Farming system nutrient legacies – impacts of N strategies on N inputs, cycling and recovery over multiple years

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Take home messages

- Soil mineral N and fertility status has a long-term influence on productivity of a farming system
- Robust N application strategies have legacies of building/maintaining higher soil N status beyond the immediate crop
- Fertilising crops to maximum compared to average yield potential (approx. double N budget) has only required an average of 100 kg of N/ha extra applied over 6 years
- A high proportion of surplus N is recycled or recovered in the soil mineral N pool and is available in subsequent crops
- Robust nutrient strategies have incurred additional costs ($134/ha over 6 years on average), but much of this is 'invested' in soil mineral N stores ($75/ha)
- Only in above median seasons, when crops are responsive to high N rates will economic benefits accrue, but these can be significant.

Introduction

Nitrogen (N) inputs is a major variable cost in most cropping systems and matching the supply to crop demand is critical to maximising water use efficiency and system profitability. Hence, developing a nutrient management strategy that provides sufficient N when crops need it whilst also mitigating the risk of losses to the environment is critical. This problem has been the focus of a plethora of research, with well tested and refined recommendations available to optimise fertiliser applications to individual crops (Angus and Grace 2017). However, nutrient budgeting and evaluation of nutrient use efficiencies has typically taken a crop-by-crop approach, which often overlooks some of the legacy impacts that can occur. For example, a crop provided with N surplus to its requirements often have low NUE and return on investment in that year because the extra N provided was not converted into grain yield; this often occurs in dry seasons. However, the unused N from that crop can contribute significantly to the N supply in subsequent years and may even be used more effectively by the next crop than fertiliser applied in that season (Dowling 2018). Hence, there is a need to take a longer-term more systematic view of N application approaches or strategies.

In the northern farming systems research project, we have been comparing 2 main fertiliser N management approaches over several years. We have tracked the dynamics of N over multiple seasons and how these fertiliser strategies have impacted nutrient input requirements, N utilisation and cycling, and overall system nutrient use efficiency.

System N management strategies deployed

Across the various farming systems experiments we have been deploying two different strategies to apply N fertiliser to crops – a *Baseline* (or standard approach) and a *High Nutrient* system. Both systems have employed the same sequence of crops and have varied only in their fertiliser inputs. A range of yield predictions were generated using APSIM for the specific location, crop sowing date and soil water content at sowing (see Figure 1).

In the *Baseline* system, crops were fertilised to a nutrient budget targeting a predicted yield in the 50^{th} percentile of seasons. That is, adequate N is applied for the crop to reach its yield potential in half of seasons (or an average yield outcome), while in seasons with higher yield potentials it is possible that the crop may not have sufficient N supply to meet its water-limited yield potential.

In the *High Nutrient* systems, crops were fertilised to a nutrient budget targeting a predicted yield in the 90^{th} percentile of seasons. That is, the crops are fertilised so that they should never be limited by nutrient availability in any season, but this means that the crops are 'over-fertilised' in all but the best seasons.

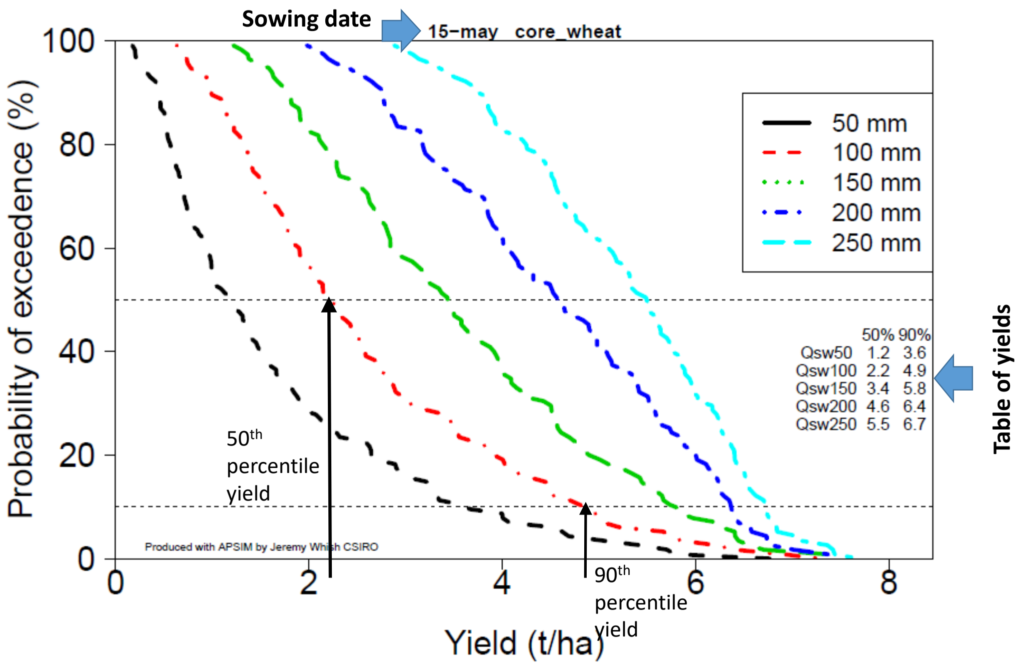

Figure 1. APSIM predictions of wheat yield probabilities with different starting soil water levels (50, 100, 150, 200 and 250 mm plant-available water). For 100 mm PAW at sowing (indicated by red line), the yield predictions for a 50^{th} percentile season and a 90^{th} percentile season are shown; these are used to calculate the N budgets for the crop.

The crop N budgets are determined prior to sowing of every non-legume crop from the predicted yield using well established N requirement calculations. An example for wheat is below (Equation 1). So, for the example crop situation above in Figure 1, this would equate to a crop N fertiliser budget of 83 kg N/ha in the *Baseline* system and 185 kg N/ha in the *High Nutrient* system.

Equation 1 - Wheat $_{N\ budget}$ ***= Predicted yield (t/ha) x 12 (% protein) x 1.75 x 1.8***

Prior to each crop, the amount of fertiliser N to be applied was determined by deducting the amount of soil mineral N available in the top 90 cm of the soil profile from the total crop budget (Equation 2). Hence, if there was sufficient mineral N available in the soil to meet the crop demand, then no synthetic N fertiliser was applied (other than starter to provide other nutrients). This method also did not assume or account for additional in-crop N mineralisation or adjust this based on crop history (e.g., following legumes). In the experimental locations in Queensland, all the fertiliser N was applied at sowing, while in NSW locations a portion (up to 50%) was applied in-crop at the start of stem elongation.

Equation 2 - N to be applied = Crop $_{Nbudget}$ – Soil mineral N (0-90cm)

N inputs and export from systems

Over the various experimental locations there has been a large difference in the amount of applied N fertiliser across the 6 experimental years (Table 1). This is due to significant differences in the natural fertility and background starting N status at the sites. For example, the Billa Billa site was relatively new country and was only recently brought into crop production. This site had over 400 kg of mineral N in the soil profile at the outset of the experiments. No N fertiliser was applied to meet the annual crop budget for the first 5 years while this background N was exploited; only a small amount of N associated with starter fertilisers has been applied. Other sites have received significant N inputs of over 200 kg N/ha over the 6 years, but these application rates are still only 30-40 kg/ha/yr. over the life of the experiment (close to long-term averages nationally).

Despite the significantly different approach to crop N budgeting resulting in typically double the N budget in the *High Nutrient* system compared to the *Baseline*, when balanced over several years and the whole crop sequence this rarely translated into dramatically higher N inputs applied. The extra N applied over the whole 6 years was on average 100 kg/ha of extra N, or only 17 kg N/ha/yr., over the 6 years higher across all sites in the *High Nutrient* strategy. The difference ranged from only an extra 9 kg/ha at Emerald to 260 kg/ha at the Trangie – red soil site, with the larger differences accumulating at sites where the soil fertility or N cycling was lower.

Table 1. Total fertiliser N applied over 6 years of experiments across 11 farming system comparisons spanning the northern region between different N budgeting strategies: *Baseline* (Budget to 50th percentile yield prediction) and the *High Nutrient* (budget to a 90th percentile yield prediction).

Site comparison	Applied N (kg N/ha)			Exported N (kg N/ha)			System N balance		
	Base	High N	Extra	Base	High N	Extra	Base	High N	Diff
Emerald	51	60	9	399	411	12	-348	-351	-3
Billa Billa	17	77	60	344	378	34	-327	-301	26
Narrabri	205	442	237	270	268	-2	-65	174	239
Mungindi	70	154	84	178	193	15	-108	-39	69
Spring Ridge	234	304	70	377	393	16	-143	-89	54
Trangie – Red soil	137	396	259	297	384	87	-160	12	172
Trangie – Grey soil	63	139	76	289	284	-5	-226	-115	111
Pampas Mixed	50	152	102	435	453	18	-385	-301	84
Pampas - Summer	85	127	42	389	379	-10	-304	-252	52
Pampas - Winter	45	104	59	400	396	-4	-355	-292	63
Pampas - High inten.	138	274	136	420	422	2	-282	-148	134
AVERAGE			**103**			**15**			**91**

The *High Nutrient* strategy has not resulted in significantly higher exported N in any of the systems except Trangie on the red soil. This is largely because we have not seen any significant yield increases due to the higher N applications at any of the other sites (discussed further below). However, what can be seen is that across all sites the *Baseline* system is still exporting more N than is being applied. The *High Nutrient* strategy is maintaining a positive or neutral balance at several sites, but at sites with higher natural fertility (e.g., Billa Billa, Emerald or Pampas) the soil continues to meet most crop demand and provide most of the N inputs in the system even under a robust N fertilisation approach.

Crop responses to nutrient strategies

As mentioned above there have been few cases amongst these experiments where the higher nutrient application approach has resulted in a significant yield or protein increases. This is largely because of the below-average seasonal rainfall conditions across most of the seasons in these experiments, and hence the yields and crop demand for N has rarely exceeded the N available in the *Baseline* system. This occurred only at Trangie on a red soil in the wet and high yielding winter of 2016, where we saw a 1.2 t/ha yield increase and a grain protein difference (14.4% vs 11.8%) in the *High Nutrient* system. This highlights that the higher nutrient application approach is only likely to bring about significant yield gains in seasons with high yielding conditions, otherwise the *Baseline* provides sufficient nutrition.

In a couple of situations, we have seen a small reduction in grain yield associated with the *High Nutrient* strategy, where crops produced more vegetative biomass which is likely to have induced more severe water stress during dry grain filling periods. For example, at Mungindi in 2015 we saw a wheat yield reduction of 0.3 t/ha from the *High nutrient* application (50 vs 130 kg of N applied at sowing), but grain protein was higher in the *High nutrient* system (13.1% vs 8.8%).

Recycling and recovery of N

Because in most seasons we have provided N fertiliser in surplus to the requirement of the crop, it is critical to understand the proportion of fertiliser that is still available in the soil. On average across the various cereal crops, we have recovered 80% of the additional N applied at the post-harvest soil sampling after that crop. That is, most of the additional N available at sowing (from both fertiliser applied and starting mineral N) was still present in the soil mineral N pool when soil was sampled after crops were harvested. This value has varied from about 60-100% in most situations but has been lower particularly where crops grew more biomass with the higher nutrient applications but have not converted this to grain yield. In many seasons we have also observed additional N mineralisation in subsequent fallows in the higher nutrient systems.

In Figure 2 we show for 3 different sites the mineral soil N status and the accumulated N applications in the *Baseline* and *High Nutrient* systems. This demonstrates how N applications can have a long legacy in our farming systems. For example, at the Pampas site the legacy of the higher N application in October 2016 can be seen in the subsequent soil mineral N, meaning that the subsequent crop sown did not require additional N fertiliser inputs to satisfy the higher nutrient budget. The additional fertiliser applied in October 2018 sorghum crop is still available in the soil profile 2 years later in 2020. These legacies can take time to become clear, as is shown at Mungindi (Figure 2, bottom). Here, the only additional fertiliser application was made in Jun 2015, and this additional N was taken up by that crop. However, this was not recycled into the system until the fallow between December 2016 and March 2018, after which the difference in soil mineral N has been maintained.

Hence, over the long term a large proportion of the applied N is recovered again in the system, becoming available for use in subsequent crops. This recovery and recycling has been the main reason why the *High Nutrient* system has not required large additional inputs of fertilisers, because residual N from previous applications is contributing to the budget in subsequent years and hence offsetting the need for additional fertilisers.

At the last sampling across almost all sites, the *High Nutrient* system has between 25 and 100 kg of additional mineral N available in the soil profile compared to the *Baseline* system (Table 2). If you account for this current difference in soil mineral N and any additional export of N in grain from the

High Nutrient systems compared to the *Baseline*, we have recovered on average 85% of the additional fertiliser N applied in the systems (Table 2). At some locations our calculations suggest this value is over 100, which is an indication of other inputs of N, such as from legume fixation, increased mineralisation of soil organic matter in those systems, and/or the variability in measuring soil N. Importantly, these recovery figures do not include the nitrogen in organic form and if there was any increased soil organic matter in those systems.

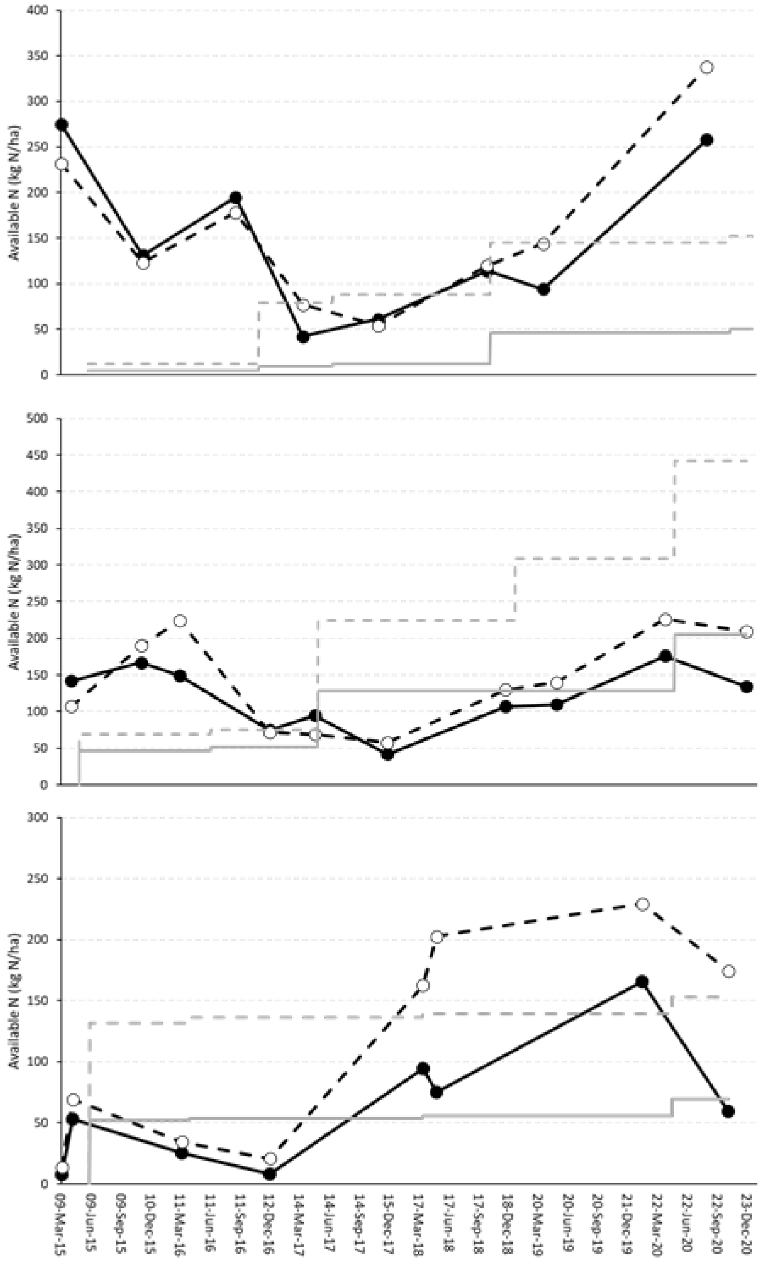

Figure 2. Changes in soil mineral N availability (Black lines - kg N/ha to 90 cm depth) and accumulated fertiliser N applied (grey lines) between *Baseline* (solid) and *High Nutrient* (dotted) systems at Pampas (top), Narrabri (middle) and Mungindi (bottom) over 6 years of experiments.

Table 2. Difference between *High Nutrient* compared to the *Baseline* fertiliser strategy in terms of soil mineral N status (at last sampling), recovery of additional fertiliser N applied (either present in the soil mineral pool or exported by crops), costs of additional fertilisers applied (over 6 years), the total relative economic position of the two systems after 6 years when either excluding or including the differences in most recent soil mineral N status.

Site comparison	Difference in change in soil mineral N at last sampling	Recovery of additional N applied	Cost of extra N fertilisers applied ($/ha)	Net benefit or cost excl. soil N ($/ha)	Net benefit or cost incl. soil N ($/ha)
Emerald	25	na	12	276	309
Billa Billa	47	135%	78	-214	-153
Narrabri	109	45%	308	-703	-561
Mungindi	99	136%	109	-201	-72
Spring Ridge	30	66%	91	-141	-102
Trangie – Red soil	31	46%	337	354	394
Trangie – Grey soil	36	41%	99	-662	-615
Pampas Mixed	123	138%	133	-85	75
Pampas Summer	89	188%	55	-76	40
Pampas Winter	4	0%	77	-442	-437
Pampas High intensity	38	29%	177	-321	-272
AVERAGE	**57**	**82%**	**134**	**-201**	**-127**

Return on investment from N strategies

Over the 6 years, the *High Nutrient* systems have incurred additional costs associated with the higher inputs of N fertilisers applied. While this value has varied between sites, depending on their inherent fertility, on average this has equated to $134/ha, or $22/ha/yr. difference in the costs incurred (noting we have assumed a fertiliser price of $1.30 per kg N). As mentioned earlier, rarely has there been a significant yield increase, and in some cases, some risks of yield penalties occurred. Only at Trangie on the red soil can we see an additional $354/ha has been generated. Across all sites on average the *High Nutrient* systems are around $200/ha behind the *Baseline* in terms of gross margin accumulated over the 6 years. However, if the additional fertiliser that has been invested into the soil mineral N pool is valued in these calculations this net cost is reduced to $127/ha or $21/ha/yr.

Conclusions

Over the experimental years we have been comparing the N strategies in the farming systems we have not had sufficiently favourable conditions to see significant grain yield increases. We have seen crop biomass increases from the additional N inputs, but this has not been converted into grain yield. Only time will tell how the expected higher returns in good seasons will change the long-term profitability and return on investment from this strategy. Regardless, this farming system strategy is likely to play out over the longer-term by maintaining the soils fertility, or lowering the net export of nutrients, and maintaining soil mineral N at a level that ensures crops have the nutrition available to utilise the better years. Ultimately our data shows that the *High Nutrient* strategy does not have a huge cost or risk to the farming system, with a high proportion of the extra N applied being recovered in subsequent years and potentially offsetting subsequent N applications. However, when conducting crop N budgets, it is critical to account for the current mineral N status which accounts for N recycling to avoid wasting unneeded fertiliser.

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References

Angus, J and Grace, P (2017) Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. Soil Research 55:435-450.

Dowling, C (2018) Nitrogen Management. A seasonal journey with many routes and destinations. GRDC Updates, https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/12/nitrogen-management.-a-seasonal-journey-with-many-routes-and-destinations

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