yield potential under favourable conditions was investigated, by implementing a system that increases nutrient supply budgets to target 90th percentile yield (higher nutrient) compared to only 50th percentile yields in the baseline.

As predicated the higher nutrient system increased the amount of N fertiliser applied at each site over the cropping sequence. On average across all sites an extra 83 kg N/ha was applied between 2015 and 2018 relative to the baseline system. The additional N increased N export at seven of the eleven sites. This was most significant at Trangie (red soil), which exported 49 kg N/ha more than the baseline system (Table 4). It is interesting to note that this site had the lowest starting mineral N levels, resulting in the highest N application rates during the first four years of the project.

The additional N that was applied in the higher nutrient system reduced the depletion of background soil mineral N status at ten of the sites. On average across all sites the higher nutrient system had 43 kg more soil mineral N at last sampling than the baseline – meaning about 55% of the additional N applied was found in the mineral N pool at this time or we are recovering about 55% of the additional previous N applications in subsequent years. However, this recovery % varied greatly across the sites, ranging from full recovery (e.g. Billa Billa, Pampas summer rotations) to low recovery of less than 10% (e.g. Mungindi and Pampas winter rotations). This value is likely to be highly dependent on the timing of sampling influenced by the previous crop, residue loads and types, and soil moisture conditions.

These results show that applying N fertiliser to aim for a 90th percentile yield potential may reduce the mining of soil available N, especially in soils with high fertility (such as Billa Billa) and that significant amounts of additional N applied remains in the mineral N pool and is available in subsequent crops. To confirm this, longer term trends of underlying soil fertility such as organic carbon or total N pools will need to be assessed.

Table 4. Cumulative nitrogen export, inputs in fertiliser, depletion of the soil mineral N pool (starting soil N – final soil N) and total system N use (soil mineral N use + applied N) between the higher nutrient and baseline system at 11 sites in northern grain region (2015 – 2018)

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

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

The additional P applied to the higher nutrient system did not influence grain P export across the first four seasons in the Farming System project, as sites resulted in minor variances between the higher nutrient and baseline systems. Similarly, there was no difference between K export of the higher nutrient systems and the baseline systems at the eleven sites in the northern grains region, as we did not see significant yield responses to the higher nutrient application strategies.

Table 5. Cumulative phosphorous and potassium removal and phosphorus inputs from the higher nutrient system and the baseline system across northern farming systems experiments (2015 – 2018)

Site	P export (kg/ha)		Applied fertiliser P (kg N/ha)		K export (kg K/ha)	
	Baseline	Higher nutrient	Baseline	Higher nutrient	Baseline	Higher nutrient
Billa Billa	41	42	27	66	57	58
Emerald	29	32	22	35	56	60
Mungindi	12	11	7	22	24	20
Narrabri	26	24	24	33	42	42
Spring Ridge	32	31	33	33	53	54
Trangie (grey soil)	15	13	35	35	19	16
Trangie (red soil)	17	21	35	35	23	29
Pampas (mod intensity)	37	39	23	34	53	56
Pampas (high intensity)	41	41	25	46	59	61
Pampas (summer)	40	40	21	31	45	46
Pampas (winter)	40	38	18	39	66	64

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

What are the implications of increasing crop intensity for nutrient use and requirements?

The Northern region farming system is centred on growing crops mainly on stored soil moisture. With very low fallow efficiencies, the belief is often, “use it or lose it”. However, the grains industry are often unsure the impact a higher crop intensity cropping system has on underlying soil fertility. The question is often asked, “will growing more crops improve or reduce soil fertility?” So far across the various farming systems sites, four have significantly increased the cropping intensity compared to the baseline crop sequence (Billa Billa, Emerald, Pampas). The NSW sites (Narrabri and Spring Ridge) did not meet water thresholds to trigger planting additional crops. They were fertilised with the same regime as *baseline* i.e. 50th yield potential.

Although Billa Billa, Emerald and Pampas did grow extra crops between 2015 and 2018, there was no increase in cumulative grain yield and thus N, P and K export was actually lower or similar across the three sites between the higher intensity and the baseline systems (Table 6).

At Pampas the higher intensity system had an additional 88 kg N/ha applied to the cropping sequence compared to the baseline (Table 6), but the cumulative exported N was lower by 22 kg N/ha. Interestingly the higher intensity system at Pampas resulted in a reduction of 37 kg N/ha mineral N more than the baseline system. This means that the extra crop produced at Pampas resulted in a loss of 137 kg N/ha (of plant available N) from the system, while the baseline system increased mineral N by 10 kg N/ha. It is unclear where this N has ended up, but it is possible this has been accumulated in the soil carbon pool. Analysis of soil carbon levels and the completion of additional seasons will help to answer the impact cropping intensity has on soil fertility.

Table 6. Cumulative nitrogen dynamics of the higher intensity and baseline systems at 3 sites in northern grains region (2015 – 2018)

Site	N export (kg/ha)		Applied fertiliser N (kg N/ha)		Mineral N change (kg N/ha)		Total system N use (kg N/ha)	
	Baseline	Higher intensity	Baseline	Higher intensity	Baseline	Higher intensity	Baseline	Higher intensity
Billa Billa	220	195	12	13	249	220	261	233
Emerald	227	211	91	94	52	30	143	124
Pampas	271	249	13	101	248	285	261	385

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

Table 7. Cumulative phosphorus and potassium removal from the higher intensity and baseline systems at 3 sites in the northern grains region (2015 – 2018)

Site	P export (kg/ha)		Applied fertiliser P (kg N/ha)		K export (kg K/ha)	
	Baseline	Higher intensity	Baseline	Higher intensity	Baseline	Higher intensity
Billa Billa	41	31	27	29	57	40
Emerald	29	29	22	29	56	43
Pampas	37	41	23	25	53	59

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

How do different crops impact on N cycling and fallow accumulation?

Grain legumes fix N and are renowned for increasing mineralisation during the subsequent fallow period prior to the next crop. Also some legumes are thought to be more efficient at doing this than others (e.g. fababean provides more N benefit than chickpea). The diversity of crops grown across various sites in this project provides an opportunity to compare the mineral N dynamics in-crop and also in the fallow period after harvest for various crop types across multiple seasons.

In three of four comparisons between chickpea and wheat that were grown in the same season (Emerald 2015 and 2016, Pampas 2016) we did not observe any additional N accumulation after chickpea compared to wheat and had the same mineral N available for subsequent crops. There may have been a small amount of extra N at the end of the chickpea crop but this was often associated with a higher N at sowing and hence crop N extraction was similar or in some cases higher. For example at Emerald in 2016, chickpea utilised 130 kg N/ha from the soil mineral pool compared to 114 kg N/ha for wheat. The one exception across these comparisons was during a long-fallow at Pampas after winter crops in 2015. This showed that following chickpea accumulated an additional 38 kg of N accumulated compared to wheat, but owing to lower soil N at harvest there was still actually less mineral N available following chickpea than wheat.

A further comparison of mineral N dynamics between different legumes grown in the same season occurred across 3 locations (Narrabri and Spring Ridge in 2016, Pampas 2015). These results show very little significant difference between the various legumes in N utilisation, and accumulation during the subsequent fallow.

While these results suggest there has been little N benefit for subsequent crops following grain legumes across sites, because mineral N status is affected by mineralisation rates, denitrification, and microbial tie-up, it may be that these crops may provide additional N supply in the subsequent crops. This does raise questions about the commonly held belief that legumes will provide N benefits for subsequent crops and that some legumes are better than others. More seasons and sites may be required to more fully understand this.

Table 8. Comparisons of crop effects on soil N use and subsequent fallow N accumulation across multiple sites and seasons in the northern grains region

Site Season	Crop	Sowing mineral N (kg N/ha)	Harvest mineral N (kg N/ha)	End of fallow mineral N (kg N/ha)	Subsequent fallow mineral N accumulation (kg N/ha)
Emerald 2015					
	Wheat	105	59	153	94
	Chickpea	78	32	126	94
Emerald 2016					
	Wheat	126	12	114	102
	Chickpea	153	23	141	118
Narrabri 2016					
	Chickpea	69	38	43	5
	Fieldpea	86	41	49	8
	Fababean	77	41	38	-3
Spring Ridge 2016					
	Chickpea	157	173	277	105
	Fieldpea	169	156	248	92
	Fababean	160	154	237	84
Pampas 2015 – long fallow					
	Wheat	184	117	179	62
	Fababean	186	58	153	97
	Chickpea	203	68	168	100
	Field pea	190	94	217	123
	Canola	186	93	183	90
Pampas 2016 – short fallow					
	Wheat	83	17	61	44
	Chickpea	93	34	76	42

Discussion

The first four years of the farming system project showed that modifying crop systems through higher nutrients, higher intensity and the higher frequency of legumes provided limited benefits for improving nutrient status relative to localised growers practice (baseline). Only when higher nutrients were provided did we manage to balance the net export of all nutrients (N, P, K) relative to the inputs in several cases. However, there have been few cases where we have seen a positive yield advantage from providing these additional nutrients. However as soils age and their inherent fertility declines this may change.

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

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

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