A nutrient survey of legume evaluation sites on red earths, solodic soils and black earths in central Queensland

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Abstract

Soil fertility was assessed over a wide range of sites using *Stylosanthes hamata* cv. Verano in glasshouse experiments. Samples were collected from red earths, solodic soils and black earths, over the rainfall range 600 to 760 mm annually.

Yield increases by stylo in a phosphorus rates experiment occurred on all but one soil. Principal responses to other elements in a screening experiment were to sulphur on seven soils and to molybdenum on five, with minor responses to potassium on two and zinc on one. No responses were found to lime in an experiment where basal nutrients had been applied. There was no obvious pattern of deficiencies to distinguish the soil groups or geographical areas. Thus, single superphosphate with molybdenum should generally overcome nutrient deficiencies for pasture legume establishment throughout the region. Implications of surface sealing and hardsetting with some soils, of the accumulation of sulphate at depth and of phosphorus sorption characteristics are discussed.

Resumen

En un ensayo de invernadero, utilizando Stylosanthes hamata *cv. Verano, se evaluó la fertilidad de suelos rojos, solódicos y negros, recolectados al este de Queensland en un amplio rango de sitios con precipitación entre 600 y 760 mm/año.*

Exceptuando uno de los sitios, en los demás los niveles de P incrementaron la productividad de S. hamata. *En un ensayo selectivo se encontró respuesta a la aplicación de S en suelos de siete sitios y a Mo en cinco sitios. La respuesta a K fue baja en dos sitios y a Zn en uno. En suelos que recibieron aplicación basal de nutrimentos no se encontró respuesta a la aplicación de cal. No se encontró una tendencia definida en el patrón de deficiencias para distinguir grupos de suelos de áreas geográficas. De esta manera, la aplicación de superfosfato y molibdeno deben superar las deficiencias nutricionales en el establecimiento de leguminosas en las pasturas de la region. Se discuten, además, las implicaciones del endurecimiento de los suelos, la acumulación de sulfatos y la absorción de fósforo en los suelos.*

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Introduction

Information on fertilizer requirements for pastures in central Queensland is limited and somewhat confusing. Field experiments by J.H. Wildin (unpublished data) with a factorial combination of nutrients [phosphorus (P), potassium (K), sulphur (S), molybdenum (Mo), copper (Cu), zinc (Zn) and boron (B)] and lucerne (*Medicago sativa L.*) on two solodic soils and on a non-gilgaied clay showed responses only to P. His studies of legume introductions in pastures on four duplex soils and on one red earth indicated the need for superphosphate or for potassium chloride and superphosphate incorporating Mo but the deficient elements (P, S, Ca, Mo or K) were not identified. With lucerne there were universal responses to P, eventual responses to S and a marginal response to Zn on gilgaied clays (Webb 1977) and general responses to P and S but only occasional responses to lime, Mo, Zn and K on soils of the Brigalow Research Station, Theodore (Webb *et al.* 1977) and on solodic soils (Maltby and Webb 1983). Walker *et al.* (1979) grew *Macroptilium atropurpureum* cv. Siratro on brown earth, podzolic and solodic soils. They reported universal responses to P and Mo, occasional responses to S, K, Cu and lime induced responses to Zn in pot trials but consistent responses only to P and K in the field.

In order to screen a number of legumes in central Queensland east of the Great Dividing Range, three contrasting soil types were selected at each of three locations to cover the range of soil and climatic conditions. The initial stage of the programme was to identify likely nutrient deficiencies so that these could be corrected with appropriate fertilizers. This involved firstly, characterizing the soil profiles and associated natural vegetation (Standley *et al.* 1990) and secondly, identifying possible nutrient deficiencies in glasshouse experiments. The objectives of this paper are to describe the glasshouse experiments with *Stylosanthes hamata* cv. Verano as the indicator species and to discuss the nutrient responses in relation to soil and plant analyses.

Materials and methods

Sites and sampling

Areas of one hectare of red earth (RE), solodic (S) and cracking clay/black earth (BE) soils were selected in each of three locations: in the northern part of east-central Queensland near Moranbah, in the southern part near Moura and in the coastal lowlands near Marlborough. They represent the range in physical and chemical properties of the majority of soils with potential for pasture development in the Fitzroy region which covers about 200,000 km² (Gunn and Nix 1977).

The RE and S sites and one BE site (Marlborough) originally supported eucalypt woodlands whereas the other BE sites were located on treeless bluegrass tussock grassland. A comprehensive description of the sites is given by Standley *et al.* (1990) and a summary is presented in Table 1. For this paper sites have been identified according to Great Soil Group (Stace *et al.* 1968) and average annual rainfall. Thus, red earths (Aridisols) for the Moranbah, Moura and Marlborough areas become RE600, RE700 and RE760, with similar nomenclature for solodic soil (Alfisol) and black earth (Vertisol) sites. Surface soil (0 to 10 cm) for the glasshouse experiments was collected from five areas within each hectare site.

Nutrient screening experiments

Four pot experiments were conducted in the glasshouse to screen the soils for nutrient deficiencies. *Stylosanthes hamata* cv. Verano was the indicator plant. Treatments and designs used are given in Table 2. Sources and rates of nutrients are given in Appendix 1.

In all experiments, 15 cm diameter polystyrene pots with polythene liners were used. Pots were filled to a constant volume with soil. Soil weights ranged from 1700 to 1890 g. Nutrient additions (Table 1) were calculated on a surface area basis. Legume seed was inoculated and planted. Then lime was mixed with the topsoil by means of a glass rod. Finally, other nutrients were pipetted onto the surface. Pots were watered at least once a day with double deionized water to a weight corresponding to pF 2.

Four plants were grown in each pot. They were harvested by cutting about 1 cm above the soil, dried at 105 °C and weighed. Samples from selected treatments were retained for chemical analysis.

Table 1. Site information and summary of soil descriptions

Nearest town	Latitude and longitude		Annual rainfall (mm)	Soil Taxonomy[1]	Great Soil Group[2]	Principal Profile Form[3]	Site abbreviation
	S	E					
Moranbah	21°58′	148°14′	600	Typic Camborthid	Red earth	Gn 2.11	RE600
Moura	24°56′	149°49′	700	Typic Camborthid	Red earth	Gn 2.12	RE700
Marlborough	22°41′	150°07′	760	Typic Camborthid	Red earth	Gn 2.11	RE760
Moranbah	22°16′	147°59′	600	Aridic Paleustalf	Solodic soil	Dy 3.43	S600
Moura	24°36′	149°52′	700	Typic Natrustalf	Solodic soil	Dy 2.43 and Dd 1.43	S700
Marlborough	22°52′	150°18′	760	Typic Natrustalf	Solodic soil	Dy 3.4	S760
Moranbah	22°06′	148°06′	600	Mollic Torrert	Black earth	Ug 5.14	BE600
Moura	24°38′	149°29′	700	Type Pellustert	Black earth	Ug 5.15 and Ug 5.16	BE700
Marlborough	22°58′	150°13′	760	Typic Pellustert	Black earth	Ug 5.15 and Ug 5.13	BE760

[1] Soil Survey Staff (1975). [2] Stace *et al.* (1968). [3] Northcote (1971).

Table 2. Treatments and designs used in the glasshouse experiments

Experiment A	
Design:	½ × 2^6 on 9 soils.
Treatments:	B, Mo, Zn, K, S, (Cu + MG + Mn + Fe)
Basal:	P
Experiment B	
Design:	6 P rates × 9 soils × 3 replicates
Treatments:	0, 10, 20, 40, 60, 80 kg P/ha as $Ca(H_2PO_4)_2.H_2O$
Basal:	B, Mo, Zn, K, S, Cu, Mg, Mn, Fe
Experiment C	
Design:	2 lime rates × 9 soils × 3 replicates
Treatments:	0, 500 kg ha^{-1} $CaCO_3$
Basal:	P, K, S, Mo, Cu, Zn, B, Mn, Mg, Fe
Experiment D	
Design:	½ × 2^6 on Moranbah red earth (RE600)
Treatments:	$CaCO_3$, Mo, Zn, K, S, (Cu + Mg + Mn + Fe + B)
Basal:	P

Chemical analyses

Details of soil analysis procedures have been given by Standley *et al.* (1990). After Kjeldahl digestion, plant samples were analysed for N and P by an Auto-Analyzer procedure (Roofayel, unpublished) based on the ammonia-phenate-hypochlorite reaction for N and the sulphuric acid-molybdate-ANSA method for P, for K by flame photometry and for Ca and Mg by atomic absorption spectrophotometry. Analyses for Cu, Zn and Mn were by atomic absorption spectrophotometry following perchloric acid digestion. Sulphur was determined by X-ray fluorescence spectrometry. Samples for B analysis were dry ashed and assayed by the curcumin complex method of Hayes and Metcalfe (1962).

Results

Analytical data for soils used in these experiments are given in Table 3.

A: General nutrient screening experiment

Verano stylo gave significant yield responses to S, Mo, Zn and K. Relative yields where these responses occurred are given in Table 4.

Sulphur was the most widespread deficiency with responses, often marked, on seven of the soils. For a treatment where S was not applied (Mo, Zn, K, Cu, Mg, Mn, Fe) the mean plant concentrations of S (0.07%) and of N (1.89%) were low. Soil extractable sulphate values were low in all soils but tended to be lower where responses occurred (mean 1.3 mg/kg S, range 0.1 to 2.9) than where they did not (2.8 and 3.3 mg/kg S).

Molybdenum responses were found on five of the nine soils and these were not confined to particular soils or pH ranges. Nitrogen concentrations increased in treated plants. Mean values were 2.34 and 2.77% N without and with Mo respectively. An effect of Mo on leaf colour was observed with BE600 at harvest but dry matter yields and N concentrations (2.57% with Mo, 2.63% without) were not increased.

A Zn response only occurred on RE760. The DTPA-extractable Zn was 1.2 mg/kg Zn, higher than for four other soils (Table 3) on which there was no response. On RE760 the mean Zn concentration for plants without added Zn was low (10 mg/kg Zn). Interveinal yellowing of younger leaves was apparent on some plants halfway through the experiment, which, according to a rating system, appeared to be due to Zn deficiency.

Potassium treatments depressed plant yields in S700 and BE700 and increased plant yields (only in the presence of S) in RE760 and S600. Despite the high exchangeable potassium in S700 and BE700 (0.65 and 0.80 meq % K respectively), the depressions are not attributable to excessively high plant K; mean values with K added were 2.36 and 2.57% K on S700 and BE700 respectively. Where yield increases with K were found, K concentrations of unfertilized plants were not very low, being 1.0% K with RE760 and 1.95% with S600. The respective values for exchangeable potassium were 0.16 meq % (3% saturation) and 0.48 meq % (8% saturation) which, in general, are not considered indicative of deficiency for stylo.

Table 3. Analyses of soils (0 to 10 cm) for nutrient screening experiments

Analysis[1]	Soil type and average annual rainfall (mm)								
	Red earth			Solodic			Black earth		
	600	700	760	600	700	760	600	700	760
Coarse sand (%, 2.0 to 0.2 mm)	55	46	43	27	29	5	9	4	9
Fine sand (%, <0.20 to 0.02 mm)	29	30	39	57	45	15	17	26	25
Silt (%, <0.020 to 0.002 mm)	14	14	14	14	14	61	21	19	21
Clay (%, <0.002 mm)	6	10	8	4	10	22	53	51	47
Air dry moisture (%)	1.2	1.0	0.9	0.8	1.2	1.6	6.6	5.6	7.0
− ⅓ bar moisture (%)	11	12	9	9	15	31	35	38	42
− 15 bar moisture (%)	5	6	5	3	7	7	24	26	24
1:5 pH	5.4	6.6	6.4	6.3	6.6	6.4	6.9	7.2	6.5
1:5 electrical conductivity (dS/m)	0.02	0.03	0.03	0.02	0.04	0.07	0.04	0.07	0.05
Chloride (mg/kg)	10	10	10	10	10	70	20	20	30
Exchangeable K (meq %)	0.09	0.45	0.16	0.48	0.65	0.16	0.52	0.80	0.24
Exchangeable Na (meq %)	<0.1	<0.1	<0.1	<0.1	<0.1	0.4	0.4	1.5	0.4
Exchangeable Ca (meq %)	1.6	5.3	2.8	2.7	6.9	3.4	25	20	13
Exchangeable Mg (meq %)	0.7	1.4	0.5	0.7	1.6	2.8	22	22	26
CEC (meq %)	6	7	5	6	10	9	41	39	44
Bicarbonate-extractable P (mg/kg)	5	5	4	7	35	4	4	6	7
0.005M H_2SO_4 extractable P (mg/kg)	6	12	4	11	64	4	9	12	8
Equilibrium P concentration (μg/L)[2]	6.5	10	7	31	60	3	4.5	6	8
Phosphorus buffer capacity[3]	20	15	7	18	17	49	31	32	35
Phosphate extr. sulphate (mg/kg S)	1.9	0.9	1.2	0.1	0.8	3.3	1.2	2.9	2.8
Organic carbon (%)	1.3	1.1	0.8	0.5	0.8	1.4	0.9	1.2	1.5
Total nitrogen (%)	0.06	0.06	0.05	0.03	0.05	0.07	0.07	0.07	0.11
Total phosphorus (%)	0.023	0.034	0.017	0.038	0.052	0.014	0.024	0.034	0.021
Total potassium (%)	0.10	0.47	0.08	0.91	1.38	0.50	0.23	0.70	0.08
Total sulphur (%)	0.023	0.022	0.015	0.010	0.024	0.011	0.015	0.020	0.023
DTPA-extractable-									
Copper (mg/kg)	0.3	1.2	0.3	0.6	0.7	1.8	2.1	2.4	3.9
Zinc (mg/kg)	0.3	1.2	1.2	1.5	1.5	2.0	0.3	0.4	0.3
Iron (mg/kg)	52	17	24	27	40	102	30	36	72
Manganese (mg/kg)	8	120	27	30	42	96	40	48	90

[1] Methods detailed by Standley *et al.* (1990). Results reported for air dry (40°C) soil samples.
[2] At zero sorbed P, from 0 to 10 cm profile samples (Standley *et al.* 1990).
[3] From 0 to 10 cm profile samples (Standley *et al.* 1990).

Table 4. Relative yields for treatments giving significant[1] responses in Experiment A

Soil and average annual rainfall (mm)	Nutrient and relative yield[2] of Verano stylo				Stylo yield[3] (g/pot)
	S	Mo	Zn	K	
Red earth (600)	0.82**	0.79**			2.4
Red earth (700)	0.32**				9.1
Red earth (760)	0.21**		0.87*	0.91[4]	6.8
Solodic (600)	0.26**	0.87**		0.91[4]	7.7
Solodic (700)	0.36**			1.16**	6.2
Solodic (760)		0.79*			5.4
Black earth (600)	0.48**				3.2
Black earth (700)	0.64**	0.82**		1.12*	6.1
Black earth (760)		0.72**			1.1

[1] * $P < 0.05$; ** $P < 0.01$.
[2] $\text{Relative yield} = \dfrac{\text{Yield in absence of nutrient}}{\text{Yield in presence of nutrient}}$.
[3] Yield of complete treatment in experiment.
[4] Response significant only in the presence of S.

Table 5. Verano stylo dry matter yields and phosphorus concentrations from Experiment B

P rate (kg/ha)	Soil type and average annual rainfall (mm)								
	Red earth			Solodic			Black earth		
	600	700	760	600	700	760	600	700	760
	Dry matter yield (g/pot)								
0	2.5	3.7	0.5	2.4	6.7	0.6	0.7	2.6	0.6
10	2.7	4.0	3.6	3.1	7.6	1.3	1.2	3.3	1.1
20	2.5	6.1	4.5	4.9	7.3	1.4	1.9	4.2	1.4
40	3.1	7.1	5.8	6.7	9.3	1.9	2.7	5.6	1.1
60	3.1	6.1	6.1	6.6	7.9	1.8	3.1	5.6	1.5
80	3.9	6.5	6.8	7.3	9.4	1.7	2.9	6.6	1.9
F test[1]	**	n.s.	**	**	n.s.	**	**	**	n.s.
	P concentration (%)								
0	0.11	0.11	0.06	0.14	0.20	0.13	0.06	0.11	0.10
10	0.15	0.09	0.09	0.16	0.21	0.15	0.08	0.15	0.19
20	0.16	0.12	0.12	0.18	0.24	0.18	0.13	0.14	0.17
40	0.14	0.17	0.20	0.24	0.26	0.19	0.14	0.17	0.20
60	0.17	0.20	0.24	0.26	0.29	0.21	0.19	0.20	0.25
80	0.18	0.23	0.29	0.28	0.30	0.21	0.17	0.20	0.24

[1] ** $P < 0.01$; n.s. — not significant at $P = 0.05$.

B: Phosphorus rates experiment

Stylo dry matter yields and phosphorus concentrations are given in Table 5. Significant responses to P were found on all soils except RE700, S700 and BE760. Some fertilized plants on RE700 were damaged by the automatic watering machine, thereby introducing greater variability which would have masked a significant response. Low yields and considerable variability amongst plants on BE760 would also have masked a response. Stylo P concentrations for nil P treatments were 0.11% for RE700 and 0.10% for BE760, both indicative of deficiency.

Only S700 had reasonable bicarbonate-extractable phosphorus (35 mg/kg P compared to all others ⩽ 7 mg/kg P) and acid-extractable phosphorus (64 mg/kg P compared to ⩽ 12 mg/kg P). Control plants from S700 contained 0.20% P, much higher than from other soils and above an approximate critical concentration of 0.18%.

C: Lime experiment

No significant responses to calcium carbonate were found (data not presented). This experiment was conducted because lime was not included in Experiment A where the assumption was that all soils, with the possible exception of RE600, had pH and exchangeable calcium levels which would be adequate for Verano stylo. Experiment C confirmed this assumption. However, although on RE600 the effect of lime on stylo yield was not significant ($P = 0.05$), being 2.88 g/pot without lime and 3.20 g/pot with lime, the corresponding N concentrations were 2.32% and 3.00%.

D: Nutrient experiment including lime

This experiment was conducted because the low pH (5.4) of RE600 could have affected stylo growth and lime additions could affect responses to other nutrients which would not have been detected in Experiment A. As before, there were responses to S and Mo but, in addition, there were responses to lime, Zn and the bulk treatment (Cu + Mg + Mn + B + Fe). Yield ratios for these treatments were: 0.81 (S), 0.84 (Mo), 0.89 ($CaCO_3$), 0.84 (Zn) and 0.91 (bulk treatment). The yield of the complete treatment was 3.12 g/pot.

Stylo analyses are given in Table 6. These show low concentrations of N and S in the absence of S (treatment 32); an intermediate concentration of N in the absence of Mo but in the presence of lime (treatment 13); higher N when Mo and S were present (treatment 16) and highest N when lime, Mo and S were all present (treatments 6, 22 and 30). Other stylo analyses show low Zn in the absence of Zn (treatment 6) but lowest Cu in the absence (treatment 30) or presence (treatment

Table 6. Nutrient concentrations in Verano stylo grown on soil RE600 in Experiment D
(Key figures for interpretation of treatment effects in bold

Treatment number and nutrients[1]	N	S	Ca	Mg	Zn	Cu	Mn	B
	%				mg/kg			
22 Complete	2.73	0.17	1.73	0.41	19	6	320	36
8 Nil	1.68	0.06	1.49	0.55	15	7	220	48
30 Lime, Mo, Zn, S	**2.72**	0.20	1.61	0.58	17	**5**	230	41
16 Mo, Zn, S, Bk[1]	**2.50**	0.19	1.66	0.53	24	6	320	24
13 Lime, Zn, S, Bk	**2.38**	0.20	1.90	0.60	16	6	270	29
6 Lime, Mo, S, Bk	2.66	0.19	1.82	0.60	**13**	7	290	34
32 Lime, Mo, Zn, Bk	**2.03**	**0.07**	1.72	0.49	15	5	220	48

[1] Bk = bulk treatment (Cu + Mg + Mn + B + Fe).

32) of Cu. These data support the ideas of deficiencies of S, Mo and Zn and that lime at 500 kg/ha can release some Mo and contribute to N uptake. However, the Cu analyses do not confirm that the reduced yield in the absence of the bulk treatment was due to Cu.

Discussion

Glasshouse experiments: non-nutritional factors

Glasshouse experiments may be valuable not only as a means of identifying possible nutrient deficiencies but also as indicators of establishment problems related to soil structure. Verano stylo was chosen as the indicator plant because of its suitability for central Queensland. However, it did not grow well on all the soils, even with the complete nutrient treatment. Growth of Verano was poor on RE600, BE600 and BE760 in Experiments A and B and on S760 in Experiment B (Tables 4 and 5). In Experiment B basal nutrients were applied to all pots and for the high P treatments the legume P concentrations indicated that deficiencies had been overcome. Therefore we conclude that the problem of low yields was attributable to adverse soil physical conditions.

The red earths and solodic soils have hard setting surface soils and the black earths are self mulching clays or cracking heavy clays (Standley *et al.* 1990). When such soils are used in glasshouse experiments water entry can be slow and so the surface can stay moist for a long time. Thus there can be problems with water distribution and, indeed, with determining the pF2 moisture content of the soils and the right watering weight for the pots. Other workers have had problems growing legumes on Vertisols at pF2, which is apparently too wet for good nodulation and growth (P.C. Kerridge, personal communication).

We encountered particular problems with RE600, S760, BE600 and BE760. Red earth RE600 had a high proportion of coarse sand (55%) and a low proportion of clay (6%). Germination was poor and the stylo was replanted after five days. Solodic soil S760 had higher percentages of silt and clay and higher exchangeable sodium (Table 3) than S600 and S700. On this soil the yield in Experiment A was higher than in Experiment B, presumably because it was harvested two weeks later in Experiment A. Reasons for the poor growth on BE600 and BE760 are not understood: particle size distributions were similar to that of BE700 while the exchangeable sodium concentrations were much lower (Table 3). BE600 was replanted after five days because of poor germination and (as with S760) in Experiment A the plants were grown for two weeks longer than on the other seven soils in an attempt to improve yields. BE760 had damping off problems.

Glasshouse experiments: nutrient responses

Verano stylo grew better on some soils than on others. However, there was a similarity in patterns of responses. Phosphorus, S and Mo were the major deficiencies. Zinc, K and possibly Cu (on acid RE600) were the minor ones.

Phosphorus

Responses to P on all soils but S700 would have been predicted on the basis of foliar and soil analyses. Values of 0.06 to 0.14% P for the nil P treatments (Table 5) indicate deficiency according to critical concentrations given by Smith (1986) for other stylos, namely 0.10 to 0.18% P. Soil extractable P values (Table 3) of < 12 (acid) and < 7 (bicarbonate) mg/kg imply deficiency according to calibrations from other areas or for other species. Probert and Jones (1982) considered 15 to 20 mg/kg P marginal for Verano stylo in north-eastern Queensland while critical concentrations of 21 mg/kg P (bicarbonate extraction) and 31 mg/kg P (acid extraction) were found by Maltby and Webb (1983) for lucerne on solodic soils. The equilibrium phosphorus concentrations (Table 3) are lower (for seven of the nine soils) than the critical concentration of 15 μg/l P for Verano suggested by Probert and Jones (1982).

Sulphur

Responses to S would have been expected on all soils according to foliar and soil analyses. Gilbert and Shaw (1989) proposed a critical concentration of 0.10% S for Verano shoots. In Experiment A the mean value for all soils and the selected treatment without S was 0.07%, with a range of 0.05 to 0.09% across the soils: with RE600 in Experiment D treatments 8 and 32 gave stylo with 0.06% and 0.07% S respectively (Table 6). To distinguish responsive from non-responsive sites, Probert and Jones (1977) derived (for legumes on soils of pH 5.2 to 6.7) extractable sulphate concentrations of 15 mg/kg S for surface soils and 4 mg/kg S where the whole profile was taken into account. Lucerne in pot experiments responded where extractable sulphate was < 12 mg/kg S (Webb 1977). Walker *et al.* (1979) recorded S responses by *Macroptilium atropurpureum* cv. Siratro on some soils with < 5 mg/kg S.

Sulphur did not increase yields on two soils, S760 and BE760, a result that might be attributable to greater mineralization associated with these soils of relatively high organic carbon and extractable S when compared with the others (Table 3). BE700 had 2.9 mg/kg S but lower organic carbon (1.2%) and a S response occurred. For the selected treatment without S the stylo N concentrations were 2.27% from BE760, 2.23% from S760, 2.10% from BE700 and 1.65 to 1.99% from the other soils. Sulphur responses by legumes in glasshouse experiments are quite common. In central Queensland with lucerne Maltby and Webb (1983) found them on eight of nine solodic soils and Webb (1977) recorded them on several gilgaied clays.

Molybdenum

The responses to Mo on five of the nine soils were not altogether unexpected. Bruce (1978) noted that such responses occur frequently in pot studies but this has not always been the case with central Queensland experiments. Whereas Webb (1977) claimed that Mo was unlikely to be deficient on the gilgaied clays, Walker *et al.* (1979) found responses on all six soils from the Mackay coast and Maltby and Webb (1983) reported responses on one-third of solodic soils after the S deficiency had been corrected.

Potassium

Responses to K on RE760 and S600 (Table 4) were only about 10% and would not have been predicted for S600 according to foliar and soil analyses. While there are no critical concentrations for Verano, Smith (1986) cites 0.6 to 1.3% K for other stylos. The critical range for exchangeable K of 0.10 to 0.20 meq % can be inferred (Standley 1981; Walker *et al.* 1979). Mean foliar concentrations for treatments without K were 1.0% on RE760 and 1.95% on S600. Exchangeable K was 0.16 meq % for RE760 and comparatively high (0.48 meq %) for S600 (Table 3).

Reduction in stylo yields with potassium chloride on S700 and BE700 was surprising in view of the low salt concentrations in the surface soils (Table 3). Webb *et al.* (1977) and Maltby and Webb (1983) each reported an instance of reduced legume yield possibly attributable to chloride toxicity. If such toxicity could occur on S700 and BE700 it raises the question of why it was not a problem on the other soils.

Zinc and copper

A response to Zn would have been expected on RE600 but not on RE760, according to the range of 0.1 to 0.5 mg/kg DTPA-extractable Zn suggested by Bruce (1978) as an area of unclear response. However, the extractable Zn values for this experiment (Table 3) and those of corresponding 0 to 10 cm samples from profile cores (Standley *et al.* 1990) are sometimes inconsistent; e.g. they report 0.3 mg/kg Zn for RE760.

For Cu the critical concentration may be as low as 0.1 mg/kg DTPA-extractable Cu (Bruce 1978). Thus, if 0.3 mg/kg Cu was marginal for RE600 where a Cu response was inferred in Experiment D, RE760 would also be classified as deficient.

Fertilizer requirements and soil properties

These nutrient screening experiments provide the basis for selecting fertilizer treatments in confirmatory field experiments. They cannot truly reflect the field situation because only surface soil was tested.

In some soils there was considerable salt accumulation at depth (Standley *et al.* 1990) which could create physical limitations to plant growth. Thus, severely restricted root development would be expected in the B horizon of the solodic soils, below 80 to 90 cm in BE600 and BE760, and below 50 to 60 cm in BE700.

A need for P fertilizer throughout the region is predicted. Additional information was obtained on P buffer capacity during the survey (Standley *et al.* 1990). This indicates that more P will be required to correct deficiencies in the black earths than in the red earths. Results from solodic soils were more variable and suggest that fertilizer requirements will need to be determined for each site. Vesicular-arbuscular mycorrhizae may reduce P requirements (M.N. Hunter, personal communication).

Though a widespread S deficiency is predicted from the screening of the surface soil, sulphate further down the profile may compensate. Below 30 cm there were increases in phosphate-extractable sulphate for all sites except RE600 and RE700 (Standley *et al.* 1990). This should overcome deficiencies, provided that root morphology and soil conditions allow this sulphate to be accessed (Robert and Jones 1977; Walker *et al.* 1979; Rayment *et al.* 1983). Such an accumulation at depth may account for the lack of response by lucerne to S in the field nutrient screening experiments in 1968/69 (J.H. Wildin, unpublished data) on solodic and clay soils.

Frequent occurrence of Mo deficiency is indicated by Experiments A and D. This may not be so common in the field (Bruce 1978; Walker *et al.* 1979).

There was no obvious pattern of deficiencies to distinguish the soil groups (red earths, solodic soils and black earths) or the regions (coastal near Marlborough or inland near Moranbah or Moura). Field experiments should aim to validate requirements for P, S and Mo and then elucidate possible requirements for Zn, K and the cause of the response to the bulk treatment on RE600 in Experiment D. Based on the principal responses found to P, S and Mo, we predict that a fertilizer recommendation of single superphosphate (9% P, 10% S, 20% Ca) with Mo would generally overcome nutritional limitations to pasture legume establishment in the Fitzroy region.

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Appendix 1. Sources and rates of nutrient treatments and basal dressings

Treatment	Compound	Rate of compound	Field equivalent	
			Compound	Element
		(g/pot)	(kg/ha)	
Lime	$CaCO_3$	0.885	500	200
Mo	$Na_2MoO_4.2H_2O$	5.9×10^{-4}	0.33	0.130
Zn	$ZnCl_2$	0.009	5	2.4
K	KCl	0.168	95	50
S	Na_2SO_4	0.16	88	20
Cu	$CuCl_2.2H_2O$	0.009	5	1.9
Mg	$MgCl_2.6H_2O$	0.106	60	5
Mn	$MnCl_2.4H_2O$	0.018	10	2.8
B	$Na_2B_4O_7.10H_2O$	0.009	5	0.567
Fe	$FeCl_3.6H_2O$	0.018	10	2.1
P	$Ca(H_2PO_4)_2.H_2O$	0.354	200	50

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