Can poultry litter supply adequate P nutrition to irrigated cotton in an alkaline Vertosol?

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Abstract
In the Riverina, NSW, abundant poultry litter (PL) could offer an alternative, environmentally sustainable and economically beneficial, P-nutrition source for irrigated cotton growers. To assess production reliability and implications for soil fertility, an experiment to compare PL amended alone, (4, 10, 15 t/ha) and integrated with monoammonium phosphate (4 t/ha PL+150 kg/ha MAP), against a standard practice of applying 150 kg/ha MAP, was established on a commercial cotton field, Carrathool, NSW. Soil Colwell-P and BSES-P were not different among treatments 12-wk after planting. The 10 t/ha and 15t/ha PL treatments increased crop P uptake and dry matter yield compared with non-fertilised control at first-flower. Cotton P-uptake, number of nodes and squares, and dry matter yield were related to soil P availability at first-flower (r=0.45-0.72, P<0.05). Application of 10 t/ha or higher PL rates would supply adequate cotton P-nutrition and substitute for MAP fertilisers for irrigated cotton production in the Riverina.

Keywords: manure, organic amendment, soil fertility, nutrient management, sodic soil

Introduction
Cotton is a prominent crop in the Riverina region of southern NSW, Australia with an acreage of approximately 90,050 ha in 2018. Most cotton growing soils in the region are commonly alkaline and have high clay contents, conditions in which soil P is largely fixed through its precipitation predominately into Ca phosphates as well as to some extent into Al and Fe phosphates and/or adsorption onto clay and $CaCO_3$ minerals (Moody et al. 2013). Moreover, high levels of sodicity (≥6% ESP) in these soils exacerbate root P absorption, in addition to other essential nutrients, by affecting soil's physical and chemical conditions (Rochester 2010). Phosphorus is an essential nutrient element required for cotton plant genetic and metabolic processes and especially during early development. In Australian cotton systems, producers typically apply some form of chemical P-fertilisers, particularly in soils with bicarbonate extractable P (Colwell-P) levels below 6-12 mg P/kg, and the P application rates mostly depend on the target lint yields (McLaren et al. 2013). However, crop utilisation of the applied P-fertilisers rarely exceeds 25% in a single growing season due to conversion of soluble P into plant-unavailable forms (McLaren et al. 2013). Whereas low soil P availability stunts plant's growth, agronomic P surplus and its overaccumulation in soils can lead to non-point source P pollution to water bodies by surface flows. Moreover, there is an increasing concern on depleting worldwide reserves of rock-phosphate, a non-renewable P resource used in synthesizing most mineral P-fertilisers. Therefore, effective soil P management strategies that increase crop P use efficiency is necessary for sustained cotton production in the region.

In the Riverina, abundant poultry litter (PL) could offer an alternative, environmentally sustainable and economically beneficial, P-nutrition source for irrigated cotton growers as PL are typically rich in P content that can meet the crop P requirement (Table 1). In soils, plant roots uptake P essentially as phosphate ions from the solution. As the soil solution P is depleted, various soil physico-chemical and biological processes can replenish solution P, where the rate of P replenishment is related to several soil characteristics, such as pH, carbonates, clay, and organic matter contents, as well as to the nature and amounts of P-fertiliser added (Moody et al. 2013). Poultry litter amendment, besides adding P directly into soils, can improve soil P availability and crop P nutrition by mobilising native soil P caused by changes in soil properties that favour P release into solution via desorption from soil minerals, dissolution of slowly available P pools, or mineralisation of organic P pools (Yu et al. 2013). For instance, decomposition of PL produces organic acids that can solubilize soil P compounds, form organometallic complexes with Ca minerals releasing tied-up P and compete with phosphate anions for the binding sites on the soil particles, all resulting in increased P amounts in the solution (Yu et al. 2013). Poultry litter amendment is also expected to enhance microbial mineralisation of soil organic P to release phosphate by providing energy (C) source needed for microbial biomass and enzyme activities (Moody et al. 2013). Additionally, PL amendment to heavy clay soils has potential for soil sodicity amelioration by introducing and replacing Na^+ in the exchange sites with other cations (Ca^{2+}, Mg^{2+}, and K^+) from litter, improving soil structure, overall soil health and crop productivity (Rochester 2010; Lin et al. 2018). Some cotton growers in the Riverina region are applying the available PL in combination with synthetic P-fertilisers mainly to improve soil physical condition and biological health, but P supply from PL is usually not considered in crop P nutrition management largely due to uncertainty in P availability from PL. For a wide grower adoption of PL for cotton P nutrition in P-deficient soils of Riverina, it is essential to know whether PL can effectively substitute for mineral P-fertilisers to adequately supply cotton P needs. Therefore, we aim to assess the use of PL as a P-fertiliser by comparing soil P availability, cotton P uptake and growth, and crop productivity when amending PL alone and integrated with MAP against a standard practice of applying chemical P-fertiliser in a typical alkaline soil of southern NSW over a single cotton growing season. Additionally, the aim is to assess soil P transformation processes with these P amendments and determine the amount of PL required to optimise cotton productivity.

Table 1. Selected properties of the poultry (chicken) litter applied in the study.

Dry matter	pH	EC	CEC	TC	TN	TP	Available								
							N	P	K	Ca	Mg	S	Zn	Cu	Mn
%		dS/m	cmol/kg	----------------------------g/kg----------------------------------									-------mg/kg-------		
79.1	6.86	12.1	32.5	401	48	10.7	5.78	8.24	6.24	0.87	1.19	4.89	293	51.8	327

Methods

An experiment was established on a 36-ha commercial cotton field at Carrathool, NSW (34°26'48" S, 146°29'47" E) in November 2019. Twelve soil cores (90 cm deep) were randomly collected across the entire area using a tractor-mounted hydraulic probe (4.8-cm diam) and composited by depth increments of 0-10, 10-30, 30-60, and 60-90 cm to determine baseline soil properties (Table 2). In mid-January 2020, eighteen 812 m long x 24 m wide plots were laid out in a randomised complete block design (RCBD) to include six treatments with three replicates each. Each replicate plot consisted of 32 cotton beds shaped in camel-humps, spaced 0.75 m apart. The treatments were (i) no-fertiliser control (0), (ii) 150 kg/ha MAP (0/150), (iii) 4 t/ha PL + 150 kg/ha MAP (4/150), (iv) 4 t/ha PL (4/0), (v) 10 t/ha PL (10/0), and (vi) 15 t/ha PL (15/0). Poultry litter and MAP were broadcast and immediately incorporated within 0-20 cm of the soil profile in early-February. All plots received 2.5 t/ha gypsym ($CaSO_4$) and were deep-ripped at an angle to beds upto a depth of 60-80 cm on the following day. The fresh PL, obtained from a commerical broiler production facility near the farm was sampled by combining 6 composite sub-samples and analysed at EAL, Lismore, NSW, to assess litter characteristics (Table 1). The plots were maintained under fallow with weeds managed and beds reshaped according to the commercial practise until cotton (var. Sicot 746B3F) planting on 2nd October 2020. All treatments received ~267 kg urea-N/ha, fertigated in 4-splits at seeding (120 kg N/ha), 75-d after seeding (DAS) (61 kg N/ha), 103 DAS (66 kg N/ha), and 115 DAS (20 kg N/ha). Weeds, pests and irrigation were managed as commerical practise. At planting, sub-plots measuring 10 m long x 24 m wide were marked 30-m inside from the southern border within each replicate plot to delineate an area for collecting soil and plant samples, which hereinafter are referred to as experimental plots.

Two 0-30 cm deep soil cores (4.8 cm diam.) were collected and composited from the middle cotton hills (14th and 19th rows) at the centre of each experimental plot 3-d prior to planting and then onwards at 6-wk interval. All soils were oven-dried (60°C), and ground to pass through a 2-mm sieve prior to laboratory analyses (Macdonald et al. 2017). Plant establishment counts were made from 1-m of rows in the middle of each plot at 6-wk after planting (19th November, 2020). On 7th January, 2020 (first-flower, 12-wk after planting), whole aboveground plants from four rows x 0.5-m within the middle of each experimental plot were cut at the cotyledons and composited. Plant growth parameters were assessed of five plants from the sample composites. The entire sample was then air-dried until constant weight was attained, mulched, and subsamples were fine ground prior to plant nutrient concentration determination. All data were subjected to analysis of variance in a RCBD using a mixed model of SAS with fixed treatment and random replication effects, and means were compared using Tukey test at 0.05 level of significance, unless otherwise stated. Pearson’s correlations were assesed to evaluate bivariate relationships among plant and soil parameters.

Results and Discussion

P-fertilisers effect on soil chemical properties and P availability

A comparison of soil chemical properties at baseline and planting showed decreases in soil pH, ESP and Ca:P ratio, and increases in EC and nutrient availabilities (except Mg and Fe) for all treatments over the 8-month period (Table 2). At planting, soil ESP were notably below 6% in all treatments. While ESP were not significantly different across treatments, ESP levels were generally lower in the PL only treatments. The 15 t/ha PL treatment resulted in significantly greater total C, total N, and available Cu compared to the control and/or 4 t/ha litter treatments (Table 2). These highlight the greater potential of litter-gypsum combinations for ameliorating soil sodicity and improving soil fertility, particularly with PL application rates >10 t/ha.

Table 2. Soil chemical properties at 0-30 cm profile measured at baseline and cotton planting.

Soil	pH	EC	CEC	ESP	Ca:P	TC	TN	Available K	Available Ca	Available Mg	Available S	Available Cu	Available Fe	Available Zn
		dS/m	cmol/kg	%		--------------------g/kg				-----------------	-------------mg/kg			-----------
Baseline	7.74	0.20	30.8	7.83	167	5.66	0.53	0.44	2.71	1.67	65	1.79	34.5	0.90
Planting														
0	6.77	0.51	31.3	5.23	88.1	$6.81^{b\ddagger}$	0.64^{b}	0.57	2.96	1.63	252	1.98^{b}	32.5	1.07
0/150	6.76	0.39	30.3	5.59	61.3	7.40^{ab}	0.69^{ab}	0.55	2.77	1.63	139	2.15^{ab}	31.5	1.31
4/150	6.64	0.50	31.2	5.25	59.0	7.88^{ab}	0.74^{ab}	0.62	2.84	1.67	206	2.18^{ab}	46.4	1.27
4/0	6.74	0.36	30.3	4.57	61.6	6.92^{b}	0.69^{ab}	0.60	2.80	1.63	126	2.14^{ab}	32.0	1.98
10/0	6.67	0.50	31.2	4.78	58.6	7.27^{ab}	0.79^{ab}	0.63	2.87	1.66	165	2.22^{ab}	34.1	2.57
15/0	6.59	0.48	30.9	4.78	53.9	8.41^{a}	0.84^{a}	0.53	2.89	1.61	174	2.74^{a}	37.6	1.63
Std err.	0.17	0.10	0.6	0.52	15.9	0.39*	0.05*	0.03	0.12	0.05	65	0.20*	6.7	0.67

[‡]Within each column (at seeding), means with same superscript letters are not different by Tukey's HSD test at α=0.05*.

At planting, soil total P were not different among treatments (Figure 1a). P-buffering index (PBI) for all soils were low at planting ranging between 112-124 (Moody et al. 2013) and did not differ significantly among treatments (Figure 1a). Nevertheless, the 4/150 treatment had the highest soil PBI among P-fertilisers, which was likely due to slightly higher Fe solubility and availability (Table 2) that increased P sorptivity (Yu et al. 2013). This is further supported by a significant positive correlation (r=0.83, P<0.05) found between PBI and extractable Fe for all soils at planting. Soil Colwell-P and BSES-P were not significantly different among treatments during the early season, 12-wk period, however, were generally low in the 4 t/ha PL treatment among P-fertilisers (Figures 1b & 1c). Soil P availability indices varied widely among replications as evident from the standard error values (Figures 1a-c) that probably masked treatment differences (Moody et al. 2013). It is also likely that mechanisms other than P-sorption/desorption could have buffered P availability because Colwell-P was not related to PBI (r=-0.14, P>0.05). However, highly significant relationships (r=0.92-0.96, P<0.05) occurred between Colwell-P and BSES-P for all soils and at all sampling events, suggesting probable P transformation (dissolution) from the slowly available P-pool to the labile P-pool (McLaren et al. 2013). Overall, the 4/150 treatment and ≥10 t/ha PL amendments consistently maintained the baseline Colwell-P and BSES-P levels, whereas P availability dropped sharply in the 150 kg/ha MAP and 4 t/ha PL treatments at 12-wk after planting (first-flower). The 15 t/ha PL treatment also resulted in about 3 times more soil available N compared to the MAP applications at 6-wk after planting (Figure 1d), which further highlights the added benefit of nutrients other than P supply from PL over chemical P fertilisation.

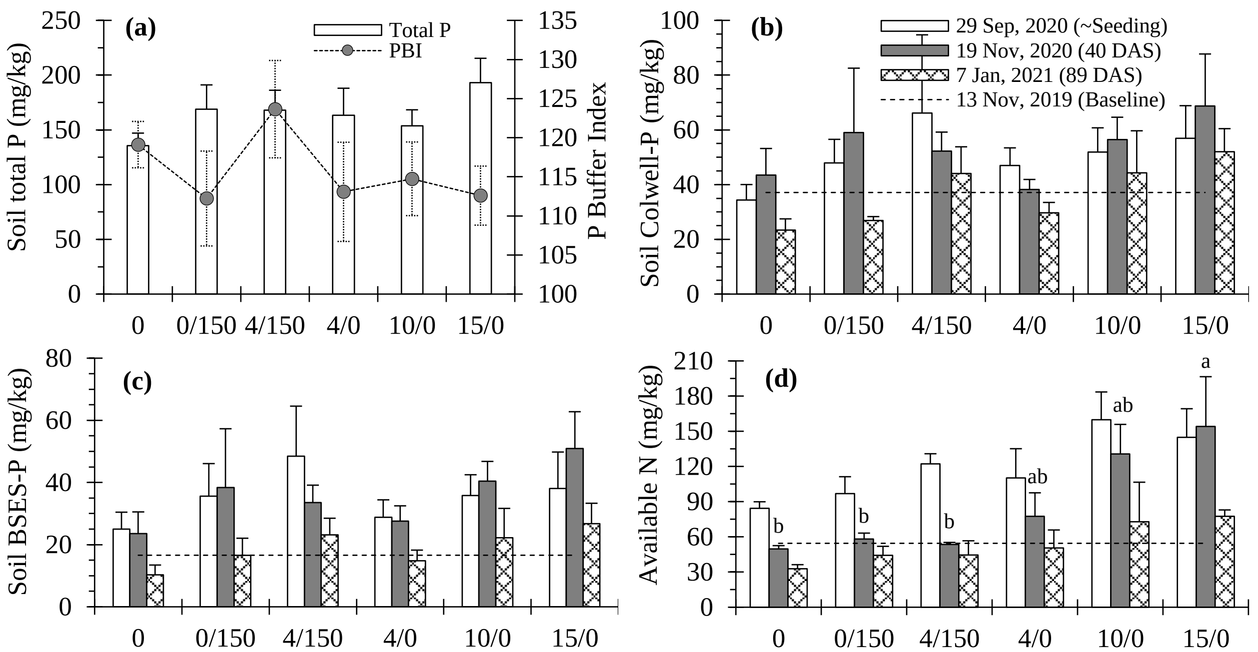

Figure 1. P-fertilisers effect on (a) soil total P and P buffering index (PBI) at planting, and temporal changes in soil (b) Colwell-P, (c) BSES-P, and (d) available N at 0-30 cm soil profile. Means ± std err (n=3) with same letters are not different by Tukey's HSD test at α=0.05. DAS, days after seeding.

Table 3. P-fertilisers effect on plant growth parameters and nutrient uptake at first-flower.

Treatments	Plants m^{-1}	Plant height	Nodes $plant^{-1}$	Squares $plant^{-1}$	First-fruiting position	NAWF $plant^{-1}$	Dry matter	P uptake	N uptake	K uptake
		cm			%		t/ha	-----------kg/ha-----------		
0	12.1	47.0[b‡]	18.6	18.5	79.7	10.4	1.94[b]	5.07[b‡]	61.0[b]	54.2[b]
0/150	12.2	50.9[ab]	18.9	20.6	83.3	10.1	2.50[ab]	6.78[ab]	80.9[ab]	71.0[ab]
4/150	13.6	53.8[ab]	19.3	20.8	80.2	10.2	2.58[ab]	6.89[ab]	83.3[ab]	73.3[ab]
4/0	12.1	48.5[ab]	18.7	18.5	85.8	10.2	2.13[ab]	6.07[ab]	67.5[ab]	64.7[ab]
10/0	12.7	53.8[ab]	18.9	22.9	86.9	9.6	2.76[a]	7.66[a]	90.1[a]	80.4[a]
15/0	12.3	55.5[a]	19.3	21.6	83.9	10.1	2.68[ab]	7.73[a]	88.1[a]	82.0[a]
Std err.	0.7	2.5[†]	0.5	2.3	4.5	0.4	0.27[†]	0.71*	7.3*	8.9[†]

[‡]Within each column, means with same superscript letters are not different by Tukey's HSD test at α=0.05* or α=0.10[†].

P-fertilisers effect on plant growth parameters and nutrient uptake at first-flower

Poultry litter amendments at ≥10 t/ha increased plant height and dry matter yield over the control at first-flower (P<0.10), however, other plant growth parameters were not different among the treatments (Table 3). Although not significant, number of plants m^{-1}, plant height, number of nodes and squares $plant^{-1}$, and dry matter yield were generally low in the 150 MAP and 4 t/ha PL treatments among P-fertilisers. Plant nutrient uptake was invariably low in the control treatment. The high PL-rate treatments (10 t/ha and 15 t/ha), on average, increased P uptake by 34%, N uptake by 32% and K uptake by 33% compared with the control. Similar increments were observed for Ca, Mg, S, Cu, Zn, and Mn uptake (by 27% to 39%) in the ≥10 t/ha PL treatments over the control (data not presented). Bivariate correlations revealed that plant growth parameters (plant height, number of nodes, squares, dry matter yield) and nutrient uptake (P, N, and K) were related to soil P availability indices (Colwell-P and BSES-P) at first-flower (r=0.45-0.72, P<0.05). Overall, these results indicated that plant growth was limited by P availability at first-flower. Whilst P supply from MAP applications (with or without 4 t/ha PL) may optimise early crop growth, PL amendments at higher rates (≥10 t/ha) increased crop development probably by increasing the period of an ample supply of available P. The results suggest, in these soils, a 4 t/ha PL amendment may not meet the required P recommendation.

Conclusions

Phosphorus fertilisation is required to optimise early cotton growth, and application of 10 t/ha or higher poultry litter rates would adequately supply cotton P needs and substitute for the commercially applied MAP fertilisers for irrigated cotton production in alkaline soils of the Riverina. However, 4 t/ha poultry litter would not meet the applied P recommendation. Dissolution of recalcitrant P pools rather than P sorption/desorption is a more likely mechanism that increases P availability in these soils with P amendments. The trial is ongoing and further monitoring of plant P uptake at maturity, cotton productivity, and investigating soil P fractions will specify P release mechanisms to clarify the reliability of poultry litter amendments for crop nutrition and the sustainability of soil P reserves.

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