Lessons learnt about nitrogen and phosphorus from a 30 year study in a sub-tropical continuous cropping system on a vertosol

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Abstract
*A nitrogen (0, 40, 8*0 & 120 kgN/ha) x phosphorus (0, 5 (15 pre-1999), 10 & 20 kgP/ha) cropping rotation experiment was established on the central Darling Downs property "Colonsay" in 1985. In this time 23 grain crops were harvested along with 3 failed crops. The unfertilised control (0N:0P) produced 69.7 t/ha grain while 120 N:5(15)P gave maximum yield of 102.4 t/ha. Highest apparent fertiliser N recovery in grain of 48.5% was observed in response to 40N:10P which generated an additional 22 kg grain/kg applied N with an N balance of -511kgN/ha when compared with 0N:10P. Similar grain N recovery was reported for 80N:10P, but with a near neutral N balance of -24 kgN/ha. Maximum grain production in response to P was reported in the 80N:10P treatment with an extra 47.1 kg grain/kg applied P when compared with 80N:0P. 80N:10P gave a P deficit of -79 kgP/ha, with replacement P rate estimated at 13-14 kgP/ha/crop. A simple economic comparison with the unfertilised control 0N:0P, reveals maximum net return of $4,095/ha at 80N:5(15)P with a net loss of $1,026/ha for the 0N:10P treatment (grain @ $220/tonne farm gate, N @ $1.30/kg & P @ $3.50/kg). The addition of "replacement" rates of P where adequate N was applied increased net returns by more than $1,500/ha compared with no P application. The replacement P strategy maintained soil P levels at or above recognised critical levels.

Key words
Long term, Darling Downs, nutrient efficiency, economics

Introduction
Understanding the long term interaction between fertiliser N and P in southern Queensland is critical to optimising nutrient efficiency given evidence that optimal production and financial outcomes can be achieved with a "replacement" strategy. In contrast, departure from this strategy can result in adverse agronomic and financial outcomes impacting soil quality and yield potential. Agronomists and growers can deploy this information to retain more N in the system and to optimise P strategies over time.

Methods
The "Colonsay" experiment was established in 1985 as a factorial combination of four nitrogen (N) rates (0, 40, 80 and 120 kg/ha) at each of four phosphorus (P) rates (0, 5 (15 pre-1999)10, 20 kg/ha) with three replicates in randomised complete blocks. Further experimental details can be found in Lester (2012). The 5 kg P treatment commenced in 1999-00 on plots previously treated with 15 kgP/ha. As a result cumulative nutrient application from 1985-2013 comprised:

- 60, 940, 1,820 & 2,700 kgN/ha for 0, 40, 80 & 120N treatments n.b. 60 kgN/ha applied across all plots in 1991/92
- 0, 245, 230 & 460 kgP/ha for 0, 5(15), 10 & 20P treatments

To date 23 grain crops (12 sorghum, 6 wheat, 4 barley, 1 maize) have been harvested with another 3 crops (2 chickpea, 1 sorghum) unharvested due to crop failure.

Table 1. Soil chemical characteristics at "Colonsay", in Autumn 1985 (Lester 2012).

	0-0.1 m	0.1-0.6 m
$pH_{1:5}$ (H_2O)	8.5	9.0
Colwell P (mg/kg)	10	3
BSES P (mg/kg)	61	50
Nitrate N (mg/kg)	2.5	1.4

For this study the following calculations were adapted to gauge differences in nutrient efficiency:

(a) Apparent fertiliser N recovery in grain:

$$\frac{\text{Cumulative grain N (treatment) – cumulative grain N (0N)}}{\text{Cumulative N applied}}$$

(b) Additional grain production per kg additional N applied:

$$\frac{\text{Cumulative grain production (treatment) – cumulative grain production (0N)}}{\text{Cumulative N applied}}$$

(c) Nutrient balance:

Nutrient removed in grain – nutrient applied

Results and discussion

Production data, N efficiency and N balance

Table 2: Cumulative grain yield t/ha, [grain N uptake kg/ha], ***apparent fertiliser N recovery in grain*** **&** ***(additional grain production per kg additional N applied)*** **after 23 harvests at "Colonsay" 1985-2013**

N rate – kgN/ha/crop	P rate - kgP/ha/crop				
	0	10	5 (15)	20	Mean
0	69.7 [1,103]	68.7[1,024]	76.4 [1,175]	76.9 [1,195]	73.0 [1,124]
40	85.5 [1,489] *43.8% (16.8)*	88.0 [1,451] *48.5% (20.5)*	89.2 [1,432] *29.3% (13.6)*	90.9 [1,558] *41.3% (14.9)*	88.4 [1,483]
80	89.0 [1,633] *30.1% (10.6)*	99.8 [1,844] *46.6% (17.1)*	100.3 [1,820] *36.7% (13.1)*	99.9 [1,838] *36.6% (12.6)*	97.2 [1,784]
120	90.9 [1,715] *23.2% (7.8)*	96.1[1,845] *31.1% (10.1)*	102.4 ([1,921] *28.3% (9.6)*	100.3 [1,912] *27.2% (8.7)*	97.4 [1,848]
Mean	83.8 [1,485]	88.2 [1,541]	92.1 [1,587]	92.0 [1,626]	89.0 [1,560]
	N rate	P rate	N x P		
l.s.d	2.54 [51.08]	2.54 [51.08]	5.08 [102.17]	c.v. = 3.4%	
F pr	<0.001 [<0.001]	<0.001 [<0.001]	0.083[0.004]	[c.v. = 3.9%]	

As expected, the addition of P generated a significant yield response based on starting (10 mg/kg) and current (8.9 mg/kg) Colwell P levels in the 0P control. There was a yield response between 10P and 5(15)P of 3.9 t/ha which was not observed when additional N was applied at these P rates. When the dataset was broken into pre-1999 when the 5(15)P treatment was 15 kgP/ha and post-1999 when this treatment was lowered to 5 kgP/ha there remains a significant difference in cumulative yield. This warrants further analysis given the small difference in total P inputs between these two treatments over the duration of the experiment. N generated incremental yield responses up to 80 kgN/ha. At higher N rates (80 & 120 kgN/ha) P response was maximised whereas at lower N rates response to P was lower.

The significantly lower grain N uptake in the 0N/10P treatment in contrast with higher P rates gave higher calculated N recovery for both 40 & 80N at 10 P although the effect is less at 120N. Apparent fertiliser N recovery in grain can be allied to agronomic efficiency described by Dobermann (2007) who asserted that it was more suited as a short term indicator of the impact of applied nutrients on productivity. When N balance is considered it was noted that added N was used very efficiently in this system up to and including the 80N rate where N is in negative balance other than where no P was added. At 120N a surplus is observed which is not accounted for by either profile residual mineral N or elevated organic carbon levels suggesting leakage from the system through denitrification which may account for losses of 60-80 kgN/ha for each event (Schwenke et al 2014) and leaching of residual N with Turpin et al (1998) reporting losses of around 30% of fertiliser N in a zero till system on a well-structured Darling Downs vertosol. The significant N deficit at 0 and 40 N was not accounted for by soil NO_3-N levels and while it would be logical to conclude that this deficit was met by N mineralised from organic matter, this is not supported by the surface (0-10 cm) organic carbon data. The other possibility is that some of the N deficit was bridged by contributions from the two failed chickpea crops one of which grew significant dry matter but was terminated by flooding.

At the lower (40)N rate it was unclear whether the addition of P improved grain production per kg applied N as the 0N/10P treatment gave no improvement in yield while other P treatments provided yield increase at 0N. At higher N rates however it appeared that the addition of some P did improve grain yield per kgN applied. Typically incremental yield per kgN applied decreased as N rate increased implying greater partitioning of N to protein at higher N rates and leakage from the system at higher than optimum rates.

Table 3: N balance – the deficit / surplus of N (kg/ha), (profile NO_3-N 0-90 cm) and *surface organic carbon % 0-10 cm after 2013 crop*

N rate – kgN/ha/crop	P rate - kgP/ha/crop			
	0	10	5 (15)	20
0	-1043 (37) *0.85*	-964 (37) *0.77*	-1115 (39) *0.93*	-1135 (40) *0.82*
40	-549 (58) *0.74*	-511 (47) *0.94*	-492 (38) *0.74*	-618 (54) *0.87*
80	187 (95) *0.88*	-24 (39) *0.77*	0 (76) *0.93*	-18 (72) *0.86*
120	985 (189) *0.83*	855 (121) *0.85*	779 (103) *0.91*	788 (121) *0.83*

P efficiency

The addition of P at the 0N rate provided unexpected results – at 10P there was no yield increase suggesting that yield was held back by N deficiency, however at 5(15)P a significant increase in grain production per kgP was observed. It is postulated that the additional P provided in the 5(15)P treatment in the early phases of the trial may have driven higher initial plant N uptake which remained cycling through this system – this is supported by higher yields observed for the 0N/5(15)P treatment and higher soil organic carbon % implying greater dry matter production over the duration of the experiment for the 0N/5(15)P treatment compared with 0N/10P. This yield response was also consistent with surface Colwell P levels –based on the Better Fertiliser Decisions for cropping data base (Speirs et al 2013), the 0N/10P treatment was in the responsive range for wheat on a black vertosol (90% relative yield) while the 0N/5(15)P treatment was outside this range and at the upper limit for 95% of maximum yield. This difference was also consistent for DGT P with a responsive reading for 10P and a near critical reading for 5(15)P .Subsurface Colwell P (10-30 cm) appeared to be more depleted in the 5(15)P treatment implying greater root exploration with this treatment – this was also supported by BSES P levels in the subsurface layer. We conclude that higher initial P inputs supported greater subsurface root exploration driving more efficient accumulation of sub-surface N reserves which in turn generated increased dry matter and grain production in an N-limited scenario. This was supported by the significant N x P interaction observed for grain N uptake in table 2.

Additional grain production /kgP was maximised at 80 kgN/ha where a deficit of 79 and 66 kgP/ha was observed for the 10 and 5(15)P treatments implying that the optimum P rate would be around 13 – 14 kgP/ha/crop in order to balance P removal and also to maintain soil P levels at or above recognised critical levels. Given the nature of the system and the evidence of P stratification, careful thought needs to be given to how the future P program would be applied.

Table 4: P balance – the deficit / surplus of P (kg/ha) & [additional grain production per kg additional P applied]

N rate – kgN/ha/crop	P rate - kgP/ha/crop			
	0	10	5 (15)	20
0	-202	17 [-4.4]	8 [27.3]	206 [15.6]
40	-248	-43 [10.9]	-31 [14.9]	160 [11.7]
80	-258	-79 [47.1]	-66 [46.1]	130 [23.7]
120	-264	-68 [22.3]	-72 [46.8]	129 [20.4]

Economic analysis

An economic analysis was conducted for each treatment by assigning a gross farm gate value of grain production and subtracting the cost of nutrients applied. Four scenarios were modelled including low grain price with low nutrient cost, low grain price with high nutrient cost, high grain price with low nutrient cost and moderate grain price with moderate nutrient cost. Regardless, returns net of nutrient cost were optimised at 80N and 10 or 5(15)P. The analysis demonstrates that grain price was a more influential factor on returns from investing in nutrients than the cost of nutrients and that over the long run a strategy that replaced N removed and that maintained P at or about recognised critical levels was likely to optimise returns.

Table 5: Modelled economic returns at "Colonsay": 1985-2013 returns net of nutrient cost ($/ha).

kgN/crop	0 kgP/ha/crop				10 kgP/ha/crop			
Grain $/t	150	220	150	260	150	220	150	260
N $/kg	1.10	1.30	1.70	1.10	1.10	1.30	1.70	1.10
P $/kg	2.00	3.50	5.00	2.00	2.00	3.50	5.00	2.00
0	0	0	0	0	-610	-1,026	-1,300	-721
40	1,487	2,592	1,487	3,223	1,403	2,337	713	3,414
80	1,123	2,469	1,123	3,237	**2,287**	**4,045**	**1,597**	**5,592**
120	536	2,019	536	2,866	847	2,344	157	3,742
kgN/crop	5 (15) kgP/ha/crop				20 kgP/ha/crop			
0	514	615	-221	1,250	157	-30	-1,223	947
40	1,545	2,537	810	3,682	1,372	2,163	-8	3,698
80	**2,327**	**4,095**	**1,592**	**5,683**	1,840	3,259	460	5,154
120	1,765	3,682	1,030	5,355	1,022	2,471	-358	4,383

Conclusions

Results from Colonsay strongly endorse a nutrient replacement strategy in terms of optimising economic outcomes from investing in N and P. The experiment shows that where nutrients were managed in a balanced fashion little leakage can be expected from the system. Where nutrients were balanced it is practical to set an agronomic efficiency target for N fertiliser at 35- 45%. On P deficient soils, the application of greater than replacement rates during the building phase may improve harvesting of N from the soil and assist in retaining this N in the system for future use. In continuous cropping systems, while maintaining surface Colwell P at or around recognised critical levels has been a sound practice over the last 30 years, more research is required into which soil layers / P pools have been supplying P in order to maintain surface P at this level when in a negative net P balance. Consideration needs to be given to placement of P due to stratification arising from historical P placement strategies and accumulation of P in surface residues.

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