CHAPTER 5 : PLANT NUTRITION POT TRIALS WITH BOUGAINVILLE MINE TAILINGS

5.1 Nutrient Addition and Omission Pot Trials

5.1.1 Introduction

In order to successfully revegetate mine wastes it is necessary to have an understanding of their ability to supply plant nutrients under the range of chemical conditions expected as they weather. Pot trials can be used to assess which nutrients are deficient for the growth of selected indicator plants.

Hartley (1976) established that fresh (un-oxidising) Bougainville mine tailings (pH 7.5 to 9) were deficient in N, P and B. This is supported by the soil analyses of Chapter 4. The mine wastes become acid as a result of residual sulphide oxidation. Acidity can affect plant growth through a number of mechanisms, particularly Al toxicity and induced nutrient imbalances. Liming of acid tailings was shown to improve plant growth (Marshman, 1980a).

The aim of this experiment was to examine the response of plants to a range of nutrient additions when growing on both acid and limed acid tailings. The results could lead to the development of a fertiliser strategy for the revegetation of the mine wastes.

5.1.2 Materials and Methods

General

Four separate but similar pot trials were established. They were a nutrient addition and a nutrient omission trial, each in turn divided in two, with a legume (*Desmodium intortum*) and a grass (*Paspalum dilatatum*) as the indicator species. Both species grow well around the Panguna mine site and data are available on their performance under a range of nutrient regimes.

Each pot trial had a number of fertiliser treatments in combination with a lime/no-lime addition. There were four replicates per treatment. The tailings were collected from the banks of the lower Jaba river system at XS29. The material had been deposited for approximately 18 months. The tailings were acid, contained no organic matter and soil tests indicated that deficiencies in N, P, K, Ca, Mg and B were likely. The CEC was low and exchangeable Al moderate. EDTA extractable Cu was high (Table 5.1).

TABLE 5.1 : SOIL AND PARTICLE SIZE ANALYSIS OF TAILINGS USED IN THE FERTILISER ADDITION AND OMISSION POT TRIALS; BEFORE TREATMENT*

Soil Analysis	Result	Screen Size (microns)	% Passing
Nt%	<0.003	600	95
OC %	0.04	300	73
P av ppm	5.6	150	31
K ex me%	0.07	106	16
Ca ex me%	0.45	53	3
Mg ex me%	0.11		
Na ex me%	<0.02		
Al ex ppm	119.0		
Mn av ppm	4.9		
Cu av ppm	98.0		
B av ppm	<0.2		
Mo av ppm	0.7		
St%	0.23		
SO_4-S t ppm	117.0		
CEC me%	3.0		
Cond. m	0.06		
pH 1:5 H_2O	4.5		

* Average of two bulk samples taken as the pots were being filled.

** Analyses as described in Chapter 4.

t = total, av = available, ex = exchangeable.

Treatments

Calcium hydroxide (lime) was applied to one half the pots at a rate of 2 tonne/ha. The aim being to lime to neutrality.

For the addition treatments, a basal fertiliser of diammonium phosphate at the equivalent of 250 kg/ha, and representing N at 50 kg/ha and P at 21.5 kg/ha was used. The base fertiliser was ground in an industrial blender and sub-sampled to gain a representative sample. Each treatment then had one element added as analytical grade reagents. The treatments are summarised in Table 5.2. Fertiliser rates were calculated on an area asis.

Nitrogen, P, K, Ca, Mg and B were added because soil tests indicated that deficiencies may occur. Acid mineral soils have the ability to fix the anions of P, S and Mo. Tailings have relatively large amounts of S and Mo in the primary mineral form. However, their availability to plants under acid conditions was uncertain. As such, S and Mo treatments were added. Zinc was added because of doubts about its availability after lime and P fertiliser addition.

For the omission treatments a base fertiliser containing N, P, K, Mg, B, Zn and Mo was applied to the controls. For each treatment one element was subtracted (Table 5.3).

Procedure

Plastic pots 13 cm in diameter were set up in a greenhouse in randomised blocks. Two kg of air dried tailings were weighed into each pot. Lime was applied factorially to the pots and mixed into the top eight cm. Fertiliser treatments were applied to the surface of the respective pots, with the minor nutrients applied as a solution. Pots were watered to field capacity gravimetrically and maintained at, or close to that condition for the remainder of the trial. Pots were re-randomised within four blocks three times per week and at that time they were weighed and brought up to field capacity. Pots were freely draining.

Paspalum and Desmodium seed was germinated in sterile sand. Desmodium seed was inoculated with Cowpea Rhizobium. After one week equilibration of lime and fertiliser, seven, two week old seedlings were transferred to their respective pots. After a further two weeks the plants were thinned to four per pot with dead or the smaller seedlings being removed.

Twelve weeks after transplanting, plant tops were harvested one cm. above the surface and the roots washed free of tailings. Plant tops and roots were separately washed six times in deionised water, dried for 48 hours in a forced draught oven at

TABLE 5.2 : FERTILISER ADDITION TREATMENTS, POT TRIAL WITH ACID AND LIMED TAILINGS

Treatments	Total Rate of Element Added (kg/ha)	Additional Element Added As :
Control		
Control + N	120	NH_4NO_3
Control + P	60	$Na_2HPO_4.2H_2O$ + $NaH_2PO_4.2H_2O$
Control + K	60	KCl
Control + Ca	150	$CaCl_2$
Control + Mg	50	$MgCl_2.6H_2O$
Control + Zn	2.0	$ZnSO_4.7H_2O$
Control + Mo	0.6	$Na_2MoO_4.2\ H_2O$
Control + B	1.0	$Na_2B_4O_7.10H_2O$
Control + S	25	Na_2SO_4
Control + Fe	150 (as FeEDTA)	FeEDTA

TABLE 5.3 : BASE FERTILISER ADDED TO THE OM ISSION TREATMENTS POT TRIAL WITH ACID AND LIMED TAILINGS*

Element	Rate (kg/ha)	Element Applied As:
N	100	$Ca(NO_3)_2$
P	45	$K_2HPO_4.2H_2O$ + $NaH_2PO_2.2H_2O$
K	58	$K_2HPO_4.2H_2O$
Ca	143	$Ca(NO_3)_2$
Mg	50	$MgCl_2.6H_2O$
Zn	2	$ZnSO_4.7H_2O$
Mo	0.6	$Na_2MoO_4.2H_2O$
B	1	$Na_2B_4O_7.10H_2O$

*For the omission treatments -

Control - N, Ca was added as $CaCl_2$.
Control - P, K was added as KCl.
Control - K, Additional P was added as $Na_2HPO_4 \cdot 2H_2O$.
Control - Ca, N was added as $NaNO_3$.

75^0 C, weighed, bulked per treatment (all replicates) and analysed for nutrients. Tailings were bulked per treatment and analysed for plant available and total nutrients. For the lime addition treatments tailings were divided into the limed zone and the non-limed zone.

Tailings were analysed as outlined in Chapter 4.

Foliar samples were ground in an industrial blender and analysed by the BCL Environmental Laboratory as outlined below. As a check the U.S. Bureau of Commerce National Basic Standards 1571 (orchard leaves) and 1572 (citrus leaves) were used.

The analyses used were -

Nitrogen : Kjeldahl digestion method.

Calcium, K, Mg, Cu, Mn, Zn, Fe and Al : Sample digested with nitric and percloric acid and determined with a Perkin Elmer 603 AAS.

Phosphorus : Sample digested with nitric and perchloric acid and P determined as a yellow phosphor molybdate complex using a Varian UV/VIS model 635 spectrophotometer.

Sulphur : The sample was digested in a saturated magnesium nitrate solution, the residue ashed to magnesium oxide plus sulphate, the ash dissolved in dilute HCl and the S determined by barium chloride precipitation - gravimetric finish.

Boron : Sample ashed at 500°C and dissolved in dilute HCl. Oxalic acid - curcumin added, evaporated to dryness, the residue dissolved in ethanol, filtered and adsorption measured on a Varian UV/VIS spectrophotometer model 635.

Molybdenum : Sample digested in nitric and perchloric acids and Mo determined by the thiocyanate - stannous chloride colo rimetric method using a Bausch and Lomb Model 88 Spectrophotometer.

5.1.3 Results and Discussion

No-Lime Treatments

Plants in pots not receiving lime failed to respond to the treatments. Thus the experiment was reduced by half.

All Desmodium plants had died by week eight and all Paspalum plants except for the FeEDTA addition by the end of the trial. Other than FeEDTA addition, treatment did not appear to affect rate of plant death or the symptoms exhibited by plants.

Desmodium seedlings planted without lime treatment did not grow and plants rapidly suffered from interveinal chlorosis, followed by general chlorosis, necrosis and death. *Paspalum* seedlings were generally more hardy although they did not grow. Seedlings became dull coloured and the leaf sheaths tinged with purple anthocyanin before becoming necrotic.

Paspalum plants with FeEDTA addition lived until the end of the experiment but they exhibited little growth. However, they looked reasonably healthy. Soil analyses for the FeEDTA addition treatment were not significantly different from the control. Hangar (1969), added FeEDTA to solution cultures containing red clover plants and excess Cu, Mn or Mo and found that in all cases plant growth was improved. Whether the improved survival of the *Paspalum* was due to chelating effects of EDTA on Cu, Al or Mn, the extra Fe ameliorating Fe deficiencies, or a combination of the above, is uncertain.

The rapid death of all plants (excluding the *Paspalum* FeEDTA treatments) for the no-lime treatments suggests some pH mediated toxicity rather than nutrient deficiencies. The pH of the tailings originally placed in the pots was 4.5. Following addition of fertiliser and equilibration over the 12 weeks of the experiment, pH dropped in the order of one unit to an average of 3.6 for all treatments without lime. The precise reason for the pH drop is uncertain. It may have been due to a combination of factors including the addition of fertiliser salts, residual pyrite oxidation and the fact that the pots were not under a leaching regime. pH below 4.5 has not been measured in tailings in the field, thus the addition of fertiliser salts and the non-leaching of acidity generated by pyrite oxidation may have contributed significantly to the pH fall and rapid plant death.

Helyar (1978) considered that one of the problems with pot trials investigating Al toxicity was that they frequently involved the mixing of basal fertilisers with the soil. This favours equilibration between the added cations and exchangeable Al, leading to more severe Al toxicity in the pot than would be expected under field conditions. Similarly, an increase in Al in soil solutions decreases pH.

Corresponding to the very low pH were high levels of exchangeable Al and EDTA extractable Cu (Table 5.4). Mean exchangeable Al for all pots without lime (regardless of treatment) was 181 + 41 ppm. Mean CEC was 3.3 $\pm$ 0.4 me%. This gives a mean exchangeable Al saturation of the CEC of 61%. Thus, Al toxicity was a likely cause of plant failure (Kamprath, 1970; 1978). Observed foliar symptoms for the *Paspalum* plants in particular were consistent with Al toxicity. The chloritic foliar symptoms of the *Desmodium* plants were also consistent with symptoms of Cu toxicity which the soil conditions favoured (Robson and Reuter, 1981). Mean EDTA extractable Cu was 150 $\pm$ 41 ppm.

TABLE 5.4 : SOIL ANALYSES FOR POTS NOT RECEIVING LIME, BUT RECEIVING NUTRIENT ADDITION AND OMISSION TREATMENTS *

Analyses	Nutrient Addition**				Nutrient Omission+			
	Desmodium		Paspalum		Desmodium		Paspalum	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
N tot ppm	73	16	64	19	37	13	52	26
P av ppm	5.4	1.5	7.7	2.4	8.4	2.7	8.3	2.1
K ex me %	0.02	0.01	0.02	0.01	0.16	0.02	0.16	0.02
Ca ex me %	0.36	0.09	0.61	0.09	0.53	0.12	0.57	0.07
Mg ex me %	0.20	0.03	0.28	0.05	0.29	0.06	0.23	0.05
Na ex me %	0.02	0.01	0.03	0.07	0.02	0.02	0.04	0.02
CEC	3.31	0.11	3.43	0.16	2.86	0.15	3.62	0.41
pH 1:5	3.5	0.1	3.4	0.1	3.8	0.1	3.7	0.2
Al ex ppm	197	18	230	26	131	20	152	12
Mn av ppm	7.9	0.7	10.1	1.0	7.0	0.7	7.5	1.1
Mo av ppm	1.0	0.6	1.4	0.9	2.2	0.8	2.3	0.6
Cu av ppm	170	15	159	14	143	15	122	14
Zn av ppm	31	4	29	7	27	4	26	25
Fe av ppm	183	22	186	28	129	16	185	18
S tot %	0.26	0.02	0.23	0.02	0.23	0.02	0.25	0.03
SO_4-S tot ppm	536	55	726	55	362	58	356	21

* Mean analyses for all pots irrespective of nutrient treatment.

In most cases nutrient addition or omission slightly affected the particular soil test. Treatments did not significantly affect soil analyses within experiments.

** Mean of 11 nutrient addition treatments.
+ Mean of 9 nutrient omission treatments.

tot = total, av = available, ex = exchangeable, Analyses as outlined in Chapter 4.

It is apparent then, that under similar conditions in the field, liming to an adequate pH is required for plant establishment.

Addition of Nutrients in the Presence of Lime

Liming the acid tailings permitted plant establishment and growth. The results for the addition and omission trials refer to the lime treatments only. They were analysed as a randomised block experiment.

Nutrient addition significantly affected the dry weights of *Desmodium* tops and roots ($p<0.01$) and *Paspalum* tops ($p<0.01$). There was no significant difference between replicates (Table 5.5).

Growth of the *Desmodium* plants was poor with P addition the only nutrient to significantly increase the dry weights of tops and roots compared to the control ($p<0.05$). Potassium addition also appeared to increase dry weight production of tops over those of the control, although the increase was not significant (Figure 5.1).

The *Paspalum* plants as a group performed better than the *Desmodium*. Nitrogen addition significantly increased tops dry weight ($p<0.05$) and Ca addition significantly decreased tops dry weight ($p<0.05$) compared to the control. Boron and Fe addition slightly increased tops dry weights and the other nutrient additions slightly decreased tops dry weights although they were not significant (Figure 5.2). Root dry weights were not significantly affected by nutrient additions.

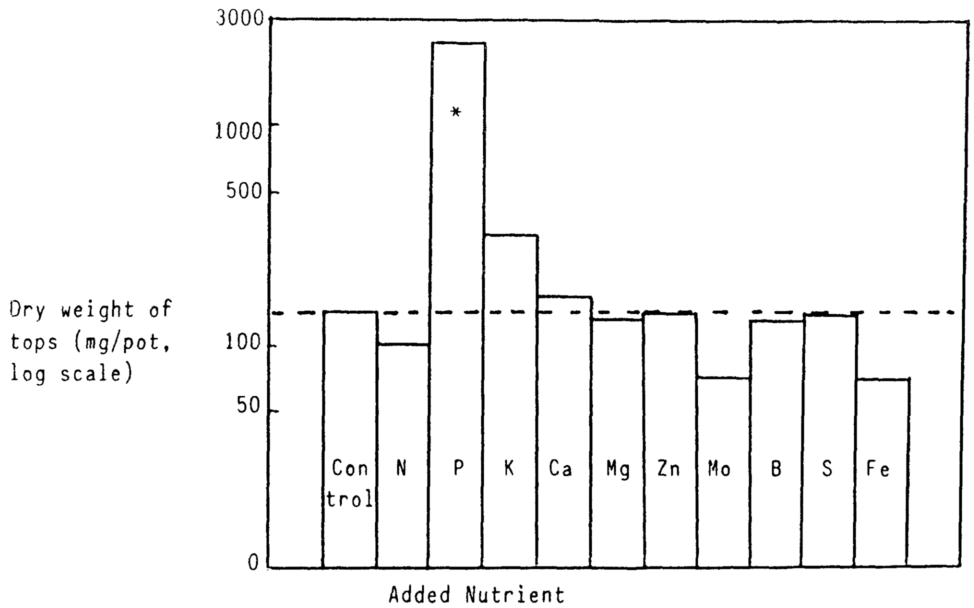
In all treatments, foliar P concentrations (Table 1, Appendix 1) for the *Desmodium* plants were low to deficient (0.09 to 0.12% P), with P addition substantially increasing plant growth without a similar effect on foliar P concentrations; most probably as a result of nutrient dilution. For all treatments, foliar Zn concentrations were high and for the B addition treatment, foliar Cu and Zn concentrations were very high. All other measured foliar nutrients were in the optimum range (Andrew and Pieters, 1972a).

Although there was little variation between foliar P concentrations, they were weakly correlated with tops dry weight such that;

Tops weight (gm) = $-3.341 + 36.261$ P (foliar), $r^2 = 0.324$, $p<0.1$.

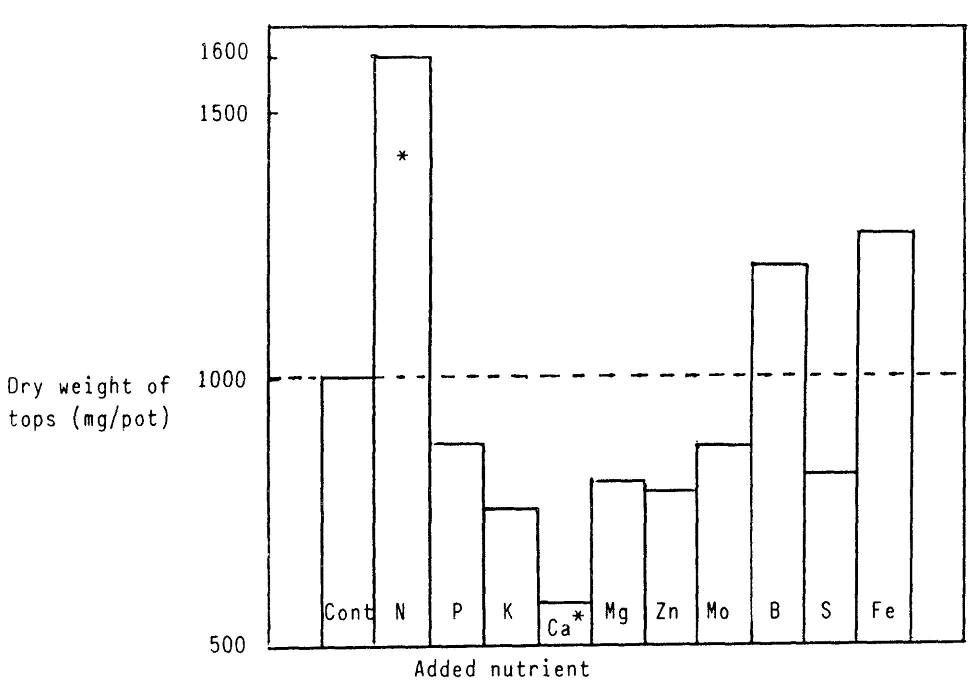
There was no significant correlation between any other foliar nutrient and plant tops dry weight, nor was there any correlation between any soil test and plant weight or foliar nutrient concentration.

FIGURE 5.1 : DRY WEIGHT OF TOPS OF DESMODIUM GROWN ON TAILINGS IN THE PRESENCE OF LIME AND WITH NUTRIENT ADDITION TREATMENTS



* Significantly different from control (p <0.05, Duncans multiple range, mean of four reps.)

FIGURE 5.2 : DRY WEIGHT OF TOPS OF PASPALUM GROWN ON TAILINGS IN THE PRESENCE OF LIME AND WITH NUTRIENT ADDITION TREATMENTS



* Significantly different from control (p <0.05, Duncans multiple range, mean of four reps.)

TABLE 5.5 DRY WEIGHTS (mg) OF DESMODIUM AND PASPALUM TOPS AND ROOTS GROWN IN TAILINGS WITH LIME AND NUTRIENT ADDITIONS+

TREATMENTS		DESMODIUM++		PASPALUM+++	
		Mean	SD	Mean	SD
N	tops	103	24	1597*	398
	roots	36	2	642	204
P	tops	2413*	578	879	184
	roots	684*	110	526	132
K	tops	327	516	758	127
	roots	22	13	508	87
Ca	tops	171	91	581*	237
	roots	46	16	286	127
Mg	tops	133	71	860	188
	roots	45	37	463	167
Zn	tops	137	66	790	246
	roots	40	32	460	166
Mo	tops	68	57	880	295
	roots	41	29	487	147
B	tops	133	71	1217	484
	roots	45	37	600	120
S	tops	137	66	824	260
	roots	40	32	443	158
Fe	tops	73	60	1282	215
	roots	25	19	673	196
Control	tops	154	53	1049	209
	roots	47	26		

\+ Average of four replicates. No significant difference between replicates.
++ Significant difference between dry weights of tops and roots ($p<0.01$).
+++ Significant difference between dry weights tops only ($p<0.01$).
* Significantly different from the control (Duncan's Multiple Range ($p<0.05$).

Foliar nutrient analyses for the Paspalum plants (Table 2 Appendix 1) show that increasing N application from 50 kg/ha for the control to 120 kg/ha for the N additions increased foliar N concentrations from 0.81% to 1.08% respectively. Both these concentrations are below optimum.

For all treatments foliar P concentrations were well below the critical concentration of 0.25% suggested by Andrew *et al.* (1971).

Magnesium concentrations were low except for the Mg addition treatments and foliar Zn, Cu and Mo concentrations were high in all treatments. Although Ca addition caused a significant reduction in tops dry weight, this was not reflected by high foliar Ca concentrations. There was however, a significant negative correlation between plant tops weight and foliar Ca concentrations such that;

Tops weight (gm) = 3.519 - 4.314 Ca (foliar) $r^2 = 0.707$, $p<0.01$.

There was no correlation between soil exchangeable Ca and plant tops weight, nor was there any correlation between plant weights and any other soil analysis.

Omission of Nutrients in the Presence of Lime

In contrast to the addition treatments, growth of the legumes was good while that of the grasses was poor.

Nutrient omission significantly affected the dry weights of tops and roots for the *Desmodium* plants ($p<0.01$) and the dry weights of the tops and roots for the *Paspalum* plants ($p<0.05$). There was no significant difference between replicates (Table 5.6).

For *Desmodium*, P omission significantly reduced both tops and roots dry weight ($p<0.05$). Nitrogen, K and Mg omission slightly reduced plant tops weight although not significantly and Ca, Zn and B omission caused a slight non-significant increase in growth compared to the control (Figure 5.3).

Control plants had foliar P concentrations of 0.15% and P omission reduced foliar concentrations to 0.1% (Table 3 Appendix I), a concentration that is clearly deficient. Tops dry weight was subsequently correlated with foliar P concentration such that;

Tops dry weight (gm) = -5.797 + 83.145P (foliar), $r^2 = 0.524$ $p<0.05$.

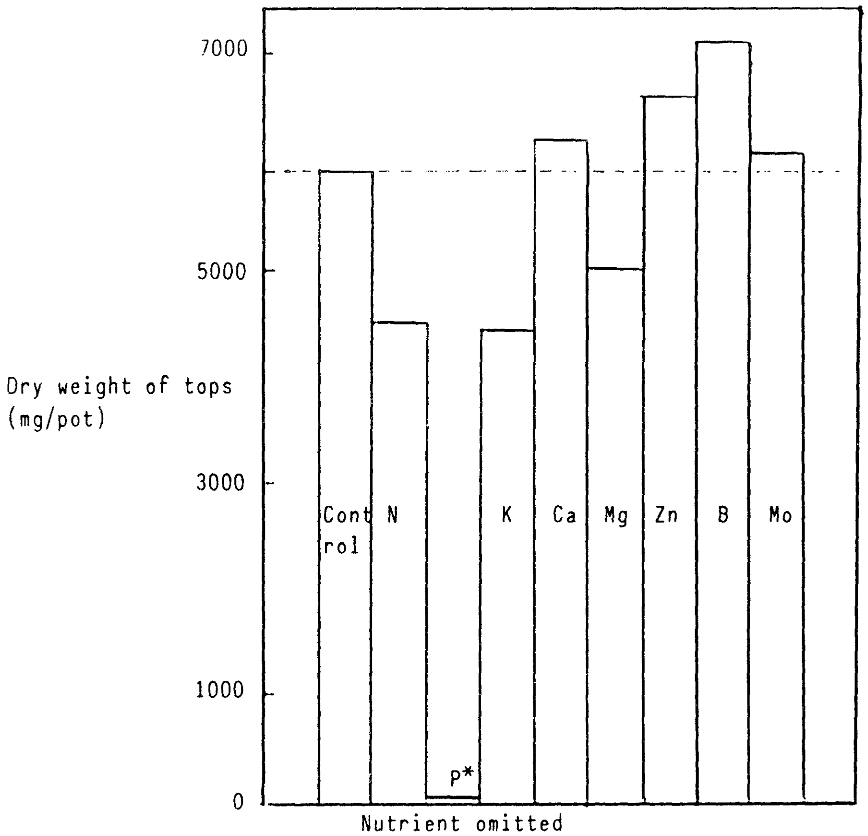
Other nutrient omissions generally affected foliar nutrient concentrations but with no significant effects on plant dry weights. For control plants foliar P concentrations were below optimum, while B, Mo and Zn were above optimum. All other foliar nutrients appeared satisfactory (Andrew and Pieters, 1972a).

TABLE 5.6 : DRY WEIGHTS (mg) OF DESMODIUM AND PASPALUM TOPS AND ROOTS GROWN IN TAILINGS WITH LIME AND NUTRIENT OMISSIONS+

TREATMENTS	DESMODIUM++		PASPALUM+++	
	Mean	SD	Mean	SD
N^- tops	4538	885	41	10
roots	923	151	27*	12
P^- tops	54*	13	61	43
roots	14*	20	137	202
K^- tops	4440	1554	865*	972
roots	956	299	513*	561
Ca^- tops	6191	799	178	125
roots	1121	127	106	67
Mg^- tops	4975	1145	33	7
roots	1189	286	41	12
Zn^- tops	6609	1553	40	13
roots	1279	216	42	18
B^- tops	7128	1303	132	103
roots	1480	228	97	65
Mo^- tops	6134	409	30*	4
roots	1334	162	44	7
Control tops	5868	1979	63	43
Control roots	1273	387	50	29

\+ Average of four replicates. No significant difference between replicates.
++ Significant difference between dry weights of tops and roots ($p<0.01$).
+++ Significant difference between dry weights of tops and root ($p<0.05$).
* Significant different from the control (Duncan's Multiple Range, $p<0.05$).

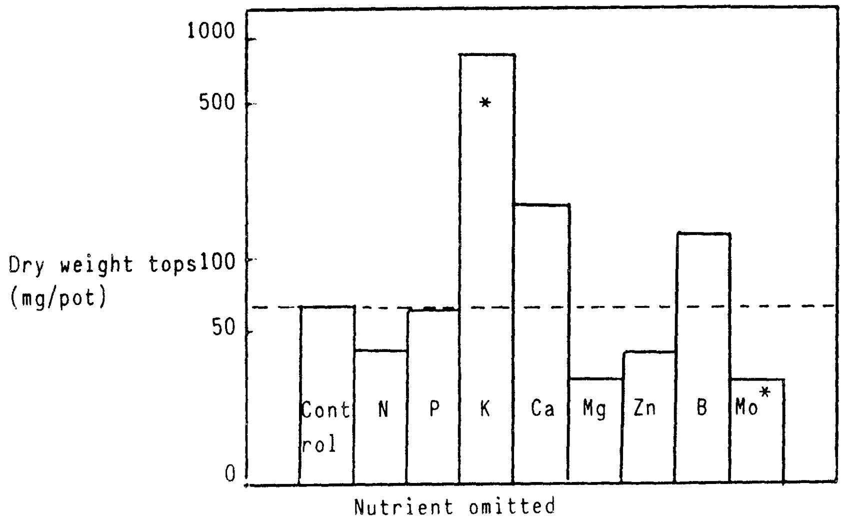
FIGURE 5.3 : DRY WEIGHT OF DESMODIUM TOPS GROWN ON TAILINGS IN THE PRESENCE OF LIME AND WITH NUTRIENT OMISSION TREATMENTS



* Significantly different from control (Duncans multiple range, mean of 4 reps.)

FIGURE 5.4 : DRY WEIGHT OF PASPALUM TOPS GROWN ON TAILINGS IN THE PRESENCE OF LIME AND WITH NUTRIENT OMISSION TREATMENTS

* Significantly different from control (Duncans multiple range, mean of 4 reps.)



For *Paspalum* plants, K omission significantly increased tops and roots dry weight ($p<0.05$). Nitrogen omission significantly decreased roots dry weight ($p<0.05$) and Mo omission significantly decreased tops dry weight ($p<0.05$). Calcium and B omission caused a small non-significant increase in tops dry weight with respect to the control, while other nutrient omission treatments caused small non-significant decreases in tops dry weight (Figure 5.4).

The substantial increase in tops dry weight with K omission is difficult to explain. The dry weights for the four K omission replicates were 590, 460, 1360 and 1990 mg respectively. Such a discrepancy is unlikely through normal variability. Certainly exchangeable K in the tailings was low and foliar K concentrations (average) were not excessive at 2.53% for the control and 2.43% for the K omission treatments.

There was not enough material for complete foliar analysis due to the unsatisfactory plant growth. From the data obtained (Table 4 Appendix I) most foliar nutrient concentrations were considered acceptable. Foliar P concentrations for the P omission treatment was severely deficient whilst foliar Cu concentrations for the Mg and Mo omission treatments were very high.

Exchangeable and available nutrient levels in the limed zone of the tailings (Table 5.7) do not show any reason for the poor growth of the plants, with most nutrients in the adequate to non-toxic range. The pH is higher than expected at between 7.1 and 8.2.

The reason for the poor growth of the *Paspalum* plants is unclear. Nitrogen omission would be expected to decrease the growth of a grass. In this case the N omission only significantly affected roots dry weights. Thus some explanation may be found in the form of N fertiliser used. It was shown in Chapter 4 that N fertiliser, in particular nitrates, is subject to rapid leaching from tailings. Similarly, a simple experiment (Appendix 2), in which *Eucalyptus deglupta* seedlings were raised on tailings with either an NH_4- N or NO_3- N source, showed virtually no growth for the plants receiving the NO_3. Plants receiving the NH_4 exhibited a thirteen fold increase in growth. It was concluded that plants with the NO_3- N source had a low utilisation of the applied N due to leaching of the fertiliser. Although the pots in this experiment were under a non-leaching regime, some loss of the highly soluble $Ca(NO_3)_2$ from the root zone may have occurred for the omission trial and it may have been sufficient to severely limit growth.

TABLE 5.7 : SOIL ANALYSES FOR THE POTS RECEIVING LIME, AND NUTRIENT ADDITION AND OMISSION TREATMENTS

Analyses	Nutrient Addition**				Nutrient Omission+			
	Desmodium		Paspalum		Desmodium		Paspalum	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
N tot ppm	74	22	60	23	30	0	77	16
P av ppm	5.0	1.1	6.4	1.3	8.2	1.8	12.2	3.4
K ex me %	0.09	0.02	0.12	0.01	0.10	0.01	0.13	0.02
Ca ex me %	3.77	0.74	4.32	0.49	3.44	0.74	4.96	0.21
Mg ex me %	0.08	0.05	0.08	0.04	0.18	0.04	0.15	0.04
Na ex me %	0.02	0.02	0.05	0.10	0.07	0.05	0.03	0.03
CEC me %	2.68	0.23	3.03	0.12	2.81	0.11	3.32	0.43
pH 1:5	7.6	1.2	6.0	1.1	6.5	1.4	7.7	0.4
Al ex ppm	7	17	15	18	2	5	1	1
Mn av ppm	1.0	1.2	1.6	1.2	1.8	1.0	1.0	0.6
Mo av ppm	0.6	0.6	1.0	0.5	2.2	0.7	2.6	1.0
Cu av ppm	49	22	38	11	61	13	25	10
Zn av ppm	14	7	9	3	16	3	12	10
Fe av ppm	41	20	57	19	42	7	58	7
S tot %	0.26	0.03	0.24	0.05	0.23	0.02	0.27	0.02
SO_4-S tot ppm	282	54	376	70	271	16	327	31

* Mean analyses for all pots irrespective of nutrient treatment. In most cases individual nutrient addition or omission slightly effected the respective soil test. Treatments did not significantly affect soil analyses within experiments.

** Mean of 11 nutrient addition treatments.

\+ Mean of 9 nutrient omission treatments.

tot = total, av = available, ex = exchangeable.

Analyses as outlined in Chapter 4.

Tailings Analysis

Liming the tailings raised the pH in the order of three units from an initial pH of 4.5. The pH increase was only apparent in the zone of the pots where lime was applied. With the benefit of hindsight, this would be expected, lime being relatively immobile in soils. This points to the necessity of mixing the lime throughout the whole root zone for optimum results.

There was little evidence of movement of applied fertiliser from the top to the bottom of the pot, with the tailings in the bottom generally being much lower in P, K and Ca and higher in Al, Cu, Mn and Fe. The difference between nutrient levels was largely associated with pH.

Combining all the soil data, regardless of treatment or location in the pots, provided an insight into the effects of pH on nutrient availability (Table 5.8). EDTA-extractable Cu and Fe, available Mn and exchangeable Al were negatively correlated with pH. Exchangeable Ca was positively correlated with pH and the sum of the exchangeable bases Ca, Mg and K was negatively correlated with exchangeable Al. There was little correlation between soil available P and exchangeable Al or pH.

The decrease in exchangeable basic cations with increasing exchangeable Al is consistent with acid weathering of mineral soils (McLean, 1983). Thus, in addition to Al toxicity *per se*, high levels of exchangeable Al in tailings deposits are likely to promote leaching of basic cations that are released from primary mineral weathering or added as fertiliser salts. For the no-lime treatments, exchangeable K and Ca in the tailings appeared unsatisfactory.

Liming reduced exchangeable Al, available Mn and EDTA Cu levels substantially in comparison to the no-lime treatments. In most cases exchangeable Al and available Mn were negligible, whilst EDTA Cu was still high in comparison to uncontaminated soils. Metal toxicity symptoms were not noticed for plants growing on limed tailings.

General Discussion

Clearly, the most limiting nutrient for *Desmodium* was P. Unfortunately it appears that the basal P addition of 21.5 kg/ha for the plants with addition treatments was grossly inadequate and the basal rate of 45 kg/ha P for the omission experiment inadequate. As such, P deficiency may have masked responses to the other nutrients. Increasing the P application rate to 60 kg/ha for the P addition treatment still did not produce optimum foliar P concentrations. This suggests that application rates in excess of 60 kg/ha may be necessary in the

TABLE 5.8 : RELATIONSHIP BETWEEN SELECTED SOIL PARAMETERS AND pH AND ALUMINIUM IN THE TAILINGS FROM ALL POTS, REGARDLESS OF FERTILISER TREATMENT.

Equation	r^2	p
Log Cu* = 2.62 - 0.14 pH	0.72	<0.01
Log Fe = 2.62 - 0.13 pH	0.77	<0.01
Log Mn = 1.85 - 0.27 pH	0.90	<0.01
Log Al = 4.28 - 0.57 pH	0.92	<0.01
Ca = -2.54 + 0.92 pH	0.87	<0.01
Exch (Ca+Mg+K) = -2.18 + 0.90 pH	0.87	<0.01
Exch (Ca+Mg+K) = 4.42 - 1.49 log Al	0.85	<0.01

* Cu, Fe, Mn, available.
Al, Mg, Ca, K exchangable.

field. Problems with P nutrition may also have arisen through P fixation. P is generally considered to be most soluble in the pH range 6.5 to 7.0. In this experiment, P may have been precipitated as Ca-phosphates in the top layers of the tailings where the pH was between 7.0 and 8.0 and where the exchange complex was dominated by Ca. If any P had leached to the lower layers, it would have complexed with Al, Mn, Cu and Fe to become unavailable to plants.

As expected for the grass Paspalum, N addition significantly increased growth, although even at a rate of 120 kg/ha N for the N addition treatment, foliar N concentrations were sub-optimal.

Foliar N concentrations for the Desmodium were adequate. Excavated roots were well nodulated, indicating that conditions were conducive to effective nodulation and Rhizobial function.

Responses to the other nutrients were not as apparent. On average foliar K, Ca and Mg appeared adequate for the Desmodium while for the Paspalum foliar K and Ca appeared adequate and Mg inadequate. Soil analyses for the acid tailings, on average, showed very low levels of exchangeable K and Ca. For the lime treatments, exchangeable K and Mg were low (Table 5.7). Soil tests indicated that if N and P were not limiting growth, responses to K and Mg may have occurred.

The negative growth response of Paspalum plants to Ca addition and foliar Ca concentrations is difficult to explain and it could be related to a number of factors. When Ca is added to the soil as a neutral salt it will replace adsorbed ions such as K^+, and NH_4^+. Although the tailings in this experiment were not subject to a leaching regime, competition between Ca and other cations for adsorption sites may have resulted in the removal of some beneficial ions (NH_4^+) from the root zone. There may also have been a detrimental anion effect from the Cl, which was used as the carrier for the additional Ca. The problem should not be encountered in the field however, as over-liming, as was the case in this experiment, would be discouraged, and where lime was used there would be no requirement for additional Ca fertiliser. In this case Ca was added to the treatments primarily as a nutrient for the plants under the no-lime treatments. Calcium addition did not significantly affect soil pH or available Al when compared to the other treatments. Zinc, B, Mo and S addition or omission did not appear to affect the growth of either Desmodium or Paspalum. Foliar analyses showed that Zn and Mo addition increased foliar concentrations well above those considered optimum by Andrew and Pieters (1972a), while for treatments where Zn and Mo were not added, foliar concentrations were in the optimum range. Similarly, available Zn and Mo in the soil were adequate. Therefore their continued use as a fertiliser does not appear warranted.

The *Desmodium* omission treatments were the only ones to produce enough tops material to permit satisfactory foliar S determinations. The analyses showed adequate concentrations. With the relatively high sulphide levels in tailings, sulphur deficiencies should not be a problem.

Plants receiving B generally had foliar concentrations slightly in excess of those considered optimum by Andrew and Pieters (1972a). However, available B for the tailings was very low. In light of the soil tests and results reported by Hartley (1976) B use should not be discouraged although the rate and form applied requires more study.

Iron addition did not affect the growth of *Desmodium* plants, but it increased the growth of *Paspalum* plants (not significantly) and kept the *Paspalum* plants alive in the no-lime treatment. Iron EDTA addition does not appear warranted for adequately limed tailings.

5.1.4 Conclusions

The results of this trial have improved our understanding of the ability of tailings to support plant establishment.

The failure of the plants for the no-lime treatments suggests that Al and possibly Cu toxicity may be a major limitation to plant growth on acid wastes. However, liming to an adequate pH may overcome the effects of Al and possibily Cu toxicity and permit satisfactory plant establishment. pH can significantly affect the availability of Al, Cu, Mn, Ca, Mg and K in tailings.

On adequately limed tailings, P availability is the main limitation to the growth of *Desmodium* (and presumably other legumes), while N availability is the main limitation to the growth of *Paspalum*.

Growth responses were not observed for K, Mg and B fertilisers. However, soil and foliar data supports the need for their continued evaluation. The use of other fertiliser nutrients does not appear warranted.

5.2 Phosphorus Nutrition of a Legume Growing on Bougainville Mine Tailings

5.2.1 Introduction

The nutrient with the greatest potential to effect plant growth on Bougainville mine wastes is P. This has become apparent from soil and foliar analyses, limited field trials and the previous pot trials. Additions of P fertiliser in the past may have been sub-optimal and much larger additions may be necessary for successful revegetation.

The aim of this experiment was to determine the effect of P fertiliser addition on the growth and development of the tropical pasture legume Desmodium intortum and to observe the effects of large applications of P on the soil chemistry of tailings.

5.2.2 Materials and Methods

General

Desmodium intortum cultivar greenleaf, was chosen as the indicator species. It grows extensively in naturalised stands at Panguna, was used in the previous pot experiment and data are available on its performance under a range of conditions.

Acid tailings that had been limed to above neutrality were used as the growth medium. The tailings before amendment were acid (pH 4.5), deficient in N and P, low in exchangeable Ca, K and Mg and relatively high in exchangeable Al and EDTA-extractable Cu. Available B was not detected (Table 5.9). Although the previous pot experiment did not show a growth requirement for K, Mg or B fertiliser, it was considered that the soil analyses as well as soil and foliar data collected in the field provided sufficient justification for their inclusion in a base fertiliser.

Procedure

Acid tailings were collected from XS29. The tailings were air dried and 2 kg weighed into each of 42, 13 cm diameter plastic pots. Pots were freely draining. Fertiliser rates were determined on an area basis.
Calcium hydroxide (lime) at the equivalent of two tonnes/ha was added to each pot and thoroughly mixed throughout.
A base fertiliser was applied to the surface of each pot. It comprised of ; N at 60 kg/ha as NH_4NO_3,
K at 60 kg/ha as KCl,
Mg at 20 kg/ha as $MgCl_2.6H_2O$,
B at 1 kg/ha as $Na_2B_4O_7.10H_2O$

Seven P fertiliser rates were applied, with six replicates per rate. Phosphorus rates were equivalent to 16, 32, 64, 128, 250, 500 and 1,000 kg/ha (P1 to P7 respectively). One half of the P fertiliser was applied as $NaH_2PO_4.2H_2O$ and one half as $Na_2HPO_4.2H_2O$. This gave a pH for the P fertiliser of between 6.5 and 7.0 in a 5% aqueous solution.

The pots were arranged in a randomised block in a greenhouse at Panguna and they were re-randomised thrice weekly.

The fertiliser was watered in using deionised water and the pots brought to field capacity gravimetrically. The pots were maintained at, or close to field capacity, with weights checked at the time of randomisation.

TABLE 5.9 : SOIL ANALYSIS FOR TAILINGS BEFORE AND AFTER ADDING LIME AND PHOSPHORUS TREATMENTS

Analysis		Before Lime Treatment	Phosphorus Addition (kg/ha)						
			16	32	64	128	250	500	1000
N tot ppm	H1*	30	40	10	40	30	40	60	40
	H2**		90	50	60	80	60	50	230
P av ppm	H1	5.6	5.1	7.2	11.0	18.0	63.0	81.0	127.0
	H2		4.4	7.6	12.0	30.0	62.0	71.0	102.0
K ex me %	H1	0.07	0.11	0.13	0.11	0.10	0.11	0.12	0.14
	H2		0.10	0.10	0.10	0.11	0.11	0.12	0.19
Ca ex me %	H1	0.5	2.7	3.0	2.9	2.7	2.7	2.5	2.0
	H2		1.8	2.1	2.1	2.2	2.1	2.3	2.1
Mg ex me %	H1	0.11	0.18	0.26	0.29	0.22	0.23	0.21	0.28
	H2		0.17	0.23	0.24	0.24	0.25	0.25	0.26
Al ex ppm	H1	119	<1	<1	<1	<1	<1	<1	<1
	H2		5	3	9	16	5	1	<1
Mn av ppm	H1	49.0	0.3	1.8	2.1	1.3	0.9	0.4	0.7
	H2		2.4	2.9	3.1	2.2	1.9	1.5	0.9
Cu av ppm	H1	98	31	54	55	37	39	25	42
	H2		60	55	62	59	46	43	53
pH 1:5	H1	4.5	7.1	6.9	6.3	7.1	7.2	7.9	7.7
	H2		5.3	5.8	5.3	5.4	5.9	6.9	8.0

* H1 = Harvest one; One replicate destructively harvested and the tailings analysed for each treatment.

* H2 = Harvest two; Tailings bulked per treatment (5 replicates), subsampled and analysed.

tot = total, av = available, ex = exchangeable.

Analyses as outlines in Chapter 4.

Desmodium seed was inoculated with Cowpea *Rhizobium* and germinated in sterile sand. After one week equilibration of lime and fertiliser, eight, two week old seedlings were transferred to each pot. Two weeks after transplanting seedlings were thinned to four per pot.

Eight weeks after transplanting plant tops were harvested (H1) one cm above ground level. Plant tops were washed six times in deionised water and dried for 48 hours in a forced draught oven at $75^{o}C$. Tops dry weights were determined, tops bulked per treatment (over replicates) and analysed for nutrients. One pot per treatment was destructively harvested and the tailings analysed for total and available plant nutrients. The analyses used were as specified in Sections 5.1 and 4.2 respectively.

Nine weeks after H1, all pots were harvested again (H2). Tops were treated as for H1. Roots were washed out, dried and weighed. Tailings were bulked per treatment, subsampled and analysed for total and available plant nutrients.

5.2.3 Results and Discussion

Addition of P significantly affected plant weights, foliar nutrient concentrations and soil chemistry.

Phosphorus application rates significantly affected both tops and roots dry weights at the 1% level (Table 5.10).

For both harvests tops dry weight increased with P addition to the 250 kg/ha treatment and then decreased, while root weight increased to the 64 kg/ha P addition and then decreased. Plotting tops weight against log P addition (Figure 5.5) produced parabolic curves to which second degree polynominals could be fitted such that :

H1, Tops weight = $-3.37 + 5.38 \log P - 1.22 \text{Log } P^2$
$r^2 = 0.92$, $P < 0.01$.

H2, Tops weight = $-11.65 + 15.96 \log P - 3.84 \text{Log } P^2$
$r^2 = 0.92$, $P < 0.01$.

These curves suggest that tops dry weight was maximised at 158 kg/ha P addition of for H1 and 112 kg/ha P for H2.

For both harvests foliar P concentrations (Tables 5.11) increased with increasing P application, such that; H1, P (foliar) = $-0.17 + 0.25 \log P$ $r^2 = 0.82$, $p < 0.01$ and H2, P (foliar) = $-0.18 + 0.23 \log P$, $r^2 = 0.98$, $P < 0.01$.

Foliar P concentrations for H2 were lower than the corresponding concentrations for H1. This could be due to dilution in plant tissue due to the larger bulk of material at H2 and the fact that the material at H2 was physiologically older than that sampled at H1.

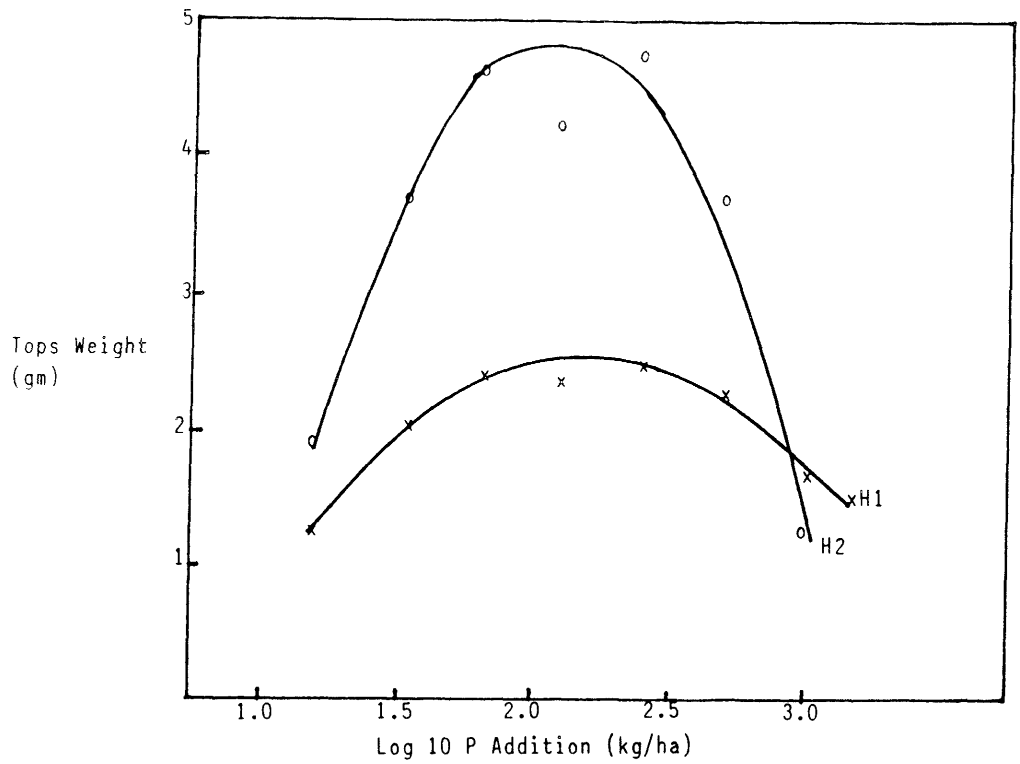
TABLE 5.10 : DRY WEIGHTS OF TOPS AND ROOTS OF DESMODIUM INTORTUM GROWN ON TAILINGS WITH LIME AND VARIOUS PHOSPHORUS TREATMENTS (gm).

Phosphorus Addition (kg/ha)	Harvest One		Harvest Two			
	Tops		Tops		Roots	
	Mean **	SD	Mean **	SD	Mean **	SD
16	1.30	0.58	1.94	1.32	1.18	0.71
32	2.07	0.38	3.77	1.23	1.91	0.60
64	2.39	0.41	4.70	1.23	1.99	0.61
128	2.37	0.37	4.20	1.36	1.20	0.36
250	2.56	0.14	4.78	0.97	1.77	0.23
500	2.43	0.40	3.74	0.82	0.91	0.19
1000	1.73	0.31	1.32	0.30	0.24	0.12

Harvest one, mean of six replicates.
Harvest two, mean of five replicates.

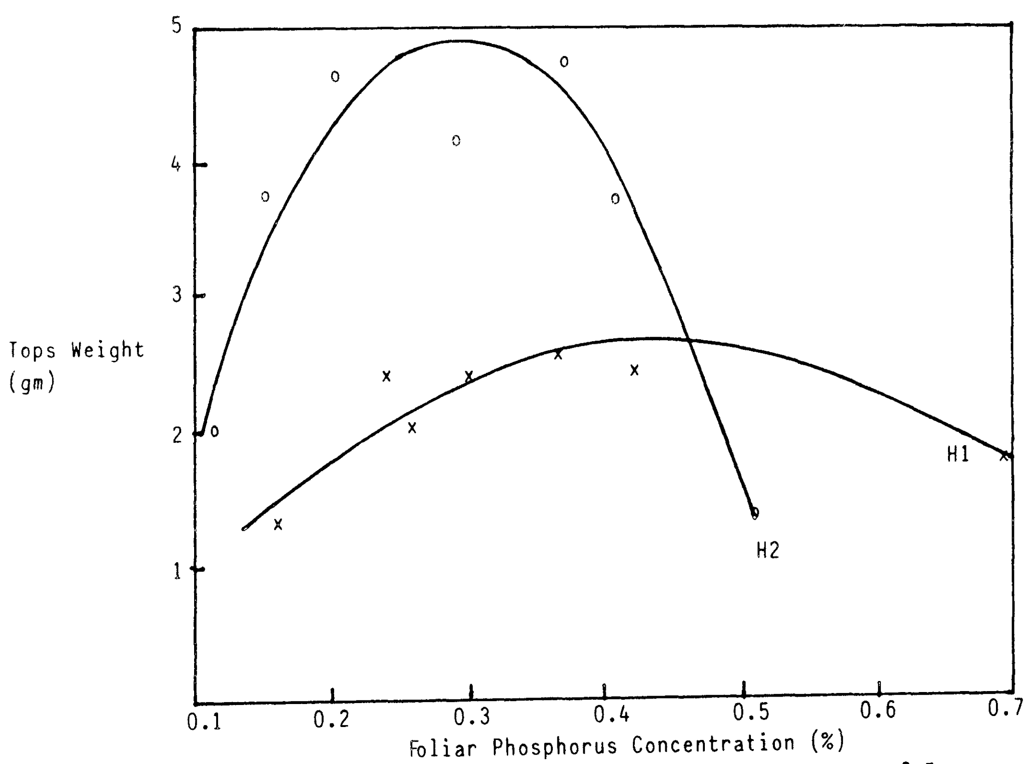
** Significantly different ($p < 0.01$).

FIGURE 5.5 : TOPS WEIGHT OF DESMODIUM INTORTUM GROWN ON TAILINGS TREATED WITH LIME AND VARING RATES OF PHOSPHORUS FERTILISER



Curves fitted from polynomial equations given in the text

FIGURE 5.6 : TOPS WEIGHT OF DESMODIUM INTORTUM GROWN ON TAILINGS TREATED WITH LIME AND VARING RATES OF PHOSPHORUS FERTILISER AND AS A FUNCTION OF FOLIAR PHOSPHORUS CONCENTRATION.



H1 = Harvest one, mean of 6 reps. H2 = Harvest two, mean of 5 reps.

TABLE 5.11 : FOLIAR ANALYSES OF DESMODIUM INTORTUM GROWN IN POTS ON TAILINGS WITH LIME AND PHOSPHORUS FERTILISER TREATMENTS

Analysis * (total concentration)		Phosphorus Addition (kg/ha)						
		16	32	64	128	250	500	1000
N %	H1	3.14	3.23	3.53	3.53	3.40	2.95	3.35
	H2	2.55	3.23	3.36	4.07	3.61	3.49	3.50
P %	H1	0.16	0.26	0.24	0.30	0.37	0.42	0.70
	H2	0.11	0.15	0.20	0.29	0.37	0.41	0.51
K %	H1	2.46	2.75	2.69	2.61	2.88	2.64	2.77
	H2	1.92	1.94	2.12	2.62	2.64	2.46	2.35
Ca %	H1	1.30	1.36	1.34	1.36	1.45	1.38	1.38
	H2	0.85	0.75	0.81	0.98	0.98	0.94	1.06
Mg %	H1	0.23	0.24	0.24	0.23	0.23	0.23	0.27
	H2	0.18	0.18	0.18	0.22	0.20	0.19	0.19
S %	H1	0.26	0.33	0.32	0.36	0.33	0.43	0.42
	H2	0.22	0.28	0.28	0.31	0.29	0.32	0.28
Al ppm	H1	83	69	89	105	110	90	59
	H2	97	113	102	76	79	85	68
Cu ppm	H1	30	28	31	35	37	25	21
	H2	52	67	65	55	62	47	30
Mn ppm	H1	189	178	191	176	164	137	147
	H2	199	169	135	127	115	79	90
Zn ppm	H1	141	94	98	76	125	103	96
	H2	152	98	92	97	96	120	91
Fe ppm	H1	181	174	222	266	259	212	151
	H2	252	277	379	229	248	241	199
B ppm	H1	42	40	44	46	42	43	41
	H2	44	45	42	49	43	37	44
Mo ppm	H1	13	17	14	14	16	29	44
	H2	8	5	9	7	8	17	31

* Analyses for a bulked sample of 6 replicates for H1 and 5 replicates for H2.
Analyses as outlined in Chapter5.

** H1 = Harvest One.
H2 = Harvest Two.

Plant tops weights were also related to foliar P concentrations, particularly at H2. Plotting tops weight against foliar P concentrations again produced parabolic curves well correlated to second degree polynomials (Figure 5.6) such that;

H1, Tops weight = $-0.15 + 12.47$ P (foliar) $- 14.05$ P^2(foliar), $r^2 = 0.85$, $p < 0.05$.

H2, Tops weight = $-1.61 + 44.54$ P (foliar) $- 76.18$ P^2(foliar), $r^2 = 0.88$, $p < 0.05$.

Andrew and Robins (1969a) gave a critical foliar P concentration (after Macy, 1936) at the pre-flowering stage of growth of *Desmodium intortum* of 0.22%. Andrew and Pieters (1972a) showed P deficiency symptoms at a P concentration of 0.13%.

For H1, only the P1 plants (16 kg/ha P) had foliar concentrations below Andrew and Robins' (1969a) critical value, while for H2, the P1, P2 and P3 plants had foliar P concentrations below 0.22%. However, the H1 plants were younger than the immediate pre-flowering stage of growth. From the polynomial for tops weight against foliar P for H2, the critical foliar P concentration corresponding to 95% maximum growth is 0.24%. From the regression equations, 95% maximum growth and a foliar P concentration of 0.24% can be achieved by a P addition of 64 kg/ha.

The decline in plant growth at high additions of P suggests some form of P mediated toxicity. Phosphorus toxicity in normal agricultural soils can manifest itself through induced Cu and Zn deficiencies (Bingham, 1973). Foliar Cu and Zn concentrations did not indicate deficiencies although foliar Zn concentrations require careful interpretation (Andrew and Kamprath, 1978). It is unlikely that such problems would be experienced with Bougainville mine wastes. Lonergan and Asher (1967) suggested that foliar symptoms of P toxicity *per se* were quite different from the general symptoms of induced deficiencies of Cu, Zn or Fe. They found that necrotic leaf symptoms for a range of temperate plants were related to P toxicity when P concentration in the tops exceeded 0.9%. In the P nutrition experiment with tailings, decreasing yields were observed at P concentrations exceeding 0.41%, with a maximum P concentration of 0.7%. Necrotic symptoms were not observed. The increasing pH with increasing P application may also have had an effect on the growth of the plants. *Desmodium* is better adapted for growing on neutral to acid soils (Davies and Hutton, 1975) and it may be that the higher pH contributed to the growth suppression.

As expected, available P (soil) increased with log P addition, ($r^2 = 0.87$, $p < 0.01$ and $r^2 = 0.92$, $p < 0.01$ for H1 and H2 respectively). For H2, available P corresponding to the 64 kg/ha P addition and 95% of the maximum growth of the plants, was 12 ppm, a level well in excess of that found for unfertilised tailings (Table 5.9).

Foliar N concentrations were high for all treatments, suggesting effective root nodulation and N fixation. For H1 they were relatively stable with P treatment, while for H2 they increased with P treatment to P4 and then fell, though only over a small range. Foliar K, Ca, Mg, B and S concentrations were fairly constant between treatments and in all cases adequate. Foliar K, Ca and Mg concentrations were lower for H2 than for H1, suggesting some exhaustion of the applied nutrients.

Total N (soil) was generally low overall and was not affected by P treatment. Exchangeable K, Ca and Mg were lowest for the P1 treatments and highest for the P7 treatments and were pH related. Conversely exchangeable Al, available Mn and EDTA Cu were highest for the P1 treatments, which also had the lowest pH. Sodium was used as a carrier for the P fertiliser, thus exchangeable Na increased with P addition (Table 5.9).

The foliar concentrations of Al, Cu, Zn, Mn and Fe tended to be higher for the low P additions and lower for the high P additions. Conversely, foliar Mo concentrations tended to increase with increasing P addition. These affects again appear pH related.

Foliar Cu and Mo concentrations were, on average, higher than those considered normal (Andrew and Pieters, 1972a) however, adverse effects were not apparent.

Addition of K and Mg fertiliser, in general, raised exchangeable levels in the soil to acceptable amounts and this was reflected in adequate foliar nutrient concentrations. Similarly foliar B concentrations were adequate. This would suggest that under similar conditions to those experienced in this pot trial, liming at up to 2 t/ha of $Ca(OH)_2$ and adding K, Mg and B fertiliser at rates of 60, 20 and 1 kg/ha respectively will supply acceptable amounts of the respective nutrients for plant establishment.

pH generally increased with P addition and was on average 1.1 units higher for H1 than H2. It appears then, that the lime raised the tailings pH, after which the pH for the lower P addition treatments started to fall. Conversely, the pH for the high P treatments remained relatively constant. Thus, the high P additions imparted some acid buffering capacity to the tailings.

The increasing pH with increasing P addition is interesting for two reasons - what is causing the pH to fall after liming and how the P fertiliser is acting as a buffer.

Bougainville tailings are devoid of organic matter and clay sized particles. As such they are poorly buffered and require relatively small amounts of lime (or acid) to effect a given pH change. This was reflected in the liming rates and pH changes for this and the previous pot experiment.

When finely ground $Ca(OH)_2$ is added to a poorly buffered soil it reacts quickly with a typical response curve being that of a rapid pH rise followed by a slower decline to a more stable level (Tisdale and Nelson, 1975). A similar response would have been likely with this trial. Similarly, the addition of fertiliser salts, continued pyrite oxidation and the non-leaching regime may all have contributed to a fall in pH; as was discussed for the previous experiment.

The pH before liming was 4.5, exchangeable Al 119 ppm, EDTA extractable Cu 98 ppm and exchangeable Ca 0.45 me%. Liming raised the pH to 7.5 to 8, reduced exchangeable Al to less than one ppm, increased exchangeable Ca to between 2.5 and 3 me% and substantially reduced EDTA Cu. Thus liming would have resulted in precipitation of Al, and to a lesser extent Cu and Fe ions, with their replacement on exchange sites and in the soil solution with Ca from the lime and K and Mg from the fertiliser additions. Calcium phosphates may also have precipitated (Mattingly, 1974).

The addition of H ions would have neutralised any remaining basic ions in the soil solution and started the dissolution of Ca phosphates and Al, Cu and Fe hydroxy compounds. If the soil solution was saturated with phosphate (as for the higher P additions), the dissolution of acidic metal cations may have been accompanied by the precipitation of Al, Fe and Cu phosphates; the phosphate in effect acting as a buffer.

Munns (1964a) cites Pierre and Stuart (1933) as having associated growth responses following heavy phosphate applications to effects of phosphate in countering Al toxicity. Munns offered the hypothesis that Al toxicity in unlimed acid soils could reduce responses to phosphate unless sufficient phosphate was added to counteract toxicity; generally much more than would be necessary to supply adequate P. Munns (1964b) attempted to explain this hypothesis. Using pot experiments he showed that lime modified P response curves. Lime increased the response to small additions of P and decreased the apparent nutritional P requirement. The largest additions of P (approximately 320 kg/ha) eliminated the lime response. In this experiment with tailings , the P response curve was much flatter for H1, when the pH was on average 1.1 units higher.

Munns also showed that soil pH was increased greatly by lime and slightly by P and that at non-deficient P levels, growth responses to either P or lime could be associated with a reduction in soil solution Al. Soils that Munns used were acid with high levels of exchangeable Al. The slight increase in pH that he found with P addition may be been due in part to the removal of Al from soil solution through complexation, much as may have happened in this pot trial.

5.2.4 Conclusions

Excellent establishment of tropical legumes can be achieved when grown in pots and on tailings that have been limed and supplied with adequate amounts of fertiliser.

This experiment confirmed the role of P nutrition in the growth of plants on Bougainville mine tailings, with both deficiency and possibly toxicity capable of substantially reducing production. For the conditions experienced under this experiment, P applications of up to 160 kg/ha may be required to maximise biomass production (H1), while at a slightly lower pH, 95% of maximum growth may be obtained at an addition of approximately 64 kg/ha (H2). This corresponded to an available soil P of 12 ppm.

This experiment has confirmed that optimum Desmodium performance is achieved with foliar P concentrations around 0.24% in the immediate pre-flowering stage of growth (H2). Desmodium is a suitable plant for the revegetation of Bougainville mine wastes, therefore this may be used as an indicator of the P status of the mine wastes after planting.

It is apparent that the effects of lime are relatively short lived. Supplying additional buffering capacity by large additions of lime may be detrimental to plant growth.

Large additions of soluble P fertiliser may provide some buffering capacity but at the rates required (> 500 kg/ha?), it is expensive and P toxicity may result. The answer may lie in the use of a relatively cheap and insoluble P fertiliser such as rock phosphate. Rock phosphate can be solubilised by acid (thus providing buffering capacity), with the release of phosphate. Under the right conditions it acts as a slow release P fertiliser. The field trials in the next chapter investigate this further.

CHAPTER 6 : FIELD TRIALS - EFFECTS OF ROCK PHOSPHATE APPLIED TO BOUGAINVILLE MINE WASTES

6.1 Introduction

Previous research has shown that acid tailings and waste rock can be deleterious to plant establishment and growth. This appears related to Al toxicity and disruption of P availability and metabolism. In addition, on limed mine wastes an adequate P supply is essential for satisfactory plant growth.

Water soluble phosphates may be leached from substrates such as Bougainville mine wastes and in acid or heavily limed substrates a significant proportion of the applied phosphate may be fixed in a form unavailable to most plants.

It was shown in the P nutrition pot experiment that large additions of soluble phosphate could impart some acid buffering capacity to oxidising tailings. However, the rates of P involved would be uneconomic, some of the added phosphate may be leached, and at high rates P toxicity may result.

The specific aims of the field trials were to investigate the benefits of rock phosphate as a phosphate fertiliser for waste rock and tailings, to observe any interaction between rock phosphate and lime with regard to acid buffering capacity, plant nutrition and plant growth, and to observe the effects of agricultural lime when applied to acid and oxidising waste rock.

6.2 Materials and Methods

6.2.1 General

Two waste types were chosen, waste rock and freshly dumped tailings. The analyses presented in Table 6.1 for the waste rock used in this trial are typical for material in which the oxidation processes are underway. The waste rock is acid, with relatively high exchangeable acidity. The ECEC is 6.5 me% and 45% saturated by exchangeable Al. In comparison, the fresh tailings have a much higher pH of 9.4, a very low ECEC of 1.8 me% and are base saturated - primarily with Ca from the concentrator.

For the waste rock, Ca, K and Mg represent 22, 2 and 5% of the ECEC respectively, while for the tailings they represent 87, 4, and 9% respectively. As such, deficiencies in K and possibly Mg may occur.

TABLE 6.1 : SOIL ANALYSES, MINE WASTES BEFORE TREATMENT WITH ROCK PHOSPHATE AND LIME

Analysis	Waste Rock * +	Alkaline Tailings•
P tot ppm	1770	678
P av ppm	10.3	0.4
pH 1.5	4.6	9.4
Al ex ppm	261	<1
H ex me%	1.73	<0.05
Ca ex me%	1.40	1.56
Mg ex me%	0.33	0.17
K ex me%	0.14	0.07
Cu av ppm	263	62
OC% tot	0.13	0.02
SO_4-S tot ppm	193	49
S tot ppm	8500	1800
Mn av ppm	6.6	1.38
CEC me%	6.5	1.4
ECEC me%	6.5	1.8
Zn av ppm	Not Determined	0.6
Fe av ppm	265	27

* Average of 10 bulked samples taken randomly throughout the trial area.

\+ Sample pre-sieved to less than 2mm before analysis.

tot = total, av = available, ex = exchangeable
Analyses as outlined in Chapter 4.

The waste rock, with its lower pH, has considerably higher available Cu, Fe and Mn than the tailings. The sulphide content of the waste rock is also much higher. Thus it has a greater potential for acidification.

Total P concentration of the waste rock is greater than that for the tailings. This appears to be a common occurrence. The total P concentration of concentrate is low so it is likely that the difference in P concentration is related to rock type or particle size. In turn, available P for waste rock is much higher than that for tailings. This appears a function of both total P and pH. Available P for both wastes is low and likely to cause plant deficiencies.

The rock phosphate used in this trial was a ground blend of Nauru and Christmas Island rock with approximately 16% P which was 1.6% citrate soluble (after Horwitz, 1980). The agriculture lime was ground $CaCO_3$. Chemical and sizing data for the rock phosphate and agricultural lime are given in Table 6.2.

6.2.2 Waste Rock Procedure

A split-plot factorial treatment combination was used. Lack of space limited the trial to two replicates. There were three rock phosphate (RP) application rates, 250, 500 and 1000 kg/ha in factorial combination with two lime (L) rates of 2 tonne/ha and 4 tonne/ha. Each sub-plot was 20m x 3m. The layout is depicted in Figure 6.1. The area was ripped with a large tracked tractor and the treatments were added to their respective plots and lightly raked in.

After one week lime equilibration a tropical grass and legume seed mix was surface spread at 40 kg/ha and fertiliser, N:P 18:18, was spread at 250 kg/ha. The legume seed had been inoculated. After a further month, N:P 18:18 was applied at 250 kg/ha and after three months, N:P:K:Mg:B 6:18:12:2:1 was applied at 500 kg/ha. The fertilisers were commerical products, the later made to specification by Australian Fertilisers Ltd.

Twenty nine weeks after sowing all vegetative material 5 cm above the ground was cut and weighed on a per plot basis and soil and foliar samples were collected (H1). The soil sample was a bulked sample from 10 sites randomly located in each plot. The foliar sample was a bulked collection of growing tips of Siratro (Macroptilum atropurpureus) randomly collected from each plot. Siratro was chosen as the indicator species due to the poor establishment of Desmodium on the tailings. Soil and foliar samples were analysed as outlined in Chapters 4 and 5.

A second harvest (H2) was carried out as above after another 21 weeks - 50 weeks from planting.

TABLE 6.2 : CHEMICAL AND SIZING ANALYSES FOR ROCK PHOSPHATE AND LIME USED IN THE FIELD TRIALS

Analysis*	Rock Phosphate	Lime
P %	15.8	<0.1
Ca %	34.9	38.7
Mg %	0.58	0.35
$CaCO_3$ %	Not Determined	96.0
Al %	<1	<0.1
% passing 1180um sieve	100	99
% passing 600um sieve	99	92
% passing 300um sieve	94	74
% passing 212um sieve	87	63
% passing 150um sieve	75	50
% passing 106um sieve	63	31
% passing 75um sieve	51	12

um = micron

* Total concentrations; complete digestion, wet analysis.

FIGURE 6.1 : EXPERIMENTAL LAY-OUT;WASTE ROCK, ROCK PHOSPHATE AND LIME FIELD TRIALS

Replicate 1.						Replicate 2.					
RP* 500	RP 1000	RP 250	RP 1000	RP 500	RP 250	RP 250	RP 500	RP 1000	RP 1000	RP 250	RP 500
L4**			L2			L4			L2		

FIGURE 6.2 : EXPERIMENTAL LAYOUT : ALKALINE TAILINGS, ROCK PHOSPHATE FIELD TRIALS

Replicate 1				Replicate 2				Replicate 3			
RP* 1000	RP 0	RP 500	RP 250	RP 0	RP 1000	RP 250	RP 500	RP 500	RP 0	RP 1000	RP 250

* Rock phosphate application rate (kg/ha)

** Lime application rate (tonne/ha)

6.2.3 Alkaline Tailings Procedure

The tailings had been dredged from the Jaba River and placed on land to a depth greater than two metres.

A randomised block layout was used with four treatments and three replicates. Treatments were 0, 250, 500 and 1,000 kg/ha of rock phosphate, representing 0, 40, 80 and 160 kg/ha of contained P. The design is depicted in Figure 6.2.

The RP and 250 kg/ha of N:P 18:18 were surface spread and incorporated with a chisel plough. A seed mixture of grasses and legumes was surface spread at 40 kg/ha and lightly harrowed.

After one month 250 kg/ha of N:P 18:18 was surface spread and after three months a further 500 kg/ha of N:P:K:Mg:B was applied.

25 weeks after planting the plots were harvested and soil and foliar samples taken as for 6.2.2. After a further 19 weeks, 44 weeks from planting, a second harvest was carried out.

6.3 Results

The results showed that for waste rock both lime and rock phosphate could significantly affect plant biomass, soil chemistry and foliar nutrient concentrations. Plant weights were also well correlated with soil and foliar nutrient parameters.

Rock phosphate did not affect the growth of plants on the tailings, the pH being too high to mobilise the phosphate.

6.3.1 Waste Rock

General

Lime treatments significantly affected plant weights at H2 only ($p<0.01$). Rock phosphate treatments significantly affected plant weights at both harvests ($p<0.05$).

At H1 there was a significant lime by RP interaction ($p<0.05$), while for H2 there was no significant interaction with any effects (Table 6.3) probably masked by the extremely positive lime response.

There was no significant difference between replicates (blocks) for either H1 or H2.

Effects of Lime

Increasing lime rate from two tonne/ha (L2) to four tonne/ha (L4) substantially improved plant establishment and increased plant weights 131% and 274% for H1 and H2 respectively (Figure 6.3). The establishment and growth of the plants receiving the L4 application was excellent with complete ground cover obtained by H1. In contrast, the establishment and growth for the L2 applications was poor, ground cover was patchy to sparce and plants appeared "stressed". Foliar symptoms of P deficiency/Al toxicity were observed for the herbaceous legumes in particular.

The effects of lime rate on foliar and soil parameters are presented in Tables 6.3 and 6.4.

At both harvests, foliar P concentrations were sub-optimal irrespective of lime treatment (Andrew & Pieters, 1972b). However, foliar P concentrations for the L4 treatments averaged 44% and 18% higher than those for the L2 treatments at H1 and H2 respectively.

The increase in foliar N concentration with lime rate probably resulted from improved Rhizobum nodulation and performance as a result of a more favourable pH and Ca supply (Robson, 1978; Bramfield et al., 1983). Foliar N concentrations were acceptable for both lime rates (Andrew and Pieters, 1972b). Molybdenum supply may also have affected foliar N. Robson (1978) considered that the Mo requirements for maximum Rhizobum N production exceeded those for maximum plant dry matter production and thus increasing Mo supply tends to increase foliar N concentrations. Molybdenum availability increases with pH in the pH range exhibited in this trial (Kerridge, 1978). The foliar Mo concentrations for the L2 treatments appeared adequate (Bruce, 1978) while those for the L4 treatments were above normal.

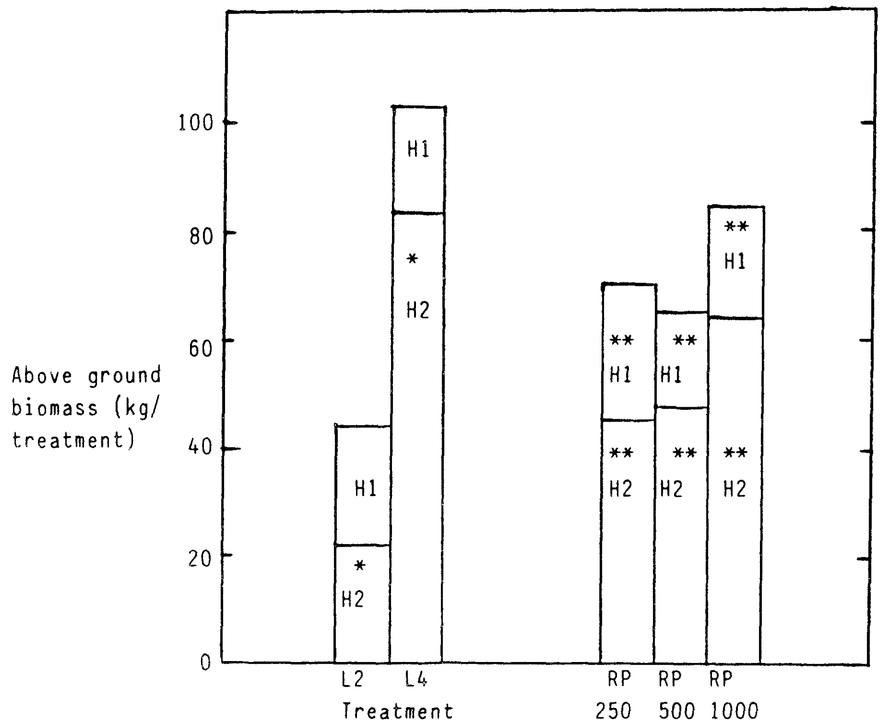
Increasing lime rate reduced foliar concentrations of Al, Mn and Fe and increased the concentrations of K and B for both harvests. Foliar Cu concentrations were unresponsive to lime rate.

Irrespective of lime rate, foliar concentrations of N, K, Ca, Mg, Mn, B and Zn were acceptable, while those for Fe and Cu were high (Andrew and Pieters, 1972b).

Doubling the lime rate did not affect available P (soil) at H1, but by H2 available P for the L4 treatments was on average 10% higher than that for the L2 treatments. As expected, increasing the lime rate substantially increased exchangeable Ca. It also slightly increased exchangeable K and CEC.

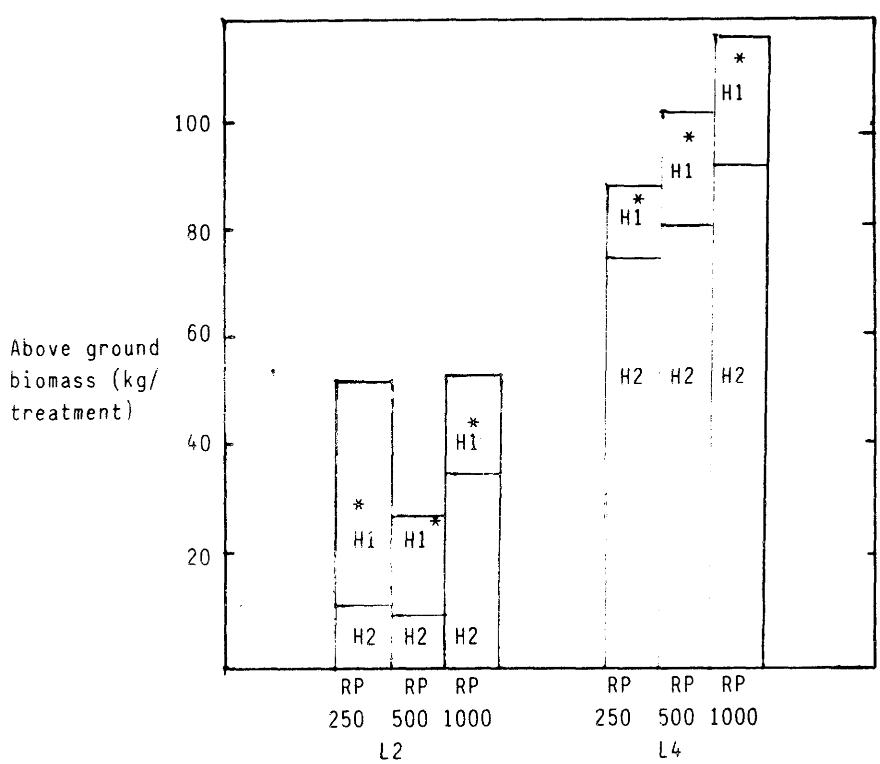
pH for the L4 treatments was approximately one unit higher than for the L2 treatments.

FIGURE 6.3 : ABOVE GROUND BIOMASS OF PLANTS GROWING ON WASTE ROCK TREATED WITH LIME AND ROCK PHOSPHATE. TREATMENT EFFECTS



L = Lime rate (tonne/ha). Mean of 6 replicates.
RP = Rock phosphate (kg/ha). Mean of 4 replicates.
H1 = Harvest 1, H2 = Harvest 2.
Significant difference between treatments (* $p<0.05$, ** $p<0.01$)

TABLE 6.4 : ABOVE GROUND BIOMASS FOR PLANTS GROWING ON WASTE ROCK TREATED WITH LIME AND ROCK PHOSPHATE ; LIME BY ROCK PHOSPHATE INTERACTION



* Significant interaction ($p<0.05$) Treatments mean 2 reps.

TABLE 6.3 FOLIAR ANALYSES OF SIRATRO, ROCK PHOSPHATE FIELD TRIAL ON WASTE ROCK, LIME COMPARISONS*

Analysis	HARVEST ONE		HARVEST TWO	
	Lime rates (tonne/ha)			
	2	4	2	4
N %	2.24	2.53	2.3	2.49
P %	0.09	0.13	0.11	0.13
K %	1.38	1.72	1.50	1.64
Ca %	0.74	0.9	0.78	0.77
Mg %	0.14	0.17	0.17	0.16
B ppm	8.7	10.8	16.3	25.2
Mo ppm	0.2	1.2	13.0	15.0
S %	0.17	0.21	0.18	0.19
Al ppm	621	576	474	437
Mn ppm	86	55	60	46
Cu ppm	112	111	103	103
Fe ppm	1136	1122	1086	1012
Zn ppm	26	31	34	34

* Average of 6 plots per lime treatment. Analyses as outlined in Chapter 5.

TABLE 6.4 : SOIL ANALYSES, ROCK PHOSPHATE FIELD TRIAL ON WASTE ROCK, LIME COMPARISONS*

Analysis	HARVEST ONE		HARVEST TWO	
	Lime Rates (tonnes/ha)			
	2	4	2	4
P tot ppm	1723	1741	1550	1677
P av ppm	24.5	24.5	15.4	17.0
K ex me %	0.30	0.37	0.26	0.29
Ca ex me %	4.3	8.0	3.4	8.9
Mg ex me %	0.58	0.64	0.48	0.47
Na ex me %	0.04	0.03	0.05	0.04
CEC me %	10.4	10.9	8.8	9.2
H ex me %	1.16	0.56	1.41	0.59
OC %	0.21	0.26	0.18	0.32
ECEC me%	8.9	10.4	8.9	11.2
pH 1:5	4.8	5.7	4.5	5.8
Al ex ppm	226	71	301	81
Mn av ppm	15	7	15	8
Cu av ppm	328	304	356	339
Fe av ppm	256	131	271	164
Zn av ppm	7.5	6.3	6.0	6.8
S tot %	0.75	0.96	0.71	0.80
SO_4-S tot ppm	374	383	497	666

* Average of 6 plots per lime treatment. Analyses as outlined in Chapter 4.

tot = total, av = available, ex = exchangeable.

Effects of Rock Phosphate

Rock Phosphate addition increased plant biomass and affected soil chemistry and foliar nutrient concentrations. Visually, it was difficult to separate the RP effects due to the extremely positive lime response.

Figure 6.3 and Tables 6.5 and 6.6 show the average effect of rock phosphate treatment on foliar and soil data.

At H1 highest plant yields were for the RP1000 treatments, followed by the RP250 and RP500 treatments. At H2 yield increased with RP application, with RP500 treatments yielding on average 5% more than RP250 treatments and RP1000 treatments yielding 35% more than RP500 treatments.

Foliar P concentrations followed a similar trend to plant weights. At H1, highest foliar P concentrations were for the RP1000 treatments, followed by RP250 and RP500 treatments. At H2, the P concentrations were highest for RP1000 treatments, whilst those for RP500 and RP250 treatments were the same. In all cases foliar P concentrations were below Andrew and Robins (1969) critical concentration of 0.24%.

Foliar N concentrations followed a similar trend to plant weights and foliar P for H1, whilst for H2, foliar N increased with increasing RP treatment. Increased foliar N was probably related to improved *Rhizobium* nutrition and function. Nitrogen concentrations were satisfactory.

Foliar metal concentrations were unresponsive to RP treatments. The highest Al and Mn concentrations were for the RP500 treatments at H1 whilst at H2, the highest concentrations of Al, Cu and Fe were also for the RP500 treatments.

With the soil data there appeared to be increasing total P concentrations with increasing RP treatment, however, additions were masked by the high concentrations of native P. Available P showed a similar trend to plant weights and foliar P; that of highest available P for RP1000 treatments and lowest available P for the RP500 treatments.

Average pH at H1 increased slightly with increasing RP treatment. However at H2 average pH for RP500 treatments was 0.7 units higher than that for RP1000 treatments. The plot by plot soil data suggests that there may have been some sampling error. For plots 5 and 12, both RP500 treatments, the pH at H1 was 5.8 and 6 respectively, whilst at H2 it was 6.3 and 7.3. Such a rise in pH is abnormal. The pH for the other plots remained relatively stable or fell. Thus, for plots 5 and 12 some residual lime may have been included in the soil sample. Further, RP500

TABLE 6.5 : FOLIAR ANALYSES OF SIRATRO, ROCK PHOSPHATE TRIAL TRIAL ON WASTE ROCK, ROCK PHOSPHATE COMPARISONS*

	HARVEST ONE			HARVEST TWO		
	Rock Phosphate Application Rates (kg/ha)					
Analysis	250	500	1000	250	500	1000
N %	2.35	2.25	2.57	2.33	2.37	2.48
P %	0.11	0.10	0.12	0.11	0.11	0.13
K %	1.55	1.46	1.64	1.52	1.59	1.60
Ca %	0.79	0.79	0.89	0.77	0.77	0.78
Mg %	0.14	0.15	0.17	0.16	0.16	0.17
B ppm	10.0	10.1	9.1	17.9	22.3	22.1
Mo ppm	0.9	0.6	0.6	11.0	18.0	14.0
S %	0.19	0.18	0.21	0.17	0.18	0.19
Al ppm	540	629	626	440	510	417
Mn ppm	70	74	67	60	50	48
Cu ppm	95	117	123	97	118	94
Fe ppm	994	1185	1208	956	1201	991
Zn ppm	29	31	27	35	34	34

* Average of four replicates per rock phosphate treatment.
Analyses as outlined in Chapter 5.

TABLE 6.6 : SOIL ANALYSES, ROCK PHOSPHATE FIELD TRIAL ON WASTE ROCK, ROCK PHOSPHATE COMPARSIONS*

	HARVEST ONE			HARVEST TWO		
	Rock Phosphate Application Rates (kg/ha)					
Analysis	250	500	1000	250	500	1000
P tot ppm	1680	1658	1860	1505	1663	1673
P av ppm	23.8	20.0	29.8	16.7	13.1	18.8
K ex me %	0.32	0.35	0.33	0.27	0.25	0.31
Ca ex me %	6.0	6.9	5.6	4.9	8.0	5.6
Mg ex me %	0.54	0.72	0.57	0.47	0.48	0.48
Na ex me %	0.04	0.04	0.03	0.04	0.04	0.05
CEC me %	10.7	11.1	10.1	9.2	9.0	8.9
ECEC me %	9.7	10.3	8.1	9.8	10.9	9.5
OC %	0.25	0.23	0.23	0.24	0.28	0.23
pH 1:5	5.1	5.3	5.4	4.8	5.7	5.0
H ex me %	0.99	0.60	0.10	1.39	0.62	0.99
Al ex ppm	163	154	128	245	140	187
Mn av ppm	12	13	9	14	11	10
Cu av ppm	350	307	292	357	347	338
Fe av ppm	203	223	154	277	169	206
Zn av ppm	7.2	8.5	5.1	5.6	8.7	5.1
S tot %	0.85	1.06	0.66	0.87	0.71	0.69
SO_4-S tot ppm	357	332	446	778	460	506

* Average of four replicates per rock phosphate treatment.
Analyses as outlined in Chapter 4.

tot = total, av = available, ex = exchangeable.

treatments had the highest foliar metal concentrations and poor plant growth. This suggests a more acidic substrate than indicated by the pH. If the soil tests for plots 5 and 12 are disregarded, there is a slight increase in pH with increasing RP treatment, similar to H1.

At H1 there was a decrease in exchangeable Al with increasing RP treatment ($P<0.1$). At H2 exchangeable Al was least for the RP500 treatment and in line with the high pH. At both harvests there was a decrease in EDTA extractable Cu with increasing RP treatment and there was a decreasing trend for available Mn with increasing RP treatment.

Lime by Rock Phosphate Interactions

Increasing lime rate affected foliar parameters by increasing plant weights and foliar P concentrations and decreasing foliar metal concentrations. Within the lime treatments, increasing RP application generally increased plant weights and foliar P (Tables 6.7 and 6.8 and Figure 6.4). No clear trend was apparent for foliar metal concentrations.

Increasing RP application within lime treatments tended to decrease extractable soil metal concentrations, especially Cu and Mn. This was most apparent at the L2 application rate. For L4, the higher lime rate appears to have overcome some of the liming effect of the RP (Tables 6.9 and 6.10).

It appears that the principal interaction was that of rock phosphate acting as an additional liming agent.

Foliar and Soil Data

Plant weights were correlated with a number of foliar and soil parameters (Table 6.11). There was a moderate positive correlation between plant weights and both foliar P and N concentrations at both harvests. Thus there was a moderate to strong positive correlation between foliar N and foliar P concentrations. There was no significant correlation between P concentrations and soil available P or exchangeable Ca. There was however, a moderate positive correlation between foliar N and soil exchangeable Ca for H1 only. This would result from the effect of Ca supply and pH on Rhizobium nodulation, an effect that would only manifest itself in the plant establishment phase. Increasing P supply can also increase foliar N concentrations through improved Rhizobium nutrition (Robson, 1978).

Plant weights were correlated with a number of soil parameters, all of which centred around pH. There was little correlation between plant weights and pH, exchangeable Al and

TABLE 6.7 : FOLIAR ANALYSIS OF SIRATRO, LIME BY ROCK PHOSPHATE INTERACTION, FIELD TRIAL ON WASTE ROCK, HARVEST ONE

TREATMENTS

Analyses	2 tonne/ha Lime			4 tonne/ha Lime		
	Rock Phosphate Application Rates (kg/ha)					
	250	500	1000	250	500	1000
N %	2.29	2.19	2.26	2.42	2.31	2.88
P %	0.09	0.09	0.09	0.13	0.10	0.15
K %	1.51	1.30	1.33	1.59	1.63	1.96
Ca %	0.75	0.70	0.75	0.82	0.87	1.02
Mg %	0.15	0.13	0.15	0.13	0.17	0.20
B ppm	9.65	7.75	8.6	10.4	12.5	9.6
Mo ppm	0.1	0.1	0.5	1.73	1.2	0.75
S %	0.16	0.18	0.18	0.22	0.18	0.24
Al ppm	522	645	695	558	613	557
Mn ppm	88	91	80	53	57	55
Cu ppm	83	123	131	107	111	114
Fe ppm	853	1230	1325	1135	1140	1090
Zn ppm	27	26	26	30	35	28.5

* Total nutrients average of two replicates per treatment.

TABLE 6.8 : FOLIAR ANALYSIS OF SIRATRO, LIME BY ROCK PHOSPHATE INTERACTION, FIELD TRIALS ON WASTE ROCK, HARVEST TWO

TREATMENTS

Analyses	2 tonne/ha Lime			4 tonne/ha Lime		
	Rock Phosphate Application Rates (kg/ha)					
	250	500	1000	250	500	1000
N %	2.20	2.28	2.44	2.46	2.47	2.53
P %	0.09	0.11	0.12	0.13	0.11	0.15
K %	1.52	1.35	1.63	1.52	1.84	1.58
Ca %	0.81	0.78	0.74	0.73	0.76	0.82
Mg %	0.16	0.17	0.18	0.16	0.16	0.17
B ppm	12.3	17.5	19.3	23.5	27.0	25.0
Mo ppm	11.0	15.5	13.0	11.0	21.0	14.0
S %	0.18	0.18	0.18	0.17	0.19	0.21
Al ppm	408	607	408	473	414	426
Mn ppm	71	63	46	50	38	51
Cu ppm	89	135	84	105	101	104
Fe ppm	926	1395	937	986	1006	1045
Zn ppm	36	35	32	34	32	36

* Total nutrient, average of two replicates per treatment.
Analyses as outlined in Chapter 5.

TABLE 6.9 : SOIL ANALYSIS, LIME BY ROCK PHOSPHATE INTERACTION, ROCK PHOSPHATE FIELD TRIAL ON WASTE ROCK, HARVEST ONE:

	2 tonne/ha Lime			4 tonne/ha Lime		
	Rock Phosphate Application Rates (kg/ha)					
	250	500	1000	250	500	1000
P tot %	1585	1660	1925	1775	1655	1795
P av ppm	16.0	21.0	36.5	31.5	19	23
K ex me %	0.27	0.32	0.32	0.38	0.39	0.35
Ca ex me %	3.65	4.45	4.90	8.25	9.35	6.30
Mg ex me %	0.46	0.71	0.56	0.62	0.72	0.59
Na ex me %	0.03	0.05	0.03	0.05	0.03	0.02
CEC me %	9.8	11.5	9.8	11.7	10.8	10.2
ECEC me %	8.5	9.7	8.6	10.8	10.9	9.5
pH 1:5	4.6	4.6	5.2	5.6	5.9	5.6
H me %	1.34	0.89	1.26	0.65	0.30	0.83
Al ex ppm	246	297	135	80	11	122
Mn av ppm	17	19	11	7	8	6
OC%	0.22	0.20	0.21	0.27	0.27	0.25
Cu av ppm	411	305	270	290	309	315
Zn av ppm	8	8.2	6.3	6.4	8.8	3.9
Fe av ppm	255	349	163	151	96	145
S tot %	0.84	0.79	0.63	0.87	1.33	0.69
SO_4-S tot ppm	386	480	256	329	184	637

* Average of 2 replicates per treatment.
tot = total, av = available, ex = exchangeable

TABLE 6.10 : SOIL ANALYSIS, LIME BY ROCK PHOSPHATE INTERACTION, ROCK PHOSPHATE FIELD TRIAL ON WASTE ROCK, HARVEST TWO*

	2 tonne/ha Lime			4 tonne/ha Lime		
	Rock Phosphate Application Rates (kg/ha)					
	250	500	1000	250	500	1000
P tot %	1440	1615	1595	1570	1710	1750
P av ppm	14.5	12.8	18.9	18.9	13.4	18.7
K ex me %	0.26	0.27	0.25	0.29	0.23	0.37
Ca ex me %	3.45	3.83	2.95	6.35	12.05	8.20
Mg ex me %	0.47	0.55	0.42	0.48	0.41	0.53
Na ex me %	0.05	0.06	0.05	0.04	0.03	0.04
CEC me %	8.9	9.1	8.4	9.5	8.9	9.35
ECEC me %	9.4	9.0	8.5	10.3	12.7	10.5
pH 1:5	4.5	4.6	4.5	5.1	6.8	5.5
H ex me %	1.67	1.24	1.32	1.11	<0.1	0.66
Al ex ppm	312	278	314	179	2	61
Mn ex ppm	19	16	12	10	6	8
OC %	0.22	0.14	0.19	0.26	0.42	0.28
Cu av ppm	388	358	324	326	337	353
Zn av ppm	7	7	5	5	11	5
Fe av ppm	336	231	245	219	107	166
S tot %	0.80	0.83	0.51	0.93	0.60	0.88
SO_4-S tot ppm	481	545	465	1075	374	548

* Average of 2 replicates per treatment. Analyses as outlined in Chapter 4.
tot = total, av = available, ex = exchangeable

TABLE 6.11 : RELATIONSHIP BETWEEN SELECTED FOLIAR DATA FOR SIRATRO GROWING ON WASTE ROCK TREATED WITH LIME AND ROCK PHOSPHATE AND THE RELATIONSHIP FOR SELECTED SOIL DATA FOR THE SAME WASTE ROCK**

HARVEST ONE Regression	r^2	p	HARVEST TWO Regression	r^2	p
wt = -40.99 + 853.68P(F)*	0.40	<0.05	wt = -24.25 + 655.77P(F)	0.26	<0.10
wt = -79.01 + 63.95N(F)	0.45	<0.05	wt = -227.40 + 137.97N (F)	0.45	<0.05
N(F) = 1.48 + 8.31P (F)	0.31	<0.10	N(F) = 1.78 + 5.23P (F)	0.72	<0.01
N(F) = 0.73 + 2.03 Ca (F)	0.62	<0.01	N(F) = 2.73 - 0.43 Ca (F)	0.04	<0.55
wt = -144.71 + 36.03 pH	0.58	<0.01	wt = -78.87 + 25.51 pH	0.50	<0.01
wt = 94.52 - 0.14 Al	0.46	<0.05	wt = 76.93 - 0.13 Al	0.46	<0.05
wt = 132.67 - 5.26 Mn	0.64	<0.01	wt = 118.66 - 5.62Mn	0.71	<0.01
wt = 12.85 + 9.91 Ca	0.50	<0.05	wt = 6.88 + 7.50 Ca	0.62	<0.01
log Al = 8.6 - 1.35 pH	0.71	<0.01	log Al = 8.03 - 1.22pH	0.94	<0.01
log Mn = 2.07 - 0.20 pH	0.55	<0.01	log Mn = 1.88 - 0.17pH	0.66	<0.01
log H = 2.18 - 0.45 pH	0.85	<0.01	log H = 2.13 - 0.43pH	0.86	<0.01
Ca = -9.72 + 3.03 pH	0.81	<0.01	Ca = -13.06 + 3.72pH	0.96	<0.01
log Al = 2.06 + 2.88 Log H	0.77	<0.01	log Al = 2.10 + 2.14 log H	0.94	<0.01

** Regressions are for all data collected on a per plot basis, regardless of treatment. (n = 12).

* P(F) = foliar P concentration. All foliar nutrient data for total nutrient concentrations (%). Wt = plant weights (kg/ha), pH = 1:5. Al = exchangeable (ppm). H = exchangeable (me%). Ca = exchangeable (me%). Mn = available (ppm).

Data not indicated by (F) refers to soil parameters.

extractable Mn. Conversely, there was a moderate positive correlation between plant weights and exchangeable Ca. There was no correlation between plant weights and EDTA extractable Cu, Fe or Zn.

Although exchangeable Ca was sub-optimal in some plots by H2, it is unlikely that it alone significantly affected plant weights. Similarly, pH (hydrogen ion concentration) alone rarely has a serious deleterious effect on plant growth - certainly in the pH range experienced in this trial (Jackson, 1967; Black, 1968; Islam et al., 1980). Thus, Al and or Mn may have a significant deleterious effect on plant growth in waste rock. It was suggested previously that Al toxicity could limit the growth of plants in acid tailings. Visual symptoms of Al toxicity have also been noted for plants growing on waste rock in the field. Conversely, no clear cases of Mn toxicity have been delineated. Further, the foliar Mn concentrations observed in this trial were much less than those considered toxic, or even normal for Siratro (Andrew and Hegarty, 1969; Andrew and Pieters, 1972b).

Although there was a relatively strong negative correlation between plant weights and extractable soil Mn, it is difficult to say whether toxicity was involved. A decrease in pH resulted in an increase in both exchangeable Al and extractable Mn (Table 6.11) thus, we may have only been observing an Al effect. Regardless of which metal, or combination of metals is affecting plant performance, they are both well correlated to pH and by liming to a acceptable pH toxicity problems can be largely avoided.

Both exchangeable Al and H (representing the exchangeable acidity) were strongly correlated with pH and there was a strong positive correlation between exchangeable Al and exchangeable H. This is consistent with pyrite oxidation which releases H ions. The H ions react with gangue, with Al being one of the major acidic cations released. Hydrogen ions would also be available for the mobilisation of P from the rock phosphate, although there was no significant correlation between pH or H ions and soil available P.

6.3.2 Alkaline Tailings

Analysis of variance for the plant weights showed no significant difference between replicates or RP treatments (Table 6.12). For all plots plant establishment and growth was excellent, with rapid ground cover achieved.

Effects of Rock Phosphate

Rock phosphate treatments did not affect either the foliar nutrient concentrations or the soil analyses. The average RP effects are presented in Tables 6.13 and 6.14.

TABLE 6.12 : ABOVE GROUND BIOMASS OF PLANTS GROWING ON ALKALINE TAILINGS TREATED WITH ROCK PHOSPHATE

Rock Phosphate kg/ha	Plant weights Harvest One	(kg/plot) Harvest Two
0	197.2	76.5
250	258.9	80.5
500	198.9	53.0
1000	205.9	69.0
0	237.0	58.5
250	236.1	54.0
500	204.0	57.0
1000	250.5	48.5
0	212.7	69.5
250	220.6	79.0
500	197.7	55.4
1000	213.3	85.1

No significant difference between replicates or treatments.

TABLE 6.13 : FOLIAR ANALYSES OF SIRATRO GROWING ON TAILINGS TREATED WITH ROCK PHOSPHATE

	HARVEST ONE				HARVEST TWO			
	Rock Phosphate Treatments (kg/ha)							
Analysis**	0	250	500	1000	0	250	500	1000
N %	2.59	2.61	2.66	2.52	2.02	2.07	2.05	2.10
P %	0.15	0.15	0.14	0.15	0.09	0.08	0.08	0.08
K %	2.62	2.53	2.55	2.55	1.43	1.36	1.42	1.34
Ca %	0.85	0.82	0.88	0.83	0.80	0.86	0.86	0.89
Mg %	0.18	0.17	0.19	0.17	0.18	0.19	0.19	0.19
Mo ppm	22.0	20.0	25.0	29.3	not determined			
S %	0.22	0.23	0.22	0.24	0.15	0.15	0.14	0.16
B ppm	11.3	12.7	14.0	13.7	28.3	23.7	23.0	20.0
Al pp	30	32	65	29	194	271	234	258
Mn pm	78	74	65	70	61	69	75	68
Cu ppm	14	15	14	15	18	23	21	22
Fe ppm	118	135	213	117	607	845	691	835
Zn ppm	51	44	45	43	22	28	28	28

* Average of 3 replicates. ** Total Concentrations. Analyses outlined in Chapter 5.

TABLE 6.14 : SEDIMENT ANALYSES, ALKALINE TAILINGS TREATED WITH ROCK PHOSPHATE

	HARVEST ONE				HARVEST TWO			
	Rock Phosphate Treatments (kg/ha)							
Analysis	0	250	500	1000	0	250	500	1000
P tot %	937	990	813	883	937	1030	827	823
P av ppm	3.5	2.9	2.6	2.0	2.1	2.3	1.6	1.5
K ex me %	0.11	0.12	0.11	0.11	0.07	0.07	0.08	0.07
Ca ex me %	2.20	2.17	2.03	2.17	2.0	2.0	1.9	1.9
Mg ex me %	0.08	0.08	0.07	0.07	0.27	0.29	0.22	0.25
Na ex me %	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
CEC me %	1.7	2.0	1.7	2.0	2.0	2.0	1.7	2.0
pH 1:5	7.8	7.9	8.1	7.9	6.8	6.7	6.8	6.9
Al ex ppm	0.7	1.0	1.5	1.2	0.3	1.3	0.7	1.7
Mn av ppm	1.3	0.8	0.8	0.9	0.6	0.57	0.53	0.3
OC %	0.04	0.06	0.03	0.04	<0.1	<0.1	<0.1	<0.1
Cu av ppm	65	70	73	70	78	71	75	77
Zn av ppm	not determined				1.0	1.3	1.2	1.2
Fe av ppm					41	44	36	36
S tot %	0.19	0.15	0.17	0.15	0.23	0.22	0.17	0.21
SO_4-S tot ppm	62.3	58.4	46.7	45.3	57.0	47.0	44.0	44.0

* Average of 3 replicates , as outlined in Chapter 5.

Foliar and Soil Data

In comparison with the data from the waste rock, there was much less plot by plot variation. This reflects the more neutral and homeogeneous nature of the tailings.

At H1, foliar nutrient concentrations for Siratro were generally in the adequate to optimum range (Andrews and Pieters, 1972b). By H2 however, N, P and K concentrations had fallen and foliar P concentrations were deficient. There was no correlation between foliar P and soil P or pH.

For H1, foliar B concentrations were below levels considered deficient (18ppm) by Andrew and Pieters (1972b). However, by H2 they were generally adequate. For both harvests, foliar K, Ca, Mg, Mn, Zn and Cu were adequate while Fe and Mo concentrations were high.

Available soil P was extremely low for both harvests despite the moderate total P concentrations and the RP and soluble phosphate additions. However, available P was higher than for the untreated tailings (Table 6.1). There appeared to be some relationship between available P and pH at H1. If the data for plot seven was excluded (it appeared erroneous) then there was a significant negative correlation between available P and pH ($r^2 = 0.96$, $p < 0.05$). At H2 there was no correlation, however the pH range was very narrow. There was no significant correlation between available P and any other soil tests, nor was there any correlation between pH and extractable cations.

The low availability of P suggests that a significant proportion of the added water soluble P was either fixed by Ca (and perhaps other fertiliser salts) or leached from the root zone. The pH was unfavourable for mobilisation of RP. The average pH for all the plots fell from 9.4 at the start of the trial, to 8.0 at H1 and 6.8 at H2.

6.4 Discussion

Superphosphate is probably the best known P fertiliser. It is produced by treating RP with concentrated sulphuric acid. Free phosphoric acid is produced first and it reacts with the crude phosphate to form anhydrite and Ca-dihydrogenphosphate.

The P content of superphosphate is more than 90% soluble in water and thus reacts almost immediately in the soil. Rock phosphate on the other hand is not water soluble but it is soluble to varying degrees in acid. Thus the value of RP as a fertiliser depends not only on its solubility properties but also on the mobilisation conditions of the soil (Finck, 1982). Rock phosphate is mobilised more intensively at lower pH values, higher temperatures and higher moisture conditions. Rock phosphate is most suited as a fertiliser at a soil pH of 6 to 6.5. Cabala-Rosand and Wild (1982) considered that the soil conditions necessary for the dissolution of RP were a source of H and sinks for Ca and H_2PO_4.

One of the products of pyrite oxidation is sulphuric acid. This acid in turn reacts with gangue, minerals in the soil solution, or is leached. The H ions released from pyrite oxidation would be expected to react with the RP (Table 6.11). Bougainville mine wastes do not have a high buffer capacity for Ca. However, the low CEC and coarse structure of the wastes ensures high leaching of added basic cations. This is enhanced as the wastes become more acid or by the leaching of N fertilisers. In neutral wastes, leaching of phosphate is likely to occur, while acid wastes are likely to have a high phosphate sorption capacity. The high temperatures, humidity and rainfall experienced on Bougainville would also favour the mobilisation of P from RP.

The significant increase in plant weights with RP addition exhibited in this trial for the waste rock indicates phosphate mobilisation. There was no indication of phosphate mobilisation in the tailings. This is to be expected at the pH experienced.

Removal of P from soil solution is generally a result of orthophosphate ions reacting with the soil mineral fraction. In most alkaline soils the activity of Ca is high, resulting in the formation of Ca phosphates. In soils containing free $CaCO_3$ the activity of P may also be decreased from precipitation on the surface of $CaCO_3$ particles (Mattingly, 1974).

In this trial, not only was the pH of the tailings unfavourable for mobilisation of P from RP or native phosphate, but the high pH and free Ca would have resulted in immobilisation of the water soluble P applied in the plant establishment phase. This is supported by soil available P and foliar P concentrations.

The RP and immobilised water soluble P is not lost. It should have considerable residual value.

At the start of this trial the pH for the tailings was 9.4. After 44 weeks (H2), the pH had fallen to between 6.4 and 7. The pH will continue to fall and it will likely reach the mid fours. As the pH falls, exchangeable Ca decreases whilst exchangeable H and Al increase (Table 6.11). The H ions released should dissolve precipitated Ca phosphates and react with the RP releasing P for plant use. In this manner RP, and any Ca phosphates formed from soluble fertiliser addition, should provide a slow release form of P.

Leaching of water soluble P from sandy soils can be significant. Gillman (1973) showed a loss of 50% of applied superphosphate from a deep siliceous sand at Cape York over 3 years. Alston and Chin (1974) found that for an acid sandy soil, at given levels of

P, RP was as effective as superphosphate in increasing dry matter yield and P uptake by clover in the year of application. Rock phosphate also increased the yield and P uptake in subsequent years. Superphosphate had little residual effect. Leaching losses from RP were 20% less than that for superphosphate over three and one half years. Most of the P lost from the superphosphate was leached within two months of application. Russell(1960) considered that RP might be used to most advantage where the labile P content of the soil has been raised by previous fertilisation to the extent that further supplies are needed only to maintain the labile store. He considered that RP might be particularly useful where water soluble P is readily leached.

The lysimeter leaching experiment (Chapter 4) failed to show significant leaching of P from alkaline tailings (pH 9.1). However, the column of tailings was large (80 cm) and the time of the experiment relatively short (64 days). In addition, it is likely that at that pH, much of the P was complexed with free Ca. As tailings begin to acidify, exchangeable Ca decreases and leaching of water soluble P from the root zone may occur. As a result, RP should prove valuable as a residual fertiliser.

Rock phosphate may also prove beneficial as a liming agent. This was shown for the waste rock trial where there was a significant lime by RP interaction at H1. There was no significant interaction for H2, although a positive lime effect by the RP is still apparent in Figure 6.2 and Tables 6.7 to 6.10.

It was shown in Chapter 4 that acid Bougainville mine wastes can be detrimental to plant growth and that liming to an adequate pH is essential for plant establishment. The optimum pH is thought to lie between 5.5 and 6.5.

The L2 lime rate for the waste rock in this trial failed to raise the pH to the required level, resulting in inadequate plant establishment and growth. The L4 lime rate permitted excellent plant establishment and growth. Plant growth on the waste rock was subsequently well correlated with pH and pH related parameters (Table 6.11).

Shoop et al. (1965) showed a tendency for lime and P to compensate for each other to some degree on an acid subsoil. The yield increase due to lime was apparent up to the point at which the exchangeable Al was immobilised. Munns (1964) showed in pot experiments that lime modified P response curves, increasing the response to small additions of P and decreasing the apparent nutritional P requirement. He found that at non-deficient P levels, growth responses to either P or lime, could be associated with a reduction in soil solution Al. Further, in the previous pot experiment with Bougainville tailings, it was shown that large additions of soluble P fertiliser could supply some acid buffering capacity.

Finck (1982) suggested that the lime effect of many P fertilisers was a side effect of special, largely positive, significance. He suggested assessing the lime effect on the basis of all basically reacting substances and indicating their possible effect as total CaO. However as Finck pointed out, this procedure is only correct if the whole Ca component becomes fully effective as a basically reacting substance. If conversion is slow and if Ca phosphates are formed in the soil, the lime effect becomes delayed and incomplete. The rock phosphate used in this experiment had a theoretical total CaO content of 49% (Table 6.2). It would only be fully effective as a liming agent in extremely acid soils (Finck, 1982). In the waste rock it is difficult to assess what percentage of the theoretical CaO content was effective as a liming agent in the life of this experiment. If all of the theoretical CaO content of the RP applied was utilised, it would be equal to 217, 435 and 870 kg/ha of agricultural lime for the RP250, RP500 and RP1000 treatments respectively.

Thus, as the tailings material acidifies, RP, as well as suppyling P and Ca, should add some buffering capacity to the substrate.

Apart from improving the short-term growth of plants in acid wastes, the main benefit of RP should result from its residual value. In tailings this should become apparent once the pH has fallen below 6.0. The RP should continue supplying P to plants much longer than could be expected from initial additions of water soluble P fertiliser and at a relatively slow and steady rate. This will limit the need for aftercare of the establishing vegetation.

The increase in lime rate for the waste rock substantially inproved plant growth and increased foliar P concentrations. It is now accepted that liming generally does not increase P availability and it can, in fact, decrease availability through increased P sorption by hydroxy Al and Fe species or by Ca and free lime (Haynes, 1982; Debnath and Mandal , 1983; Holford, 1983). However, since Al toxicity is characterised by the inhibition of the uptake, translocation and utilisation of phosphate by plants, liming often increases the utilisataion of soil phosphate through amelioration of Al toxicity (Haynes, 1983). This may have been the effect seen for the waste rock.

The increase in soil metal levels (exchangeable and available) and decrease in basic cations with decreasing pH as observed in this field trial, and the first pot trial, was consistent with work carried out by Curtin and Smillie (1983). It points to the need for a sound liming programme to overcome the effect of Al and possibly Mn toxicity in the plant establishment phase at least.

There was no correlation between soil EDTA Cu and plant weights. This supports data gathered in the field that suggests that Cu toxicity is not a major limitation to plant growth on the mine wastes. Severe chloritic foliar symptoms were noticed for a range of plant species growing on revegetated mine pit slopes (weathered overburden). Soil analyses indicated EDTA extractable Cu to be extremely high at between 400 and 750 ppm (much higher than any levels found during the course of this study). The pH of the soil was 6 to 6.5 and exchangeable Al and available Mn were low. Chloritic plants were sprayed with a ferrous sulphate solution and within days the foliage had returned to a normal green colour where the spray had landed. This indicated that the plants were suffering from induced Fe deficiencies, most probably caused by Cu toxicity. The problem was overcome by applying an application of soluble P fertiliser. The phosphate probably complexed Cu removing it from the soil solution. Such a process is supported by data from the pot trials of Chapter 5 and the rock phosphate field trial. Similar chloritic symptoms have occasionally been noticed in isolated areas in the field. The symptoms are relatively short lived and do not appear to markedly affect plant establishment or growth.

The good correlation between exchangeable Ca and foliar N concentrations for the waste rock at H1 suggest that an adequate liming programme is also essential for effective nodulation of legumes (Robson, 1978). This can be taken a step further, with the correlation between foliar N and foliar P concentrations pointing to the role optimum P nutrition plays in rhizobial function. Andrew and Robins (1969b) found a similar, strong correlation, between foliar N concentrations and P supply and foliar P concentrations for a range of legumes, including Siratro. They found that foliar N concentrations attained at the higher P applications were in excess of those corresponding to maximum dry matter production and critical foliar P concentrations. They subsequently posed the question as to whether a pasture should be fertilised for maximum dry matter production or for maximum N production of the system as a whole. This may be of significance for revegetation where legumes will be relied upon to supply N in the long term.

6.5 Conclusions

Rock phosphate is beneficial to the Bougainville Copper revegetation programme. In acid wastes it can supply P in a relatively slow release form and at the same time supply some liming effect. This should prove beneficial to the objective of establishing vegetation that requires the minimum of maintenance.

Liming of the waste rock to raise the pH on average from 4.7 (L2) to 5.7 (L4) reinforced the need for a sound liming programme on acid wastes. Improved plant establishment and growth appears to result from reduced Al toxicity and improved P nutrition.

The relatively slow reaction of the RP, especially in alkaline tailings means that the application of soluble P fertiliser is still required, at least in the plant establishment phase.

The excellent growth for plants in field trials on both waste rock and tailings after additions of N, P, K, Mg, and B and the correction of pH where required, supported data from the pot trials, and leads to the general conclusion that a good vegetative cover can be established on Bougainville mine wastes if the appropriate amelioratory measures are implemented.

CHAPTER 7 : GENERAL DISCUSSION AND CONCLUSIONS

The primary aims of this study were to determine the ability of Bougainville mine wastes to support plant establishment and growth, to assess the major nutrient limitations to plant establishment and growth and to prescribe means of overcoming the limitations and establishing vegetation on the wastes. These aims have largely been achieved.

A good understanding of the wastes ability to supply and retain plant nutrients has been obtained and the principal limitations to plant establishment and growth delineated.

Both waste rock and tailings (that are not water saturated) become acid due to pyrite oxidation. Acidification of waste rock is rapid, occurring in a matter of months after material has been dumped.

Acidification of tailings is slower, requiring up to two years for the pH to fall below 5.0. This is due to both the lower sulphide content of tailings and their greater acid buffering capacity. The latter is largely supplied by $Ca(OH)_2$ added during treatment. The higher sulphide content of waste rock suggests that its acid phase will last longer than the one to three years experienced for tailings.

Tailings are discharged from the concentrator at a pH of between 9.5 and 11.0. They are base saturated with Ca that is added in the grinding circuit. Tailings that are deposited above water level by floods, or tailings that are dredged from the river, are freely draining. The CEC of such deposits is low, free Ca is quickly leached and oxidation of sulphide minerals begins. Hydrogen ions generated by sulphide oxidation either react with gangue or are leached. The result is a shift from base saturation and a falling pH.

Acid weathering of gangue in wastes releases the acidic metal cations Al, Mn, Fe and Cu (Chapters 5 and 6). Aluminium is strongly adsorbed by exchange sites, with two principal effects on basic cation availability. It lowers the net negative charge of colloidal particles, with a co-commitment lowering of CEC and thus the soil's ability to retain cations. Aluminium also replaces basic cations on exchange sites (Chapter 5). Basic cations released are then leached. The ability of tailings to supply Ca, K and Mg to plants subsequently diminishes and deficiencies of K and Mg in particular are likely. A similar process occurs with waste rock although it is not Ca saturated at the beginning of the weathering process.

When the pH of waste material falls below 5.5 the stage is reached of acid solubility of Al and, of less importance Cu and Mn. As pH falls below 5.0, Al saturation of exchange sites increases and toxicity to plants becomes apparent. Direct evidence of Mn or Cu toxicity was not shown in this study, although in the field trials there was a strong negative correlation between plant weights and available soil Mn. There was no correlation between soil or foliar Cu and plant growth. In some cases foliar Cu concentrations were well above those considered normal. However, evidence gathered in this study and in the field, has lead to the conclusion that Cu toxicity is not a major limitation to plant growth. Induced chlorosis of plants in the field has been markedly reduced by applying soluble P fertiliser (generally as part of normal plant establishment procedures).

All waste types examined, regardless of pH, were severely deficient in organic matter and plant available P, and deficient in K, B and possibly Mg. Other nutrients appeared to be available in adequate amounts, with plant-available Mo being high in some instances. Molybdenum toxicity of plants was not apparent.

Both waste rock and tailings have a low CEC and, in combination with high rainfall experienced at the mine site, water-soluble fertilisers can be rapidly leached from them (Chapter 4). Consequently, careful selection of fertiliser type, rate and frequency of application is required if optimum and economic use is to be made of applied nutrients.

Once the nutrient limitations of the mine wastes were defined, the next step was to determine appropriate ameliatory measures.

Deleterious effects of acidity and Al toxicity on plant establishment and growth can be overcome by liming (Chapters 5 and 6). If Mn toxicity is a problem then liming to reduce exchangeable Al will reduce available Mn. Liming did not significantly effect available Cu in the field trials.

Liming to a pH of between 5.5 and 7.0 appears most acceptable. The lime applications applied in the pot trials were too large, with the pH raised to 7.5 to 8.0. At such levels, nutrient imbalances and reduced P availability may result. Excellent plant establishment was obtained in the field trials on waste rock with agricultural lime rates of 4 tonne/ha of $CaCO_3$ (Chapter 6). This raised the pH to between 5.5 and 6. In this range most exchangeable Al is precipitated. Liming in excess of neutrality does not appear warranted. Nutrient imbalances may result and the additional cost for a short term maintenance of pH would be difficult to justify.

Liming acid wastes also overcomes Ca deficiencies and this assists legume nodulation and function (Chapters 5 and 6). Calcium is freely available to plants in fresh tailings.

The other ameliorants required for either fresh tailings or limed (formally acid) tailings and waste rock are N, P, K, B and Mg.

It is shown that N fertiliser, particularly when applied as nitrate, was rapidly leached from tailings. Slow release N fertilisers were considered, but their residual benefit must be restricted when they are subject to a humid tropical climate. The study showed that on limed tailings and waste rock and fresh (alkaline) tailings, legumes can effecively nodulate and function if the correct strain of Rhizobium is present. By including a majority of legumes in the species mix for a revegetation programme, N applications may be kept to a minimum and restricted to the plant establishment phase. Ammonium N appears the more appropriate as it is less susceptible to leaching than nitrate. Nitrifying bacteria can effectively function in the wastes.

Phosphorus must be applied to the wastes if adequate plant establishment and growth is to be achieved. As well as being inherently deficient in plant available P, it is likely that the wastes can sorb significant quantities of applied soluble P. Fresh tailings, or over-limed acid wastes, may contain free calcium which can complex phosphates. As the wastes become acid Al and Fe hydroxy compounds are formed which again can significantly complex phosphates. This adds an extra dimension to a sound liming programme - maximum P solubility occurring at a pH between 6 and 7. However, maximum P solubility coincides with maximum P leaching.

Phosphorus leaching from fresh tailings was not confirmed with the lysimeter experiment. However, tailings in the field trials had very low available P following soluble P additions. This suggests that some leaching of P from the plant root zone may have occurred.

Pot trials with limed tailings showed that soluble P applications in excess of 100 kg/ha may be required to maximise biomass production under a controlled non-leaching environment. However, the pot trials suggested that 95% of maximum growth of a tropical legume could be achieved with a P addition of 64 kg/ha. Excellent plant establishment was obtained on tailings in the field trial where 81 kg/ha of soluble P were applied. No response was evident to rock phosphate applied in addition to the soluble P. Similarly, excellent plant establishment was obtained on waste rock with the addition of 4 tonne/ha of agricultural lime and 81 kg/ha of soluble P. Rock phosphate addition improved P supply and plant growth on the waste rock. At the lower lime rate of 2 tonne/ha it is likely that higher P application rates would have been required to achieve optimum plant establishment and growth.

Soil and foliar analyses from the study programme support the use of K, Mg and B fertiliser although addition and omission pot trials did not produce a quantitative requirement for them. Excellent plant establishment and growth was obtained in the field trials with the use of a grower fertiliser containing K, Mg and B (N:P:K:Mg:B 6:18:12:2:1) at a total rate of 500 kg/ha.

This study has shown that plants can be successfully established on Bougainville mine wastes if adverse pH is corrected with lime, N deficiencies corrected with N fertilisers and through the use of legumes, and P, K, B and Mg provided as inorganic fertilisers. However, the question of sustained plant growth remains unaddressed.

In pot trials, pH of tailings fell after liming. In pots without lime, pH fell from 4.5 to a low of 3.6 after 12 weeks. At this pH most plants will not grow due to the effects of both Al and H ion toxicity. With the field trials the pH fall after liming was not as rapid. The lowest pH measured in the field trials was 4.2. This was for a plot on waste rock that had only received 2 tonne/ha of lime and at the second harvest, 51 weeks after lime applications. This is the lowest pH that has been measured for waste rock. The lowest pH measured for tailings in the field was 4.5. This suggests that leaching of acid occurs in the field and that it is unlikely that a pH as low as 3.5 would be obtained.

The very acid phase of tailings is relatively short lived at one to three years, after which pH rises slightly to 5.0 to 5.5. Numerous tropical plants, in particular some legumes and grasses, can survive and grow successfully at a pH as low as 4.0 (Andrew, 1978; Humphreys, 1980). The most pH-sensitive stage of their life cycle is at plant establishment, and for legumes, at nodulation. If pH is corrected for the plant establishment phase, and acid-tolerant plant species are used, then a subsequent reduction in pH from residual pyrite oxidation should not be a major concern.

Similarly, many plant species have the ability to grow in soils that have high concentrations of available Al and Mn and the ability to extract P from mineral soils very low in available P (Andrew, 1978; Helyar, 1978). Their use should be encouraged.

The use of effectively nodulated legumes will, to a large extent, overcome the longer term N needs of established vegetation.

There does not appear to be significant residual value from soluble P addition, especially to coarser tailings of neutral pH, where leaching of P may occur. Rock phosphate can be effectively mobilised in waste rock. When the pH of tailings falls below 6.0 to 6.5, conditions should also allow mobilisation of rock phosphate. Rock phosphate will thus act as a slow release P fertiliser as well as providing some acid buffering capacity for the waste material.

Bougainville mine wastes contain considerable concentrations of P, K, Mg and Ca. These nutrients are largely present as primary minerals such as feldspars and micas. In the early stages of a revegetation programme they are relatively unavailable to plants (Chapter 4). However, as wastes weather they will be slowly released. The wastes may be able to meet the plants requirements for Ca and Mg in particular from this source.

Boron is not present in the wastes in significant quantities either in plant available form, or in primary mineral form. Boron is only needed by plants in small quantities. If B is supplied to wastes in the plant establishment phase, and if a rapid vegetative cover can be established with the production of large amounts of organic matter, then cycling of B through organic matter can prove sufficient for the long-term needs of revegetated wastes.

Nutrient cycling through organic matter will provide a similar function for other essential plant nutrients and it is the basis of the native rainforest nutrient supply.

Organic matter is essential for the long-term success of a revegetation programme for many other reasons. It supplies an energy source for micro-organisms, it improves soil structure and it helps in the removal of harmful metal cations from soil solution, particularly Cu. Organic matter also increases CEC and thus it will improve the retention of nutrients released from waste weathering and organic matter decomposition.

Bougainville mine wastes are poorly buffered, thus only small additions of lime or acid are required to effect a given pH change. Consequently, if oxidising wastes are limed to neutrality, further inputs of acid from residual sulphide oxidation will result in pH reductions in a matter of months. Waiting until sulphide oxidation has finished is not acceptable as the process can continue for many years. Providing acid buffering capacity by large additions of lime is uneconomic and more importantly, overliming can affect nutrient availability and plant performance.

Nutrient deficiencies associated with the mine wastes can be overcome by applying inorganic fertilisers. However, excessive leaching of some fertiliser types due to the high rainfall experienced at the mine sites and the coarse and low CEC wastes, means that large and frequent fertilizer applications may be required. Such applications would be unattractive both economically and ecologically.

The favoured approach to establishing a sustainable vegetative cover on the wastes would be to carry out the minimum required substrate amelioration and to utilise plants suited for growth on poor, generally acid, mineral soils.

It appears that the most susceptible stage of plant growth is germination and early seedling growth when plants are changing their nutrient supply from seed to soil medium. By liming to a pH of between 5.5 and 7.0, good germination and establishment can be assured. The pH of Bougainville mine wastes generally does not fall below 4.5 and by using plants suited to such conditions, plant die-back after establishment should be overcome. Fresh (alkaline) tailings do not require the addition of lime. In their case, a good plant cover should be attainable before the wastes become acid (Chapter 6).

Plants most suited for establishing a vegetative cover on acid wastes appear to be species of tropical legumes and grasses. Excessive leaching of N fertiliser makes biological N fixation essential for the long term stability of the revegetation programme. For this reason, legumes with the proven ability to be inoculated and to nodulate effectively under a wide pH range should be given preference.

Herbaceous plant species with the ability to provide rapid ground cover should be favoured. They will assist in erosion control and provide large amounts or organic matter with it's associated benefits for soil structure, chemistry, microflora and nutrient cycling.

Pulse, shrub and tree species with the proven ability to grow on the mine wastes should be included in the revegetation programme to provide some longer term stability to the plant community.

Despite the use of plant species adapted for growth on poorer, mineral soils, some fertiliser applications will be required in the plant establishment phase.

Residual P fertiliser can be provided by applying rock phosphate. A rate of approximately 160 kg/ha of contained P gave good results in the field trials of this study. Rock phosphate will also provide some acid buffering capacity and a slow release Ca supply.

Rock phosphate will not immediately supply phosphate to plants, especially on fresh tailings, where the substrate is still alkaline to neutral in pH. Subsequently, with sowing, a soluble form of P will be required as well as smaller additions of N, K, Mg and B. Actual rates will depend upon plant performance in the field. The fertiliser and application rates used in the field trials gave excellent plant establishment and as such should provide a good guideline. They consisted of two applications of N:P: 18:18 at 250 kg/ha each and one application of N:P:K:Mg:B 6:18:12:2:1 at 500 kg/ha. Splitting the later application in two may improve utilisation.

Most of the natural vegetation growing around the Bougainville mine site is growing on a highly organic soil of neutral pH. As such, it is unlikely that many of the native species will successively colonise the mine wastes. Thus, in the initial stages of a revegetation programme as outlined, plants growing on the revegetated mine wastes may differ quite markedly from those in the surrounding natural rainforest. However, as the mine wastes pass through the very acid phase and soil organic matter levels build up, native species should begin to volunteer.

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APPENDIX 1 : FOLIAR ANALYSIS FOR DESMODIUM AND PASPALUM GROWING ON LIMED TAILINGS WITH NUTRIENT ADDITION AND OMISSION TREATMENTS

Table 1 : Foliar Analysis For *Desmodium* Grown in Pots on Tailings with the Addition of Lime and Nutrients.

Table 2 : Foliar Analysis For *Paspalum* Grown in Pots on Tailings with the Addition of Lime and Nutrients.

Table 3 : Foliar Analyses for *Desmodium* Grown in Pots on Limed Tailings with Nutrient Omission Treatments.

Table 4 : Foliar Analysis For *Paspalum* Grown in Pots on Limed Tailings with Nutrient Omission Treatments.

TABLE 1 : FOLIAR ANALYSES FOR DESMODIUM GROWN IN POTS ON TAILINGS WITH THE ADDITION OF LIME, NUTRIENTS**

Analysis	Nutrient Addition Treatments										
	N+	P+	K+	Ca+	Mg+	Zn+	Mo+	B+	S+	Fe+	CONTROL
N %	*	2.75	*	*	*	*	*	*	*	*	*
P %	0.11	0.12	0.11	0.09	0.10	0.09	0.11	0.11	0.10	0.09	0.09
K %	2.16	1.90	2.05	2.21	2.12	2.01	2.10	2.29	2.06	1.94	1.48
Ca %	1.62	1.05	1.70	1.81	1.58	1.59	1.75	1.67	1.75	1.48	1.40
Mg %	0.23	0.16	0.23	0.25	0.24	0.31	0.24	0.27	0.22	0.26	0.25
B ppm	*	72	*	*	*	*	*	*	*	*	*
Mo ppm	*	1.5	*	*	*	*	*	*	*	*	*
Cu ppm	14	10	26	16	13	19	19	370	28	26	18
Al ppm	52	48	107	84	76	73	101	53	77	49	70
Mn ppm	168	213	264	194	179	228	273	266	265	185	272
Fe ppm	136	132	214	181	179	224	242	140	102	123	161
Zn ppm	87	104	120	79	102	97	147	350	169	96	98
S ppm	*	2280	*	*	*	*	*	*	*	*	*

* Insufficient sample for analysis. Analyses as outlined in Chapter 5.

** Bulked above ground biomass for four replicates.

TABLE 2 : FOLIAR ANALYSES FOR PASPALUM, GROWN IN POTS WITH THE ADDITION OF LIME AND NUTRIENTS**

Analysis	Nutrient Addition Treatments										
	N+	P+	K+	Ca+	Mg+	Zn+	Mo+	B+	S+	Fe+	Control
N %	1.08	0.80	0.80	0.90	0.83	0.77	0.74	0.77	0.77	0.74	0.81
P %	0.11	0.10	0.06	0.10	0.09	0.08	0.11	0.10	0.08	0.09	0.07
K %	3.30	2.68	2.87	2.92	2.86	2.76	2.49	2.53	2.46	2.53	2.44
Ca %	0.50	0.67	0.62	0.64	0.64	0.64	0.57	0.55	0.58	0.51	0.57
Mg %	0.09	0.08	0.09	0.09	0.13	0.07	0.06	0.05	0.06	0.05	0.06
B ppm	22	23	24	29	32	24	21	20	22	23	25
Mo ppm	8.1	6.9	9.6	11.0	9.0	9.5	17.0	6.3	8.5	8.9	9.4
Cu ppm	138	244	231	112	232	332	196	119	171	321	201
Al ppm	42	68	138	49	58	82	47	74	58	52	42
Mn ppm	287	381	321	322	325	365	244	196	233	153	200
Fe ppm	212	223	242	183	216	269	182	213	154	257	160
Zn ppm	275	232	192	232	247	196	150	129	202	148	149
S ppm	5662	*	*	*	*	*	*	*	*	*	5570

* Insufficient sample for analysis. Analyses as outlined in Chapter 5.
** Bulked above ground biomass for four replicates.

TABLE 3 : FOLIAR ANALYSES FOR DESMODIUM GROWN IN POTS ON LIMED TAILINGS, WITH NUTRIENT OMISSIONS**

Analysis	Nutrient Omission Treatment								
	N-	P-	K-	Ca-	Mg-	Zn-	B-	Mo-	Control
N %	2.98	*	2.79	3.09	2.91	3.5	3.04	3.16	3.10
P %	0.14	0.10	0.12	0.12	0.12	0.16	0.14	0.13	0.15
K %	2.14	1.96	2.05	1.76	2.13	2.15	2.00	2.03	2.09
Ca %	0.97	0.93	0.99	0.72	0.91	0.97	0.93	0.92	1.06
Mg %	0.18	0.21	0.20	0.17	0.15	0.23	0.22	0.20	0.25
B ppm	80	*	89	89	100	105	61	108	107
Mo ppm	24.0	*	27.0	13.0	9.6	14.0	15.0	0.8	13.0
Cu ppm	23	16	9	8	12	12	13	11	15
Al ppm	30	63	29	31	42	45	44	43	56
Mn ppm	111	228	160	125	194	203	190	197	224
Fe PPM	119	126	116	106	135	134	156	122	206
Zn ppm	66	115	83	68	102	98	95	102	100
S ppm	1880	*	1930	2590	2370	2630	2390	2140	2130

* Insufficient sample for analysis. Analyses as outlined in Chapter 5.

** Bulked above ground biomass for four replicates.

TABLE 4 : FOLIAR ANALYSIS FOR PASPALUM GROWN IN POTS ON LIMED TAILINGS WITH NUTRIENT OMISSIONS**

Analysis	Nutrient Omissions								
	N-	P-	K-	Ca-	Mg-	Zn-	B-	Mo-	Control
N %	*	*	0.77	*	*	*	*	*	*
P %	0.14	0.07	0.11	0.14	0.14	0.14	0.12	0.13	0.17
K %	2.27	2.43	2.43	2.21	2.05	2.31	2.48	2.01	2.53
Ca %	1.06	0.76	0.53	0.62	0.62	0.85	0.77	0.84	0.94
Mg %	0.11	0.13	0.09	0.11	0.07	0.12	0.10	0.10	0.17
B ppm	*	*	24	*	*	*	*	*	*
Mo ppm	*	*	16	*	*	*	*	*	*
Cu ppm	128	38	212	77	648	81	39	342	38
Al ppm	111	137	398	82	110	76	104	124	125
Mn ppm	333	262	164	219	296	275	208	261	396
Fe ppm	234	223	281	258	305	227	221	237	293
Zn ppm	426	499	109	146	492	131	109	283	359
S ppm	*	*	*	*	*	*	*	*	*

* Insufficient sample for analysis. Analyses as outlined in Chapter 5.
** Bulked above ground biomass for four replicates.

APPENDIX 2 : AMMONIUM AND NITRATE AS NITROGEN SOURCES FOR EUCALYPTUS DEGLUPTA GROWING ON LIMED TAILINGS

1. Aim
2. Materials and Methods
3. Results
4. Discussion and Conclusions

APPENDIX 2 : AMMONIUM AND NITRATE AS NITROGEN SOURCES FOR EUCALYPTUS DEGLUPTA GROWING ON LIMED TAILINGS

1 Aim

To assess the effectiveness of NH_4 and NO_3 as sources of N for plant growth on Bougainville mine tailings under natural rainfall and, therefore, strong leaching conditions.

2 Materials and Methods

Twenty plastic pots, 22 cm in diameter, were filled by weight with equal amounts of air dried, acid (pH 4.5) tailings collected from the banks of the Jaba river at XS29.

Calcium hydroxide (lime) at 2 tonne/ha was added to each pot and thoroughly mixed throughout. Pots were brought to field capacity by gravimetric measurement and left in that condition for one week to allow the lime to equilibrate. After one week, each pot received an application of basal fertiliser containing : P at 60 kg/ha as K_2HPO_4 and $NaH_2PO_4.2H_2O$
K at 50 kg/ha as K_2HPO_4
B at 30 mg per pot as H_3BO_3
As part of the fertiliser application, one half of the pots received N as NH_4Cl at 100 kg/ha and the other half received N as $NaNO_3$ at 100 kg/ha.

Pots were placed outside under natural rainfall conditions in a single randomised block so that there were two treatments with 10 replicates per treatment. Pots were re-randomised once per week.

Three days after applying the fertiliser, two Eucalyptus deglupta seedlings were sown in each pot. They had been raised on sterile sand.

Ten weeks after planting pots received a second application of N in accordance with the original application.

Twenty two weeks after planting seedlings were harvested. Tops were cut one cm above ground level, washed six time in deionised water, dried at 75°C for 48 hours in a forced draught oven, weighed, leaves bulked per treatment and analysed for foliar nutrients according to the specifications given in Chapter 5. Roots were washed thoroughly, dried at 75°C and weighed.

3 Results

The different N sources significantly affected tops and roots dry weights (p less than 0.01; Table 1). Mean dry weight of tops for plants receiving NH_4-N was 6.95 gm/pot, compared to 0.46 gm/pot for plants receiving NO_3-N.

Foliar analyses for the plants are presented in Table 2. For all nutrients except K, nutrient concentration in the leaves was highest for plants receiving NO_3-N. This was probably due to the massive increase in growth of the plants receiving NH_4-N compared to the plants receiving NO_3-N. The increased growth would have resulted in dilution of the finite nutrient supply. Irrespective of N treatment, foliar analyses indicate that N, P and Mg concentrations were low to deficient. Foliar analysis did not suggest any reason for the poor growth of the plants receiving NO_3-N.

Tops of plants receiving NH_4-N contained 54.21 mg of N (6.95 gm at 0.78% N) compared to 3.82 mg for plants receiving NO_3-N. One thousand and thirty two mg of N were added to each pot, thus N utilisation by tops of the plants receiving NH_4-N was 4.4%, compared to 0.31% for plants receiving NO_3-N.

4 Discussion and Conclusions

Plants differ in their ability to utilise various forms of N. However, it is unlikely that the *Eucalyptus deglupta* seedlings could not use N as NO_3. It was shown in Chapter 4 that NO_3 was rapidly leached from tailings by natural rainfall, while a greater proportion of NH_4 was retained on cation exchange complexes. It is probable that the poorer growth and lower N utilisation of the plants receiving NO_3-N was due to it's greater leaching. The cationic nature of NH_4 on the other hand, may have permitted the retention of enough N to substantially improve plant growth. Thus, NH_4-N acted as a slightly more slow release form.

It appears that if soluble N fertiliser is to be used in the revegetation of Bougainville mine wastes, that NH_4-N would be preferable to NO_3-N.