A REVIEW OF THE TRACE ELEMENT NUTRITION OF TROPICAL PASTURE LEGUMES IN NORTHERN AUSTRALIA

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ABSTRACT

This paper reviews the incidence of molybdenum, copper, zinc, manganese and cobalt deficiencies in the nutrition of tropical legumes in northern Australia. Published data for these elements in soils and plants are discussed, particularly from the viewpoint of diagnosis of deficiency. Fertilizer rates for correction of deficiencies are given and species are grouped on the basis of their responsiveness.

Where tropical pastures are grown molybdenum deficiency has been found on a wide range of soils and parent materials; copper and zinc deficiencies have been restricted to very sandy soils; manganese deficiency has not been found but a few cases of toxicity are recorded; a deficiency of cobalt has not been found for plant growth but has been reported for sheep and cattle.

It is concluded that none of the soil and plant diagnostic techniques currently in use have been satisfactorily correlated with field response and several suggestions are made for future research.

INTRODUCTION

Acute nitrogen and phosphorus deficiencies are almost universal in Australian soils but trace element deficiencies have also been shown to occur in many areas. The important role that identification and correction of these deficiencies has played in the widespread success of introduced pasture plants has been reviewed by Loneragan (1970) and by Williams and Andrew (1970). However neither of these reviews emphasizes tropical legumes or tropical soils probably because of the lack of published information available at that time.

This paper deals with the molybdenum, copper, zinc, manganese and cobalt nutrition of tropical legumes on soils of tropical and subtropical Australia. It reviews the occurrence of deficiencies, the diagnosis and correction of deficiencies, and the relative responses of different species.

MOLYBDENUM

Occurrence of molybdenum deficiency

The first indications of molybdenum deficiency in northern Australia were found using temperate legumes in the 1950's since testing of tropical legumes was then in its infancy. In northern New South Wales, responses to molybdenum were found in pot experiments with clovers grown on krasnozems derived from basalt (Anderson and Arnott 1953, McLachlan 1955, Swain 1959) and on soils derived from granite (McLachlan 1955). McLachlan (1953) tested four soils from the Northern Territory in pot experiments and found that subterranean clover responded to molybdenum on two of them—a yellow podzolic on granite and a stony red loam on volcanic material.

In subtropical Queensland, Andrew and Bryan (1955, 1958) found small responses to molybdenum with clovers in field experiments on two soils (low humic gley and lateritic podzolic soil) of the coastal lowlands. Cassidy (1957) mentions an indication of a response in the field in the Gympie district but the first definite field response was observed in 1959 with white clover in the Cooran district (Douglas

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1962a). This was confirmed by a field experiment with white and red clovers in which four-fold increases in yield were measured (Douglas 1962b). The first response in a tropical legume was with glycine (*Glycine wightii*) on a latosolic soil near Pinbarren in 1961 (Luck and Douglas 1966). Subsequent recordings of molybdenum responses with tropical legumes in field experiments are given in Table 1. These cover a wide range of soils, soil pH and parent materials but there is a preponderance of legumes more responsive to molybdenum (see later section) among the species listed.

TABLE 1

Instances where molybdenum responses have been found in field experiments with tropical legumes

Soil	Soil pH‡	Parent Material	Legume	Reference
latosol	5.3	phyllite	glycine	Luck and Douglas (1966)
solodic	6.2	sandstone	Siratro	Truong *et al.* (1967)
krasnozem	—	—	Siratro Silverleaf	Ostrowski (1970)
krasnozem	5.2	basalt	glycine	Mears and Barkus (1970)
deep sand	5.0	marine sand	Siratro	Teitzel and Bruce (1973)
xanthozem	5.5	granodiorite	Greenleaf	Kerridge *et al.* (1973)
xanthozem	4.9†	granite	Greenleaf glycine	Kerridge and Everett (1975)
xanthozem		phyllite	Siratro glycine Greenleaf lotononis	Johansen *et al.* (1977)
red podzolic	5.1	phyllite	Siratro	
prairie	5.4	andesite	Siratro	
yellow podzolic	5.9	sandstone	glycine Siratro	
yellow podzolic	6.4	granite	Siratro	
brown earth	6.0	—	Siratro	Walker *et al.* (in press)

‡soil:water =1:5
†soil:$CaCl_2$ =1:5

*Siratro (*Macroptilium atropurpureum*); glycine (*Glycine wightii*); Silverleaf (*Desmodium uncinatum* cv. Silverleaf); Greenleaf (*Desmodium intortum* cv. Greenleaf); lotononis (*Lotononis bainesii*): Townsville stylo (*Stylosanthes humilis*); Schofield stylo (*Stylosanthes guianensis* cv. Schofield); Cook stylo (*Stylosanthes guianensis* cv. Cook); Oxley stylo (*Stylosanthes guianensis* cv. Oxley); Verano stylo (*Stylosanthes hamata* cv. Verano); puero (*Pueraria phascoloides*).

Response to molybdenum has frequently been reported from pot experiment studies (Mannetje *et al.* 1963, Shaw *et al.* 1966, Roe and Jones 1966, Havilah and Mears 1968, Mears and Barkus 1970, Hall 1970, Jones and Crack 1970, Crack 1971, Kerridge *et al.* 1972, Teitzel and Bruce 1972a, 1972b, 1973, Jones 1973, Walker *et al.* [in press]). These extend the pH range slightly, add Townsville stylo (*Stylosanthes humilis*), Schofield stylo (*Stylosanthes guianensis* cv. Schofield) and phasey bean (*Macroptilium lathyroides*) to the list of species and include some additional soils and parent materials.

Where the same soils were studied in pot and field experiments, responses in the glasshouse were not always confirmed in the field (e.g. Roe and Jones 1966, Jones 1973, Johansen *et al.* 1977). Reasons for this are not readily apparent. A restricted volume of soil in pots together with optimum conditions for plant growth and, in some instances, the use of sensitive species are possible explanations for the greater sensitivity of pot culture. Release of nitrogen through cultivation would act to reduce legume dependence on symbiotic nitrogen and hence reduce the appearance of molybdenum deficiency in the field, at least in the first year. The use of pure chemicals in the glasshouse and fertilizer grade materials in the field could also be a contributing factor, although Anderson (1956a) did not support this possibility. Johansen *et al.* (1977) also suggest that pH trend down the profile may need to be considered for deep rooted perennial species, as molybdenum could be more available at depth if pH increases.

There are no instances of molybdenum response occurring in the field after not being detected in pot experiments except for a statement by Teitzel *et al.* (1978) that on some soils derived from granite, molybdenum responses have been obtained in pastures established for several years.

Molybdenum in plants

Molybdenum has a dual role in the nutrition of leguminous plants. It is required for protein metabolism since it is involved in nitrate reduction reactions with the enzyme nitrate reductase. In addition, molybdenum is required for symbiotic nitrogen fixation by *Rhizobium* bacteria in root nodules.

Field experiments with herbage legumes in Australia have not indicated deficiencies of molybdenum for protein metabolism. However, Andrew and Pieters (1972a, 1972b, 1976a, 1976b) have described molybdenum deficiency symptoms for Greenleaf desmodium (*Desmodium intortum*), Siratro (*Macroptilium atropurpureum*), lotononis (*Lotononis bainesii*) and glycine. These were induced in solution culture by growing plants in the absence of molybdenum but with adequate nitrate.

Field responses of legumes to applied molybdenum in Australia have invariably been due to the effect of molybdenum on symbiotic nitrogen fixation. More molybdenum is needed for symbiotic nitrogen fixation than for general metabolism of the host plant (Anderson 1956a). In this situation a deficiency of nitrogen is induced and visual symptoms are indistinguishable from those associated with nitrogen deficiency. The nodules of molybdenum deficient plants are often white or green in colour compared with the pink or red colour of those on non deficient plants. In addition, there are usually many small nodules on a deficient plant but fewer, larger nodules on a normal plant (Anderson 1956b, Mannetje *et al.* 1963, Mears and Barkus 1970).

Molybdenum concentrations in plant tops have been reported for glycine (Luck and Douglas 1966, Mears and Barkus 1970), Siratro (Ostrowski *et al.* 1978) and several *Stylosanthes* species (Jones 1974). Concentrations are generally less than 1 ppm Mo and usually less than 0.5 ppm Mo. Molybdenum concentrations do not always increase with increasing application rates.

Molybdenum concentrations in legume tops are unlikely to be a useful diagnostic aid. This is because the important function of molybdenum is in nitrogen fixation in nodules, so a deficient plant is limited in growth by a restricted nitrogen supply.

Molybdenum concentrates in the seed of legumes to a greater extent than in other plants. Vinogradova (1943) found the mean concentration of molybdenum from 41 analyses of legume seed to be 5.5 ppm Mo. The concentration in seed depends on the conditions under which the plant is grown. Meagher *et al.* (1952) found that molybdenum deficiency was easily demonstrated in plants grown from seed which was produced by plants grown in molybdenum deficient nutrient solutions, and contained 0.05 to 0.1 ppm Mo. On the other hand, commercially produced seed contained 0.5 to 5 ppm Mo and molybdenum deficiency could not always be demonstrated. They claim that molybdenum is unique among essential elements in that normal seed of some plants may store, in available form, many times the total need of the plant to be grown from that seed.

The analysis of legume seed does not seem to have been used as a diagnostic aid. With the wide range of seed size in legumes, the amount of molybdenum per seed rather than the concentration in the seed might be of more use. Warrell (personal communication) found that glycine seed produced in a molybdenum deficient area of the Atherton Tableland contained 0.06 ppm Mo while seed produced in a non-deficient area contained 1.5 ppm Mo.

Root nodules contain much higher concentrations of molybdenum than roots or tops (Jensen and Betty 1943). Jensen (1948) suggested that nodules should contain a certain concentration of molybdenum for maximum nitrogen fixing efficiency and proposed 4 to 8 ppm Mo for subterranean clover and 10 to 25 ppm Mo for lucerne. There is no information available on the optimum nodule molybdenum concentration for tropical legumes.

Soil molybdenum

Stephens and Donald (1958) listed the total molybdenum contents of some Australian Great Soil Groups. The range of means for the Groups were from < 2 ppm to 11 ppm Mo but there appeared to be little predictive value in the figures. Barrow and Spencer (1971) suggested that the molybdenum content of parent rock was important in determining molybdenum status of a soil. The data of Oertel and Giles (1963) for molybdenum content of surface samples of Queensland soils show that most soils have values less than 5 ppm Mo.

Molybdate is specifically adsorbed on surfaces of iron and aluminium oxides and weathered edges of clay particles. The extent of adsorption decreases as pH is raised above 4, the pH corresponding to pK, the dissociation constant of molybdic acid (Barrow 1978). Soils vary in their ability to adsorb molybdenum according to their pH and to the occurrence of adsorbing sites. Parent material from which the soils have formed and rainfall are two important factors determining a soil's mineralogy and acidity and hence its adsorption properties (Barrow and Spencer 1971). Adsorption of molybdate has two consequences in plant nutrition. Adsorbed ions are protected against leaching, but on the other hand, they are less available to plants. Strongly adsorbing soils should be more responsive and also require heavier applications for maximum yields.

Barrow and Spencer (1971) used the amount of molybdenum adsorbed at a final supernatant concentration of 0.1 ppm Mo as an index of a soil's ability to absorb and showed that soil molybdenum status (assessed from pot experiments) decreased with increasing ability to adsorb molybdenum. Little and Kerridge (1978) found that the same index was the most promising laboratory method in a comparison of four methods of assessing molybdenum status of nine Queensland soils. It was better related to the amount of molybdenum required for maximum dry matter yields of tropical legumes over a five year period in field experiments than soil solution molybdenum, total molybdenum or oxalate extractable molybdenum.

An acid solution of ammonium oxalate (Grigg 1953) has been the most widely used extractant in soil tests for molybdenum. Oxalate is specifically adsorbed and appears to be an effective displacer of molybdenum (Barrow 1978). Barrow and Spencer (1971) and Spencer and Govaars (1974) have used this extractant in experiments with clovers but the only published information in Australia for tropical legumes or tropical soils is that of Little and Kerridge (1978). In their work there was no correlation between extractable molybdenum and molybdenum requirement. As no data was reported for soils not deficient in molybdenum no judgement can be made as to the ability of the extractant to distinguish between deficiency and sufficiency, which is the usual role of soil tests.

The effect of soil pH in modifying the availability of soil molybdenum is well documented in both temperate and tropical soils. Acid conditions lead to low availability and liming may increase availability to such an extent as to overcome deficiency. However there are some soils in which molybdenum appears inadequate, regardless of change in pH (Kerridge *et al.* 1972).

Forms of fertilizer

Sodium molybdate, ammonium molybdate, calcium molybdate and molybdenum trioxide have all proved to be effective sources of molybdenum in fertilizer experiments in Australia. In commercial practice, molybdenum is applied as molybdenized superphosphate which is a mixture of single superphosphate and molybdenum trioxide. It is available in Queensland at four molybdenum concentrations: 0.02% Mo, 0.04% Mo, 0.08% Mo and, together with copper and zinc, at 0.03% Mo.

Some doubts have been expressed about the homogeneity of molybdenum trioxide-superphosphate mixtures. No published information is available on the distribution of molybdenum in bulk batches, but Lipsett and David (1977) studied the distribution of molybdenum in a single bag of molybdenized superphosphate. They found that while the whole bag contained slightly more than the guaranteed amount, nearly half of this was carried in only one-tenth of the material—the medium and fine particles. They also showed that the fine material had settled out in the lower layer of the bag. This would lead to uneven spreading on crops and pastures. Partly because of this, Teitzel *et al.* (1978) recommend spraying a solution of sodium molybdate (together with copper and zinc sulphates if required) on pastures.

Incorporation of molybdenum into a seed pellet has been suggested as a means of obtaining a more even spread of molybdenum and also being advantageous in soils with a high molybdenum requirement. In field experiments 100 g ha^{-1} Mo, as molybdenum trioxide, in a rock phosphate seed pellet was as effective as a similar soil application in correcting molybdenum deficiency over a five year period (Johansen *et al.* 1977). At the end of the first year, nodulation, yield and molybdenum concentrations of four tropical legumes were similar regardless of the method of application (Kerridge *et al.* 1973). Sodium molybdate is not suitable for seed pelleting.

Rates of applications

On reviewing experience with herbage legumes in southern Australia, Anderson (1956a) concluded that 90 g ha^{-1} Mo (1.3 oz acre^{-1} Mo) was a fully effective rate of application. Higher rates of 280 to 700 g ha^{-1} Mo were used in early fertilizer experiments in Queensland (Andrew and Bryan 1955, 1958), but the first recommendation for tropical pastures (Andrew and Bryan 1958) was for 110 g ha^{-1} Mo (1.6 oz acre^{-1} Mo) which was in line with Anderson's conclusion. Subsequent general recommendations for tropical pastures have quoted rates of 100 to 200 g ha^{-1} Mo (Douglas and Luck 1964, Ostrowski 1969, Teitzel and Bruce 1972c, Cook 1978a). A rate of 100 g ha^{-1} Mo is now widely accepted; this is conveniently supplied by 500 kg ha^{-1} of 0.02% Mo superphosphate or by 250 kg ha^{-1} of 0.04% Mo superphosphate. Justification for these rates can be found in the results quoted by Luck and Douglas (1966), Kerridge (1972), Kerridge and White (1977) and Johansen *et al.* (1977).

An exception to the above recommendations was made for glycine (Douglas and Luck 1964, Ostrowski 1969, Cook 1978a) where rates of 200 to 300 g ha^{-1} Mo were recommended. These recommendations seem to be based on the work of Luck and Douglas (1966) who found that 230 g ha^{-1} Mo gave maximum yield of glycine on a latosolic soil and Mears and Barkus (1970) who found that 112 g ha^{-1} Mo was not enough for maximum yield of glycine on a krasnozem. In both of these experiments there was little growth in the first year after planting, so responses are for growth in the second year after fertilizer addition. This, together with the fact that both soil types would be expected to adsorb molybdenum, could be responsible for the higher apparent requirement of glycine. The results of Johansen *et al.* (1977) allow a limited comparison of glycine with other legumes and tend to support the contention that glycine requires higher rates of molybdenum than other legumes, but still show that 100 g ha^{-1} Mo is adequate for glycine for at least two years on a soil which Little and Kerridge (1978) showed to be a strong adsorber of molybdenum.

Frequency of application

The question of frequency of application of molybdenum has not been satisfactorily resolved. In reviewing work under temperate conditions in Australia, Anderson (1956a) concluded that "... a single dressing of 2 ounces per acre remains effective for many years". It is not clear whether he meant 2 oz of molybdenum trioxide or elemental molybdenum. Traditionally care has been taken with recommendations for molybdenum application to avoid excessive amounts because of the known effects of molybdenum on copper and sulphate metabolism in animals (Dick 1956). General recommendations are to reapply molybdenum at intervals of three to five years (Douglas 1962b, Cassidy 1967, Ostrowski 1969, Teitzel *et al.* 1978, Cook 1978b).

Swain (1959) worked in subtropical northern New South Wales with a red basaltic soil and found a response to molybdenum in the field three years after an initial application of 70 g ha^{-1} Mo. Similarly Mannetje *et al.* (1963) found that on a prairie-like soil fertilized with 110 g ha^{-1} Mo three to four years previously, phasey bean and lucerne responded to molybdenum in a pot experiment. Bryan and Evans (1971) failed to find a response to molybdenum in grazed tropical pastures 6 and 11 years after an initial dressing of 280 g ha^{-1} Mo but as the soils were not acutely deficient to begin with (Bryan 1973) this finding is of doubtful importance.

Kerridge (1972) found that an initial dressing of 100 g ha^{-1} Mo applied to Greenleaf desmodium was fully effective for two years on soils derived from acid volcanic parent material, for three years on soils from basalt, and for at least three years for soils from schist and granodiorite. More recent work by Johansen *et al.* (1977) has shown that residual value of molybdenum depends on soil type and legume species. On their most responsive soil, 100 g ha^{-1} Mo ensured maximum yield of glycine for two years, of desmodium for three years, and of lotononis for at least five years. Their data suggest that 100 g ha^{-1} Mo remains effective for at least three years, and often for five years, except for sensitive species on strongly adsorbing soils.

Species differences

Differences between tropical legumes in their susceptibility to molybdenum deficiency have been recorded by several workers (Luck and Douglas 1966, Crack 1971, Kerridge *et al.* 1973, Johansen *et al.* 1977). Based on these reports, the species are grouped below as most responsive, intermediate and least responsive.

Most responsive	glycine, Greenleaf desmodium
Intermediate	Siratro, phasey bean
Least responsive	lotononis, Townsville stylo, Schofield stylo, Cook stylo (*Stylosanthes guianensis* cv. Cook)

COPPER

Occurrence of copper deficiency

In northern Australia the first reported incidence of copper deficiency for pasture establishment was with temperate legumes on soils of the coastal lowlands of Queensland (Andrew and Bryan 1955, 1958). Responses with tropical legumes as indicator plants followed and are given in Table 2. They have been found on sandy soils (sands, sandy podzolics, yellow earths) using Siratro, lotononis and members of the *Stylosanthes* genus. Copper responses in pot experiments have been reported by Andrew and Bryan (1955), Andrew and Thorne (1962), Russell (1966), Jones and Crack (1970), Teitzel and Bruce (1971, 1973), Jones (1973), Isbell *et al.* (1976) and Walker *et al.* (in press). Phasey bean was often used as an indicator plant. Pot response was found in some soils of higher organic matter status (humic gleys) and solodic soils, but not confirmed by field studies. No responses have been found on structured earths. Agreement between pot and field responses appears to have been good.

Copper in plants

Symptoms of copper deficiency in tropical legumes have been described by Andrew (1963), by Andrew and Pieters (1972a, 1972b, 1976a, 1976b) and by Jones and Clay (1976). Generally the initial effect of copper deficiency is partial

TABLE 2

Instances where copper and zinc responses have been found in field experiments with tropical legume

Soil	Parent Material	Legume*	Reference
COPPER			
podzolic	granite	Siratro Schofield stylo	Teitzel (1969)
podzolic	granite	Siratro	Teitzel and Bruce (1971)
deep sand	marine sand	Siratro	Teitzel and Bruce (1973)
deep sand	granite	Townsville stylo	Jones (1973)
ground water podzol	marine and aeolian sand	lotononis	Wentholt (unpubl.)
yellow earth	sandstone	Cook stylo Oxley stylo	Winter and Jones (1977)
ZINC			
podzolic	granite	puero	Teitzel and Bruce (1971)
deep sand	granite	Townsville stylo	Jones (1973)
yellow earth	fluviatile sand	Townsville stylo	Bishop (1974)
yellow earth	sandstone	Cook stylo Oxley stylo	Winter and Jones (1977)
red earth	sandstone	Cook stylo	Anning (1977)
mottled grey earth	fluviatile sand	Verano stylo	Hall (pers. comm.)
sandy duplex soil	fluviatile sand	Verano stylo	Hall (pers. comm.)

*For botanical names see Table 1.

wilting of the younger growth, with sometimes a loss of chlorophyll and necrosis of younger leaves and shoots. Leaflets curl inwards bilaterally as necrosis occurs. Teitzel (1969) found greatly reduced numbers of seed pods in plots of copper deficient Siratro.

Andrew and Thorne (1962) compared the responses to copper of five tropical and five temperate pasture legumes and also presented the copper contents of plant tops, roots and seed. Copper concentrations in dry plant material from the various species did not vary significantly at any one level of application and over all treatments the range in values was 1.7 to 11.3 ppm Cu. They concluded that, for the legumes they studied, a concentration above 5 ppm was satisfactory, 4 to 5 ppm was marginal and less than 4 ppm indicated copper deficiency.

These guidelines have been found useful in interpreting yield responses in fertilizer experiments by a number of workers in Queensland (Table 3).

TABLE 3

Copper and zinc concentrations in various tropical legumes when grown under nutrient deficient and/or sufficient conditions

Pasture species	Zinc (ppm)		Copper (ppm)		Reference
	Deficient	Sufficient	Deficient	Sufficient	
phasey bean	20–25	—	—	11–17	Russell (1966) /
	—	45–63	—	11–17	Jones and Crack (1970)
	15–18	19–24	—	—	Crack (1971)
	9–25	20–35	1–2	3–8	Verrall (unpubl.)
Townsville stylo	28	45	—	—	Jones and Crack (1970)
	19	23	—	3–6	Crack (1971)
	20	43	—	—	Jones (1973)
	—	45–64	—	5–6	Isbell *et al.* (1976)
	—	—	—	3–5	Webb (1975a)
	12–16	35–100	5	5–9	Webb (1975b)
	9	17–22	—	5	Day (pers. comm.)
Greenleaf desmodium	—	22–38	—	3–7	Kerridge *et al.* (1972)
Siratro	—	21–24	—	—	Truong *et al.* (1967)
Cook stylo	10	30	3–4	7	Winter and Jones (1977)
Verano stylo	7	10–21	—	8	Hall (pers. comm.)
lotononis	—	25	—	5	Wentholt (unpubl.)

Low copper levels in plants have resulted in low liver copper concentrations and visual symptoms of copper deficiency in animals (Gartner *et al.* 1968).

Copper in soil

Oertel and Giles (1963) analyzed 118 Queensland surface soils and showed that total copper contents were mostly < 60 ppm Cu and frequently < 20 ppm Cu. This is in agreement with the range of 3 to 60 ppm Cu for means of some Great Soil Groups presented by Stephens and Donald (1958). McKenzie (1966) found that some Victorian soils with more than 8 ppm total copper were not deficient.

Several authors have given total copper contents of north Queensland soils and these are presented in Table 4. With the exception of the neutral red duplex soils, which were not deficient in copper, all values are low and suggest that total copper could be of diagnostic use if studied further.

TABLE 4

Total copper and zinc concentrations in some soils from northern Australia

Soil	Range in values (ppm) Cu	Zn	References
yellow earths	3–5	3–5	Isbell *et al.* (1976)
red earths	4–6	3–6	
sands	4–5	2–5	
yellow earths	6–13	3–10	Isbell and Smith (1976)
red earths	4–22	5–21	
grey earths	6–11	3–7	
deep sands	2–5	5–14	Jones (1973)
solodic	9	7	Russell (1966)
neutral red duplex	33–54	22–58	Crack (1971)
sandy red earth	5	10	Day (pers. comm.)
lateritic yellow earth	5	10	
lateritic red earth	5	8	
humic gley	5	10	

The DTPA soil test of Lindsay and Norvell (Follett and Lindsay 1971) has been used in Queensland by commercial soil testing laboratories and by the State Department of Primary Industries for a number of years. The extractant is 0.005 M DTPA, 0.01 M $CaCl_2$ and 0.1 M triethanolamine buffered at pH 7.3. There has been no calibration of the method for pastures. Experience suggests the critical level is low, possibly 0.1 ppm Cu, but it is poorly defined. Verrall (unpublished data) found no yield response by phasey bean above 0.1 ppm Cu in a study of 15 soils in the glasshouse. Webb (1975b) grew Townsville stylo on nine soils whose DTPA extractable copper ranged from 0.1 to 0.4 ppm but a response was obtained on only one soil. More research is required to compare a range of soil analyses as indicators of copper deficiency for pasture legumes, particularly in acid, sandy soils.

Copper fertilizers

Copper sulphate has been the most commonly used source of copper for fertilizer experiments and for commercial pastures. Copper chloride has been used in experiments where sulphur is also a treatment. Recommended rates are 2 kg ha^{-1} Cu (Teitzel and Bruce 1972c, Cook 1978a). This can be supplied as 8 kg ha^{-1} copper sulphate. The most convenient way of applying copper to pastures is by topdressing with superphosphate fortified with copper. This is commercially available as a superphosphate-copper sulphate blend containing 0.9% Cu. Gilkes and Sadlier (1978) showed this to be an available source of copper in spite of the reaction which occurs between copper sulphate and superphosphate after mixing.

Wentholt (unpublished data) experimented with rates of copper sulphate on lotononis and found higher yields with 2.2 and 0.55 kg ha^{-1} Cu than with 0.14 kg ha^{-1} Cu. In most harvests, 2.2 kg was better than 0.55 kg. Teitzel (1969) found that rates above 2.8 kg ha^{-1} Cu were not required for Schofield stylo. Winter and Jones (1977) found that a mixture of 1.25 kg ha^{-1} Cu and 1.13 kg ha^{-1} Zn gave maximum yields of Cook stylo in each of two years on a soil deficient in both copper and zinc. Use of a mixture of copper and zinc sulphates means that results of Winter and Jones are not conclusive with regard to rate of copper, but taken together, the three references cited above support a general recommendation of 2 kg ha^{-1} Cu.

Residual value of copper in soil is not fully understood but appears to be considerable. Reapplication of copper by Bryan and Evans (1971) six and eleven years after an initial application of 2 kg ha^{-1} Cu gave no yield responses on a copper deficient soil. However Teitzel and Bruce (1973) measured a response in the glasshouse with a sandy soil that had been fertilized with 14 kg ha^{-1} Cu for sugar cane five years previously.

Current recommendations in Queensland are to reapply copper after four to eight years (Bruce 1973, Teitzel *et al.* 1978).

Species differences

Andrew and Thorne (1962) showed that tropical legumes differed in their tolerance of copper deficiency. Considering their results, together with those of Andrew and Bryan (1955, 1958), Walker *et al.* (in press) and Wentholt (unpublished data) the following groupings have been made.

Most responsive	*Stylosanthes* species, lotononis
Intermediate	Siratro, centro, *Indigofera spicata*
Least responsive	Silverleaf desmodium (*Desmodium uncinatum* cv. Silverleaf)

ZINC

Occurrence of zinc deficiency

As for molybdenum and copper, the first instance of zinc deficiency in pastures in northern Australia was obtained with temperate legumes (Andrew and Bryan 1955, 1958). Subsequent responses to zinc with tropical legumes in field experiments are given in Table 2. All of the soils in Table 2 are sandy and acidic. This probably explains why *Stylosanthes* species are the indicator plants in all but one case. Consideration of responses in pot experiments (Andrew and Bryan 1955, Jones and Crack 1970, Crack 1971, Teitzel and Bruce 1971, 1973, Jones 1973, Webb 1975b, Isbell *et al.* 1976) adds phasey bean to the list of species and a humic gley and a neutral red duplex soil to the list of soils. No structured earths have been found deficient.

Most of the field experiments listed were terminated after one year. Hall (personal communication) found that in two experiments (Table 2) a strong response to zinc occurred in the first season (or first effective season) after planting but not in the second and third seasons. Reasons for this are not readily apparent. The only other experiment in Table 2 which ran for more than one year was that of Winter and Jones (1977). They measured responses in each of two years to a mixture of copper and zinc sulphates, but plant analyses suggested that both copper and zinc were still deficient in the second year.

While all soils in Table 2 are acidic there are large areas of alkaline clay soils in northern Australia, some of which have been shown to be low in zinc (Duncan 1967, Webb 1977). In the absence of well adapted pasture legumes for these soils (Cameron 1975) little legume nutrition work has been done on them. Some responses with soybean (*Glycine max*) are known.

Zinc in plants

Zinc deficiency symptoms in Greenleaf desmodium, Siratro, lotononis and glycine have been described by Andrew and Pieters (1972a, 1972b, 1976a, 1976b) while Jones and Clay (1976) described symptoms for Townsville stylo. Andrew and Pieters also stress the complexity of zinc nutrition and warn that the use of plant analysis in the diagnosis of zinc deficiency requires careful interpretation. A number of authors have recorded zinc concentrations of legumes in their experiments and these are given in Table 3. The data are insufficient to reach firm conclusions but do suggest that < 20 ppm Zn is a reasonable indicator of deficiency in the species listed.

Zinc in soils

Of the Queensland surface soils analyzed by Oertel and Giles (1963) most had total zinc contents < 100 ppm Zn but there was a fairly uniform distribution of soils in the range 0 to 100 ppm. This is in contrast to their copper results which showed a more frequent occurrence of soils with contents <20 ppm Cu. Red earths and various podzolic soils had the lowest content. This agrees with the data presented by Stephens and Donald (1958) for southern Australia where podzols and podzolic soils had the lowest group means.

Soil total zinc contents taken from several authors are given in Table 4. As for the copper data most values are low and this analysis could be of diagnostic value. Mackenzie (1966) used a combination of soil total zinc and pH to separate zinc deficient and sufficient soils e.g. for soils of pH 6.5, approximately 5 ppm Zn was a critical value.

A DTPA soil test is in use for zinc (see section on copper) but there are no field-based interpretations. Cox and Kamprath (1972) suggest 0.5 ppm Zn as a general guide for this test. Verrall (unpublished data) studied 15 acid soils in the glasshouse and found no significant response by phasey bean to zinc when DTPA extractable zinc exceeded 0.2 ppm. Webb (1975b) measured responses by Townsville stylo to zinc in six out of nine acid sandy soils ranging in DTPA extractable zinc from 0.1 to 0.4 ppm Zn, but the extractant did not distinguish between responsive and non responsive soils.

Zinc fertilizers

Zinc sulphate has been the most widely used source of zinc in fertilizer experiments but zinc oxide and zinc chloride have sometimes been used. Recommended rate of application for pastures is approximately 1.8 kg ha^{-1} Zn which is conveniently supplied as 8 kg ha^{-1} zinc sulphate (Teitzel and Bruce 1972c, Cook 1978a). Winter and Jones (1977) found that a mixture of 1.13 kg ha^{-1} Zn and 1.25 kg ha^{-1} Cu gave maximum yields of Cook stylo on a soil deficient in both zinc and copper. Commercially, zinc is usually applied as a blend of superphosphate and zinc sulphate. In Queensland, a superphosphate-trace element mixture containing 0.8% Zn, 1.2% Cu and 0.03% Mo is sold.

Little experimentation has been done on the residual value of zinc in the soil but, as for copper, it is thought to last a considerable time and reapplication is recommended after 4 to 8 years (Bruce 1973, Teitzel *et al.* 1978). Bryan and Evans (1971) found no response to additional zinc six and eleven years after an initial application of 1.8 kg ha^{-1} Zn at Beerwah in southern Queensland.

Species differences

No direct comparison of the responsiveness of tropical legumes to zinc has been made. Considering the results of Andrew and Bryan (1958), Russell (1966), and Crack (1971) the following two groups have been made.

More responsive :	*Stylosanthes* species, phasey bean puero (*Pueraria phaseoloides*)
Less responsive :	Greenleaf desmodium

COBALT

No dry matter yield responses to cobalt have been recorded for tropical legumes in Australia although subterranean clover is known to respond on some soils of southern Australia (Powrie 1960). Low soil total cobalt concentrations were found by Bryan *et al.* (1960) in a lateritic podzolic soil (0.03 to 0.05 ppm Co) and a low humic gley soil (0.09 to 0.10 ppm Co) on the coastal lowlands of southern Queensland but it is not known whether soil total cobalt is an index of availability of cobalt to plants. Silverleaf desmodium growing on these soils contained 0.06 to 0.09 ppm Co, but there has been no evidence of cobalt deficiency in grazing animals and no response to cobalt therapy in wether sheep grazing pastures on these soils (Bryan *et al.* 1960, Bryan and Evans 1971). Elsewhere in the coastal lowlands Norton and Hales (1976) have recorded cobalt deficiency in lactating ewes and their lambs grazing pangola grass (*Digitaria decumbens*).

The only response to cobalt therapy in cattle is that reported for 2 year old steers grazing Schofield stylo pastures on a yellow earth in north Queensland (Winter *et al.* 1977). Isbell *et al.* (1976) drew attention to the low cobalt concentration in these yellow earth soils (4 to 5 ppm Co) while Winter and Jones (1977) recorded very low concentrations of cobalt in unfertilized Cook stylo (0.015 ppm and 0.003 ppm in successive years) grown on them. Seasonal changes in the cobalt concentration in Schofield stylo are given by Winter *et al.* (1977).

Little is known of the cobalt status of other soils of northern Australia or of the ability of tropical legumes to accumulate cobalt in their tissues. In the experiments of Winter and Jones (1977), cobalt concentration in Cook stylo increased with rate of applied cobalt but concentrations were still low from an animal nutrition point of view. Collection of information of this type is handicapped by the difficulty in analyzing for cobalt but would be relevant to animal nutrition.

MANGANESE

Although manganese has often been included as a treatment in testing the nutrient status of soils in tropical and sub-tropical Australia no deficiencies have been found. Isbell *et al.* (1976) drew attention to the low soil total manganese (12 to 20 ppm Mn) in some yellow and red earths in north Queensland but a deficiency was not confirmed by Winter and Jones (1977) in subsequent field experimentation. However they did find that Cook stylo grown in the absence of manganese contained quite low manganese concentrations (12 to 21 ppm Mn).

Manganese toxicity is known on some soils (Fergus 1954) of northern Australia, particularly where high rates of acidifying fertilizer have been used (Siman *et al.* 1971). Andrew and Hegarty (1969) found that tropical legumes as a group were as much affected by manganese excess as temperate legumes. They found that centro, Townsville stylo and lotononis were relatively tolerant to high levels of manganese, phasey bean, leucaena (*Leucaena leucocephala*) and Silverleaf desmodium were intermediate in tolerance and glycine and Siratro much less tolerant. Toxicity threshold concentrations of manganese in the plant tops are also given. In their paper Andrew and Pieters (1970) describe manganese toxicity symptoms in all of the above mentioned tropical legumes except leucaena.

Instances of manganese toxicity in the field have been given by Diatloff and Luck (1972) with glycine and Greenleaf desmodium and by Philpotts (1975) with glycine and Siratro. There is no published information relating manganese toxicity in tropical legumes to soil tests for manganese.

FUTURE RESEARCH

Techniques

The number of pot experiments that has been conducted far exceeds the number of field experiments. The pot culture technique appears more sensitive than field experimentation in detecting molybdenum deficiency but gives similar results for copper and zinc. Since confirmation of pot responses in the field is required, the best use of pot experiments appears to be in the regional soil fertility screening investigations where a large number of soils can be tested in the glasshouse and responses can be followed up in field experiments at a few representative sites. Another application in areas of developed pastures could be in re-testing soils previously screened (or in comparing virgin and developed soils) to check on the appearance of new deficiencies or on the re-appearance of previously corrected deficiencies. Any responses need confirmation in the field but the pot technique has the advantage of enabling a large number of sites to be tested under comparable conditions with nutrition as the only limiting factor. For these experiments, soil should be collected from as many sites as practicable in a fertilized area to minimize uneveness in distribution of nutrients in the field and then sieved and potted with a minimum of drying and storage to prevent nutrient release—particularly nitrogen, in view of its effect on molybdenum requirement by legumes.

In field experiments there are advantages in following responses over more than the first growing season. Data collected should include: full soil description and classification; fertility analyses, including some determinations down the profile (pH, conductivity) and nitrate analyses where molybdenum is tested; plant analyses; and some indication of depth of rooting.

While the distribution of trace elements in fertilizer mixtures remains for the manufacturers to resolve, avoidance of mixtures in experimentation seems desirable, or at least, only well mixed samples whose composition has been checked by analysis should be used.

Diagnosis

For each of the trace elements there is a need for more basic research into their chemistry in soils of northern Australia. This is necessary for a better understanding of availability and residual value and also to provide a unifying principle among deficient soils. Undoubtedly such research has been restricted by the difficulty in analysing for these elements, particularly molybdenum and cobalt, but some improved analytical techniques are now available (Little and Kerridge 1978).

Interpretations based on field experimentation are required for extractable trace element analyses. None of the analyses currently used can be properly interpreted, nor have alternative procedures been evaluated. Molybdenum adsorption by soils deserves more study, probably in conjunction with extractable molybdenum. The diagnostic use of total copper and zinc analyses also needs to be evaluated.

At present, plant analysis is only a general guide to deficiency and some new approach is required. Seed analysis could be rewarding, as could nodule analysis for molybdenum.

A philosophy sometimes expressed with respect to trace element application is that accurate diagnosis of requirement is not necessary as the additional costs are small and usage can be regarded as an "insurance measure". Current fertilizer prices do not support this philosophy. Molybdenized superphosphate costs approximately 7 to 20% more than ordinary superphosphate, depending on molybdenum content. An application of 100 g ha^{-1} Mo adds approximately 10% to the fertilizer cost if applied in 250 kg ha^{-1} superphosphate. Another consideration is that excessive use of molybdenum causes problems with animal health. Superphosphate fortified with copper costs 50% more than ordinary superphosphate, while the addition of copper, zinc and molybdenum almost doubles the cost. The "insurance" philosophy may be acceptable for establishment fertilizers but is extravagant and potentially harmful for regular fertilizer applications.

REFERENCES

ANDERSON, A. J. (1956a)—Molybdenum as a fertilizer. *Advances in Agronomy*. 8: 163-202.
ANDERSON, A. J. (1965b)—Molybdenum deficiencies in legumes in Australia. *Soil Science*. 81: 173-258.

Anderson, A. J., and Arnott, R. H. (1953)—Fertilizer studies on basaltic red loam soil from the Lismore district, New South Wales. *Australian Journal of Agricultural Research.* **4:** 29-43.

Andrew, C. S. (1963)—Copper deficiency symptoms of some tropical and temperate pasture legumes. *Australian Journal of Agricultural Research.* **14:** 654-59.

Andrew, C. S., and Bryan, W. W. (1955)—Pasture studies on the coastal lowlands of subtropical Queensland. I. Introduction and initial plant nutrient studies. *Australian Journal of Agricultural Research.* **6:** 265-90.

Andrew, C. S., and Bryan, W. W. (1958)—Pasture studies on the coastal lowlands of subtropical Queensland III. The nutrient requirements and potentialities of *Desmodium uncinatum* and white clover on a lateritic podzolic soil. *Australian Journal of Agricultural Research.* **9:** 267-85.

Andrew, C. S., and Hegarty, M. P. (1969)—Comparative responses to manganese excess of eight tropical and four temperate pasture legume species. *Australian Journal of Agricultural Research.* **20:** 687-96.

Andrew, C. S., and Pieters, W. H. J. (1970)—Manganese toxicity symptoms of one temperate and seven tropical pasture legumes. C.S.I.R.O., Australia, Division of Tropical Pastures, Technical Paper No. 4.

Andrew, C. S., and Pieters, W. H. J. (1972a)—Foliar symptoms of mineral disorders in *Desmodium intortum.* C.S.I.R.O. Australia, Division of Tropical Pastures, Technical Paper No. 10.

Andrew, C. S., and Pieters, W. H. J. (1972b)—Foliar symptoms of mineral disorders in *Phaseolus atropurpureus.* C.S.I.R.O., Australia, Division of Tropical Pastures, Technical Paper No. 11.

Andrew, C. S., and Pieters, W. H. J. (1976a)—Foliar symptoms of mineral disorders in *Lotononis bainesii.* C.S.I.R.O., Australia, Division of Tropical Agronomy, Technical Paper No. 17.

Andrew, C. S., and Pieters, W. H. J. (1976b)—Foliar symptoms of mineral disorders in *Glycine wightii.* C.S.I.R.O., Australia, Division of Tropical Agronomy, Technical Paper No. 18.

Anning, P. (1977)—A preliminary field assessment of the nutrient status of a red earth on Kalinga Station, Cape York Peninsula. Queensland Department of Primary Industries, Agriculture Branch Project Report No. P-7-77.

Barrow, N. J. (1978)—Inorganic reactions of phosphorus, sulphur, and molybdenum in soil. Proceeding of Workshop on Mineral Nutrition of Tropical Legumes on Acid Tropical Soils. Brisbane, 1978 (in press).

Barrow, N. J., and Spencer, K. (1971)—Factors in the molybdenum and phosphorus status of soils on the Dorrigo Plateau of New South Wales. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **11:** 670-76.

Bishop, H. G. (1974)—Pasture investigations in the sandy forest country of north-west Queensland. 1. Nutritional Requirements. *Queensland Journal of Agricultural and Animal Sciences.* **31:** 329-36.

Bruce, R. C. (1973)—Fertilizer recommendations for pasture establishment and maintenance. *In* "Developing a property in the Southern Wallum". Department of Primary Industries, Queensland, mimeographed report.

Bryan, W. W. (1973)—A review of research findings concerned with pastoral development on the Wallum of south-eastern Queensland. *Tropical Grasslands.* **7:** 175-94.

Bryan, W. W., and Evans, T. R. (1971)—Grazing trials on the Wallum of south-eastern Queensland. 3. A nursery grazed by sheep. *Australian Journal of Experimental Agriculture and Animal Husbandry* **11:** 633-39.

Bryan, W. W., Thorne, Peggy M., and Andrew, C. S. (1960)—Cobalt status of the Wallum. *Journal of the Australian Institute of Agricultural Science.* **26:** 273-75.

Cameron, D. G.(1975)—Regional pasture development and associated problems. III Queensland. *Tropical Grasslands.* **9:** 93-100.

Cassidy, G. J. (1957)—Pasture improvement on the Mary Valley alluvial and coastal hillside soils. *Queensland Agricultural Journal.* **83:** 297-311.

Cassidy, G. J. (1967)—Pastures that help dairymen to succeed. *Queensland Agricultural Journal.* **93:** 656-69.

Cook, B. G. (1978a)—Pastures for the Gympie district. Part 2. Pasture species. *Queensland Agricultural Journal.* **104:** 162-73.

Cook, B. G. (1978b)—Pastures for the Gympie district. Part 3. *Queensland Agricultural Journal.* **104:** 226-31.

Cox, F. R., and Kamprath, E. J. (1972)—Micronutrient soil tests. *In* "Micronutrients in Agriculture". Proceedings of a symposium held at Muscle Shoals, Alabama, April 20-22, 1971. (Soil Science Society of America, Madison, Wisconsin).

Crack, B. J. (1971)—Studies on some neutral red duplex soils (Dr 2.12) in north-eastern Queensland. 2. Glasshouse assessment of plant nutrient status. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **11:** 336-42.

Diatloff, A., and Luck, P. E. (1972)—The effects of the interactions between seed inoculation, pelleting and fertilizer on growth and nodulation of desmodium and glycine on two soils in S.E. Queensland. *Tropical Grasslands* **6:** 33-38.

Dick, A. T. (1956)—Molybdenum in animal nutrition. *Soil Science.* **81:** 229-36.

Douglas, N. J. (1962a)—Fertilizers promote legume growth at Cooran. *Queensland Agricultural Journal.* **88:** 133-35.

Douglas, N. J. (1962b)—Molybdenum and super improve Nambour clover. *Queensland Agricultural Journal.* **88:** 83-85.

Douglas, N. J., and Luck, P. E. (1964)—Farmer's guide to tropical pastures in S.E. Queensland. *Queensland Agricultural Journal.* **90:** 583-94.

Duncan, O. W. (1967)—Correction of zinc deficiency in maize on the Darling Downs, Queensland. *Queensland Journal of Agricultural and Animal Sciences.* **24:** 293-99.

Follett, R. H., and Lindsay, W. L. (1971)—Changes in DTPA extractable zinc, iron, manganese, copper in soils following fertilization. *Soil Science Society of America Proceedings.* **35:** 600-02.

Fergus, I. F. (1954)—Manganese toxicity in an acid soil. *Queensland Journal of Agricultural Science.* **11:** 15-27.

Gartner, R. J. W., Young, J. G., and Pepper, Patricia M. (1968)—Hepatic copper concentration of steers grazing pastures on developed wet heath land in south-eastern Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **8:** 679-82.

Gilkes, R. J., and Sadlier, S. B. (1978)—The availability to wheat of copper from various sources including copper superphosphate. *Australian Journal of Soil Research.* **16:** 113-20.

Grigg, J. L. (1953)—Determination of available molybdenum in soils. *New Zealand Journal of Science and Technology* **34A:** 405-14.

Hall, R. L. (1970)—Pasture development in the spear grass region at Westwood in the Fitzroy Basin. *Tropical Grasslands* **4:** 77-84.

Havilah, E. J., and Mears, P. T. (1968)—Plant nutrition research—beef cattle pastures of coastal northern N.S.W. *Tropical Grasslands.* **2:** 84-91.

Isbell, R. F., Jones, R. K., and Gillman, G. P. (1976)—Plant nutrition studies on some yellow and red earth soils in northern Cape York peninsula. 1. Soils and their nutrient status. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **16:** 532-41.

Isbell, R. F., and Smith, G. McL. (1976)—Some properties of red, yellow, and grey massive earths in north Queensland C.S.I.R.O., Australia, Division of Soils, Technical Paper No. 30.

Jensen, H. L. (1948)—Nitrogen fixation in Leguminous plants. VII. The nitrogen fixing activity of root nodule tissue in *Medicago* and *Trifolium. Proceedings of the Linnean Society of New South Wales.* **72:** 265-83.

Jensen, H. L., and Betty, R. C. (1943)—Nitrogen fixation in leguminous plants. III. Importance of molybdenum in symbiotic nitrogen fixation. *Proceedings of the Linnean Society of New South Wales.* **68:** 1-8.

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:** 961-68.

Jones, R. K. (1973)—Studies on some deep sandy soils in Cape York Peninsula, North Queensland. 2. Plant nutrient status *Australian Journal of Experimental Agriculture and Animal Husbandry.* **13:** 89-97.

Jones, R. K. (1974)—A study of the phosphorus responses of a wide range of accessions from the genus Stylosanthes *Australian Journal of Agricultural Research.* **25:** 847-62.

Jones, R. K., and Clay, H. J. (1976)—Foliar symptoms of nutrient disorders in Townsville stylo (*Stylosanthes humilis*) C.S.I.R.O Australia, Division of Tropical Agronomy. Technical Paper No. 19.

Jones, R. K., and Crack, B. J. (1970)—Studies on some solodic soils in north-eastern Queensland. 2. Glasshouse assessment of plant nutrient status. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **10:** 342-49.

Kerridge, P. C. (1972)—Nutrition of dairy pastures in north Queensland. C.S.I.R.O., Australia, Division of Tropical Pastures, Annual Report 1971-72: 43.

Kerridge, P. C., Andrew, C. S., and Murtha, G. G. (1972)—Plant nutrient status of soils of the Atherton Tableland, North Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **12:** 618-27.

Kerridge, P. C., Cook, B. G., and Everett, M. L. (1973)—Application of molybdenum trioxide in the seed pellet for subtropical pasture legumes. *Tropical Grasslands.* **7:** 229-32.

Kerridge, P. C., and Everett, M. L. (1975)—Nutrient studies on some soils from Eungella and East Funnel Creek, Mackay hinterland, Queensland. *Tropical Grasslands.* **9:** 219-28.

Kerridge, P. C., and White, R. E. (1977)—The residual effect of molybdenum fertilizer on a krasnozem on basalt at Maleny, south east Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **17:** 669-73.

Little, I. P., and Kerridge, P. C. (1978)—A laboratory assessment of the molybdenum status of nine Queensland soils *Soil Science.* **125:** 102-6.

Loneragan, J. F. (1970)—The contribution of research in plant nutrition to the development of Australian pastures. Proceedings of the XI International Grassland Congress, Surfers Paradise, Australia: A13-A22.

Luck, P. E., and Douglas, N. J. (1966)—Dairy pasture research and development in the near North Coast centred on Cooroy, Queensland. The Tropical Grassland Society of Australia, Proceedings No. 6, 35-50.

McKenzie, R. M. (1966)—The relation of laboratory analyses for copper, zinc, and molybdenum in some Victorian soils to the results of field trials. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **6:** 170-74.

McLachlan, K. D. (1953)—Phosphorus, sulphur and molybdenum deficiencies on some soils of the Northern Territory. *Journal of the Australian Institute of Agricultural Science.* **19:** 197-99.

McLachlan, K. D. (1955)—Phosphorus, sulphur, and molydbenum deficiencies in soils from eastern Australia in relation to nutrient supply and some characteristics of soil and climate. *Australian Journal of Agricultural Research.* **6:** 673-84.

Mannetje, L. 't., Shaw, N. H., and Elich, T. W. (1963)—The residual effect of molybdenum fertilizer on improved pastures on a prairie-like soil in subtropical Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **3:** 20-25.

Meagher, W. R., Johnson, C. M., and Stout, P. R. (1952)—Molybdenum requirement of leguminous plants supplied with fixed nitrogen. *Plant Physiology.* **27:** 223-30.

Mears, P. T., and Barkus, B. (1970)—Response of *Glycine wightii* to molybdenized superphosphate on a krasnozem. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **10:** 415-25.

Norton, B. W., and Hales, J. W. (1976)—A response of sheep to cobalt supplementation in south-eastern Queensland. *Proceedings of the Australian Society of Animal Production.* **11:** 393-96.

Oertel, A. C., and Giles, J. B. (1963)—Trace element contents of some Queensland soils. *Australian Journal of Soil Research.* **1:** 215-22.

Ostrowski, H. (1969)—Tropical pastures for south-east Queensland. *Queensland Agricultural Journal.* **95:** 508-16.

Ostrowski, H. (1970)—Molybdenized superphosphate requirement for pasture establishment on red forest soils in subtropical Queensland. Proceedings of the XI International Grassland Congress, Surfers Paradise, Australia: 124-26.

Ostrowski, H., Diatloff, A., and Williams, H. R. (1978)—Molybdenum responses of Siratro (*Macroptilium atropurpureum*) on a red volcanic soil in coastal south east Queensland. *Tropical Grasslands.* **12:** 75-79.

Philpotts, Helen (1975)—The effect of lime and *Rhizobium* strain on the nodulation of *Glycine wightii* and *Macroptilium atropurpureum* on acid soils. *Tropical Grasslands.* **9:** 37-44.

Powrie, J. K. (1960)—A field response by subterranean clover to cobalt fertilizer. *Australian Journal of Science.* **23:** 198-99

Roe, R., and Jones, R. J. (1966)—Soil fertility and pasture species investigations on soils derived from phyllites in the North Deep Creek and Kin Kin areas. The Tropical Grassland Society of Australia, Proceedings No. 6, 13-22.

Russell, J. S. (1966)—Plant growth on a low calcium status solodic soil in a subtropical environment. I. Legume species calcium carbonate, zinc, and other minor element interactions. *Australian Journal of Agricultural Research.* **17:** 67:-86.

Shaw, N. H., Gates, C. T., and Wilson, J. R. (1966)—Growth and chemical composition of Townsville lucerne (*Stylosanthes humilis*). 1. Dry matter yield and nitrogen content in response to superphosphate. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **6:** 150-56.

Siman, A., Cradock, F. W., Nicholls, P. J., and Kirton, H. C. (1971)—Effects of calcium carbonate and ammonium sulphate on manganese toxicity in an acid soil. *Australian Journal of Agricultural Research.* **22:** 201-14.

Spencer, K., and Govaars, A. G. (1974)—An assessment of the nutrient status of soils in northern East Gippsland. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **14:** 85-92.

Stephens, C. G., and Donald, C. M. (1958)—Australian soils and their responses to fertilizers. *Advances in Agronomy.* **10:** 167-256.

Swain, F. G. (1959)—Responses to molybdenum three years after previous application on red basaltic soils on the Far North Coast of *N.S.W. Journal of the Australian Institute of Agricultural Science.* **25:** 51-54.

Teitzel, J. K. (1969)—Responses to phosphorus, copper and potassium on a granite loam of the wet tropical coast of Queensland. *Tropical Grasslands.* **3:** 43-8.

Teitzel, J. K. and Bruce, R. C. (1971)—Fertility studies of pasture soils in the wet tropical coast of Queensland. 2. Granitic soils. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **11:** 77-84.

Teitzel, J. K., and Bruce, R. C. (1972a)—Fertility studies of pasture soils in the wet tropical coast of Queensland. 3. Basaltic soils. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **12:** 49-54.

Teitzel, J. K., and Bruce, R. C. (1972b)—Fertility studies of pasture soils in the wet tropical coast of Queensland. 4. Soils derived from metamorphic rocks. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **12:** 281-87.

Teitzel, J. K., and Bruce, R. C. (1972c)—Pasture fertilizers for the wet tropics. *Queensland Agricultural Journal.* **98:** 15-23

Teitzel, J. K., and Bruce, R. C. (1973)—Fertility studies of pasture soils in the wet tropical coast of Queensland. 6. Soils derived from beach sand. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **13:** 312-18.

Teitzel, J. K., Standley, J., and Wilson, R. J. (1978)—Maintenance fertilizer strategies for wet tropics pastures. *Queensland Agricultural Journal.* **104:** 126-30.

Truong, N. V., Andrew, C. S., and Skerman, P. J. (1967)—Responses by Siratro (*Phaseolus atropurpureus*) and white clover (*Trifolium repens*) to nutrients on solodic soils at Beaudesert, Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **7:** 232-36.

Vinogradova, Kh., G. (1943)—Presence of molybdenum in Leguminosae. *Doklady Akademii Nauk S.S.S.R.* **40:** 26-9.

Walker, B., Kerridge, P. C., and Webb, A. A. (in press)—Soil fertility studies for pastures in the Mackay wet tropical coast of central Queensland. *Tropical Grasslands* (in press).

Webb, A. A. (1975a)—Studies on major soils of the Forsayth Granite. 2. Glasshouse nutrient assessment. *Queensland Journal of Agricultural and Animal Sciences.* **32:** 37-46.

Webb, A. A. (1975b)—Plant nutrient status of soils of the Mayvale Land System, north Queensland. *Queensland Journal of Agricultural and Animal Sciences.* **32:** 19-26.

Webb, A. A. (1977)—Studies on the gilgaied clay soils (Ug 5.2) of the Highworth Land System in central Queensland. 2. Glasshouse assessment of plant nutrient status. *Queensland Journal of Agricultural and Animal Sciences.* **34:** 67-74.

Williams, C. H., and Andrew, C. S. (1970)—Mineral nutrition of pastures. *In* "Australian Grasslands". (Ed. R. M. Moore). Australian National University Press: Canberra.

Winter, W. H., and Jones, R. K. (1977)—Nutrient responses on a yellow earth soil in northern Cape York Peninsula. *Tropical Grasslands.* **11:** 247-55.

Winter, W. H., Siebert, B. D., and Kuchel, R. E. (1977)—Cobalt, phosphorus and copper deficiency in cattle on improved pastures in northern Cape York Peninsula. *Australian Journal of Experimental Agriculture and Animal Husbandry.* **17:** 10-15.

(Accepted for publication September 8, 1978)