SOIL FERTILITY STUDIES FOR PASTURES IN THE MACKAY WET TROPICAL COAST OF QUEENSLAND

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ABSTRACT

The nutrient status of two brown earths, two podsolic and two solodic soils on the Central Queensland wet coast were studied in pot culture and field experiments with Macroptilium atropurpureum *cv. Siratro as the test plant.*

In pot culture, all soils responded to P and Mo, three soils to S and one to K, while there were lime induced Zn responses in two soils and to Cu on one of these soils. There were similar responses to P and K in the field experiments, although the P responses were of a lower magnitude. A similar lime induced Cu and Zn response occurred on one soil. However, there was little agreement between Mo and S responses in the field with those in pot experiments. The lack of response to Mo in the field was associated with increasing pH with depth and to S with increasing phosphate extractable S with depth.

Phosphorus was the main deficiency, with the brown earths showing a lower requirement than the podsolic or solodic soils. There was no consistent relationship between extractable soil P or plant P and yield response.

INTRODUCTION

The Mackay wet coast, that area between Proserpine (20° S) and Carmila (22° S) and inland to the Coastal Range, is developing as an important area for improved pastures. It is only a few kilometres wide in places but up to 80 km wide at the head of the Pioneer River valley. In excess of 1,000,000 hectares receive an annual rainfall of more than 1150 mm, and while 90,000 hectares are assigned to sugar cane, there are still 400,000 hectares considered suitable for tropical pasture development. The remaining land is unsuitable for development because it is too steep, is subject to flooding, or has been set aside as National Parks or Timber and Forestry Reserves. About 35,000 hectares have already been sown to tropical pastures and a furter 2,000–5,000 ha are being sown each year. When fully developed, the area will be capable of carrying in excess of 500,000 cattle, compared to the present population of 165,000 head.

Preliminary exploratory work (unpublished) which permitted this development to begin, indicated a widespread response to phosphorus, but did not provide critical data on which rates should be used or indicate other nutrients needed. The studies reported here sought to provide this information.

MATERIALS AND METHODS

Soils and Sites

The soils of the area, as mapped by Isbell *et al.* (1967) were examined. Units with similar dominant profile forms (Northcote 1971) were grouped together to give three broad land types; gradational brown earths (Gn 3.24), gradational red earths (Gn 3.11, Gn 3.12 and Gn 3.14) and duplex soils (Dy 2.12, Dy 3.41, Dy 3.42 and

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Dy 3.43). Six representative soils, thought to be the most suitable for pasture development, were selected; two brown earths (Gn 3.22 and Gn 3.93), two podsolic (Dy 3.41) and two solodic (Dy 3.42) soils (see Figure 1). No sites were chosen on the red earths as these soils occurred mainly in National Parks, Timber or Forestry Reserves.

Three soil profiles were sampled at each site and samples from the same depth at each site were bulked for analysis. All sites were of previously undisturbed, unfertilized woodland and were cleared and cultivated before planting. All sites had an average annual rainfall in excess of 1400 mm (Table 1). The Koumala and Carmila sites were waterlogged for long periods in 1970 and 1971.

Glasshouse Experiments

These experiments were carried out in 1970 in glasshouses at the CSIRO, Cunningham Laboratory, Brisbane. The surface soils (0–10 cm) were air dried, sieved (0.5 cm) and 1500 g of soil weighed into pots lined with clear polythene bags. There were two experiments on each soil, *Macroptilium atropurpureum* cv. Siratro being grown as the test plant and harvested after seven weeks' growth. In Experiment 1 plant samples were bulked for each treatment and analysed for K and S.

Experiment 1: Two replicates of six rates of P (with basal application of K, S, Mo, Cu and Zn) plus two additional treatments at the second highest rate in which K and S were omitted in turn.

Experiment 2: A half replicate of a 2^7 factorial, fully randomized, with basal P, K and S. Factors were presence or absence of lime, Mo, Cu, Zn, Mg, Co and a combination of B and Mn.

Nutrients were applied as follows: $CaH_4(PO_4)_2.H_2O$, 0, 0.14, 0.28, 0.56, 0.84 and 1.12 g pot^{-1} (Exp. 1) and 0.84 g pot^{-1} (Exp. 2); $KHCO_3$, 0.37 g pot^{-1} (Exp. 1), $CaSO_4.2H_2O$, 0.24 g pot^{-1} (Exp. 1); K_2SO_4, 0.32 g pot^{-1} (Exp. 2); $Ca(OH)_2$, 1.2 g pot^{-1}; $(NH_4)_6Mo_7O_{24}.4H_2O$, 0.0007 g pot^{-1}; $CuSO_4.5H_2O$, 0.014 g pot^{-1}; $ZnSO_4.7H_2O$, 0.02 g pot^{-1}; $MgSO_4.7H_2O$, 0.08 g pot^{-1}; H_3BO_3, 0.005 g pot^{-1}; $MnSO_4.4H_2O$, 0.014 g pot^{-1}, $CuCl_2.6H_2O$, 0.007 g pot^{-1}. The rates of P were equivalent to 0, 20, 40, 80, 120, 160 kg ha^{-1} P on the basis of 0.127 g pot^{-1} = 100 kg ha^{-1}.

Field Experiments

Two experiments were established at each site with Siratro as the test species. The sampling covered the period 1970-72. Treatments and design were:

Experiment 3: There were five replications of five P rates in a randomized block design using plots 5 m × 4 m. Rates were 0, 20, 40, 80 and 160 kg ha^{-1} P as $Ca(H_2PO_4)_2.H_2O$. Basal applications of 100 kg KCl, 500 kg $CaSO_4.2H_2O$, 7 kg $ZnSO_4.7H_2O$ and 0.5 kg MoO_3 ha^{-1} were applied at planting. Gypsum and potassium chloride were re-applied at half the initial levels in the second year and for Koumala, also in the third year.

Experiment 4: The presence and absence of six nutrients were compared in a 1/2 replicate of a 2^6 factorial design, with blocks of 16 plots, each measuring 5 m × 4 m. Treatments were:

Lime	0 and 1000 kg ha^{-1} $CaCO_3$ (34.5% Ca)
S	0 and 75 kg ha^{-1} elemental S
K	0 and 100 kg ha^{-1} KCl
Cu	0 and 7 kg ha^{-1} $CuCl_2.2H_2O$
Zn	0 and 7 kg ha^{-1} $ZnCl_2$
Mo	0 and 0.5 kg ha^{-1} MoO_3

Basal P applications of 60 kg ha^{-1} P at planting and 40 kg ha^{-1} P in the second year were applied as $Ca(H_2PO_4)_2.H_2O$. Re-application of the S and K treatments at half the initial rates were made in the second year and for Koumala, also in the third year.

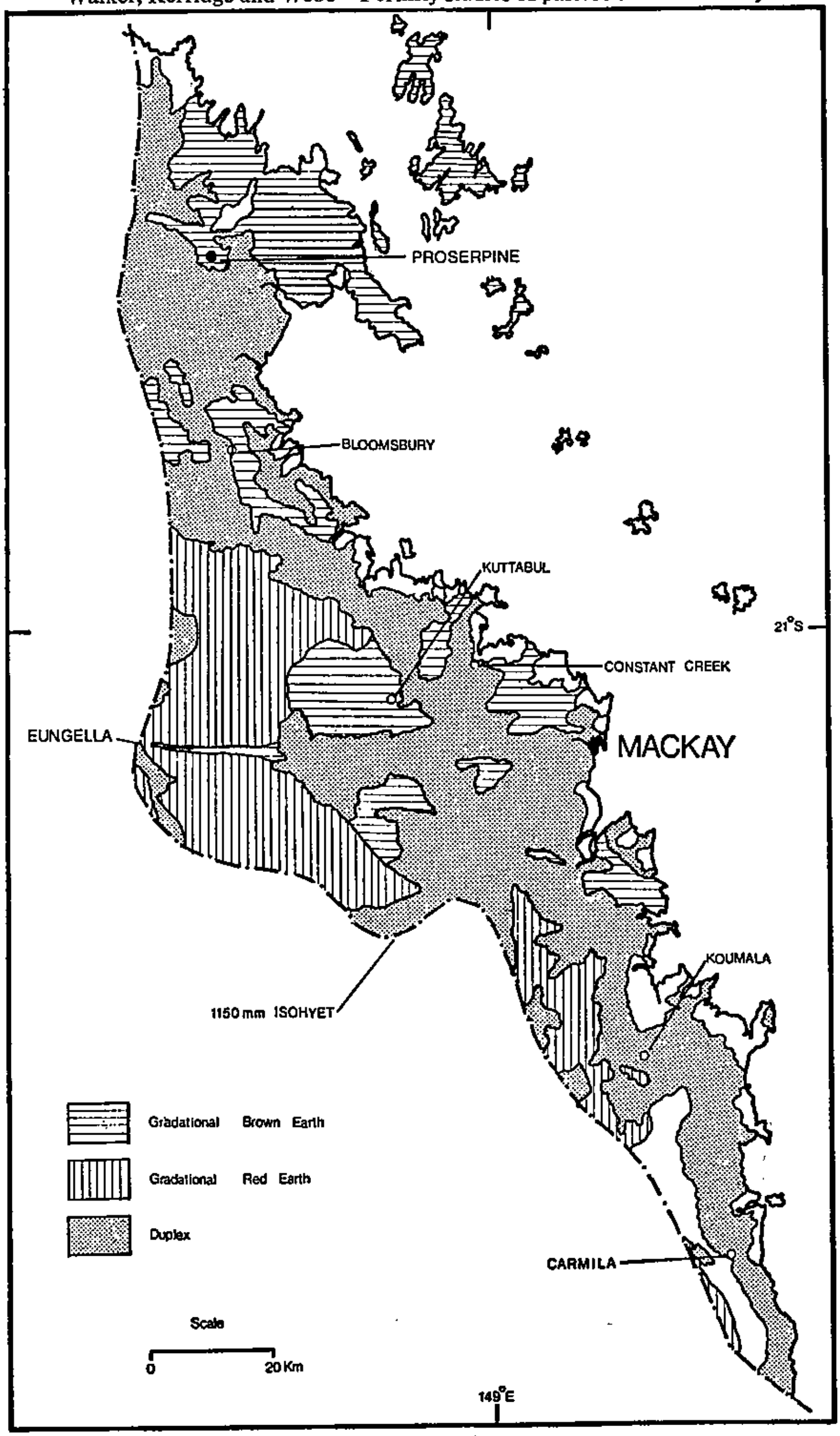

FIGURE 1

Distribution of the three main soil associations on the Mackay coast. Sites chosen for glasshouse and field experiments are shown thus O.

TABLE 1

Soil profile morphology and chemical data for six soils on the Mackay Coast

Site and soil classification	Depth of sample (cm)	pH	Cl (ppm)	Organic C (%)	Total N (%)	Avail. P (ppm)	Exchangeable cations Ca (me 100g⁻¹)	Mg	Na	K	C.E.C.	Particle size (%) CS	FS	Silt	Clay
Bloomsbury Gn	0–10+	5.7	112	1.9	0.15	17	9.0	4.0	0.3	0.23	14	23	27	22	28
Brown structured earth	10–20	6.1	134			<2	7 4	4.3	0.3	0.16	11	28	25	16	31
(Gn 3.22)	20–30	6.0	190			<2	6.6	4.3	0.1	0.13	10	24	26	13	37
	50–60	6.1	217			8	9.3	7.9	0.2	0.13	13	20	24	13	43
A.R. 1430 mm	80–90++	6.4	217			114	12.0	8.7	0.7	0.07	14	27	36	13	24
Kuttabul	0–10+	5.7	98	2.4	0.21	7	5.9	4.4	0.3	0.30	12	24	25	16	35
Brown structured earth	10–20	5.5	170			4	6.3	7.4	0.5	0.18	15	16	30	14	40
(Gn 3.93)	20–30	6.0	40			<2	6.7	10.0	1.3	0.09	18	12	22	13	53
	50–60	7.2	63			<2	11.0	14.0	3.0	0.16	21	10	13	11	66
A.R. 1710 mm	80–90	8.5	109			3	26.0	15.0	3.8	0.16	26	9	18	11	62
Bloomsbury Dy	0–10+	5.8	83	1.2	0.15	15	3.6	2.5	0.2	0.23	6	42	28	10	20
Yellow podsolic (Dy 3.41)	10–20	5.4	43			8	1.4	1.3	0.1	0.07	6	41	29	10	20
	20–30	6.4	54			7	2.4	2.6	0.9	0.07	7	38	31	11	20
	50–60	6.2	235			<2	2.2	10.0	5.2	0.07	14	38	19	10	33
A.R. 1430 mm	80–90	6.5	615			<2	2.4	15.0	7.0	0.16	15	4	27	12	57
Constant Creek	0–10+	5.1	34	1.2	0.09	5	0.5	1.1	0.1	0.13	3	28	44	10	18
Yellow podsolic	10–20	5.9	27			5	1.9	1.6	0.4	0.11	4	50	27	7	16
(Dy 3.41)	20–30	5.9	54			<2	5.0	6.9	1.3	0.13	12	26	12	9	53
	50–60	6.1	36			<2	4.3	8.3	1.3	0.07	13	17	20	11	52
A.R. 1706 mm	80–90	6.4	36			<2	4.2	9.3	1.9	0.09	11	25	19	13	43
Koumala	0–10+	5.7	36	0.9	0.06	5	2.0	1.5	0.2	0.10	4	25	33	19	23
Solodic (Dy 3.42)	10–20	6.1	25			<2	2.6	2.5	0.7	0.03	5	25	30	20	25
	20–30	6.4	40			<2	2.8	2.9	1.5	0.05	7	28	27	19	26
	50–60	6.4	138			<2	6.4	6.9	2.7	0.13	15	22	19	15	44
A.R. 1560 mm	80–90	7.0	398			<2	6.2	7.2	3.6	0.09	13	28	21	13	38
Carmila	0–10+	5.6	31	0.5	0.12	7	2.7	2.2	0.2	0.23	5	26	40	13	21
Solodic (Dy 3.42)	10–20	6.1	36			3	2.2	1.5	0.5	0.07	5	41	28	11	20
	20–30	6.2	38			<2	2.9	3.2	1.0	0.07	8	26	30	13	31
	50–60	6.3	69			<2	5.4	6.4	2.3	0.13	14	20	23	12	45
A.R. 1480 mm	80–90	7.6	235			<2	5.9	7.9	3.2	0.11	15	25	23	11	41

\+ Analyses of soil used in pot trials ++ Weathered rock A.R.—mean annual rainfall 1925-65

In both the field experiments, Siratro was broadcast at 12 kg ha^{-1}, after being inoculated with rhizobia inoculum CB 756. Fertilizers were broadcast and lightly raked into the top soil, except for Cu, Zn and Mo in Experiment 4, which were watered on at planting.

At harvests, two quadrats (1 m^2) were taken at random from each plot and the herbage was cut to 2 cm above ground level. The herbage was sorted into Siratro and weeds, which were then dried to constant weight at 80° C. In 1970 chemical analyses for N, P and K were done on whole plant samples, but in 1971 and for the Koumala site in 1972, chemical analyses were carried out on the last five fully developed leaves of Siratro.

Harvests were not obtained in 1970 from both experiments at Kuttabul and Experiment 4 at the Bloomsbury Dy site. These sites were badly eroded during cyclone "Ada" in January 1970 and the experiments were replanted in March 1970 on new sites. At Koumala there were no yield harvests in 1970 (waterlogged) and 1971 (marsupial damage), but leaf samples were collected in 1971 and in 1972 a full harvest was taken.

A composite soil sample of six cores (0–10 cm) was collected from each plot in June 1972 and analyzed for available P (Experiment 3) and pH (Experiment 4).

Chemical analysis

Soil pH and chloride were determined using a 1:5, soil:water suspension, extractable P after shaking with 0.01 N H_2SO_4 for 16 hours (Kerr and von Stieglitz 1938) and total N by a Kjeldahl method with a copper catalyst. Organic carbon was determined by the Walkley-Black method (Piper 1950). Exchangeable cations were extracted with neutral normal ammonium chloride and the C.E.C. determined by replacement of NH_4^+ by Na^+. Particle size analyses were carried out using the dispersion method of Hutton (1955) and the plummet balance (McIntyre and Loveday 1974).

Plant N and P were determined on an auto-analyser and K on a flame photometer, all following Kjeldahl digest. Sulphur contents were analyzed by quantometer (Johnson and Simons 1972).

RESULTS

Soil analysis

Soil pH was slightly acid in the upper part of the profile and varied little between sites (Table 1). The acid extractable P in the surface soil was very low, except at the Bloomsbury sites, and extremely low in the sub-surface of all soils except the Bloomsbury Gn, where a high level was found in the weathered C horizon. Total N content in the 0–10 cm zone was low, especially at Koumala and Constant Creek. The C.E.C. was very low for the surface samples from the four duplex soils. Exchangeable K values were low for Koumala and Constant Creek and exchangeable Na was low at all sites.

The presence of lime in the Kuttabul profile would have inflated the exchangeable Ca values on these soils. Chloride values were low throughout all soils except the Bloomsbury Dy and Koumala, where although values became moderate to high at depth, they were not considered to be detrimental to plant growth (M. J. Fisher, personal communication).

Particle size data show the gradational nature of the Gn 3 profiles. There are differences in the clay and sodium values between the two Gn soils. The Kuttabul soil is on a lower slope and is formed on colluvial material, whilst the Bloomsbury soil is formed on weathered rock on a broad crest. The coarse sand values at 10–20 cm in the Constant Creek and Carmila soils are much higher than those of the surface or the 20–30 cm increments. This is noticeable in the field and is associated with a bleached A_2 horizon.

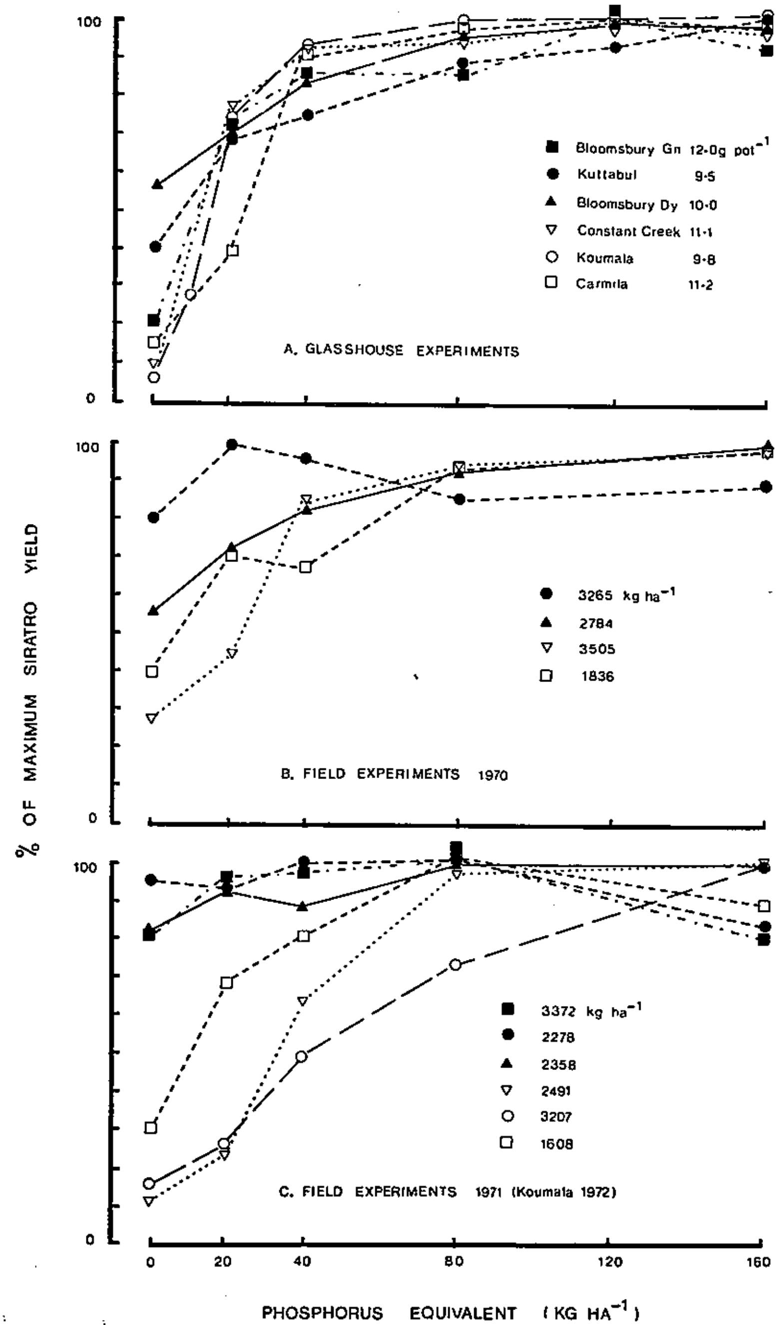

FIGURE 2

Phosphorus responses expressed as percentage of maximum yields of Siratro on six soils from glasshouse and field experiments for 1970 and 1971 (Koumala 1972). Maximum yields for pot (g pot^{-1}) and field (kg ha^{-1}) experiments are given for each site.

Phosphorus response

The addition of phosphorus increased Siratro yields on all soils in both pot and field experiments (Figure 2). The pot experiments demonstrated a large difference in the magnitude of the P response between soils (Figure 2A). Yield without applied P varied from 5 (Koumala) to 55 (Bloomsbury Dy) per cent of the maximum yield with fertilizer.

A similar difference in magnitude of response was found in the field experiments. The relative yield of the nil treatment varied from 25 (Constant Creek) to 80 (Bloomsbury Gn) percent at the four sites sampled in 1970 (Figure 2B) and from 10 (Constant Creek and Koumala) to 95 (Bloomsbury Gn) percent in the 1971 and 1972 harvests (Figure 2C). However the nature of the response varied between pot and field experiments and between field experiments with time.

There was little response to P on the brown earth soils. In 1970 the Bloomsbury Gn soil responded to 20 kg ha^{-1} P, but in 1971 gave no response. Kuttabul also only responded to 20 kg ha^{-1} P in the one year (1971) a harvest was taken.

The podsolic soils showed a strong response in the first year, 40 kg ha^{-1} P being required to give approximately 80 percent of maximum yield. However, while the response increased in the second year at Constant Creek it was much lower at the Bloomsbury Dy site.

On the solodic Carmila site the response decreased slightly in the second year, 40 kg ha^{-1} P giving 70 and 80 percent of maximum yield in the first and second years respectively. However, at Koumala there was a strong response to the maximum P rate at the one (1972) harvest. Observations in 1970 and 1971 had indicated a similar response to P in these years.

The P concentration in the last five expanded leaves of Siratro increased with each increment of added P (Figure 3). However, from the four soils where there was some response and a maximum yield was attained (Kuttabul, Bloomsbury Dy, Constant Creek and Carmila) the P concentration was in the range 0.15–0.17 percent for near maximum yield (90 percent). A strict determination of critical P is not possible because of the lack of sufficient data points.

Nitrogen concentration was correlated with P concentration ($r = 0.69$ $P < 0.001$). That is, there was a trend for a continued increase in nitrogen concentration at P levels where there was no further increase in yield. This can be seen from the different slope of the N yield curve than the Siratro yield curve at the higher P concentrations for the Kuttabul, Bloomsbury Dy and Constant Creek soils (Figure 3).

Soil extractable P analyses (Table 2) show an upward trend with increasing rates of applied P. However, due to high variance, the only significant increases over the nil treatment were at 160 kg ha^{-1} P for all soils and 80 kg ha^{-1} P for the Bloomsbury Gn soil.

TABLE 2

Acid extractable soil phosphorus concentrations (ppm P) in 0-10 cm lay two years after phosphorus application (Experiment 3)

P kg ha^{-1}	Brown earths		Podsolics		Solodics	
	Bloomsbury Gn	Kuttabul	Bloomsbury Dy	Constant Ck	Koumala	Carmila
0	7.2	7.0	7.4	5.0	5.4	9.0
20	5.8	8.2	8.8	5.0	6.0	9.8
40	8.2	7.4	13.0	5.6	7.4	14.0
80	12.0	8.0	12.8	7.2	9.0	17.8
160	15.2	13.4	20.4	10.2	28.8	44.8
L.S.D. (P=0.05)	3.4	4.0	6.6	2.9	6.3	10.2

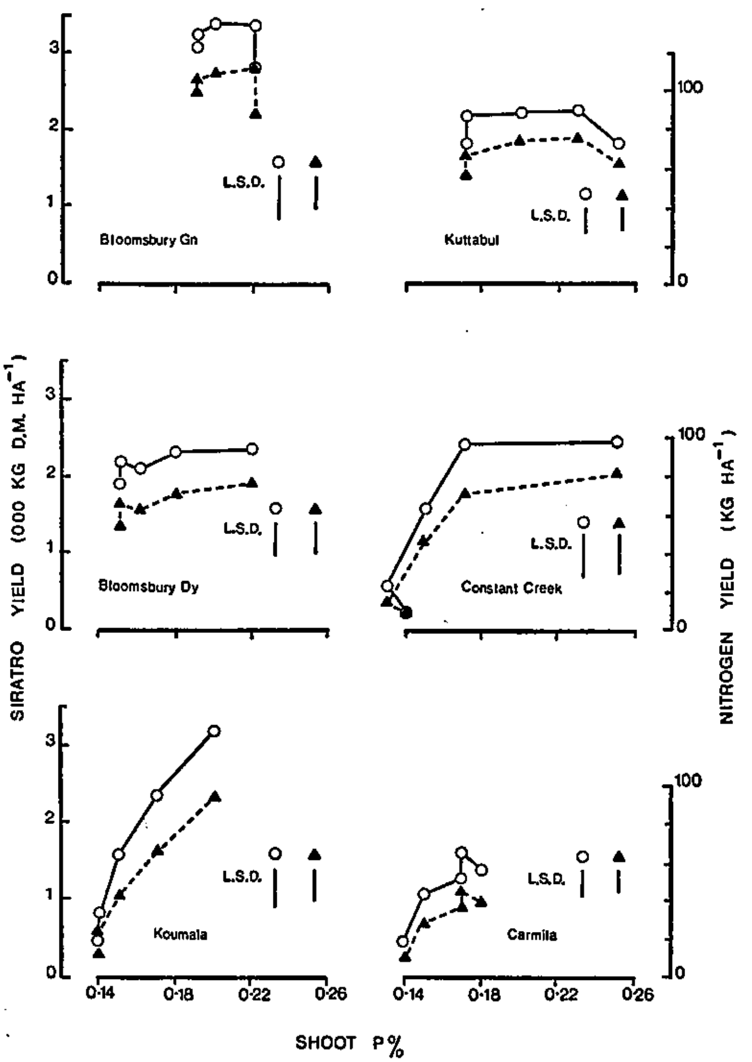

FIGURE 3
The relationship between Siratro yield (O——O) and nitrogen yield (▲----▲) with shoot P concentration for 1971 (Koumala 1972). The least significant differences ($P < 0.05$) for Siratro and nitrogen yields are given for each site.

Other nutrient responses

Pot experiments

Large yield responses to S were found in soils from Kuttabul, Bloomsbury Dy and Carmila (Table 3). Plant S concentrations were below the critical percentage of 0.15 on the minus S treatment for all soils (Andrew 1977).

Potassium increased Siratro yield significantly ($P < 0.01$) only on the Koumala soil (Table 3), but the low plant K concentration of 0.6% at Constant Creek also indicates a low available K status for this soil (Andrew and Robbins 1969).

There was a significant Mo response (Table 4) and Mo × lime interaction ($P < 0.01$) for each soil. Significant Zn × lime interactions ($P < 0.01$) were found for both the Constant Creek and Koumala soils and a Cu × lime interaction

TABLE 3

Responses by Siratro to potassium and sulphur (Experiment 1)‡

Sites	P+K+S			P+S—K		P+K—S	
	Yield g pot^{-1}	Plant† K%	Plant† S%	Yield g pot^{-1}	Plant† K%	Yield g pot^{-1}	Plant† S%
Brown earths							
Bloomsbury Gn	11.2	1.5	0.19	12.1	1.3	10.7	0.10
Kuttabul	9.5	1.8	0.19	8.6	1.3	6.3*	0.09
Podsolics							
Bloomsbury Dy	10.0	1.9	0.16	10.7	1.3	7.5*	0.09
Constant Creek	11.1	1.3	0.16	10.6	0.6	9.0	0.07
Solodics							
Koumala	9.8	1.3	0.17	6.5**	0.6	8.7	0.08
Carmila	11.2	1.5	0.15	10.0	0.9	7.2*	0.07

‡ Analyses of variance carried out on log transformed data.
* or ** Difference between yield of the complete nutrient control and the omission treatment significant at the $P < 0.05$(*) or $P < 0.01$ level (**).
† Plant samples bulked across replications for S and K analyses.

TABLE 4

Responses by Siratro to molybdenum in the absence of lime addition (g pot^{-1}) (Experiment 2)

Treat	Brown earths		Podsolics		Solodics	
	Bloomsbury Gn	Kuttabul	Bloomsbury Dy	Constant Ck	Koumala	Carmila
—Mo	6.8	3.4	6.2	8.3	4.6	4.4
+Mo	11.2	10.8	7.2	10.0	11.2	10.1
L.S.D. (P=0.01)	1.0	1.8	1.0	0.8	1.4	1.9

($P < 0.05$) for the Constant Creek soil. On these soils there was a response to Zn or Cu, in the presence but not the absence of lime addition.

Field experiments

At all sites the application of lime significantly ($P < 0.05$) raised soil pH. Sulphur depressed soil pH ($P < 0.05$) at Bloomsbury Gn, Kuttabul and Constant Creek. However, these effects were relatively small, the largest change being + 0.3 pH units.

There were no consistent response patterns between soils for the significant main effects and interactions for Siratro yields (Table 5). Hence, these results, together with plant N concentration are discussed separately for each site.

Bloomsbury Gn: The main responses in 1970 were to Mo (1868 to 2580 kg ha^{-1} Siratro) and lime (1845 to 2603 kg ha^{-1}). In the K × S interaction the addition of either nutrient alone reduced yields. Potassium lowered the plant N concentration (2.02–1.92). In 1971 lime increased the percent N from 2.87 to 3.05.

Kuttabul: Sulphur significantly increased the percent N (3.15–3.38) and in 1970 this effect could be clearly seen by the darker green leaves on the S treated plots. Sulphur also increased the yield of weeds (800–1205 kg ha^{-1}, $P < 0.05$). The weeds were mostly *Ageratum houstonianum* and annual grasses.

Bloomsbury Dy: The two significant responses were those involving Zn (Zn × S and Zn × K). There was an increased yield in the presence of either nutrient alone but no effect when they were applied together.

TABLE 5

Significant main effects and interactions of six nutrients on Siratro yields (kg ha^{-1}) at six sites (Experiment 4)

Treatment	Brown earths			Podsolics			Solodics		
	Bloomsbury Gn		Kuttabul	Bloomsbury Dy	Constant Ck		Koumala	Carmila	
	1970	1971	1971	1971	1970	1971	1972	1970	1971
K							**		
S						**			
Ca	**				*	**			
Mo	**								
Zn						***			
Cu						**			
‡Ca x Zn						*			
K x S	*								
K x Zn				*					
K x Mo						***			
S x Zn				*		*			
S x Cu						**			*
S x Mo						***			
Mo x Cu					*	**			
Mo x Zn					*	***		*	
Mean yield	2224	2621	1993	2942	2691	2545	3057	1590	1221
Coefficient of variation	21.1	22.9	16.5	14.3	12.4	6.2	26.6	41·2	20.0

* $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$
‡ only significant ($P < 0.05$) interactions included

Constant Creek: Lime depressed Siratro yield in 1970 from 2830 to 2550 kg D.M. ha^{-1}. For the interactions, Mo × lime and Mo × Zn, the presence of both nutrients together depressed yields. The addition of K lowered the plant N concentration (2.30–2.17).

In 1971 there were a large number of significant yield responses which could be incidental due to the low (6.2%) coefficient of variation. Both lime (2700–2390 kg D.M. ha^{-1}) and S (2650–2440) depressed yields, whereas Cu (2440–2650) and Zn (2390–2700) increased yields. For the Zn × lime and Zn × S interactions, yields were depressed by lime and S in the absence of Zn. For the Cu × S interaction there was a response to Cu only in the absence of S. For the Mo × Cu and Mo × Zn interactions, these were significant to either Cu or Zn in the absence of Mo; for Mo × S, there was a slight response to Mo in the absence but a depression in the presence of S; and for Mo × K, either nutrient alone depressed yields.

Carmila: In both significant interactions, Zn × Mo (1970) and S × Cu (1971), the addition of either nutrient alone depressed yield, whereas together they increased yield below the nil level (S × Cu).

Koumala: There was a substantial yield response in 1972 to K (2560–3616 kg D.M. ha^{-1}). The N concentration was increased by lime (2.89–3.09) in 1971 and in the K × lime interaction, lime increased the N concentration in the absence of K, but had no effect with K added. In 1972 the N concentration was increased by S (2.90–3.05) and depressed by Zn (3.07–2.88).

DISCUSSION

Phosphorus was shown to be a major factor affecting Siratro yields in the field on the solodic soils at Koumala and Carmila and the podsolic soil at Constant Creek. On the brown earth at Kuttabul a similar response would have been expected from the low extractable soil P concentration and the response obtained from the pot experiment. However, an establishment year response may have been missed by not having a harvest for the first year. That is, it may have responded in a similar manner to the Bloomsbury Dy soil. It is also possible that more P was available than determined by the 0.01 N sulphuric acid extractant (Table 1) due to soil factors such as the high organic matter content.

The low P requirement on the Bloomsbury soils can be attributed to higher extractable P in the surface soil (Table 1). The high acid extractable P in the C horizon of the Bloomsbury Gn soil may not contribute much to the surface nutrition of pastures at that site because it probably comes from apatite crystals (Probert 1975). The lower extractable P values obtained in the 1972 sampling (Table 2) for the Bloomsbury soils are contradictory to the initial analyses. They could not have been due only to the removal of P in the harvested Siratro, but may be associated with soil disturbance or time of sampling.

The increase in extractable P (Table 2) with applied P fertilizer was of similar magnitude to that reported by Bruce (1972) for equivalent rates of phosphorus. Except for the Carmila soil and the 160 kg ha^{-1} P rate on the Koumala and Bloomsbury Dy soil, the values represent less than 10 percent of the applied P. The very low values for Constant Creek correspond with the loss in effectiveness of the lower rates of applied P in the second year (Figures 2B and 2C) for this soil.

The available yield and soil data are insufficient to test the relationship between soil P and plant response. In south east Queensland it was observed for established Siratro pastures that a response to P was likely below 13 ppm acid extractable P and unlikely above 22 ppm P (Rayment *et al.* 1977). The data in Table 2 suggests a lower critical value for the soils used in these experiments. A critical range for shoot P of 0.15–0.17 percent is suggested for four sites (Figure 3), however, the critical value is obviously higher for the Koumala soil. Critical values for shoot P for Siratro have been shown to be dependent on soil moisture and soil type (White and Haydock 1970) and on stage of growth (C. Johansen, unpublished data). Thus while soil and plant analysis might be used to monitor changes due to a P fertilizer program, sufficiently good relationships between them and crop response have not been obtained or confirmed in this study to use them to predict P fertilizer requirement.

Nevertheless, a general recommendation for phosphorus application can be made from the actual yield response data. It is suggested that 20 kg ha^{-1} P be applied to the brown earth soils and 40 kg ha^{-1} P to the podsolic and solodic soils for the establishment of Siratro based pastures. The previous recommendation of 40 kg ha^{-1} P for all soils has given satisfactory establishment in commercial practice. It is expected that annual maintenance application requirements would be approximately one-third of the initial application.

The field responses to K at Koumala were expected in view of the low soil K levels and pot responses to potassium. A response may develop on the Constant Creek soil as exchangeable K is low (Table 1) and plant K concentration was below the critical value of 0.75 percent (Andrew and Robins 1969) in the 'minus K' treatment of the pot experiment. Potassium requirements are likely to be greater in a mixed legume-grass pasture (Hall 1971) due to competition from the grass. This has been shown by a further experiment at Koumala with Siratro and *Setaria anceps* (cv. Kazungala), where there was a highly significant yield response to the addition of potassium in 1973 (B. Walker, unpublished data).

The sulphur profiles of the experimental sites, except for Kuttabul, have been described by Probert and Jones (1977). In all cases the surface soils were low in phosphate extractable sulphur (< 5 ppm), but values increased with depth to the 30 to 60 cm layer and then declined. This variation in S levels between the surface and subsoil probably accounts for the differences in the response to added sulphur between the glasshouse and field experiments. Pot culture experiments in Queensland often overemphasise the incidence and degree of S deficiency compared with field experimentation (Andrew *et al.* 1974). Despite the absence of significant field yield increases, the increase in N concentration at the Koumala and Kuttabul sites in the second year suggests the brown earths and solodic soils should receive a minimal annual S application of 10–15 kg ha^{-1}. Further work with grass-legume mixtures needs to be undertaken to determine the long term requirement.

The absence of Mo responses in the field, except on the Bloomsbury Gn soil in the first year, was unexpected as large responses were obtained in pot experiments on the brown earth and solodic soils. Poor correlation between pot and field responses was also observed for Siratro in south east Queensland (Johansen *et al.* 1977). This may be due to rapid depletion of N in pots due to small soil volume and more favourable conditions for growth. Molybdenum responses may have been more pronounced in the field if the Siratro had been grown with a grass, as grasses are generally more competitive for soil N than legumes in a grass-legume mixture (Vallis 1978). Further, Mo availability increases with increasing pH (Anderson 1956) and in the field the general increase of pH with depth (Table 1) may have increased Mo availability to a deep rooting plant such as Siratro. The Mo × lime interaction observed in the pot experiments appeared to be due to the release of Mo by liming as there was no further response to lime in the presence of molybdenum. The addition of lime in the pot experiment increased the pH 0.7 to 0.9 units on the different soils, that is, to a pH similar to that occurring in the subsoils (Table 1). Although the field evidence suggests that there is no or a very low requirement for Mo fertilization of Siratro based pastures, it is recommended that, because of the relatively low cost, 100 g ha^{-1} Mo be applied at establishment on all soils. It can be assumed from experience with Mo fertilization of Siratro in south east Queensland that, where a response occurs, this application would be adequate on the brown earths, podsolic and solodic soils for five years (Johansen *et al.* 1977).

Neither Cu nor Zn are considered essential for establishment of Siratro as responses in pot and field experiments were small and associated with liming. However, Cu may be marginal on the podsolic soils as responses to Cu occurred with *Stylosanthes guianensis* cv. Schofield in pot experiments (P. C. Kerridge, unpublished data). Small amounts of Cu and Zn are usually added as contaminants of phosphatic fertilizer.

Some of the interactions at Constant Creek are probably real effects which could be due to complex interactions of pH and nutrient availability (Lindsay 1972). Our results did show significant changes at this site in soil pH from the application of lime and sulphur. These responses should be further examined although they represent only minor effects on Siratro yield.

Once pastures have been established, further deficiencies might be expected over time, but pot experiments on soils from commercial pastures at Koumala (6½ years) and Kuttabul (3½ years), which had been planted to Siratro and Kazungula setaria and received the recommended rates of molybdenumised single superphosphate, showed that P, S and Mo remained the most important deficiencies (R. C. Bruce, personal communication).

These results suggest that pot culture experiments to survey nutrient responses need to be interpreted with caution. While the responses between pot and field experiments were similar for P and K there was poor agreement between responses to S and Mo. Lime induced Cu and Zn responses were found in both pot and field experiments for the podsolic soil at Constant Creek, but the similar lime × Zn response obtained for the Koumala solodic soil in the pot culture experiment did not occur in the field.

Further expression of nutrient response may have occurred using a grass-legume mixture rather than a pure legume sward. However, the vigorous growth of Siratro at all sites, except for Carmila, supports our contention that the results obtained are representative of the nutrient requirements for Siratro based pastures in the Mackay coastal area.

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REFERENCES

ANDERSON, A. J. (1956)—Molybdenum as a fertilizer. *Advances in Agronomy* 8: 163-202.

ANDREW, C. S. (1977)—The effect of sulphur on the growth, sulphur and nitrogen concentrations, and critical sulphur concentrations of some tropical and temperate pasture legumes. *Australian Journal of Agricultural Research* 28: 807-820.

ANDREW, C. S., CRACK, B. J. and RAYMENT, G. E. (1974)—*In* "Handbook on sulphur in Australian agriculture". Ed. K. D. McLachlan (CSIRO: Melbourne). 55-60.

ANDREW, C. S. and ROBINS, M. F. (1969)—The effect of potassium on the growth and chemical composition of some tropical and temperate pasture legumes. I. Growth and critical percentages of potassium. *Australian Journal of Agricultural Research* 20: 999-1007.

BRUCE, R. C. (1972)—The effect of topdressed superphosphate on the yield and botanical composition of a *Stylosanthes guyanensis* pasture. *Tropical Grasslands* 6: 135-140.

HALL, R. L. (1971)—The influence of potassium supply on competition between Nandi setaria and Greenleaf desmodium. *Australian Journal of Experimental Agriculture and Animal Husbandry* 11: 415-419.

HUTTON, I. J. (1955)—A method of particle size analysis of soils. Division of Soils, CSIRO, Australia. Divisional Report Number 11/55.

ISBELL, R. F., THOMPSON, C. H., HUBBLE, G. D., BECKMANN, G. G. and PATON, T. R. (1967)—Explanatory data for sheet 4, Brisbane-Charleville-Rockhampton-Clermont Area. Atlas of Australian Soils (CSIRO: Australia).

JOHANSEN, C., KERRIDGE, P. C., LUCK, P. E., COOK, B. G., LOWE, K. F. and OSTROWSKI, H. (1977)—The residual effect of molybdenum fertilizer on growth of tropical pasture legumes in a sub-tropical environment. *Australian Journal of Experimental Agriculture and Animal Husbandry* 17: 961-968.

JOHNSON, A. D. and SIMONS, J. G. (1972)—Direct reading emission spectroscopic analysis of plant tissue using a briquetting technique. *Communication in Soil Science and Plant Analysis* 3: 1-9.

KERR, H. W. and VON STIEGLITZ, C. R. (1938)—The laboratory determination of soil fertility. Bureau of Sugar Experiment Stations, Queensland. Technical Communication No. 9.

LINDSAY, W. L. (1972)—Inorganic Equilibria of Micro-nutrients in soils. Micro-nutrients in Agriculture. (Soil Science Society of America, Inc.: Madison, Wisconsin, U.S.A.).

MCINTYRE, D. S. and LOVEDAY, J. (1974)—Particle size analysis. *In* Methods for Analysis of Irrigated Soils. Technical Communication No. 54, Commonwealth Bureau of Soils (Commonwealth Agricultural Bureaux: Farnham Royal, England).

NORTHCOTE, K. H. (1971)—A Factual Key for the Recognition of Australian Soils. Third Edition (Rellin Technical Publications: Glenside).

PIPER, C. S. (1950)—Soil and Plant Analysis. (University of Adelaide Press: Australia).

PROBERT, M. E. (1975)—Studies on some neutral red duplex soils (Dy 2.12) in north-eastern Queensland. 3. Availability of phosphorus in the C-horizon. *Australian Journal of Experimental Agriculture and Animal Husbandry* 17: 689-693.

PROBERT, M. E. and JONES, R. K. (1977)—The use of soil analysis for predicting the response to sulphur of pasture legumes in the Australian tropics. *Australian Journal of Soil Research* 15: 137-146.

RAYMENT, G. E., BRUCE, R. C. and ROBBINS, G. B. (1977)—Response of established Siratro (*Macroptilium atropurpureum* cv. Siratro) pastures in south-east Queensland to phosphorus fertilizer. *Tropical Grasslands* 11: 67-77.

VALLIS, I. (1978)—Nitrogen relationships in grass/legume mixtures. *In* "Plant Relations in Pastures". Ed. John R. Wilson. (CSIRO, Melbourne). 190-201.

WHITE, R. E. and HAYDOCK, K. P. (1970)—Phosphorus concentration in Siratro as a guide to its phosphate status in the field. *Australian Journal of Experimental Agriculture and Animal Husbandry* 10: 426-430.

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