CHAPTER 4

SULFUR AND PHOSPHORUS SOURCES FOR PASTURES

4.1 INTRODUCTION

The experiment reported in Chapter 3 showed that the grain yield of flooded and non-flooded rice was significantly influenced by different sources of S. Under these conditions, the oxidation of elemental S-based products was affected by the water regimes. The question arises as to how effective these sources are for pastures under leached and non-leached conditions.

Although different sources of S under flooded and non-flooded rice conditions behaved similarly, further studies are required to evaluate the effectiveness of different S sources under different crops and different water managements for a longer period of time.

Many studies have been conducted on the effectiveness of S and P sources for pastures (Bolland and Bowden, 1984; Boswell, 1987; Friesen *et al.*, 1987a,b; Chisholm and Blair, 1988a,b,c; Bolland *et al.*, 1989). Several studies have been undertaken to investigate the effectiveness of elemental-S-containing products, as well as sulphate-based materials, for pastures under glasshouse as well as under grazing conditions (Shedley, 1982; Blair, 1987a; Boswell, 1987; Bowdler and Pigott, 1990). These results have generally shown that sulphate-containing products, such as gypsum, contribute sulphate to growing crops more quickly than elemental S. However, higher leaching S losses are generally recorded from gypsum in areas with high rainfall and soil with low adsorption capacity (Blair, 1979; Morris, 1987).

Greater quantities of high-analysis fertilisers, such as urea and triple superphosphate, are now produced by the fertiliser industries because of the cost advantage in transportation and application (Suryosunarko, 1989). The increasing use of high-analysis fertilisers, which contain none or only a small amount of S, and a declining use of conventional single superphosphate are the main reasons for increasing sulfur deficiency (Lefroy, 1989).

Phosphate rock has been reported to be an effective source of P for crops in some areas, particularly when soil pH is low (Rajan, 1987). In contrast, many investigators report that this material was not an effective P source due to the slow release of P (Bolland *et al.*, 1989;

Bolland and Gilkes, 1990). A greater acidulation of rock phosphate has been reported when this material was mixed with elemental S (Rajan, 1987) and this might be used to increase its effectiveness. However, the satisfactory performance of the combination of rock phosphate and elemental S will depend on intimate contact between the elemental S and rock phosphate constituents (Palmer and Gilkes, 1983). This experiment was undertaken to study the effects of different S and P sources for pastures under leaching and non-leaching conditions.

4.2 MATERIALS AND METHODS

a. Cores

PVC tubes, 16 cm in internal diameter and 13 cm deep, were driven into an S-deficient, unfertilised pasture on a granitic Aquic Haplustalf soil (Soil Taxonomy, 1975) at Uralla, N.S.W. The chemical analysis of the soil is presented in Table 3.1. The cores with the intact pastures were then removed from the field, capped at the base and for the leached treatments the cores were fitted with special leaching bases. The cores were then transported into the glasshouse and maintained at field capacity by daily weighing and watering with distilled water. The original grasses present were cut to approximately 0.5 cm above the soil surface. The cores were then oversown with perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) seeds. Shade cloth was used to cover the pots in order to facilitate seed germination. The pots were kept in a glasshouse with minimum and maximum temperatures of 15 and 25 °C.

b. Basal nutrients and ^{35}S labelling

Basal nutrients (Table 4.1) were diluted in distilled water and applied 14 days before the main treatments were applied. On the same day, carrier free ^{35}S obtained from Amersham Australia Pty. Ltd., was diluted with distilled water to give a solution containing 2.93 MBq ml^{-1}. A syringe was used to apply 5 ml of the radioactive solution to the surface of the soil to enable the reverse-dilution method of Shedley *et al.* (1979), as described in Chapter 3, to be used.

Table 4.1 Basal nutrient application rates.

Nutrients	Source	Application kg nutrient ha^{-1}	mg product pot^{-1}
N	$Ca(NO_3)_2$	10.0	8.7
K	KCl	40.0	52.0
Mg	$MgCl_2.6H_2O$	24.0	17.0
Zn	$ZnCl_2$	2.0	1.7
Cu	$CuCl_2.2H_2O$	0.2	0.17
Mn	$MnCl_2.4H_2O$	1.0	0.9
Mo	$Na_2MoO_4.2H_2O$	0.02	0.017
B	H_3BO_3	0.5	0.17

c. Experimental design, treatments and statistical analysis

Two randomized block design experiments with three replicates were conducted in the glasshouse, of the Department of Agronomy and Soil Science, The University of New England, Armidale, N.S.W, Australia.

In the main experiment the treatments (Table 4.2) consisted of the factorial combination of 2 S sources (elemental S and gypsum), 2 P sources, triple superphosphate (TSP) and rock phosphate (RP), 2 methods of S and P application (S mixed with granulated TSP or RP and S coated onto TSP or RP). One unfertilised treatment (C) was included in the experiment in order to calculate the percentage of S in the plant that was derived from the fertiliser. Two watering regimes were imposed where the soil in the non-leached (NL) treatment was maintained at or near field capacity by weighing and a leached (L) treatment where an excess of 25 % of water above field capacity was added every watering. The rock phosphate used in this experiment was from North Carolina, USA, with a P content of 14 %. The rock was finely ground prior to the experiment to a particle size less than 400 µm. Before the RP was coated with elemental S, the RP was granulated using a seed coating device and PVA glue (12 % w/v) was used to make granules. The granule size of the RP was made similar to the TSP granules (2 - 4 mm in diameter). The granulated rock phosphate and TSP were then coated with elemental S of particle size < 100 µm using the same device and procedures as in the previous chapter. Polyvinyl alcohol was used as an adhesive material to bind elemental S with the granulated TSP or granulated rock phosphate. Each fertilised treatment received the same amount of S and P at the rates of 40 mg elemental S pot^{-1} or 216 mg gypsum pot^{-1} (equivalent to 20 kg S ha^{-1} based on the surface area of the pot) and 402 mg TSP or 574 mg rock phosphate (equivalent to 40 kg P ha^{-1}).

In a subsidiary experiment the effectiveness of different TSP-S sources (Table 4.3) was investigated under non-leaching conditions. This experiment consisted of 5 fertilised treatments: TSP-S with PVA (PVA), TSP-S with slack wax (SW), TSP-S with sodium ligno-sulfonate (LS), TSP + gypsum (G), a commercial TSP-S which was manufactured by Hifert Fertiliser Ltd., Victoria, Australia, and a control (C). These treatments were replicated three times. Data of PVA, G and C were derived from the non-leached treatment in the main experiment. The same computer program as used in Chapter 3 was used in this experiment to analyse the data. Data from control were excluded from the analysis of variance, but the means of these data are presented in each graph for comparison. Data presented throughout this study are from the S × P × L interaction due to the non-significant difference recorded between coated and mixed fertilisers at each observation time. The comparisons among treatments are presented at each harvest except for percentage of S derived from the fertiliser and percentage of fertiliser S recovery in pasture tops analysed at 5 harvests in split plot in time to establish time trends.

To analyse for serial correlation between repeated harvests the BMDP-2V computer program was initially used to analyse the data. In this analysis there was no serial correlation observed and, on the advice of a statistician, analysis of variance at each harvest was used (Burr, 1982). Because of the complexity of the experimental design, data from the S × P × L interaction is generally presented to highlight consistent trends.

Table 4.2 Treatments and treatment codes for pasture experiments.

Treatment	Treatment code	S and P application	
		kg ha^{-1}	mg product pot^{-1}
S source			
Elemental S	E	20	40
Gypsum	G	20	216
P source			
Triple superphosphate	TSP	40	402
Rock phosphate	RP	40	574
S and P application			
S-coated TSP or RP	SC		
S mixed with TSP or RP	SM		
Water management			
Non-leached	NL		
Leached	L		
Control	C		

Table 4.3 Source and rate of S and P applied under non-leached conditions.

Treatment	Treatment code	S and P application S (kg ha^{-1})	P (kg ha^{-1})	product (mg pot^{-1})
Control	C	0	0	0
TSP + gypsum	G	20	40	618
TSPS-PVA	PVA	20	40	442
TSPS-sodium lig. sul.	LS	20	40	442
TSPS-slack wax	SW	20	40	442
TSPS-hifert	HF	20	40	442

d. Experimental Procedure

Two weeks after the application of basal nutrients and ^{35}S, the treatments shown in Table 4.2 and 4.3 were applied. The fertilisers were spread on the surface of the sward and the pots were watered daily. In the leached treatments leachates were collected and weighed every two days and stored in plastic bottles in a cold room at 4°C. The S and P content of leachates, as well as the radioactivity was measured following each harvest, using ICP Spectrometry and liquid scintillation counting respectively.

Successive harvests were made at intervals of between four and eight weeks depending on the growth rate of the pastures. At harvesting, plants were cut approximately 2 cm above the soil surface and the tops were separated into the grass and clover and oven-dried at 80 °C until a constant weight was achieved. The samples were then ground to pass a 2 mm sieve and digested in a sealed container with a mixture of 70 % perchloric acid and hydrogen peroxide (Anderson and Henderson, 1986). The concentration of S and P in the plant digest was then determined by ICP, and for radioactivity by liquid scintillation counting.

After the fourteenth harvest (96 weeks) the pastures were first cut in the same way as previously. The plant material between 0 and 2 cm was then cut and washed and mixed with the plant top. The soils were then pushed out of the pot and roots were removed. The soils were then mixed thoroughly and air-dried for analysis. Soil analysis included total S (Till *et al.*, 1984) and $Ca(H_2PO_4)_2$ extractable S (Barrow, 1967). The percentage of S in plant derived from the fertiliser was calculated by the same method as in the previous experiment.

4.3 RESULTS - S AND P SOURCES EXPERIMENT

4.3.1 Yield

a. Clover

For ease of comparison, data of S source (S) × P source (P) × leaching (L) interaction are presented in each graph, mainly because of the non-significant differences recorded between coated and mixed fertilisers throughout the experiment and the fact that significant interaction was recorded only among the S, P and L factors, although the interaction between these factors was not always significant at each harvest.

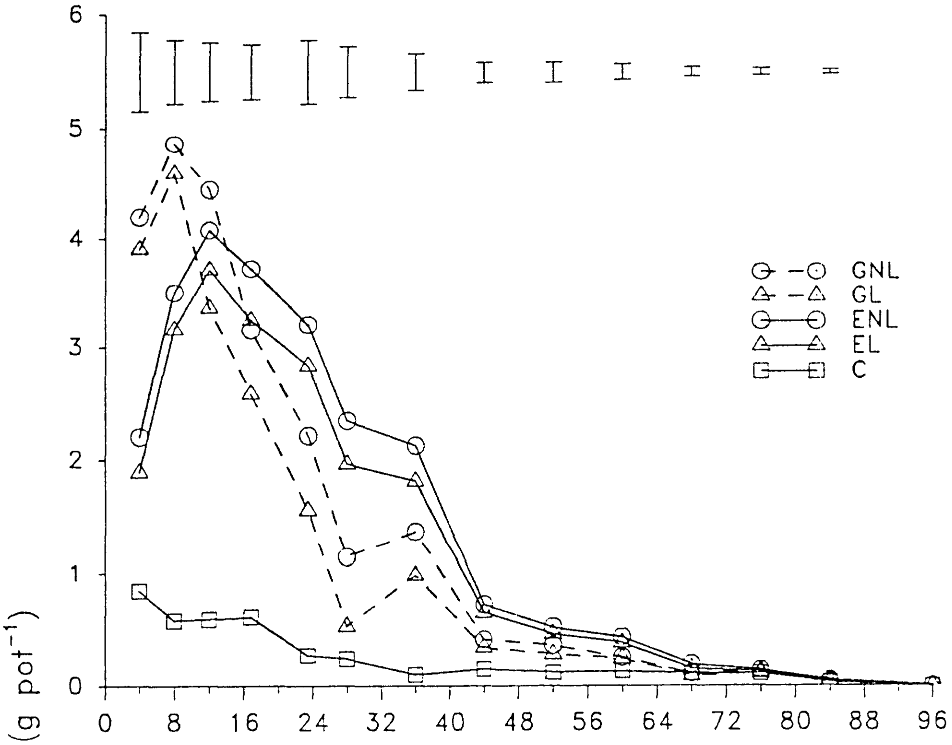
There were no significant differences recorded between leached and non-leached treatments up to the 8th week of application. In harvests between weeks 8 and 44, the combination of gypsum and TSP resulted in significantly lower yield under leached than under non-leached conditions. There was no significant difference in dry matter yield recorded between leached and non-leached treatments in the elemental S treatments at any harvest, although the yield was always lower under the leached condition (Figure 4.1).

There were significant S × P and S × L interactions recorded for clover dry matter yield, although these interactions were not significant at each harvest (Appendix 4.1). At all harvests up to week 28 clover yield was higher in the TSP than the RP treatments (Figure 4.1).

Clover yield from the gypsum treatments increased between 4 and 8 weeks and then declined with time and the yield from elemental S increased up to week 17 and declined after this harvest. In the TSP treatments, gypsum resulted in a significantly higher yield than that of elemental S in the first 8 weeks after fertiliser application. At week 12 and under non-leached condition, no significant differences were recorded between gypsum and elemental S treatments. A higher yield with elemental S than with gypsum was recorded in harvests between weeks 17 and 44 (Figure 4.1).

Among the RP treatments, gypsum resulted in significantly higher yield than that of elemental S in the first 8 weeks. However, a higher yield from elemental S was observed at week 28 and in harvests between weeks 44 and 60. In the gypsum treatments, a significantly lower yield was recorded from leached than non-leached treatments in harvests between weeks 24 and 44. There was no significant difference in dry matter yield recorded between the leached and non-leached treatments where elemental S was applied (Figure 4.1).

(a) TRIPLE SUPERPHOSPHATE



(b) ROCK PHOSPHATE

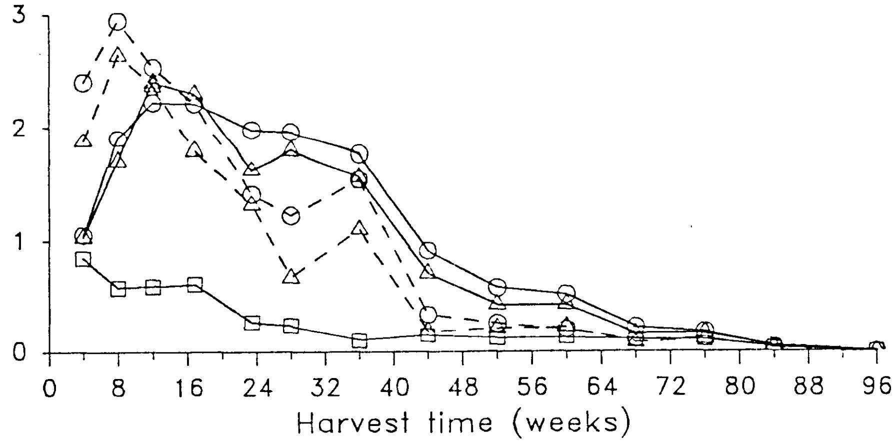


Figure 4.1 The effect of different S and P sources on dry weight of clover under leached and non-leached conditions. Vertical bars indicate LSD (P = 0.05) for P × S × L interaction at each harvest.

b. Grass

There were significant S x P and S x L interactions recorded in grass dry matter yield, although these interactions were not significant at each harvest (Appendix 4.2). At each harvest, there was no significant difference in grass dry matter yield recorded between leached and non-leached treatments, although the leached treatments tended to produce lower yield than that of non-leached treatments. In general, grass yield in the TSP treatments was higher than in the RP treatments at 8 weeks and no differences were observed after this harvest (Figure 4.2).

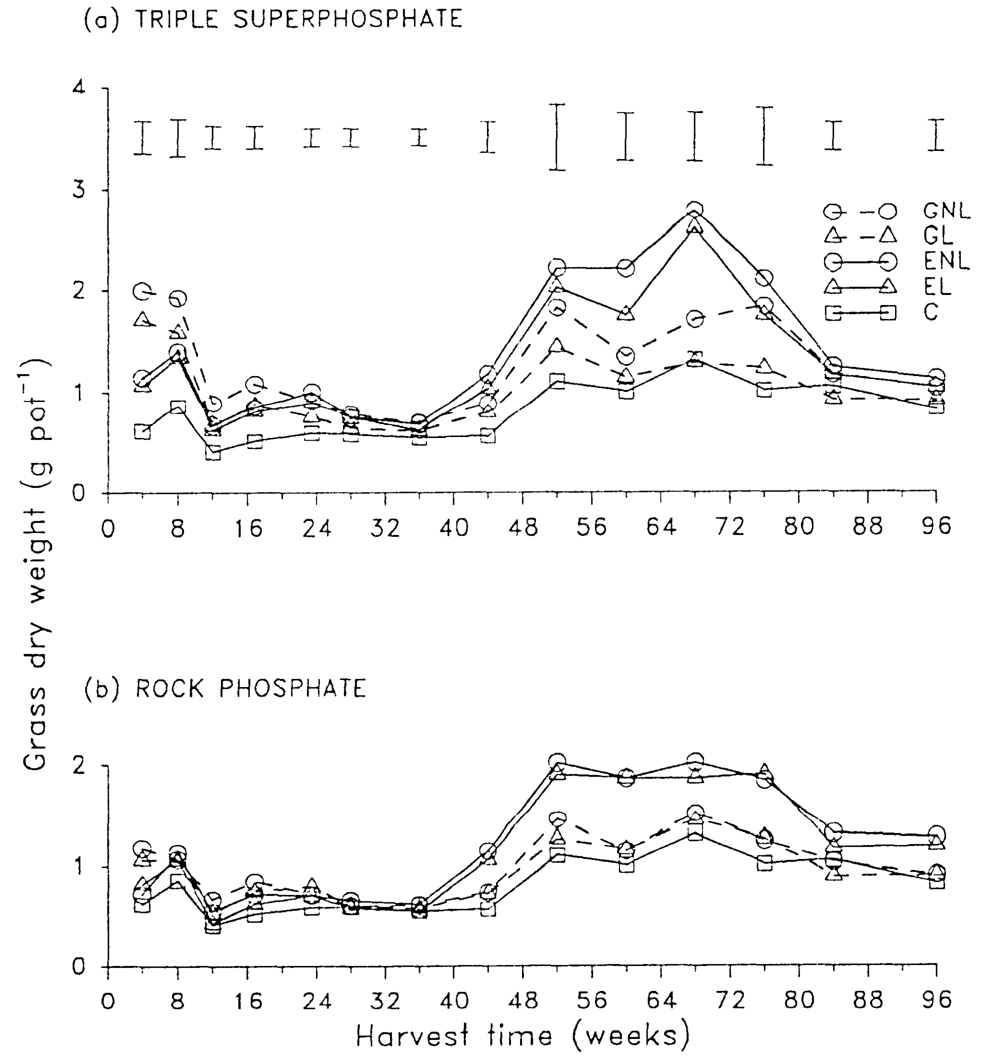


Figure 4.2 The effect of different S and P sources on dry weight of grass under leached and non-leached conditions. Vertical bars indicate LSD (P = 0.05) for S x P x L interaction at each harvest.

In general, with gypsum grass yield declined up to week 12 and increased after week 44. The yield with elemental S was relatively constant up to week 44 and increased after this time.

The grass response to applied fertilisers was not as strong as that of clover. Among the TSP treatments, gypsum resulted in the highest dry matter yield at 8 weeks. No significant differences were recorded between elemental S and gypsum in harvests between weeks 8 and 52. A significantly higher dry matter yield with elemental S than with gypsum was recorded between weeks 52 and 76 (Figure 4.2).

Among the RP treatments, gypsum resulted in a higher yield than those of elemental S at 4 weeks after application. A significantly higher yield with elemental S than with gypsum was observed in harvests between weeks 44 and 84 (Figure 4.2).

c. Total tops

There were significant S × P and S × L interactions recorded in total tops dry matter yield, although the significant interaction was not recorded at each harvest (Appendix 4.3). In general the pasture yield with gypsum declined with time. The yield with elemental S increased up to week 24 and declined after this time. Among the TSP treatments, gypsum resulted in the highest yield at 8 weeks. No differences were recorded between gypsum and elemental S in harvests between weeks 8 and 24. From week 24 up to week 68 higher yields were observed with elemental S than with gypsum, although the yield with gypsum under non-leached conditions did not differ significantly from that of elemental S under leached conditions at weeks 24 and 52. The yield with gypsum was lower under leached than under non-leached conditions in harvests between weeks 8 and 44. No significant differences were observed between the leached and non-leached treatments in the elemental S treatments (Figure 4.3).

Among the RP treatments, gypsum resulted in the highest yield at the first 8 weeks. A significantly higher yield was recorded with elemental S than with gypsum in harvests between weeks 36 and 84. No significant differences were recorded between leached and non-leached treatments, except in the gypsum treatments at weeks 28 and 36. At these harvests there was a lower yield from the leached than from the non-leached treatments (Figure 4.3).

In general, significantly higher dry matter yields were recorded with TSP than with RP in the earlier harvests and no differences were observed after week 44 (Figure 4.3).

d. Roots

There was no significant interaction recorded in root dry matter yield. Highest yield was observed in the combination of elemental S with TSP under non-leached condition, although this did not differ significantly from that under leached conditions. The combination of gypsum with TSP resulted in similar yield to that of the RP treatments (Appendix 4.4).

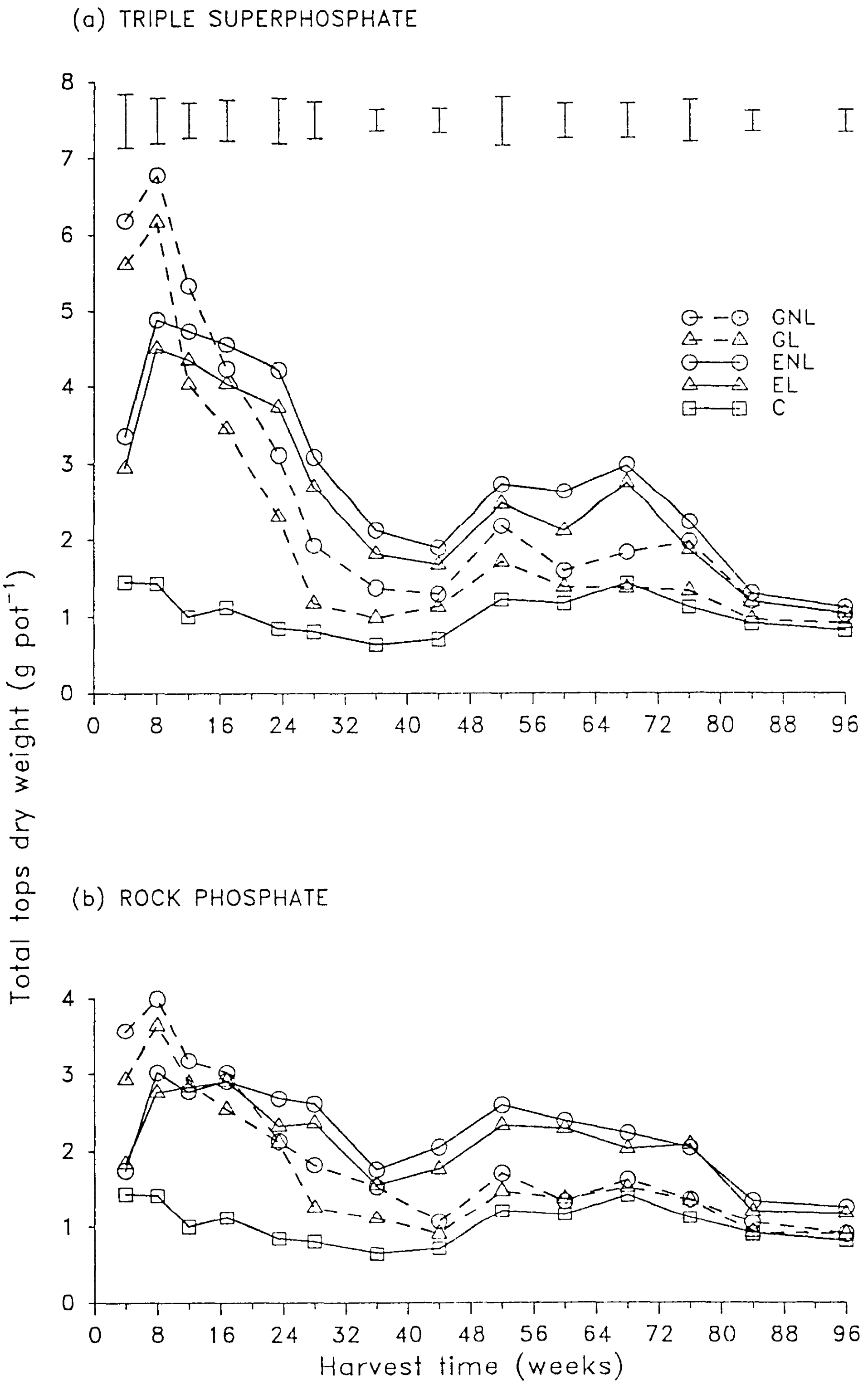


Figure 4.3 The effect of different S and P sources on total tops dry weight under leached and non-leached conditions. Vertical bars indicate LSD (P = 0.05) for S × P × L interaction at each harvest.

4.3.2 S Content

a. Clover

There were significant S × P and S × L interactions recorded in clover S content, although the interaction was not significant at each harvest (Appendix 4.5). In general, the clover S content with gypsum declined with time. The S content with elemental S increased up to week 12 and then declined. Among the TSP treatments highest S content was recorded in the gypsum treatments at 8 weeks. A significantly higher S content was recorded with elemental S than with gypsum in harvests between weeks 12 and 60. No significant differences were observed after the week 60 harvest (Appendix 4.6).

Among the RP treatments, gypsum resulted in the highest total S content at the first two harvests. This was reversed in harvests between weeks 17 and 60. A significantly lower S content from the leached than the non-leached treatments was recorded in the combination of gypsum with TSP in the first 12 weeks and at week 24 as well as week 36 after fertiliser application. No significant differences were observed between leached and non-leached treatments from the elemental S treatments. In general, a significantly higher S content was recorded with TSP than with RP up to week 24 and no differences were observed after this harvest (Appendix 4.6).

b. Grass

In general, there was no significant interaction recorded in grass S content, except at weeks 44 and 68, where significant S × L and S × P interactions were recorded respectively (Appendix 4.7). In general, the grass S content declined with gypsum up to week 12 and increased after week 44. The S content with elemental S was relatively constant up to week 44 and increased after this time. Among the TSP treatments gypsum resulted in the highest S content in the first 12 weeks. A higher S content was recorded with elemental S than with gypsum in harvests between weeks 36 and 76. No differences were observed after week 76 (Appendix 4.8).

Among the RP treatments, no significant differences were recorded between gypsum and elemental S treatments in the first 36 weeks. A higher S content was recorded with elemental S than with gypsum in harvests between weeks 36 and 76 (Appendix 4.8). In general, no significant differences were recorded in grass S content between TSP and RP treatments. Leaching had no significant effect on grass S content, except with gypsum and TSP at week 12.

At this harvest a significantly lower S content was recorded in the leached than in the non-leached treatments (Appendix 4.8).

c. Total tops

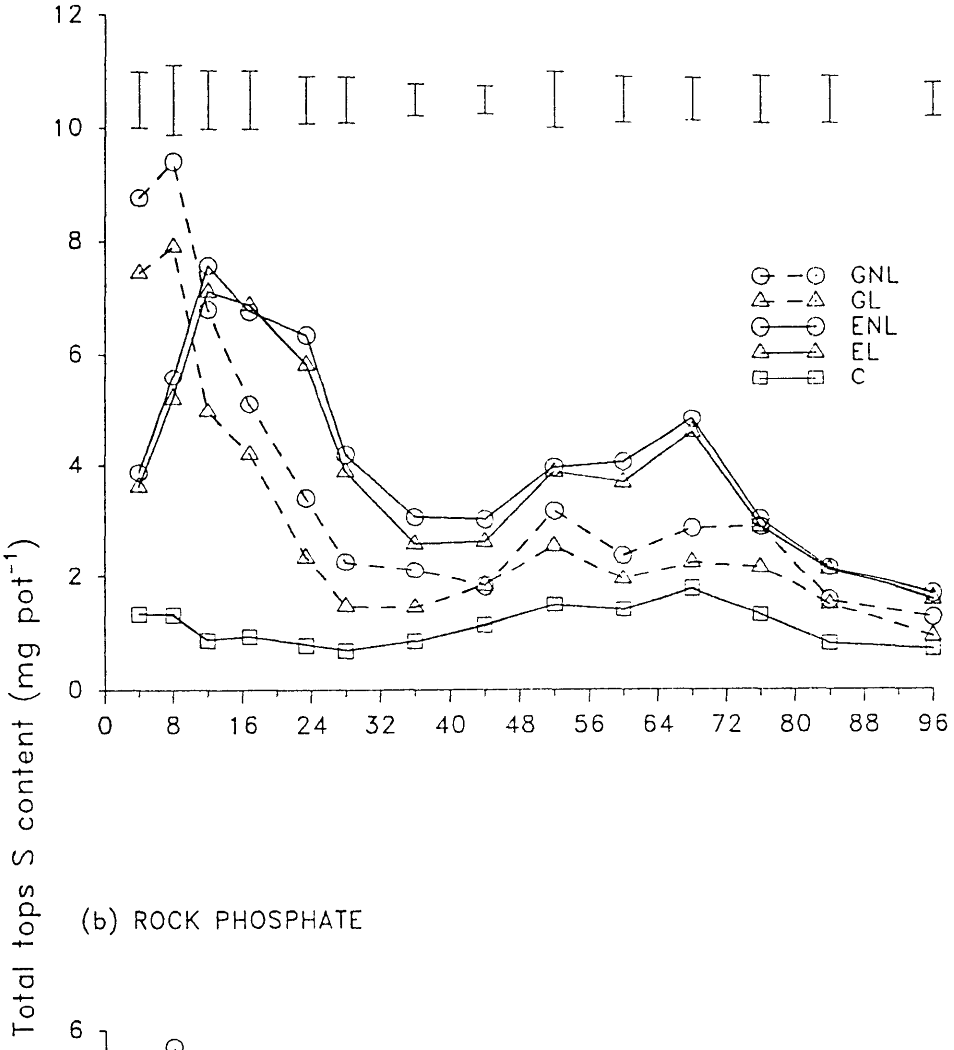
There were significant S × P and S × L interactions recorded in total tops S content (Appendix 4.9). In general the total tops S content declined with time in the gypsum treatments. The S content with elemental S increased up to week 17 and declined after this time. Among the TSP treatments, gypsum resulted in the highest S content at 8 weeks. A significantly higher S content was recorded with elemental S than with gypsum in harvests between weeks 12 and 76. No differences were observed after week 76. Under leached conditions the combination of gypsum and TSP resulted in a significantly lower S content than that of non-leached conditions in the first 12 weeks and at week 36. No significant differences were observed between the leached and non-leached treatments in the elemental S treatments either with TSP or RP (Figure 4.4).

Among the RP treatments, gypsum resulted in a significantly higher S content than that of elemental S at the first two harvests. This was reversed in harvests between weeks 17 and 76. No significant differences were recorded between leached and non-leached treatments at each harvest, although a lower rate was observed in the gypsum treatment under leached than under non-leached conditions at the first harvest (Figure 4.4). In general, the S content was higher with TSP than with RP in earlier harvests and no significant differences were recorded after week 24 (Figure 4.4).

d. Roots

There were no significant differences between treatments in root S content, although the S content with gypsum under leached conditions tended to be lower than that of elemental S under non-leached condition (Appendix 4.4).

(a) TRIPLE SUPERPHOSPHATE



(b) ROCK PHOSPHATE

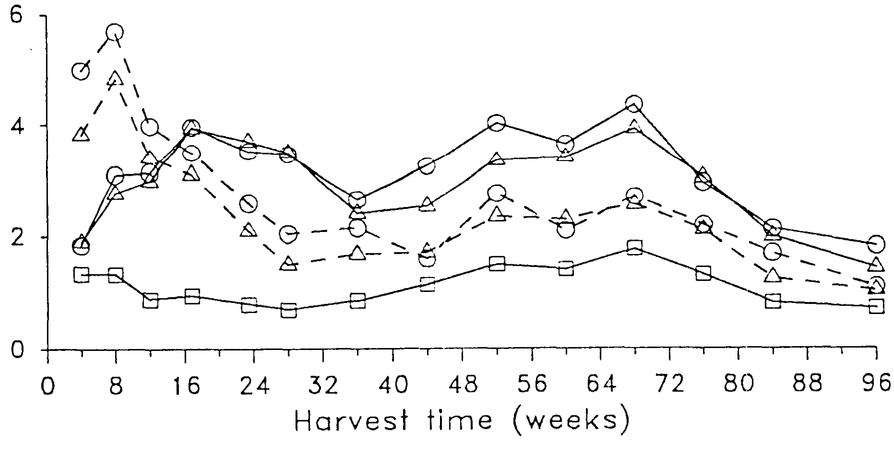


Figure 4.4 The effect of different S and P sources on total tops S content under leached and non-leached conditions. Vertical bars indicate LSD (P = 0.05) for S x P x L interaction at each harvest.

4.3.3 P content

a. Total tops

At weeks 36 and 68, there was a significant S × P interaction recorded in pasture P content (Appendix 4.10). Among the TSP treatments, gypsum resulted in the highest P content up to week 17. In harvests between weeks 17 and 36 and between weeks 36 and 68, a significantly higher P content was recorded with elemental S than with gypsum. Under leached conditions, the gypsum treatment resulted in significantly lower P content than that of under non-leached conditions between weeks 36 and 68. No significant differences were recorded in harvests between weeks 68 and 96, except in the gypsum treatments under leached conditions, which was lower than that of elemental S under non-leached conditions (Table 4.4).

Among the RP treatments, gypsum resulted in significantly higher P content than elemental S in the first 4 weeks. This was reversed in harvests after week 36. The highest total P content was recorded in the elemental S + TSP treatments, although this did not differ significantly from that of gypsum + TSP (Table 4.4).

In general, a higher P content was recorded with TSP than with RPin the first 36 weeks and no significant differences were observed after week 36 (Table 4.4).

Table 4.4 The effects of S and P sources on P content of pastures under leached and non-leached conditions.

Treatment	P content (mg pot $^{-1}$)				
	---------------------- Harvest Times (weeks)	--------------------			
	0 - 17	17 - 36	36 - 68	68 - 96	Total
TSP					
ENL	40.39 b[A]	19.57 a	15.53 a	6.94 ab	82.43 a
EL	37.62 b	18.61 a	14.52 ab	6.59 a-c	77.34 b
GNL	47.99 a	14.38 bc	10.51 c	5.47 b-d	78.35 ab
GL	44.59 a	13.32 cd	8.65 d	5.12 cd	71.68 c
RP					
ENL	21.15 d	14.87 bc	15.17 ab	7.68 a	58.87 d
EL	20.46 d	15.81 b	13.65 b	6.79 ab	56.71 d
GNL	25.91 c	12.92 cd	8.68 d	5.16 cd	52.67 d
GL	24.77 c	11.48 d	8.44 d	4.55 d	49.24 e

[A] *Data followed by the same letter in the same column are not significantly different ($P > 0.05$) (Duncan's multiple range test)*

b. Roots

In general, the root P content did not differ significantly among the treatments, except in the gypsum treatments, which resulted in a significantly lower P content under leached than under non-leached conditions (Appendix 4.4).

4.3.4 Percentage of S derived from the fertiliser

a. Tops

There was significant S × P interaction recorded in the percentage of S in pastures derived from the fertiliser, although the significant interaction was not recorded at each harvest (Appendix 4.11). In the gypsum treatments, the percentage of S derived from the fertiliser declined significantly over time. However, in the elemental S, TSP combination, the rate increased significantly up to week 8 and declined after that time. In the elemental S, RP combination the percentage of S derived from the fertiliser increased significantly up to week 36 and declined after that time (Table 4.5).

In general, gypsum treatments had a higher percentage of S in the tops derived from the fertiliser than did elemental S at the first two harvests. This was reversed in harvests between weeks 8 and 96. Leaching had no significant effect on the percentage of S in the plant derived from the fertiliser, except in the gypsum, RP combination at week 36 where a significantly lower proportion of S was derived from the fertiliser in the leached than the non-leached treatment (Table 4.5).

Table 4.5 The effect of S and P sources on the percentage of S in the tops derived from the fertiliser under leached and non-leached conditions.

Treatment	S derived from the fertiliser (%) Harvest Times (weeks) 4	8	36	68	96
T S P					
ENL	27.8 j[A]	50.5 e	43.7 f	18.0 k	8.0 l-n
EL	27.6 j	49.8 e	41.3 fg	17.3 k	8.3 l-n
GNL	77.7 a	72.9 bc	32.0 hi	10.7 l	7.0 mn
GL	76.3 ab	71.4 c	29.0 ij	8.9 lm	5.7 n
R P					
ENL	19.4 k	27.1 j	51.6 e	20.2 k	9.2 lm
EL	18.9 k	29.1 ij	50.4 e	16.7 k	9.5 lm
GNL	72.1 bc	65.9 d	38.0 g	10.2 lm	5.8 n
GL	70.3 c	64.8 d	33.1 h	9.9 lm	5.5 n

[A] *Data followed by the same letter are not significantly different ($P > 0.05$) (Duncan's multiple range test).*

b. Roots

Elemental S treatments had the highest percentage of S in root derived from the fertiliser and no significant differences were recorded between leached and non-leached treatments or between TSP and RP (Appendix 4.4).

4.3.5 Recovery of fertiliser S

a. Total tops

There were significant S × P and S × L interactions recorded in the recovery of fertiliser S in the tops, although there was no significant interaction recorded after week 28 (Appendix 4.12). Among the TSP treatments, gypsum resulted in significantly higher recovery than that of elemental S at the first two harvests. This was reversed in harvests between weeks 12 and 76 (Figure 4.5). A significantly lower recovery of fertiliser S was recorded with gypsum in the leached than in the non-leached treatments in the first 24 weeks. No significant differences were recorded between the leached and non-leached treatments with elemental S, except at weeks 24 and 36 where the leached treatment resulted in a lower recovery (Fig 4.5).

Among the RP treatments, the recovery of fertiliser S in the tops was higher with gypsum than with elemental S at 12 weeks. This was reversed in harvests between weeks 24 and 76 (Figure 4.5). No significant differences were observed between the leached and non-leached treatments at each harvest, although the recovery of fertiliser S in the gypsum treatment was significantly higher in the non-leached than in the leached treatment at week 4 (Figure 4.5).

In general, the recovery of fertiliser S in the TSP treatments was significantly higher than that in RP treatments at the first five harvests and no significant differences were observed after week 24 (Figure 4.5).

b. Roots

In general, the recovery of fertiliser S in roots was significantly higher with elemental S than with gypsum and no significant differences were observed between leached and non-leached treatments (Appendix 4.4).

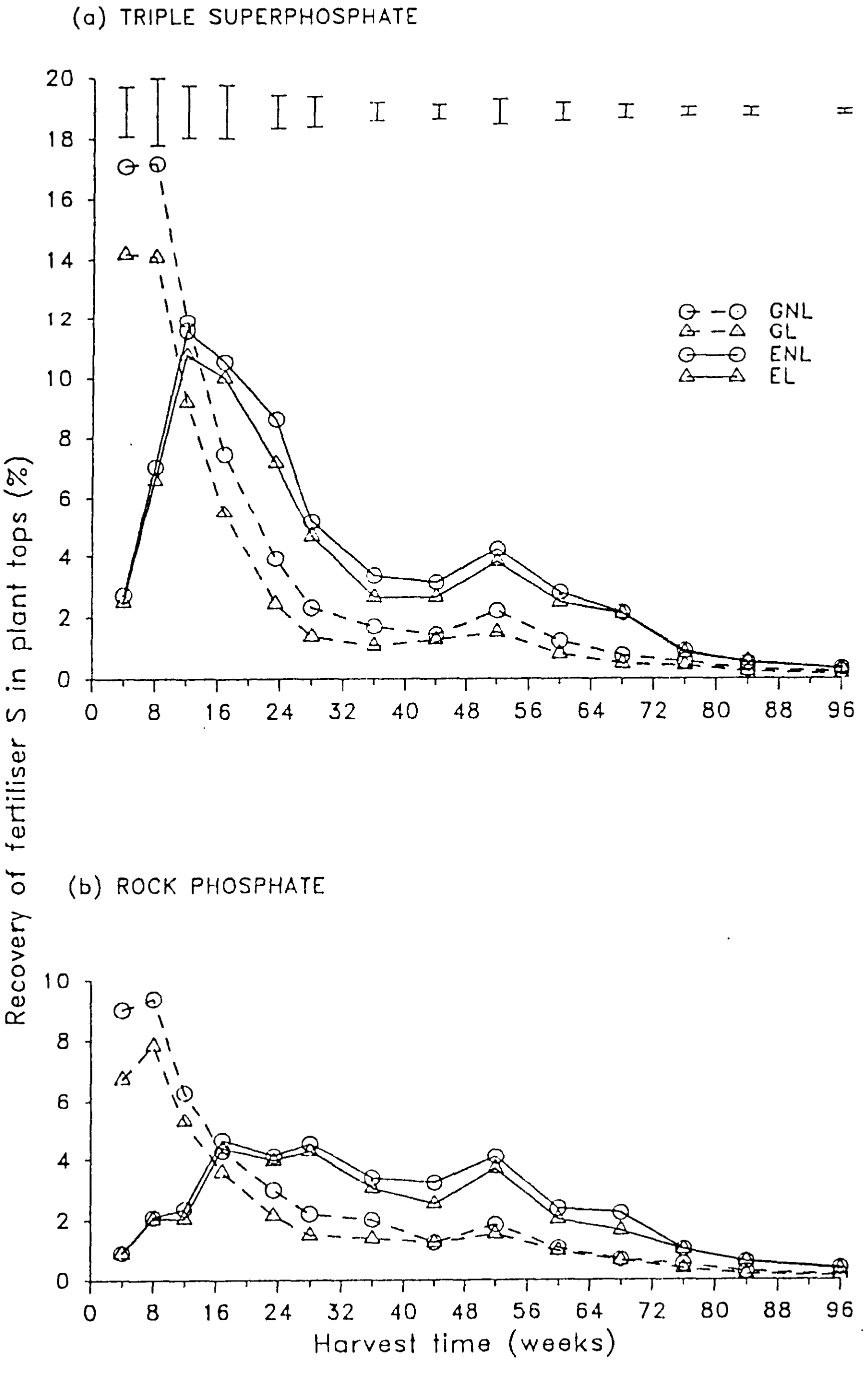


Figure 4.5 The effect of different S and P sources on the recovery of fertiliser S in plant tops under leached and non-leached conditions. Vertical bars indicate LSD (P = 0.05) for S × P × L interaction at each harvest.

4.3.6 S and P loss through leaching

a. S content of leachates

At each harvest, there was no significant interaction recorded in the amount of S in leachates among the treatments (Appendix 4.13). Up to week 36 the highest S content of leachates was recorded in the gypsum treatments, and the loss from the RP treatments was lower in the first 17 weeks. No significant differences were observed between the treatments in harvests between weeks 36 and 68 and 68 and 96. The total S loss was lower with elemental S than with gypsum (Appendix 4.14).

b. P content of leachates

There was no significant interaction recorded in the P content of leachate at each observation (Appendix 4.15). In general, the P content of leachates did not differ significantly among the treatments, although it was higher from TSP than from RP in the first 17 weeks (Appendix 4.16).

c. Percentage of S in leachates derived from the fertiliser

There were significant S × P interactions in the percentage of S in leachates derived from the fertiliser at week 4 and 68 (Appendix 4.17) with the level generally declining with time with the gypsum and increasing up to week 36 and then declining in the elemental S treatments (Table 4.6).

Table 4.6 The effect of S and P sources on the percentage of S in leachates derived from the fertiliser.

Treatment	S derived from the fertiliser (%)				
	Harvest Times (weeks)				
	4	8	36	68	96
TSP					
E	30.87 f-h[A]	70.40 c	66.58 c	37.79 e	26.73 gh
G	92.94 a	83.79 b	58.70 d	36.76 ef	24.91 h
RP					
E	9.96 i	67.54 c	65.01 cd	38.23 e	26.27 gh
G	92.05 a	81.04 b	59.67 d	31.89 e-g	24.41 h

[A] *Data followed by the same letter are not significantly different (P > 0.05) (Duncan's multiple range test)*

d. Recovery of fertiliser S in leachates

There were significant S × P interactions recorded in the amount of fertiliser S recovered in the leachates at week 4 and 12 (Appendix 4.18). In general, fertiliser S losses were higher from the gypsum treatments in the first 17 weeks. No significant differences were recorded after week 17 (Figure 4.6).

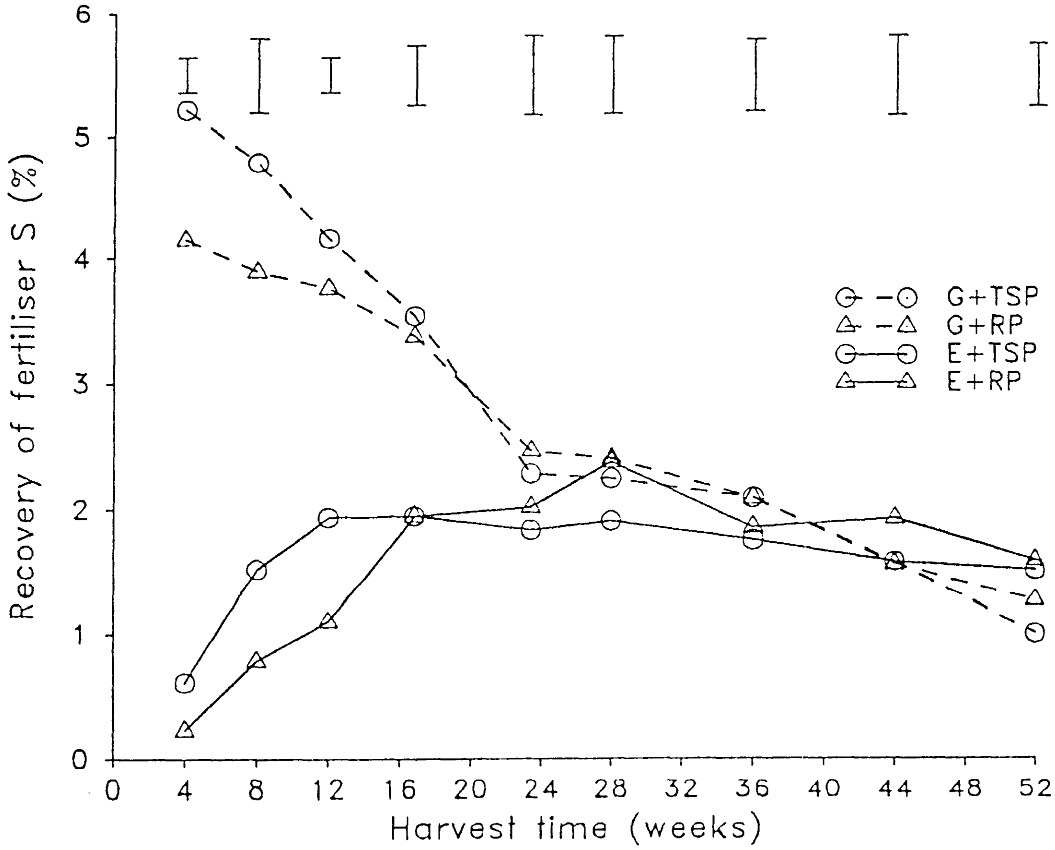


Figure 4.6 The effect of different S and P sources on the recovery of fertiliser S in leachates. Vertical bars indicate LSD (P = 0.05) for S × P interaction at each observation time.

4.3.7 Soil S pools

At the end of the experiment, the extractable S levels did not differ significantly among the treatments. No significant differences were observed in the percentage of S derived from the fertiliser and in the recovery of fertiliser S in the extractable S fraction among the treatments (Appendix 4.19).

There was no significant difference in organic S level recorded between the treatments (Appendix 4.19). However, significant S × P, S × L and S × P × L interactions were recorded in the percentage of S in this fraction derived from the fertiliser. In general, the percentage of S derived from the fertiliser in the organic S fraction was higher in the RP than in the TSP treatments (Appendix 4.19).

At the end of the experiment, there were no significant differences in soil total P content recorded among the treatments (Appendix 4.20).

4.4 RESULTS - S SOURCES EXPERIMENT

4.4.1 Yield

For ease of presentation of data, two or more harvests have been combined. At weeks 4 + 8, highest yield was recorded in the G treatment, intermediate yields with PVA and LS and lowest yield in the control. At weeks 12 + 17, the ranking was G = PVA = LS > SW = HF > C; at weeks 24 + 28, PVA = LS = HF = SW > G > C and at weeks 36 + 44, SW = HF > PVA = LS > G > C. Highest total yield was recorded in the G and lowest in the C treatment (Table 4.7).

4.4.2 S content

Highest S content was recorded in the G treatment at weeks 4 + 8. At these Harvests the S content with PVA was not significantly different from that with LS and this was higher than SW and HF. The lowest S content was in the control at each harvest. At weeks 12 + 17, highest S content was recorded with PVA and LS whilst at 36 + 44 SW and HF had the highest S content. The highest total S content was recorded in the LS treatment, although this did not differ from that of G and PVA. Among the fertilised treatments, SW resulted in the lowest S content, although this was similar to that of HF and G (Table 4.7).

4.4.3 P content

Highest P content was recorded in the G treatment at weeks 4 + 8 with intermediate levels with PVA and LS. The lowest P content was recorded in the C treatment at each observation time (Table 4.7). At weeks 12 + 17, highest P content was recorded in the G, LS and PVA treatments. At weeks 24 + 28 and 36 + 44 the ranking was SW = HF > PVA = LS > G > C. Highest total P content was recorded in the G, LS and PVA treatments (Table 4.7).

Table 4.7 The effect of S source on dry weight (g pot $^{-1}$), S and P content (mg pot $^{-1}$) of plant tops at different harvest times.

Treatment	Harvest Times (weeks)				
	4 + 8	12 + 17	24 + 28	36 + 44	Total
Yield (g pot $^{-1}$)					
G	13.5 a[A]	9.2 a	4.8 b	2.5 c	30.0 a
PVA	8.0 b	9.2 a	7.5 a	4.2 b	28.9 ab
SW	5.2 c	8.1 b	8.6 a	5.5 a	27.4 b
HF	5.5 c	7.8 b	8.4 a	5.6 a	27.3 b
LS	8.6 b	9.2 a	7.6 a	3.6 b	29.0 ab
C	2.9 d	2.3 c	1.7 c	1.4 d	8.3 c
S content (mg pot $^{-1}$)					
G	18.8 a	11.1 b	5.6 b	3.6 c	39.1 a-c
PVA	8.6 b	14.2 a	10.9 a	6.5 b	40.2 ab
SW	5.8 c	10.7 b	12.2 a	8.1 a	36.8 c
HF	6.1 c	10.7 b	12.2 a	8.3 a	37.3 bc
LS	9.8 b	14.1 a	11.0 a	5.8 b	40.7 a
C	2.8 d	2.0 c	1.5 c	1.9 d	8.3 d
P content (mg pot $^{-1}$)					
G	28.1 a	19.8 ab	10.5 c	5.1 c	63.5 ab
PVA	17.9 b	22.1 a	15.5 b	9.0 b	64.5 ab
SW	11.2 c	15.7 c	18.9 a	13.1 a	58.9 b
HF	11.0 c	16.7 bc	18.8 a	14.2 a	60.6 b
LS	20.5 b	23.6 a	16.3 b	9.2 b	69.6 a
C	4.2 d	3.4 d	2.5 d	2.2 d	12.3 c

[A] Data in each component followed by the same letter in the same column are not significantly different ($P > 0.05$) (Duncan's multiple range test).

4.4.4 Percentage of S derived from the fertiliser

In the gypsum treatment, the percentage of S derived from the fertiliser in the plant tops declined significantly with time after week 8 (S source × harvest time interaction). In the PVA and LS treatments, the contribution of S from the fertiliser increased up to week 17 and then declined, whilst in the HF and SW treatments the rate increased up to week 28 and then declined (Table 4.8).

In general, the percentage of S derived from the fertiliser was higher with gypsum than with the elemental S in earlier harvests and this was reversed after week 17 (Table 4.8).

Table 4.8 The effect of S source on the percentage of S in pastures derived from the fertiliser at different harvest times.

Treatment	S derived from the fertiliser (%) Harvest Times (weeks)				
	4	8	17	28	44
G	78.96 a^A	73.41 a	57.03 cd	40.13 g	31.28 hi
PVA	27.46 i	49.84 f	63.37 b	51.32 ef	41.59 g
SW	17.93 j	32.90 h	55.34 de	58.45 b-d	47.10 f
HF	18.39 j	31.34 h	56.62 cd	57.10 cd	44.07 f
LS	27.72 i	50.47 ef	62.08 bc	51.48 ef	39.61 g

^{A} *Data followed by the same letter are not significantly different (P > 0.05) (Duncan's multiple range test).*

4.4.5 Recovery of fertiliser S

Gypsum resulted in the highest recovery of fertiliser S in the plant tops at weeks 4 + 8. No differences were observed between PVA and LS and also between HF and SW (Table 4.9). At weeks 12 + 17, highest recovery was recorded in the PVA and LS treatments, whilst the lowest recovery was recorded from SW and HF. The ranking at weeks 24 + 28 and 36 + 44 was HF = SW > LS = PVA > G. The total recovery of fertiliser S was highest in the gypsum treatment and lowest with SW and HF. A non-significant difference was also recorded between PVA and LS (Table 4.9).

Table 4.9 The effect of S source on the recovery of fertiliser S (%) in pastures at different harvest times.

Treatment	Harvest Times (weeks)				
	4 + 8	12 + 17	24 + 28	36 + 44	Total
G	35.7 a^A	17.8 b	6.0 c	2.9 c	62.4 a
PVA	8.8 b	21.8 a	14.6 b	7.0 b	52.3 b
SW	3.9 c	12.1 c	17.6 a	9.9 a	43.5 c
HF	4.1 c	12.7 c	17.8 a	10.1 a	44.7 c
LS	10.0 b	22.0 a	14.7 a	6.1 b	52.9 b

^{A} *Data followed by the same letter in the same column are not significantly different (P > 0.05) (Duncan's multiple range test).*

4.4.6 Soil S pools

At the end of the experiment, the extractable S levels did not differ significantly among the S sources and no significant differences were observed in the percentage of S in this fraction derived from the fertiliser. The recovery of fertiliser S in this fraction was highest with HF, PVA, SW and LS (Appendix 4.21).

There was no significant difference in organic S level recorded among the treatments (Appendix 4.21). The percentage of S derived from the fertiliser and the recovery of fertiliser S in this fraction did not differ significantly among the treatments (Appendix 4.21).

At the end of the experiment, there was no significant difference in total P content recorded among the treatments (Appendix 4.22).

4.5 DISCUSSION

a. S and P sources

In the main experiment, no significant differences were observed between coated and mixed fertilisers at each harvest, although the mixed fertiliser tended to produce higher yield in the early harvests. This was probably because the water soluble glue which was used to bind elemental S with the granulated fertilisers did not impair the oxidation of elemental S.

A rapid reduction in clover growth was recorded and higher grass yields were measured after week 36. This is the result of N transfer from the legume to the grass which has been shown by Walker and Adams (1958). They also demonstrated that grass was a more effective competitor for limited sulfur than white clover.

The lower dry matter yield and S content of the clover in the elemental S treatments in the first two harvests resulted from the delay in oxidation of elemental S. Sulfatic fertiliser such as gypsum has been reported by Scott *et al.*, 1983; Klessa *et al.*, 1989 to be effective in supplying S to pasture in the first year of application with a small residual value observed from this source.

The percentage of S derived from the fertiliser and the recovery of fertiliser S in the plant data indicated different rates of sulfate release from the different sources of S. Gypsum, in which the sulfur is in the soluble sulfate form, resulted in an immediate release of sulfate to the plant as reflected by the higher recovery of fertiliser S in the plants from gypsum at the early harvests. On the other hand, the elemental S provided a slower and more sustained sulfate release. A similar response in an irrigated white clover pasture in South-east Queensland was reported between gypsum and elemental S Bowdler and Pigott (1990). They found that both flowers of sulfur and gypsum were effective as source of S for pastures.

The effectiveness of elemental S in providing S to crops depends on the oxidation rate and this is influenced by many factors including soil temperature (Li and Caldwell, 1966, Nor and Tabatabai, 1977, Janzen and Bettany, 1987b), soil moisture (Janzen and Bettany, 1987b, Nevell and Wainwright, 1987), soil pH (Nor and Tabatabai, 1977), soil organic matter (Wainwright *et al.*, 1986), soil texture (Rehm and Caldwell, 1969), particle size of elemental S (Blair, 1987, Janzen and Bettany, 1987a), sulfur-oxidizing microorganisms (Vitolins and Swaby, 1969) and nutrient status of the soil (Bloomfield, 1967). Activity of sulfur-oxidizing microorganisms in soil is of major importance where elemental S-containing fertilisers are used. Many different microorganisms are reported to be capable of oxidizing inorganic S compounds including chemolithotropic organisms such as the *Thiobacillus* spp. and a variety of heterotrophic bacteria, actinomycetes and fungi (Wainwright *et al.*, 1986). Lindemann *et al.*(1991) found that no oxidation in the elemental S occurred in the absence of *Thiobacillus* spp.

Although there was a significant S × P interaction in pasture P content (Appendix 4.10), the availability of S in the soil was the most important factor. This was described by the fact that higher P content was recorded in the gypsum treatment up to week 17. However, between weeks 17 and 68 a higher P content was recorded in the elemental S treatment (Table 4.4). This was most likely due to the higher availability of S as a result of S oxidation.

The higher yield with TSP was due to the higher availability of P from this source compared to RP, since the availability of P from RP is dependent on the dissolution rate of this material. This result is consistent with the previous results reported by Bolland *et al.* (1988). Rajan (1987) reported that the reactive phosphate rocks applied with or without sulfur were as effective as superphosphate in the first and third year of application when used in soils of pH less than 5. The pH of the soil used in the present experiment was 6.1 (1:5 H_2O); therefore rockphosphate was not an effective source of P in this pH range. This was compounded by the granulation of the RP source.

It is generally accepted that the phosphate rock is effective when it is finely ground, reactive and applied to acid soils of low exchangeable calcium (Khasawneh and Doll, 1978). Many factors are associated with the dissolution of RP, including the source of rock : reactive rock phosphate is more effective than non-reactive (Hughes and Gilkes, 1986a); soil acidity (Hughes and Gilkes, 1986b, Kanabo and Gilkes, 1987, Rajan *et al.*, 1991 a, b); particle size (Khasawneh and Doll, 1978, Kanabo and Gilkes, 1988b, Gilbert *et al.*, 1990); rate of application (Bolland and Barrow, 1988) and method of application (Kanabo and Gilkes, 1988a). Finer particle size increases the agronomic effectiveness of RP because of the increase in surface area which leads to an increase in the degree of contact between RP and soil (Olsen, 1975). The effectiveness also depends on the degree of mixing of RP with soil, with maximum effectiveness when it is uniformly mixed (Khasawneh and Doll, 1978). In the present study, re-granulation of RP probably reduced its effectiveness due to the reduction of the surface area.

Although many studies have found that RP was an ineffective source of P in the year of application (Chien and Hammond, 1978 and Bolland and Gilkes, 1990), a greater residual value of this material has been observed compared with single superphosphate (Mackay and Wewala, 1990).

In the leaching treatments, only small amounts of P were detected in the leachates during the course of the experiment. This would most likely be associated with the low mobility of P in the soil due to adsorption. Direct extrapolation of results from pot experiments to the field situation is dangerous. However, the loss of 2.37 mg P pot^{-1} (Appendix 4.16) from TSP equates to 1.3 kg ha^{-1}. This agrees with other studies reported in the literature (Brady, 1990). The movement of P within the soil profile is affected by soil pH, its concentration in the soil solution and the nature of the adsorption complex in the soil (Bar-Yosef *et al.*, 1988). A leaching-loss study of nitrogen, phosphorus and potassium was conducted recently on tobacco soils in North Queensland (Littlemore *et al.*, 1990). They estimated that 50 - 80 kg P ha^{-1} was lost through leaching. Similar results were reported by Weaver et al. (1988 a, b).

Under leached conditions higher clover yield was recorded in the gypsum than in the elemental S treatments in the early harvests. However, after week 8 clover yield and S content were lower in the gypsum than the elemental S treatments. This was because of the combination of higher S offtake and greater loss of S through leaching when gypsum was applied. The low loss of fertiliser S from elemental S is consistent with the results of Jones *et al.*, 1968 and Korentajer *et al.*, 1984. The movement of sulphate in the soil is influenced by the amount of water movement within the soil, the particle size of the product used (Korentajer *et al.*, 1984), its concentration in the soil solution, and its reaction with solid phase components of the soil (Harward and Reisenauer, 1966).

Although there was no significant difference in dry matter yield between leaching and non-leaching in the elemental S treatments, the yield under leaching conditions was always lower than non-leaching conditions. This was probably due to the reduced aeration, from the reduction in pore space associated with the watering regime in the leached treatments, which resulted in slower oxidation of elemental S.

S loss through leaching was also affected by the P sources. In this study the recovery of S in the leachate was higher from the TSP than from the RP treatments in the early harvests (Appendix 4. 14). The most likely reason for this is through competition by phosphorus for adsorption sites in the soil (Parfitt, 1982 and Barrow, 1970). The sulfate desorbed is easily lost through leaching or taken up by the plant. Liming has also been reported to increase S losses through leaching and generally has a stronger effect than phosphate in relation to S leaching (Chao *et al.*, 1962a).

Figure 4.7 shows the fate of fertiliser S and its transformation into the different soil S and plant pools. This figure illustrates that in the RP treatments a higher amount of applied S was recovered in to the soil organic S pool due to the poorer growth of pastures which resulted in less S uptake by the plant. A higher S loss through leaching with gypsum than with elemental S was also recorded, which is similar to the previous findings of Mahler and Maples (1987).

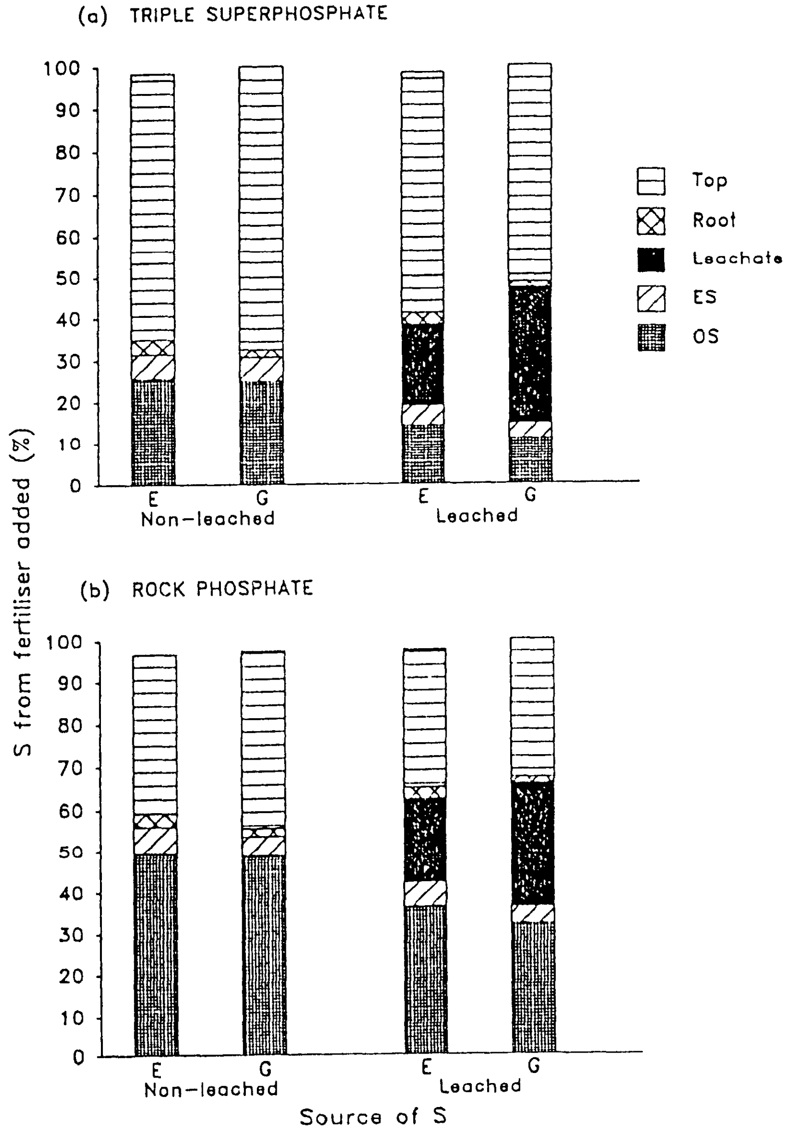


Figure 4.7 The effect of S and P sources on the percentage of fertiliser S incorporated into the plant and soil components under leached and non-leached conditions.

b. Comparison of S sources

Whilst the effectiveness of different sources of S in a wide variety of crops has been investigated (Gupta and MacLeod, 1984, Dijksterhuis and Oenema, 1990 and Lindemann *et al.*, 1991), there are few studies which have examined TSP-S combinations. In this study, gypsum treatments resulted in the highest yields in the early harvests; however, between weeks 8 and 24, no differences were observed in the pasture yield between gypsum and PVA or LS treatments (Table 4.7).

A lower yield in the SW and HF than in the PVA and LS treatments in the early harvests is most likely due to the impairment of S oxidation from these materials because of the slow dispersion of elemental S from the granules. The use of slack wax to bind elemental S to the TSP granules in this study resulted in the impairment of water penetration into the granules which inhibited elemental S dispersion in the soil. The use of wax in coated or cogranulated commercial fertilisers is generally aimed at slowing nutrient release from the product (Beaton and Fox, 1971).

Chapman (1989) reported that additives (wetting and diffusing agents) in commercial elemental S sources inhibited oxidation of elemental S at high concentration but stimulated it at low concentration. In this experiment the different adhesives clearly showed a different response, particularly early after fertiliser application. PVA and LS, which are soluble in water, released more S compared to SW and HF.

Figure 4.8 shows the fate of S from the different sources. This figure illustrates that there were no significant differences in total recovery of fertiliser S in the pasture tops among the gypsum, PVA and LS treatments. The recovery from HF and SW was similar and was significantly lower than that of gypsum. There were no significant differences in the recovery of fertiliser S in roots among the treatments. A higher amount of S was recovered in the organic S pool from HF and SW than from gypsum, PVA and LS. This most likely results from the slower S release from HF and SW products which resulted in poorer pastures growth. Immobilization of S which was released from these products is probably the main reason for higher S transformation into the organic S fraction.

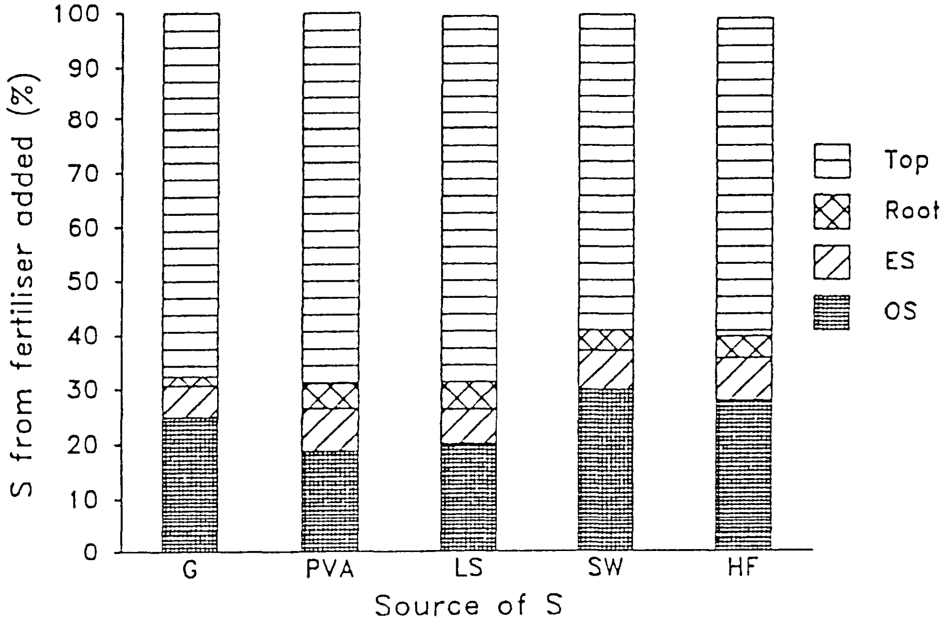


Figure 4.8 The effect of S source on the percentage of fertiliser S incorporated into the plant and soil components.

Using the model developed by McCaskill and Blair (1989), PVA and LS are more appropriate S-coated fertilisers to match the S demand for pastures compared to SW and HF, hence it was observed that there was a significant correlation between predicted S demand and recovery of fertiliser S observed in the pasture tops with a stronger correlation recorded in the PVA and LS compared to HF and SW (Figure 4.9).

This study has shown that gypsum, PVA and LS were effective S Sources for pastures. However, in areas with high rainfall and low S adsorption capacity PVA or LS could be more appropriate because of less S loss by leaching. In addition, the slower release of S from the elemental source in these products avoids the extremely high S concentration found in gypsum fertilised pastures following S application and hence improves the efficiency of S cycling.

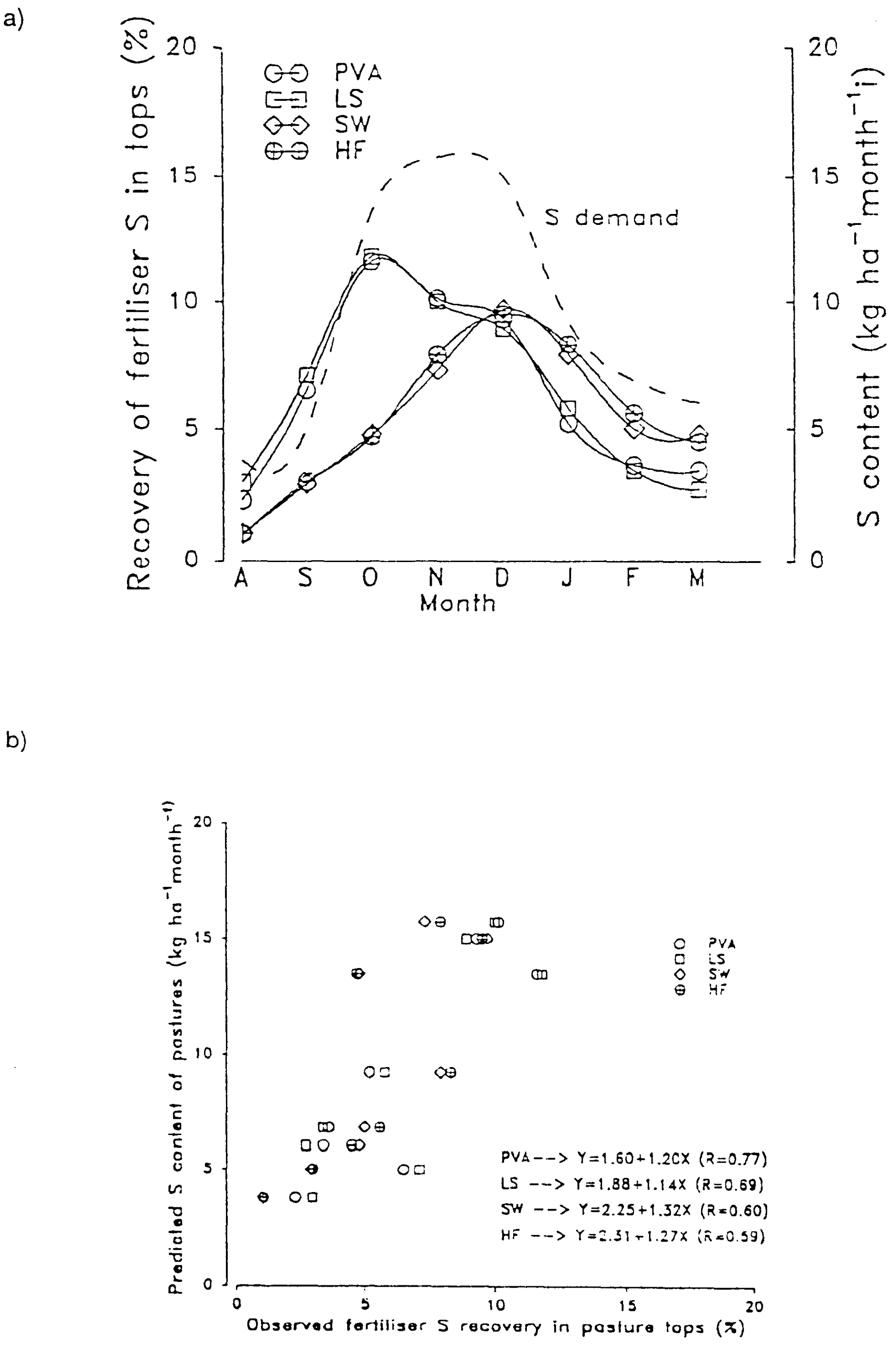


Figure 4.9 a) Prediction of pasture S content and observed fertiliser S recovery in pasture tops and b) correlation between predicted S content and recovery of fertiliser S in pasture tops as influenced by different S sources.

CHAPTER 5

PHYSICAL TESTS OF S-COATED FERTILISERS

5.1 INTRODUCTION

In the experiments reported in this thesis, coated fertilisers were tested under flooded and non-flooded rice and under pasture conditions and showed different S release patterns. The response of crops to different coated fertilisers appears to be related not only to the chemical characteristics but also to physical properties of the fertilisers.

Some measurements which are commonly undertaken to determine physical properties of fertilisers include hygroscopicity, hardness and caking tendency (Bhatti, 1991). Studies on the factors influencing the rate of nutrient release from coated fertilisers and the evaluation of adhesive materials on nutrient release have mainly focused on nitrogen and phosphorus fertilisers (Oertli and Lunt, 1962; Dahnke *et al.*, 1963; Brown *et al.*, 1966; Hall and Baker, 1967; Giordano and Mortveld, 1970).

Two physical characteristics need to be considered in choosing coated fertilisers in order to achieve the maximum efficiency of fertiliser application. The first is the strength of bonding of the coat against frictional forces. This is an important consideration during transportation and application. The second is the strength under the conditions experienced in or on the soil. This relates directly to the agronomic effectiveness of the products. The rate of dispersion of the coated fertiliser under soil conditions directly affects the rate at which the fertiliser comes in contact with plant roots.

In this study, two experiments were undertaken to investigate the physical strength of coated fertilisers against friction forces and against simulated rain.

5.2 EXPERIMENT 1 - MECHANICAL TEST

5.2.1 Materials and methods

A 30 cm diameter and 4 cm deep perspex cylinder ("friabilator") was set up to rotate at 25 rpm on its central axis, in a vertical plane (Scott, 1986). During each rotation the material placed in the friabilator was lifted by a small plate attached to the edge of the cylinder, dropped from a height of approximately 15 cm and then rolled for approximately 3/4 of the circumference until the plate was encountered again.

Prior to the friabilator test, three sub samples (0.002 g) of intact granules of each coated fertiliser as described in Chapters 3 and 4 : TSP-S with PVA (PVA), TSP-S with sodium lignosulfonate (LS), TSP-S with slack wax (SW) and TSP-S Hifert (HF) were digested separately for total S and P using a nitric-perchloric digestion mixture in which potassium dichromate was included (Till *et al.*, 1984). The S and P content of the fertiliser extracts were determined by ICP.

Three samples (20 g) of each fertiliser were placed separately in the friabilator. Rotation was stopped after 1, 2, 4, 8, 16 and 32 minutes. At each of these times the material was sieved through a 20 mesh (841 μm) screen. The fine material was removed and weighed, and the coarse material was returned for further testing. A sub-sample (0.001 g) of the fine particle was taken and then digested for total S and P using the same procedure as previously. The results were subjected to analysis of variance as a split plot in time using the same computer program outlined in Chapter 3.

5.2.2 Results and discussion

The S and P contents of the intact granules were not different among the coated fertilisers tested. The S content ranged between 10.6 (LS) to 10.9 % (SW) and the P content ranged between 19.6 (LS) to 20.4 % (HF).

There was no phosphorus detected in the fine particles after the coated fertilisers were tested in the friabilator. This indicated that the fine particle lost from the granules was derived from the coat of the granules.

There was a significant fertiliser source × time interaction recorded in the amount of particulate loss from the granules. The amount of particle loss increased with time in all treatments, but the rate and extent of loss differed. The highest particle loss was recorded in the HF and there were no significant differences recorded among the PVA, LS and SW (Figure 5.1).

There was a significant fertiliser source × time interaction recorded in the amount of elemental-S lost from the granules. The amount of loss increased with time in all treatments with the highest loss recorded in the HF with no significant differences recorded among the PVA, LS and SW (Figure 5.2).

In interpreting these findings, the history of the products needs to be considered, for instance, the length of storage time, storage conditions or handling method during transportation. Storage and bagging are important stages in the fertiliser manufacture before the fertiliser is ready to be used by consumers (Tisdale and Nelson, 1975). The HF material was obtained from Hi-Fert Pty. Ltd. and the storage length was not known, whereas the PVA, LS and SW products were produced in a bench plant and had not been subjected to transportation.

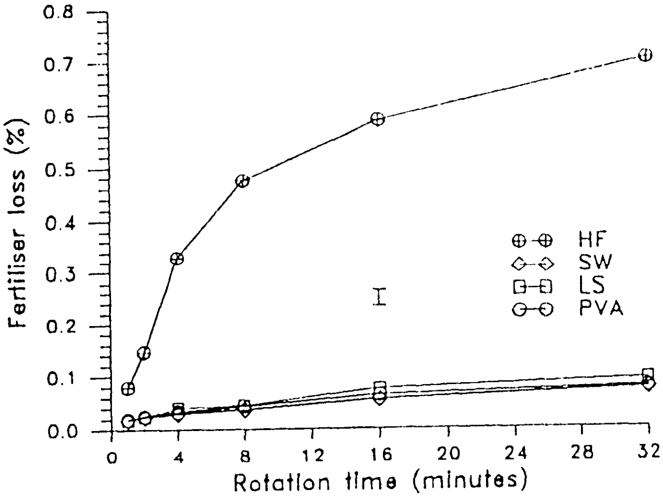


Figure 5.1 Effect of fertiliser source and rotation time on fertiliser loss (%) during the rotation period. Vertical bar indicates the 5% LSD for the fertiliser source × rotation time interaction.

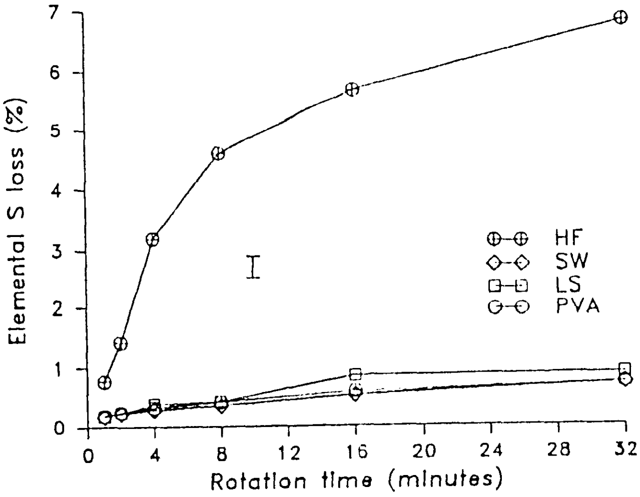


Figure 5.2 Effect of fertiliser source and rotation time on elemental S loss (%) during the rotation period. Vertical bar indicates the 5% LSD for the fertiliser source × rotation time interaction.

5.3 EXPERIMENT 2 - LEACHING EXPERIMENT

5.3.1 Materials and methods

Two gram samples of each fertiliser, TSP-S with PVA (PVA), TSP-S with sodium lignosulfonate (LS) and TSP-S Hifert (HF) were placed in a 3.4 cm (internal diameter) and 7.5 cm (high) plastic vial between layers of 500 μm nylon mesh. Droplets of deionized water were pumped onto the fertiliser at a rate of 20 mL min^{-1} through three 1.5 mm internal diameter tubes. The solution and fine material ran to waste. The fertiliser remaining between the layers of mesh was collected, after 3, 6, 12, 24, 36, 48 and 96 hours, dried at 30 °C, weighed and analysed for calcium and phosphorus content after digestion in a mixture of perchloric and nitric acid (Till *et al.*, 1984) and also for elemental S remaining in the granules after extraction with acetone (Shedley, 1982). The experiment was replicated three times. The same statistical procedure as used in the physical strength study was used to analyse the data.

Before and after 24 hours of leaching, one granule was taken from each fertiliser. These granules were dried in an oven at 80 °C for 4 hours. The granule was mounted on a bronze stub (0.5 cm diameter) with Selleys superglue and rubbed with a fine sandpaper to form a cross-section. The granule was then gold-coated and a photograph of the cross-section taken under an electron microscope. A cross-section of each fertiliser was also scanned using the electron microprobe. The microscopic and scanning work was conducted by Mr. Rick Porter, Electron Microscope Unit, University of New England. The scanning for S was conducted on four spots of the granule surface as shown in Figure 5.3.

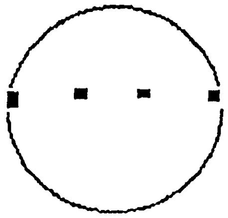


Figure 5.3 Cross-section of S coated fertiliser and areas where the scanning microprobe was used.

A separate test was also conducted to study the dispersion of different coated fertilisers in distilled water at different times (0, 48 and 96 hours). In this study, one granule of each product : TSP-S with PVA (PVA), TSP-S with slack wax (SW), TSP-S Hifert (HF) and TSP-S with sodium lignosulfonate (LS), was placed in a petridish (4 cm diameter) which was filled with distilled water. The petridishes were left undisturbed and a photographic record was taken.

5.3.2 Results and discussion

a. Elemental-S release from granules

There was a significant fertiliser source × leaching time interaction on the release of elemental S from the granules. In all products there was a rapid release of S from the coat in the first 24 hours and a slower release thereafter. The release of elemental S from the PVA and LS products did not differ significantly and was greater than the release from the HF product (Figure 5.4). This was probably due to the differing response of each product to humidity as affected by the adhesive materials and coating process.

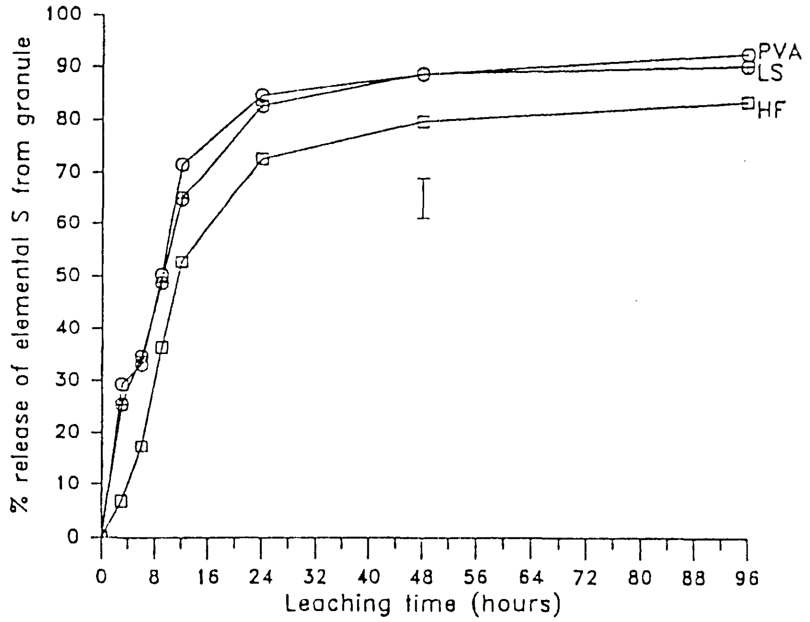


Figure 5.4 Effect of fertiliser source and leaching time on percentage of elemental S lost through leaching. Vertical bar indicates the 5 % LSD for the fertiliser source × leaching time interaction.

b. Phosphorus and calcium losses from granules

There was a significant fertiliser source × leaching time interaction in the loss of calcium and phosphorus from the coated fertilisers. The amount of calcium and phosphorus loss increased with time and the losses from the PVA and LS products did not differ significantly and were greater than the loss from the HF product (Figure 5.5). A greater loss of Ca and P from PVA and LS compared to HF was most likely due to the different dispersion rate of the granules under the leaching conditions. This was directly affected by the strength of the coat.

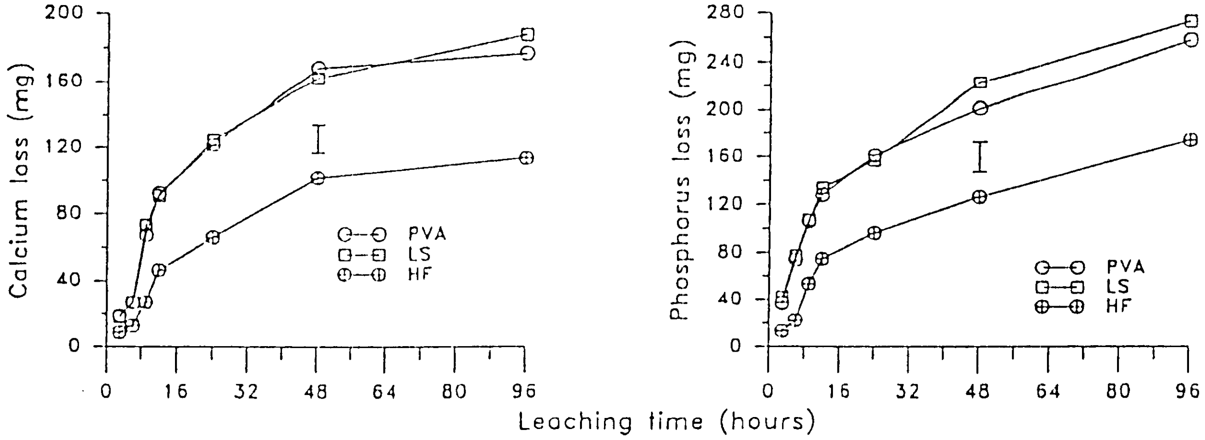
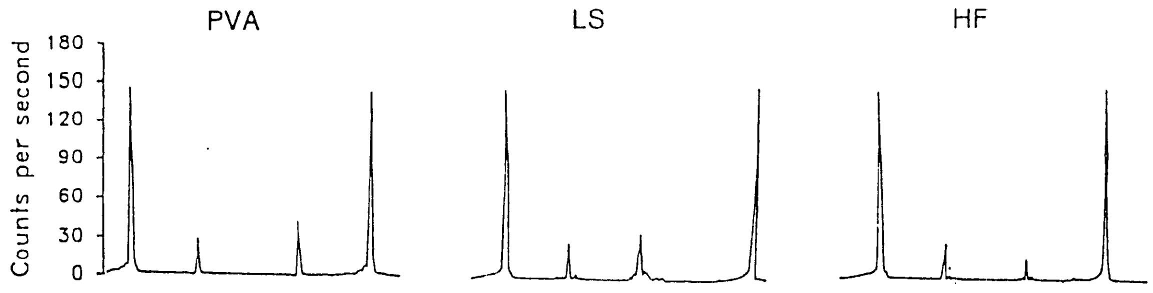


Figure 5.5 Effect of fertiliser source and leaching time on loss of calcium and phosphorus through leaching. Vertical bar indicates the 5 % LSD for the fertiliser source × leaching time interaction.

c. Microprobe scanning of granules

The microprobe scanning data from the coated fertilisers prior to and after 24 hours of leaching agreed with the chemical analysis of the granules. Prior to the leaching, no differences were observed in the percentage of S among PVA, LS and HF. The amount of S remaining in the granule, shown as counts per second, from HF was higher than from PVA and LS after 24 hours of leaching. This indicates that a higher amount of S was lost from the PVA and LS than from the HF granules (Figure 5.6).

(a) Before leaching



(b) After leaching

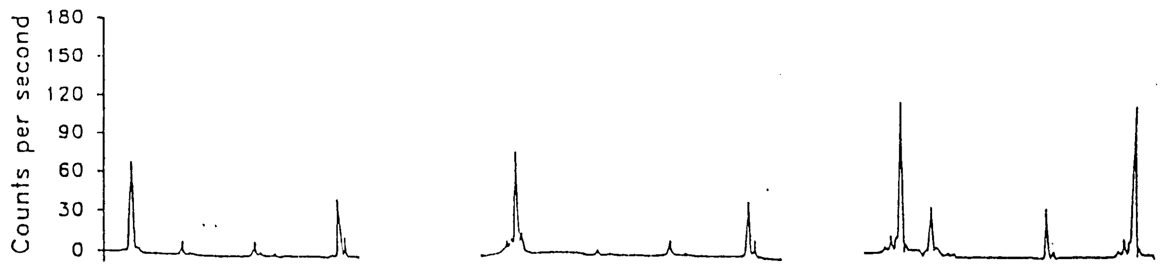


Figure 5.6 Scanning micrograph of S-coated fertiliser prior and after 24 hours of leaching.

The results of these studies showed that the release rate of S from the HF fertiliser was lower than from the other sources. These differences are believed to be affected by the adhesive material used to bind the elemental S to the TSP. The greater release of S from the coat was followed by a greater rate of release of Ca and P from the TSP granules. These findings support the earlier studies (Chapter 3) where it was found that the oxidation of elemental S from the PVA and LS products was greater than that of HF. Release of S from fertilisers has been investigated by Janzen and Bettany (1986), who found differing rates of release from the different S sources, and suggested that this was related to the initial particle size of the product and the dispersion of the particles in the soil. The effect of temperature on the release of nutrients from coated fertiliser had been reported by Oertli and Lunt (1962). They found an approximate 100 % increase in initial release rate of nutrients when the temperature was increased from 10 to 20 °C. Brown *et al.* (1966) reported that a significant decrease in urea release was recorded with increasing coating thickness of resin from 9.0 to 13.2 % .

The photographs in Figure 5.7 show the cross-section of the granules (a) prior to and (b) after 24 hours in the leaching bed. After 24 hours, the elemental S remaining on the HF granule was greater than on the PVA and LS granules (Figure 5.7 b). The photographs show that in the cross-section (Figure 5.7 b) the HF granule was rougher than both the PVA and LS granules. It was observed that the moisture content of the HF granule was less than the other two when taken from the leaching bed, hence during the cutting process the sandpaper fractured the dry particle to a greater extent as compared to a relatively smooth surface for the initially moister PVA and LS granules.

The photographs in Figure 5.8 show the dispersion of the coated fertiliser in distilled water at different observation times. These photographs again illustrate the different properties of the coated fertilisers. This figure shows that HF was similar to SW and these sloughed less than the PVA and LS. This and earlier data suggest that PVA and LS are more effective coated fertilisers because of the faster granule dispersion.

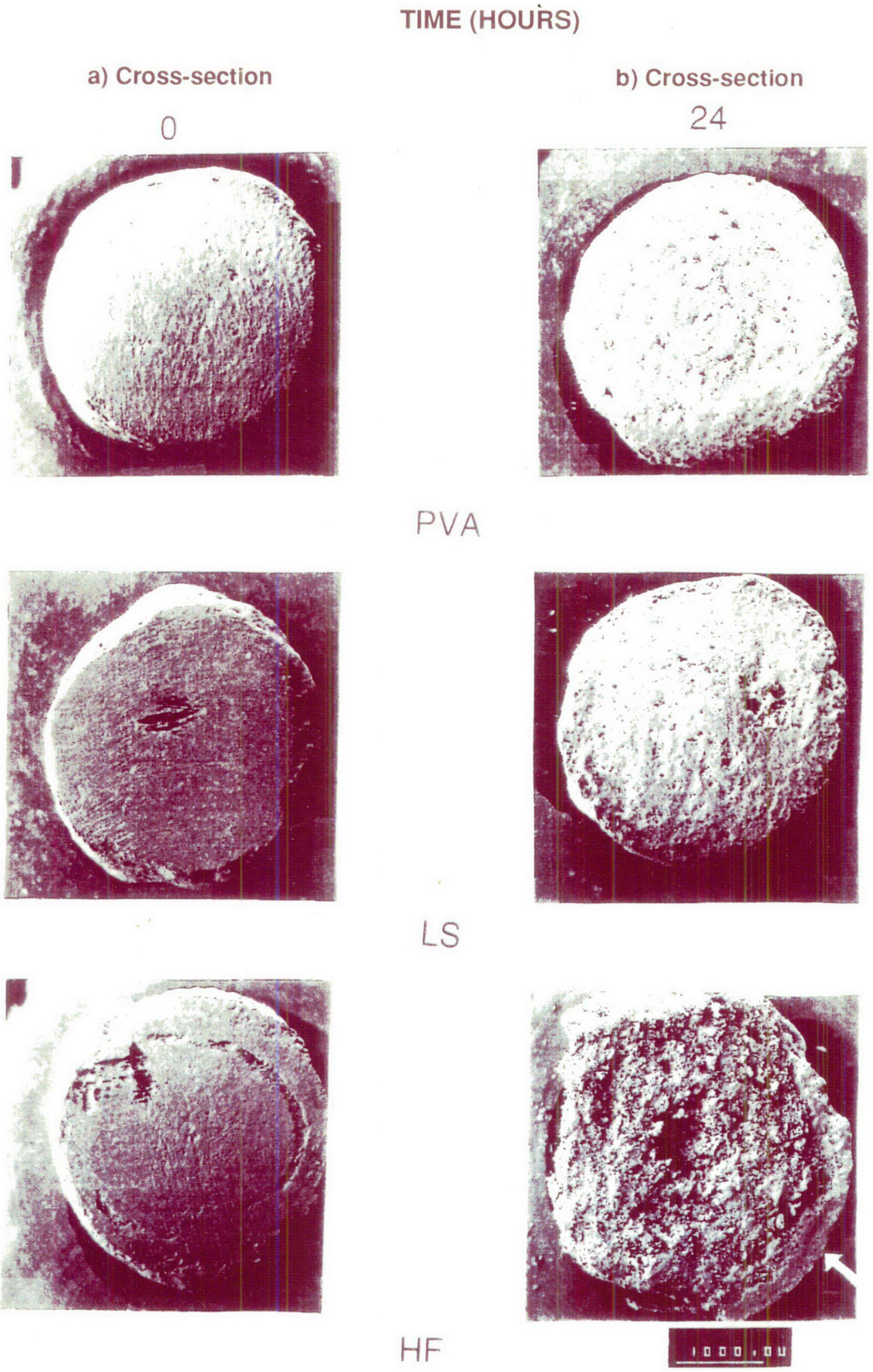


Figure 5.7 Electron micrographs of cross-section of coated fertilisers treated in a leaching bed for 24 hours.

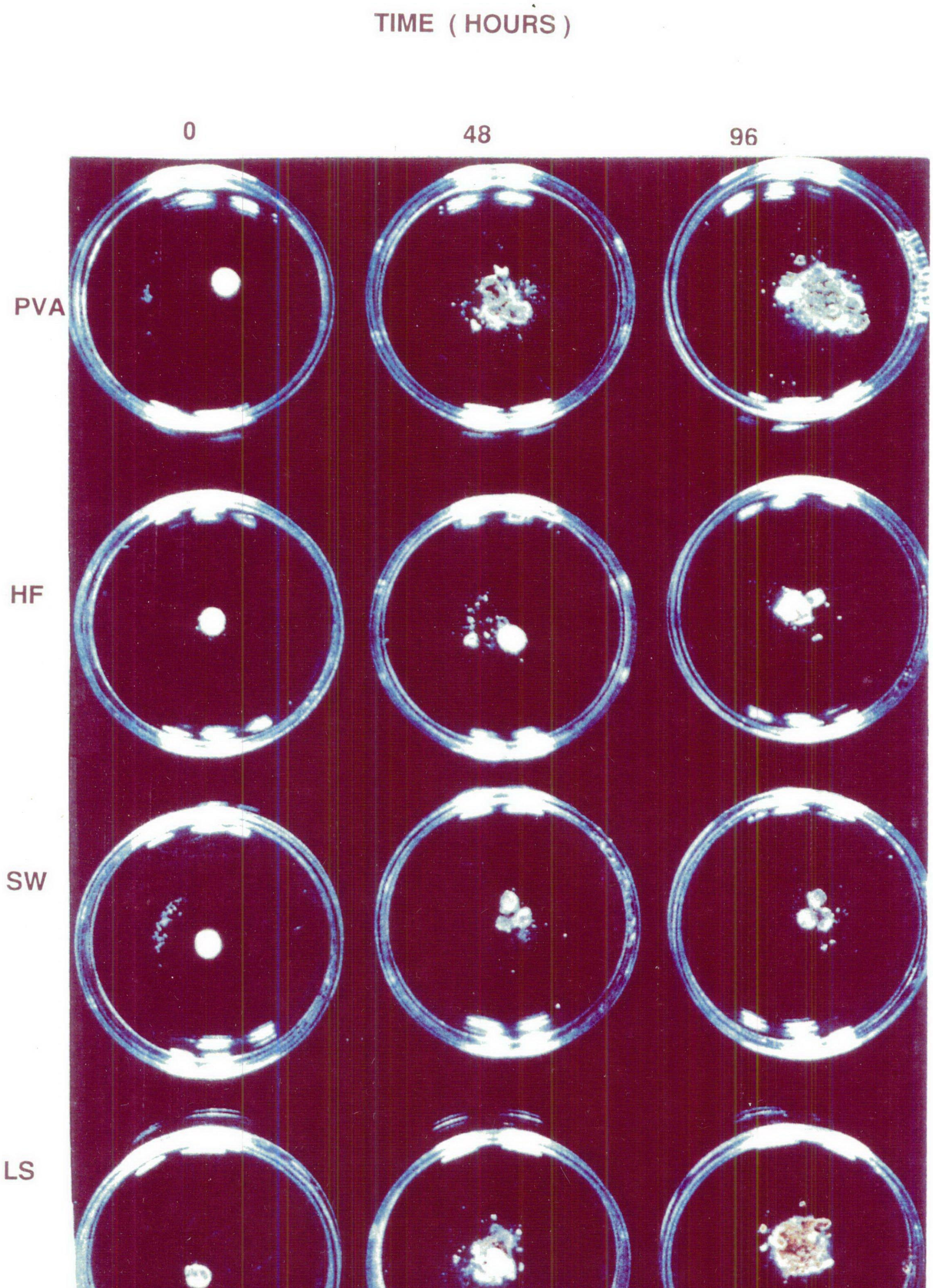


Figure 5.8 Coated fertiliser dispersion in distilled water at different observation times.

CHAPTER 6

INTEGRATING DISCUSSION AND THE MATCHING OF ELEMENTAL S RELEASE TO PLANT DEMAND

6.1 EFFECTIVENESS OF S TO CROPS AS AFFECTED BY AGRICULTURAL MANAGEMENT

To improve our understanding on the effectiveness of S for crops from different S sources under different soil conditions, the characteristic of S release from each source and the S requirement for each crop species needs to be known.

In this study, it was observed that there were differences between flooded and non-flooded rice in terms of growth rate but the S demand patterns were similar (Table 6.1). Although dry matter production was higher under flooded than under non-flooded conditions, the rate of S uptake by the crops was similar at each growth stage (Table 6.1) as was the rate of fertiliser S uptake (Table 6.1).

Table 6.1 Dry matter yield, S content and rate of fertiliser S uptake by flooded and non-flooded rice fertilised with gypsum at 5 mg S kg^{-1} soil at AT, MT and M

Growth stage	Water regime	growth rate (g pot^{-1} day^{-1})	S upt. rate (mg pot^{-1} day^{-1})	Fert. S upt. rate (% day^{-1})
Trans. - AT	F	0.39	0.97	0.41
	NF	0.31	1.07	0.46
AT - MT	F	1.08	0.49	0.33
	NF	1.01	0.43	0.33
MT - M	F	0.63	0.48	0.32
	NF	0.43	0.39	0.29

Under field conditions, a higher amount of S could be lost through surface as well as downward movement of water. This could affect the efficiency of utilization of the applied fertiliser with the sulfate form being more susceptible to loss soon after application. This higher susceptibility to loss has to be balanced against the high initial S demand rate to produce tillers. The experiments reported here have shown that fertilisers such as sulfur bentonite (SB) and sulfur coated urea (SCU) do not release their S fast enough to meet the initial plant demand, although they have a higher residual value in the following crop.

The results of these experiments also indicate the importance of bonding strength when S is coated onto finished fertiliser products. The Hifert bonding process results in a coating which delays not only the S release rate (Tables 3.11, 3.27, 4.9) but also significantly reduces the rate of Ca and P movement from the TSP granules under laboratory leaching conditions (Figure 5.5).

Among the adhesive materials used in these studies, PVA and LS proved to be superior to SW. It is of interest to note that the initial rate of fertiliser S uptake from fertilisers where PVA and LS was used to bond the elemental S to the TSP was greater than from elemental S of the same particle size. This is most likely due to the enhanced oxidation rate of the elemental S when in intimate contact with P, as reported by Santoso (1989).

To maximize the effectiveness of fertiliser application many factors should be considered such as type and form of fertiliser used, crop species, method of application, soil conditions and other climatic factors.

In this study, it was observed that the sulfate form resulted in a higher recovery in crop 1 but a lower recovery in crop 2. To maximize the yield and efficiency of utilization of applied fertiliser in each crop, fertiliser application is required for each crop.

Although the slow release S fertilisers such as SB and SCU contributed more S for the second crop, the efficiency of fertiliser utilization was low because of the yield penalty in the first crop after application.

Similar S release patterns were also observed under pasture conditions. Under these conditions the sulfate form tends to contribute an excess amount of S in the early growth stages. This results in a higher S concentration in the pasture which can lead to increased losses in dung and urine. At the same time more S can be lost through leaching as measured in Chapter 4 (appendix 4.18). To improve fertiliser S efficiency in this system, controlled release S materials which are able to meet the S demand for the pasture throughout the year are more appropriate. In this study the TSP-S bonded with PVA or LS supplied S to the pasture at a faster rate than HF or SW up to 17 weeks after application and between 24 and 44 weeks HF was superior to these two products (Table 4.9). The performance of the LS and PVA could possibly be improved by modifying the particle size of elemental S used in the coat. A mixture of finer and coarser particles could be used to meet this demand. It would be expected that the finer particles would provide S in the early stages and the larger particles would continue to supply S for a longer period.

Under field conditions the S oxidation will be significantly affected by climatic factors such as rainfall and temperature. Therefore, the effect of climatic factors from different areas on oxidation of elemental S with different particle sizes needs to be understood. Earlier studies at UNE by McCaskill and Blair (1988, 1989) developed a simulation model of S release from elemental S and this provided a means to test this hypothesis.

6.2 THE USE OF COMPUTER SIMULATION TO DEVELOP COATINGS TO MATCH S RELEASE RATE TO PLANT DEMAND

6.2.1 Introduction

Several authors have developed models to estimate the oxidation rate of elemental S (Shedley, 1982; McCaskill and Blair, 1989; Watkinson, 1989). In formulating his model Shedley (1982) used an empirical approach to formulate mathematical relationships, which was a multiplication of particle size, soil moisture, soil temperature, the nature of soil microbe populations and soil phosphate concentration functions. From this simulation, he estimated that 29 % of the elemental S (100 μm particle size) was oxidized within a 1-year period. The low S release predicted by this model was suggested to be due to the lack of consideration of interactions among the environmental factors and to the fact that the simulation was drawn mainly from incubation studies.

McCaskill and Blair (1989) used a mechanistic approach to predict S release from elemental S. In this model, the S release was predicted based on the spherical particles and the equations used are presented in the literature review. This model was used in the present study to estimate the release of S from different particle sizes applied at different times of the year at four locations in Australia.

McCaskill and Blair (1989) predicted that with a constant release of 0.4 μm day^{-1} and under a non-restricted environment, particles less than 0.5 mm were almost completely oxidized after 12 months, but that 40 % of larger particles (> 1.0 mm) remained in the elemental form. From this prediction a mixture of fine and coarse particles was able to maintain the S status in the soil for a longer period to meet the S demand of crops and pastures.

In the present study, the model was used to estimate the S release and S demand for pastures as affected by different particle sizes of elemental S and different times of application. In each area, three different application times were simulated (Figures 6.1 and 6.2). This was based on fertiliser application times which are commonly used by farmers in each area.

The S demand for C_3 pastures estimated under non-limiting nutrients and different climatic conditions is presented in Figures 6.1 and 6.2. S release (kg ha day^{-1}) is expressed as the product of oxidation rate (% day^{-1}) and S-application rate (20 kg ha^{-1}). The release pattern is predicted from two particle sizes (100 and 200 μm) and a mixture of 50% 100 μm + 50% 200 μm using a constant release rate of 0.3 μm day^{-1}. This value was fitted in this model because of the overestimate of S oxidation compared to the oxidation rate which was observed in the earlier experiments (Chapter 3) when the attrition rate of 0.4 mm day^{-1} was fitted in the model.

The model was run for four different temperature and moisture regimes around Australia : 2 tropical areas (Darwin and Cairns; North and North-east parts of Australia, respectively) and 2 temperate areas (Armidale, N.S.W. and Dalwallinu, Western Australia). The mean weekly climatic data used in this simulation were mean of maximum and minimum temperature, solar radiation, rainfall and evaporation, from 1969 to 1989. These data are presented in Figures 6.1 and 6.2.

6.2.2 S release from different particle sizes

The difference in oxidation rate of a 100 μm diameter elemental S at different application times indicates the important effects of moisture and temperature on elemental S oxidation. In Armidale, for instance, the application of fertiliser in March resulted in a greater oxidation rate soon after application compared to the late application (in May). This was largely due to the higher temperatures in March and April than in May (Figure 6.1). The greater oxidation from the March application resulted in a lower oxidation rate during the spring period where the S demand of pastures is high. Fertiliser application in May is probably a better choice due to the higher S release during the spring period where the pastures require more S. The application of 200 μm particles at this location was less suitable because of the slow S release during the Spring period.

By contrast, total oxidation of elemental S was less at Dalwallinu than at Armidale although the temperature at Dalwallinu is higher than that at Armidale. This was mainly due to moisture limitation over summer at Dalwallinu compared to that at Armidale.

In tropical areas (Darwin and Cairns), temperature was not a limiting factor to S oxidation. At both locations higher oxidation rates were predicted compared to the temperate areas particularly for coarser particles(Figure 6.2). The oxidation rate of 100 μm particles exceed the S demand early in the season, therefore application of larger particle sizes was more appropriate. The mixture of 50 % 100 μm + 50 % 200 μm particles was better able to match the S demand.

The effect of different particle sizes on oxidation of elemental S in different areas is presented in Table 6.2. The total predicted oxidation of elemental S with the 100 μm particle size in the temperate area ranged between 86.3 % to 96.5 % in one calendar year (Table 6.2). Higher oxidation rates (99.9 to 100 %) were predicted in tropical areas.

From this simulation, S release from the 100 μm particles was initially more rapid than from the 200 μm or mixture treatments in all four environments. However, over longer periods, the amount of S released from finer particles would decrease as the amount of elemental S remaining falls rapidly. These simulations indicated that a finer particle size (100 μm) of elemental S is more appropriate when this material is used to match S demand for pastures in temperate areas. In addition, a mixture of fine and coarse particles of elemental S (50 % 100 μm + 50 % 200 μm) is more suitable when this material is used in tropical areas.

Table 6.2 Effect of different particle sizes on the annual oxidation of elemental S at four locations in Australia.

Location	Particle size (μm)	Total oxidation (%)
Armidale	100	96.5
	Mixture	82.4
	200	71.2
Dalwallinu	100	86.3
	Mixture	69.2
	200	56.7
Darwin	100	99.9
	Mixture	91.6
	200	83.6
Cairns	100	100.0
	Mixture	94.5
	200	88.4

The simulation undertaken in this study was not intended to supply all of S requirement for pastures as S mineralization from organic sources is an important source. In the earlier experiment (Table 4.5), the TSP + elemental S treatment and under non-leaching conditions derived 27.8 % of S in the pasture tops from the fertiliser at the first harvest and this increased up to 50.5 % in the second harvest and then declined in the following harvests.

The simulation showed that the model can be used to predict the oxidation rate of elemental S in order to match S supply from fertilisers to the S demand of pastures. There are several disadvantages associated with the handling and application of fine particle of elemental S. These problems can be solved by combining elemental S with TSP granules through the coating process which has been developed in this study. In the coating process a mixture of fine and coarse particle can be used to match the S demand for crops or pastures in a wide range of different climatic conditions. In the earlier experiment (Chapter 3) it was found that S-coated TSP (with PVA or LS as a binding agent) was as effective as gypsum in increasing grain yield of rice.

In the pasture experiment (Chapter 4) and under non-leaching conditions it was observed that there was no significant difference in total pasture yield (Figure 4.3) or S content (Figure 4.4) recorded between the elemental S and gypsum treatments over one year period. In contrast, under leaching conditions, a significantly higher total yield (Figure 4.3) and S content (Figure 4.4) of pastures was recorded with elemental S than with gypsum. This difference was most likely due to the higher S loss through leaching in the gypsum treatment.

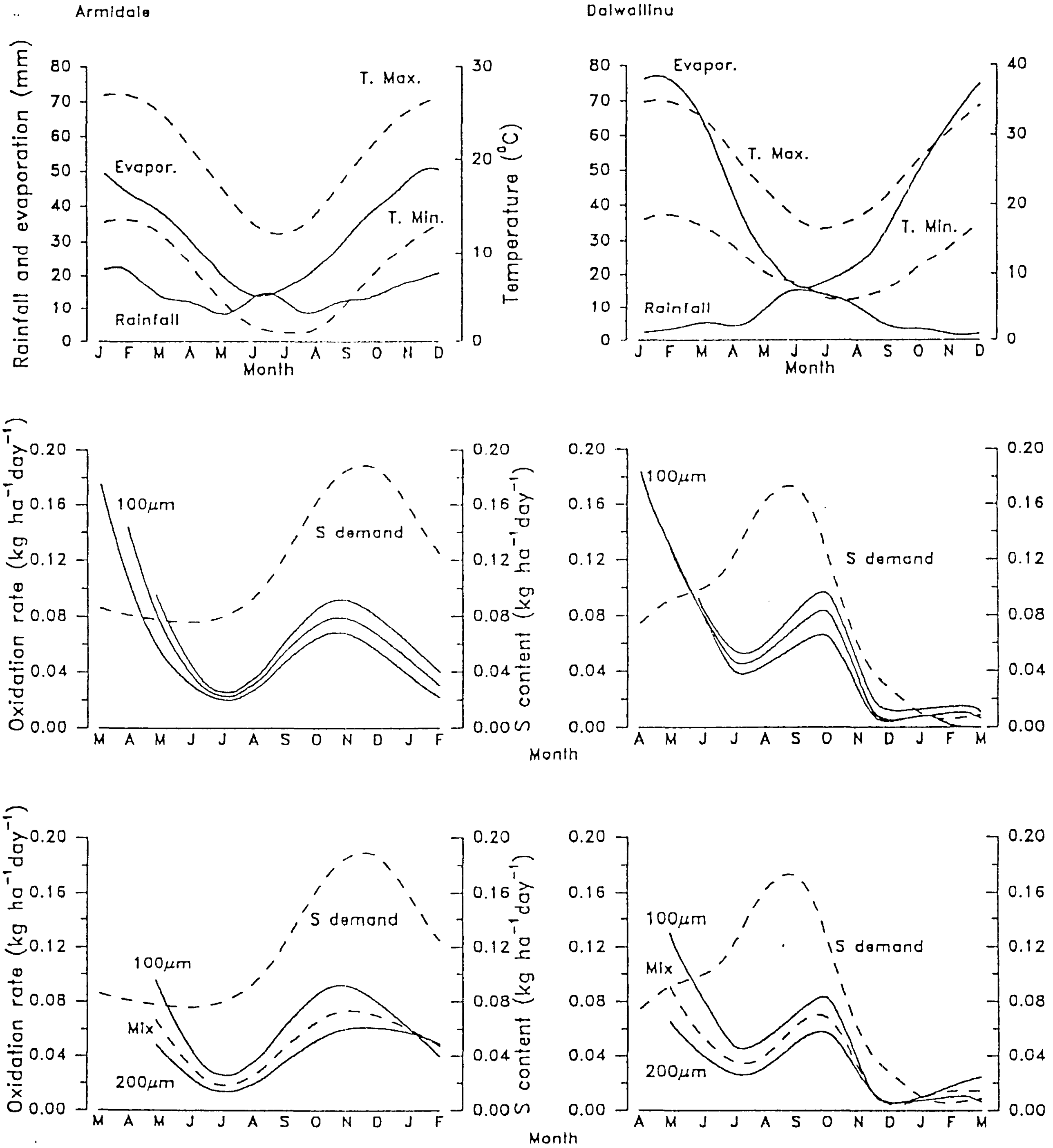


Figure 6.1 Prediction of S demand of pastures under non-limiting nutrient conditions and oxidation of elemental S as affected by temperature, moisture, time of application and particle sizes in two temperate locations in Australia.

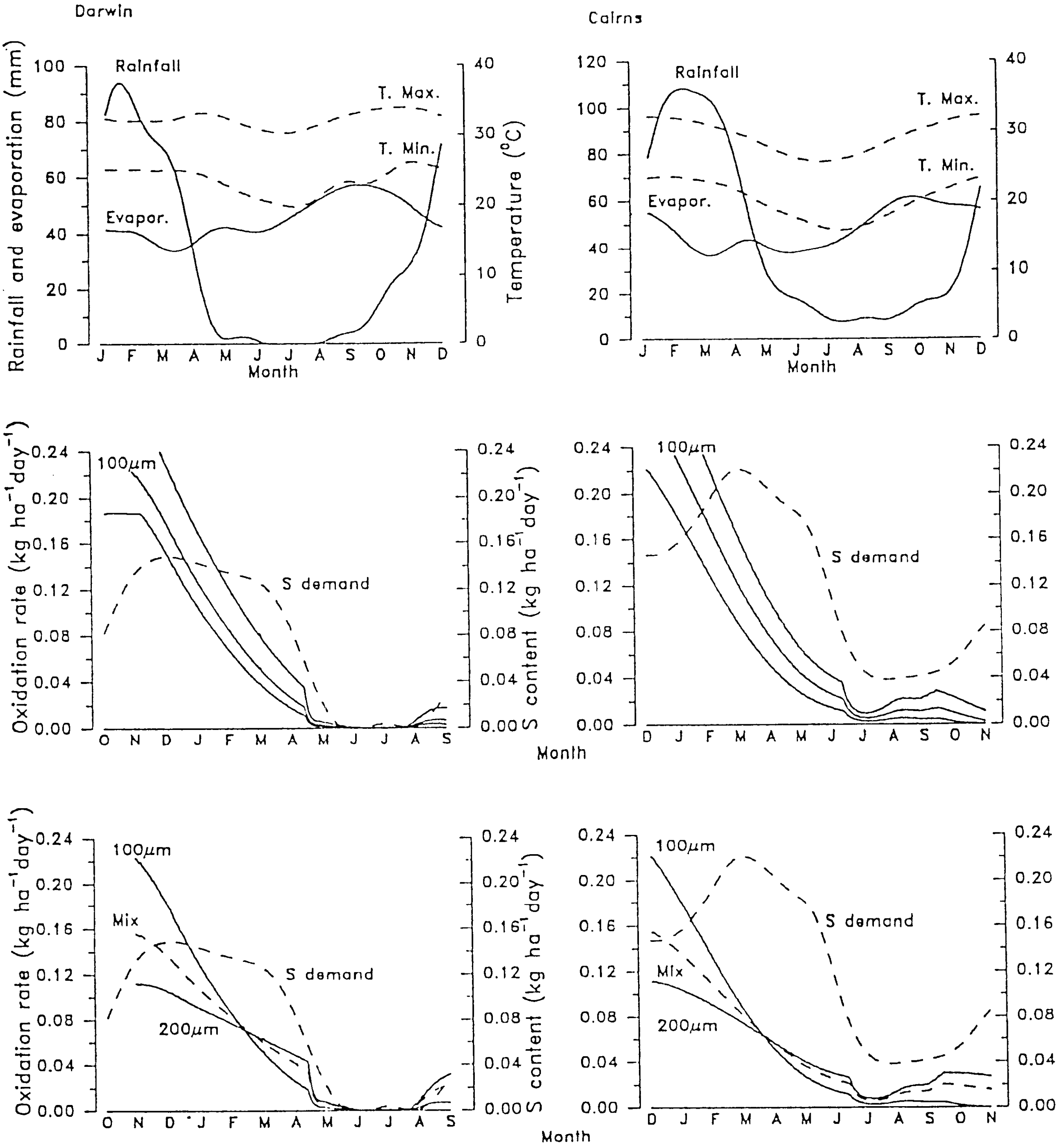


Figure 6.2 Prediction of S demand of pastures under non-limiting nutrient conditions and oxidation of elemental S as affected by temperature, moisture, time of application and particle sizes in two tropical locations in Australia.

These series of experiments have identified two S coated TSP candidate products where litter polyvinyl alcohol (PVA) or calcium ligno sulfonate (LS) is used as an adhesive to bind the elemental S to the fertiliser. Patents have been obtained for this invention and studies are in progress to scale up the process for a commercial venture. The combination of glasshouse trials, laboratory evaluation, microscopic and microprobe scans and computer simulation presented in this study have developed a fertiliser product that firstly matches plant requirements and secondly is mechanically robust.

This study complements earlier work (Samosir, 1981; Santoso, 1989; Chaitep, 1990) and studies still in progress at UNE to match fertiliser release rates to plant demand. This will lead to more efficient use of nutrients, better economies of fertiliser use and less environmental problems from nutrient leaching and runoff.

This approach should be extended to nitrogenous (urea) and NP fertilisers (DAP, MAP) where S coating may serve not only to supply S to the plant but modify the release pattern of the other nutrients.

6.3 FUTURE RESEARCH AND DEVELOPMENT REQUIRED

To confirm the results from the glasshouse experiment, further field trials are required. These trials should involve S rate studies using sulfate forms such as gypsum or ammonium sulfate and elemental S coated materials. For flooded rice it would seem to be most appropriate to concentrate on P-S products as Lefroy (1989) argues that these are more appropriate than N-S sources. These studies would provide S response curves for each product under the prevailing conditions to enable a comparison of the effectiveness of the different sources. This would allow a horizontal comparison and substitution value to be calculated. These studies should be undertaken at well defined field sites where environmental conditions can be adequately monitored. This would include soil temperature, moisture and water movement (both in floodwater and through the profile). In these studies S would need to be applied to each crop and the residual value of fertiliser calculated by the rate of movement of the response curves to the left from year to year.

The S requirement for different species of crops needs to be considered. This becomes particularly complex in situations where flooded rice is followed by non-flooded crops such as grain legumes or corn.

In pastures, field evaluations become even more complex because of the need to graze the plot to obtain realistic nutrient cycling conditions. This means that it would be unrealistic to examine a series of products applied over a range of rates. For this reason a rate which is towards the upper end of the response curve needs to be chosen for the evaluation.

The fertiliser materials evaluated in the studies reported in this thesis were made in the batch process in a rotating drum. For commercial productions this must be changed to a continuous process so that large tonnages can be produced. Such work has commenced at UNE (Blair, personal communication).

BIBLIOGRAPHY

Adams, F. and Rawajfih, Z. (1977). Basalunite and alunite: A possible cause of sulfate retention by acid soils. *Soil Sci. Soc. Am. J.* **41**, 686-92.

Amer, F., Saleh, M.E. and Mostafa, H.E. (1991) Phosphate behavior in submerged calcareous soils. *Soil Science.* **151**, 306-11.

Anderson, G.C. (1988). Dissolution of Rock Phosphate in Soil, Plant and Fertiliser Systems. M. Rur. Sc. Thesis. The University of New England, Armidale, Australia.

Alexander, M. (1961). Introduction to Soil Microbiology. John Wiley and Sons, Inc., New York.

Anderson, D.L. and Henderson, L.J. (1986). Sealed chamber digestion for plant nutrient analyses. *Agronomy Journal.* **78**, 937-9.

Bailey, L.D. (1985). The sulfur status of eastern Canadian prairie soils : The relationship of sulfur, nitrogen and organic carbon. *Can. J. Soil Sci.* **65**, 179-86.

Barrow, N.J. (1961). Studies on the mineralization of sulphur from soil organic matter. *Aust. J. Agric. Res.* **12**, 306-19.

Barrow, N.J. (1967). Studies on extraction and on availability to plants of adsorbed plus soluble sulfate. *Soil Science.* **104**, 242-9.

Barrow, N.J. (1970). Comparison of the adsorption of molybdate, sulfate and phosphate by soils. *Soil Science.* **109**, 282-8.

Barrow, N.J. (1971). Slowly available sulphur fertilisers in south-western Australia. 2. Pyrites and pyrrhotite. *Aust. J. Exp. Agric. Animal Husb.* **11**, 211-16.

Barrow, N.J. (1972). Influence of solution concentration of calcium on the adsorption of phosphate, sulphate, and molybdate by soils. *Soil Science.* **133**, 175-80.

Barrow, N.J. (1975). Reactions of fertilizer sulphate in soils. In 'Sulphur in Australasian Agriculture'. McLachlan, K.D. (ed.), pp. 50-7. Sydney University Press, Sydney, Australia.

Barrow, N.J. and Shaw, T.C. (1977). The slow reaction between soil and anions : Effects of time and temperature of contact between an adsorbing soil and sulphate. *Soil Science.* **124**, 347-54.

Bar-Yosef, B., Kafkafi, U., Rosenberg, R. and Sposito, G. (1988). Phosphorus adsorption by kaolinite and montmorillonite : I. Effect of time, Ionic strength and pH. *Soil Sci. Soc. Am. J.* **52**, 1580-5.

Beaton, J.D. (1987). Desirable characteristics of sulphur containing fertilizers suitable for Asia and the Pacific region. Proceedings of the Symposium on Fertilizer sulphur Requirement and Sources in Developing Countries of Asia and the Pacific. p. 101-11. FADINAP, FAO, The Sulphur Institute, ACIAR.

Beaton, J.D and Fox, R.L. (1971). Production, marketing and use of sulfur products. In 'Fertilizer Technology and Use' Second Edition. Olson, R.A., Army, T.J., Hanway, J.J. and Kilmer, V.J. (ed.) pp. 335-79. Soil Science Society of America, Inc. Madison.

Bettany, J.R., Stewart, J.W.B. and Halstead, E.H. (1973). Sulfur fractions and carbon, nitrogen, and sulfur relationships in grassland, forest and associated Transitional soils. *Soil Sci. Soc. Am. Proc.* **37**, 915-8.

Bettany, J.R., Stewart, J.W.B. and Saggar, S. (1979). The nature and forms of sulfur in organic matter fractions of soils selected along an environmental gradient. *Soil Sci. Soc. Am. J.* **43**, 981-5.

Bhatti, M.E. (1991). Quality control measures for developing of 10 : 20 : 20 grade fertilizer. *Fertilizer Research*, **28** : 213-6.

Blair, G.J. (1979). Sulfur in the Tropics. International Fertilizer Development Center. Alabama, U.S.A.

Blair, G.J. (1983). Sulfur deficiencies in the agriculture of Southern China. In 'Sulfur in S.E. Asian and S. Pacific Agriculture'. (Eds G.J. Blair and A.R. Till) pp. 147-54. (University of New England, Armidale, N.S.W., Australia).

Blair, G.J. (1984). Sulphur fertilizer sources for upland and flooded rice soils of the tropics. In 'Proc. of Sulphur-84'. pp. 717-23. (Calgary : Canada).

Blair, G.J. (1986). Sulfur cycling in flooded rice. 'In Proc. of Sulphur in Agricultural Soils' pp. 453-68.

Blair, G.J. (1987a). Sulfur supply to crops and pastures from elemental S. In 'Proc. Int. Symp. Elemental Sulphur in Agriculture' pp. 483-90.

Blair, G.J. (1987b). The occurence of S defficiency and the sulfur supply/demand relationship in Asian agriculture. In 'Proc. of Sulphur-87' pp. 75-90.

Blair, G.J. and Lefroy, R.D.B. (1987). Sulphur cycling in tropical soils and economic impact of increasing use of S free fertilizers increased crop production and burning of crop residues. In 'Proc. of the symp. on fertilizer sulphur requirements and sources in developing countries of Asia and the Pacific'. pp. 12-17. Bangkok.

Blair, G.J., Mamaril, C.P. and Momuat,E. (1978). Sulfur nutrition of wetland rice. *IRRI research paper series*. **21**, 1-28.

Blair, G.J. and Momuat, E.O. and Mamaril, C.P. (1979). Sulfur nutrition of rice. II. Effect of source and rate of S on growth and yield under flooded conditions. *Agronomy Journal*. **71**, 477-80.

Bloomfield, C. (1967). Effect of some phosphate fertilizers on the oxidation of elemental sulfur in soil. *Soil Science*. **103**, 219-23.

Bohn, H.L., Barrow, N.J., Rajan, S.S.S. and Parfitt, R.L. (1986). Reactions of inorganic sulfur in soils. In 'Sulfur in Agriculture'. Tabatabai, M.A. (ed), pp. 233-49. Agronomy Series. No. 27. ASA, CSSA, SSSA, Madison, U.S.A.

Bolin, B. Crutzen, P.J., Vitousek, P.M., Woodmansee, R.G., Goldberg, E.D. and Cook, R.B. (1983). Interactions of biogeochemical cycles. In ' The Major Biogeochemical Cycles and Their Interactions'. Bolin, B. and Cook, R.B. (ed.). pp.1-39. Scope 21. John Wiley and Sons, New York.

Bolland, M.D.A. and Barrow, N.J. (1988). Effect of level application on the relative effectiveness of rock phosphate. *Fertilizer Research*. **15**, 181-92.

Bolland, M.D.A. and Bowden, J.W. (1984). The initial and residual value for subterranean clover of phosphorus from crandallite rock phosphates, apatite rock phosphates and superphosphate. *Fertilizer Research*. **5**, 295-307.

Bolland, M.D.A. and Gilkes, R.J. (1990). Rock phosphates are not effective fertilizers in Western Australian soils : a review of one hundred years of research. *Fertilizer Research*. **22**, 79-95.

Bolland, M.D.A., Gilkes, R.J. and Allen, D.G. (1988). The residual value of superphosphate and rock phosphates for lateritic soils and its evaluation using three soil phosphate tests. *Fertilizer Research.* **15**, 253-80.

Bolland, M.D.A., Weatherley, A.J. and Gilkes, R.J. (1989). The long-term residual value of rock phosphate and superphosphate fertilizers for various plant species under field conditions. *Fertilizer Research.* **20**, 89-100.

Boswell, C.C. (1983). An Assessment of Phosphorus and Sulfur Interactions on Aspects of the Sulfur Cycle in Pasture. Ph.D Thesis, University of New England.

Boswell, C.C. (1987). Elemental sulphur fertilizers for pastures in New Zealand. In 'Proc. Int. Symp. Elemental Sulphur in Agriculture'. pp. 493-507.

Boswell, C.C., Owers, W.R., Swanney, B. and Rothbaum, H.P. (1988a). Sulfur/sodium bentonite mixtures as sulfur fertilizers. 1. The effects of S/Na-bentonite ratios on the rate of dispersion and particle size distribution of elemental sulfur dispersed from laboratory-produced prills. *Fertilizer Research.* **15**, 13-31.

Boswell, C.C., Swanney, B. and Owers, W.R. (1988b). Sulfur/sodium bentonite prill as sulfur fertilizers. 2. Effect of sulfur-sodium bentonite ratios on the availability of sulfur to pasture plants in the field. *Fertilizer Research.* **15**, 33-46.

Bowdler, T.M. and Pigott, F.J. (1990). The response of white clover to sulphur on an irrigated pasture in south-east Queensland. *Tropical Grasslands.* **24**, 111-2.

Brady, N.C. (1990). The Nature and Properties of Soils. Tenth Edition. Macmillan Publishing Company. New York.

Brown, M.J., Luebs, R.E. and Pratt, P.F. (1966). Effect of temperature and coating thickness on the release of urea from resin coated granules. *Agronomy Journal,* **58** : 175-8.

Burr, E.J. (1982). NEVA User's Manual. University of New England Computer Centre, Armidale, N.S.W., Australia.

Buttrey, S.A., Allen, V.G., Fontenot, J.P. and Reneau, Jr. R.B. (1987). Corn forage yield and chemical composition as influenced by sulfur fertilization. *Commun. in Soil Sci. Plant Anal.* **18**, 875-95.

Chaitep, W (1990). The use of fertilisers and crop residues as sources of sulfur in flooded and unflooded rice cropping systems. Ph.D Thesis, The University of New England, Armidale, Australia.

Chang, M.L. and Thomas, G.W. (1963). A suggested mechanism for sulfate adsorption by soil. *Soil Sci. Soc. Am. Proc.* **27**, 281-3

Chao, T.T., Harward, M.E. and Fang, S.C. (1962a). Movement of 35S tagged sulfate through soil columns. *Soil Sci. Soc. Proc.* pp. 27-32.

Chao, T.T., Harward, M.E. and Fang, S.C. (1962b). Adsorption and desorption phenomena of sulfate ions in soils. *Soil Sci. Soc. Proc.* pp. 234-7.

Chao, T.T., Harward, M.E. and Fang, S.C. (1962c). Soil constituents and properties in the adsorption of sulfate ions. *Soil Science.* **94**, 276-83.

Chao, T.T., Harward, M.E. and Fang, S.C. (1963). Cationic effects on sulfate adsorption in soils. *Soil Sci. Soc. Am. Proc.* **27**, 35-38.

Chapman, S.J. (1989). Oxidation of micronized elemental sulphur in soil. *Plant and Soil.* **116**, 69-76.

Chapman, S.J. (1990). Thiobacillus population in some agricultural soils. *Soil Biol. Biochem.* **22**, 479-82.

Charoenchamratcheep, C., Smith, C.J., Satawathananont, S. and Patrick Jr. W.H. (1987). Reduction and oxidation of acid sulfate soils of Thailand. *Soil Sci. Soc. Am. J.* **51**, 630-4.

Chaudhry, I.A. and Cornfield, A.H. (1967a). Effect of moisture content during the incubation of soil treated with organic materials on changes in sulphate and sulphide levels. *Journal of Science in Food Agriculture.* **18**, 38-40.

Chaudry, I.A. and Cornfield, A.H. (1967b). Effect of temperature of incubation on sulphate levels in aerobic and sulphide levels in anaerobic soils. *Journal of Science in Food Agriculture.* **18**, 82-4.

Chien, S.H., Friesen, D.K. and Hamilton, B.W. (1988). Effect of application method on availability of elemental sulfur in cropping sequences. *Soil Sci. Soc. Am. J.* **52**, 165-9.

Chien, S.H. and Hammond, L.L. (1978). A comparison of various laboratory methods for predicting the agronomic potential of phosphate rocks for direct application. *Soil Sci. Soc. Am. J.*, **42**, 935-39.

Chien, S.H., Hellums, D.T. and Henao, J. (1987). Greenhouse evaluation of elemental sulfur and gypsum for flooded rice. *Soil Sci. Soc. Am. J.* **51**, 120-3.

Chisholm, R.H. and Blair, G.J. (1988a). Phosphorus efficiency in pasture species. I. Measures based on total dry weight and P content. *Aust. J. Agric. Res.* **39**, 807-16.

Chisholm, R.H. and Blair, G.J. (1988b). Phosphorus efficiency in pasture species. II. Differences in the utilization of P between major chemical fractions. *Aust. J. Agric. Res.* **39**, 817-26.

Chisholm, R.H. and Blair, G.J. (1988c). Phosphorus efficiency in pasture species. III. Correletions of dry matter accumulation with phosphorus pool sizes and their net transfer rate. *Aust. J. Agric. Res.* **39**, 827-36.

Couto, W., Lathwell, D.J. and Bouldin, D.R. (1979). Sulfate sorption by two oxisols and an alfisol of the tropics. *Soil Science.* **127**, 108-16.

Curtin, D. and Syers, J.K. (1990). Mechanism of sulphate adsorption by two tropical soils. *Journal of Soil Science.* **41**, 295-304.

Dahnke, W.C., Attoe, O.J., Engelbert, L.E. and Groskopp, M.D. (1963). Controlling release of fertilizer constituents by means of coatings and capsules. *Agronomy Journal*, **55** : 242-44.

Dijksterhuis, G.H. and Oenema, O. (1990). Studies on the effectiveness of various sulfur fertilizers under controlled conditions. *Fertilizer Research.* **22**, 147-59.

D. G. F. C. (1986). Luas panen, rata-rata hasil dan produksi padi dan palawija di Indonesia. Direktorat Bina Program Tanaman Pangan. Dit. Jen. Pertanian Tanaman Pangan, Jakarta. (Production area, total and average productions of rice and second crops in Indonesia. Directorate General of Food Crop, Jakarta).

D. G. F. C. (1990). Luas panen, rata-rata hasil dan produksi padi dan palawija di Indonesia. Direktorat Bina Program Tanaman Pangan. Dit. Jen. Pertanian Tanaman Pangan, Jakarta. (Production area, total and average productions of rice and second crops in Indonesia. Directorate General of Food Crop, Jakarta).

Donahue, R.L., Miller, R.W. and Shickluna, J.C. (1983). Soils. Fifth edition. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Duke, S.H. and Reisenauer, H.M. (1986). Roles and requirements of sulphur in plant nutrition. In 'Sulfur in Agriculture'. Tabatabai, M.A. (ed), pp. 123-68. Agronomy Series. No. 27. ASA, CSSA, SSSA, Madison, U.S.A.

Evans, L.T. (1975). Sulphur in Agriculture. In 'Sulphur in Australasian Agriculture'. McLachlan, K.D. (ed.). pp. 3-8. Sydney University Press, Sydney, Australia.

Fenster, W.E. (1965). M.S. Thesis. University of Wisconsin.

Fox, R.L., Asgar, M. and Cable, W.J. (1983). Sulfate accretions in soils of the tropics. In 'Sulfur in S.E. Asian and S. Pacific Agriculture'. Blair, G.J. and Till, A.R. (ed.), Indonesia. University of New England, Armidale, N.S.W. pp. 23-7.

Fox, R.L. and Blair, G.J. (1986). Plant response to sulfur in tropical soils. In 'Sulfur in Agriculture'. Tabatabai, M.A (ed.). pp. 405-34. Agronomy series. No. 27. ASA, CSSA, SSSA. Madison, U.S.A.

Fox, R.L. and Hue, N.V. (1986). Sulfur cycling in the tropics and sulfur requirements for agriculture. In 'Proc. of Sulphur in Agricultural Soils' pp. 139-62.

Fox, R.L., Olsen, R.A., and Rhoades, H.F. (1964). Evaluating the sulfur status of soils by plant and soil test. *Soil Sci. Soc. Am. Proc.* **28**, 243-6.

Freney, J.R. (1961). Some observations on the nature of organic sulphur compounds in soil. *Aust. J. Agric. Res.*, **12**, 424-32.

Freney, J.R. (1986). Forms and reaction of organic sulfur compounds in soils. In 'Sulfur in Agriculture'. Agronomy Series No. 27. pp. 207-31. ASA, CSSA, SSSA, Madison, USA.

Freney, J.R. and Boonjawat, J. (1983). Sulfur transformation in wetland soils. In 'Sulfur in S.E. Asian and S. Pacific Agriculture. Blair G.J and Till, A.R. (ed.). Indonesia. University of New England, Armidale, Australia. pp. 28-38.

Freney, J.R., Ivanov, M.V. and Rhode, H. (1983). The sulphur cycle. In 'The Major Biogeochemical Cycles and Their Interaction'. Bolin, B. and Cook, R.B. (ed.), pp. 56 - 65. John Wiley and Sons. New York.

Freney, J.R., Melville, G.E. and Williams, C.H. (1971). Organic sulphur fractions labelled by addition of ^{35}S-sulphate to soil. *Soil Biol. Biochem.* **3**, 133-41.

Freney, J.R., Melville, G.E. and Williams, C.H. (1975). Soil organic matter fractions as sources of plant-available sulphur. *Soil Biol. Biochem.* **7**, 217-21.

Freney, J.R., Stevenson, F.J. and Beavers, A.H. (1972). Sulfur-containing amino acids in soil hydrolysates. *Soil Science.* **114**, 468-75.

Freney, J.R. and Swaby, R.J. (1975). Sulfur transformation in soils. In 'Sulfur in Australasian Agriculture'. McLachlan, K.D (ed.). pp. 31-9. Sydney University Press, Sydney, Australia.

Friesen, D.K. and Chien, S.H. (1986). Sulfur fertilizers and their application: General review and S source evaluation at IFDC. In 'Proc. of Sulphur in Agricultural Soils' pp. 407-34.

Friesen, D.K., Sale, P.W.G. and Blair, G.J. (1987a). Long-term greenhouse evaluation of partially acidulated phosphate rock fertilizers: I. Effect of acidulant and degree of acidulation on availability of P from two phosphate rock. *Fertilizer Research.* **13**, 31-44.

Friesen, D.K., Sale, P.W.G. and Blair, G.J. (1987b). Long-term greenhouse evaluation of partially acidulated phosphate rock fertilizers: II. Effect of cogranulation with elemental S on availability of P from two phosphate rocks. *Fertilizer Research.* **13**, 45-54.

Gebhardt, H. and Coleman, N.T. (1974). Anion adsorption by allophanic tropical soils : II. Sulfate adsorption. *Soil Sci. Soc. Am. Proc.* **38**, 259-62.

Gilbert, M.A., Shaw, K.A., Armour, J.D., Teitzel, J.K. and Standley, J. (1990). Low effectiveness of Duchess rock phosphate on pastures in Queensland. *Aust. J. Exp. Agric.* **30**, 61-71.

Giordano, P.M. and Mortvedt, J.J. (1970). Release of nitrogen from sulfur-coated urea in flooded soil. *Agronomy Journal,* **62** : 612-4.

Goh, K.M. and Tsuji, T. (1979). Changes in soil sulfur fractions during incubation with and without added sulfur. *New Zealand Journal of Agricultural Research.* **22**, 585-94.

Grist, D.H. (1986). Rice. Longman, London and New York.

Gupta, U.C. and MacLeod, J.A. (1984). Effect of various sources of sulfur on yield and sulfur concentration of cereals and forages. *Can. J. Soil Sci.* **64**, 403-9.

Hall, J.K. and Baker, D.E. (1967). An evaluation of asphalt coatings on phosphorus fertilizers. *Agronomy Journal*, **59** : 503-5.

Hamdallah, G.M., Prasad, J.D. and Al-Hendi, A.A. (1988). Crop response to sulfur-coated urea (SCU) and other N-carriers in sandy soils of Saudi Arabia. *Fertilizer Research*. **15**, 47-54.

Harrison, R.B., Johnson, D.W., and Todd, D.E. (1989). Sulfate adsorption and desorption reversibility in a variety of forrest soils. *J. Environ. Qual.* **18**, 419-26.

Harward, M.E. and Reisenauer, H.M. (1966). Reactions and movement of inorganic soil sulfur. *Soil Science*. **110**, 326-35.

Haynes, R.J. (1983). Effect of lime and phosphate application on the adsorption of phosphate, sulfate, and molybdate by a spodosol. *Soil Science*. **135**, 221-7.

Hingston, F.J., Posner, A.M. and Quirk, J.P. (1972). Anion adsorption by goethite and gibbsite. I. The role of proton in determining adsorption envelopes. *Journal of Soil Science*. **23**, 178-92.

Hughes, J.C. and Gilkes, R.J. (1986a). The effect of a rock phosphate properties on the extent of fertilizer dissolution in soils. *Aust. J. Soil Res.* **24**, 209-17.

Hughes, J.C. and Gilkes, R.J. (1986b). The effect of soil properties and level of fertilizer application on the dissolution of sechura rock phosphate in some soils from Brazil, Colombia, Australia and Nigeria. *Aust. J. Soil Res.* **24**, 219-27

Ismunadji, M. (1985). Effect of sulphate application on the performance of IR36 rice variety under submerged and dryland conditions. *Indonesian Journal of Crop Science*. **1**, 21-8.

Ismunadji, M. (1987). Sulphur and rice production. In 'International Symposium Elemental Sulphur in Agriculture' pp. 313-21. (Nice, France).

Ismunadji, M., Blair, G.J., Momuat, E.O. and Sudjadi, M. (1983). Sulfur in the agriculture of Indonesia. In 'Sulfur in South-East Asian and South Pacific agriculture'. Blair, G.J and Till, A.R (ed.) pp. 165-79. Indonesia. University of New England, Armidale, N.S.W. Australia.

Ivanov, M.V., Grinenko, V.A. and Rabinovich, A.P. (1983). The sulfur cycle in continental reservoirs. In 'The Global Biogeochemical Sulfur Cycle'. Ivanov, M.V. and Freney, J.R. (ed.). pp. 297-356. Scope 19. John Wiley and Sons, New York.

Janzen, H.H. and Bettany, J.R. (1986). Release of available sulfur from fertilizers. *Can. J. Soil Sci.* **66**, 91-103.

Janzen, H.H. and Bettany, J.R. (1987a). Measurement of sulfur oxidation in soils. *Soil Science.* **143**, 444-52.

Janzen, H.H. and Bettany, J.R. (1987b). The effect of temperature and water potential on sulfur oxidation in soils. *Soil Science.* **144**, 81-9.

Jensen, H.R and Williams, M.S. (1963). Economics of fertilizer use. In 'Fertilizer Technology and Use'. McVickar, M.H., Bridger, G.L. and Nelson, L.B. (ed.), pp. 23-45. Soil Science Society of America. Madison, Wisconsin.

Jones, M.B., Martin, W.E. and Williams, W.A. (1968). Behavior of sulfate sulfur and elemental sulfur in three California soils in lysimeters. *Soil Sci. Soc. Am. Proc.* **32**, 535-40.

Jones, M.B., Williams, W.A. and Martin, W.E. (1971). Effect of waterlogging and organic matter on the loss of applied sulfur. *Soil Sci. Soc. Am. Proc.* **35**, 542-6.

Kamprath, E.J and Till, A.R. (1983). Sulfur cyling in the tropics. In 'Sufur in South-east Asian and South Pacific Agriculture'. Blair, G.J. and Till, A.R. (ed.). pp. 1-14. Indonesia. University of New England, Armidale, N.S.W. Australia.

Kanabo, I.A.K. and Gilkes, R.J. (1987). The role of soil pH in the dissolution of phosphate rock fertilizers. *Fertilizer Research.* **12**, 165-74.

Kanabo, I.A.K. and Gilkes, R.J. (1988a). A comparison of mixed and band applications on the dissolution of North Carolina phosphate rock and on bicarbonate-soluble soil phosphorus. *Fertilizer Research.* **15**, 3-12.

Kanabo, I. and Gilkes, R.J. (1988b). The effect of particle size on North Carolina phosphate rock on its dissolution in soil and on levels of bicarbonate-soluble phosphorus. *Fertilizer Research.* **15**, 137-45.

Khasawneh, F.E. and Doll, E.C. (1978). The use of phosphate rock for direct application to soils. *Advances in Agronomy.* **30**, 159-206

Kittams, H.A. and Attoe, O.J. (1965). Availability of phosphorus in rock phosphate-sulfur fusions. *Agronomy Journal.* **57**, 331-4.

Klessa, D.A., Frame, J., Golightly, R.D. and Harkess, R.D. (1989). The effect of fertilizer sulphur on grass production for silage. *Grass and Forage Science.* **44**, 277-81.

Korentajer, L., Byrnes, B.H. and Hellums, D.T. (1984). Leaching losses and plant recovery from various sulfur fertilizers. *Soil Sci. Soc. Am. J.* **48**, 671-6.

Lee, A., Watkinson, J.H., Orbell, G., Bagyaraj, J. and Lauren, D.R. (1987). Factors influencing dissolution of phosphate rock and oxidation of elemental sulphur in some New Zealand soils. *New Zealand Journal of Agricultural Research.* **30**, 373-85.

Lefroy, R.D.B (1989). Alternative Sulfur Sources : ACIAR Research. In 'Sulfur Fertilizer Policy for Lowland and Upland Rice Cropping System in Indonesia'. Blair, G.J. and Lefroy, R. (ed.) pp. 120-4.

Lefroy, R.D.B., Santoso, D. and Ismunadji, M. (1989). Incidental S inputs in rainfall and irrigation water. In 'Sulfur Fertilizer Policy for Lowland and Upland Rice Cropping System in Indonesia'. Blair, G.J and Lefroy, R. (ed.) pp. 101-6.

Li, P. and Caldwell, A.C. (1966). The oxidation of elemental sulphur in soil. *Soil Sci. Soc. Am. Proc.* **30**, 370-2.

Lindemann, W.C., Aburto, J.J., Haffner, W.M. and Bono, A.A. (1991). Effect of sulfur source on sulfur oxidation. *Soil Sci. Soc. Am. J.* **55**, 85-90.

Littlemore, J. Martin, C. and Nordheim, J.V. (1990). Leaching losses of nitrogen, phosphorus and potassium on tobacco soils in North Queensland. *Commun. In Soil Sci. Plant Anal.*, **21**, 965-77.

Mackay, A.D. and Wewala, G.S. (1990). Evaluation of partially acidulated phosphate fertilisers and reactive phosphate rock for hill pastures. *Fertilizer Research.* **21**, 149-56.

Mahler, R.J. and Maples, R.L. (1987). Effect of sulfur on soil and the nutrition of wheat. *Commun. in Soil Sci. Plant Anal.* **18**, 653-73.

Mamaril, C.P. and Gonzalez, P.B. (1987). Sulphur status and requirements of the Philippines. In 'Proc. of the symp. on fertilizer sulphur requirements and sources in developing countries of Asia and the Pacific'. pp. 67-75. Bangkok.

Marsh, K.B., Tillman, R.W. and Syers, J.K. (1987). Charge relationships of sulfate sorption by soils. *Soil Sci. Soc. Am. J.* **50**, 318-23.

Maynard, D.G., Stewart, J.W.B. and Bettany, J.R. (1985). The effects of plants on soil sulfur transformations. *Soil Biol. Biochem.* **17**, 127-34.

McCaskill, M.R. and Blair, G.J. (1987). Particle size and soil texture effects on elemental sulfur oxidation . *Agronomy Journal.* **79**, l079-83.

McCaskill, M.R. and Blair, G.J. (1988). Development of a simulation model of sulfur cycling in grazed pastures. *Biogeochemistry.* **5**, 165-81.

McCaskill, M.R. and Blair, G.J. (1989). A model for the release of sulfur from elemental S and superphosphate. *Fertilizer Research.* **19**, 77-84.

Morris, R.J. (1986). The importance of sulphur in agriculture - an overview. In 'Proc. of Sulphur in Agricultural Soils' pp. 1-17.

Morris, R.J. (1987). The importance and need for sulphur in crop production in Asia and the Pacific region. In 'Proc. of the symp. on fertilizer sulphur requirements and sources in developing countries of Asia and the Pacific'. pp. 4-11. Bangkok.

Nearpass, D.C. and Clark, F.E. (1960). Availability of sulfur to rice plants in submerged and upland soil. *Soil Sci. Soc. Am. Proc.* **24**, 385-7.

Nevell, W. and Wainwright, M. (1987). Influence of soil moisture on sulphur oxidation in brown earth soils exposed to atmospheric pollution. *Biol. Fertil. Soils.* **5**, 209-14.

Nodvin, S.C., Driscoll, C.T. and Likens, G.E. (1986). The effect of pH on sulfate adsorption by a forest soil. *Soil Science.* **142**, 69-75.

Noellemeyer, E.J., Bettany, J.R. and Henry, J.L. (1981). Sources of sulfur for rapeseed. *Can. J. Soil Sci.* **61**, 465-7.

Nor, Y.M. and Tabatabai, M.A. (1977). Oxidation of elemental sulfur in soils. *Soil Sci. Soc. Am. J.* **41**, 736-41.

Oertli, J.J. and Lunt, O.R. (1962). Controlled release of fertilizer minerals by incapsulating membrane : I. Factors influencing the rate of release. *Soil Sci. Soc. Am. Proc.*, **26** : 579-583.

Olsen, R.A. (1975). Rate of dissolution of phosphate from minerals ans soils. *Soil Sci. Soc. Am. Proc.*, **39** : 634-9.

Palmer, B. and Gilkes, R.J. (1983). The fertilizer effectiveness of calcined Christmas Island C-grade aluminium-iron phosphate rock and superphosphate during the early stages of plant growth. *Fertilizer Research.* **4**, 31-43.

Parfitt, R.L. (1978). Anion adsorption by soils and soil materials. *Advances in Agronomy.* **30**, 1-50

Parfitt, R.L. (1982). Competitive adsorption of phosphate and sulphate on goethite (a-FeOOH) : A note. *New Zealand Journal of Science.* **25**, 147-8.

Parfitt, R.L. and Smart, R.S.C. (1978). The mechanism of sulfate adsorption on iron oxides. *Soil Sci. Soc. Am. J.* **42**, 48-50.

Patrick, W.H. Jr. and Mikkelsen, D.S. (1971). Plant nutrient behavior in flooded soil. In 'Fertilizer Technology and Use' Second Edition. Olson, R.A., Army, T.J., Hanway, J.J. and Kilmer, V.J. (ed.). pp. 187-215. Soil Science Society of America, Inc. Madison.

Ponnamperuma, F.N. (1972). The chemistry of submerged soils. *Advances in Agronomy.* **24**, 29-96.

Ponnamperuma, F.N. (1975). Growth-limiting factors of aerobic soils. In 'Major Research in Upland Rice'. p. 40-3. The International Rice Research Institute, Los Banos, Philippines.

Rajan, S.S.S. (1978). Sulfate adsorbed on hydrous alumina, ligands displaced, and changes in surface charge. *Soil Sci. Soc. Am. J.* **42**, 39-44.

Rajan, S.S.S. (1979). Adsorption and desorption of sulfate and charge relationships in allophanic clays. *Soil Sci. Soc. Am. J.* **43**, 65-9.

Rajan, S.S.S. (1983). Effect of sulphur content of phosphate rock/sulphur granules on the availability of phosphate to plants. *Fertilizer Research.* **4**, 287-96.

Rajan, S.S.S. (1987). Phosphate rock and phosphate rock/sulphur granules as phosphate fertilizers and their dissolution in soil. *Fertilizer Research.* **11**, 43-60.

Rajan, S.S.S., Fox, R.L., Saunders, W.M.H. and Upsdell, M. (1991). Influence of pH, time and rate of application on phosphate rock dissolution and availability to pastures. I. Agronomic benefits. *Fertilizer Research*, **28** : 85-93.

Rajan, S.S.S., Fox, R.L. and Saunders, W.M.H. (1991). Influence of pH, time and rate of application on phosphate rock dissolution and availability to pastures. II. Soil chemical studies. *Fertilizer Research*, **28** : 95-101.

Rehm, G.W. and Caldwell, A.C. (1969). Relationship of soil texture to sulphur oxidation. *Agronomy Journal.* **61**, 333-4.

Rendig, V.V. (1986). Sulfur and crop quality. In 'Sulfur in Agriculture'. Tabatabai, M.A. (ed.). p. 635-52. ASA, CSSA, SSSA. Madison, Wisconsin.

Russell, J.S. and Chapman, A.L. (1988). Sulfur deficiency in rice grown on the alkaline soils of the Ord irrigation area, Western Australia. *Aust. J. Exp. Agric.* **28**, 111-7.

Sachdev, M.S. and Chhabra, P. (1974). Transformations of S-labelled sulfate in aerobic and anaerobic soil conditions. *Plant and Soil.* **41**, 335-41.

Saggar S., Bettany, J.R. and Stewart J.W.B. (1981). Sulfur transformations in relation in relation to carbon and nitrogen in incubated soils. *Soil Biology and Biochemistry.* **13**, 499-511.

Salim, M and Rahmatullah (1987). Evaluation of Sulphur Status and Potential for its Application in Pakistan Soils. In 'Proc. of the symp. on fertilizer sulphur requirements and sources in developing countries of Asia and the Pacific'. pp. 49-56. Bangkok.

Samosir, S. (1981). Some aspects of sulfur nutrition of rice. M.Sc.Ag. Thesis, University of New England, Armidale, N.S.W., 2351, Australia.

Samosir, S and Blair, G.J. (1983). Sulfur nutrition of rice. III. A comparison of fertilizer source for flooded rice. *Agronomy Journal.* **75**, 203-6.

Sanchez, P.A. (1976). Properties and Management of Soils in the Tropics. Wiley, New York.

Sanchez, P.A., Gavidia O, A., Ramirez, G.E., Vergara, R. and Minguillo, F. (1973). Performance of sulfur-coated urea under intermittently flooded rice culture in Peru. *Soil Sci. Soc. Am. Proc.* **37**, 789-92.

Santoso, D (1989). Phosphorus and sulfur characteristics and fertilization of upland acid soils of the humid tropics. Ph.D Thesis, The University of New England, Armidale, Australia.

Scott, J.M. (1986). Seed Coating as an Aid to Pasture Establishment. Ph.D. Thesis. University of New England, Armidale, N.S.W., Australia.

Scott, N.M., Dyson, P.W., Ross, J. and Sharp, G.S. (1984). The effect of sulphur on the yield and chemical composition of winter barley. *Journal of Agricultural Science.* **103**, 699-702

Scott, N.M., Watson, M.E., Caldwell, K.S. and Inkson, R.H.E. (1983). Response of grassland to the application of sulphur at two sites in North-east Scotland. *Journal of Science, Food and Agriculture*, **34** : 357-61.

Shedley, C.D. (1982). An Evaluation of Elemental Sulfur as a Pasture Fertilizer. Ph.D. Thesis. University of New England.

Shedley, C.D., Till, A.R. and Blair, G.J. (1979). A radiotracer technique for studying the nutrient release from different fertilizer materials and its uptake by plant. *Commun. in Soil Science and Plant Analysis.* **10**, 737-45.

Singh, B.R. (1984a). Sulfate sorption by acid forest soils : 2. Sulfate adsorption isotherms with and without organic matter and oxides of aluminum and iron. *Soil Science.* **138**, 294-7.

Singh, B.R. (1984b). Sulfate sorption by acid forest soils : 3. Desorption of sulfate from adsorbed surfaces as a function of time, desorbing ion, pH, and amount of adsorption. *Soil Science.* **138**, 346-53.

Singh, B.R.(1984c). Sulfate sorption by acid forest soils : 4. Kinetics and effecs of temperature and moisture. *Soil Science.* **138**, 440-7.

Soil Taxonomy (1975). A basic system of soil classification for making and interpreting soil survey. U.S. Dept. Agr. Handbook. No. 436. Washington D.C. Gov. Printing Office.

Spencer, K. (1975). Sulphur requirements of plants. In 'Sulphur in Australasian Agriculture'. McLachlan, K.D. (ed.). pp. 98-108. Sydney University Press, Sydney, Australia.

Starkey, R.L. (1966). Oxidation and reduction of sulfur compounds in soils. *Soil Science.* **101**, 297-306.

Suryosunarko, S.A. (1989). The Fertilizer Industry in Indonesia. In 'Sulfur Fertilizer Policy for Lowland and Upland Rice Cropping System in Indonesia'. Blair, G.J. and Lefroy, R. (ed.) pp. 19-25.

Tabatabai, M.A. and Bremner, J.M. (1972). Forms of sulfur, and carbon, nitrogen and sulfur relationships, in Iowa soils. *Soil Science.* **114**, 380-5.

Till, A.R. and Blair, G.J. (1978). The utilization by grass of sulphur and phosphorus from clover litter. *Aust. J. Agric. Res.* **29**, 235-42.

Till, A.R. and May, P.F. (1970). Nutrient cycling in grazed pastures. II. Further observations with [^{35}S]gypsum. *Aust. J. Agric. Res.* **21**, 253-60.

Till, A.R. and May, P.F. (1971). Nutrient cycling in grazed pastures.IV. The fate of sulfur-35 following its application to a small area in a grazed pastures. *Aust. J. Agric. Res.* **22**, 391-400.

Till, A.R., McArthur, G.S. and Rocks, R.L. (1984). An automated procedure for the simultaneous determination of sulphur and phosphorus and radioactivity in biological samples. In 'Proc. of Sulphur-84' pp. 649-60.

Tisdale, S.L. and Nelson, W.R. (1975). Soil Fertility and Fertilizers. Third Edition. Macmillan Publishing Co., Inc. New York.

Tisdale, S.L., Reneau,JR.R.B. and Platou, J.S. (1986). Atlas of sulfur deficiencies. In 'Sulfur in Agriculture'. Tabatabai, M.A. (ed.) pp. 295-322. Agronomy Series. No. 27. ASA, CSSA, SSSA, Madison, U.S.A..

Trudinger, P.A. (1986). Chemistry of the sulfur cycle. In 'Sulfur in Agriculture'. Tabatabai, M.A. (ed.) pp. 1-22. Agronomy series, No.27. ASA, CSSA, SSSA. Madison, U.S.A.

Vitolins, M.I. and Swaby, R.J. (1969). Activity of sulphur-oxidizing microorganisms in some Australian soils. *Aust. J. Soil Res.*, **7**, 171-83.

Wainwright, M. (1984). Sulfur oxidation in soils. *Advances in Agronomy.* **37**, 349-96.

Wainwright, M., Nevell, W. and Grayston, S.J. (1986). Effects of organic matter on sulphur oxidation in soil and influence of sulphur oxidation on soil nitrification. *Plant and Soil.* **96**, 369-76.

Walker, T.W. and Adams, A.F.R (1958). Competition for sulfur in a grass-clover association. *Plant and Soil*, **9** : 353-56

Watkinson, J.H. (1989). Measurement of the oxidation rate of elemental sulfur in soil. *Aust. J. Soil Res.* **27**, 365-75.

Weaver, D.M., Ritchie, G.S.P., Anderson, G.C.and Deeley, D.M. (1988a). Phosphorus leaching in sandy soils.I. Short-term effects of fertilizer applications and environmental conditions. *Aust. J. Soil Res.* **26**, 177-90.

Weaver,D.M., Ritchie, G.S.P. and Anderson, G.C. (1988b). Phosphorus leaching in sandy soils. II. Laboratory studies of the long-term effects of the phosphorus source. *Aust. J. Soil Res.* **26**, 191-200.

Weir, R.G. (1975). The oxidation of elemental sulphur and sulphides in soil. In 'Sulphur in Australasian Agriculture'. McLachlan, K.D (ed.). pp. 40-9. Sydney University Press, sydney, Australia.

Wells, B.R. and Shockley, P.A. (1975). Conventional and controlled-release nitrogen sources for rice. *Soil Sci. Soc. Am. Proc.* **39**, 549-51.

Williams, C.H. (1967). Some factors affecting the mineralization of organic sulphur in soils. *Plant and Soil.* **2**, 205-23.

Williams, C.H. (1975). The chemical nature of sulphur compounds in soils. In 'Sulphur in Australasian Agriculture'. McLachland, K.D. (ed.). pp. 21-30. Sydney University Press, Sydney, Australia.

Yoshida, S. (1975). Factors that limit the growth and yields of upland rice. In 'Major Research in Upland Rice'. p. 46-71. The International Rice Research Institute, Los Banos, Philippines.

Yoshida, S and Chaudry, M.R. (1979). Sulfur nutrition of rice. *Soil Sci. Plant. Nut.*, **25** : 121-34.

APPENDICES

3.1 Examples of variance analysis using NEVA computer program.

(a) The effect of S application rate on grain yield under flooded conditions.

```
  FILE GGR1.OUT   CREATED BY NEVA VERSION  3.3
                          ON   9/ 3/88 AT 12H 34M
#    1  NEVA EXP ( THE EFFECT OF S RATE ON GRAIN YIELD )
#    2  FACTORS R3 T4

   **         2 FACTORS
   **        12 ITEMS
#    3  C R=REPLICATE T=S RATE (0, 5, 10, 20)
#    4  DATA
#    5  16.485 16.003 14.226
#    6  25.151 26.930 24.400
#    7  30.683 30.777 30.678
#    8  35.615 34.569 36.529
#    9  END

       12 ITEMS,    0 MISSING OBS

      12 ITEMS, MIN      14.226000 MEAN       26.837170 SUM         322.046000
                MAX      36.529000 S.D.        7.793984

#   10  EFFECTS R T RT/
#   11  AOV MEANS D5 RES PLOT

SOURCE                DF        SUM OF SQUARES           MEAN SQUARE         F        PROB

GRAND MEAN             1          8642.80400000         8642.80400000    7140.4820  0.00000***
R                      2             0.87500000            0.43750000       0.3615  0.71086
T                      3           660.06900000          220.02300000     181.7779  0.00000***
RT/                    6             7.26237000            1.21039500

RAW SS                            9311.01000000
COR SS                             668.20610000


SD OF MEANS BASED ON PLOT ERROR       1.100180    DF=    6

GRAND MEAN      MEANS OF   12. SD=   0.31759        5PC LSD=   1.09951        1PC LSD=   1.66541

            26.83717

R               MEANS OF    4. SD=   0.55009        5PC LSD=   1.90441        1PC LSD=   2.88457

              R 1       R 2       R 3
            26.98350 27.06975 26.45825

T               MEANS OF    3. SD=   0.63519        5PC LSD=   2.19902        1PC LSD=   3.33081

              T 1       T 2       T 3       T 4
            15.57133 25.49367 30.71267 35.57100

        2           3           4
5PC DUNCANS MULTIPLE RANGE
     2.19808     2.27827     2.31826


MAX. ABS. RESIDUAL    1.3369
  0.7673  0.1991 -0.9664
 -0.4890  1.2038 -0.7147
 -0.1760 -0.1682  0.3442
 -0.1023 -1.2346  1.3369

FREQUENCY PLOT OF ABSOLUTE RESIDUALS AGAINST CLASS MEANS OF X.
           RMS DENOTES THE ROOT MEAN SQUARE RESIDUAL IN EACH CLASS.

FREQUENCY     MEAN X   RMS RESIDUAL   0.0000         0.6685         1.3369
-----------------------------------------------------------------------------

    3        15.5713         0.7217   .   1          . 1  1        .
                                                      RMS

    0

    2        24.7755         0.6124   .          1   .1              .
                                                    RMS

    1        26.9300         1.2038   .              .             1 .
                                                                  RMS

    3        30.7127         0.2434   .   2   1      .               .
                                          RMS

    3        35.5710         1.0523   . 1            .            1 1
                                                               RMS
-----------------------------------------------------------------------------

 SLOPE OF REGRESSION OF LOG ABSOLUTE RESIDUAL ON LOG(X) IS    -0.3982
                              APPROXIMATE S.D. OF SLOPE IS      0.8217 WITH DF =   11.
#   12  STOP

END OF NEVA JOB
     12 LINES INPUTTED
     76 LINES OUTPUTTED
```

(b) The effect of different S sources on relative grain yield under flooded conditions.

```
  FILE GRCR.OUT   CREATED BY NEVA VERSION   3.3
                          ON    9/ 3/88 AT 12H 34M
#    1  NEVA EXP ( RELATIVE GRAIN YIELD UNDER FLOODED CONDITIONS )
#    2  FACTORS R3 T10

   **        2 FACTORS
   **       30 ITEMS
#    3  DATA
#    4  53.272  51.997 46.372
#    5  100.000 100.000 100.000
#    6  88.459 79.231 93.856
#    7  78.698 87.845 87.665
#    8  74.970 71.284 62.028
#    9  82.254 94.593 81.443
#   10  95.030 98.778 89.703
#   11  100.766 79.797 76.977
#   12  93.579 92.527 95.192
#   13  59.378 72.574 52.549
#   14  END

       30 ITEMS,    0 MISSING OBS

      30 ITEMS, MIN      46.372000 MEAN      81.360570 SUM        2440.817000
                MAX     100.766000 S.D.      16.319570

#   15  EFFECTS R T RT/
#   16  AOV MEANS D5 RES PLOT

SOURCE                DF        SUM OF SQUARES           MEAN SQUARE        F        PROB

GRAND MEAN             1         198586.200000         198586.200000   4144.1680  0.00000***
R                      2            116.350000             58.175000      1.2140  0.32019
T                      9           6744.633000            749.403700     15.6388  0.00000***
RT/                   18            862.550000             47.919450

RAW SS                           206309.800000
COR SS                             7723.531000

SD OF MEANS BASED ON PLOT ERROR    6.922387     DF=  18

GRAND MEAN      MEANS OF   30. SD=  1.26385         5PC LSD=   3.75809        1PC LSD=   5.14510

            81.36057

R               MEANS OF   10. SD=  2.18905         5PC LSD=   6.50921        1PC LSD=   8.91158

              R 1      R 2      R 3
            82.64059 82.86259 78.57850

T               MEANS OF    3. SD=   3.9966         5PC LSD=  11.8841         1PC LSD=  16.2702

        T 1    T 2      T 3      T 4      T 5      T 6      T 7      T 8      T 9      T10
     50.5470 100.0000  87.1820  84.7360  69.4273  86.0967  94.5037  85.8467  93.7660  61.5003

 SORTED MEANS
 50.5470     61.5003     69.4273     84.7360     85.8467     86.0967     87.1820     93.7660     94.5037    100.0000

    2           3           4           5           6           7           8           9          10
5PC DUNCANS MULTIPLE RANGE
 11.8747     12.4593     12.8296     13.0852     13.2717     13.4125     13.5213     13.6066     13.6741


MAX. ABS. RESIDUAL    13.639
   1.445  -0.052  -1.393
  -1.280  -1.502   2.782
  -0.003  -9.453   9.456
  -7.318   1.607   5.711
   4.263   0.355  -4.617
  -5.123   6.994  -1.872
  -0.754   2.772  -2.019
  13.639  -7.552  -6.088
  -1.467  -2.741   4.208
  -3.402   9.572  -6.169

FREQUENCY PLOT OF ABSOLUTE RESIDUALS AGAINST CLASS MEANS OF X.
          RMS DENOTES THE ROOT MEAN SQUARE RESIDUAL IN EACH CLASS.

FREQUENCY    MEAN X    RMS RESIDUAL   0.0000         6.8197        13.6393
---------------------------------------------------------------------------

    4       51.0475         3.2439     1  2          1.              .
                                            RMS

    2       60.7030         4.0556     .      1  1    .              .
                                              RMS

    2       71.9290         6.7728     .1             .     1        .
                                                    RMS

    7       79.0529         6.3798     .  1     1 1 1 .11   1        .
                                                   RMS

    4       88.4180         3.1334     1  2        1 .               .
                                            RMS

   11       96.7564         5.8124     . 13 3   1     1     1        1
                                                  RMS
---------------------------------------------------------------------------

 SLOPE OF REGRESSION OF LOG ABSOLUTE RESIDUAL ON LOG(X) IS      0.9903
                              APPROXIMATE S.D. OF SLOPE IS      1.2258 WITH DF =   29.
#   17  STOP

END OF NEVA JOB
    17 LINES INPUTTED
    83 LINES OUTPUTTED
```

3.2 The effect of S-application rate on yield components at different growth stages under flooded conditions.

Yield component	growth stages	S rate (kg ha^{-1}) 0	5	10	20
Number of tillers	31 dat	1.3 b[A]	2.7 b	4.7 a	5.0 a
	45 dat	2.0 c	5.7 b	8.0 a	8.7 a
	AT	3.0 c	8.3 b	12.0 b	13.3 a
	MT	7.0 c	10.7 b	15.3 a	18.0 a
	M	9.0 c	12.7 b	16.0 ab	18.0 a
Number of panicles	M	8.7 c	12.0 b	15.0 a	17.7 a
Number of grain per panicle	M	80.4 b	105.4 a	99.0 a	98.1 a
Dry weight of grain per panicle (g)	M	1.6 b	2.1 a	2.0 a	2.0 a
Dry weight of 100 grains (g)	M	2.0 a	2.0 a	2.1 a	2.1 a
Dry weight of empty grains (g pot^{-1})	M	1.1 a	1.4 a	1.3 a	1.3 a
Percentage of empty grain (%)	M	6.5 a	4.2 b	4.9 b	4.8 b
Harvest index	M	0.36 a	0.37 a	0.34 a	0.35 a

[A] *Data followed by the same letter in the same row are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.3 The effect of S-application rate on extractable S (ES) (mg pot^{-1}) and organic S (OS) (mg pot^{-1}) at different growth stages under flooded conditions.

	------- AT ------		------- MT -------		--------- M ---------	
Treatment	ES	OS	ES	OS	ES	OS
	(mg pot^{-1})		(mg pot^{-1})		(mg pot^{-1})	
C	38.5 d[A]	630.4 c	20.3 d	602.1 b	14.5 c	575.7 a
G_1	49.9 c	638.9 bc	25.0 c	608.7 b	15.8 bc	579.2 a
G_2	61.8 b	643.3 ab	32.3 b	616.8 ab	17.9 ab	582.1 a
G_3	70.7 a	652.8 a	37.0 a	627.8 a	19.6 a	585.0 a

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.4 The effect of S sources on yield components at maturity under flooded conditions.

Source of S	No. of panicles	Dwt. of grains panicle^{-1} (g)	Dwt. of 100 grain (g)	percentage of empty grain (%)	Harvest index
G	15.0 a[A]	2.1 a	2.1 a	4.2 b	0.34 a
PVA	14.0 ab	2.1 a	2.1 a	5.0 b	0.35 a
LS	13.3 bc	2.2 a	2.0 a	4.6 b	0.36 a
HF	11.0 d	2.4 a	2.0 a	4.5 b	0.39 a
SW	11.7 d	2.3 a	2.1 a	4.5 b	0.38 a
US	12.0 cd	2.2 a	2.0 a	4.8 b	0.36 a
SCU	8.0 e	2.7 a	2.0 a	5.0 b	0.38 a
E	12.3 cd	2.2 a	2.0 a	4.9 b	0.36 a
SB	8.3 e	2.3 a	2.1 a	5.4 ab	0.38 a
C	8.0 e	2.0 a	1.1 a	6.5 a	0.36 a

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.5 The effect of S sources on relative yield of plant components at different growth stages under flooded conditions.

(a) AT

Source of S	Relative yield (%) stem + leaf	root	total
G	100.0 a[A]	100.0 a	100.0 a
PVA	76.8 b	65.5 b	72.6 b
LS	72.4 b	55.4 c	66.1 c
HF	58.5 c	33.9 e	49.2 e
SW	56.9 c	37.3 e	49.5 e
US	60.4 c	34.0 e	50.5 de
SCU	32.1 d	13.1 g	25.0 f
E	63.2 c	44.8 d	56.3 d
SB	35.3 d	23.3 f	30.8 f
C	28.9 d	17.8 fg	24.8 f

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

(b) MT

Source of S	Relative yield (%) stem + leaf	root	total
G	100.0 a[A]	100.0 a	100.0 a
PVA	94.4 ab	87.9 ab	92.2 ab
LS	90.6 a-c	86.5 ab	89.0 a-c
HF	64.4 de	64.0 cd	64.4 d
SW	78.6 cd	69.3 bc	75.6 cd
US	78.8 cd	70.6 bc	74.8 cd
SCU	56.1 ef	37.2 e	49.7 e
E	83.3 bc	76.8 bc	80.9 bc
SB	51.3 ef	44.6 de	49.0 e
C	45.3 f	35.1 e	41.8 e

[A] Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).

(c) M

Source of S	grain	Relative yield (%) stem + leaf	root	total
G	100.0 a[A]	100.0 a	100.0 a	100.0 a
PVA	94.5 ab	94.4 a	78.4 bc	90.3 ab
LS	93.8 ab	91.6 ab	81.0 b	89.7 ab
HF	86.1 b	75.7 c	61.8 cd	75.7 c
SW	85.8 b	78.7 c	65.4 bc	77.9 c
US	84.7 b	82.0 bc	73.5 bc	80.8 c
SCU	69.4 c	64.3 d	46.7 de	61.7 d
E	87.2 b	84.2 bc	74.4 bc	82.8 bc
SB	61.5 cd	55.1 de	47.3 de	55.3 de
C	50.7 d	50.9 e	39.5 e	47.9 e

[A] Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).

3.6 The effect of S sources on relative S content of plant parts at different growth stages under flooded conditions.

(a) AT

Source of S	Relative S content (%) stem + leaf	root	total
G	100.0 a[A]	100.0 a	100.0 a
PVA	86.4 b	75.8 b	83.8 b
LS	78.5 bc	56.7 c	72.4 c
HF	65.0 d	38.7 e	57.9 d
SW	63.0 d	43.0 de	57.3 d
US	66.8 d	42.7 de	60.0 d
SCU	35.9 e	18.0 f	31.2 e
E	70.9 cd	49.8 cd	64.9 cd
SB	39.0 e	26.0 f	35.5 e
C	32.5 e	23.8 f	30.1 e

[A] Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).

(b) MT

Source of S	Relative S content (%) stem + leaf	root	total
G	100.0 a[A]	100.0 a	100.0 a
PVA	92.7 ab	85.9 ab	90.9 ab
LS	88.2 b	73.9 bc	84.4 b
HF	68.1 c	51.1 d	63.3 d
SW	70.8 c	60.7 cd	67.8 cd
US	73.6 c	61.7 cd	70.4 cd
SCU	52.0 d	35.2 e	47.5 e
E	77.0 c	60.1 cd	72.5 c
SB	48.1 de	36.0 e	45.0 e
C	42.5 e	30.9 e	39.5 e

[A] *Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).*

(c) M

Source of S	grain	Relative S content (%) stem + leaf	root	total
G	100.0 a[A]	100.0 a	100.0 a	100.0 a
PVA	94.2 ab	94.2 a	94.8 a	95.2 ab
LS	89.9 b	90.5 a	92.0 a	91.9 b
HF	76.6 c	70.0 b	70.4 b	73.9 c
SW	74.4 c	76.1 b	71.2 b	75.7 c
US	79.5 c	74.4 b	72.8 b	77.4 c
SCU	62.7 d	56.0 c	57.4 c	60.0 d
E	79.4 c	79.0 b	73.0 b	79.3 c
SB	54.9 d	53.5 cd	58.0 c	55.7 d
C	45.0 e	43.5 d	38.9 d	42.0 e

[A] *Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).*

3.7 The effect of different S sources on extractable S (ES) at different growth stages under flooded conditions.

Source of S	AT	Extractable S (mg pot $^{-1}$) MT	M
G	61.8 a[A]	32.3 h	17.9 j
PVA	54.8 b	33.1 h	19.2 j
LS	53.4 b	31.7 h	18.8 j
HF	45.1 de	30.4 h	19.5 j
SW	48.1 cd	30.4 h	21.2 j
US	46.4 de	31.9 h	18.2 j
SCU	41.9 f	25.5 i	24.5 i
E	49.8 c	32.0 h	18.7 j
SB	43.5 ef	25.8 i	26.4 i
C	38.5 g	20.3 j	14.5 k

[A] *Data followed by the same letter are not significantly different (P < 0.05) (Duncan's multiple range test).*

3.8 The effect of S sources on organic S (OS) at different growth stages under flooded conditions.

Source of S	Organic S (mg pot^{-1}) AT	 MT	 M
G	643.3 a[A]	616.8 bc	582.1 e
PVA	637.6 a	613.6 c	583.0 e
LS	636.4 a	613.9 c	584.0 e
HF	634.3 a	612.0 c	584.3 e
SW	633.7 a	615.3 c	585.5 e
US	634.2 a	613.1 c	583.8 e
SCU	635.0 a	616.0 c	589.0 de
E	635.9 a	615.1 c	584.8 e
SB	634.7 a	612.4 c	588.1 de
C	630.4 ab	602.1 cd	575.7 e

[A] Data followed by the same letter are not significantly different ($P < 0.05$) (Duncan's multiple range test).

3.9 The residual effect of S-application rate on yield components under flooded conditions.

Yield component	S rate (kg ha^{-1}) 0	 5	 10	 20
Number of tillers	8.0 [A]	8.7 ab	9.0 ab	10.7 a
Number of panicles	7.3 b	8.3 ab	8.7 ab	10.0 a
Number of grains per panicle	52.3 a	60.0 a	61.4 a	60.6 a
Dry weight of grain panicle^{-1} (g)	1.06 a	1.20 a	1.24 a	1.22 a
Dry weight of 100 grains (g)	2.02 a	2.00 a	2.02 a	2.02 a
Percentage of empty grain (%)	7.3 a	5.8 ab	5.7 ab	5.5 b
Harvest index	23.5 b	27.9 ab	28.2 ab	29.1 a

[A] Data followed by the same letter in the same row are not significantly different ($P < 0.05$) (Duncan's multiple range test).

3.10 The residual effect of S-application rates on extractable S (ES) and organic S (OS) under flooded conditions.

Treatment	ES (mg pot^{-1})	OS (mg pot^{-1})
C	6.9 b[A]	404.6 a
G_1	7.7 ab	413.9 a
G_2	8.4 ab	416.1 a
G_3	10.5 a	421.5 a

[A] Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).

3.11 The residual effect of S-application rate on the percentage of fertiliser S incorporated into the extractable S (ES) and organic S (OS) fractions under flooded conditions.

S rate (kg ha^{-1})	Recovery of fertiliser S (%) ES	OS
0	--	--
5	0.48 a[A]	24.9 a
10	0.91 a	31.9 a
20	1.74 a	45.1 a

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.12 The residual effect of S sources on yield components under flooded conditions.

Source of S	No. of tillers	No. of panicles	Dwt. of grains panicle^{-1} (g)	Dwt. of 100 grain (g)	percentage of empty grain (%)	Harvest index
G	9.0 bc[A]	8.7 bc	1.24 a	2.02 a	5.7 ab	0.28 ab
PVA	9.7 a-c	9.3 a-c	1.18 a	2.02 a	5.9 ab	0.28 ab
LS	10.3 a-c	9.7 a-c	1.16 a	2.03 a	5.2 b	0.27 ab
HF	10.7 a-c	10.3 ab	1.14 a	2.03 a	4.8 b	0.28 ab
SW	11.3 ab	11.0 ab	1.08 a	2.03 a	5.6 ab	0.29 a
US	10.3 a-c	10.0 ab	1.15 a	2.01 a	6.0 ab	0.28 ab
SCU	12.0 a	11.3 a	1.13 a	2.02 a	4.9 b	0.28 ab
E	10.0 a-c	9.7 a-c	1.16 a	2.03 a	6.2 ab	0.28 ab
SB	12.3 a	11.7 a	1.17 a	2.02 a	4.8 b	0.29 a
C	8.0 c	7.3 c	1.06 a	2.02 a	7.3 a	0.23 b

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.13 The residual effect of different sources of S on extractable S (ES), organic S (OS) and acetone-extractable elemental S (AES) under flooded conditions.

Source of S	ES (mg pot^{-1})	OS (mg pot^{-1})	AES (mg pot^{-1})
C	6.9 c[A]	404.6 b	--
G	8.4 bc	416.1 ab	--
PVA	8.5 bc	418.7 ab	0.6 a
LS	8.7 bc	419.7 ab	0.7 a
HF	10.3 a-c	423.7 ab	0.9 a
SW	9.7 a-c	425.8 ab	1.1 a
US	9.4 a-c	421.1 ab	1.0 a
SCU	11.9 ab	427.3 a	1.2 a
E	9.3 a-c	419.1 ab	0.7 a
SB	12.8 a	429.1 a	1.8 a

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.14 The effect of S-application rate on yield components at different growth stages under non-flooded conditions.

Yield component	Growth stages	S rate (kg ha^{-1}) 0	5	10	20
Number of tillers	31 dat	2.3 c^{A}	3.3 bc	5.0 ab	5.7 a
	45 dat	5.0 c	6.7 bc	9.0 ab	9.7 a
	AT	7.7 c	9.7 bc	13.3 ab	15.0 a
	MT	10.3 b	12.7 b	17.7 a	19.0 a
	M	11.6 b	13.0 b	18.3 a	19.7 a
Number of panicles	M	10.7 b	12.3 b	17.7 a	19.0 a
Number of grain per panicle	M	54.0 a	56.7 a	44.6 a	47.4 a
Dry weight of grains per panicle (g)	M	1.1 a	1.1 a	0.9 a	1.0 a
Dry weight of 100 grains (g)	M	2.0 a	2.0 a	2.1 a	2.1 a
Percentage of empty grains (%)	M	6.2 a	5.0 b	4.5 b	3.6 c
Harvest index	M	0.22 a	0.23 a	0.22 a	0.23 a

^{A} Data followed by the same letter in the same row are not significantly different ($P < 0.05$) (Duncan's multiple range test).

3.15 The effects of S-application rate on extractable S (ES) and organic S (OS) at different growth stages under non-flooded conditions.

Treatment	--------- AT -------- ES	 OS	------- MT ------ ES	 OS	--------- M --------- ES	 OS
	(mg pot^{-1})		(mg pot^{-1})		(mg pot^{-1})	
C	35.2 d^{A}	628.8 c	19.6 c	608.1 b	11.1 c	585.1 a
G_1	42.9 c	639.3 bc	23.6 c	616.8 ab	12.7 bc	602.0 a
G_2	58.7 b	648.9 ab	30.2 b	622.5 ab	14.1 b	611.5 a
G_3	69.3 a	663.6 a	34.2 a	630.8 a	17.7 a	619.4 a

^{A} Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).

3.16 The effect of S sources on yield components at maturity under non-flooded conditions.

Source of S	No. of panicles	Dwt. of grains panicle^{-1} (g)	Dwt. of 100 grains (g)	Percentage of empty grains (%)	Harvest index
G	17.7 a^{A}	0.9 a	2.04 a	4.5 b	0.22 a
PVA	16.0 ab	0.9 a	2.01 a	5.2 ab	0.22 a
LS	15.7 a-c	1.0 a	2.03 a	5.1 ab	0.22 a
HF	12.3 d-f	1.1 a	2.02 a	5.4 ab	0.23 a
SW	13.0 c-f	1.1 a	2.03 a	5.2 ab	0.22 a
US	13.7 b-e	1.1 a	2.02 a	5.6 ab	0.22 a
SCU	15.3 a-c	1.0 a	2.02 a	5.1 ab	0.21 a
E	15.0 a-d	1.0 a	2.01 a	5.2 ab	0.22 a
SB	11.7 ef	1.1 a	2.03 a	5.6 ab	0.22 a
C	10.7 f	1.1 a	2.01 a	6.2 a	0.21 a

^{A} Data followed by the same letter in the same row are not significantly different ($P < 0.05$) (Duncan's multiple range test).

3.17 The effect of S source on relative yield of plant components at different growth stages under non-flooded conditions.

(a) AT

Source of S	Relative yield (%)		
	stem + leaf	root	total
G	100.0 a^A	100.0 a	100.0 a
PVA	83.9 b	91.6 ab	84.0 b
LS	82.6 bc	76.8 bc	79.7 b
HF	76.2 b-d	67.0 cd	71.0 bc
SW	80.3 b-d	67.7 cd	74.2 bc
US	76.1 b-d	62.6 cd	71.3 bc
SCU	76.9 b-d	73.1 b-d	75.8 bc
E	80.7 b-d	67.4 cd	74.4 bc
SB	68.6 cd	52.7 d	63.0 c
C	67.0 d	62.5 cd	63.4 c

[A] *Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).*

(b) MT

Source of S	Relative yield (%)		
	stem + leaf	root	total
G	100.0 a^A	100.0 a	100.0 a
PVA	93.3 ab	90.0 ab	92.8 ab
LS	87.5 a-c	88.1 ab	87.7 bc
HF	79.4 bc	69.4 cd	77.3 c-e
SW	83.3 bc	73.1 b-d	81.2 b-d
US	82.9 bc	76.3 b-d	81.6 b-d
SCU	87.6 a-c	81.1 bc	86.2 bc
E	90.6 ab	84.5 a-c	89.4 ab
SB	73.8 cd	68.2 cd	72.7 de
C	64.1 d	61.9 d	63.5 e

[A] *Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).*

(c) M

Source of S	Relative yield (%)			
	grain	stem + leaf	root	total
G	100.0 a^A	100.0 a	100.0 a	100.0 a
PVA	95.0 ab	95.1 a	94.5 a-c	94.9 ab
LS	94.2 a-c	93.8 ab	96.3 ab	94.1 ab
HF	85.9 cd	82.5 cd	83.3 cd	83.3 de
SW	86.3 c	84.2 cd	86.0 bcd	84.8 d
US	88.0 bc	87.0 bc	88.5 a-c	87.3 cd
SCU	93.2 a-c	93.7 ab	93.2 a-c	93.5 a-c
E	93.0 a-c	93.0 ab	92.9 a-c	93.0 a-c
SB	77.8 de	77.0 de	76.3 de	77.0 ef
C	71.6 e	73.6 e	69.7 e	72.8 f

[A] *Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).*

3.18 The effect of S sources on relative S content of plant components at different growth stages under non-flooded conditions.

(a) AT

Source of S	Relative S content (%) stem + leaf	root	total
G	100.0 a^{A}	100.0 a	100.0 a
PVA	84.9 b	74.5 b	82.1 b
LS	81.2 bc	74.2 b	79.8 bc
HF	72.5 cd	62.6 c	69.6 de
SW	73.3 cd	63.3 c	70.5 de
US	76.3 b-d	65.7 bc	73.4 c-e
SCU	75.0 b-d	64.4 bc	72.1 de
E	78.5 b-d	70.3 bc	76.3 b-d
SB	68.3 de	61.3 c	66.0 ef
C	60.9 e	64.4 bc	61.5 f

^{A} *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

(b) MT

Source of S	Relative S content (%) stem + leaf	root	total
G	100.0 a^{A}	100.0 a	100.0 a
PVA	94.0 ab	83.1 b	91.7 ab
LS	90.7 bc	76.2 bc	87.5 bc
HF	81.2 de	67.5 c	78.3 cd
SW	76.0 ef	68.8 c	74.5 de
US	83.5 c-e	70.9 c	80.8 cd
SCU	89.3 b-d	68.7 c	85.0 bc
E	88.9 b-d	73.7 bc	85.6 bc
SB	68.0 fg	65.8 c	67.5 ef
C	62.0 g	65.0 c	62.5 f

^{A} *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

(c) M

Source of S	grain	Relative S content (%) stem + leaf	root	total
G	100.0 a^{A}	100.0 a	100.0 a	100.0 a
PVA	95.6 ab	96.3 ab	92.1 ab	95.5 ab
LS	93.1 a-c	95.1 ab	89.2 bc	93.6 a-c
HF	82.9 c-e	82.8 cd	73.9 e	81.4 de
SW	84.5 b-d	87.6 b-d	77.4 de	85.0 cd
US	81.5 de	88.9 bc	76.2 de	84.8 c-e
SCU	93.4 a-c	93.6 ab	86.8 bc	92.4 a-c
E	90.3 a-d	90.6 a-c	83.5 cd	89.3 b-d
SB	71.9 ef	79.0 de	70.0 ef	75.6 ef
C	62.9 f	70.6 e	64.8 f	67.5 f

^{A} *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.19 The effect of different S sources on extractable S (ES) at different growth stages under non-flooded conditions.

Source of S	Extractable sulphate S (mg pot $^{-1}$) AT	MT	M
G	58.7 a[A]	30.2 fg	14.1 l
PVA	56.7 ab	34.2 ef	14.8 kl
LS	55.2 a-c	33.0 e-g	15.3 j-l
HF	47.4 d	31.4 e-h	17.5 i-k
SW	49.5 cd	32.8 e-g	18.0 ij
US	48.7 cd	31.1 fg	17.3 i-k
SCU	50.5 b-d	32.2 e-g	15.5 j-l
E	52.1 a-d	33.5 e-g	16.2 j-l
SB	46.5 d	29.1 g	22.3 h
C	35.2 e	19.6 hi	11.1 m

[A] *Data followed by the same letter are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.20 The effect of S sources on organic S (OS) at different growth stages under non-flooded conditions.

Source of S	AT	Organic S (mg pot $^{-1}$) MT	M
G	648.9 a[A]	622.5 a-f	611.5 b-g
PVA	643.1 ab	620.2 a-f	603.7 e-g
LS	638.5 a-c	621.5 a-f	606.8 c-g
HF	632.4 a-e	628.4 a-f	598.1 fg
SW	634.4 a-e	625.9 a-f	604.3 a-g
US	635.3 a-e	624.9 a-f	602.9 e-g
SCU	638.4 a-c	622.2 a-f	596.7 fg
E	637.7 a-d	625.5 a-f	602.1 e-g
SB	629.9 a-f	624.1 a-f	615.9 a-g
C	626.8 b-f	608.1 c-g	585.1 g

[A] *Data followed by the same letter are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.21 The residual effect of S-application rate on yield components under non-flooded conditions.

Yield component	S rate (kg ha $^{-1}$) 0	5	10	20
Number of tillers	10.7 b[A]	11.3 ab	12.0 ab	13.7 a
Number of panicles	10.0 a	10.3 a	11.0 a	12.3 a
Number of grains per panicle	20.2 a	22.8 a	24.5 a	31.0 a
Dry weight of grains per panicle (g)	0.41 a	0.46 a	0.49 a	0.63 a
Dry weight of 100 grains (g)	2.01 a	2.02 a	2.02 a	2.02 a
Percentage of empty grain (%)	15.4 a	10.8 ab	10.8 ab	9.0 b
Harvest index	0.19 a	0.21 a	0.21 a	0.25 a

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

3.22 *The residual effect of S-application rate on extractable S (ES), organic S (OS) and the recovery of fertiliser S in these fractions under non-flooded conditions.*

			Recovery of fertiliser S	
S rate (kg ha^{-1})	ES (mg pot^{-1})	OS (mg pot^{-1})	ES (%)	OS (%)
0	3.1 a[A]	394.5 a	--	--
5	3.2 a	405.7 a	0.8 a	32.0 a
10	3.4 a	408.2 a	1.4 a	36.8 a
20	4.1 a	413.8 a	2.1 a	51.3 a

[A] Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).

3.23 *The residual effects of different S sources on yield components under non-flooded conditions.*

Source of S	No. of tillers	No. of panicles	Dw. of grains panicle^{-1} (g)	Dw. of a 100 grain (g)	percentage of empty grain (%)	Harvest index
G	12.0 bc[A]	11.0 ab	0.49 a	2.02 a	10.8 b	0.21 a
PVA	12.3 a-c	11.0 ab	0.59 a	2.02 a	10.3 b	0.23 a
LS	12.7 a-c	11.3 ab	0.55 a	2.01 a	10.0 b	0.22 a
HF	13.7 ab	12.3 a	0.62 a	2.00 a	10.1 b	0.23 a
SW	13.3 a-c	11.7 ab	0.60 a	2.03 a	10.7 b	0.23 a
US	13.0 a-c	11.3 ab	0.57 a	2.03 a	11.3 b	0.22 a
SCU	12.3 a-c	11.0 a	0.63 a	2.02 a	10.2 b	0.23 a
E	12.3 a-c	11.0 ab	0.60 a	2.03 a	10.3 b	0.24 a
SB	15.0 a	13.0 a	0.65 a	2.03 a	9.0 b	0.23 a
C	10.7 c	10.0 b	0.41 a	2.01 a	15.4 a	0.19 a

[A] Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).

3.24 *The residual effects of different S sources on extractable S (ES) and organic S (OS) under non-flooded conditions.*

Source of S	ES (mg pot^{-1})	OS (mg pot^{-1})
C	3.1 c	394.5 a
G	3.4 bc[A]	408.2 a
PVA	3.6 bc	404.4 a
LS	3.5 bc	407.3 a
HF	4.4 ab	407.7 a
SW	4.0 bc	408.6 a
US	3.9 bc	405.0 a
SCU	3.8 bc	410.8 a
E	3.5 bc	403.9 a
SB	5.2 a	419.2 a

[A] Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).

4.1 Main effects and interaction terms for the clover yield occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	All	4	8	12	17	24	28	36	44	52	60	68	76	84	96	S × T
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	*	*	*	-	*	*	*	*	*	*	*	*	*	-	-	*
P	*	*	*	*	*	*	-	-	-	-	-	-	-	*	-	*
L	*	-	*	*	*	*	*	*	*	*	-	*	-	-	-	-
CS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SP	-	*	-	*	*	*	*	*	*	-	-	-	*	-	-	*
SL	*	-	-	*	-	-	*	-	-	-	-	-	-	-	-	-
PL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* = significant at 0.05.

4.2 Main effects and interaction terms for the grass yield occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	All	4	8	12	17	24	28	36	44	52	60	68	76	84	96	S × T
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	*	*	*	*	*	-	-	-	*	*	*	*	*	*	*	*
P	*	*	*	*	*	*	*	*	-	-	-	*	-	-	-	*
L	*	-	-	*	*	-	-	-	-	-	-	-	*	-	-	-
CS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SP	-	*	*	-	-	*	-	-	-	-	-	-	-	-	-	*
SL	*	-	-	*	-	-	*	-	-	-	-	-	-	-	-	-
PL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* = significant at 0.05.

4.3 Main effects and interaction terms for the pasture yield occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	All	4	8	12	17	24	28	36	44	52	60	68	76	84	96	S × T
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	*	*	*	-	*	*	*	*	*	*	*	*	*	*	*	*
P	*	*	*	*	*	*	-	-	-	-	-	-	*	-	-	*
L	*	-	*	*	*	*	*	*	*	*	*	*	*	*	-	*
CS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SP	*	*	*	-	-	*	-	*	*	-	-	*	-	-	-	-
SL	*	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-
PL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* = significant at 0.05.

4.4 The effects of S and P sources on dry weight, S content, P content, percentage of S derived from the fertiliser and the recovery of fertiliser S in root under leached and non-leached conditions.

Treatment	Dry weight (g pot $^{-1}$)	S content (mg pot $^{-1}$)	P content (mg pot $^{-1}$)	S derived from the fertiliser (%)	Recovery of fertiliser S (%)
TSP					
ENL	11.2 a[A]	12.6 a	13.7 a	11.0 ab	3.6 a
EL	10.2 ab	11.0 a-c	12.0 ab	10.2 ab	2.8 a-c
GNL	8.5 bc	9.4 a-c	11.9 ab	7.7 c	1.8 bc
GL	8.2 bc	8.1 c	9.2 cd	7.4 c	1.5 c
RP					
ENL	8.7 bc	11.5 ab	11.3 a-c	11.9 a	3.4 ab
EL	8.4 bc	10.2 a-c	11.2 bc	11.1 ab	2.9 a-c
GNL	8.1 bc	9.3 bc	10.9 bc	8.9 bc	2.1 a-c
GL	7.3 c	7.9 c	8.3 d	7.7 c	1.5 c

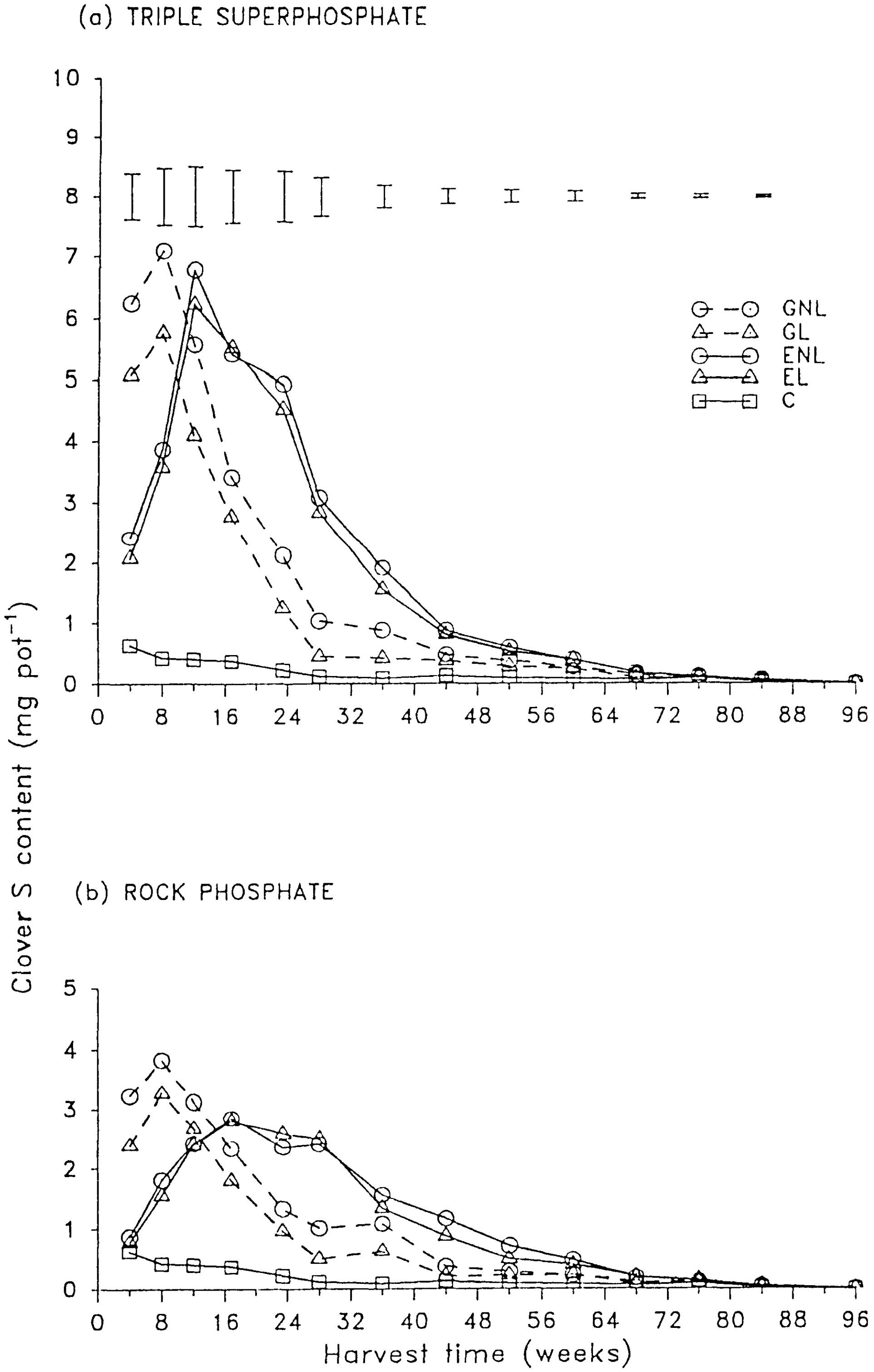
[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

4.5 Main effects and interaction terms for the clover S content occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	All	4	8	12	17	24	28	36	44	52	60	68	76	84	96	S × T
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	*	*	*	-	*	*	*	*	*	*	*	*	*	-	-	*
P	*	*	*	*	*	*	-	-	-	-	-	-	-	*	-	*
L	*	*	*	*	-	*	*	*	*	*	-	-	-	-	-	*
CS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SP	*	*	-	*	*	*	-	*	*	-	-	-	-	-	-	*
SL	*	*	-	*	-	-		-	-	-	-	-	-	-	-	-
PL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* = significant at 0.05.

4.6 The effects of S and P sources on clover S content under leached and non-leached conditions. Vertical bars indicate LSD (P = 0.05) for S x P x L interaction at each harvest.



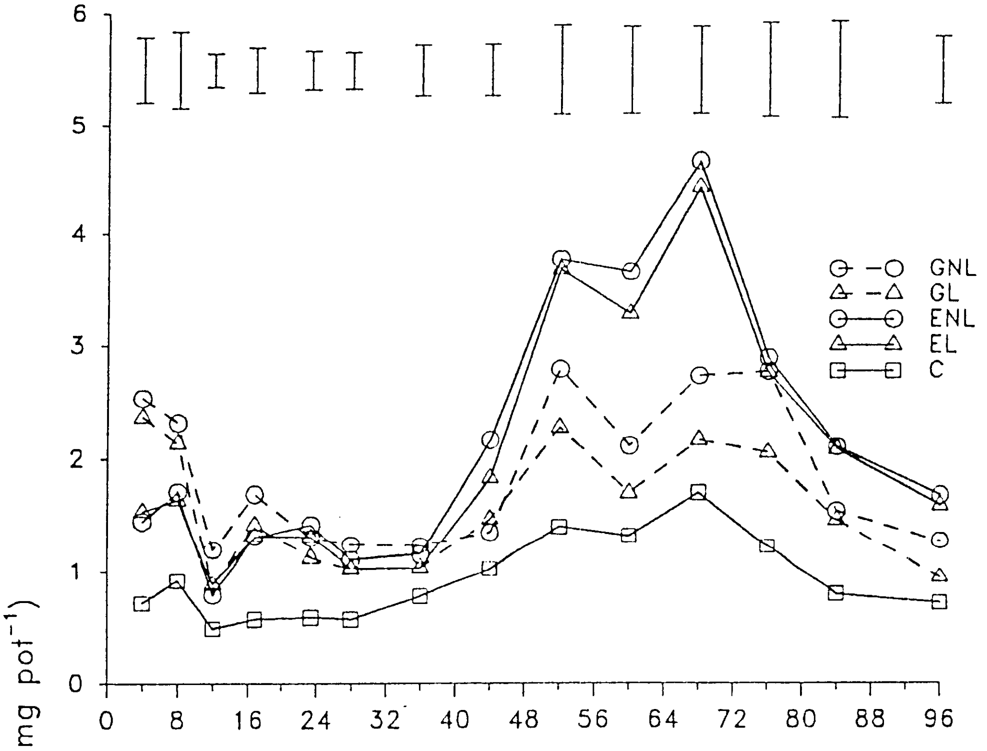
4.7 Main effects and interaction terms for the grass S content occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	All	4	8	12	17	24	28	36	44	52	60	68	76	84	96	S × T
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	*	*	*	*	*	-	-	-	*	*	*	*	*	*	*	*
P	*	*	*	*	*	-	-	-	-	-	-	*	-	-	-	*
L	*	-	-	-	-	-	-	-	-	-	-	*	-	-	*	-
CS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SP	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-
SL	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-
PL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

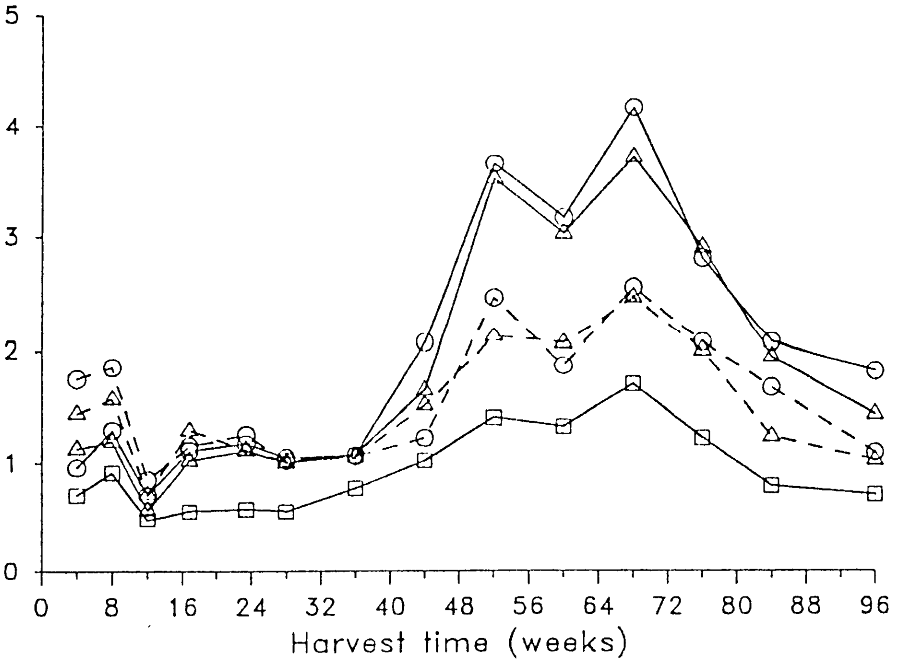
* = significant at 0.05.

4.8 The effects of S and P sources on grass S content under leached and non-leached conditions. Vertical bars indicate LSD (P = 0.05) for S x P x L interaction at each harvest.

(a) TRIPLE SUPERPHOSPHATE



(b) ROCK PHOSPHATE



4.9 Main effects and interaction terms for the pasture S content occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	All	4	8	12	17	24	28	36	44	52	60	68	76	84	96	S × T
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	*	*	*	-	*	*	*	*	*	*	*	*	*	*	*	*
P	*	*	*	*	*	*	-	-	-	-	-	-	-	-	-	*
L	*	*	*	*	-	*	*	*	*	*	-	*	-	-	*	-
CS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SP	*	*	-	*	*	*	-	-	-	-	-	-	-	-	-	*
SL	*	*	-	*	*	-	*	-	-	-	-	-	-	-	-	-
PL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* = significant at 0.05.

4.10 Main effects and interaction terms for the pasture P content occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	0 - 17	17 - 36	36 - 68	68 - 96	Total
C	-	-	-	-	-
S	*	*	*	*	*
P	*	*	*	*	*
L	*	-	-	*	*
CS	-	-	-	-	-
CP	-	-	-	-	-
CL	-	-	-	-	-
SP	-	-	*	-	*
SL	-	-	-	-	*
PL	-	-	-	-	-
CSP	-	-	-	-	-
CSL	-	-	-	-	-
CPL	-	-	-	-	-
SPL	-	-	-	-	-
CSPL	-	-	-	-	-

* = significant at 0.05.

4.11 Main effects and interaction terms for the percentage of S in pastures derived from the fertiliser occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	All	4	8	36	68	96	S × T
C	-	-	-	-	-	-	-
S	*	*	*	*	*	*	*
P	*	*	*	*	-	-	*
L	*		-	*	*	-	*
CS	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-
CL	-	-	-	-	-	-	-
SP	*	*	*	*	-	-	*
SL	-	-	-	-	-	-	*
PL	-	-	-	-	-	-	-
CSP	-	-	-	-	-	-	-
CSL	-	-	-	-	-	-	-
CPL	-	-	-	-	-	-	-
SPL	-	-	-	-	*	-	-
CSPL	-	-	-	-	-	-	-

* = significant at 0.05.

4.12 Main effects and interaction terms for the recovery of fertiliser S in pastures occurring with C, S, P and L factors when analysis was performed at each harvest.

Source	All	4	8	12	17	24	28	36	44	52	60	68	76	84	96	S × T
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
P	*	*	*	*	*	-	*	-	-	-	-	-	-	-	-	*
L	*	*	*	*	*	*	*	*	*	*	*	*	-	-	-	*
CS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SP	*	-	*	*	*	*	-	-	-	-	-	-	-	-	-	*
SL	*	*	-	*	-	*	*	-	-	-	-	-	-	-	-	*
PL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CSPL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* = significant at 0.05.

4.13 Main effects and interaction terms for the S content of leachate occurring with C, S and P factors when analysis was performed at each harvest.

Source	0 - 17	17 - 36	36 - 68	68 - 96	Total
C	-	-	-	-	-
S	*	*	-	-	*
P	*	*	-	-	-
CS	-	-	-	-	-
CP	-	-	-	-	-
SP	-	-	-	-	-
CSP	-	-	-	-	-

* = significant at 0.05

4.14 The effects of S and P sources on the S content of leachate (mg pot $^{-1}$) at each observation time.

Treatment	0 - 17	17 - 36	36 - 68	68 - 96	Total
TSP					
E	3.90 c[A]	3.30 c	4.63 a	3.88 a	15.72 b
G	8.89 a	4.30 ab	4.56 a	3.75 a	21.5 a
RP					
E	3.20 c	3.77 bc	4.96 a	4.19 a	16.11 b
G	7.79 b	4.56 a	4.73 a	3.87 a	20.95 a

[A] *Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).*

4.15 Main effects and interaction terms for the P content of leachate occurring with C, S and P factors when analysis was performed at each harvest.

Source	0 - 17	17 - 36	36 - 68	68 - 96	Total
C	-	-	-	-	-
S	-	-	-	-	-
P	*	-	-	-	*
CS	-	-	-	-	-
CP	-	-	-	-	-
SP	-	-	-	-	-
CSP	-	-	-	-	-

* = significant at 0.05.

4.16 The effects of S and P sources on the P content of leachate (mg pot $^{-1}$) at each observation time.

Treatment	0 - 17	17 - 36	36 - 68	68 - 96	Total
TSP	1.16 a^{A}	0.44 a	0.42 a	0.34 a	2.37 a
RP	0.63 b	0.45 a	0.44 a	0.39 a	1.9 b

^{A} *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

4.17 Main effects and interaction terms for the percentage of S in leachates derived from the fertiliser occurring with C, S and P factors when analysis was performed at each harvest.

Source	All	4	8	36	68	96	S × T
C	-	-	-	-	-	-	-
S	*	*	*	*	*	*	*
P	*	*	-	-	-	-	*
CS	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-
SP	*	*	-	-	*	-	*
CSP	-	-	-	-	-	-	-

* = significant at 0.05.

4.18 Main effects and interaction terms for the recovery of fertiliser S in leachates occurring with C, S and P factors when analysis was performed at each harvest.

Source	All	4	8	12	17	24	28	36	44	52	60	68	76	84	96	S × T
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	*	*	*	*	*	-	-	-	-	-	-	-	-	-	-	*
P	*	*	*	*	-	-	-	-	-	-	-	-	-	-	-	*
CS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SP	-	*	-	*	-	-	-	-	-	-	-	-	-	-	-	*
CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* = significant at 0.05.

4.19 The effects of S and P sources on extractable S (ES), organic S (OS), percentage of S derived from the fertiliser and the recovery of the fertiliser S in these fractions under leached and non-leached conditions.

Treatment	ES (mg pot $^{-1}$)	S derived from the fertiliser (%)	Recovery of the fertiliser S (%)	OS (mg pot $^{-1}$)	S derived from the fertiliser (%)	Recovery of the fertiliser S (%)
TSP						
ENL	17.4 a[A]	16.0 a	6.8 a	199.6 a	5.2 b	25.3 c
EL	16.7 a	13.1 a	5.6 a	178.8 a	3.1 c	13.6 d
GNL	13.5 a	13.9 a	5.6 a	204.8 a	4.9 b	24.3 c
GL	13.2 a	12.8 a	4.4 a	153.9 a	2.8 c	10.2 e
RP						
ENL	19.1 a	14.2 a	6.6 a	191.7 a	11.2 a	50.8 a
EL	15.4 a	11.7 a	4.6 a	148.0 a	10.2 a	36.7 b
GNL	15.2 a	12.2 a	4.7 a	175.3 a	11.2 a	47.7 a
GL	14.9 a	12.1 a	4.7 a	189.7 a	6.7 b	31.0 b

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

4.20 The effects of S and P sources on total P content (mg pot $^{-1}$) of soil under leached and non-leached conditions.

Treatment	Total P (mg pot $^{-1}$)
TSP	
ENL	242.8 a[A]
EL	217.6 a
GNL	248.0 a
GL	207.0 a
RP	
ENL	231.7 a
EL	200.0 a
GNL	230.8 a
GL	213.2 a

[A] *Data followed by the same letter in the same column are not significantly different ($P < 0.05$) (Duncan's multiple range test).*

4.21 The effects of different S sources on extractable S (ES), organic S (OS), percentage of S derived from the fertiliser and recovery of the fertiliser S in these fractions.

Treatment	ES (mg pot $^{-1}$)	S derived from the fertiliser (%)	Recovery of the fertiliser S (%)	OS (mg pot $^{-1}$)	S derived from the fertiliser (%)	Recovery of the fertiliser S (%)
G	12.6 a[A]	13.4 a	4.2 b	212.9 a	4.7 a	25.0 a
PVA	16.3 a	15.6 a	5.7 ab	212.2 a	4.9 a	24.9 a
SW	18.8 a	16.1 a	7.1 ab	229.2 a	5.6 a	32.0 a
HF	20.9 a	16.5 a	8.7 a	228.1 a	5.8 a	33.5 a
LS	17.6 a	12.5 a	5.3 ab	226.3 a	4.5 a	25.3 a
C	14.5 a	-	-	164.2 a	-	-

[A] *Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).*

4.22 The effect of different S sources on total P content (mg pot $^{-1}$) of soil.

Treatment	Total P (mg pot $^{-1}$)
G	258.9 a[A]
PVA	258.2 a
SW	262.8 a
HF	267.0 a
LS	237.8 a
C	199.8 a

[A] *Data followed by the same letter in the same column are not significantly different (P < 0.05) (Duncan's multiple range test).*