CHAPTER IV

FIELD EXPERIMENTS WITH SULPHUR 35-LABELLED
GYPSUM FERTILIZER (SECOND SERIES 1972-74)

1. INTRODUCTION

The overall objective of these experiments was to confirm the results obtained in CHAPTER III by repeating the investigations at two of the seven soil-pasture systems studied previously.

Initially it was intended to apply radioactive gypsum at the same time (early September) of the year as in CHAPTER III. Delays in transportation of the radioactive gypsum from the U.S.A. prevented fertilizer application until the beginning of November. Hence, a direct comparison with results from the previous year was not possible.

At each trial, specific objectives were similar to those listed in CHAPTER III. However, additional specific objectives were investigated and these include a more detailed study of the effect of fertilizer S application on levels of S in plant roots and the influence of using a lower rate of radioactive S\(^{35}\)-labelled gypsum fertilizer on the fate of fertilizer S in soils.
2. MATERIALS AND METHODS.

(1) SITE SELECTION.

Two of the seven SITES used in CHAPTER III, were selected for the experiments described in this CHAPTER (i.e. SITES II and IV).

At SITE II (improved Kowai sandy loam) grass grub damage of pasture prevented the establishment of an adjacent trial. The trial SITE was therefore relocated in an adjoining paddock with a similar history to that of SITE II, but without any evidence of grass grub infestation. At SITE IV (improved Gorge silt loam), a new trial location was established in an adjacent position and this was designated SITE VIII, as distinct from SITE IX, on the improved Kowai sandy loam.

(2) TRIAL DESIGN AND OPERATION (1972).

The trial design at SITES VIII and IX, included five treatments in a randomized complete block layout of four replicates.

Treatments S0, S1 and S2 corresponded to the following S application rates of 0, 22.5 and 45.0 kgS/ha. Treatments S3 and S4 were selected to assess the effect of fertilizer S on root S levels. Treatment S3 was the control plot and treatment S4, like S3, received 45.0 kgS/ha.

Each main plot was 2 m x 2 m containing a subplot (1 m x 1 m) located centrally within the mainplot.
Trial SITE preparation was identical to that outlined previously in CHAPTER III.

(a) Fertilizer Application. On 31 October 1972, agricultural gypsum (non-labelled) was spread by hand on each of the S1, S2 and S4 mainplot treatments, with the exception of their respective subplots. In the same manner as outlined in CHAPTER III, agricultural gypsum was then applied to the subplots of the S4 treatment and to the subplots on two replicates of the S1 treatment.

(i) Application of Radioactive Gypsum: Radioactive gypsum was obtained from T.V.A. (U.S.A.) and applied (1/11/72) to the subplots of the two remaining replicates of the S1 treatment and all subplots of the S2 treatment. The rate used was similar to that of the non-labelled S applied to the remainder of the mainplot.

The method of fertilizer application was similar to that described in CHAPTER III.

The amount of radioactivity applied was 5.2 mc/m² on the S1 treatment and 10.4 mc on the S2 treatment. The radioactivity of S applied was 5120 disintegrations / minute (d.p.m)/microgramme (µg) compared with 4030 d.p.m./µg applied in CHAPTER III. Originally, it was planned to apply 15-20 mc/m² on the S2 treatment, but transportation and preparation delays resulted in a reduced level of radioactivity at application time.
(ii) Basal Topdressing: A basal topdressing of calcium mono-phosphate was applied at the rate of 20 kgP/ha to each trial. At SITE VIII, potassium chloride (100 kg/ha) was applied as a basal topdressing after every second harvest.

(b) Herbage Sampling for Yield Determination and Chemical Analyses. Only the subplot of each mainplot was harvested for yield determinations. Pasture was cut in each subplot with hand clippers and subsampled for dissection and dry matter analyses. The dissected grass and clover components of the S0, S1 and S2 treatments were used for chemical analyses. After subplot harvesting, the trial SITE was trimmed with a rotary motor mower, and all clippings were removed and discarded from the trial area.

On D37, D182 and D357 (20/9/73), six root core samples (4.3 cm diameter x 20 cm depth) were taken from the subplot of the S3 and S4 treatments of each trial. One root core of similar dimensions as above was also taken from the subplot of the S0 and S2 treatment. After sampling, cores were divided into a 0-10 cm and 10-20 cm depth.

After removing the stubble, root extraction procedures were similar to that described in CHAPTER III. The 0-10 cm core sample from the subplot of the S2 treatment was dissected into grass and clover roots.

To assess labelled S uptake in the root system of the S2 treatment (45.0 kgS/ha as labelled gypsum), the root weights as determined for the S4 treatment (45.0 kgS/ha as non-labelled gypsum) were used.

Sample preparation of both pasture and root plant material for chemical analyses was similar to the method outlined in CHAPTER III.
(c) **Soil Sampling.** Soil sampling, carried out at each pasture sampling, was confined to the S0 and S2 subplots and the two radio-active subplots of the S1 treatment.

At each sampling, four soil cores (2.5 cm diameter) were taken from each subplot at 10 cm intervals. At D37, D146, D182 and D323 soil sampling was carried out to a depth of 100 cm (40 cm deeper than at similar SITES in CHAPTER III). Strengthened soil samples were constructed for this purpose. At other soil sampling times, soil sampling was terminated at 30 cm. The upper 0-10 cm depth was divided into a 0-5 and 5-10 cm depth. Other soil sampling procedures were similar to that described in CHAPTER III.

(d) **Chemical Analyses of Pasture, Roots and Soil Samples.** Similar chemical analytical procedures were used as in CHAPTER III. An additional chemical measurement, to those listed, was hydriodic acid (HI)-reducible S determination on clover and grass root samples from the D182 and D357 samplings. Essentially, the technique is similar to total S determination except that plant material is unignited and introduced directly to the digestion flask. This fraction is considered to be mainly free $\text{SO}_4^-\text{S}$ and ester-bound $\text{SO}_4^-\text{S}$ (Beatson *et al.*, 1968).

An attempt was made to keep the number of analytical samples to a minimum. When soil sampling was done to a depth of 100 cm, only samples from one replicate were analysed for labelled $\text{SO}_4^-\text{S}$ (p.e.). From these results the depth of labelled S penetration was determined. Subsequently,
soil samples from the remaining replicates containing labelled S were analysed. Additionally, soil samples from depths greater than 20 cm on the S1 and S2 radioactive subplots were analysed for labelled $\text{SO}_4^-\text{S}$ (p.e.) only. At these depths total labelled S was assumed to be the same as labelled $\text{SO}_4^-\text{S}$ (p.e.).

(e) **Determination of Soil Physical Properties.** Similar measurements were made as in CHAPTER III. Data obtained from textural determinations made in CHAPTER III for SITES II and IV were used respectively for SITES IX and VIII. The amount of water percolation was estimated at SITES VIII and IX, assuming a rooting zone of 60 cm as in CHAPTER III.

(3) **TRIAL DESIGN AND OPERATION (1973).**

As in the experiments of CHAPTER III, the experiments laid down in 1972 and described in this CHAPTER were also extended for another year.

On 21 October 1973, treatments S1 and S2 were retopdressed with agricultural gypsum at the original application rates. Each mainplot of treatment S1 and S2 was divided in half and one half randomly selected for retopdressing. The retopdressed treatments were designated as S1+ and S2+ in comparison to the non-retopdressed treatments (S1- and S2-). The divided subplots were also topdressed separately as described in CHAPTER III. Yield measurements of the S3 and S4 treatments were discontinued on 24 October 1973.

Basal topdressing was identical to that used the previous year.
(a) Herbage and Soil Sampling (1973-74). On treatments S0, S1 and S2, herbage was harvested with hand clippers from the non-retop-dressed (-) and retopdressed (+) areas of each mainplot subplot. Subsamples were also taken for dissection and dry matter analyses. The clover and grass components of the dissected samples from the S0 and S1 and S2 treatments, both non-retopdressed (-) and topdressed (+), were used for chemical analyses.

(b) Herbage and Soil Chemical Analyses. Chemical analyses of pasture were similar to those used in 1972-73. Up to D406 non-labelled and labelled S\textsubscript{4}\textsuperscript{-}S (p.e.) was determined on soil samples from the S0 and S2 treatments. Sulphate -S (p.e.) determinations on the S1 treatment were terminated at D323. Total sulphur (S\textsuperscript{32} and S\textsuperscript{35}) was determined on soil samples from the S2 treatment up to D406 and ceased on the S1 treatment at D323.
3. RESULTS AND DISCUSSION.

(1) PASTURE AND ROOT RESPONSES TO SULPHUR APPLICATION.

Response patterns for total pasture and clover dry matter yields during 1972-73 and 1973-74 are shown in TABLES 24 and 25.

Dry matter yields (total pasture and clover) for each treatment and each harvest are in APPENDIX XI, TABLES 1 and 2, along with their statistical analyses. Second year (1973-74) yield data are presented in APPENDIX XII, TABLES 1 and 2, along with their statistical analyses.

Total yield results for 1973-74 (TABLE 24a) showed that significant S responses were measured at only SITE IX (Kowai sandy loam). At this SITE, the yield difference for total pasture measured between the 22.5 kgS/ha treatment and the 45.0 kgS/ha treatment, was not significant. On the other hand, total clover yield data for 1972-73 showed a significant yield increase between these two S treatments (TABLE 25).

Sulphur response patterns obtained at SITES VIII and IX are similar to those recorded in 1971-72 for their counterpart SITES (i.e. SITES IV and II, see TABLES 4 and 5).

In 1973-74, SITE VIII (Gorge silt loam) remained non-S responsive, with SITE IX (Kowai sandy loam) continuing to give a large S response. At SITE IX retopdressing of the original S1 (22.5 kgS/ha) and S2 (45.0 kgS/ha)
Mean Total Pasture and Clover Dry Matter Yields at SITES VIII and IX in 1972-73. Mean Root Dry Matter Yields at SITES VIII and IX at Different Sampling Times (1972-73).

(a) Mean Total Pasture and Clover Dry Matter Yields (kg/ha).

<table>
<thead>
<tr>
<th>SITE</th>
<th>Pasture Yield</th>
<th></th>
<th>Clover Yield</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VIII</td>
<td>IX</td>
<td>VIII</td>
<td>IX</td>
</tr>
<tr>
<td>Total Number of Harvests</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Treatment S0 (Control)</td>
<td>8740</td>
<td>6124</td>
<td>3305</td>
<td>1926</td>
</tr>
<tr>
<td>Treatment S1 (22.5 kgS/ha)</td>
<td>9152</td>
<td>7294</td>
<td>3708</td>
<td>2537</td>
</tr>
<tr>
<td>Treatment S2 (45.0 kgS/ha)</td>
<td>9476</td>
<td>7704</td>
<td>4098</td>
<td>3865</td>
</tr>
<tr>
<td>Treatment S3 (Control)</td>
<td>8707</td>
<td>6421</td>
<td>3712</td>
<td>1857</td>
</tr>
<tr>
<td>Treatment S4 (45.0 kgS/ha)</td>
<td>9015</td>
<td>7136</td>
<td>3392</td>
<td>2636</td>
</tr>
<tr>
<td>F&lt;sub&gt;4,12&lt;/sub&gt; Calculated</td>
<td>1.0</td>
<td>11.8**</td>
<td>1.1</td>
<td>9.6**</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td>-</td>
<td>583</td>
<td>-</td>
<td>802</td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td>-</td>
<td>817</td>
<td>-</td>
<td>1124</td>
</tr>
<tr>
<td>C.V. %</td>
<td>7.1</td>
<td>5.5</td>
<td>16.5</td>
<td>20.3</td>
</tr>
</tbody>
</table>

F<sub>4,12</sub> required ** 1% = 5.41

5% = 3.26

L.S.D. Least Significant Difference

C.V. Coefficient of Variation
(b) Mean Total Root Dry Matter Yields (kg/ha) in the 0-20 cm Soil Depth.

<table>
<thead>
<tr>
<th>SITE</th>
<th>VIII</th>
<th>IX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 37</td>
<td>Day 37</td>
</tr>
<tr>
<td></td>
<td>Day 182</td>
<td>Day 182</td>
</tr>
<tr>
<td></td>
<td>Day 357</td>
<td>Day 357</td>
</tr>
<tr>
<td>Treatment S3 (Control)</td>
<td>3695</td>
<td>5407</td>
</tr>
<tr>
<td></td>
<td>2603</td>
<td>6670</td>
</tr>
<tr>
<td>Treatment S4 (45.0 kgS/ha)</td>
<td>4828</td>
<td>4645</td>
</tr>
<tr>
<td></td>
<td>2627</td>
<td>6115</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td>367</td>
<td>650</td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td>515</td>
<td>911</td>
</tr>
</tbody>
</table>

L.S.D. Least Significant Difference between sampling times.
TABLE 25

Mean Total Pasture and Clover Dry Matter Yields (kg/ha) at SITES VIII and IX in 1973-74.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Pasture Yield</th>
<th>Clover Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VIII</td>
<td>IX</td>
</tr>
<tr>
<td>Total Number of Harvests</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Treatment S0 (Control)</td>
<td>8802</td>
<td>7188</td>
</tr>
<tr>
<td>Treatment S1 (22.5 kgS/ha)</td>
<td>8678</td>
<td>8518</td>
</tr>
<tr>
<td>Treatment S2 (45.0 kgS/ha)</td>
<td>8936</td>
<td>8813</td>
</tr>
<tr>
<td>++ $F_{2,6}$ calculated</td>
<td>0.2</td>
<td>7.3*</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td>-</td>
<td>1112</td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td>-</td>
<td>1686</td>
</tr>
<tr>
<td>C.V. %</td>
<td>8.4</td>
<td>11.1</td>
</tr>
</tbody>
</table>

+ Mainplot treatments i.e. S2 = 45 kgS/ha in 1972-73 and 45 kgS/ha on half the original plot in 1973-74.

++ $F_{2,6}$ required ** 1% = 10.92
** 5% = 5.14

L.S.D. Least Significant Difference
treatments gave no additional yield increases for either total pasture or clover yields (TABLE 26). In contrast, its counterpart trial (SITE II) when retopdressed in 1972-73 gave a large response to retopdressing on both the original 22.5 kgS/ha and 45.0 kgS/ha treatments (TABLE 9).

In the first series of experiments (1971-73) grass grub infestation of SITE II occurred and was considered to contribute to the S retopdressing responses in 1972-73. At SITE IX no grass grub infestation occurred in the year of retopdressing and this may have predisposed to the lack of S responses by allowing greater root exploitation of the soil.

Other possible reasons for the difference in second year retopdressing results between SITES II and IX are discussed in a later section with respect to "residual" fertilizer S recovery.

Root yields at the three sampling times at each SITE are shown in APPENDIX XI, TABLES 3 and 4. At each SITE, statistical analyses (split plot in time with time as the subplot treatment) revealed significant differences between times of sampling (TABLE 24b), but not between the sulphur treatments. At both SITES, significant dry matter increases in root dry matter yield were shown between the late autumn (D182) and late spring (D357) samplings. Additionally, at SITE VIII significant decreases in root weight were recorded over the summer-autumn period (D37-D182). These changes in root weights between samplings are consistent with the conclusions drawn by Baker and Garwood (1959) who found that common pasture species increase their root volume from late winter until mid summer when there is a steady decline until late winter then the cycle is repeated.
### TABLE 26

Main Effect of Retopdressing on Mean Total Pasture and Total Clover Yields (kg/ha) at SITES VIII and IX in 1973-74.

<table>
<thead>
<tr>
<th>SITE Treatment</th>
<th>Total Pasture VIII</th>
<th>Total Pasture IX</th>
<th>Total Clover VIII</th>
<th>Total Clover IX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retopdressed</td>
<td>8829</td>
<td>8536</td>
<td>3367</td>
<td>4151</td>
</tr>
<tr>
<td>Non-retopdressed</td>
<td>8786</td>
<td>8795</td>
<td>3059</td>
<td>4150</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C.V. %</td>
<td>10.5</td>
<td>8.1</td>
<td>11.1</td>
<td>6.4</td>
</tr>
</tbody>
</table>

L.S.D. Least Significant Difference  
C.V. Coefficient of Variation

### TABLE 27

Mean Total Recovery (%) of labelled Sulphur in the Pasture-Soil Systems at SITES VIII and IX by DAY 182.

(a) 22.5 kgS/ha

<table>
<thead>
<tr>
<th>SITE (a)</th>
<th>SOIL (b)</th>
<th>PASTURE (^+)</th>
<th>TOTAL ((a+b))</th>
<th>PASTURE (\text{++})</th>
<th>TOTAL ((a+c))</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII (Gorge)</td>
<td>55.1 ± 1.8</td>
<td>32.9 ± 3.2</td>
<td>88.0 ± 9.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IX (Kowai)</td>
<td>51.4 ± 8.3 (\text{+++})</td>
<td>27.6 ± 0.5</td>
<td>78.9 ± 1.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(b) 45.0 kgS/ha

| VIII (Gorge) | 68.2 ± 4.3 | 24.3 ± 0.5 | 92.5 ± 4.2 | 30.8 ± 1.2 | 99.0 ± 4.6 |
| IX (Kowai) | 64.0 ± 3.9 | 22.8 ± 1.5 | 86.9 ± 3.9 | 30.7 ± 2.4 | 94.7 ± 5.4 |

\(^+\) Harvested pasture or "above ground" herbage  
\(\text{++}\) Harvested pasture plus roots and stubble  
\(\text{+++}\) Standard error.
Of interest is the weight of roots relative to the yield of pasture at each SITE. At the S responsive SITE IX, the ratio of pasture:root yield on the S3 (control) treatment, approximates 1.2:1.0 at D182 (Autumn) while at the non-S responsive SITE VIII, on the same treatment, a ratio of 3.3:1.0 exists (TABLE 34b). This result confirms, in the field, the glasshouse findings of Spencer (1959) who showed that under S deficient conditions the root system formed a proportionately larger weight of the plant.

(2) RECOVERY OF LABELLED SULPHUR.

(a) Total Recovery from the Pasture-Soil System. Total recovery of S from S$^{35}$-labelled gypsum fertilizer was assessed from pasture and soil measurements made on the S1 and S2 treatments at D182 (early May). Results are presented in TABLE 27.

Despite yield differences between SITES VIII and IX, total recovery (%) is similar and high at both rates of S application.

When the total recovery mean values for the 45.0 kgS/ha treatment (TABLE 27b) are contrasted with those obtained from their counterpart SITES in CHAPTER III (TABLE 12), higher values are obtained for both the SITES measured in this present experiment.

In CHAPTER III, it was suggested that a portion of the fertilizer S applied in SITE II may have moved beyond the maximum depth of soil sampling (60 cm) by early May. Hence, the higher recovery of fertilizer S at SITE IX, in the present investigation, may be a result of fertilizer S
remaining entirely within the upper soil layers in early May. (See Figures 16b and 26b). However, this explanation for the difference in SITE recoveries on the Kowai sandy loam, does not account for the difference in fertilizer S recovery at SITES IV and VIII on the Gorge silt loam. At SITE IV, no fertilizer S had penetrated beyond 60 cm by early May.

In comparison with SITES II and IV, a greater amount of $^{35}$S radioactivity remained at SITES VIII and IX in early May. Hence, it is probable that fertilizer S was detected more accurately in the various soil depths of SITES VIII and IX due to the higher radioactivity of the gypsum added and subsequent less dilution effect.

The lower level of radioactivity at D182, may also explain the lower total recoveries on the S1 treatment at SITES VIII and IX in comparison with those on the S2 treatment (TABLE 27a and b).

(b) Pasture Recovery of Labelled Sulphur 1972-73. Percentage recovery of labelled S on the S1 and S2 treatments in 1972-73 at SITES VIII and IX is shown in TABLE 28.

Labelled S recovery was low, but similar, at both SITES for the two application rates. A slightly higher recovery was obtained for the pasture on the S1 treatment at both SITES (TABLE 28a).

In spite of a shorter harvest period in 1972-73, the extent of labelled S recovery on the S2 treatment (45.0 kgS/ha) of SITES IX and
<table>
<thead>
<tr>
<th>SITE</th>
<th>1972-73 (a)</th>
<th>1973-74 (b)</th>
<th>1973-74++</th>
<th>1972-74 (a + b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII (Gorge)</td>
<td>32.9 ± 3.2+++</td>
<td>8.0 ± 0.3</td>
<td>5.1 ± 1.1</td>
<td>39.9 ± 4.5</td>
</tr>
<tr>
<td>IX (Kowai)</td>
<td>27.6 ± 0.5</td>
<td>7.6 ± 0.1</td>
<td>7.2 ± 0.6</td>
<td>35.1 ± 0.8</td>
</tr>
</tbody>
</table>

(b) S2 (45.0 kgS/ha) Treatment

<table>
<thead>
<tr>
<th>SITE</th>
<th>1972-73 (a)</th>
<th>1973-74 (b)</th>
<th>1973-74++</th>
<th>1972-74 (a + b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII (Gorge)</td>
<td>24.3 ± 0.5</td>
<td>8.3 ± 0.3</td>
<td>6.9 ± 0.4</td>
<td>32.6 ± 0.5</td>
</tr>
<tr>
<td>IX (Kowai)</td>
<td>22.8 ± 1.5</td>
<td>8.4 ± 0.2</td>
<td>7.9 ± 0.4</td>
<td>31.2 ± 1.5</td>
</tr>
</tbody>
</table>

+ Non-retopdressed treatment
++ Retopdressed treatment
+++ Standard error.
VIII was similar to labelled S uptake measured on the same treatment in their counterpart trials at SITES II and IV (TABLE 13) in 1971-72.

As at SITES II and IV in CHAPTER III, labelled S comprised a relatively large proportion (Figure 21) of the total S uptake in the first year on SITE VIII (37%) and SITE IX (50%). The grass component recovered a greater proportion of labelled S than the clover component. The higher recovery of labelled S by grasses at each SITE was a result of both its higher dry matter yield and its overall higher concentration of labelled S (Figure 22) at most harvests. The higher content of labelled S in grasses is a reflection of its higher total S concentration as, during 1972-73, clover specific activities were significantly higher than that for grasses (Figure 22).

The general pattern of labelled S uptake at each SITE is shown in Figure 21. At both SITES, most of the total labelled S uptake had occurred by D76.

(i) Plant Recovery of Labelled Sulphur in Relation to S Uptake Zones in the Soil: As indicated earlier, during the first year (up to D182) the clover component of pastures had a higher S.A. than the grass component, at both SITES. This indicates that the relative amounts of S taken up from various soil zones varied between species as specific activities of $S_{4}$-$S$ (p.e.) were found to increase with depth (APPENDIX XV, TABLES 3 and 4).

For each SITE, the S.A. for both grass and clovers is plotted over time (up to D406) against the S.A. of the soil $S_{4}$-$S$ (p.e.) found
Figure 21 Cumulative Labelled and Non-Labelled Pasture Sulphur Uptake (1972-73) on the S2 (45.0 kgS/ha) Treatment Subplot at SITES VIII and IX.

(i) improved
Figure 22. Total Sulphur (T.S.) and Labelled Sulphur (L.S.) Content of Grasses and Clovers on the S2 (45.0 kgS/ha) Treatment Subplot and Sulphur Specific Activity (S.A.) of Grasses and Clovers on the S2 and S1 (22.5 kgS/ha) Treatment Subplot at SITES VIII and IX (1972-74).

** highly significant 1% (Paired T-test)
* significant 5%
(i) improved
Figure 22 continued
in the 0-10 and 0-30 cm depths (Figure 23). Linear regression analyses of these data (APPENDIX XVII, TABLE 3) are shown in TABLE 29. All regressions were very highly significant.

Consideration of data in Figure 23 for the first year (DO - 182) only, shows that at SITE VIII both clover and grass specific activities appear to be related more closely to that in the 0-30 cm depth which suggests that this is the major uptake zone.

At SITE IX the same relationship holds for clover but not for grasses. The grass S.A. relates more to that in the S0 -S (p.e.) in the 0-10 cm depth. This suggests that at this SITE the uptake zone of grasses and clovers may differ. However, at this SITE, Brash (1973) found that pasture roots penetrated to 100 cm. It is therefore possible that grasses may take up S from depths greater than 10 cm. Thus the S.A. of grasses during the first year at SITE IX may be an integrated value over a considerable depth. This value may approximate the 0-10 cm S.A.

These major uptake zones, as defined by S.A. relationships, are confirmed by the results from concurrent field experiments described in CHAPTER V. Results from experiments described in CHAPTER V show that where soil uptake zones were determined specifically at both SITES VIII and IX, the major S uptake zone of pasture plants was confined to the upper 30 cm or A horizon at both SITES.

(ii) Comparison of Actual and "Apparent" Recovery: Apparent recovery of labelled S was calculated for each harvest, and all harvests combined, as the difference in pasture S uptake between the S2 and S0 treatments for each SITE in the first year. Actual labelled S recovery
Figure 23 Specific Activity of Clover and Grass Sulphur in Relation to the Specific Activity of Sulphate Sulphur (p.e.) in Various Soil Depths on the S2 (45.0 kgS/ha) Treatment Subplot at SITES VIII and IX (1972-73).
(i) improved
### TABLE 29

Relationship Between the Specific Activity\(^+\) (Y) of Sulphur in Grasses and Clovers and the Specific Activity(X) of Soil Sulphate Sulphur (p.e.) at Selected Soil Depths on SITES VIII and IX (1972-73).

<table>
<thead>
<tr>
<th>SITE Soil Depths (cm)</th>
<th>Pasture Species</th>
<th>Linear Regression Equation</th>
<th>Coefficient of Determination (R^2)</th>
<th>Coefficient of Correlation (r)</th>
<th>Level of Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 - 10</td>
<td>Grasses</td>
<td>(Y = 722.4 + 0.39X)</td>
<td>0.61</td>
<td>0.78</td>
<td>***</td>
</tr>
<tr>
<td>0 - 30</td>
<td>Grasses</td>
<td>(Y = 376.2 + 0.71X)</td>
<td>0.59</td>
<td>0.77</td>
<td>***</td>
</tr>
<tr>
<td>0 - 10</td>
<td>Clovers</td>
<td>(Y = 801.9 + 0.50X)</td>
<td>0.77</td>
<td>0.88</td>
<td>***</td>
</tr>
<tr>
<td>0 - 30</td>
<td>Clovers</td>
<td>(Y = 237.1 + 0.98X)</td>
<td>0.66</td>
<td>0.82</td>
<td>***</td>
</tr>
<tr>
<td>IX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 - 10</td>
<td>Grasses</td>
<td>(Y = 1169.3 + 0.35X)</td>
<td>0.54</td>
<td>0.74</td>
<td>***</td>
</tr>
<tr>
<td>0 - 30</td>
<td>Grasses</td>
<td>(Y = 843.0 + 0.43X)</td>
<td>0.69</td>
<td>0.83</td>
<td>***</td>
</tr>
<tr>
<td>0 - 10</td>
<td>Clovers</td>
<td>(Y = 947.1 + 0.67XX)</td>
<td>0.82</td>
<td>0.91</td>
<td>***</td>
</tr>
<tr>
<td>0 - 30</td>
<td>Clovers</td>
<td>(Y = 495.6 + 0.76X)</td>
<td>0.85</td>
<td>0.92</td>
<td>***</td>
</tr>
</tbody>
</table>

*** very highly significant (0.1%)

+ Specific Activity in disintegrations/minute/µgS.
was determined from the S2 treatment using the \( {\text{S}}^{35} \) measurements and treatment yield. Results for each method and for the first and combined first year harvests are presented in APPENDIX XVII, TABLE 1.

Mean results for each SITE are shown in TABLE 30. Significant differences were measured between the two methods at SITE VIII (Gorge silt loam) for both first harvest data and all harvests combined. These results from the first harvest data at this SITE, are similar to those determined at the counterpart SITE IV in the previous year (TABLE 18). In both years, recovery was less using the "apparent" recovery method.

The lack of significant differences at SITE IX (Kowai sandy loam) agrees with those obtained at SITE II in 1971-72 (TABLE 18).

In TABLE 31, the effect of fertilizer S addition on plant uptake of non-labelled S ("priming") has been assessed at both SITES VIII and IX for first harvest and all harvests combined. A negative "priming" effect at SITE VIII on the S2 treatment (TABLE 31) may explain the lower recovery calculated by the "apparent" recovery method at this SITE (TABLE 30). However, at SITE IX for the first harvest a similar negative "priming" effect (TABLE 31) did not lead to a lower recovery using the "apparent" recovery method (TABLE 30).

When "priming" effects are considered in the soil (TABLE 32) with respect to the "priming" effects in the plant (TABLE 31), no relationship is found. On the other hand if only non-labelled \( \text{SO}_4 \text{-S} \) (p.e.) at the 0-10 cm depth (Figure 24) is considered, both SITES VIII and IX show large positive "priming" effects at all samplings in the first year. Therefore these results show that a positive "priming" as found in the soil need not necessarily lead to a positive "priming" effect in the pasture. A likely
### TABLE 30

Actual and "Apparent" Mean Recovery of Labelled Sulphur by Pasture at SITES VIII and IX (1972-73).

(a) First Harvest

<table>
<thead>
<tr>
<th>SITE</th>
<th>Actual</th>
<th>&quot;Apparent&quot;</th>
<th>Level of Significance (T-test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII</td>
<td>$462 \pm 10^{+}$</td>
<td>$305 \pm 49$</td>
<td>*</td>
</tr>
<tr>
<td>IX</td>
<td>$485 \pm 31$</td>
<td>$392 \pm 83$</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

(b) Combined Harvests

<table>
<thead>
<tr>
<th>SITE</th>
<th>Treatment</th>
<th>Level of Significance (T-test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII</td>
<td>S0 (Control)</td>
<td>S2 (450kgS/ha)</td>
</tr>
<tr>
<td>VIII</td>
<td>783</td>
<td>627</td>
</tr>
<tr>
<td>IX</td>
<td>551</td>
<td>458</td>
</tr>
</tbody>
</table>

+ mgS/m$^2$ n.s. = not significant
++ Standard error * significant (5%)

### TABLE 31

The Effect of Fertilizer Sulphur Addition on Plant Uptake of non Labelled Sulphur at SITES VIII and IX (1972-73).

(a) First Harvest

<table>
<thead>
<tr>
<th>SITE</th>
<th>Treatment</th>
<th>Level of Significance (T-test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII</td>
<td>S0 (Control)</td>
<td>S2 (450kgS/ha)</td>
</tr>
<tr>
<td>VIII</td>
<td>2091</td>
<td>1850</td>
</tr>
<tr>
<td>IX</td>
<td>1028</td>
<td>922</td>
</tr>
</tbody>
</table>

+ mgS/m$^2$ n.s. not significant
* significant (5%)
**TABLE 32**

The Effect of Fertilizer Sulphur Addition on Soil Levels of Non-Labelled Sulphate Sulphur (p.e.) at First Sampling on SITES VIII and IX.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Treatment</th>
<th>Level of Significance (T-test)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SO (Control)</td>
<td>S2 (45.0kgS/ha)</td>
</tr>
<tr>
<td>VIII</td>
<td>10 659+</td>
<td>10 958</td>
</tr>
<tr>
<td>IX</td>
<td>1.275</td>
<td>1.071</td>
</tr>
</tbody>
</table>

+ mgS/m² to 40 cm  
n.s. not significant.

**TABLE 33**


<table>
<thead>
<tr>
<th>SOIL</th>
<th>SOIL DEPTH (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - 10</td>
</tr>
<tr>
<td>Kowai Sandy Loam</td>
<td></td>
</tr>
<tr>
<td>SITE II (1972-73)</td>
<td>38+</td>
</tr>
<tr>
<td>SITE IX (1973-74)</td>
<td>104</td>
</tr>
<tr>
<td>Gorge Silt Loam</td>
<td></td>
</tr>
<tr>
<td>SITE IV (1972-73)</td>
<td>88</td>
</tr>
<tr>
<td>SITE VIII (1973-74)</td>
<td>275</td>
</tr>
</tbody>
</table>

+ mgS/m²  
++ 22.5 cm at SITES II and IV.
Figure 24  Non-Labelled Sulphate Sulphur (p.e.) in the 0-10 cm Soil Depth of the S0 (control) S1 (22.5 kgS/ha) and S2 (45.0 kgS/ha) Treatment Subplots at SITES VIII and IX (1972-73).

** highly significant (1%) (T-test S0 versus S2)
* significant (5%)
(i) improved
explanation is that plants do not take up S from the same depths where soil "priming" effects were measured.

(c)"Residual"Recovery of Labelled Sulphur by Pasture in 1973-74. In the absence of retopdressing, the "residual" recovery of fertilizer S applied in 1972 was similar at both SITES VIII and IX and comprised approximately 30% of that recovered the previous year (TABLE 28).

A large difference exists when the extent of the "residual" recovery at these SITES, is compared with those of their counterpart SITES II and IV in 1972-73 (TABLE 13). This difference was about three times as large. At SITE IX (Kowai soil), the extent of "residual" recovery of fertilizer S was sufficient to prevent a S response occurring. At SITE II, in the previous trial, retopdressing responses occurred. Possible reasons for the differences in "residual" effects are considered.

The mean amounts of fertilizer S, as $S\textsubscript{4}\text{O}_4$-S (p.e.), in the soils at the commencement of retopdressing in the two years is shown in TABLE 33. Clearly, at any of the depths assessed, higher levels of fertilizer S exist in a plant available form at SITES VIII and IX. Hence, the higher "residual" recovery at SITES VIII and IX may be the direct result of these differences, particularly in the upper 30 cm where the major zone of plant S uptake is considered to occur. The close relationship (Figure 23) between the S.A. of plant S and the S.A. of soil $S\textsubscript{4}\text{O}_4$-S (p.e.) to 30 cm after D323 supports this viewpoint.

Whether the higher "residual" recovery of fertilizer S at SITES VIII and IX is due also to greater remobilization of fertilizer S from root and stubble reserves cannot be assessed satisfactorily. Root and stubble fertilizer S contents were not assessed beyond late autumn at SITES II and IV and were discontinued after the first harvest in the spring of 1973-74 at SITES VII and IX. No consistent increase is seen in root fertilizer S
levels (TABLE 34) at SITES VIII and IX, when the mean amounts of fertilizer S, prior to winter (D182), are compared with those at a similar time (D240) for SITES II and IV (TABLE 17). However, a similar comparison for the S in the stubble shows that a higher level of fertilizer S was measured in the stubble component of pastures at SITES VIII and IX (TABLE 17 and TABLE 34). The fertilizer S content of stubble at D357 (late spring) shows a decrease over that at D182, hence suggesting that some remobilization of labelled S may have also contributed to the higher "residual" recovery of fertilizer S in the 1973-74 trials at SITES VIII and IX (TABLE 34).

(ii) The Effect of Retopdressing on Labelled S Uptake: Labelled S uptake was calculated for the S2- and S2+ treatment for each harvest in 1973-74. Results are presented in APPENDIX XIV. Cumulative mean recoveries are shown in Figure 25. Mean recoveries for 1973-74 are shown in TABLE 28.

On both SITES VIII and IX, retopdressing has not significantly reduced labelled S uptake. This result is consistent with the effect of retopdressing on labelled S uptake obtained for the counterpart SITES II and IV in 1972-73.

(d) Root Recovery of Labelled Sulphur (1972-73). By D182 (Autumn), labelled S recovery (actual recovery) by the root system at each SITE, comprised a very small proportion of the total fertilizer S applied (see TABLE 34a). At SITES VIII and IX, only 2.5% and 4.6% of the fertilizer S applied respectively, was measured in the root system. Nevertheless, fertilizer S still comprised a significant proportion (about 25%) of the total S present in the root systems at each SITE. Over half the fertilizer S was in the clover component of the root system by D182 (Figure 21). However, at SITE IX, an earlier root sampling at D37, showed that the fertilizer S present in clover roots comprised only a small proportion of the total fertilizer S content (Figure 21). This
Figure 25  Cumulative Labelled and Non-Labelled Pasture Sulphur Uptake (1972-74) on the Non-Retopressed (S3-) and Retopressed S3+) Subplots of the S3 (45.0 kgS/ha) Treatment at SITES VIII and IX.

(a) SITE VIII-Gorge(i)

(b) SITE IX-Kowai(i)

Figure 25
Cumulative Labelled and Non-Labelled Pasture Sulphur Uptake (1972-74) on the Non-Retopressed (S3-) and Retopressed S3+) Subplots of the S3 (45.0 kgS/ha) Treatment at SITES VIII and IX.

(g) grasses  (c) bluevetches

(i) improved
TABLE 34

(a) Mean Amounts of Labelled Sulphur in the Root and Stubble Components of Pasture from SITES VIII and IX at Various Sampling Times (1972-73).

<table>
<thead>
<tr>
<th>DAY</th>
<th>ROOTS (0-20 cm)</th>
<th>STUBBLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SITE VIII</td>
<td>SITE IX</td>
</tr>
<tr>
<td>37</td>
<td>n.d.</td>
<td>116⁺</td>
</tr>
<tr>
<td>182</td>
<td>113</td>
<td>206</td>
</tr>
<tr>
<td>357</td>
<td>88</td>
<td>189</td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>F₂,₆ calculated</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>C.V. 1%</td>
<td>30.1</td>
<td>40.1</td>
</tr>
<tr>
<td>F₂,₆ required</td>
<td>** 1% 10.9</td>
<td>* 5% 5.1</td>
</tr>
</tbody>
</table>

(b) Mean Ratio of Labelled Sulphur Recovery in Pasture and Roots at SITES VIII and IX by DAY 182.

<table>
<thead>
<tr>
<th>SITE</th>
<th>Pasture+++</th>
<th>Roots (0-20 cm)</th>
<th>Ratio (Pasture:Roots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIII (Gorge)</td>
<td>1273⁺</td>
<td>113</td>
<td>11.3: 1.0</td>
</tr>
<tr>
<td>IX (Kowai)</td>
<td>1175</td>
<td>206</td>
<td>5.7: 1.0</td>
</tr>
</tbody>
</table>

+++ Cumulative Labelled Sulphur Recovery by Pasture (includes stubble)

n.d. not determined (samples lost).
variation in the amounts of clover root fertilizer S is related more to the changes in clover root yield with time rather than changes in fertilizer S content (APPENDIX XIII, TABLES 3 and 4).

Of interest is the relationship between the total S concentrations of clover and grass roots (APPENDIX XIII, TABLES 3 and 4), with that in the clover and grass component of harvested pasture at similar sampling times (APPENDIX XIII, TABLES 1 and 2 for the S2 treatments). In general at most sampling times, for both SITES, the total S concentrations of harvested clover was similar to clover root S levels. On the other hand, the total S concentration in harvested grass was much higher than the S concentration in grass roots. This finding for clovers, contrasts with the glasshouse results of Nicolson (1970) who found with white clover, that the root component had a higher S concentration than the top components in the presence of adequate S.

An attempt was made to determine "apparent" recovery of fertilizer S in 1972-73 using the dry matter yield and S concentration data obtained from the S3 (control) and S4 (45.0 kgS/ha) treatments at each SITE (APPENDIX XI, TABLES 3 and 4). The results are presented in APPENDIX XVII, TABLE 1b. At each sampling, the variability between replicates was too large to contrast "apparent" with actual recovery. It is therefore concluded that to measure fertiliser S recovery in root systems, the use of S35-labelled fertiliser is essential as under improved pastoral conditions, the variability associated with yield data is large and the effect of fertilizer S addition on root levels of fertilizer S is likely to be small.
In a similar manner to that described in CHAPTER III, the ratio of fertilizer S recovered by pasture (includes stubble) to that recovered in roots is shown in TABLE 34b at D182 (Autumn). In contrast to the previous year's results at SITE IV (TABLE 14) a smaller proportion of total herbage (harvested pasture, stubble and roots) fertilizer S recovery arises from the root component at SITE VIII. As these SITES were located adjacent to one another, it can be concluded that the difference in the time of fertilizer S application has affected the contribution of roots to the total fertilizer S recovery by herbage.

At D182 and D357 the amount of fertilizer S present in the HI-reducible fraction of both grass and clover roots was measured (APPENDIX XIII, TABLES 3 and 4). At both SITES, on D182, a larger proportion of the fertilizer S present in clover roots was HI-reducible, in comparison to the proportion present in grass roots.

Beatson et al., (1968) considered that the HI-reducible S represents free S\textsubscript{4}O\textsubscript{3}-S or ester-bound S in plant tissue. Hence, upon root decay this fraction would represent a readily available source of S to either plants or micro-organisms. The results of the above root analyses at SITES VIII and IX may explain the increases in both fertilizer S and fertilizer S\textsubscript{4}O\textsubscript{3}-S (p.e.) recorded at SITE I (0 - 15 cm) between D123-D240. (See CHAPTER III,3.(j)(b) Over this period, at SITE I, the decay of root material, dominated by clovers with a high proportion of HI-reducible S, may have occurred. More detailed root analyses over a wider range of soils and at more frequent sampling intervals, than used in the present study, are required to substantiate the above viewpoint.
(3) MOVEMENT AND DISTRIBUTION OF LABELLED SULPHUR IN SOILS.

The amount of total labelled S at each soil sampling and for each SITE is shown in APPENDIX X V, TABLES 1 and 2. Data in Figure 26 portray the distribution of total labelled S and labelled \( S_0^- \) (p.e.) only for soils sampled to a depth of 100 cm. In Figure 27 the mean amount of total labelled S at 0-30 and 30-60 cm depths is presented along with rainfall (R.F.) and estimated runoff or leaching water (R.O.) for each sampling interval. As in CHAPTER III, rainfall and runoff were considered to be similar on Gorge and Kowai soils.

Three soil sampling intervals were considered viz.

- Day 0 - D37 (First sampling)
- Day 37 - D182 (Autumn sampling)
- Day 182 - D323 (early Spring sampling).

(a) Day 0 - D37.

At both SITES, labelled S had penetrated to the 30-40 cm soil depth by D37. Most of the labelled S was confined to the upper 20 cm. On the Gorge silt loam, greater amounts of labelled S existed at 0-10 cm.

(b) Day 37 - D182.

No further penetration of labelled S beyond 40 cm had occurred at either SITE. Labelled S had become more evenly distributed to a depth of 30 cm at SITE IX and to a depth of 20 cm at SITE VIII.
Figure 26. Distribution of Total Labelled Sulphur (Sulphate Sulphur (p.e.) plus Organic Sulphur) on the S2 (45.0kgS/ha) and S1 (22.5kgS/ha) Treatment Subplot at SITES VIII and IX (1972-73).

(i) improved
Figure 26 continued
Figure 27  Labelled Sulphur Movement Within the 0-60 cm Soil Depth of the S2 (45.0 kgS/ha) Treatment Subplot at SITES VIII and IX (1972-73). L.S.D. Least Significant Difference 5% (i) improved
Over the winter period, leaching beyond a depth of 60 cm was estimated to have occurred at both SITES. Only at SITE IX (Kowai sandy loam) had labelled S penetrated beyond 60 cm to a depth of 90-100 cm.

Additionally, at both SITES, labelled S had undergone redistribution within the upper 60 cm. At SITE VIII there was a significant increase of labelled S in the 30-60 cm soil zone (Figure 27a). At SITE IX, besides labelled S moving beyond 60 cm, there was a substantial increase of labelled S in the 30-60 cm depth (Figure 27b). Inspection of Figure 26 shows this increase to be mainly in the 40-60 cm soil zone.

A difference in the time of fertilizer S application makes it difficult to compare directly the movement patterns of labelled S at SITES VIII and IX with that determined for their counterpart trials at SITES IV and II.

At SITE IX, higher levels of labelled $\text{SO}_4\text{-S}$ (p.e.) are present (0-60 cm) in the autumn following application of fertilizer in early November (1972) compared with an early September (spring) application in 1971 at SITE II (TABLE 35). By consideration of the R.O. analyses shown in APPENDIX IX (TABLE 4) a similar effect would probably have been measured if labelled S was applied in early September rather than early November at SITE IX. Similarly, if labelled S was applied on the 1st November in 1971 instead of the 9th September, then it is likely that
### TABLE 35

The Effect of Winter Leaching or Runoff on Losses of Labelled Sulphate Sulphur (p.e.) Beyond the 30 and 60 cm Soil Depth in Two Different Years (1972 and 1973) on a Gorge Silt Loam and Kowai Sandy Loam.

1972 (WINTER)

<table>
<thead>
<tr>
<th>Runoff or leaching water mm</th>
<th>Depth cm</th>
<th>SITE II (Kowai)</th>
<th>SITE IV (Gorge)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S0₄-S (p.e.) (mgS/m²)</td>
<td>% loss S0₄-S (p.e.) (mgS/m²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D24₀⁺</td>
<td>D35₀+++</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Autumn)</td>
<td>(Spring)</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>0 - 30</td>
<td>413</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 - 60</td>
<td>1258</td>
</tr>
</tbody>
</table>

1973 (WINTER)

<table>
<thead>
<tr>
<th>SITE IX</th>
<th>SITE VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>D182 (Autumn)</td>
<td>D182 (Autumn)</td>
</tr>
<tr>
<td>D323 (Spring)</td>
<td>D323 (Spring)</td>
</tr>
<tr>
<td>140</td>
<td>0 - 30</td>
</tr>
<tr>
<td>0 - 60</td>
<td>2600</td>
</tr>
</tbody>
</table>

n.a. = not applicable as labelled S did not penetrate beyond 60 cm

+ DAY 240 equivalent to D182 (Autumn) at SITES VIII and IX

+++ DAY 350 equivalent to D323 (early Spring) at SITES VIII and IX.
similar amounts of labelled $\text{SO}_4^-$ (p.e.) would have been present in the autumn of 1972 at SITE II as that found in the autumn of 1973 at SITE IX. These results show quite conclusively that the time of fertilizer $S$ application on Kowai soils affects the levels of $\text{SO}_4^-$ (p.e.) present in the soil the following year.

Although the amount of labelled $S$ lost beyond 60 cm over the winter period is similar between years (1000 mgS/m$^2$), a difference exists in the amount lost expressed as a percentage of that present in the autumn. This difference appears to relate with the difference in the amounts of leaching water between the two years (TABLE 35). At SITE II, 240 mm of leaching water was calculated to have moved beyond 60 cm over the winter (1972). Assuming that $\text{SO}_4^-$ (p.e.) is the form of $S$ liable to leaching, then approximately 72% of the labelled $\text{SO}_4^-$ (p.e.) prior to winter was found to have leached beyond 60 cm (TABLE 35). At SITE IX in the following winter the amount of leaching water was calculated to be 140 mm. However, only 46% of the labelled $\text{SO}_4^-$ (p.e.) available for leaching was removed from the upper 60 cm.

On the Gorge soils the comparison between years for SITES IV and VIII shows no movement of labelled $S$ beyond 60 cm (TABLE 35), suggesting that the time of fertilizer $S$ application is of less importance on these soils. However, as most of the plant $S$ uptake originates from the 0-30 cm zone the effect of time of application on labelled $S$ losses from this soil depth over the winter months is probably of more importance. Consideration of data in TABLE 35 shows that greater amounts of labelled
S remain as $\text{SO}_4$-S (p.e.) in the 0-30 cm depth with the later application. This situation also exists when the 0-30 cm soil depth is considered, at SITE II and IX, in a similar manner.

Differences between years in the amounts of leaching water over the two winter periods do not reflect the pattern of losses from the 0-30 cm depth of both soils. At SITES II and IX, on Kowai soils, over 80% of the labelled $\text{SO}_4$-S (p.e.) present in autumn is removed from the 0-30 cm depth irrespective of the amounts of leaching water. At SITE VIII with less leaching water, greater proportions of labelled $\text{SO}_4$-S (p.e.) are lost from the 0-30 cm depth in comparison with that measured at SITE IV. In this study leaching water was calculated assuming that available water is present in the upper 60 cm. Hence, the 0-30 cm soil depth will be subject to even greater amounts of leaching, particularly in early spring. This effect may explain the variable relationship noted for losses of labelled S from the 0-30 cm.

Over each winter period a greater proportion of labelled $\text{SO}_4$-S (p.e.) was removed from the 0-30 cm zone of the Kowai sandy loam compared with Gorge silt loam. The reason for this difference was not established. On both soils, S retention is considered to be low but on a % basis, a slightly higher % retention exists on the Gorge silt loam (APPENDIX II, TABLES 2 and 4). Hence, the results suggest that within soils of low S retention, a practical distinction in the ability of soils to hold fertilizer derived sulphate ions against leaching losses may exist. This aspect requires further investigation.

When the movement of labelled S is considered at the low S application rate (22.5 kgS/ha) on both soils (Figures 26 and 27), the
distribution and penetration of labelled S are similar proportionally to that of the 45.0 kg S/ha treatment at most sampling times. At D323, penetration at the lower rate was not as deep as that on the 45.0 kg S/ha treatment of the respective soils. These effects due to fertiliser rate are consistent with the conclusions reached by Chao et al., (1962a) under laboratory conditions.

(4) TRANSFORMATIONS OF LABELLED SULPHUR IN SOILS.

Total labelled S and S04-S (p.e.) at each soil sampling for each SITE are shown in APPENDIX XV, TABLES 1 - 4. Organic labelled S, representing the difference between the above two forms of labelled S is shown for the 0-5 and 0-20 cm soil depths in APPENDIX XV, TABLES 5 and 6.

For each SITE, mean values of labelled organic S in the 0-5 and 0-20 cm depth are shown in relation to total labelled S over time for both the S1 and S2 treatments (Figure 28).

By the time of first sampling (D37) on the S2 treatment of both SITES only a small amount of total labelled S was converted to organic S. Additionally, this labelled organic S comprised only a small proportion of the total labelled S present in the 0-20 cm zone. This result is in marked contrast to those obtained from their counterpart SITES II and IV in 1971 (Figure 17). However, this comparison is confounded by differences in the time of fertiliser S application and in the time of first sampling.
Figure 28. Incorporation of Labelled Sulphur into Soil Organic Sulphur in the S2 (45.0 kgS/ha) and S1 (22.5 kgS/ha) Treatment Subplots at SITES VIII and IX (1972-73). L.S.D. Least Significant Difference 5%

- Total Labelled Sulphur (0-15cm)
- Labelled Organic Sulphur (0-15cm)
- Labelled Organic Sulphur (0-5cm)

(i) improved
Consideration of rainfall data between the two years (APPENDIX IX, TABLE 4) shows that rainfall over the growing seasons in 1972-73 was almost similar to that in the same period in 1971-72. Therefore, both years are very similar climatically. Hence, the effect of time of application on labelled S incorporation can be assessed, provided allowance is made for differences in the time of first sampling. Day 48 was the first sampling at SITES II and IV in the 1971-72 trials. When the interpolated labelled organic S levels at D48, in SITES VIII and IX (Figure 28), were compared with those in the 1971-72 trials (Figure 17), a large difference exists on each soil. It is concluded, therefore, that the time of application has influenced the initial extent of labelled S incorporation into the organic S fraction. It was suggested in CHAPTER III, that the probable mechanism of early labelled S incorporation was directly through microbial incorporation. Hence, this effect of time of application may be related to the microbial activity.

These initial differences between years did not persist at SITE VIII (Gorge silt loam), as by D182 (Figure 28a) the amount of labelled S incorporated into the organic fraction was similar to that at SITE IV (D173) in 1971-72 (Figure 17d). Similarly, by D323 the amount of labelled S incorporated into the organic S fraction at SITE IX was somewhat similar to that amount at D350 on SITE II in 1971-72. Hence, apart from initial differences in the amount of labelled organic S, the overall incorporation pattern of labelled S was similar in the two separate investigations.

When the amounts of labelled organic S on the S1 treatment are compared with those on the S2 treatment at both SITES, much higher initial
amounts of labelled S, than expected, are incorporated into the organic fraction of the S1 treatment (Figure 28). At SITE IX by D37, labelled S had been incorporated into the 0-10 cm depth (Figure 26) and a greater amount of labelled organic S (0-20 cm) was measured on the S1 treatment compared with the S2 treatment (Figure 28). This difference was highly significant (t cal = 9.9, df = 4). The reason for this unexpected result between the two treatments may be due to the added fertilizer on the S2 treatment releasing greater amounts of non-labelled S by "priming", which leads to a more diluted S pool for microbial immobilization. However, when non-labelled SO4-S (p.e.) levels for the S1 and S2 treatments are compared with that of the SO treatment there was no measurable evidence of an increased "priming" effect on the S2 treatment at D37 for the 0-10 cm depth. The "priming" effect may have resulted immediately after fertilizer application and hence, earlier soil sampling may be necessary to detect this effect.

As in CHAPTER III, an attempt was made to assess whether labelled organic S was mineralized over the sampling period. In the first year, (1972-73) up to D182 (late autumn), fertilizer S movement was minimal beyond a depth of 30 cm at both SITES (Figures 26 and 27). If it is assumed that most of the plant uptake is in the 0-30 cm soil zone, net mineralization can be calculated. Similarly, whether net mineralization of labelled organic S occurred the following spring (1973) can also be calculated, if it is assumed that after D323 no fertilizer S moved beyond 30 cm. Results of these calculations for various sampling periods to D406 at each SITE are shown in APPENDIX XVII, TABLE 2. Despite an increase in replication and higher added radioactivity, considerable variability still exists between replicates as was the situation in CHAPTER III.
Even consideration of the labelled S in root systems (APPENDIX XIII, TABLES 3 and 4) at appropriate sampling intervals does not reduce this variability. It is therefore concluded that unless a great number of replicates are used, assessment of the mineralization of labelled S from labelled organic S will be difficult to achieve under field conditions.

(5) THE SIGNIFICANCE OF THE PROCESSES AFFECTING THE FATE OF FERTILIZER S ADDED TO SOILS.

Using similar criteria to that used in CHAPTER III, the relative significance of the various processes affecting the fate of fertilizer S added to SITES VIII and IX is shown in Figure 29. The major soil zone considered is the 0-30 cm depth.

Plant uptake and immobilization were the major processes depleting the pool of labelled $\text{SO}_4^-$ (p.e.) up to D76 at both SITES. Plant uptake was more active than immobilization. This difference remains the same from D76 to D182 (Autumn). However, the rate of plant uptake of labelled S was much slower than that in the initial period (DO - D76).

Leaching was relatively unimportant over the first year growing seasons (up to D182). However, over the winter period, leaching was the main depleting process operating, with some immobilization occurring at SITE IX.

In the following spring (Day 323-D406), plant uptake was the main operative process at both SITES, with immobilization continuing only at SITE IX.
Figure 29 Generalized Diagrams Relating Labelled Sulphate Sulphur (p.e.) Pool Depletion (A horizon) to Leaching, Immobilization and Plant Uptake of Labelled Sulphur at SITES VIII and IX (1972-73).

(i) improved
When the relative significance of leaching, plant uptake and immobilization was considered at SITES II and IV (Figure 20) for the same seasonal periods as at counterpart SITES IX and VIII, similar effects were found. This suggests, therefore, that the relative significance of the processes examined are dependent on seasonal factors.

(6) SULPHUR CYCLING POOLS.

In the same manner as in CHAPTER III, the sulphur cycling pool was calculated for SITES VIII and IX. In CHAPTER III, at the counterpart SITES IV and II, equilibrium S.A. in the herbage was established by D240 (early autumn) in 1972 (Figure 8). By early autumn (D182) at SITES VIII and IX in 1973, the S.A. of pasture was still declining (Figures 22a and c), on the comparable treatment. Equilibrium, however, was not reached until D456 at both SITES. The S.A. at D456 was used as the equilibrium S.A. for calculating the S cycling pool.

At SITE VIII (Gorge silt loam) the "effective dose rate" for the calculation of the cycling pool at D456 to a depth of 60 cm is equivalent to the application rate of 45.0 kgS/ha minus fertilizer S removed in harvested material up to that time. No fertilizer S had moved beyond 60 cm at D323 (Figure 26) and between D323 and D456, no leaching was estimated to have occurred beyond this depth. At SITE IX, the "effective fertilizer dose rate" was corrected for the fertilizer S (4.0 kgS/ha) leached beyond the 60 cm depth by D323 (see Figure 26a).

The calculated S cycling pool at both SITES is shown in TABLE 36a.
TABLE 36

Sulphur Cycling Pools (kgS/ha) at DAY 456 on SITES VIII and IX.

(a) S2 (45.0 kgS/ha) Treatment.

<table>
<thead>
<tr>
<th>SITE</th>
<th>VIII (Gorge)</th>
<th>IX (Kowai)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycling S Pool &quot;C&quot; (kgS/ha)</td>
<td>192 (162)†</td>
<td>148 (97)</td>
</tr>
<tr>
<td>S.A. Pasture (d.p.m./µgS)</td>
<td>850</td>
<td>1000</td>
</tr>
<tr>
<td>&quot;Effective Dose Rate&quot; of Fertilizer S (kgS/ha)</td>
<td>32</td>
<td>29</td>
</tr>
<tr>
<td>Extent of Dilution</td>
<td>6.0</td>
<td>5.1</td>
</tr>
</tbody>
</table>

(b) S1 (22.5kgS/ha) Treatment.

<table>
<thead>
<tr>
<th></th>
<th>VIII (Gorge)</th>
<th>IX (Kowai)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycling S Pool &quot;C&quot; (kgS/ha)</td>
<td>165</td>
<td>153</td>
</tr>
<tr>
<td>S.A. Pasture (d.p.m./µgS)</td>
<td>450</td>
<td>500</td>
</tr>
<tr>
<td>&quot;Effective Dose Rate&quot; of Fertilizer S (kgS/ha)</td>
<td>14.5</td>
<td>15.0</td>
</tr>
<tr>
<td>Extent of Dilution</td>
<td>11.4</td>
<td>10.2</td>
</tr>
</tbody>
</table>

† Cycling S pool when fertilizer S beyond 30 cm is excluded.
These pools can be compared with the S cycling pools obtained in CHAPTER III for the counterpart SITES II and IV (TABLE 23a). The size of the cycling sulphur pool at SITES II and IX for the same soil are almost identical. However, at SITE VIII, the S cycling pool is much lower than that measured at SITE IV. This suggests that at SITE VIII, the size of the S cycling pool may vary from year to year. This viewpoint is unaltered, even when fertilizer S beyond 30 cm is excluded (TABLE 23a and 36a). A similar year to year variation in the size of the S cycling pool was found by Till and May (1970a) in their study. This variation, in the present study, may be related to an incorrect assessment of the equilibrium S.A. of S in pasture.

In CHAPTER V, it is shown that at SITE IX, pasture uptake of labelled S from the 100 cm depth was measured in the Autumn of 1973. Hence, the "effective dose rate" and thus the size of the S cycling pool may be slightly higher than that calculated in TABLE 36a and for SITE II in TABLE 23a.

The calculated S cycling pools at a lower rate (22.5 kgS/ha) of fertilizer S addition gives similar results (TABLE 36b) to that determined using the higher rate of S application (TABLE 36a) on both SITES. At the lower rate of fertilizer S application, equilibrium S.A. appeared to have been established earlier than that assessed on the S2 treatment (Figure 22). The above observed difference in the time to reach equilibrium, due to the rate of S application, is contrary to that reported by Till and May (1970b), who found that the rate of fertilizer addition did not influence equilibrium time. In the study of Till and May (op.cit.) S application rates (130 mgS/ha and 7.8 kgS/ha) were much lower than those used in the present study, where rates (22.5 kgS/ha and 45.0 kgS/ha) of fertilizer S application were more closely related to those used in farming practice.
4. CONCLUSIONS

Although the results obtained in the trials at SITES VIII and IX could not be compared directly to those obtained at similar SITES (IV and II) the previous year, due to differences in the time of fertilizer S application, growing conditions at similar seasonal periods were found to be similar. Hence, it is considered that differences between the trials, laid down on the same soil type but in different years, are largely a result of the difference in time of fertilizer S application.

By applying fertilizer S in early November, rather than in early September, greater pasture recovery was obtained in the growing seasons of the first year, on both soils.

Additionally, prior to winter, greater amounts of fertilizer S remained in the upper 30 cm depth (i.e. the most active zone of plant uptake). Over the winter period, differences between years in the amount of leaching water (240 mm and 140 mm) confounded the effect of time of application on the amounts of labelled $SO_4$-$S$ (p.e.) remaining prior to next season's growth. Nevertheless, on the Kowai soil, the difference in the amount of leaching water between years was in direct proportion to the percentage of labelled S removed from the 0-60 cm zone. Thus, a greater amount of the initial fertilizer S would be carried through to the following year, in a plant available form, when fertilizer was applied in November as compared to that applied in September on Kowai soils.
It is suggested that this difference in application time may be of practical significance on soils with S-responsive pastures. Although field evidence is limited, most of the improved pastures, described in CHAPTERS III and IV and which showed S responses, invariably had spring harvests which did not show S deficiencies of such a magnitude as in later harvests. Hence, a later application of fertilizer S in early November may not be detrimental and maybe more than compensated by the high "residual" effects the following year, thus reducing the need for re-application. Retopdressing results from SITES II and XI support this suggestion. In the trial at SITE IX, the "residual" effects from an application of 45.0 kgS/ha in early November on the Kowai sandy loam prevented deficiencies of S from occurring over two years. The earlier trial (SITE II) under similar soil and pasture conditions showed that when fertilizer S was applied in early September, 45.0 kgS/ha prevented S deficiencies for only one year.

The "residual" effects due to differences in time of application could also be important when interpreting the results of fertilizer trials investigating S responses. The exact time of fertilizer applications and subsequent rainfall conditions should always be assessed when considering "residual" effects. Similarly, the time of application of the farmer's previous topdressing and the subsequent rainfall occurring should also be considered when interpreting the results of fertilizer trials in the first year.

Differences in application time appeared to influence the time at which fertilizer S reached equilibrium in the soil-plant systems studied. A later application of fertilizer S increased the time required
to reach equilibrium by almost twofold.

The inclusion of a lower rate of labelled fertilizer S application gives results on the fate of fertilizer S more closely akin to those likely to happen under normal farming conditions on these soils, as this rate was similar to that used by farmers. Despite the fact that at each SITE only two replicates of the S1 (22.5 kgS/ha) treatment were studied, the results, when compared to the S2 (45 kgS/ha) treatment, showed the magnitude of the processes measured were in proportion to the rates used. Plant uptake on the S1 treatment was only just over half that on the S2 treatment. A similar pattern of movement resulted in the soil, with slightly less penetration occurring after winter rainfall. However, the magnitude of organic immobilization of labelled S was higher than expected. A major difference between the two rates of application was in the time required for the added fertilizer S to reach equilibrium in the pasture. On the S1 treatment, equilibrium was reached almost 100 days earlier. It is thus concluded that deductions made in CHAPTER III, with respect to the effect of a lower rate on the fate of fertilizer S, were soundly based.

The application of a higher amount of radioactivity and the slower rate of dilution by the pool of soil cycling S in these trials as compared with similar studies in CHAPTER III, enabled S\textsuperscript{35} analyses of soil samples to be carried out for a longer period. Although soil determinations for S\textsuperscript{35} were terminated at D406, they could have been continued for one more half life (87 days). Hence, if the radioactivity had been applied at the intended level (15 mc/m\textsuperscript{2}), counting of soil
fractions containing $^{35}S$ would have been possible to 600 days.

An attempt, by the "apparent" recovery method, to measure the effect of fertilizer $S$ additions on root $S$ levels was unsuccessful. High variability was encountered in determining root dry matter yield and, hence, was the main limiting factor. Under these conditions the use of the actual recovery method was more precise.
CHAPTER V

ISOTOPIC STUDIES ON THE UPTAKE OF SULPHUR
BY PASTURE PLANTS

1. GENERAL INTRODUCTION

In order to assess the significance of the downward movement of fertiliser S in soils, the soil zone from which plants extract their S requirements must be known.

An indirect assessment of this soil zone was obtained at each trial in CHAPTERS III and IV by relating the specific activity of plant S to that in the soil $\text{SO}_4\text{S}$ (p.e.) fraction. As indicated in CHAPTER III, this indirect assessment had several limitations.

The purpose of the field experiments described in this CHAPTER is to determine, directly, the soil zone from which plant roots extract S. To meet this objective, field trials were established in the spring (1972) adjacent to the trials at SITE VIII (Gorge silt loam) and SITE IX (Kowai sandy loam) described in CHAPTER IV.

Using similar techniques, a further series of S uptake trials was established at the same locations the following autumn (1973) by the author and D. Brash. In comparison to the spring trials, Brash carried out a more intensive investigation into the distribution of the $\text{S}^{35}$-labelled pasture within the sampling unit. Additionally, deeper soil depths were studied in the autumn trials.
The results of the spring and autumn trials have been combined and submitted for publication as two papers. CHAPTER V in this thesis dissertation comprises these papers.

To maintain continuity within the thesis, tables, figures and descriptive material in CHAPTER V are numbered in sequence with those of adjacent CHAPTERS.

Additionally, references listed in each paper are included along with other references used in the presentation of the thesis.

APPENDIX XVIII, contains isotope and other data associated with the first harvest of the spring (1973) field experiments.
2. A METHOD FOR THE DIRECT INTRODUCTION OF $^{35}$S ISOTOPE INTO THE SOIL PROFILE UNDER FIELD CONDITIONS

by

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(1) **INTRODUCTION.**

The distribution of total and adsorbed sulphate in New Zealand soils has been reported and reviewed by several workers (e.g. Blakemore *et al.*, 1968; Metson, 1969). Although the accumulation of adsorbed sulphate in the subsoils of New Zealand soil profiles has been reported, its agricultural significance is, as yet, not fully evaluated. Furthermore, soil tests in New Zealand are usually made on samples from the top 10-15 cm depth and no information is obtained concerning the fertility at lower depths and its possible contribution to plant nutrition.

Investigations aimed at assessing the soil depth from which plants under field conditions extract their sulphur have been few. For example, Bentley *et al.* (1955), using radioactive $S^{35}$, found that sulphur uptake occurred at both the 25 cm and 50 cm soil depths under lucerne. Pawluk and Bentley (1965) showed that the uptake of $S^{35}$ by wheat, lucerne and barley occurred at all four depths (10, 20, 40 and 60 cm) studied.

For a particular isotope to be used in uptake studies the tracer must exist as carrier-free or high specific activity solutions or powders, which are not very mobile in the soil but mobile in the plant. Sulphur-$35$ in the sulphate form could be used although its mobility in the soil is greater than that of $P^{32}$. This mobility could be reduced in soils which have a high retentive capacity for adsorbed sulphate.
While the trace method is capable of yielding qualitative information of root activity, the quantitative interpretation of the results is much more difficult. Several complications could arise and some of these have been examined by several workers (e.g. Nye and Foster, 1960; D'Aoust and Taylor, 1965; Fried and Broeshart, 1967; Newbould, 1969; Bassett et al., 1970). One of the major complications is the accurate placement of the isotope in the soil profile as its introduction may disturb the feeding activity of roots near the point of injection. The probe may alter the root activity by soil compaction or by channelling roots to the injection sites. The latter is most likely to occur when the isotope is inserted into the soil vertically. An additional complication could arise from contamination of the walls of the channel during the withdrawal of the injection needle after the insertion of the isotope. Furthermore, with pasture studies under field conditions, it is extremely difficult to define exactly the sampling area. To overcome some of these difficulties the paper describes a method in which the $^{35}$S isotope is introduced horizontally into the soil profile at various soil depths under established pasture. In order to improve the accuracy and to reduce the contamination during placement, the technique of Jacobs et al., (1970), which utilizes small volumes of carrier-free isotope placed in gelatine capsules, was used. The extent of $^{35}$S uptake from a point application at a given depth was also examined.
(2) **MATERIALS AND METHODS.**

(a) **Soils.** The soils used were the Kowai sandy loam, a southern recent soil, and the Gorge silt loam, a moderately to strongly leached lowland yellow brown earth soil. Both soils occur in close proximity to where the Rakaia Gorge meets the Canterbury Plains. They were derived from greywacke loess and are sulphur deficient in the virgin state (having low atmospheric returns, being 55 km from the coast). They are under a similar climatic regime (subhumid, cool temperate climate, rainfall 1000-1250 mm per annum, warm summer, cool winter, prevailing north-west wind).

Both sites were under perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) pasture with a small proportion of weeds (e.g. yarrow - *Achillea millefolium*) and other grasses (e.g. cocksfoot - *Dactylis glomerata*). The Kowai SITE was on a terrace close to the Rakaia River, about 1 km upstream from the Rakaia Gorge bridge (N.Z.M.S. 1 sheet S74, 111603). The Gorge SITE was on a high fan surface on the Methven-Rakaia Road (N.Z.M.S. 1 Sheet S82, 101549).

(b) **Preparation and Layout of Experimental sites.** The chosen sites were fenced off and four areas of 1.5 m x 1 m were marked out at each trial site with at least 2 m between the corners of each area. This distance of 2 m was taken as sufficiently far apart to prevent any cross-contamination between each isotope application, as judged from results of previous trials by one of us (P.E.H. Gregg) using the same technique.
Pits of 1.5 m x 1 m to a depth of 1.2 m were dug in each marked out area. The purpose of digging the pits was to allow horizontal insertion of sulphur at each depth of application. Horizontal insertion minimizes bias in sulphur uptake.

(c) Sulphur Isotope Application. Isotope, as carrier-free $^{35}$S, sulphate in aqueous solution at pH 6-8, was purchased from the Radiochemical Centre, Amersham, England. In the laboratory at Lincoln College this was diluted into thirty-two 5 ml aliquots, each aliquot containing 1 millicurie of S.

The trial was laid down on the 14 March 1973. The steps involved were:

(i) Preparation of Soil Pits: At each trial site four pits were excavated, representing the four replications in a randomized complete block design. The four vertical faces of each pit were used to insert the isotope at the four different depths (22, 52, 75 and 100 cm). Randomization was carried out by randomly associating a particular depth of placement with a particular face in a pit (Figure 30). The faces of the pit walls were marked out to show the randomly chosen depth and position at which the isotope was to be placed. A cylindrical steel rod (diameter 1.2 cm, length 50 cm) was slowly hammered horizontally into the face for a distance of 30 cm and withdrawn to create a hole into which the isotope could be introduced. Five holes (10 cm apart) were made at each depth to give as great a spread of isotope as is possible within the limits of convenience. Obviously, the optimum would be an even
Figure 30. A Diagrammetric Illustration of the Location of the 
Five Capsules, Containing $S^{35}$-isotope, Inserted 
into the Pit Wall at the Desired Soil Depth.

Figure 31. Sampling Grid for the "Preliminary" Harvest as Viewed 
from Above the Plot. P-Q and R-S are the Transects 
for Plotting Lateral Spread in Figures 33 and 34.
(X is the position of the inserted middle capsule. 
The other capsules are represented by x).
spread of isotope at each depth to maximize the chance of detecting active roots at that particular depth.

(ii) Sulphur-35 Insertion: The isotope was inserted according to the method of Jacobs et al., (1970). A syringe was used to remove 1 ml (0.2 millicurie) of the 5 ml aliquot containing aqueous $^{35}\text{S}$ and this was placed into a medical gelatine capsule (diameter 10 mm, length 26 mm). The capsule was quickly frozen over dry ice.

To place the capsule in the soil at the desired location it was first clamped on the end of a hollow pipe (diameter 1.1 cm, length 50 cm). This pipe has an outside diameter small enough to be inserted into the horizontally-made holes and an inside diameter large enough to allow an inner rod (diameter 0.5 cm, length 50 cm) to eject the gelatine capsule from the clamp. The capsule was placed at the end of the 30 cm hole, ejected from the clamp and the clamp was withdrawn. The hole was then back-filled with soil from the same depth. The process was repeated until a total of five capsules were placed at each depth. Thus, at each hole, a gelatine capsule containing 0.2 millicurie of $^{35}\text{S}$ was placed in a uniform, non-contaminating way at the desired location. The capsule dissolves in the aqueous solution and soil water after the ambient soil temperature had melted the frozen solution. The relative positions of the gelatine capsules, after replacing the excavated soil, were marked with painted nails on the surface of the turf. The pit walls were lined with plastic sheeting prior to soil replacement in order to prevent pasture plants from the infilled area gaining access to the $^{35}\text{S}$. 
(iii) Harvesting Herbage: A "Preliminary" harvest was carried out on one plot in each trial site (replicate 1 at depth 22 cm) on 13 April 1973, one month after the experiment was laid down.

Its purpose was to assess the lateral spread of $^{35}S$ in pasture and to decide on the best method to sample the "Main" harvest so as to include as far as possible all the areas where uptake of $^{35}S$ is likely to occur.

The pasture in an area above the location of the isotope was harvested. To allow for lateral root development causing a spread of herbage activity an area of 100 cm x 60 cm was harvested. Hand shears were used with plastic gloves to prevent possible skin contamination and radiation injury from $^{35}S$. The 100 cm x 60 cm area was sampled using a grid constructed from iron rod and fencing wire. The grid had ten separate sampling areas and was placed on the turf with its centre (Figure 31) directly over the isotope. This area over the isotope will be referred to as the "hotspot" (see Figure 32).

The herbage was cut, bagged and brought back to the laboratory for analysis.

The "Main" harvest was carried out by cutting the areas as shown in Figure 32 on 30 April 1973. The herbage in all plots was harvested by taking three separate samples per plot (namely from areas 'a', 'b' and 'c', Figure 32). Each herbage sample was cut, bagged and brought back to the laboratory for analysis.
Figure 32  Sampling Grid for the "Main" Harvest as Viewed from above the Plot.
During this "main" harvest, another plot in each trial site was again harvested with ten samples per plot (replicate 2, depth 22 cm) to further assess the lateral spread of $S^{35}$ uptake. (See Figure 31).

(iv) Preparation of Herbage for Chemical Analysis: All herbage samples were oven-dried at 60°C under forced draught for three days. The dried samples were then weighed and ground to pass through a 1 mm sieve, using a coffee-type grinder. Precautions against oral inhalation of isotope and skin contamination were taken. This involved wearing of a face mask and plastic gloves. Close attention was given to preventing contamination between each sample. The "suspected" least active samples were ground first, the grinder was completely brushed out and cleaned between samples.

(v) Determination of $S^{35}$ Isotope and Total Sulphur: This was carried out according to the procedure of Blair and Crofts (1969).

A 0.05 g plant sample was oxidized by dry-ashing (25:1 NaHCO$_3$ : AgO) at 550°C for three hours (Steinbergs et al., 1962). A small modification of the procedure was introduced. This involved placing a "guard" layer of the oxidizing agent over the herbage-oxidizing agent mixture to prevent any possible volatilization losses of sulphur.

The modified Johnson and Nishita (1952) procedure of Dean (1956) was used to collect plant sulphur ($S^{32}$ and $S^{35}$) in 20 ml of 1 M NaOH.
The $^{35}S$ was determined using liquid scintillation counting. One ml of the collecting solution was added to 15 ml of the dioxane-based scintillation phosphor. Counting was carried out using the Packard Tricard Liquid Scintillation Counter (Model 2002) which had a counting efficiency of 45%. Each sample was counted for 10 minutes together with counting of a background sample from the untreated area.

The total plant sulphur was measured colorimetrically using the Dean's colour reagent (Dean, 1966), and the measurement made on a Bausch Lomb "Spectronic 29" at 400 m u wavelength. Standard curves were prepared from AR grade $K_2SO_4$.

(3) RESULTS AND DISCUSSION.

(a) Lateral Distribution of $^{35}S$-Uptake. Using the sampling areas as indicated in Figure 31, distribution of $^{35}S$-uptake by pasture plants in the "Preliminary" and "Main" harvests was determined for the depth of isotopic insertion at 22 cm and are shown in TABLES 37 and 38. Figures 33 and 34 diagrammatically show the lateral spread of $^{35}S$ in pasture in relation to the site of application.

The P-Q transect of Figures 33 and 34 shows that the maximum spread of uptake is over a distance of 20 to 25 cm from the site of isotope application with most of the uptake occurring at about 15 cm on either side of X, which is the approximate position of the middle capsule.
### TABLE 37

Lateral Spread of Sulphur-35 in Pasture at the "Preliminary" Harvest (Autumn 1973).

<table>
<thead>
<tr>
<th>Sampling Area</th>
<th>Weight of dried pasture herbage (g)</th>
<th>( S^{35} \text{ uptake (d.p.m. x } 10^4 \text{ per g of herbage)}</th>
<th>( S^{35} \text{ uptake (d.p.m. x } 10^4 \text{ per cm}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Preliminary&quot; Harvest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.55</td>
<td>3</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>5.98</td>
<td>185</td>
<td>1.46</td>
</tr>
<tr>
<td>KOWAI Soil (13.4.72)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6.56</td>
<td>424</td>
<td>4.63</td>
</tr>
<tr>
<td>4</td>
<td>5.96</td>
<td>132</td>
<td>1.31</td>
</tr>
<tr>
<td>5</td>
<td>5.65</td>
<td>14</td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>7.44</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>7</td>
<td>2.18</td>
<td>3</td>
<td>0.04</td>
</tr>
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<td>8</td>
<td>4.67</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>9</td>
<td>4.28</td>
<td>3</td>
<td>0.02</td>
</tr>
<tr>
<td>10</td>
<td>5.03</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>&quot;Preliminary&quot; Harvest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.00</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>2</td>
<td>5.34</td>
<td>27</td>
<td>0.20</td>
</tr>
<tr>
<td>GORGE Soil (13.4.73)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9.26</td>
<td>414</td>
<td>6.39</td>
</tr>
<tr>
<td>4</td>
<td>10.55</td>
<td>143</td>
<td>2.52</td>
</tr>
<tr>
<td>5</td>
<td>9.64</td>
<td>42</td>
<td>0.58</td>
</tr>
<tr>
<td>6</td>
<td>11.19</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>7</td>
<td>3.55</td>
<td>3</td>
<td>0.03</td>
</tr>
<tr>
<td>8</td>
<td>5.53</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>9</td>
<td>3.66</td>
<td>4</td>
<td>0.06</td>
</tr>
<tr>
<td>10</td>
<td>4.00</td>
<td>1</td>
<td>0.01</td>
</tr>
</tbody>
</table>

+ sampling areas 1 to 10 as illustrated in Figure 32
n none (counts were the same as background)
<table>
<thead>
<tr>
<th>Sampling area+</th>
<th>Weight of dried pasture herbage (g)</th>
<th>S\textsuperscript{35}-uptake (d.p.m. x 10\textsuperscript{4} per g of herbage)</th>
<th>S\textsuperscript{35}-uptake (d.p.m. x 10\textsuperscript{4} per cm\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Main&quot; Harvest</td>
<td>1 16.00 6</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>KOWAI</td>
<td>2 10.00 198</td>
<td>3.08</td>
<td></td>
</tr>
<tr>
<td>Soil (30.4.73)</td>
<td>3 9.64 346</td>
<td>5.57</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 9.37 396</td>
<td>6.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 11.27 27</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 12.50 n</td>
<td>n</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 5.20 3</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 12.21 2</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 4.30 16</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 3.50 n</td>
<td>n</td>
<td></td>
</tr>
<tr>
<td>&quot;Main&quot; Harvest</td>
<td>1 12.40 2</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>GORGE</td>
<td>2 13.89 132</td>
<td>2.61</td>
<td></td>
</tr>
<tr>
<td>Soil (30.4.73)</td>
<td>3 11.30 435</td>
<td>8.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 14.83 88</td>
<td>2.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 16.58 5</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 26.80 n</td>
<td>n</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 6.57 25</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 10.80 5</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9 6.49 67</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 10.83 4</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

+ sampling areas 1 to 10 (Figure 32) within a sampling unit - 100cm x 60 cm
n none (counts were same as background)
Figure 33. Lateral Spread of Sulphur-35 in Pasture in Relation to the Site of Application (X) at a Depth of 22 cm ("Preliminary" Harvest).
Figure 34  Lateral Spread of Sulphur-35 in Pasture in Relation to the Site of Application (X) at a Depth of 22 cm ("Main" Harvest).
It is of interest to note that the above result indicates that the lateral spread of roots of pasture plants, from the point of application of the isotope with respect to the depth studied (22 cm), is about 15 cm under field conditions. This observation is similar to those reported by other workers studying the root development of ryegrass and white clover plants (e.g. Erith, 1924; Weaver, 1926; Jacques, 1941; 1943 and Kutschera, 1960). It is also supported by the recent results of Vallis et al., (1973) in their studies using N$^{15}$-labelled fertilizers applied to the surface of microplots of Australian pastures. These workers reported that very little N$^{15}$ was recovered from pasture plants growing further than 15-30 cm from the area of application.

When the two soils are compared, pasture plants in the Kowai soil show a greater lateral distribution of roots at 22 cm than those in the Gorge soil. In addition, pasture roots penetrated to a greater depth in the Kowai soil than in the Gorge soil (see TABLE 39). Troughton (1957) noted a similar trend of greater horizontal root spread of herbage grasses when the vertical root penetration was deeper.

(b) Lateral Distribution of $^{35}$S Uptake with Depth. Total uptake of $^{35}$S-sulphur by pasture plants in the two soils studied are shown in TABLE 39. The contribution of the "hotspot" ('a' area in Figure 32) and the remaining outer areas ('b' and 'c' in Figure 32) to the total uptake from each depth are shown in Figure 35.

The data show that the lateral spread of $^{35}$S uptake varies with the soil and the depth of application. Since the uptake pattern of $^{35}$S...
TABLE 39

Mean Pasture Uptake of Sulphur-35 in Relation to the Main Sampling Areas Within the Sampling Unit (Autumn 1973).

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Weight of Pasture Herbage (g)</th>
<th>Sulphur Content of Pasture Herbage (%)</th>
<th>$^{35}S$-Uptake (d.p.m. x $10^4$ per g of Herbage)</th>
<th>Total $^{35}S$-Uptake (d.p.m. x $10^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>a</td>
</tr>
<tr>
<td>22 Kowai Gorge</td>
<td>10.93</td>
<td>15.53</td>
<td>6.66</td>
<td>0.27</td>
</tr>
<tr>
<td>52 Kowai Gorge</td>
<td>18.97</td>
<td>20.05</td>
<td>9.48</td>
<td>0.24</td>
</tr>
<tr>
<td>75++ Kowai Gorge</td>
<td>12.38</td>
<td>14.44</td>
<td>6.19</td>
<td>0.26</td>
</tr>
<tr>
<td>100++ Kowai Gorge</td>
<td>22.79</td>
<td>26.58</td>
<td>11.39</td>
<td>0.28</td>
</tr>
</tbody>
</table>

+ Sampling areas a, b, and c are as illustrated in Figure 32
++ Radioactive counts of herbage where the isotope was placed below the 52 cm depth in the Gorge soil were similar to those of the background and are therefore not shown.
+++ per sampling area.
Figure 35. Lateral Spread of Sulphur-35 in Pasture at Different Depths of Application. (Main Harvest).
is a reflection of both the root activity and root development. The results indicate that the distribution of roots is different in the two soils studied. To account for the uptake pattern in the Kowai soil, roots would be expected to grow laterally and obliquely until approximately 50 cm depth; then they grow vertically down to at least 100 cm. This root pattern would explain the distribution of uptake from each depth. In the Gorge soil, however, greater $^{35}S$ uptake occurred in the "hotspot" ('a' area) from the deeper depth. This could be due to surface roots spreading laterally at shallow depth and deep feeder roots penetrating vertically to the subsoil.

(4) **SUMMARY.**

A method for the direct introduction of $^{35}S$ isotope into different soil depths under field conditions to study the uptake of sulphur by pasture plants is described. This method was designed to minimize bias and contamination during the introduction of the isotope. It involved the horizontal introduction of the isotope enclosed in water-soluble capsules.

Recovery of $^{35}S$ by the pasture plants indicated that when $^{35}S$ was introduced at a depth of 22 cm the area above ground in which pasture plants were labelled extended little more than 15 cm from the line of placement. This lateral spread of $^{35}S$ in the pasture plants varied according to the soil and the depth of application. The results may be explained in terms of the extent and nature of root development in the soil profile.
3. PLANT UPTAKE OF SULPHUR FROM VARIOUS SOIL DEPTHS UNDER FIELD CONDITIONS

by

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Canterbury, New Zealand.

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+ New Zealand Ministry of Agriculture and Fisheries, Alexandra, New Zealand.
(1) **INTRODUCTION.**

In soils, sulphate is considered to be the plant available form of sulphur. Sulphate ions, adsorbed on soil colloids maintain an equilibrium with sulphate in soil solution.

Sulphate, in comparison with phosphate, is a relatively mobile ion in the soil. Therefore, whenever water percolates through the soil, sulphate ions are likely to be removed to a lower depth.

The extent to which the movement of sulphur through the soil profile influences the sulphur economy of crops and pastures depends on their respective zones of active nutrient uptake. This is not necessarily the same for all nutrients (Newbould, 1969).

Investigations, assessing the soil depth from which plants extract sulphur, have been few (see section 2. (1) ). It appears that no published uptake experiments, using radioactive $^{35}$S isotopes, have been conducted on permanent pastures containing ryegrass and white clover. Walker and Gregg (1975) suggest that the lack of an expected response to sulphur fertilizers in some New Zealand situations may be due to adequate S uptake from lower soil horizons.

In a series of trials in Canterbury, investigating the fate of fertilizer gypsum labelled with radioactive $^{35}$S, large differences occurred in the movement of sulphur through the soil profiles of two
contrasting soils under similar rainfall.

These trials had shown that, six weeks after the application of radioactive $^{35}$S$^{-}$-gypsum to the surface, substantial amounts of $^{35}$S were detected in the 45-60 cm depth of a recent soil. By contrast, no $^{35}$S was found below 30 cm in a lowland yellow brown earth soil. This situation prevailed throughout the spring, summer and autumn of 1971-72.

To interpret the significance of this movement, an evaluation of the depths from which plants utilized sulphur was carried out.

(2) EXPERIMENTAL.

The soils - Kowai sandy loam (southern recent) and Gorge silt loam (lowland yellow brown earth) were both free-draining loessial soils, differing in their degree of soil development.

Trials were laid down at each site on 10 September 1972. Radioactive carrier-free $^{35}$S isotopes were placed at four depths (7.5, 22.5, 37.5 and 52.5 cm) by the method as described earlier. The amount of isotope used was 0.5 millicurie (mc) of $^{35}$S for the two top depths and 2 mc for the lower depths.

Herbage was harvested by placing a sampling unit (100 cm x 60 cm) directly over the centre line of the gelatine capsules. The sampling unit
was separated into three sampling areas, with the central area (20 cm x 60 cm) designated the "hotspot" area of highest radioactivity.

After harvesting, the herbage from the "hotspot" was dissected into component pasture species of grasses and clovers.

In the autumn (1973), two additional trials were laid down adjacent to the spring trials. Sulphur-35 uptake from 22, 52, 75 and 100 cm was investigated using four replicates. One millicurie of $^{35}$S was injected at each depth.

Plant material was analysed for total sulphur (Steinbergs et al., 1964) and an extract (1 ml) used for liquid scintillation counting as outlined by Blair and Crofts (1969).

(3) RESULTS.

(a) Spring Trials. The first harvest was taken 34 days after the laying down of the experiment. TABLE 40a shows the mean $^{35}$S uptake by all herbage within the sampling unit. Data are corrected for the higher amounts of $^{35}$S added to the lower horizons. Uptake occurred from all four depths on both soils. The greater uptake of $^{35}$S at the two top depths of the Gorge soil is a reflection mainly of the higher plant yield at this site. On the other hand, the lower $^{35}$S uptake from the 37 and 52 cm depths in the Gorge soil is related to the higher levels of phosphate-extractable sulphate at these depths, creating a large dilution effect (TABLE 43a).
Mean Pasture Uptake of Sulphur-35 from Different Soil Depths.

(a) Spring 1972 (Day 34), First Harvest.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai</th>
<th>Gorge</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>$^{+11.7}_{+4.3}$a A++</td>
<td>20.110a A</td>
</tr>
<tr>
<td>22.5</td>
<td>4.272b AB</td>
<td>10.683b B</td>
</tr>
<tr>
<td>37.5</td>
<td>2.033c BC</td>
<td>797c C</td>
</tr>
<tr>
<td>52.5</td>
<td>987d C</td>
<td>193d C</td>
</tr>
</tbody>
</table>

(b) Autumn 1973 (Day 47), First Harvest.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai</th>
<th>Gorge</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>$^{5.41}_{+1.4}$a A</td>
<td>6 709a A</td>
</tr>
<tr>
<td>52</td>
<td>3 000a AB</td>
<td>509a A</td>
</tr>
<tr>
<td>75</td>
<td>1.016b B</td>
<td>Nil</td>
</tr>
<tr>
<td>100</td>
<td>1.247b B</td>
<td>Nil</td>
</tr>
</tbody>
</table>

+ disintegrations per minute x $10^4$
++ Duncan's symbols, letters in common are not significantly different ($P \leq 0.05$ denoted by small letters and $P \leq 0.01$ by capital letters). Data were log-transformed for statistical analyses.
+++ Corrected to the same amount of $S^{35}$ added (0.5 mc) in the Spring Harvest.
In comparing the $S^{35}$ uptake by white clover and ryegrass herbage from "hotspot" areas the data (TABLE 41 a) indicate that both these species were active in removing $S^{35}$ from each depth. Ryegrass plants, significantly, took up more $S^{35}$ per g of dry matter at each depth in the Kowai soil. This increase was not due entirely to its higher sulphur content as a comparison based on the specific activity of plant material still showed higher levels in the ryegrass herbage (TABLE 42).

The relative plant uptake of sulphur from each depth studied, can be evaluated by considering the size of the plant available pool of soil sulphur ($S^{32}$) in relation to the amount of $S^{35}$ added to the soil and that taken up by plants (Newbould, 1969). Results, as shown in TABLE 43 a, indicate the size of the plant available pool at each depth as determined by using the phosphate-extractable sulphur values. Large amounts of plant available sulphate are present in the Gorge subsoil. The percentage sulphur retention for each depth is also listed.

Using the isotope and available sulphate-S data at each site, the mean % relative activity of roots in relation to $S^{32}$ uptake by plants was calculated (TABLE 44a). With respect to the depths studied, approximately 50% of the total $S^{32}$ uptake occurs at 7.5 cm in both soils, with a greater relative proportion of $S^{32}$ uptake from the top depth in the Gorge soil. Of some interest is the similar % relative root activities for $S^{32}$ uptake at the 7.5 and 22.5 cm depth on the Gorge soil. Root weights from this site at a depth of 0-10 cm were on the average eight times that at 10-20 cm. Assuming this difference exists between the 7.5 and 22.5 cm soil depths, then the amount of roots present would appear to be a poor indication of their relative root uptake patterns for $S^{32}$. 
Mean Uptake of Sulphur-35 by Ryegrass and White Clover Plants from the "Hotspot" Area.

(a) Spring 1972 (Day 34), First Harvest.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai Grass</th>
<th>Kowai Clover</th>
<th>Gorge Grass</th>
<th>Gorge Clover</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>+ 4457 A</td>
<td>++ 1947 B</td>
<td>9967 A</td>
<td>3653 B</td>
</tr>
<tr>
<td>22.5</td>
<td>2200 A</td>
<td>4.85 B</td>
<td>3063 A</td>
<td>1199 A</td>
</tr>
<tr>
<td>37.5</td>
<td>748 A</td>
<td>121 B</td>
<td>357 A</td>
<td>177 A</td>
</tr>
<tr>
<td>52.5</td>
<td>204 A</td>
<td>22 B</td>
<td>73 A</td>
<td>53 A</td>
</tr>
</tbody>
</table>

(b) Autumn 1973 (Day 47), First Harvest

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai Grass</th>
<th>Kowai Clover</th>
<th>Gorge Grass</th>
<th>Gorge Clover</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>3550 A</td>
<td>650 B</td>
<td>3100 a</td>
<td>2400 a</td>
</tr>
<tr>
<td>52</td>
<td>2650 A</td>
<td>2140 A</td>
<td>110 a</td>
<td>200 a</td>
</tr>
<tr>
<td>75</td>
<td>577 A</td>
<td>340 A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1620 A</td>
<td>100 B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

+ disintegrations / minute x $10^3$/g of dry matter

++ Duncan's symbols (see TABLE 40) indicating significance of difference between pasture species.
TABLE 4.2

Mean Sulphur Specific Activities of Ryegrass and White Clover from the "Hotspot" Area.

Spring 1973 (Day 34), First Harvest.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai</th>
<th>Gorge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grass</td>
<td>Clover</td>
</tr>
<tr>
<td>7.5</td>
<td>+1720</td>
<td>A++</td>
</tr>
<tr>
<td>22.5</td>
<td>875</td>
<td>A</td>
</tr>
<tr>
<td>37.5</td>
<td>296</td>
<td>A</td>
</tr>
<tr>
<td>52.5</td>
<td>62</td>
<td>A</td>
</tr>
</tbody>
</table>

+ Duncan's symbols (See TABLE 4.0) comparing the significance of pasture species differences.
++ disintegrations / minute / μgS.

TABLE 4.3

Sulphur Retention and Mean Levels of Sulphate Sulphur (p.e.) at Different Soil Depths (Spring 1972, Autumn 1973).

(a) Spring 1972

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai</th>
<th>Gorge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% S.R.</td>
<td>SO₄⁻S (p.e.)</td>
</tr>
<tr>
<td>7.5</td>
<td>0</td>
<td>5.2</td>
</tr>
<tr>
<td>22.5</td>
<td>2</td>
<td>5.1</td>
</tr>
<tr>
<td>37.5</td>
<td>3</td>
<td>8.4</td>
</tr>
<tr>
<td>52.5</td>
<td>2</td>
<td>8.6</td>
</tr>
</tbody>
</table>

(b) Autumn 1973

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai</th>
<th>Gorge</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>1</td>
<td>5.1</td>
</tr>
<tr>
<td>52</td>
<td>4</td>
<td>8.0</td>
</tr>
<tr>
<td>75</td>
<td>16</td>
<td>10.5</td>
</tr>
<tr>
<td>100</td>
<td>8</td>
<td>7.4</td>
</tr>
</tbody>
</table>

^ μg/g
SR Sulphur Retention
### Mean Relative Root Activity for Pasture Uptake of Sulphur-32

(a) **Spring 1972 (Day 34), First Harvest**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai (%)</th>
<th>Gorge (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>56</td>
<td>41</td>
</tr>
<tr>
<td>22.5</td>
<td>20</td>
<td>46</td>
</tr>
<tr>
<td>37.5</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>52.5</td>
<td>8</td>
<td>3</td>
</tr>
</tbody>
</table>

(b) **Autumn 1973 (Day 47), First Harvest**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Kowai (%)</th>
<th>Gorge (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>33</td>
<td>79</td>
</tr>
<tr>
<td>52</td>
<td>38</td>
<td>21</td>
</tr>
<tr>
<td>75</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>12</td>
<td>0</td>
</tr>
</tbody>
</table>
(b) Autumn Trials. Uptake of sulphur occurs from all four depths in the Kowai sandy loam and from the top two depths of the Gorge soil (TABLE 40b). Data on the uptake of $S^{35}$ by the species (TABLE 41b) indicate that white clover and ryegrass roots were active at both sites.

Relative root activities for $S^{32}$ uptake from each depth are presented in TABLE 44b. In the Kowai soil, as much $S^{32}$ in the plants comes from the 22 cm depth as from the 52 cm depth, but in the Gorge soil over three times as much is taken up by plants from the 22 cm depth. These findings can be compared with the same data from the spring trial (TABLE 41a) which showed relatively less uptake from the 52 cm depth with respect to the 22 cm depth in both soils.

Soil moisture levels in the topsoils declined over the summer-autumn months and this may have restricted the uptake of sulphur from surface layers and increased uptake from lower depths, where higher levels of $S_4$-S (p.e.) exist (TABLE 43b).

The reason for the plant uptake of $S^{35}$ in the autumn ceasing at 52 cm depth in the Gorge soil was investigated to some extent. Visual observations and limited root weight sampling showed that root penetration terminated at 60 cm depth in contrast to the Kowai soil where roots penetrated to the 100 cm depth.

Soil moisture, soil porosity and soil chemical differences may be the main factors responsible for the differences in root penetration.
(4) DISCUSSION.

The main objective of these trials was to establish the significance of fertilizer sulphur movement in relation to the depth of sulphur uptake by plants at these sites. It is evident, from the results obtained, that uptake of $^{35}$S from fertilizer gypsum would have occurred to at least 52 cm in both soils during the spring. Therefore, although movement occurred to a depth of 60 cm in the Kowai soil this S would not have been lost to plants provided it remained in the plant available form. In fact, it is possible that uptake may have been occurring at depths lower than 60 cm as, in the autumn, uptake was recorded down to the depth of 100 cm.

Trials, investigating sulphur responses on each soil, were conducted concurrently on areas adjacent to the uptake trials. Sulphur responses occurred at the Kowai site. Thus, although sulphur was being utilized from depths of at least 100 cm in the Kowai soil, the magnitude of this uptake was insufficient to prevent sulphur deficiencies from occurring. On the other hand, the lack of sulphur responses in the Gorge soil may be due to uptake from lower depths (i.e. down to 52 cm) where levels of sulphate-S were much higher than those present in the top depth.

It should not be assumed that plants will always utilize sulphur from lower depths where the concentration of phosphate-extractable sulphate is high. As pointed out by Metson (1969), the factors leading to the accumulation of sulphate at depth may predispose towards low root
activity (i.e. low pH, low base saturation, high aluminium concentration) and thus low sulphur uptake.

A major problem encountered in both the series of the uptake trials conducted in the present study was the high degree of variability associated with $^{35}$S uptake data. This has been observed by other workers using P$^{32}$ isotope (e.g. Burton,1957). At our trial sites this could be related to the small sampling areas and a limited number of replicates.

(5) CONCLUSION.

The data obtained in the present study indicates that if sulphur in sulphate form, moves beyond approximately 60 cm at the Gorge site it is unavailable to plants. In contrast, uptake of sulphur occurs to at least a depth of 100 cm at the Kowai site.

The results suggest that to fully evaluate the supply of soil sulphur to plants, consideration should be given to sampling soils to a depth where roots are likely to be active in uptake. This is especially so when sulphate levels are low in the top 15 cm, yet no response to sulphur is recorded at trial sites.

Although the zone of sulphur uptake has been shown to extend to a considerable depth in both soils, it would require more detailed trial work to establish the actual contribution of sulphur at various soil depths to the total sulphur uptake by pasture herbage.
There is a paucity of New Zealand data on the depths from which pasture plants and crops extract their sulphur and other nutrients. We have no doubt that more information of this nature would assist in the efficient use of our fertilizers.

(6) **SUMMARY.**

On two contrasting soils - Kowai sandy loam (recent soil group) and Gorge silt loam (lowland yellow brown earth soil group) in inland Canterbury, New Zealand, plant uptake of $^{35}$S-sulphur placed at various soil depths and also the uptake of associated soil sulphur ($^{32}$S) present at the same depths were investigated in improved pastures under field conditions.

Results from the first harvest in spring (1972) showed that on both soils, white clover and perennial ryegrass plants utilized sulphur from all four depths studied (i.e. 7.5, 22.5, 37.5, and 52.5 cm).

The relative contribution of roots, at each soil depth, to the total plant $^{32}$S uptake was also assessed. With respect to the four depths studied, approximately 50% of the $^{32}$S uptake occurred at the 7.5 cm depth on both soils. Inclusion of the uptake from the 22.5 cm depth accounted for 76% and 90% of total $^{32}$S uptake in the Kowai and Gorge soils respectively.
In the autumn (1973) trials, adjacent to the spring trials, sulphur uptake ($^{32}\text{S}$ and $^{35}\text{S}$) from the 22, 52, 75 and 100 cm depths was investigated. On the Kowai soil, uptake by both grass and clover plants occurred from all four depths whereas on the Gorge soil, uptake occurred only in the upper two depths. Possible reasons for this difference are discussed.

A comparison of spring and autumn uptake from common depths (22 and 52 cm) indicated that in the autumn greater relative uptake of $^{32}\text{S}$ occurred from the 52 cm depth.

The results indicate that, despite variability in plant $^{35}\text{S}$ uptake data, soil-sampling below 7.5 cm is necessary at these sites to fully characterize the plant available sulphur status of the soil.
CHAPTER VI

GROWTH CABINET EXPERIMENTS WITH SULPHUR 35-LABELLED PLANT RESIDUES

1. INTRODUCTION.

As shown in the earlier studies, fertilizer S when applied to pastures is readily incorporated into plant material. Hence, the addition of plant residues, both underground (root decay) and on the surface, will constitute a potential source for the "residual" supply of fertilizer S to plants. In CHAPTER IV, levels of labelled S in roots were studied under field conditions. No significant net changes over time were found. The high variability in the root labelled S levels, prevented adequate precision in the detection of possible changes.

To obtain some information on the likely amount of fertilizer S released from plant residues within the growing seasons of one year in the field, several experiments were conducted under controlled conditions in a growth cabinet.

The overall objective of these experiments was to assess the plant availability of labelled fertilizer S incorporated into plant residues. This was measured by growing perennial ryegrass (Lolium perenne) plants in soils to which the labelled plant residues were added.

Specific objectives were to assess the relative plant availability of labelled S in:
(1) Grass and clover roots
(2) Varying proportions of grass and clover roots
(3) Grass and clover tops
(4) Grass roots of varying physical sizes
(5) Different amounts of grass roots together with varying application rates of fertilizer S.
2. MATERIALS AND METHODS.

(1) PREPARATION OF SULPHUR 35-LABELLED PLANT RESIDUES.

At SITE IX (see CHAPTER IV), S\textsuperscript{35}-labelled gypsum fertilizer was surface-applied to a small area (1.5 m x 1 m) on 1 November 1972. The application rate (45.0 kgS/ha) was similar to that on the S2 treatment at SITE IX. The added radioactivity was 10.4 mc/m\textsuperscript{2} (5120 d.p.m./µgS).

Pasture from the radioactive area was harvested on 8 December 1972 and discarded. Pasture harvested on 16 January 1973 (Day 76) was fully dissected into its clover and grass components. Each component was oven-dried at 60°C and ground in a similar manner to that described in CHAPTER III 2. (2), (d). These grass and clover samples are referred to in future reading as grass and clover tops. At the same harvest (16/1/73) the soil was removed entirely from the radioactive area to a depth of 10 cm. Clover and grass roots were extracted from the collected soil in a manner similar to that described in CHAPTER III 2.(2) (c) (ii). The separated grass and clover roots were oven-dried at 60°C and all clover and the majority of grass roots were ground in a similar manner to harvested pasture.

Ground grass and clover roots and tops were analysed for total N, C, non-labelled and labelled S, and non-labelled and labelled H\textsubscript{2}O-reducible S. Triplicate samples of grass and clover roots and tops were used for S analyses but for the other chemical analyses only duplicate samples were taken. The analytical methods, as outlined in CHAPTERS III and IV, were used. The composition of the plant residues, used in the
present study, are shown in TABLE 45.

(2) TRIAL DESIGN

Five separate experiments were conducted simultaneously in the growth cabinet. The soils used were collected from some of the SITES studied in CHAPTER III.

(a) Experiment I. Three plant residue treatments (nil, clover and grass roots) were applied to three soils collected from SITES II, IV and V. In addition, two plant residue treatments (nil and grass roots) were applied to the soil collected from SITE III. The treatments were a factorial plus two additional non-factorial treatments, viz: 3 root treatments x 3 soils + 2 (nil and grass roots added to one soil) in a completely randomized design with six replicates giving a total of 66 pots.

(b) Experiment II. Two root treatments, consisting of varying proportions of grass and clover roots, were applied to two soils from SITES IV and V. The root treatments were as follows:

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Ratio (Grass: clover roots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment I</td>
<td>2:1</td>
</tr>
<tr>
<td>Treatment II</td>
<td>1:2</td>
</tr>
</tbody>
</table>

The factorial experiment was arranged as in a completely randomized design of five replicates comprising 20 pots.
### TABLE 45
Composition of Sulphur 35-labelled Plant Residues

<table>
<thead>
<tr>
<th>Plant Residues</th>
<th>N</th>
<th>C</th>
<th>C/N</th>
<th>C/S</th>
<th>N/S</th>
<th>NLS+LS</th>
<th>Total S</th>
<th>S.A.</th>
<th>H.I. Reducible Sulphur</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td>µg/g</td>
<td>µg/g</td>
<td></td>
<td>µg/g</td>
</tr>
<tr>
<td>Grass Roots</td>
<td>1.66</td>
<td>45.1</td>
<td>27.2</td>
<td>275</td>
<td>10</td>
<td>1640 ± 10</td>
<td>480 ± 10</td>
<td>1680 ± 20</td>
<td>160 ± 5</td>
</tr>
<tr>
<td>Clover Roots</td>
<td>3.70</td>
<td>45.0</td>
<td>12.2</td>
<td>201</td>
<td>17</td>
<td>2240 ± 12</td>
<td>1000 ± 20</td>
<td>2545 ± 31</td>
<td>240 ± 5</td>
</tr>
<tr>
<td>Grass Tops</td>
<td>2.71</td>
<td>48.1</td>
<td>17.7</td>
<td>84</td>
<td>5</td>
<td>5700 ± 29</td>
<td>2670 ± 25</td>
<td>2665 ± 25</td>
<td>2400 ± 20</td>
</tr>
<tr>
<td>Clover Tops</td>
<td>3.70</td>
<td>42.0</td>
<td>11.4</td>
<td>219</td>
<td>19</td>
<td>1920 ± 11</td>
<td>1090 ± 19</td>
<td>3250 ± 50</td>
<td>290 ± 6</td>
</tr>
</tbody>
</table>

NLS  Non-labelled Sulphur
LS   Labelled Sulphur
S.A. specific activity in disintegrations / minute / microgramme of sulphur (d.p.m/µgS).
(c) **Experiment III.** Two plant residue treatments (clover and grass tops) were applied to three soils from SITES II, IV and V. The factorial experiment was arranged in a completely randomized design with five replicates and comprised 30 pots.

(d) **Experiment IV.** Three different sizes of plant residue (grass roots) were the treatments applied to the soil collected from SITE IV. These were:

1. Grass roots ground to pass 1 mm sieve
2. Grass roots cut into 3 mm lengths
3. Grass roots as extracted from the field (whole).

The size of plant residue in treatment (1) was similar to that used in all other experiments. The trial design (three treatments) was replicated six times in a completely randomized design of 18 pots.

(e) **Experiment V.** Two different amounts of grass roots (0.5 g and 1.0 g) were added with varying fertilizer S additions (nil and 45.0 kgS/ha) to soil from SITE II. In addition, where 1.0 g of roots was added, 90.0 kgS/ha was also applied. The trial design (2 weights x 2 S rates + 1) was replicated 5 times, giving 25 pots.

(3) **PREPARATION AND CONDUCT OF EXPERIMENTS.**

At SITES II, III, IV and V, a small quantity (13 kg) of the surface soil (0-10 cm) was excavated, from the non-radioactive area of the S3 treatment mainplots prior to retopdressing in 1972 (see CHAPTER III 2. (2) (b) ). The collected soil was air-dried and passed through a
For each experiment the appropriate soils were selected and to each pot was added 200 g of soil. Where treatments required the addition of plant residue, the soil from each pot was placed in an "AGEE" jar, plant residue added (1.0 g) and vigorously shaken until the plant residue was distributed evenly throughout the soil. At the same time, and in a similar manner, a basal topdressing of 20 kgP/ha (as calcium monophosphate) was also added to all experimental pots.

After mixing of plant residue, the soil was replaced in the plastic pots (8 cm in diameter at surface). Each pot was filled to within 2 cm of the pot surface by tapping firmly.

Soils, initially were watered to field capacity and left for one week.

On 19 February 1973, the soils were placed in the glasshouse and 12 perennial rye grass (Lolium perenne) seeds were placed 0.5 cm under the soil surface. When plants had reached a height of 2 cm, they were thinned to 4 plants per pot. All pots were maintained at 60% water-holding capacity with distilled water.

Pots were transferred to the growth cabinet on 13 March 1973. Growth cabinet conditions were maintained over the duration of the experiments as follows:
(a) Harvesting of Ryegrass. For each experiment, four harvests were taken at similar harvesting times. The first harvest was on 16 April 1973 and subsequent harvests at more or less regular monthly intervals. Generally, harvests were taken when ryegrass plants were 10 cm in height and were trimmed to the surface of the plastic pot.

By the end of the second harvest, nitrogen deficiency was evident visually on all pots. To alleviate the N deficiency, and the possibility of K deficiencies, \(\text{NH}_4\text{NO}_3\) and \(\text{KNO}_3\) was applied in liquid form in the first three days after the second harvest at the rate of 25 kgN/ha and 50 kgK/ha. A similar N and K application was made after the third harvest. At the final and fourth harvest, on all experiments, the remaining stubble was harvested and roots in each pot were extracted by washing as described in CHAPTER III,2,(2)(c) (ii), oven-dried, weighed and ground for chemical analyses as were ryegrass harvested at each time of sampling.

(b) Chemical Analyses of Soil and Plant Samples. The soil collected from each SITE was analysed for total C, N, S, \(\text{SO}_4\) (p.e.) and pH using the techniques described in CHAPTER III,2,(2)(d). Results are shown in TABLE 46. All analyses were done in duplicate.
### Chemical Analyses of Soils used in Plant Residue Experiments.

<table>
<thead>
<tr>
<th>SITE</th>
<th>SOIL</th>
<th>N (%)</th>
<th>C (%)</th>
<th>S (%)</th>
<th>N/S</th>
<th>C/S</th>
<th>C/N</th>
<th>pH</th>
<th>SO₄⁻S (μg S/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Kowai sandy loam (improved)</td>
<td>0.49</td>
<td>2.70</td>
<td>0.03</td>
<td>165</td>
<td>90</td>
<td>7</td>
<td>6.0</td>
<td>1.4</td>
</tr>
<tr>
<td>III</td>
<td>Kowai sandy loam (unimproved)</td>
<td>0.34</td>
<td>5.20</td>
<td>0.04</td>
<td>85</td>
<td>130</td>
<td>15</td>
<td>5.5</td>
<td>2.6</td>
</tr>
<tr>
<td>IV</td>
<td>Gorge silt loam (improved)</td>
<td>0.40</td>
<td>4.30</td>
<td>0.04</td>
<td>100</td>
<td>108</td>
<td>11</td>
<td>6.3</td>
<td>5.0</td>
</tr>
<tr>
<td>V</td>
<td>Gorge silt loam (unimproved)</td>
<td>0.48</td>
<td>7.40</td>
<td>0.05</td>
<td>96</td>
<td>148</td>
<td>15</td>
<td>5.2</td>
<td>4.7</td>
</tr>
</tbody>
</table>
3. RESULTS.

(1) UPTAKE BY RYEGRASS PLANTS OF LABELLED SULPHUR FROM GRASS AND CLOVER ROOT RESIDUES (EXPERIMENT I).

Dry matter yield, total S, specific activity and labelled S data for the first harvest and all harvests combined are shown in APPENDIX XIX, TABLE 1. The mean cumulative total and labelled S uptake by ryegrass plant for each treatment over four harvests is shown in TABLE 47.

On soils from the same SITE (i.e. SITES II, IV and V) significantly less labelled S was taken up by ryegrass from the grass root additions compared to clover root additions. Although the added clover roots contained more labelled S than the added grass roots (TABLE 45), no significant difference between the two root forms was evident in total S uptake by ryegrass grown on soil from the same SITE. This suggests, therefore, that the rate of breakdown of clover roots is faster than that for grass roots. These rate differences are consistent with the contrasting C/N, C/S ratios of these two root forms (TABLE 45).

The mean recovery of labelled S by ryegrass over 23 weeks, although varying between root treatments and SITES, were all low (<16%), with greater recovery on each SITE where clover roots were added (TABLE 47). These differences in recovery between treatments persisted from harvest to harvest (Figure 36).

The effect of either grass or clover root addition on labelled S uptake by ryegrass varied from SITE to SITE. For instance, when clover
### TABLE 47

Total and Labelled Sulphur 35 Uptake by Ryegrass from Sulphur 35-
Labelled Grass and Clover Roots Added to Soils (All Harvests
Combined.) Experiment 1.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SITE +</th>
<th>Total S µgS/pot</th>
<th>Labelled S µgS/pot</th>
<th>% Recovery (Labelled S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No roots</td>
<td>II</td>
<td>1964</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>2348</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>2944</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2214</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Grass roots</td>
<td>II</td>
<td>1911</td>
<td>37</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>2008</td>
<td>32</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>2567</td>
<td>60</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>1930</td>
<td>44</td>
<td>9.2</td>
</tr>
<tr>
<td>Clover roots</td>
<td>II</td>
<td>1945</td>
<td>95</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>2697</td>
<td>162</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>1926</td>
<td>134</td>
<td>13.4</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td></td>
<td>180</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td></td>
<td>240</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>C.V. %</td>
<td></td>
<td>9.9</td>
<td>9.6</td>
<td></td>
</tr>
</tbody>
</table>

n.a. = not applicable

L.S.D. = Least Significant Difference  
C.V. = Coefficient of variation

+ SITE II Kowai sandy loam (improved)  
SITE III Kowai sandy loam (unimproved)  
SITE IV Gorge silt loam (improved)  
SITE V Gorge silt loam (unimproved).
Figure 36  Cumulative Labelled Sulphur Recovery, by Ryegrass, from Grass and Clover Roots (containing Labelled Sulphur) and added to Various Soils.

(i) improved   (u) unimproved
roots were added to soil from SITES II and V, significantly greater amounts of labelled S were taken up by ryegrass growing on the soil from SITE V (TABLE 47). No difference was found in total S uptake between these two soils. TABLE 46 shows that there are differences in many of the chemical properties between the soils from these two SITES. It is possible that in early harvests on the soil from SITE II, the growth of ryegrass in comparison to that at the unimproved Gorge soil was limited more by a deficiency of soil S (see N/S ratio differences in TABLE 46) as occurred under field conditions in 1972-73.

(2) UPTAKE BY RYEGRASS PLANTS OF LABELLED SULPHUR FROM VARYING PROPORTIONS OF CLOVER AND GRASS ROOTS ADDITIONS (EXPERIMENT II).

Dry matter yield, total S, specific activity and labelled S data for the first harvest and all harvests combined are shown in APPENDIX XIX, TABLE 2. The mean cumulative total and labelled S uptake by ryegrass for each treatment over four harvests is shown in TABLE 48.

As would be expected from the results of Experiment I, greatest uptake and recovery of labelled S occurred where the added plant residues comprised 66% clover and 33% grass (TABLE 48).

(3) UPTAKE BY RYEGRASS PLANTS OF LABELLED SULPHUR FROM GRASS AND CLOVER TOP ADDITIONS (EXPERIMENT III).

Dry matter yield, total S, specific activity and labelled S data for the first harvest and all harvests combined are shown in APPENDIX XIX,
<table>
<thead>
<tr>
<th>Treatment</th>
<th>SITE</th>
<th>Total S pgS/pot</th>
<th>Labelled S pgS/pot</th>
<th>% Recovery (Labelled S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1 grass-</td>
<td>IV</td>
<td>2481</td>
<td>96</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2101</td>
<td>87</td>
<td>13.4</td>
</tr>
<tr>
<td>2:1 clover-</td>
<td>IV</td>
<td>2769</td>
<td>139</td>
<td>17.0</td>
</tr>
<tr>
<td>grass</td>
<td>V</td>
<td>2262</td>
<td>121</td>
<td>14.8</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.V. %</td>
<td></td>
<td></td>
<td></td>
<td>9.0</td>
</tr>
</tbody>
</table>

+ SITE IV  Gorge silt loam (improved)
SITE V  Gorge silt loam (unimproved)
L.S.D.  Least Significant Difference. C.V.  Coefficient of variation.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SITE</th>
<th>Total S pgS/pot</th>
<th>Labelled S pgS/pot</th>
<th>% Recovery (Labelled S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass tops</td>
<td>II</td>
<td>3159</td>
<td>351</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>3963</td>
<td>437</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>3572</td>
<td>527</td>
<td>19.7</td>
</tr>
<tr>
<td>Clover tops</td>
<td>II</td>
<td>1869</td>
<td>106</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>3130</td>
<td>195</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2096</td>
<td>145</td>
<td>13.3</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.V. %</td>
<td></td>
<td></td>
<td></td>
<td>7.8</td>
</tr>
</tbody>
</table>

+ SITE II  Kowai sandy loam (improved)  L.S.D. Least Significant Difference.
SITE IV  Gorge silt loam (improved)
SITE IV  Gorge silt loam (unimproved)
TABLE 3. The mean cumulative total and labelled S uptake by ryegrass for each treatment over four harvests is shown in TABLE 49.

For each soil greater amounts of labelled S are available to ryegrass plants from the addition of grass tops rather than clover tops. This plant species difference, between top additions, contrasts with their respective root additions, as in Experiment I greater recovery of labelled S by ryegrass occurred when clover roots were added.

Inspection of TABLE 45 shows that grass tops contain a greater amount of labelled S than clover tops. Furthermore, the addition of grass tops has significantly increased the amount of total S uptake by ryegrass plants from each soil (TABLE 49). The increased total S uptake by ryegrass plants when grass tops are added, in comparison to clover tops addition, are not reflected in proportionate increases in labelled S uptake. This suggests that grass top decomposition is faster than that for clover top decomposition, probably due to C/S ratio differences (see TABLE 45).

(4) UPTAKE, BY RYEGRASS, PLANTS OF LABELLED SULPHUR FROM GRASS ROOTS OF DIFFERENT SIZES (EXPERIMENT IV).

Dry matter yield, total S, specific activity and labelled S data for the first harvest and all harvests combined are shown in APPENDIX XIX, TABLE 4. The mean cumulative total and labelled S uptake by ryegrass for each treatment over four harvests is shown in TABLE 50.

The addition of roots (<1 mm) compared to whole roots has increased,
### TABLE 50

Total and Labelled Sulphur Uptake by Ryegrass from Sulphur 35-Labelled Grass Roots (Varying Sizes) Added to Soil from SITE IV (All Harvests Combined). Experiment IV.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SITE</th>
<th>Total S (µgS/pot)</th>
<th>Labelled S (µgS/pot)</th>
<th>% Recovery (Labelled S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground roots (&lt;1 mm)</td>
<td>IV</td>
<td>2781</td>
<td>60</td>
<td>12.5</td>
</tr>
<tr>
<td>Cut roots (3 mm in length)</td>
<td>IV</td>
<td>2682</td>
<td>61</td>
<td>12.7</td>
</tr>
<tr>
<td>Whole roots</td>
<td>IV</td>
<td>2718</td>
<td>47</td>
<td>9.8</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.V. %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

+ SITE IV  Gorge silt loam (improved)  C.V.  Coefficient of variation.
L.S.D.  Least Significant Difference.

### TABLE 51

Total and Labelled Sulphur Uptake by Ryegrass from Different Amounts of Grass Root and Fertilizer S Additions (All Harvests Combined) Added to Soil from SITE II.  Experiment V.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SITE</th>
<th>Total S (µgS/pot)</th>
<th>Labelled S (µgS/pot)</th>
<th>% Recovery (Labelled S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 g grass roots (nil S)</td>
<td>II</td>
<td>1951</td>
<td>49</td>
<td>4.0</td>
</tr>
<tr>
<td>0.5 g grass roots (plus 45 kgS/ha)</td>
<td>II</td>
<td>5511</td>
<td>20</td>
<td>4.2</td>
</tr>
<tr>
<td>1.0 g grass roots (nil S)</td>
<td>II</td>
<td>2231</td>
<td>32</td>
<td>6.7</td>
</tr>
<tr>
<td>1.0 g grass roots (plus 45 kgS/ha)</td>
<td>II</td>
<td>6514</td>
<td>43</td>
<td>9.0</td>
</tr>
<tr>
<td>1.0 g grass roots (plus 90 kgS/ha)</td>
<td>II</td>
<td>7551</td>
<td>33</td>
<td>6.9</td>
</tr>
<tr>
<td>L.S.D. 5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.S.D. 1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.V. %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

+ SITE = Kowai sandy loam (improved)  L.S.D. Least Significant Difference.
significantly, the uptake and recovery of labelled S by ryegrass. The magnitude of this increase was not particularly large (28%). The addition of chopped roots (3 mm) gave a similar recovery as ground roots (<1 mm). No significant differences were measured in total S uptake between the various forms.

(5) UPTAKE, BY RYEGRASS PLANTS, OF LABELLED SULPHUR FROM DIFFERENT AMOUNTS OF GRASS ROOT AND FERTILIZER SULPHUR ADDITIONS (EXPERIMENT V).

Dry matter yield, total S, specific activity and labelled S data for the first harvest and all harvests combined are shown in APPENDIX XIX, TABLE 5. The mean cumulative total and labelled S uptake by ryegrass for each treatment over four harvests is shown in TABLE 51.

In the improved Kowai sandy loam in the absence and presence of fertilizer S, the addition of grass roots at half the amount used in Experiments I, II and IV lowered the uptake of labelled S by almost half.

The effect of fertilizer S additions on labelled S uptake depended on both the amount of roots and the amount of fertilizer S added. Where 0.5 g of roots was added, the addition of 45.0 kgS/ha equivalent did not increase labelled S uptake but created large increases in total S uptake. However, where 1 g of roots was added, the addition of 45.0 kgS/ha gave significant increases in labelled S uptake. The addition of 90.0 kgS/ha with 1 g of roots did not significantly increase the uptake of labelled S over that of the treatment where no S was added with 1 g of roots. The effect of fertilizer S additions on the amount of ryegrass root production where 1 g of grass roots was added, is shown in PLATE 5. Hence, the addition of 90 kgS/ha must have created a large dilution effect on the amount of labelled S available for plant uptake, as the increase in root production would contact a large volume of soil and normally lead to greater uptake of labelled sulphur.
Perennial Ryegrass (*Lolium perenne*) Growth Prior to Final Harvest on Pots Containing Sulphur 35- Labelled Grass Roots on Soil from SITE V (unimproved Gorge silt loam) Experiment 1.

The Effect of Sulphur Fertilizer Rates on Perennial Ryegrass (*Lolium perenne*) Root Growth at Final Harvest on Soil from SITE II (improved Kowai Sandy Loam). Experiment V.
4. DISCUSSION.

Plant roots are considered to be the major source of plant residue additions in the field experiments described in CHAPTERS III and IV. In these field experiments all harvested herbage was removed from trial SITES. Hence, in the present series of experiments (CHAPTER VI), the results from Experiments I and II (grass and clover root additions) are of particular significance.

It was shown in CHAPTER IV, that at the improved SITES XI (Kowai sandy loam) and VIII (Gorge silt loam), the weight of grass roots was generally greater than the weight of clover roots at each sampling. The 2:1 grass-clover root treatment used in Experiment II of this present study, is perhaps, then, the closest to the field situation. In this experiment, recovery of labelled S from the 2:1 grass-clover treatment was 15% after 23 weeks.

While it is difficult to extrapolate the results of the growth cabinet experiment to the field situation, it is probable that recovery of labelled S from root decay, within the growing seasons of one year, will be much less in the field than the 15% measured in Experiment II. For instance, in the field, whole roots rather than ground roots will be subject to decay. The results in Experiment IV suggest that labelled S recovery from whole roots will be almost 30% less than labelled S recovery from ground roots as used in Experiment II. Furthermore, in Experiment II, 1 g of roots (oven-dry) was added to 200 g of soil. This represents 7500 kgDM (roots)/ha. Although this amount of root decay may
take place over one year, it is unlikely that the effect of adding 1 g/200 g of soil will be similar to the fluctuating amounts of root material decaying in the field. In fact in Experiment IV, the root addition of 0.5 g (instead of 1.0 g) to 200 g of soil halved the total amount of labelled S ryegrass uptake.

Overall, it would appear that under field conditions, less than 10% of the labelled S added in decomposing root material would be made available to plants within the growing seasons of one year.

On the other hand, several aspects of the experimental technique used in this study, may have predisposed toward the low recovery of labelled S from plant residues. In this investigation, the extracted roots were oven-dried prior to addition to the soil from each SITE. Whiting and Schoonover (1920) have found that dried plant material decomposed more slowly than fresh plant material added to the soil. By inference, greater recovery of labelled S from plant residues may have occurred if fresh plant residue had been added.

In Experiments I and II, by the second harvest, ryegrass plants were becoming yellow in colour on all soils studied. This suggested that either N or S deficiencies were occurring. Nitrogen and sulphur concentrations and N/S ratios for the four harvest periods are shown in TABLE 52 for Experiment I. The values presented suggest that N was probably limiting plant growth especially in the second harvest. Sulphur deficiency was acute during the third and fourth harvest following the addition of N fertilizer. Ryegrass growth at the final harvest is shown (PLATE 6) for one of the soils studied.
TABLE 52

Nitrogen and Sulphur Contents (%) of Ryegrass, at each Harvest, Grown on Soils From SITES IV and V. Experiment I.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>SITE</th>
<th>1st Harvest</th>
<th>2nd Harvest</th>
<th>3rd Harvest</th>
<th>4th Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>S</td>
<td>N/S</td>
<td>N</td>
</tr>
<tr>
<td>Nil roots</td>
<td>IV</td>
<td>2.58+</td>
<td>0.21</td>
<td>12.3</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2.73</td>
<td>0.22</td>
<td>12.4</td>
<td>1.44</td>
</tr>
<tr>
<td>Grass roots</td>
<td>IV</td>
<td>2.21</td>
<td>0.25</td>
<td>8.8</td>
<td>1.94</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2.30</td>
<td>0.22</td>
<td>10.5</td>
<td>2.49</td>
</tr>
<tr>
<td>Clover roots</td>
<td>IV</td>
<td>2.57</td>
<td>0.23</td>
<td>11.2</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2.44</td>
<td>0.22</td>
<td>11.1</td>
<td>2.17</td>
</tr>
</tbody>
</table>

+ Mean of 6 replicates.
The extent that these nitrogen and sulphur nutrient deficiencies affected the uptake of labelled S is largely unknown. Where N deficiencies occurred (second harvest) presumably microbiological activity was also restricted and mineralization of labelled S from plant roots reduced. Where S deficiency occurred (third and fourth harvests) and N was non-limiting, much of the labelled S released from plant residues by microbial action may have been immobilized by micro-organisms. Hence, the effects of N and S deficiency over the duration of the experiments with grass and clover root additions would possibly reduce the potential uptake of labelled S by ryegrass plants. In fact, in Experiment V, where fertilizer S was added to soil from SITE II, increased labelled S uptake was measured when 45.0 kgS/ha was added compared to the treatment with nil S. In Experiment V, N would only have been limiting over the second harvest.

Based on the conclusion that <10% of the labelled fertilizer S present in roots undergoing decomposition is released to plants over one year, it can be calculated that this amount would contribute to only a very small proportion (1%) of the fertilizer S recovered in harvested pasture in the first year at SITES VIII and IX in CHAPTER IV (TABLE 28). This conclusion is based on the assumption that these SITES would have 100-150 mg of fertilizer S/m² in the root system undergoing decomposition during the year (see TABLE 34). When the "residual" fertilizer S recovery at these SITES is considered for the following year (TABLE 28) and related to the probable amount of fertilizer S contained in the decomposing root mass (TABLE 34) the root contribution to fertilizer S recovery by pasture would still remain low (3%). This result contrasts with the postulation of Walker and Adams (1958b) who considered that "residual" fertilizer S recovery in their experiment could be accounted for by root decay.
Similarly, when the "residual" recovery of fertilizer S in the trials of CHAPTER III is considered at SITES II, III, IV and V (TABLE 13), in relation to the contribution of fertilizer S from root decay (TABLE 14) a relatively low (<5%) percentage of recovery is indicated at most SITES. This assumes that the amount of fertilizer S in roots at D240 is the same as that at Day 350, the beginning of the "residual" recovery period.

No other studies measuring plant S recovery from $^{35}$S-labelled plant residues have been reported. However, Nelson (1973) has added cotton (0.3% S) and corn (0.1% S) plant residues to soils, with and without S, and determined % S recovery from the residue by growing turnips and calculating "apparent" S recovery. On two soils, the average S recovery was 23% where cotton was added but no recovery where corn was added to these soils. Where fertilizer S was added in addition to plant residue, the % recovery declined. This decline was attributed to N deficiency for both plant growth and microbiological activity.

The results of Nelson (1973) for the effect of both added fertilizer S and plant residue on S recovery contrast with those found in the present study for Experiment V where the rates of S used were nil, 45 kg S/ha and 90 kgS/ha (TABLE 51). However, in this present experiment, N was possibly only limiting during the second harvest.

It is of interest to note that if "apparent" S recovery had been calculated in Experiment I of this present study, no recovery of residue S would have been measured (TABLE 47) as S uptake by ryegrass was greater where residue was not added.
Several workers (Norman and Werkman, 1943; Wallace and Smith, 1954; Moore, 1974) have conducted experiments where $N^{15}$-labelled plant residues were added to soils and the plant availability of the $N^{15}$ measured. All these investigations reported low recovery of labelled $N$. For instance, Moore (1974), adding $N^{15}$-labelled Rhodesgrass ($Chloris gayana$ cv Commercial) roots to soil, recovered only 30% of the added $N^{15}$ after 70 weeks when cropping with Rhodesgrass. After 23 weeks (a duration similar to that used in the present study) only 19% of the labelled $N^{15}$ was recovered in the presence of $N$ and 16% in the absence of $N$. These low recoveries are similar to the extent of labelled $S$ recovery measured in the present experiments.

The plant residue used in the present study was labelled unevenly with radioactive $S^{35}$, both between species and within plant tops and roots of the same species (TABLE 45). Hence, the calculated recoveries of labelled $S$ from plant residues cannot be used to identify the contribution of the different species and components of the same species to the total $S$ uptake by ryegrass. Uniform labelling can only be achieved by growing plants in a medium where the sole $S$ source, available to the plant, is radioactively labelled over the whole growing period.

The results of Experiment IV (TABLE 50) showed that grinding of plant material increased the plant availability of labelled $S$ compared with unground material. This result is to be expected on the basis of grinding increasing the surface area of plant material and hence, the area available for microbial decomposition. However, the available evidence from $N^{15}$ studies is inconsistent with respect to the effect of grinding.
Stickler and Frederick (1959) found that the release of N from four different legumes (tops and roots) was greater than with finely ground material. Sims and Frederick (1970) reported that the rate of decomposition of corn stalk pith decreased as particle size increased. Moore (1974) found that the effect of grinding was similar to chopped root additions when assessing plant availability $^{15}N$ labelled plant roots. The reason for these inconsistencies in particle size effects may be due to the amount and quality of plant residue added in these respective studies.

The fact that no previous studies had been conducted with $^{35}S$-labelled plant residues made it difficult to estimate the amount of radioactivity to be added for each treatment in each experiment. The weight (1 g/200 g of soil) of added plant residue used in all experiments, except Experiment V, was considered to represent the weight of roots present in the root system at the time of root sampling. Plant material, when added to soils, varied in radioactivity content. At the commencement of the experiments, the radioactivity added in plant residue per pot (200 g soil) ranged from 1.1 μC $^{35}S$ for grass roots to 6.1 μC $^{35}S$ for grass tops. In fact, the major reason for using grass and clover tops was to provide material of very high radioactive content to enable satisfactory detection of $^{35}S$ in case the amount of radioactive $^{35}S$ in grass roots was too low for detection. The results from Experiment I showed that when 1 g of $^{35}S$-labelled (1.1 μC) grass roots was added to 200 g of soil, the $^{35}S$ could be counted successfully in ryegrass plants for up to six months.
5. CONCLUSIONS

When plant residues containing fertilizer derived S (labelled S) are added to soils, under optimal plant residue decomposition and plant growth conditions (growth cabinet), recoveries of labelled S by ryegrass varied from 6-16% depending on the soil type, form and type of plant residue added.

Of the growth cabinet experiments conducted, the most realistic to the field experiments described in CHAPTERS III and IV were those where grass and clover roots were added. It was concluded from the results of these experiments that <10% of the labelled fertilizer S incorporated into plant roots would be made available to living plants within one year. This amount represents only a small fraction of the labelled S taken up by plants under field conditions over a similar time period.
CHAPTER VII

GENERAL SUMMARY

The major objective of the present study was to understand, more fully, some of the factors affecting the S requirement of New Zealand pastures.

To achieve this, S$^{35}$-labelled gypsum fertilizer was applied, in field trials, to several pastures in Canterbury, New Zealand. These trials were located on soils representative of major New Zealand soil groups (recent, yellow-brown earth and high country yellow brown earth). Trial locations were selected to differ principally in the degree of pastoral improvement, rainfall and the S retention capacity of their associated soils.

In the first series of seven field experiments, S$^{35}$-labelled gypsum fertilizer (45.0 kgS/ha) was applied in the early spring (1971) to four improved and three unimproved pastures. With the exception of two improved pastures, all trials exhibited S responses over the duration of the experiment (600 days).

The fate of fertilizer S was followed in both the soil and pasture for varying periods of time. Total recoveries of the added fertilizer S, in the soil-pasture systems studied, were generally > 80%.

Some major processes affecting the fate of applied fertilizer S, were examined. These included the incorporation of fertilizer S into soil organic matter, its movement in the soil and its recovery by pasture
plants. Changes in fertilizer S within the plant-available pool of soil S were also studied.

The effect of pastoral improvement on the fate of fertilizer S was studied on soils representing the recent and yellow brown earth soil groups. The major processes affecting the fate were pasture uptake and incorporation of fertilizer S into the soil organic matter fraction. By the end of the first year, the pasture recovery of fertilizer S was almost three times greater on the improved pasture of each soil. However, in the following year, greater recovery (almost twofold) was measured on the unimproved pasture of each soil. Larger amounts of fertilizer S were incorporated into the soil organic matter of the improved pasture on each soil. By the end of the first year almost all the fertilizer S in the upper 15 cm of soil was in organic combination on both the improved and unimproved pasture of each soil.

The effect of rainfall on the fate of fertilizer S was studied on two soils of similar texture and S retention capacity, within the recent soil group. One soil received an annual rainfall of 625 mm in comparison to 1000-1200 mm on the other soil. All three of the major processes studied were affected by rainfall. Prior to winter (D240) markedly different distribution patterns of fertilizer S down the profile were found. On the lower rainfall soil, most of the fertilizer S was within the 0-15 cm soil depth, whilst on the higher rainfall soil, fertilizer S was evenly distributed throughout a depth of 60 cm. Although rainfall differed over the winter period, fertilizer S was lost from both soils beyond a depth of 60 cm. By the end of the first year, a greater amount
of fertilizer S was recovered by pastures from the higher rainfall soils. This uptake pattern was reversed between soils in the following year. Although both soils displayed initial differences in fertilizer S incorporation into the organic fraction, these differences disappeared by the end of one year.

The effect of soil type on the fate of fertilizer S, was shown by comparing the results from the trials used to assess the effect of pastoral improvement on the fate of fertilizer S. When soils of different S retentive capacities, but with similar pastoral development, were compared, the main process affecting the fate of applied S was the downward movement of fertilizer S. On the yellow brown earth soil, on either the improved or unimproved pasture, fertilizer S did not penetrate beyond 60 cm by the end of one year. However, on the recent soil, with both improved and unimproved pastures, some fertilizer S was lost from the 0-60 cm soil zone over the winter period. Up until early winter, both soils had markedly different fertilizer S distribution patterns. Most of the fertilizer S on the yellow brown earth soil was above 30 cm with fertilizer S on the recent soil uniformly distributed to 60 cm, the maximum depth of sampling. Since fertilizer S remained in the upper 60 cm, even after 250 mm of leaching water was calculated to have resulted over the winter period on both the improved and unimproved yellow brown earth soil, it was suggested that \( \text{SO}_4^-\text{S (p.e.)} \) levels in the lower depths of this soil would increase rapidly with pastoral improvement. In fact, comparison of the unimproved and improved soil \( \text{SO}_4^-\text{S (p.e.)} \) levels to 60 cm on the control treatments, of these trials, showed that substantial accumulation of \( \text{SO}_4^-\text{S (p.e.)} \) had resulted on the improved soil. By contrast, soil \( \text{SO}_4^-\text{S (p.e.)} \) levels differed little between the improved
and unimproved pastures on the recent soil.

A further effect of soil type, due to differences in soil waterholding capacity, was studied when fertilizer S movement on a steepland yellow brown earth soil (low waterholding capacity) was compared with that on a similarly developed recent soil (high waterholding capacity) receiving the same rainfall. A much larger amount of fertilizer S had moved beyond 45 cm on the steepland soil, soon after application.

In order to determine the soil depth from which pasture plants extract their S requirements, the specific activity of harvested pasture was related to the specific activity of \( \text{SO}_4^-\text{S} \) (p.e.) in different soil depths. The results showed that the depth of the S uptake zone varied between soils.

Changes in the S specific activity of harvested pasture showed that equilibrium with the added fertilizer had been reached by D240 in most trials. An attempt was made to determine the size of the S cycling pool at each trial location by using their respective pasture S specific activity equilibrium levels. No relationships could be established between the size of the S cycling pool and the S response pattern measured at the various field experiments.

The significance of the various processes influencing the rate of fertilizer S was determined by considering the effect they had on the available pool of fertilizer sulphur (phosphate-extractable fertilizer S). Results showed that even within one trial location, the relative effect of one process, with respect to the other processes, altered over time. In general, leaching (or downward movement) beyond the major plant S uptake
zone, was of particular significance in only the first two months after fertilizer S application at most trials.

The design of the field experiments enabled both 'actual' and "apparent" recovery of fertilizer S to be calculated at the various trials. The results showed that with only three replicates greater experimental precision could be achieved with the actual recovery method. Mean values, from each trial for each method, showed that for practical purposes the "apparent" recovery method would suffice especially when calculated within six months of fertilizer S application.

A second series of field experiments were also conducted to further study the fate of $^{35}$S-labelled gypsum fertilizer (45.0 and 22.5 kgS/ha) applied at two of the trial locations, used in the first series, but in a different year. These trials were located on soils, representative of the recent and yellow brown earth soil groups, containing improved pastures. The time of fertilizer S application was two months later than that used in the previous series. Hence, the rates and relative significance of the various processes studied differed between years. Apart from the greater "residual" pasture recovery of fertiliser S in the second year after application, the results from both trials were as anticipated from the previous trial results at a similar location. The addition of $^{35}$S-labelled gypsum at a lower rate (22.5kgS/ha compared with 45.0 kgS/ha) gave slightly greater recovery of fertilizer S. The extent and pattern of the downward movement of fertilizer S was little affected by fertilizer rate but greater incorporation of fertilizer S into soil organic matter occurred at the lower rate on the improved recent soil.
Adjacent to the second series of field experiments with $^{35}$S-labelled gypsum fertilizer, two other field experiments were laid down in early spring to determine the soil zone from which plants obtain S. A technique was developed to insert carrier-free $^{35}$S horizontally into the soil profile at four depths (7.5, 22.5, 37.5 and 52.5 cm). The results showed that on the sandy loam (recent) and the silt loam (yellow brown earth) soils, both grasses and clovers recovered $^{35}$S from all depths. The $^{35}$S uptake data, and an assessment of the size of the plant available S at each depth, enabled calculation of the relative contribution each soil depth made to plant $^{32}$S uptake. Most $^{32}$S uptake occurred in the upper two depths studied. These depths represent the A horizon or topsoil of both soils. A trial of similar design in the following autumn showed that on the recent soil, plant uptake of $^{32}$S occurred to a depth of 100 cm but ceased on the yellow brown earth soil at 60 cm.

Growth cabinet experiments were initiated in an endeavour to assess the significance of root decay on the amount of labelled S returned to growing plants over the growing seasons of one year. Ryegrass (*Lolium perenne*) was used to assess the plant availability of the fertilizer S incorporated into plant residues (roots and tops). Labelled S recovery by ryegrass ranged from 6-16% over a period of 23 weeks and was dependent on the soil type, degree of pastoral improvement, type and form of plant residue added.

The overall results from the field and growth cabinet experiments conducted in this study, indicated that even within one agricultural region of New Zealand, the S requirements of pastures are likely to be
difficult to predict unless detailed information on the processes and factors affecting the fate of fertilizer S is available.

It was concluded that a knowledge of the soil zone from which plants extract their S requirements is of special importance in determining "residual" effects. Insect damage to plant roots may substantially affect the soil zone from which plants extract S. Rainfall, especially in the first few months after topdressing with superphosphate or gypsum fertilizer in early spring, should always be assessed in relation to likely leaching losses. Losses of fertilizer S from the root uptake zone of low S retentive soil horizons may occur soon after fertilizer S application. Large losses (70%) of fertilizer S were measured, on a steepeland yellow brown earth soil in this present study, only two months after fertilizer S application. It is likely that most of this fertilizer S loss occurred via leaching only four weeks after fertilizer S application. It was also concluded that the lack of S responses at previous field trials, on soils within this steepeland soil set, may be due to excessive initial leaching of S contained in the gypsum used in these trials. Hence, it would seem imperative that future fertilizer trials in this soil set should contain treatments with elemental S added. Additionally, when autumn spring topdressing is practised by farmers, fertilizer containing elemental S should be used.

Relatively small differences in the time of fertilizer S application appeared to be of particular importance. The second series of field experiments, using S\textsuperscript{35}-labelled gypsum fertilizer, gave larger "residual" effects than the first series of field experiments. This finding is of
particular practical significance as current trends in fertilizer use show that there is a swing away from annual topdressing. Thus it was concluded that where S is the major nutrient deficiency, topdressing pastures one to two months later than normal (early spring) could be considered. With the later application the extent of S leaching losses, beyond the soil zone where most of the plant S uptake occurred, should be reduced, thus giving higher "residual" effects. Depending on the rate of fertilizer S application, this change in fertilizer use may reduce the annual application rates of superphosphate. In some situations superphosphate may be omitted for a year or two. It is also possible that the variable S responses shown in recent S fertilizer trials in Canterbury may have been due to differences in fertilizer application time prior to the commencement of these trials.

On the free-draining yellow brown earth soil, \( \text{SO}_4 - \text{S} \) (p.e.) was found to accumulate with topdressing over the years. This in turn has led to a lack of a pasture S response in time. On these soils, and provided P status is satisfactory, the trial results suggested that superphosphate could be withdrawn for at least two years without pasture production being unduly affected. Alternatively, the use of either more concentrated P fertilizers such as di-ammonium phosphate or other P fertilizers of low S content (i.e. calciphos) could be considered without predisposing toward S deficiencies.

The extent of initial fertilizer S incorporation into organic matter on unimproved pastures was much lower than on their improved counterparts on the same soil. Hence, the potential for leaching losses
of fertilizer S is higher, initially, on unimproved soils when superphosphate is applied in the spring. Elemental S should be added to superphosphate fertilizer in order to reduce leaching losses in these situations.

It was also concluded that a knowledge of the size of the S cycling pool was of limited value in relation to determining the S response pattern. It appeared more important to establish the rate at which S was cycling between the various components of the S cycle. This aspect is worthy of more intensive study. On one soil type (Gorge silt loam) pastoral improvement increased the size of S cycling pool almost twofold. This increase was not accompanied by a change in the amount of total soil sulphur within the upper 30 cm.
ACKNOWLEDGEMENTS

I wish to record my gratitude to the following people:

Dr K.M. Goh (Department of Soil Science, Lincoln College); for his untiring encouragement, ready advice and helpful supervision throughout this study.

Professor T.W. Walker (Department of Soil Science, Lincoln College); for his interest and encouragement.

Mr S.D. Mann (Formerly Ministry of Agriculture and Fisheries); who assisted me in the harvesting and soil sampling associated with the field trials.

Mr R.W. Tillman (Department of Soil Science, Massey University); for many helpful discussions.

Mr R. McPherson (Department of Soil Science, Lincoln College); for his assistance with chemical supplies and laboratory equipment.

Professor J.K. Syers (Department of Soil Science, Massey University): for his encouragement and understanding over the last two years.

My wife (Annette); for her unfailing patience, understanding and encouragement over the duration of this study.

My parents; for their continual interest and provision of the initial opportunity to attend University.

Mrs D. Steffert; who typed this thesis in a very capable manner.

Finally, I would like to thank the New Zealand Government who granted me leave to undertake this study.
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