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THE UNIVERSITY OF ALBERTA

REVEGETATION OF FOREST SOILS ACIDIFIED BY ELEMENTAL SULPHUR

by

Ruth Ann Gal

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Revegetation of Forest Soils Acidified by Elemental Sulphur" submitted by Ruth Ann Gal in partial fulfilment of the requirements for the degree of Master of Science.

M. Nyborg
(SUPERVISOR)

Gregory Taylor

DATE Oct. 14 19 86

TO MY GRANDMOTHERS

MAGDALENE

AND

BERNICE

ABSTRACT

Windblown elemental sulphur (S^o) dust was deposited in coniferous forests adjacent to sulphur storage blocks near two sour gas plants south of Rocky Mountain House, Alberta, Canada. Soils became acidic and the ground cover declined.

Nil, LIME, S^o, and LIME + S^o treatments were initiated at a control site and two previously S^o dusted sites. NH_4NO_3 fertilizer, both N^{15}-tagged and untagged, was amended over a three year period to sites adjacent to and within the main treatments. An incubation experiment was conducted which simulated the above treatments in the laboratory.

When 2000 kg S^o ha^{-1} was added to litter taken from an uncontaminated site, 30% of the S^o was converted to sulphate after 53 days of incubation. The pH dropped 0.7 units per month. More sulphate (18000 mg kg^{-1}) was produced on the S^o treatment than on the lime plus S^o treatment (9000 mg kg^{-1}). In field experiments, soil pH was unaffected for the first year by the addition of S^o. After this initial lag period, pH dropped ($p<0.05$) in the L and FH.

Loss of NH_4NO_3 (41%) from a lime plus S^o site was greater than at any S^o site (10% lost). Liming increased nitrification from 3 to 63 mg NO_3-N kg^{-1} in the LHF of a previously S^o dusted site. Recovery of N^{15} was higher in the NIL (71%) than in the LIME + S^o (42%) treatments and greatest in the 0-5 cm mineral horizon (44%) of the NIL. Lime plus S^o increased the loss of gaseous N from 3 mg N Kg^{-1} to 116 mg N Kg^{-1} (N as N_2 or NH_3 found in net bags suspended over N^{15} treated cylinders).

Colonization on S^o dusted sites sown with cultivated grasses and red clover was unsuccessful, regardless of lime or fertilizer additions. Moss and herb cover increased with added lime (from 22 to 50% and from 5 to 39%, respectively). Addition of fertilizer N with lime decreased moss and herb cover (from 50 to 14% and from 33 to 17%, respectively). Where ground cover was absent, grasses grew best with N fertilizer and lime additions. In these sites, **Elymus innovatus** Beal, **Calamagrostis canadensis** (Michx.) Beauv., **Epilobium angustifolium** L., and **Cornus canadensis** L. were the only native colonizers.

Acidification reached a depth of 10 cm within three years on the S^o treatment of a previously S^o dusted site. A "lag" effect in S^o oxidzation occurred in the field and in the laboratory in leaf litter which had not been previously S^o dusted. Mineral N was immobilized into the LFH and 0-15 cm mineral horizon. Native grasses grew well with the addition of N fertilizer on the LIME + S^o treatment.

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1. INTRODUCTION

1.1 HISTORY

The view from the top of a sulphur stockpile at a sour gas plant in the boreal forest of Alberta is spectacular. The stockpile at the Ram River gas plant is 15 m high, 300 m wide, and 800 m long. The brightness of yellow on a sunny day is in contrast to the dark green of the coniferous forest - an island of yellow in a sea of verdant green.

Elemental sulphur (S^O) is a yellow crystalline solid which is inert and water insoluble (Tisdale **et al.**, 1985). Sulphur is a by-product of the sour gas industry. Molten sulphur is transported by pipe from the plant to the stockpile. Retaining walls contain the molten sulphur until it cools. It solidifies into a rhombic form at room temperature and pressure, although a mixture of orthorhombic and monoclinic forms may be produced during the cooling of the liquid sulphur.

In earlier years, and still at some gas plants, the sulphur stockpile was broken with front-end loaders, remelted, and made into small slates or pellets before shipping or temporary storage. Now in situ remelters are used and the liquid sulphur is piped directly to a reprocessing facility. Prill towers, up to 70 m in height, process this liquid sulphur into a readily transportable form. During prilling, the molten sulphur is dropped through plates containing numerous holes. As the droplets fall, air currents force them back up and they tumble about in the tower till they reach the bottom as round pellets (approximately 5 mm in diameter). The towers form pellets much in the same way as hail is formed in nature. Whether the sulphur stockpile is broken down with front-end loaders or the molten sulphur is made into pellets, incidental sulphur dust is formed. Both small and larger dust particles are dropped at various distances from the plant, depending on wind speed.

Ram River and Strachan are the largest and tenth-largest sour gas processing plants in Alberta, respectively. Together they process approximately 13% of the province's natural gas (Addison et al., 1984). The Ram River plant became operational in 1973 and the Strachan plant in 1974. Significant S^o dusting of the forest in the vicinity of the sulphur blocks began at Ram River 1 to 2 years earlier (1978-79) than at Strachan (1980). At the Strachan plant, before 1980, most shipments were transported as molten sulphur. At Ram River, shipping of sulphur slates commenced in 1976 and by 1979 approximately 2.5 million tonnes of sulphur had been taken from the blocks.

Studies at the Innisfail and Waterton gas processing plants showed that adequate applications of lime restored plant growth to agricultural soils that had been acidified by S^o dust (Nyborg, 1974 and Bertrand, 1973). However, in a coniferous forest adjacent to a sour gas processing plant near Fox Creek, revegetation was slow despite liming (Nyborg, 1983).

1.2 LITERATURE REVIEW

1.2.1 SULPHUR IN SOILS

Sulphur occurs in many compounds which together constitute 0.01 to 0.05% of the soil mass in field soils (Starkey, 1950). Up to 25% of this sulphur may be in the form of sulphate. Unbound sulphates are readily leached under most conditions. Under dry conditions, however, they may accumulate in the form of gypsum in a definite layer (Cca) some distance from the soil surface (i.e. in Chernozems). The sulphate ion moves only when accompanied by a cation (usually calcium) and thus the base is lost from the soil and the hydrogen ion remains. The most readily available form to plants and heterotrophic micro-organisms is sulphate. However, sulphur in plant tissue and organic matter is released slowly during organic matter decomposition (Gray and Williams, 1971). Organic sulphur in plant proteins is returned to soil in the litter, where it is decomposed by a large variety of micro-organisms with the release of H_2S. Some micro-organisms can also convert organic sulphur to sulphate directly without the intermediate production of H_2S (Alexander, 1961). The amount of readily available organic sulphur in soil represents a balance between synthesis and metabolism by micro-organisms. Most of the S-containing amino acids in soil appear to be bound to the mineral and humus fractions (Freney and Stevenson, 1966).

1.2.2 ACID SULPHATE SOILS

The majority of the research on highly acidified soils has been done with respect to acid sulphate soils. Areas near natural sour gas plants have S^0 dust, which is in a reduced state (an oxidation state of 0 compared to H_2SO_4 which is +6) added to the soils. The S^0 is oxidized and produces acidity with a pH value less than 3.5 (Addison et al., 1984).

1.2.2.1 Terminology and Definitions

The U.S. classification system (Soil Survey Staff, 1975) defines "sulphidic materials" as:

> "waterlogged mineral or organic soil materials that contain 0.75 percent or more total sulphur (on a dry weight basis), mostly in the form of sulphides and that have less than 3 times as much carbonates ($CaCO_3$ equivalent) as sulphur".

A "sulphuric horizon" is defined as:

> "a mineral or organic horizon that has both a pH < 3.5 (1:1 in water) and with yellow jarosite mottles with hues 2.5 or yellower and chromas 6 or

more in the Munsell notation".

The British system defines a "sulphuric horizon" as having a pH of 3.5 or less in 0.01 M CaCl (Avery, 1973).

A "thionic unit" is defined, in the legend of the Soil Map of the World (FAO/UNESCO, 1968), as:

> "one containing sufficient sulphur compounds to cause acidification of the soil, when oxidized, to a pH (in KCl) of less than 3.5, within 100 cm of the surface"

Bloomfield and Coulter (1973) emphasized the importance of distinguishing between potential and actual acid sulphate soils. Potential acid sulphate soils have the potential for severe acidity due to the presence of sulphidic materials. Actual acid sulphate soils have a sulphuric horizon and may be in a highly oxidized condition.

1.2.2.2 Characteristics

The two most obvious characteristics of acid sulphate soils are a low pH (3 to 4) and the presence of yellow mottles of jarosite ($KFe_3(SO_4)_2(OH)_6$) (Pons, 1973). Soils may have high sulphur contents but lack jarosite mottles, due to hydrolysis of ferric oxides (van der Kevie, 1973). An acid sulphate soil may exist only a few years and probably not more than about a hundred years before acids are neutralized or leached away (assuming no continued input of acid forming compounds or precursors) (Brinkman and Pons, 1973).

1.2.2.3 Occurrence

Acid jarosite clays (catclays) found on recent coastal marine sediments are reduced sulfide muds which have been acidified due to oxidation of the iron sulphides following drainage and aeration. Mangrove swamps and marshy backswamps such as those found in the lower tidal reaches of large river deltas are a prime example of these catclays (Bloomfield and Coulter, 1973). In the Netherlands, Dutch polders and their associated acid sulphate soils are examples found in temperate regions (Dost, 1973). Inland acid sulphate soils form on "fossil" marine sediments (Pawluk, 1971, Pawluk and Dudas, 1978, Foscolos and Kodama, 1981) which are rich in pyrite. With the advent of large sulphur stockpiles in Alberta, there could be a new occurrence of acid sulphate soils added to the list - one of localized areas near sour gas processing plants.

1.2.2.4 Genetic Processes

Under reduced, wet conditions, potential acid sulphate soils are called "mud clays" and have a pH value near neutrality (Jenny, 1980). On drying, the soil becomes oxidized and an acid sulphate soil is formed with a concomitant lowering of the pH value. A cyclic condition could occur at soil microsites during wet and dry phases.

Oxidation of pyrite may be written summarily as the following:

$$4FeS_2 + 15O_2 + 14H_2O \dashrightarrow 4Fe(OH)_3 + 8H_2SO_4$$

(Van Breemen, N., and K. Harmsen, 1975). This reaction does not go to completion and insoluble basic iron sulphate $KFe_3(SO_4)_2(OH)_6$ crystallizes as jarosite, a yellow gel that coats ped surfaces and rings root channels. In the absence of carbonates, strong sulphuric acid maintains pH values of 2 to 4 that persist for decades. Under these conditions clay minerals become unstable and decompose to form clays saturated with exchangeable aluminum (Bohn et al., 1979). Acidity liberates K from mica, converts clays to soluble Al clay aggregates, and imparts to the soil solution Al^{3+} concentrations that exceed the tolerance limits of many crops (Jenny, 1980).

1.2.3 Sulphur Oxidation by Micro-organisms

When S^o is added to soil, it is oxidized to sulphate with a concomitant lowering of the pH. Elemental sulphur in soil may be oxidized more rapidly by **Thiobacillus thiooxidans** than by heterotrophic micro-organisms. Fertile soils contain an abundance of micro-organisms that will oxidize sulphur (Starkey, 1950). **Thiobacillus thioparus, T. denitrificans, T. novellus** and **T. intermedius** occur commonly in soils: **Thiobacillus thiooxidans** and **T. ferrooxidans** have seldom been recovered, except in situations when considerable S^o or sulphate are present (Starkey, 1966). T. **thiooxidans** and T. **ferrooxidans** grow best at pH 2 to 3 and can produce 1 M H_2SO_4. A strict autotroph, **Thiobacillus thiooxidans** oxidizes S^o and thiosulphate to sulphate rapidly (Allen, 1959). In soil with a population of several different species of **Thiobacillus** the effect of pH is not clear cut, for the combined optimum ranges for T. **thiooxidans**, T. **intermedius**, T. **thioparus** and T. **novellus** cover values from 2.0 to 9.0. **Thiobacillus** is strictly autotrophic, in the sense that it requires an inorganic electron donor, an inorganic electron acceptor and uses only carbon dioxide as its major carbon source (Buchanan and Gibbons, 1974). The conversion brought about by **Thiobacillus thiooxidans** is given below:

$$2S + 3O_2 + 2H_2O \dashrightarrow 4H^+ + 2SO_4^{-2}$$

The overall reaction rate is influenced by exposed surface area, water, partial pressure of oxygen, pH, ferric ion concentration, catalytic agents (e.g. bacteria or specific ions), and inhibitors (bactericides or alkaline materials) (Barton, 1978).

Acidification may be needed when land is high in carbonates, as in the arid western regions of Canada (Tisdale **et al.**, 1985). Solonetzic soils may be acidified to reduce high concentrations of Na^+-ions. Elemental sulphur (500 mg) was added to a Solonetzic soil (50 g) with and without the addition of sulphur oxidizing microorganisms

(McCready and Krouse, 1982). After 12 weeks of incubation the original pH value of 8.4 dropped to pH 7.8 in the uninoculated soil, pH 4.6 with the addition of T. thiooxidans, and pH 3.3 with T. thioparus (24%, 34%, and 84% of the S^o was oxidized, respectively).

1.2.4 Soil Acidity and Liming

Acidity in soils has several sources: humus or organic matter, aluminosilicate clays, hydrous oxides of iron and aluminum, exchangeable aluminum, soluble salts and carbon dioxide (Tisdale et al., 1985). Clay minerals have a permanent charge due to isomorphous substitution. Sesquioxides, organic matter, and clay minerals also have a pH dependent charge, generated by the dissociation of hydrogen ions from hydroxyl, phenolic or carboxylic groups of soil organic matter. Hydrolysis of monomeric forms of Al^{+3} (displaced from clay minerals by cations) liberates H^+ and lowers pH. Addition of salts, such as those contained in fertilizers, to sesquioxide-coated interlayered minerals increases hydrolysis of nonexchangeable iron and aluminum resulting in an increase in the hydrogen-ion concentration of the soil solution. Excess H^+ ions: 1) effect root membrane permeability, 2) compete with other cations for absorption sites, and 3) interfere with ion transport (Foy, 1984).

Sulphuric acid formed from the oxidation of S^o will acidify soil. Soil behaves like a weak buffered acid which will resist sharp changes in pH. Neutralization of the soil acidity is brought about by liming. In a noncalcareous soil in a temperate region with average organic matter (Donahue et al., 1983) it took the following amounts of S to change the pH value from 7.0 to 6.5: 100 kg S ha^{-1} in sand, 170 kg S ha^{-1} in loam, and 350 kg S ha^{-1} in clay. The pH value of moss dropped from 4.7 to 3.5 on the addition of 80 kg S ha^{-1} as H_2SO_4 after 3 days of equilibrium (Nyborg, 1976). A similar experiment conducted by Nyborg (1983) showed a change in the pH value from 4.3 to 3.2 in the 0-2.5 cm layer and 4.0 to 3.6 in the 2.5-15 cm layer of the LFH of a coniferous forest to which 36 kg S ha^{-1} had been added as H_2SO_4.

In water, $CaCO_3$ reacts as follows:

$$CaCO_3 + H_2O \dashrightarrow Ca^{2+} + HCO_3^- + OH^-.$$

The rate of this reaction is directly related to the rate at which OH^- ions are removed from solution (Coleman and Thomas, 1967). As long as sufficient H^+-ions are in solution, Ca^{2+} and HCO_3^--ions will increase in number. With high H^+-ion concentrations, the solubility of Ca^{2+} and HCO_3^- is reduced. Elevating CO_2 pressures of air renders $CaCO_3$ more soluble in the form of calcium bicarbonate ($Ca(HCO_3)_2$) (Jenny, 1980). The solubility of $CaCO_3$ is marked in the A1 horizon because of high biological CO_2 production. The reaction

$$CaCO_3 + H_2SO_4 + H_2O \text{------>} CaSO_4 \cdot 2H_2O + CO_2$$

occurs instantaneously when the reactive species come into contact (Barton, 1978).

1.2.5 Fertilizer Application in the Forest

Forest fertilizer studies have shown that fertilizer N retention in the forest ecosystem is low (Keeney, 1980). Turner (1977) reported N recovery by the aboveground portion of the forest as 6.4% and 5.2% of the added N when 220 or 880 kg N ha^{-1} as urea was applied to a 45-year Douglas-fir stand.

Other N^{15} work related to forest nutrition includes decomposition of forest litter (Overrein and Broadbent, 1964) and the translocation of N in pine and spruce (Nommik, 1966). Denitrification rates were higher for urea than NH_4NO_3 in a forest soil from Sweden (Pluth and Nommik, 1981). The understory of the forest has not been studied closely as to its growth after fertilizer application.

1.3 OBJECTIVES

Studies were conducted in areas near S^o blocks to determine the feasibility of liming and fertilizing to maintain natural vegetation. The major premise was that addition of S^o dust, to a forest soil resulted in a drop in soil pH, high levels of extractable sulphate, and a reduction in both cover and composition of plant community.

(decrease in moss and herb cover; increase in grasses). The minor premise became that the addition of lime ($CaCO_3$) raised the pH. The consequent premise was that liming of forest soils before deposition of S^o will circumvent the loss of natural vegetation.

The objectives were:

1) to determine pH change with depth and over time at a control site and two sites acidified by windblown S^o dust.
2) to compare the rate of S^o oxidation in litter samples with treatments of lime, S^o, and nitrogen.
3) to determine the most probable number of sulphur oxidizing bacteria in a forest soil (control and S^o dusted).
4) to determine the recovery of NH_4NO_3 as mineral N over a three-year period.
5) to determine the amount of N^{15}-tagged NH_4NO_3 fertilizer lost from the soil as total N with and without lime and S^o.
6) to determine the rate of mineralization with and without liming.
7) to determine the effect of soil acidification, liming, and fertilizer application on natural vegetation and cultivated forages in the field.

2. STUDY SITE - ROCKY MOUNTAIN HOUSE AREA

2.1 STUDY SITE

Two gas plants, Strachan (S1) and Ram River (S2) are located 13 km apart, about 45 km southwest of Rocky Mountain House, Alberta (Figure 2.1). The two contaminated sites were situated 50 m east of the S^o stockpiles. Control sites (C1, C2, and C3) were chosen in areas with little or no S^o dusting.

2.2 CLIMATE

The climate of the study area is cool, subhumid with long, cold winters and warm summers. The mean annual summer temperature is 10°C. January is the coldest month with a mean of -13°C and July is the warmest month with a mean of 15°C. (Canadian Climate Normals, 1951-1980).

The Prairie Creek Station (Table 2.1), was cooler (by about 2.5°C) and had more rainfall during the growing season (46 mm) than the Rocky Mountain House Station. The mean daily temperature and total daily rainfall for the Prairie Creek Station are presented in Tables 2.2 and 2.3.

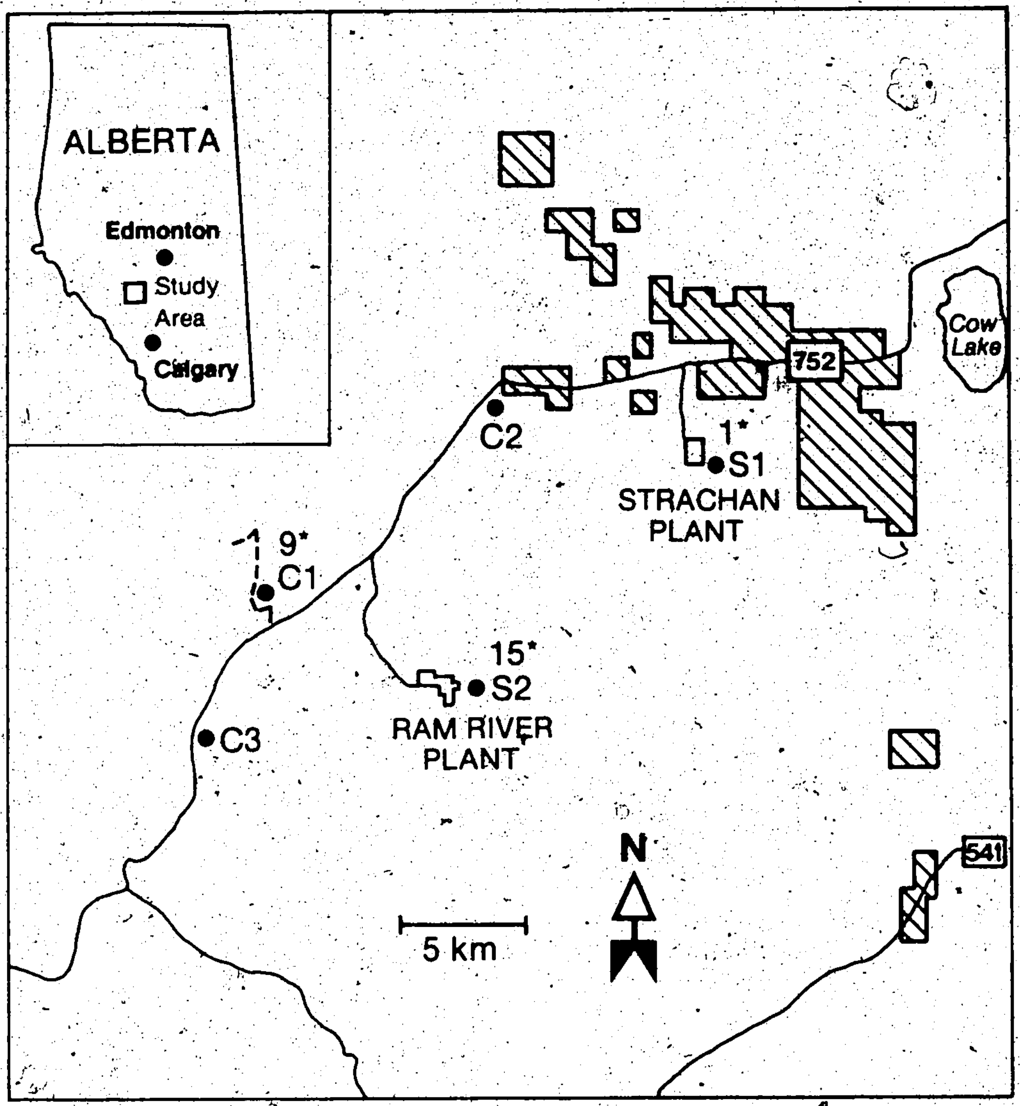

Figure 2.1. Location of sour gas processing plants and study sites in West-Central Alberta. **C1**: Control, Big Plots; **C2**: Control, Small N Plots; **C3**: Control, MPN Plot; **S1**: Strachan Plots; **S2**: Ram River Plots; 9*, 1*, and 15* were established in 1981 by Addison et. al. (1984).

▨ Improved land (Alta. ENR, 1980)

Table 2.1. Mean monthly temperature (°C) and total precipitation (mm) for Rocky Mountain House and Prairie Creek (Canadian Climate Normals, 1951 - 1980).

	ROCKY MT HOUSE 52°23′ N 114°55′ W ELEV 1015 M		PRAIRIE CREEK 52°15′ N 115°18′ W ELEV 1173 M	
MONTH	MEAN DAILY TEMP(°C)	TOTAL PPT(MM)	MEAN DAILY TEMP(°C)	TOTAL PPT(MM)
JAN	-13.0	27.6	-14.9	31.8
FEB	-7.4	19.6	-9.1	20.8
MAR	-4.6	26.7	-6.0	27.5
APR	3.0	34.5	0.8	34.5
MAY	9.2	60.5	6.4	72.6
JUN	12.8	104.4	10.2	116.2
JUL	15.3	93.1	12.6	92.3
AUG	14.3	77.1	11.7	103.8
SEP	9.7	49.7	7.1	46.3
OCT	4.9	22.7	2.3	21.2
NOV	-3.6	17.9	-5.5	16.2
DEC	-9.1	22.3	-11.3	22.9
TOTAL		556.1		606.1
MEAN	2.6		0.4	

Table 2.2. The daily mean temperature for the Prairie Creek Research Station for June-September 1983 (AES headquarters ID: 3015295).

DAY	TEMPERATURE (°C)			
	JUNE	JULY	AUG	SEP
1	9.5	11.3	18.3	13.0
2	4.3	11.0	20.8	13.8
3	9.0	14.5	14.8	8.3
4	7.8	12.8	15.0	7.8
5	12.5	15.3	17.0	8.0
6	10.8	11.0	14.5	8.5
7	11.3	11.8	17.3	7.0
8	10.8	13.0	17.5	2.0
9	13.3	12.0	17.5	5.8
10	11.8	11.3	18.0	3.5
11	7.3	13.0	16.3	6.3
12	7.8	14.5	17.0	7.0
13	9.5	16.3	14.5	7.0
14	11.5	9.5	13.5	9.5
15	14.5	7.0	12.3	7.0
16	12.5	9.5	13.0	1.5
17	12.8	10.8	13.3	2.8
18	9.0	12.0	12.5	1.0
19	8.5	13.0	10.5	2.8
20	8.5	16.0	10.0	3.0
21	10.3	13.8	10.0	6.8
22	9.5	13.0	11.3	10.0
23	10.3	14.0	13.3	8.0
24	13.0	15.0	13.5	10.3
25	11.8	14.8	13.8	11.5
26	11.5	14.0	11.5	11.8
27	12.0	11.3	11.5	2.3
28	11.5	12.5	14.8	-0.3
29	13.5	13.5	13.0	0.0
30	11.5	14.0	13.8	-0.3
31		15.8	17.5	
MEAN	10.6	12.8	14.4	6.2

Table 2.3. The total daily rainfall for the Prairie Creek Research Station for June-September 1983 (AES headquarters ID : 3015295).

DAY	RAINFALL (MM)			
	JUNE	JULY	AUG	SEP
1	0.6	0.8	1.4	6.8
2	4.9	38.0		t
3	t*	2.2		2.6
4	4.0			3.1
5	0.8	t		
6	2.0	7.0		0.4
7		24.0		0.2
8		3.0	1.6	10.2
9				t
10	1.0			
11			11.4	
12	1.0	0.6		
13	0.4			
14		1.8		
15	1.4	20.2		
16		3.0		9.6
17		0.6	0.4	
18	7.0			
19	16.6	0.4		t
20	14.4	2.2		
21	9.2			2.0
22	3.2			
23	13.2			
24	14.0	2.6		
25			t	
26				t
27	1.8			7.0¬
28		3.4		
29				
30	11.2			
31				
TOTAL	106.7	109.8	14.8	41.9

* trace

¬ 3.8 mm fell as show

2.3 VEGETATION

The dominant species for the study sites were **Pinus contorta** Loudon var. **latifolia** Engelm. with co-dominant or minor components of **Populus tremuloides** Michx., **Picea glauca** (Moench) Voss and **P. mariana** (Mill.) BSP. The ground shrub layer consisted of **Alnus crispa** (Ait.) Pursh, **Salix sp.**, **Linnaea borealis** L. var. **americana** (Forbes) Rehd., **Vaccinium myrtilloides** Michx., **V. vitis-idaea** L. var. **minus** Lodd., **Ledum groenlandicum** Oeder, **Spiraea lucida** Dougl., and **Rosa acicularis** Lindl. The major herb species were **Cornus canadensis** L., **Maianthemum canadense** Desf. var. **interius** Fern., **Calamagrostis canadensis** (Michx.) Beauv., **Elymus innovatus** Beal, and **Epilobium angustifolium** L. Moss and lichens at the control site included **Pleurozium schreberi** (Brid.) Mitt., **Ptilium crista-castrensis** (Hedw.) DeNot., **Hylocomium splendens** (Hedw.) B.S.G., **Cladonia** sp., and **Cetraria pinastri** (Scop.) S.Gray. The sites near the two gas plants had few mosses or lichens. Nomenclature for all species named followed Moss (1983) for vasculars, Conard and Redfearn (1979) for mosses, and Hale (1979) and Brodo and Hawksworth (1977) for lichens.

2.4 PHYSIOGRAPHY, GEOLOGY, AND SOILS

The study area was located on the hills of the Western Alberta Plain (Bostock, 1970) which is underlain by strata of Paleocene (Upper Cretaceous - Tertiary) age belonging to the PasKapoo formation. The formation consists of calcareous sandstones, siltstones and mudstones, which have hard and soft layers. The entire area is covered with glacially derived materials resulting from deposition during deglaciation and the resorting of these deposits by glacial meltwater or by wind (Land Resource Research Institute, 1981).

The sites were located on level to gently sloping topography of an undulating morainal plain or plateau (Addison et al., 1984) with the elevation rising from 1200 m at the Strachan gas plant to 1400 m at the Ram River gas plant and the control (C1) site. The soils in the study area were originally classified as Podzolic Grey Wooded soils (Peters and Bowser, 1960) which includes the Prentice sandy loam, Lobley loam, and Caroline loam and sandy loam soil series.

Soil pits were dug (Sep/Oct, 1982) at sites 50 m north of S2 and C1, and 50 m south of S1. The pedon was classified according to the Canadian System of Soil Classification (Canada Soil Survey Committee, 1978). Excerpts from the report of Addison et al. (1984) which give a comprehensive profile description are found in Appendix I. Strachan (S1) and the control (C1) were well to moderately well drained Brunisolic Gray Luvisols. Ram River (S2) was an imperfectly drained Gray Luvisol. The sola to depth were generally acidic (pH 5). The B horizons contained relatively high levels of pyrophosphate extractable Fe and Al (> 0.06%) which were related to the weathering of the carbonate component of the shallow eolian depths (Smith et al., 1983).

3. SOIL ACIDIFICATION AND LIMING

3.1 INTRODUCTION

Heavy applications of lime (finely ground limestone containing $CaCO_3$ with approximately 5% $MgCO_3$) have been used to reclaim soils acidified by windblown elemental sulphur since the 1970's in the vicinity of seven natural sour gas processing plants in Alberta (Nyborg, 1983). Some of the reclaimed areas were on agricultural land where annual crops or grasses now grow well. Revegetation after liming in a forest soil, however, was slow.

The purpose of the present study was to determine the rate of pH change at different depths of two soils acidified by S^o. Study sites included soils with and without heavy applications of lime.

3.2 EXPERIMENTAL PLOT LAYOUTS AND TREATMENTS

The control site (C1) was located 12 km NW of the Gulf Strachan Gas Plant, and about 1 km north of Highway 752 (Figure 2.1). Both the Strachan (S1) (Appendix IIi) and the Ram River (S2) (Appendix IIii) sites were approximately 75 m east of the sulphur blocks at the respective gas plants. The control site was established in the fall of 1981 while the Strachan and Ram River sites were established in the fall of 1980.

Four treatments were replicated three times in a randomized block design in plots 1.5 m by 20 m. The control (NIL) had no additions. "feedgrade" limestone (LIME) and elemental sulphur (S^o) were added by hand, separately and together (LIME + S^o). Plot locations were chosen to minimize the amount of under-bush and dead fallen trunks. Each treatment was spaced 0.9 m apart to eliminate contamination from lateral movement of the applied substances. Soil sampling and analyses were conducted on Experiment # 1 at S1 and S2 (Appendices IIi and IIii).

The NIL at C1 received neither lime nor sulphur. The NIL at S1 and S2 received windblown S^o from the break up of the stockpiles near the sites, beginning in 1978 at S2 and 1979 at S1. Gulf Canada Resources made two applications of "glass rock" limestone by air at S1: one in the fall of 1980 at 5600 kg ha^{-1} and another in the early winter of 1982 at 5370 kg ha^{-1}. During these aerial applications, the NIL and S^o treatments were covered with polythene (4 mil). The LIME treatment at C1 was added by hand at 6770 kg ha^{-1}; at S1 by air at 5600 kg ha^{-1}; and at S2 by hand at 9170 kg ha^{-1}. In addition to aerial contamination at S1 and S2, an S^o treatment was added by hand to all three sites at an average of 2266 kg ha^{-1}. The LIME + S^o treatment had sulphur added at the same rate as in the S^o treatment but lime was added at different rates and forms to each site: at C1, 17700 kg ha^{-1} "feedgrade" limestone; at S1, 12080 kg ha^{-1} "feedgrade" limestone and 5600 kg ha^{-1} "glass rock" limestone; and at S2, 18340 kg ha^{-1} "feedgrade" limestone. Lime was added in excess of 3 times the amount of S^o known to be present in the soil. In the case of LIME + S^o, lime was again added in excess to neutralize the additional S^o. The subsequent additions and time of application are listed in Appendices IIIi, IIIii, and IIIiii. Particle size of "feedgrade" limestone was 92% < 0.24 mm, and 8% between 0.24 mm and 2.0 mm, and of "glass rock" limestone, 29% <0.24 mm, and 71% between 0.24 mm and 2.0 mm. Nipher gauges have been used to measure snowfall (Goodison, 1978). In this study, S^o particles with an average diameter of 60 um (ranging from 2.5 um to 200 um) and < 5 um were collected in modified Nipher gauges (Nyborg, 1983) placed (at S1) 50 m east of the S^o stockpile and 400 m northeast of the prilling tower, respectively.

3.3 SAMPLING AND ANALYSES

For each replicate of each treatment, the following depths were sampled:

1) Undecomposed: A 15 cm X 15 cm area of the LFH which could be easily identified as leaves and/or needles - L layer.

2) Decomposed: A 15 cm X 15 cm area of the LFH which was in varying stages of decomposition, dark in colour and on occasion, with fungal hyphae interspersed throughout - FH layer.

3) 0-5 cm deep: mineral soil (3 cores).

4) 5-10 cm deep; mineral soil (3 cores).

5) 10-15 cm deep: mineral soil (3 cores).

Mineral soils were sampled with a "Lord" soil sampler with a core diameter of 1.9 cm. Samples were air dried and ground to pass through a 2 mm screen. For pH measurements, 3 g of undecomposed litter, 5 g of decomposed litter, or 10 g of mineral soil were mixed with 50 ml of distilled water, stirred and left to stand for one hour before measurement. A glass electrode was immersed into the partly settled suspension a calomel reference electrode was immersed into the supernatant solution. The 1983 samples were air dried and the pH taken as above (samples were not ground). A one way analysis of variance was performed on 3 replicates of 4 treatments at different sampling times. The arithmetic average pH value was used rather than the negative log of the hydrogen ion activity. The work of Baker, Kuo, and Chae (1981) demonstrated close agreement between arithmetic mean pH values of limed samples and the pH values of composite samples. When pH values were converted to H^--ion activities before averaging, results gave a lower pH value than for the composite sample.

Extractable sulphate was measured at C1, S1, and S2, from the NIL treatment using the method outlined by Carson et al. (1972). S^O was measured at S2 in the litter layers using a turbidimetric method (Hart, 1961).

3.4 RESULTS

3.4.1 Changes in pH from Year to Year

3.4.1.1 Control (C1)

Soil pH values ranged from 4.2 to 5.1 through the unlimed soil profile from the litter layer to 15 cm (Table 3.1). The pH varied less than 0.5 pH units over a two year sampling period, indicating little effect of time on the pH values. Litter layers had less variability than lower mineral horizons when comparing pH values from 4 sampling times of the NIL treatment. The trends were: a) pH of FH layer less than L layer, and b) an increase of pH in the mineral soil with depth.

When lime was added (6770 kg ha^{-1}), the pH increased ($p<0.05$) in the L layer and FH layer within 48 days (Sep/81 to Nov/81) of application (Figures 3.1a and 3.1b). However, after nine months (Jul/82), only the L layer differed ($p<0.05$). With the addition of S^{o} (2280 kg ha^{-1}), soil pH was lower ($p<0.05$) in the L layer compared to the NIL, nine months after application. With additions of lime (17700 kg CaCO$_3$ ha^{-1}) and S^{o} (2280 kg ha^{-1}), soil pH was greater ($p<0.05$) in the litter layers and the 0-5 cm mineral horizon by July 1982 (Figure 3.1c). In less than two years (Sep/81 to Jun/83) after the application of S^{o}, pH values of the organic layers were 2.2 in the L layer and 1.8 in the FH layer, with no decrease of soil pH of the 0-15 cm mineral horizons (Figures 3.1a to 3.1e).

Table 3.1. Mean and standard deviation of pH values (n=3) from four sampling times of the NIL treatment at the control site (C1) from 1981 to 1983.

DEPTH (CM)	SOIL PH (MEAN)	SOIL PH (S.D.)
L	4.4	0.09
FH	4.2	0.23
0 - 5	4.5	0.32
0 - 10	5.0	0.41
10 - 15	5.1	0.41

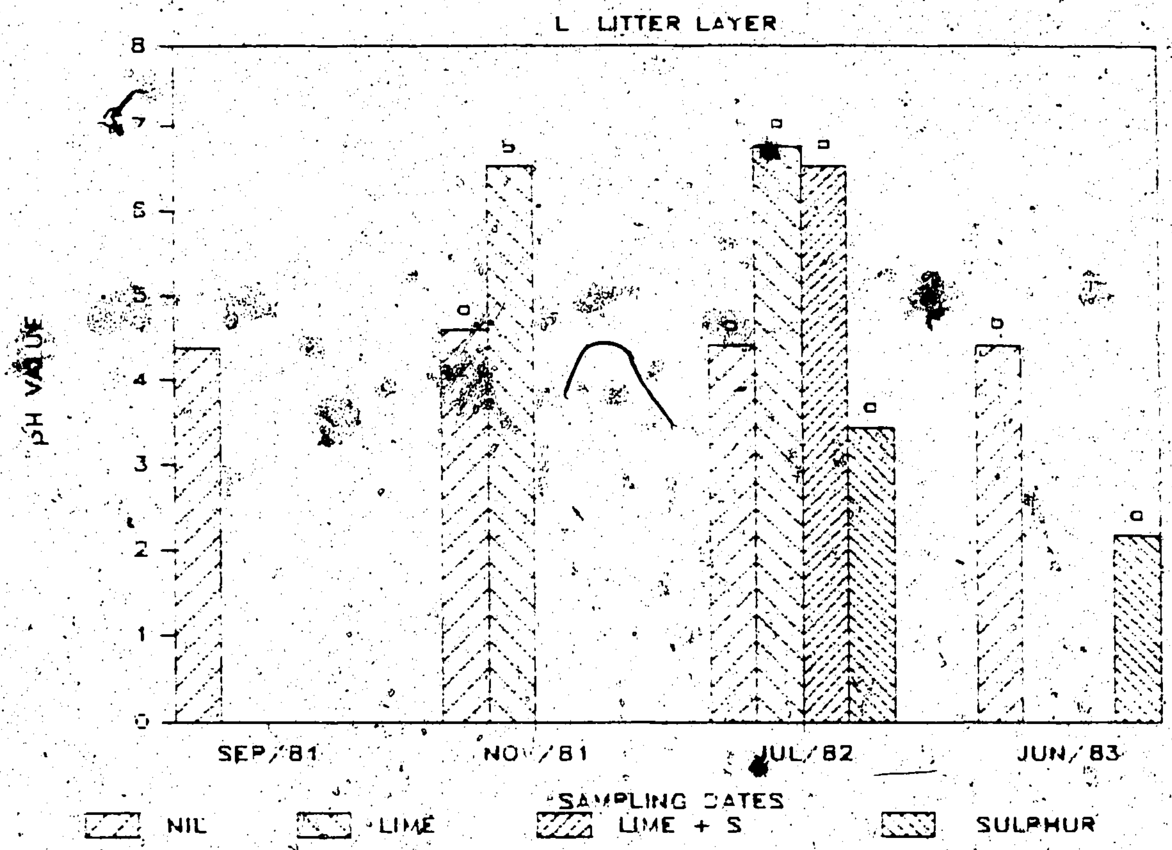

Figure 3.1a. pH values of the L layer at the Control site (C1) from September 1981 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Refer to Appendix IIIi for application rates and dates of lime and S^o.

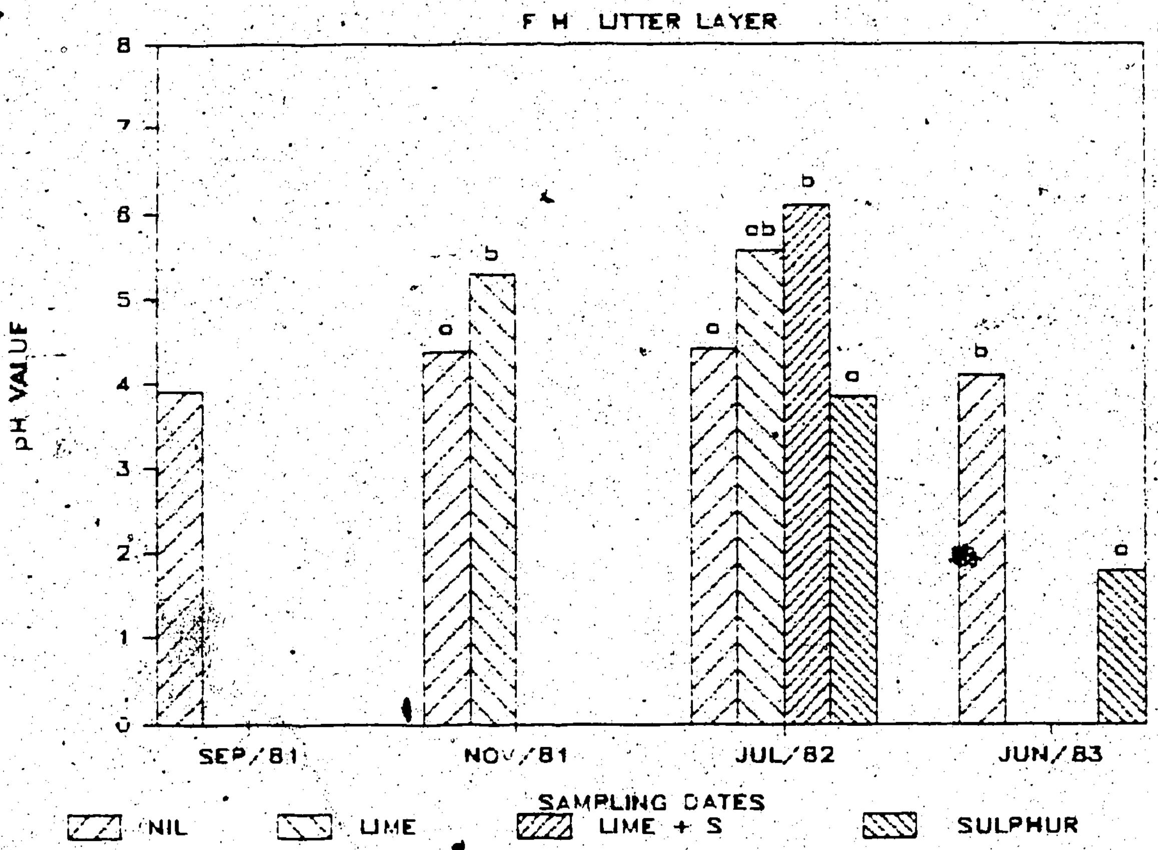

Figure 3.1b. pH values of the FH layer at the Control site (C1) from September 1981 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Refer to Appendix IIIi for application rates and dates of lime and S^0.

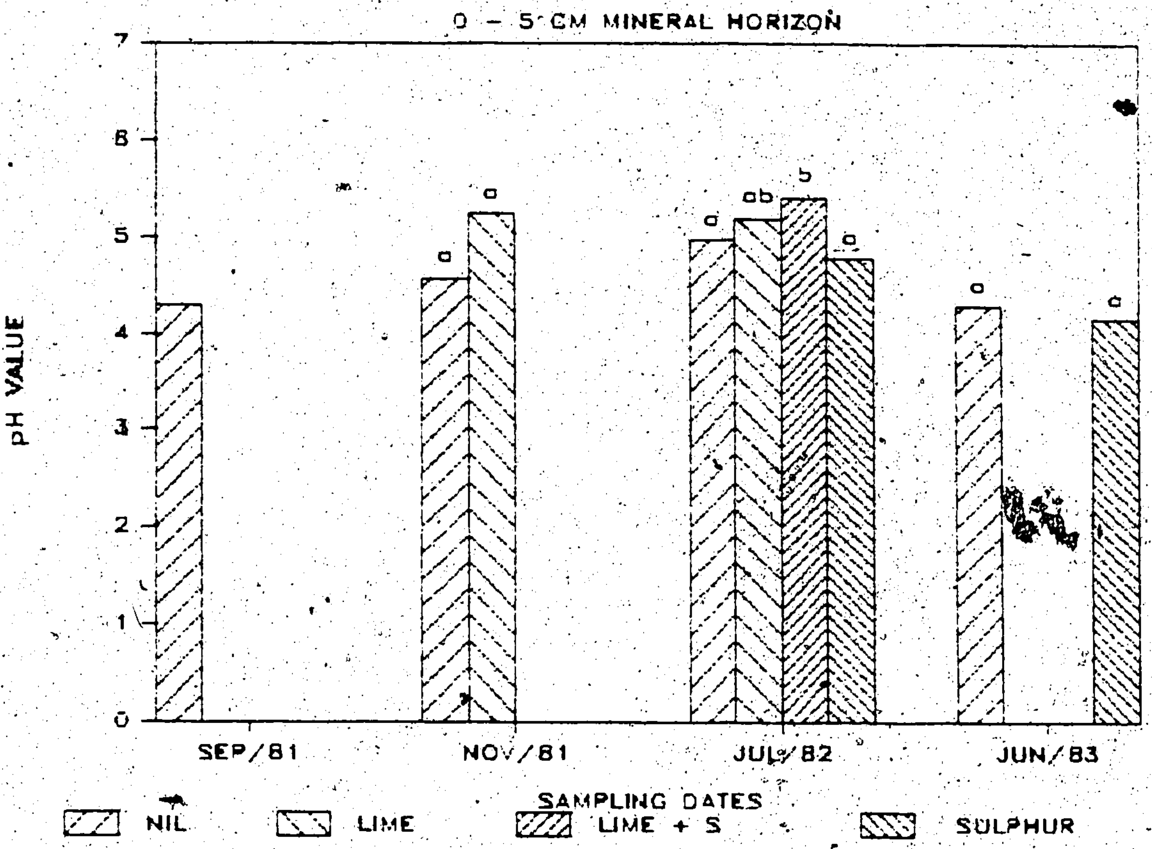

Figure 3.1c. pH values of the 0-5 cm mineral horizon at the Control site (C1) from September 1981 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Refer to Appendix IIIi for application rates and dates of lime and S^O.

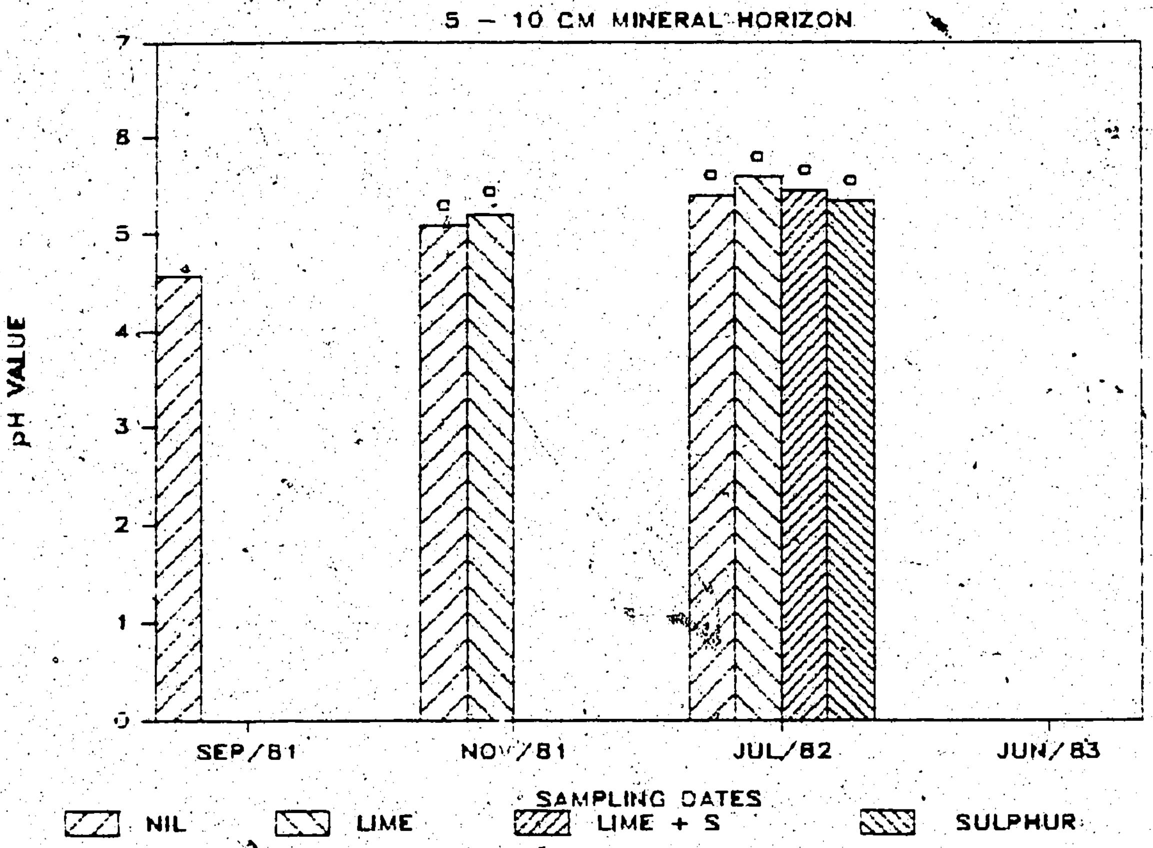

Figure 3.1d. pH values of the 5-10 cm mineral horizon at the Control site (C1) from September 1981 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Refer to Appendix IIIi for application rates and dates of lime and S^0.

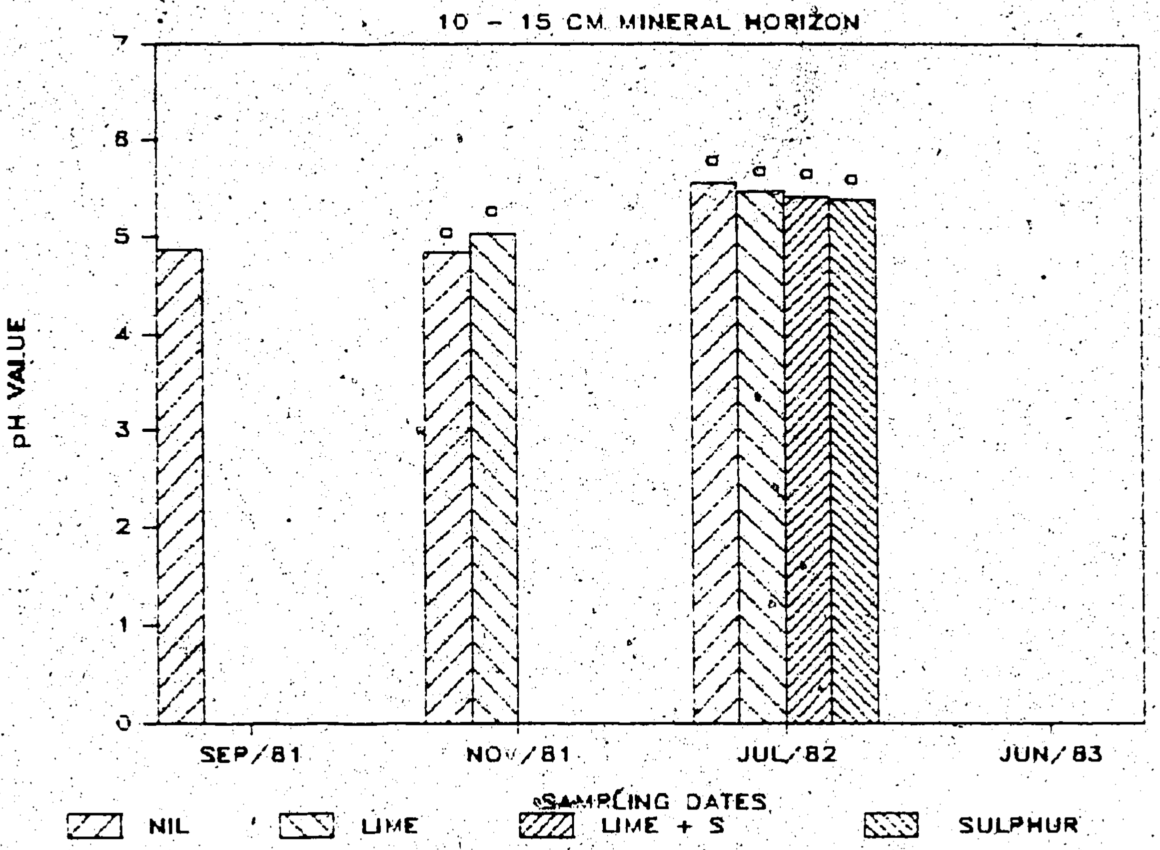

Figure 3.1e. pH values of the 10-15 cm mineral horizon at the Control site (C1) from September 1981 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Refer to Appendix IIIi for application rates and dates of lime and S^O.

3.4.1.2 Strachan (S1)

On initial sampling of the unamended treatment in Sep/80, the range of pH for the Strachan site was 4.1 to 4.8, with the lower pH found in the litter layers and pH increasing down the profile (Figures 3.2a to 3.2e). The pH decreased ($p<0.05$) with time on the NIL treatment in the litter layers and in the 0-5 cm horizon (Sep/80 to Jul/82). With addition of S^o, the pH response was similar to the NIL at all depths sampled (i.e. no significant difference between the NIL and S^o treatments) because the soil was rich in S^o before application and S^o fallout continued during 1980 to 1983. The pH value of the LIME treatment increased ($p<0.05$) down the soil profile with time compared to NIL and S^o. With an excess of $CaCO_3$ applied with the S^o in the LIME + S^o treatment, the pH value was greater ($p<0.05$) than in the LIME treatment alone. The amount of lime added (17680 kg ha^{-1}) was adequate to maintain the pH in the LIME + S^o treatment. In an effort to ensure the survival of the remaining ground cover in both the LIME and LIME + S^o treatments, $CaCO_3$ was added by hand in the fall of 1982. Later in that year, Gulf Canada Resources initiated a second aerial liming program; again, both the NIL and S^o treatments were covered with polythene. In June 1983, the pH value of the NIL, LIME and LIME + S^o treatments differed ($p<0.05$) in the FH (Figure 3.2b). Enough lime was added to neutralize S^o in the L layer, in both the LIME and LIME + S^o treatments.

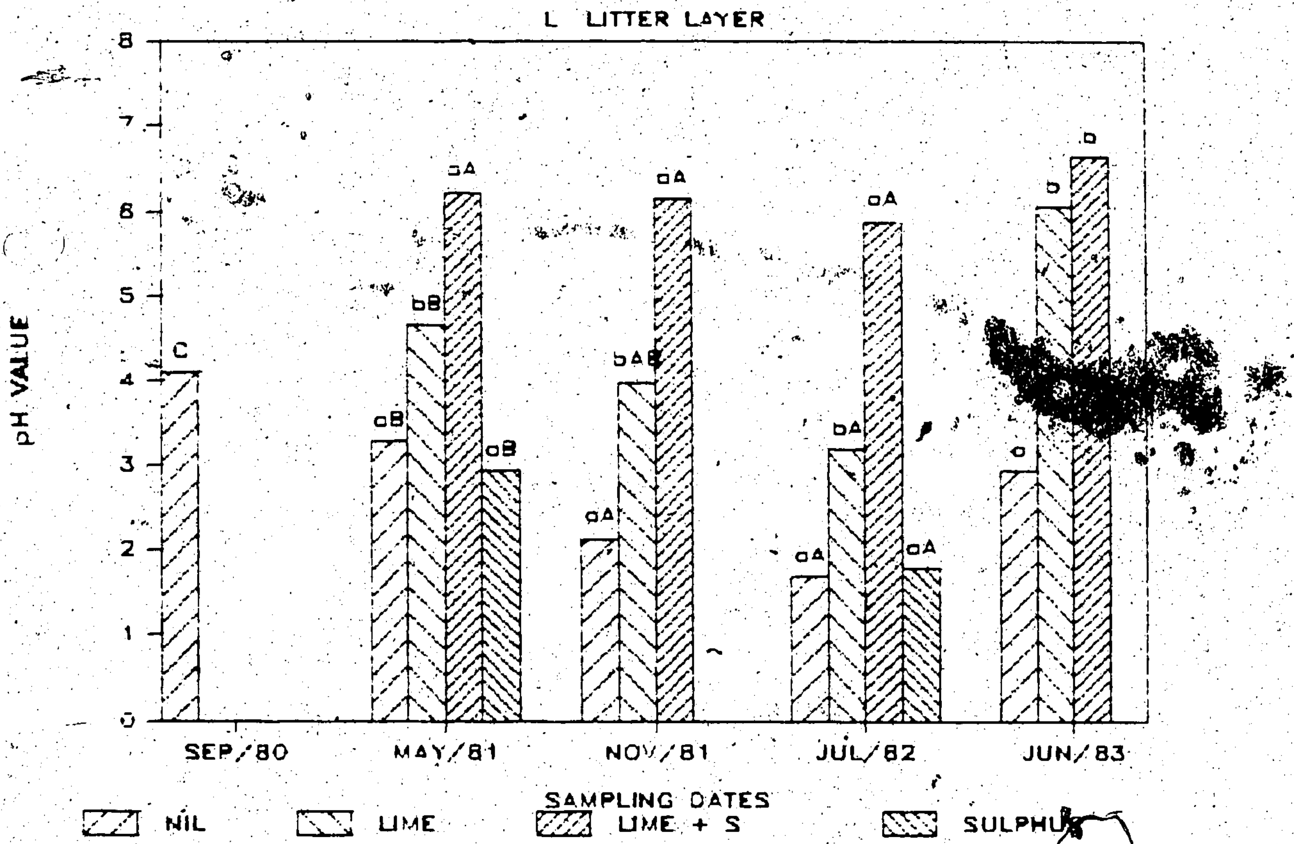

Figure 3.2a. pH values of the L layer at the Strachan site (S[illegible] from September 1980 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIii for application rates and dates of lime and S^{o}

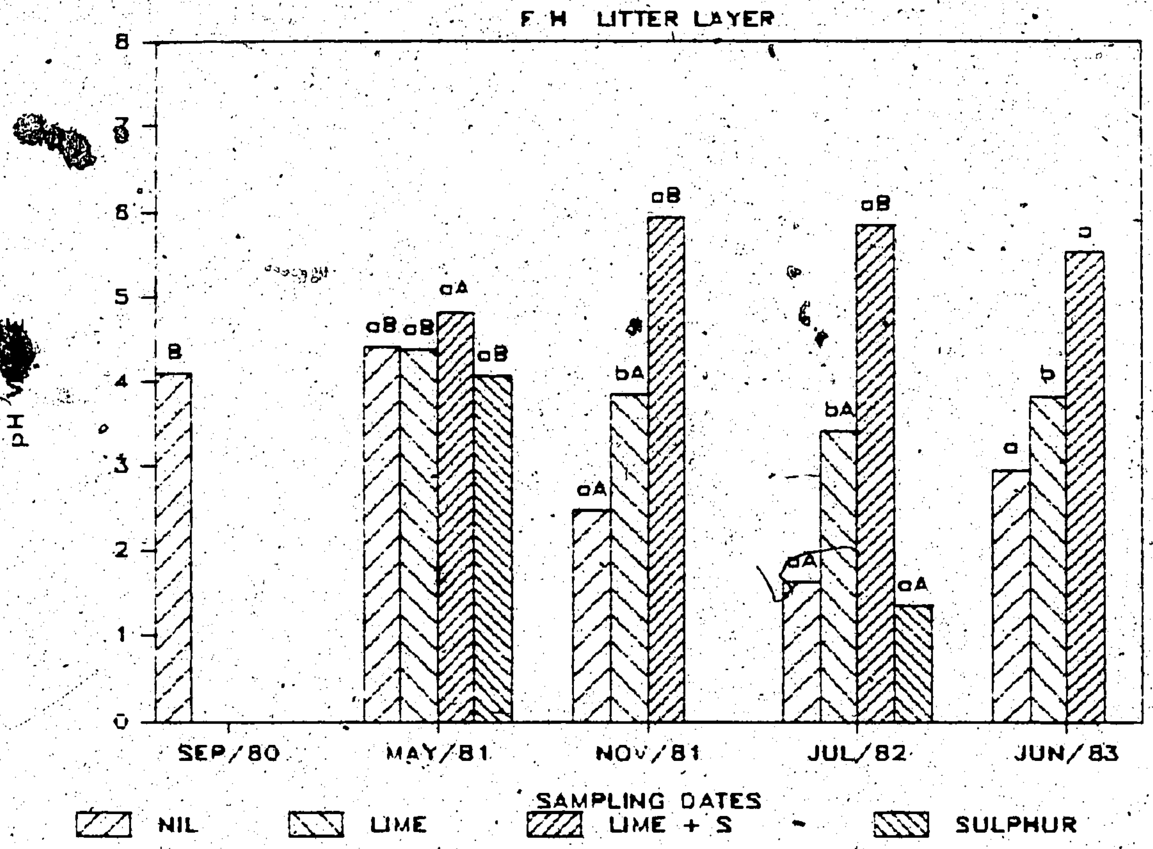

Figure 3.2b. pH values of the FH layer at the Strachan site (S1) from September 1980 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIii for application rates and dates of lime and S^{O}.

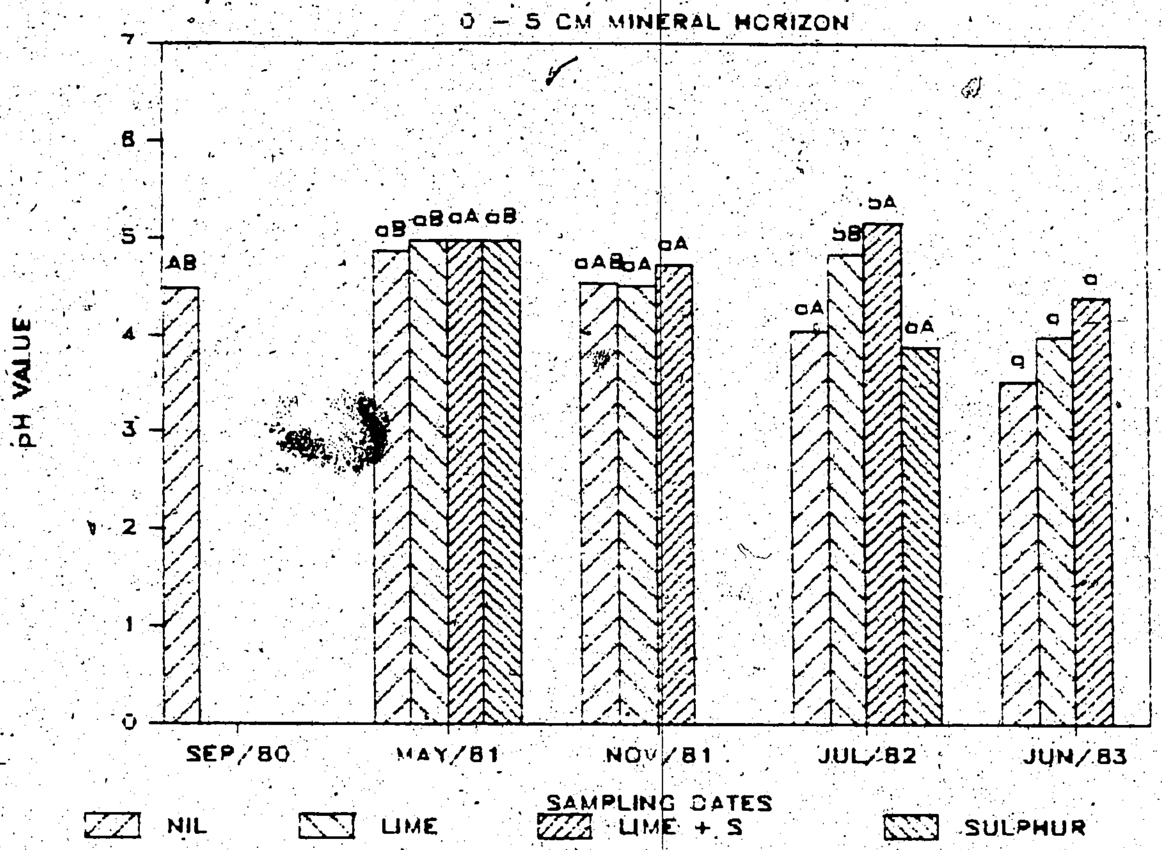

Figure 3.2c. pH values of the 0-5 cm mineral horizon at the Strachan site (S1) from September 1980 to June 1983. Different lower-case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIii for application rates and dates of lime and S^{o}.

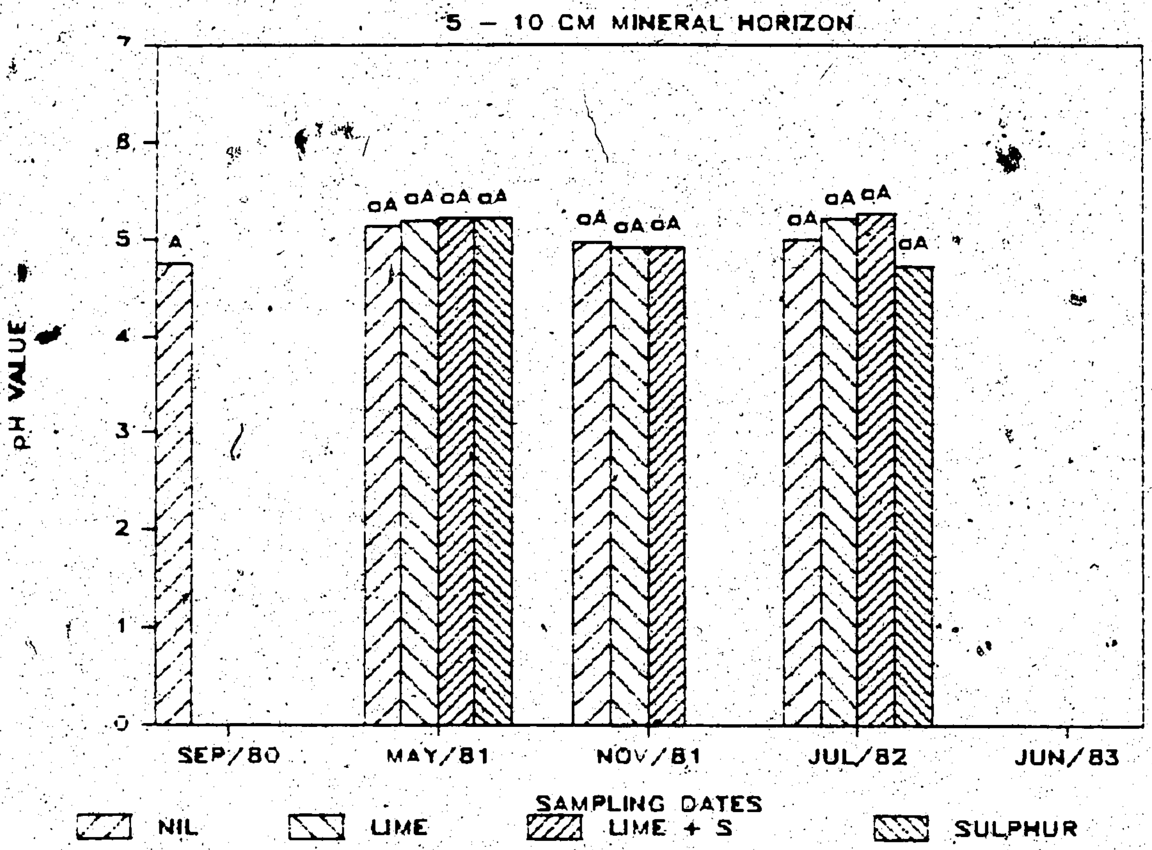

Figure 3.2d. pH values of the 5-10 cm mineral horizon at the Strachan site (S1) from September 1980 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIii for application rates and dates of lime and S^o.

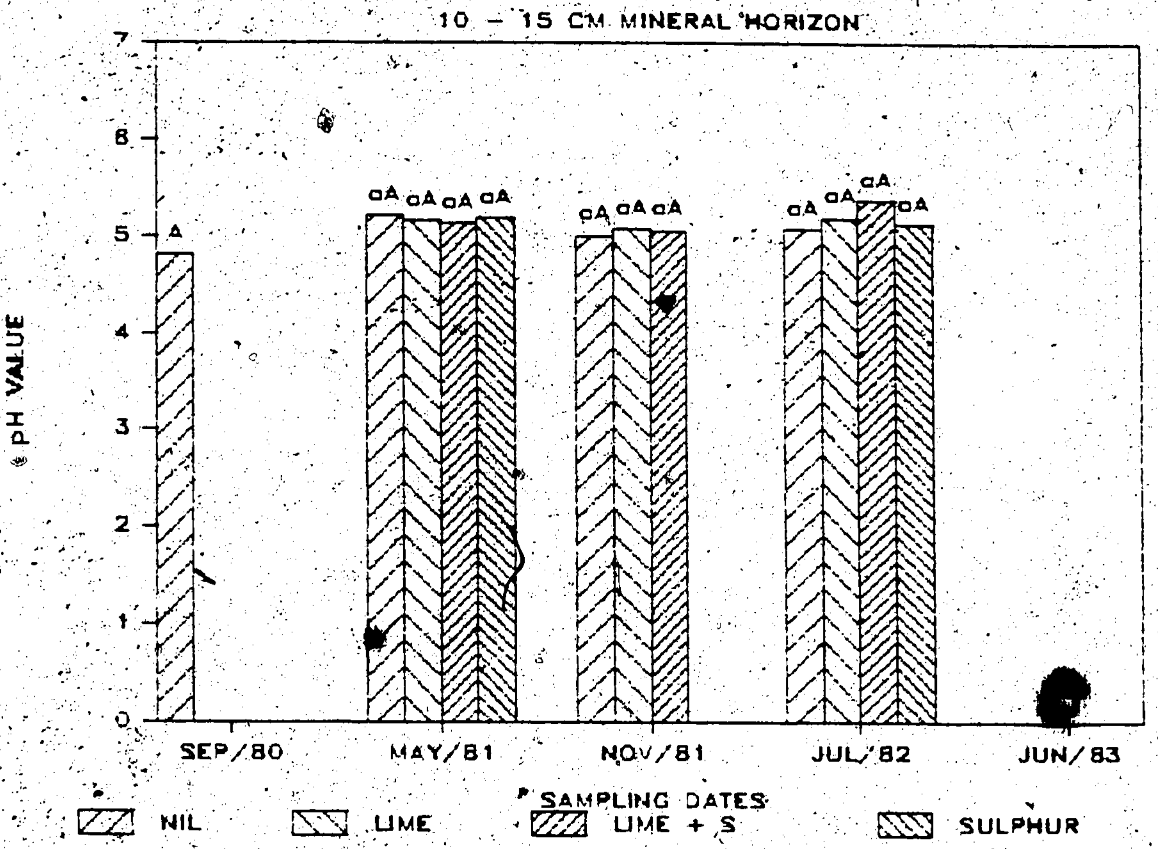

Figure 3.2e. pH values of the 10-15 cm mineral horizon at the Strachan site (S1) from September 1980 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIii for application rates and dates of lime and S^O.

However, pH in the FH of the LIME treatment had dropped.

The pH of the L layer decreased 1 pH unit on S^o treatments from Sep/80 to May/81, and 1.2 pH units from May/81 to Jul/82. The FH had no change from Sep/80 to May/81, but by Jul/82, the pH was 2.7 units lower. The pH did not change in the mineral horizons.

3.4.1.3 Ram River (S2)

The initial sampling (Nov/80) of the Ram River site (no aerial liming) showed low pH values in the surface layers with an increase of pH with depth (Figures 3.3a to 3.3e). The pH values for the NIL treatment were 2.4 for the litter layers, 4.0 for the 0-5 cm horizon, and 5.0 below this horizon to a depth of 15 cm. Twenty months later (Jul/82), the pH had dropped ($p<0.05$) to 1.9 in the L layer and 1.5 in the FH. The pH values of the 0-5 and 5-10 cm mineral horizons had decreased to 3.5 and 4.4, respectively.

The pH response in the S^o (2280 Kg ha^{-1}) treatment was similar to the NIL treatment at all depths sampled. The litter contained 2370 kg S^o ha^{-1} fallout (n=4; S.D.= 140), Jul/82. The pH value increased ($p<0.05$) in the LFH seven months (May/81) after the application of 9170 Kg lime ha^{-1}. However, in the subsequent 14 months, to Jul/82, pH in the LIME treatment dropped in the L layer from 6.0 to 2.4, and in the FH from 3.8 to 1.6. The pH values of the organic layers were less on the LIME treatment on Jul/82 than on the

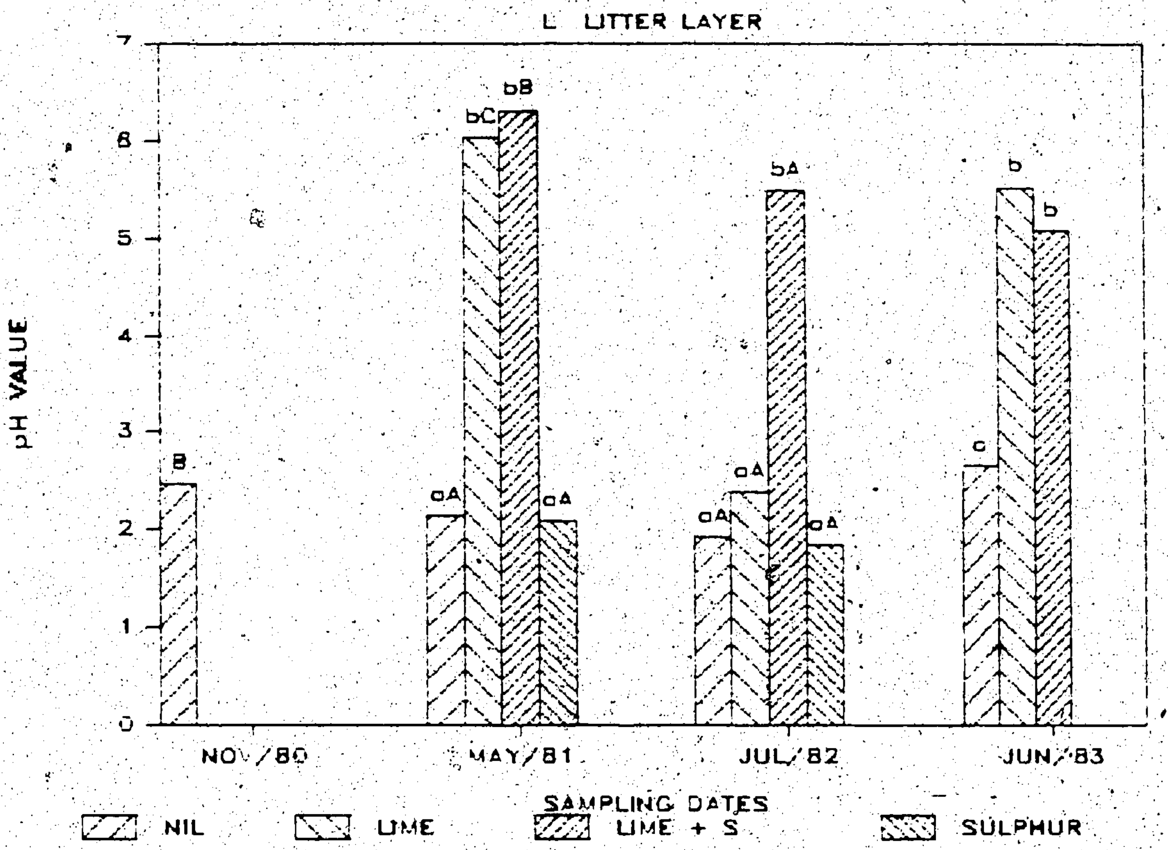

Figure 3.3a. pH values of the L layer at the Ram River site (S2) from November 1980 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIiii for application rates and dates of lime and S^{O}.

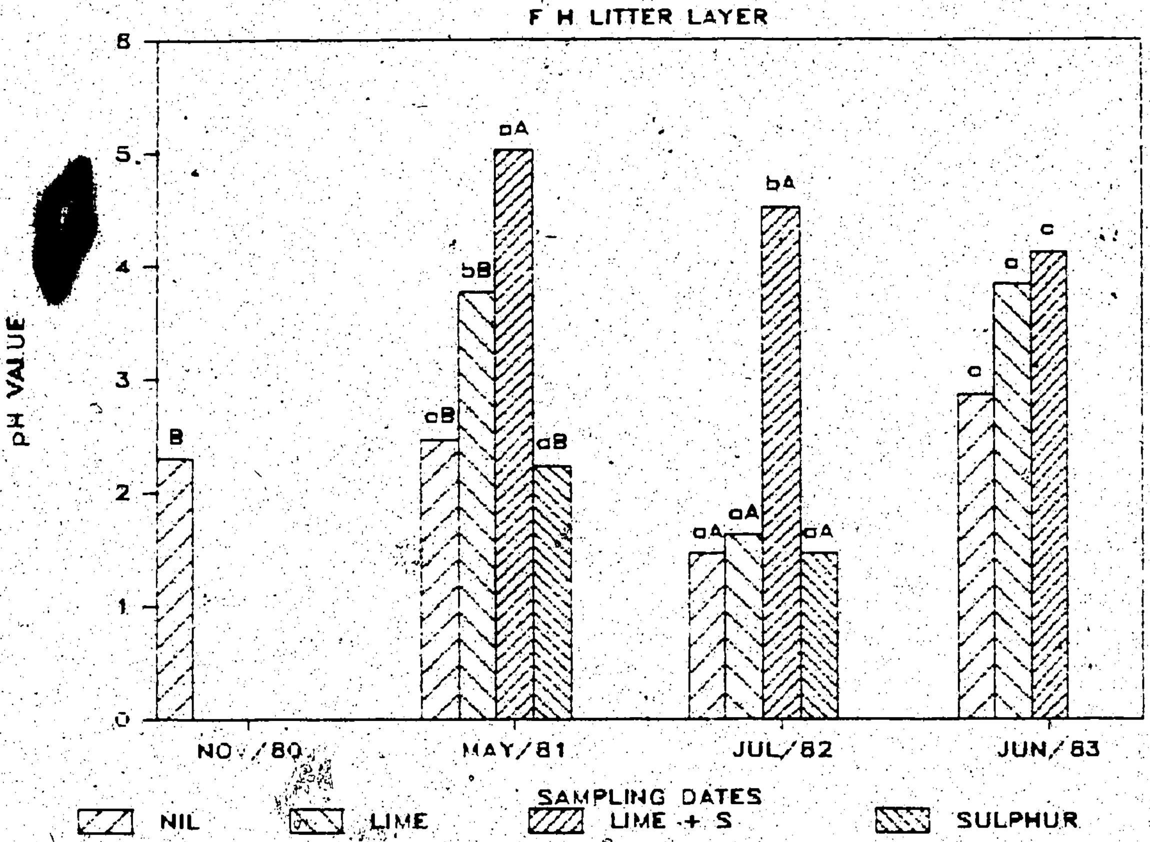

Figure 3.3b. pH values of the FH layer at the Ram River site (S2) from November 1980 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIiii for application rates and dates of lime and S^0.

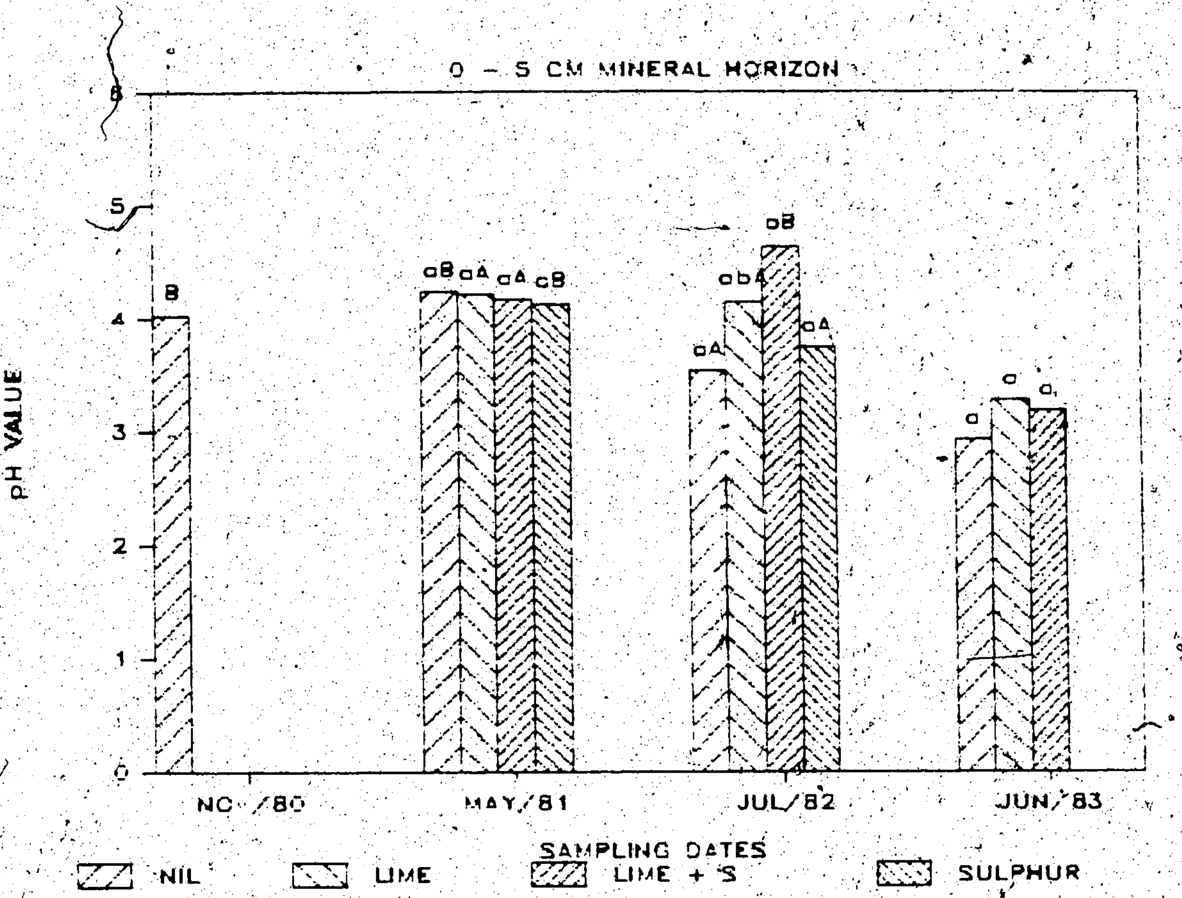

Figure 3.3c. pH values [illegible] 0-5 cm mineral horizon at the Ram River site (S2) [illegible] November 1980 to June 1983. Different lower case letters indicate significant differences (p<0.05) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences (p<0.05) in the pH value between sampling dates for one treatment. Refer to Appendix IILiii for application rates and dates of lime and S^{O}.

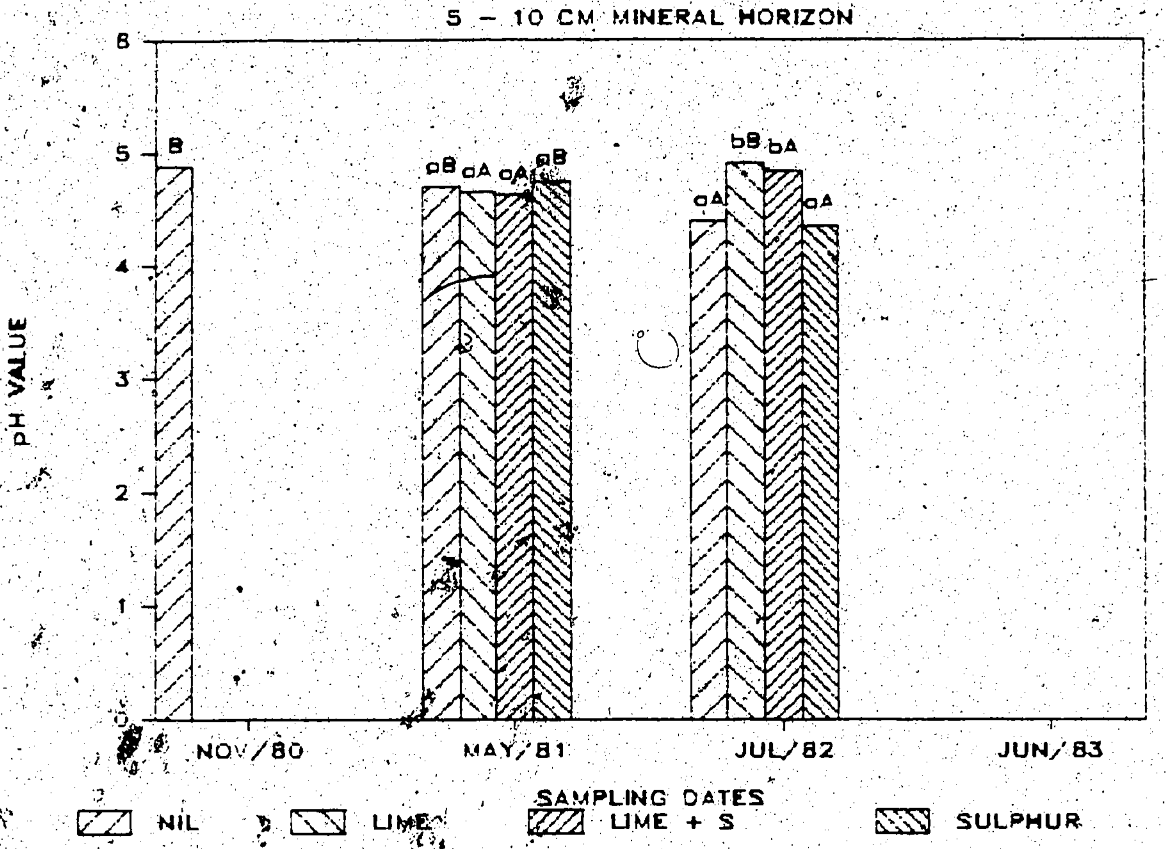

Figure 3.3d. pH values of the 5-10 cm mineral horizon at the Ram River site (S2) from November 1980 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIiii for application rates and dates of lime and S^0.

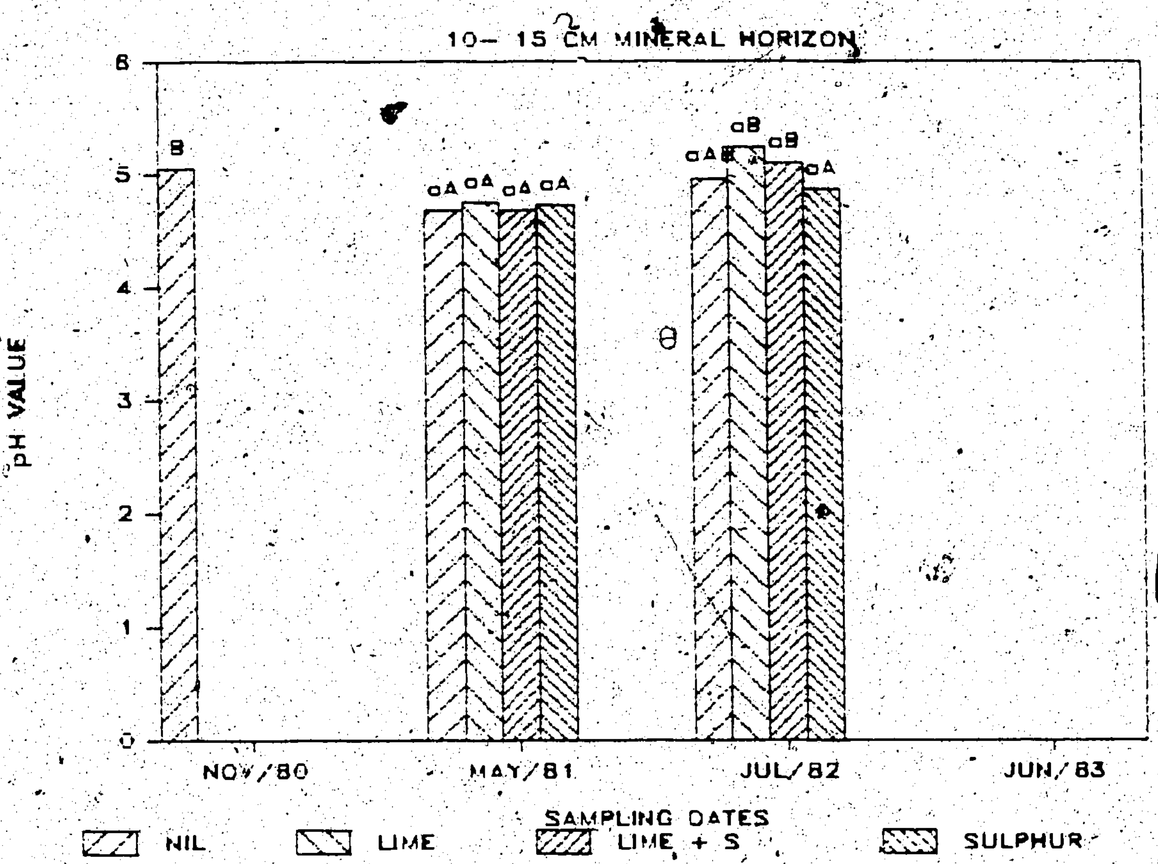

Figure 3.3e. pH values of the 10-15 cm mineral horizon at the Ram River site (S2) from November 1980 to June 1983. Different lower case letters indicate significant differences ($p<0.05$) in the pH value between treatments for one sampling date. Different upper case letters indicate significant differences ($p<0.05$) in the pH value between sampling dates for one treatment. Refer to Appendix IIIiii for application rates and dates of lime and S^O.

NIL treatment on Nov/80. Therefore, the 9170 kg lime ha^{-1} was overcome by acidity in 20 months (assuming no movement of lime into the mineral horizons).

When 18340 kg lime ha^{-1} was added in excess to that needed to counteract the S^{o}, the pH rose ($p<0.05$) in the litter of the LIME + S^{o} treatment (May/81). By July 1982, the pH value was greater ($p<0.05$) in the 0-5 cm and 5-10 cm horizons of the LIME + S^{o} treatment. This indicated that the $CaCO_3$ was moving down the soil profile. With additional lime (3750 kg ha^{-1}) (Fall/1982), the LIME and LIME + S^{o} treatments had greater pH values than the NIL treatment in the L layer when sampled in June 1983. However, the addition was either not sufficient to raise the pH values in the FH or more time was needed to allow the lime in the upper litter layer to move to a lower depth.

3.4.2 COMPARISON OF SITES

Initially, the pH change with depth was parallel between C1 and S1 while S2 was lower by 1.5 pH units in the litter layers of the NIL treatment (Table 3.2). By July 1982, the pH value of the organic layers at S1 and S2 was 2.5 units less than C1.

The sulphate-sulphur concentration in the NIL treatment was higher ($p<0.05$) at S2 than at S1 down to a depth of 30 cm (Table 3.3). The control site (C1), when compared to S1 and S2, had less ($p<0.05$) sulphate-sulphur.

Table 3.2. Soil pH with depth at C1, S1, and S2 on initial sampling and Jul/82 on the NIL treatment (Average depths of litter layers are found in Appendix VIiii).

	SITE		
	C1	S1	S2
INITIAL SAMPLING DATE	SEP/81	SEP/80	NOV/80
DEPTH (cm)			
L	4.4	4.1	2.5
FH	3.9	4.1	2.3
0-5	4.3	4.5	4.0
5-10	4.6	4.7	4.9
10-15	4.9	4.8	5.0
LATER SAMPLING DATE	JUL/82	JUL/82	JUL/82
L	4.4	1.7	1.9
FH	4.4	1.6	1.5
0-5	5.0	4.1	3.5
5-10	5.4	5.0	4.4
10-15	5.5	5.1	5.0

Table 3.3. Extractable sulphate (0.1 M $CaCl_2$) in soil samples taken from the control site (C1), Strachan (S1), and Ram River (S2), July 1982. Values are means and standard deviation of three replicates from the NIL treatment. Different upper case letters indicate significant differences ($p \leq 0.05$) in the amount of sulphate between sites.

SITE	CONTROL (C1)		STRACHAN (S1)		RAM RIVER (S2)	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
DEPTH	SULPHATE mg kg^{-1} (Kg ha^{-1})*					
LFH	73.0A (3)	1.4	10277B (640)	550	13273C (870)	196
0-15 CM	1.5A (3)	0.1	58B (120)	2	124C (240)	4
15-30 CM	0.9A (2)	0.1	33B (80)	4	46C (110)	2

* conversion from weight per weight to weight per area using known bulk densities.

with greater pH values in the L-FH layers, and in the 0-15 cm mineral horizons (Table 3.2)

Four pH responses (Jul/82) could be envisioned (Table 3.4) and compared to percent cover of ground cover in Chapter 6 and Appendix IX one year later (Jul/83):

1) EXCESS SULPHUR (S2/NIL)

The pH value was lower in the FH (1.5) than in the L layer (1.9). The pH of the 0-5 cm horizon was 3.5, then increased to 4.4 in the 5-10 cm horizon, and 5.0 in the 10-15 cm horizon. Ground cover was absent.

2)SLIGHTLY ACIDIC (C1/S^o)

The pH value was lower in the L layer (3.4) than in the FH (3.8). The pH of the 0-5 cm horizon was 4.8, then increased to 5.3 in the lower mineral horizons down to 15 cm. C1/S^o had 5% grass, 5% moss, and 5% herbs.

3) TYPICAL FOREST (C1/NIL)

The pH of the LFH was 4.4. In the mineral horizons the pH increased with depth (0-15 cm) from 5 to 5.5. C1/NIL had 22% moss and 7% herbs.

4) EXCESS LIME (C1/LIME and C1/LIME + S^o)

The pH value was greater in the L layer (6.6) than in the FH (5.7). The pH of the mineral soil (0-15 cm) was 5.4 on the average. C1/LIME had 50% moss and 15% herbs while C1/LIME + S^o had 6% moss and 12% herbs.

Table 3.4. Average pH (n=3) with depth in response to additions of lime and S^o at control (C1) and Ram River (S2), July 1982.

SITE	CONTROL (C1)				RAM RIVER S2
TREATMENT	NIL	LIME	LIME + S^o	S^o	NIL
DEPTH (cm)					
L	4.4	6.8	6.5	3.4	1.9
FH	4.4	5.5	6.1	3.8	1.5
0-5	5.0	5.2	5.4	4.8	3.5
5-10	5.4	5.6	5.4	5.3	4.4
10-15	5.5	5.5	5.4	5.4	5.0

In the absence of S^O, the typical forest ground cover was mainly mosses with some herbs. Excess sulphur showed complete absence of live ground cover while slightly acidic sites were depleted primarily of their moss cover. Excess lime increased the moss and herb covers, while excess lime plus S^O decreased the moss cover and increased the herb cover.

As the S^O content was increased (due to the additions from gas plant operations), and/or as time advanced, the pH in the litter layer declined, with the FH exhibiting the lowest pH value. At both S1 and S2, the pH value of the L layer was 1.8, and that of the FH was 1.4 in July, 1982. The mineral horizon to a depth of 10 cm also showed a significant decrease in pH. The pH value at S2 declined from 4.8 to 4.4 in the 5-10 cm mineral horizon between the sampling interval from May 1981 to July 1982.

3.5 DISCUSSION

Addison et al. (1984), reported pH values that ranged from 4.2 to 5.5 in the LFH and from 4.0 to 5.5 in the AE1 (0-5 cm) from uncontaminated sites in the area around the Strachan and Ram River gas plants. Kojima (1984) found pH values ranging from 3.5 to 5.0 in the L-H and from 3.9 to 5.6 in the A mineral horizon in a Lodgepole pine - Alder association. These results are comparable to the control site, C1 in this study. Addison **et al.** (1984) found extractable sulphate levels of 193, 11600, and 13100 mg kg^{-1} at sites near C1, S1, and S2, respectively. At their site near S2, they found 12000 mg kg^{-1} of S^{o}. These sulphate-sulphur values are comparable to this study; however, the S^{o} value was less than that found in S2 (54000 mg kg^{-1} in L and 28500 mg kg^{-1} in FH; n=4). This discrepancy was due to S2 being closer to the sulphur block than the site studied by Addison et al. (1984).

Yeung (1980) added S^{o} (280 kg ha^{-1}) to a sandy (90% sand; well drained eluviated Dystric Brunisol) forest soil and pH decreased to a depth of 15 cm within one year. In the present study, with addition of S^{o}, pH decreased initially in the litter layer. The L layer had a pH value of 4.4 in the NIL compared to 3.4 in the S^{o} treatments of C1, July 1982 (10 months after initial application of S^{o} at 2000 kg ha^{-1}). However, the mineral horizons showed only a small lowering of pH (5.0 to 4.8 in the 0-5 cm horizon). The soil textures for C1, S1, and S2 were sandy loam, loam, and silty loam, respectively (Appendix I).

When comparing the effectiveness of liming at the two gas plants, the S1 site which was well drained had a significantly higher pH value (Jul/82) in the 0-5 cm horizon but not in the 5-10 cm horizon. However, the S2 site which was imperfectly drained had a higher pH value ($p<0.05$) in the 5-10 cm horizon with no difference in the 0-5 cm mineral horizon. Bertrand (1973) concluded that subsoil pH values were altered more in a well drained soil than in a poorly drained soil of medium texture. On a sandy, well drained soil, Yeung (1980) observed no significant difference of pH values on addition of lime and sulphur after one year.

When excess lime was added with S^o, pH increased significantly in the litter layers as well as the 0-5 cm mineral horizon, within nine months of application (Jul/82) at C1. When Yeung (1980) carried out a similar experiment (S^o at 280 kg ha^{-1} and Lime at 2500 kg ha^{-1}), pH value of the litter layer increased within 3 months of application. But by the following year, the litter layer and the mineral horizons down to a depth of 90 cm did not differ. These findings indicate that pH results are transitory and that the soil has the ability to buffer large amounts of excess lime.

At C1, with addition of 2000 kg S^o ha^{-1}, there was a lag in the pH depression from Sep/81 to Jul/82 in the L and FH litter layers (Figure 3.1). The pH value decreased 0.09 units per month in the L layer and 0.01 units per month in the FH. From Jul/82 to Jun/83, the pH value decreased 0.11 pH units per month in the L layer and 0.19 units per month in the FH. The rate of pH change for C1 was an increase of 0.24 pH units per month in the L layer, and 0.16 in the FH with the addition of 7000 kg LIME ha^{-1} (Sep/81 to Jul/82).

In conclusion:

1) an initial application of S^o had a smaller decrease in pH value than subsequent applications; that is, the soil needed to be "primed" with the growth of S^o-oxidizing microorganisms before sulphate-sulphur concentrations increased,

2) on application of S^o to the forest soil, pH value in the L layer dropped initially followed by a lowering of pH value in the FH layer,

3) depth of acidification and apparent depth of lime penetration were limited to the LFH layers at C1. However, S1 and S2 showed significantly lower pH values to a depth of 5 cm and 10 cm, respectively, from 1980 to 1982.

4. SULPHUR OXIDATION

4.1 INTRODUCTION

This aspect of the investigation grew from observations and measurements made in a forested area of northern Alberta where lime was added to forest soils acidified by wind blown S^o dust (Nyborg, 1983).

In this study the objectives were: 1) to compare the rate of oxidation in litter samples from two areas of the province, Fox Creek and Rocky Mountain House, with treatments of lime, S^o, nitrogen and an inoculum of sulphur oxidizing micro-organisms (one g of ground litter which had previously quickly oxidized S^o), and 2) to determine the most probable number (MPN) of the sulphur oxidizing bacteria, **Thiobacillus thiooxidans**, in forest soils which had received S^o fallout and in a similar forest soil distant from the fallout.

4.2 MATERIALS AND METHODS

4.2.1 Incubation Experiment

Litter samples were collected from the study sites near the Strachan (RMH-S1) and Ram River (RMH-S2) gas plants and at a control (RMH-C2) area between the two plants in October, 1980 (Figure 2.1). Sites WH-C (near Whitecourt) and FC-C (near Fox Creek) were control sites near the Fox Creek gas plant. Site and sample descriptions are in Appendix IV.

Litter samples were air dried and ground to pass through a 2 mm screen. Prior to incubation, the litter samples were analyzed:

1) Total nitrogen was determined by Bremner's standard micro-Kjeldahl method (Bremner, 1960).

2) Total carbon (including carbonates) was analyzed on a Leco gas induction furnace (Tabatabai and Bremner, 1970).

3) Soil pH value was measured in a 1:10 ratio of soil to distilled water, stirred for five minutes and left to stand for one hour. A universal glass electrode (E12) was immersed well into the partly settled suspension while a Calomel reference electrode (E-6A) was immersed into the supernatant solution.

4) Sulphate-sulphur was measured using the Johnson Nishita method with modifications by Dean (Carson **et al.**, 1972). In the present procedure, from 0.2 to 2.0 g of soil was extracted with 20 ml of 0.01 M $CaCl_2$, instead of 10 g of soil.

Plastic containers (10.5 cm in diameter and 10 cm high) were filled with the ground (< 2 mm) organic soil, amendments were applied (Table 4.1) and mixed into the soil. Water was added to bring the soils to 85% of water holding capacity, and the soils were remixed with a spatula.

The containers were placed in a dark room and incubated (18°C to 22°C). The soils were weighed weekly and water added when necessary to maintain the moisture at 85% of

Table 4.1. Treatment additions for the sulphur oxidation experiment.

TREATMENTS	A	B	C	D	E	F
SITE (g of soil/pot)			AMENDMENTS			
WC-C* (96)	NIL	S L**	S L N	S N	S	S + IN
FC-C (59)	NIL	S L	S L N	S N	S	S + IN
RMH-C2 (59)	NIL	S L	S L N	S N	S	S + IN
RMH-S1 (82)	NIL	L	L N	N	ns+	ns
RMH-S2 (92)	NIL	L	L N	N	ns	ns

* SITES: WH-C was Whitecourt, mile post 102.5; FC-C was Fox Creek, 2.3 km north of gas plant; RMH-C2 was Rocky Mountain House, between S1 and S2; RMH-S1 was Strachan; RMH-S2 was Ram River.

** AMENDMENTS:
S: 2000 kg ha^{-1} (sublimed sulphur, < 150 um diameter particles, 1.7 g/pot).
L: 12,480 kg ha^{-1} ($CaCO_3$, < 150 um diameter particles, 10.61 g/pot).
N: 100 kg N ha^{-1} (NH_4NO_3, 0.243 g/pot)
IN: One g of ground litter from FC-L1.

AND: To all treatments, including NIL, KH_2PO_4 was added at 20 kg P ha^{-1} and 25 kg K ha^{-1} (0.0745 g/pot).

\+ ns: There was no sample used in the treatment.

water holding capacity. Initially, lids with holes (1 cm in diameter; 3 per lid) were used. However, the lids were later removed because leaf litter within the containers had developed a lush growth of fungi. At subsequent intervals (53 days, 147 days, and 265 days), two containers were removed for each treatment. The soil was air dried and analyzed for pH and sulphate-sulphur.

4.2.2 MPN Experiment

Litter samples were taken March 1, 1981 from the Strachan Gas Plant near S1 and an uncontaminated area (C3) 9.5 Km west of the Ram River Gas Plant (Figure 2.1). These sites were under 2 cm of snow. Samples were 15 x 15 cm^2 in area and were taken separately from the undecomposed and decomposed litter layers. Samples were obtained aseptically, (rubber gloves rinsed in 95% ethanol), placed into presterilized jars, and refrigerated (4°C to 6°C).

Nine ml of "medium S" (at initial pH 5.0, which selects for T. thiobacillus) were added to disposable test tubes, capped with "kaputs", and autoclaved at 103 kPa for 30 minutes (Aaronson, 1970). Ten g of colloidal sulphur was added to 90 ml of water and autoclaved twice at 103 kPa for 30 minutes. Five drops of the colloidal sulphur in solution was then added to each test tube containing "medium S", aseptically, by disposable pipettes. Dilutions were made in presterilized water blanks by adding 10 g of soil to 90 ml of distilled water and shaken (1:10). Ten ml of this solution was then added to 90 ml of distilled water and shaken (1:10^2). This procedure was continued up to a ratio of 1:10^5. One ml of solution was pipetted from each water blank dilution to test tubes containing "medium S" plus colloidal sulphur (5 replicates). One g of soil was added to 9 ml of "medium S" plus colloidal sulphur (5 replicates). Once inoculated, the test tubes were incubated at room temperature (22-28°C) and shaken periodically. The pH value was taken with a wire loop (flamed, dipped into test tube, and solution dropped onto colour coded litmus paper). Buffer solutions, at pH values of 4 and 7, were used as standards. To select the three dilutions employed in determining the MPN index, the highest dilution which gave positive results (pH<4.0) in all five of the portions tested (no lower dilution giving any lower results) and the next two succeeding higher dilutions were chosen (Orland, 1965).

4.3 RESULTS

Initially, the litter samples had a high N content, but wide C/N ratios (Table 4.2) RMH-S1 had a very low pH (1.4) and RMH-S2 had the potential to become very acid on oxidation of its S^o.

Table 4.2. Total carbon, total nitrogen, C/N ratio, total elemental sulphur, extractable sulphate (0.1 M $CaCl_2$), and pH of litter samples prior to incubation for the sulphur oxidation experiment.

SITE	TOTAL C (%)	TOTAL N (%)	C/N RATIO	S^o (ppm)	SO_4 (ppm)	pH
WC-C*	25.8	0.554	49	110	83	4.4
FC-C*	34.0	0.769	44	75	96	4.0
RMH-C2*	38.3	0.656	58	230	200	5.0
RMH-S1+	41.1	0.985	42	21667	13200	4.0
RMH-S2+	37.8	0.876	43	85000	15900	1.4

* non - sulphur dusted site

\+ sulphur dusted site

4.3.1 Incubation Experiment - pH Values

On incubation, the pH value of the NIL treatment rose and then levelled in the three "control" sites, WC-C, FC-C, and RMH-C2 (Figures 4.1a, 4.1b, and 4.1c). Additions of lime increased and maintained the pH at a value of 5 or greater for the "controls". RMH-S1 became more acidic with time on the NIL treatment, but LIME maintained a pH value of greater than 5.0 (Figure 4.1d) RMH-S2 increased to 5.5 with LIME, but the pH value dropped to 1.2 between day 53 and day 147 (Figure 4.1e). With the addition of S^o and the S^o + inoculum, the pH value fell below 3 during the incubation. The following is the "pH range" for the three "controls" (the average taken day 265):

S^o + L + N	pH 5.9 - 6.3
S^o + L	pH 5.8 - 5.9
NIL	pH 4.5 - 5.5
S^o + N	pH 2.0 - 2.4
S^o + Inoculum	pH 1.9 - 2.4
S^o	pH 1.9 - 2.3

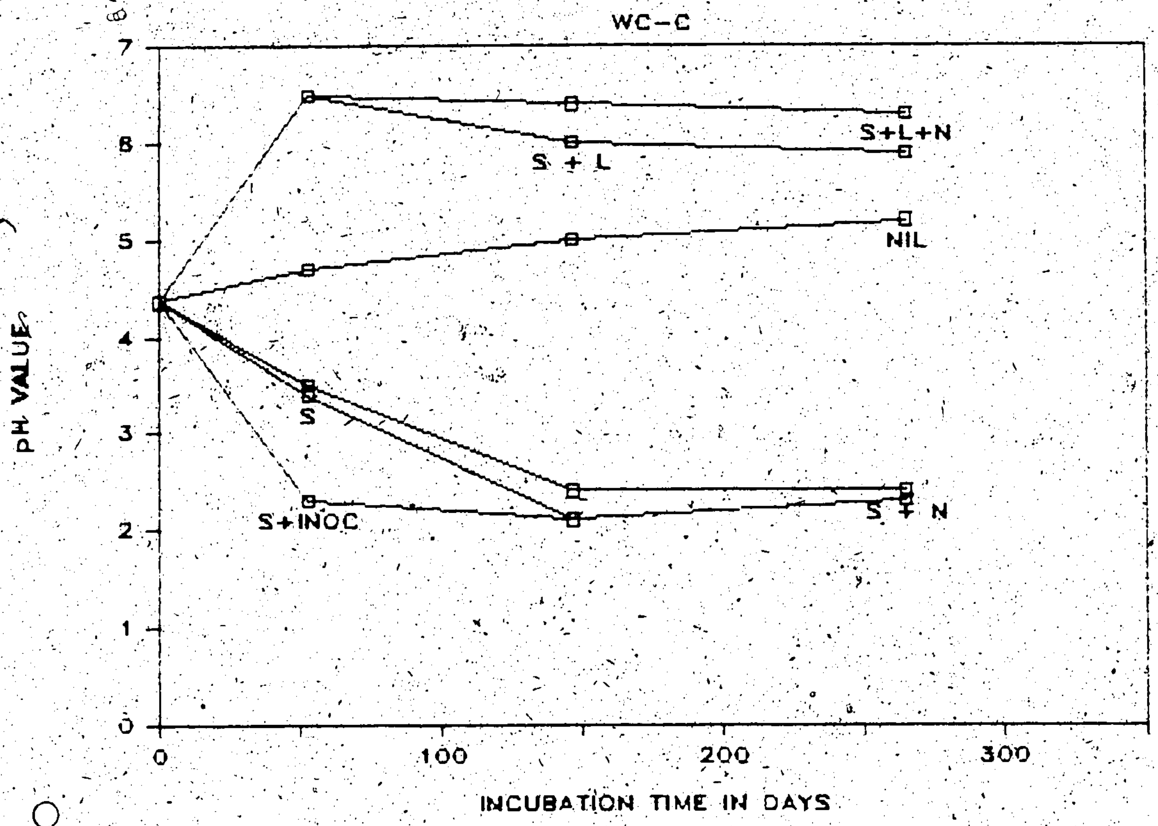

Figure 4.1a. The change in pH value over time for incubated forest litter soils (WC-C). NIL: no additions; S: S^O; SN: S^O + NITROGEN; SL: S^O + LIME; SLN: S^O + LIME + NITROGEN; S + INOC: S^O + Soil containing S^O oxidizing micro-organisms.

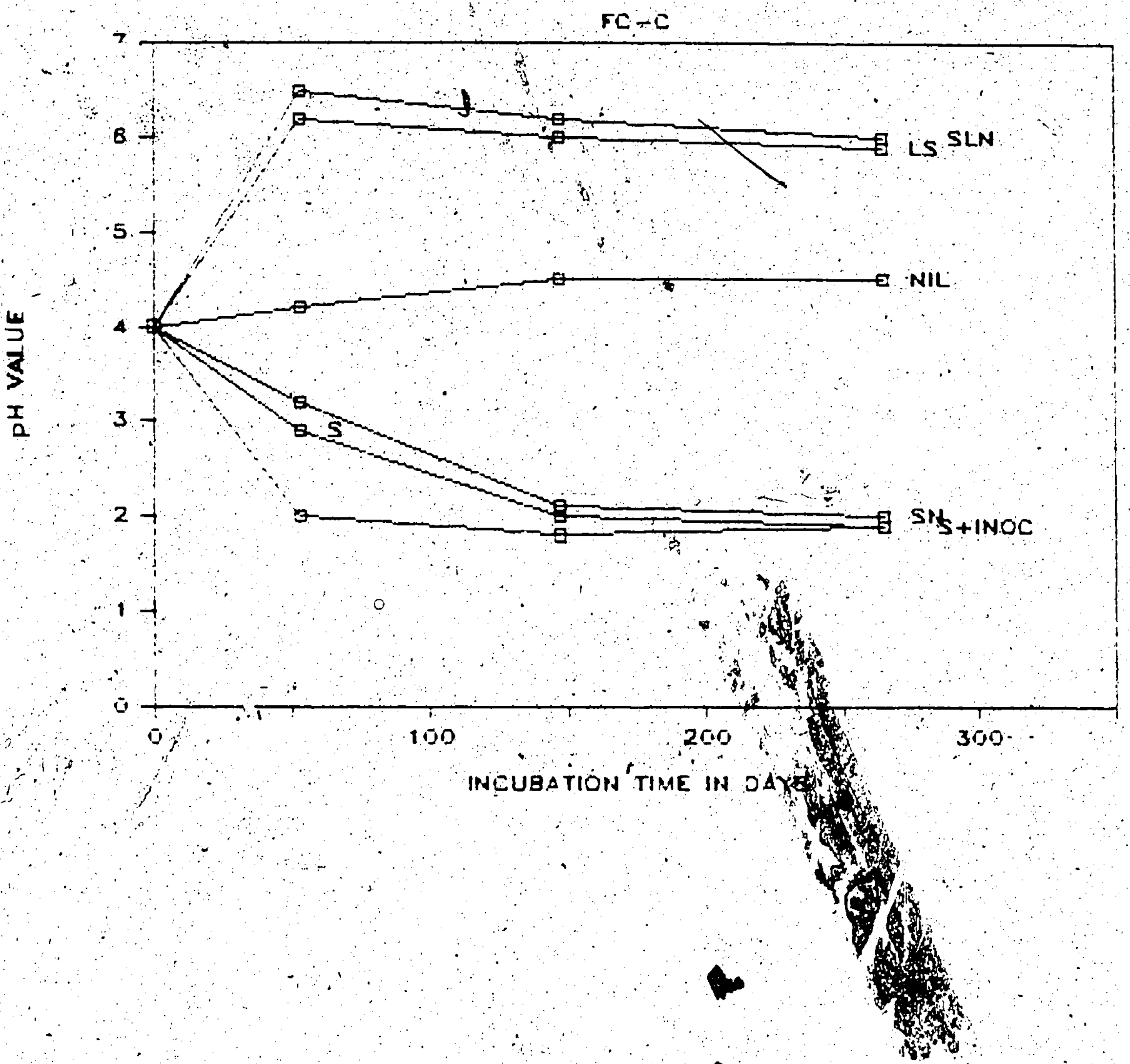

Figure 4.1b. The change in pH value over time for incubated forest litter soils (FC-C). NIL: no additions; S: S^o; SN: S^o + NITROGEN; SL: S^o + LIME; SLN: S^o + LIME + NITROGEN; S + INOC: S^o + Soil containing S^o oxidizing micro-organisms.

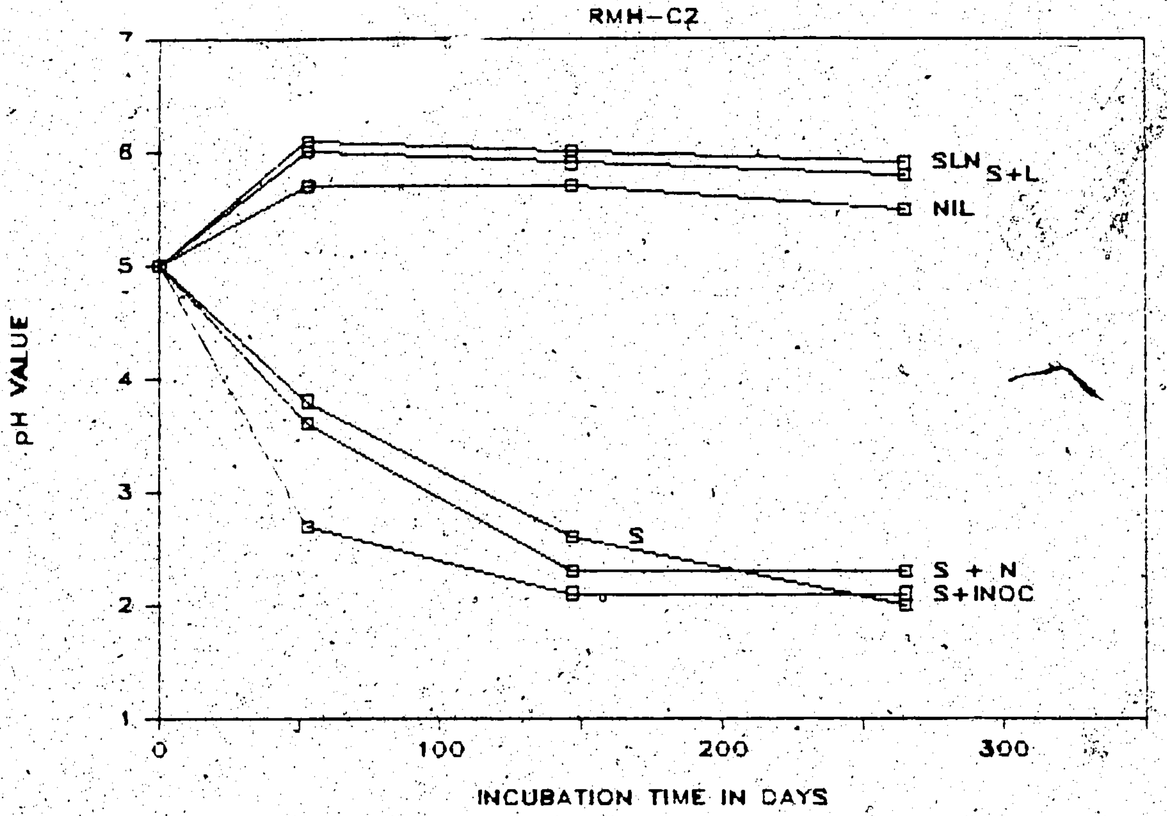

Figure 4.1c. The change in pH value over time for incubated forest litter soils (RMH-C2). NIL: no additions; S: S^{O}; SN: S^{O} + NITROGEN; SL: S^{O} + LIME; SLN: S^{O} + LIME + NITROGEN; S + INOC: S^{O} + Soil containing S^{O} oxidizing micro-organisms.

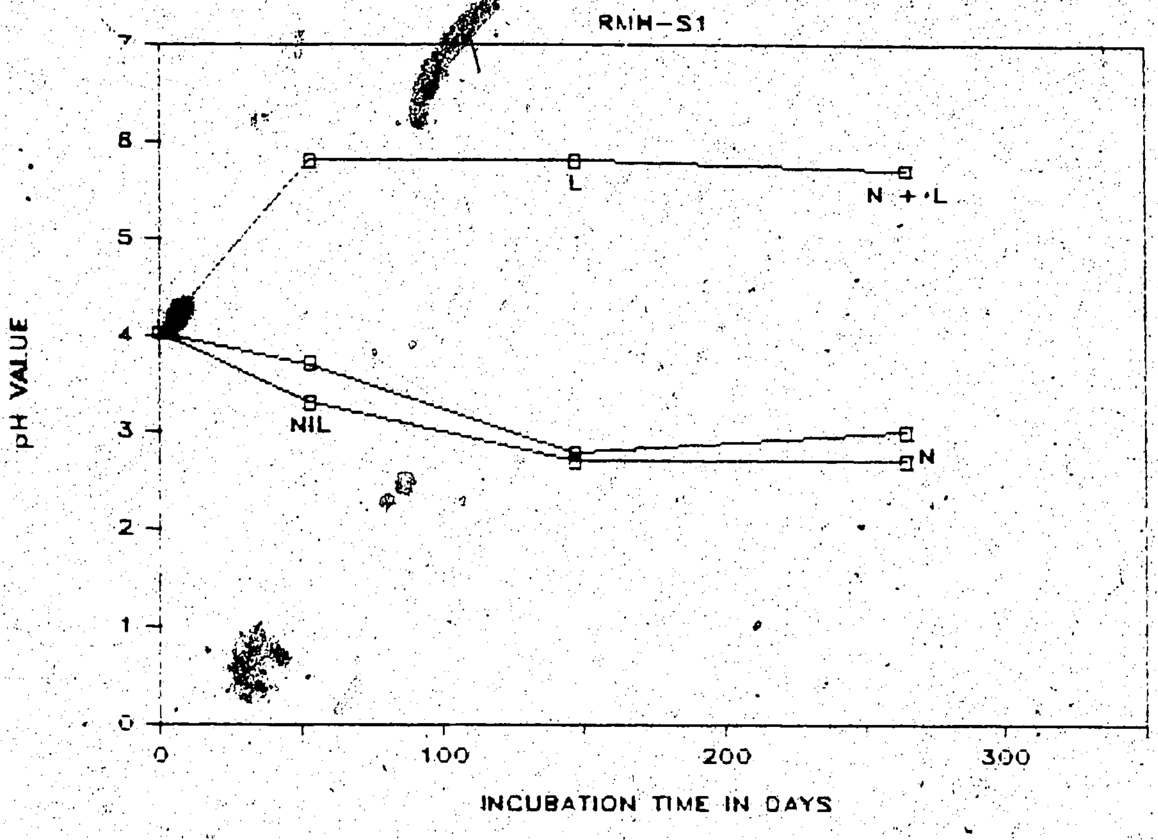

Figure 4.1d. The change in pH value over time for incubated forest litter soils (RMH-S1). NIL: no additions; L: LIME; N: NITROGEN; N + L: NITROGEN + LIME.

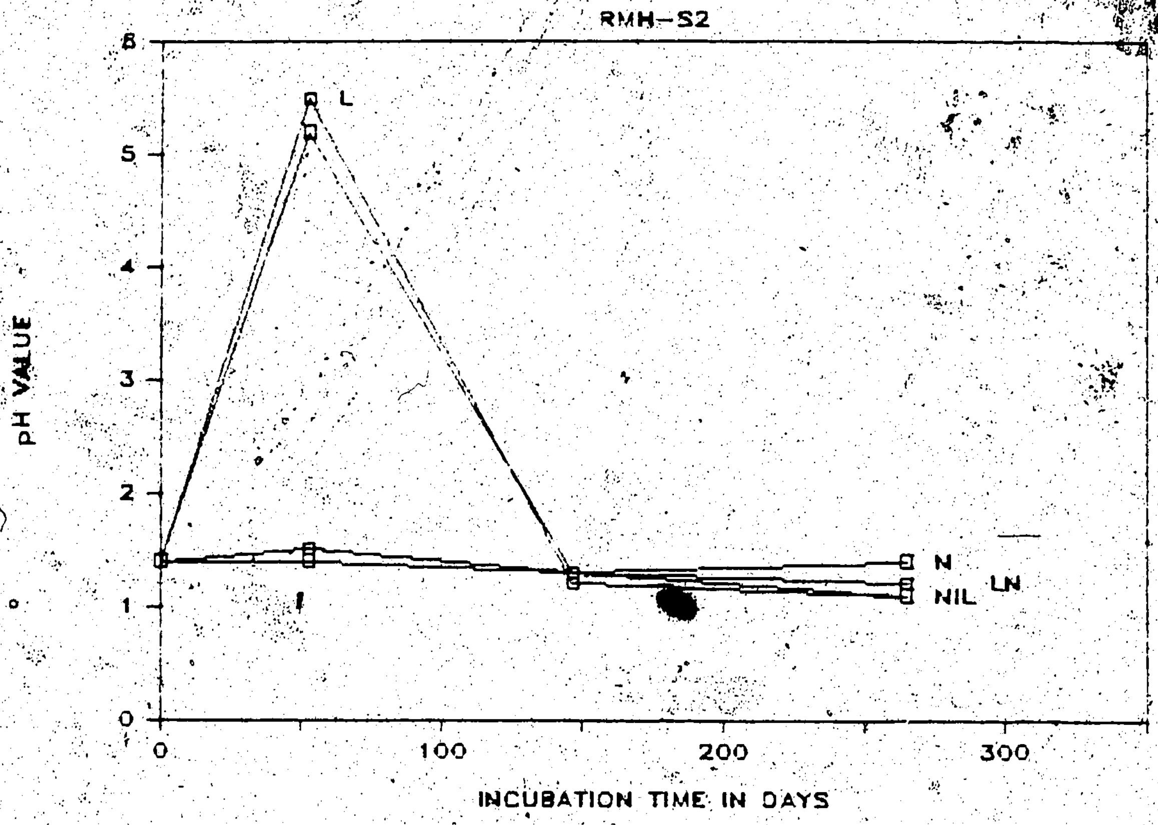

Figure 4.1e. The change in pH value over time for incubated forest litter soils (RMH-S2). NIL: no additions; L: LIME; N: NITROGEN; LN: LIME + NITROGEN.

4.3.2 Incubation Experiment - Sulphate-Sulphur Values

In the three control sites, WC-C, FC-C, and RMH-C2, initial sulphate-sulphur concentrations were less than 200 ug g^{-1}. However, once S^{o} was added (20,000 ug g^{-1}) sulphate-sulphur increased with time (Figure 4.2a,b,c). Treatments with lime had less than 10000 ug g^{-1} of sulphate-sulphur by day 265, while treatments with S^{o} alone, showed more than 15000 ug g^{-1} of sulphate-sulphur in the case of FC-C and RMH-C2. The samples from RMH-S1 and RMH-S2 were high in S^{o} (Table 4.2). The NIL treatment of RMH-S1 behaved as the S^{o} treatment of the "controls" with an increase in SO_4^{2-}-S with time (Figure 4.2d). However, the N, LIME and LIME + N treatments behaved as RMH-S2 with the highest sulphate level at the second sampling interval. At RMH-S2, sulphate-sulphur increased up to day 147 and then decreased by day 265 (Figure 4.2e). The S2 site produced over 60000 ug g^{-1} of sulphate-sulphur by day 147, while S1 oxidized 16000 to over 60000 ug g^{-1}, depending on the treatment.

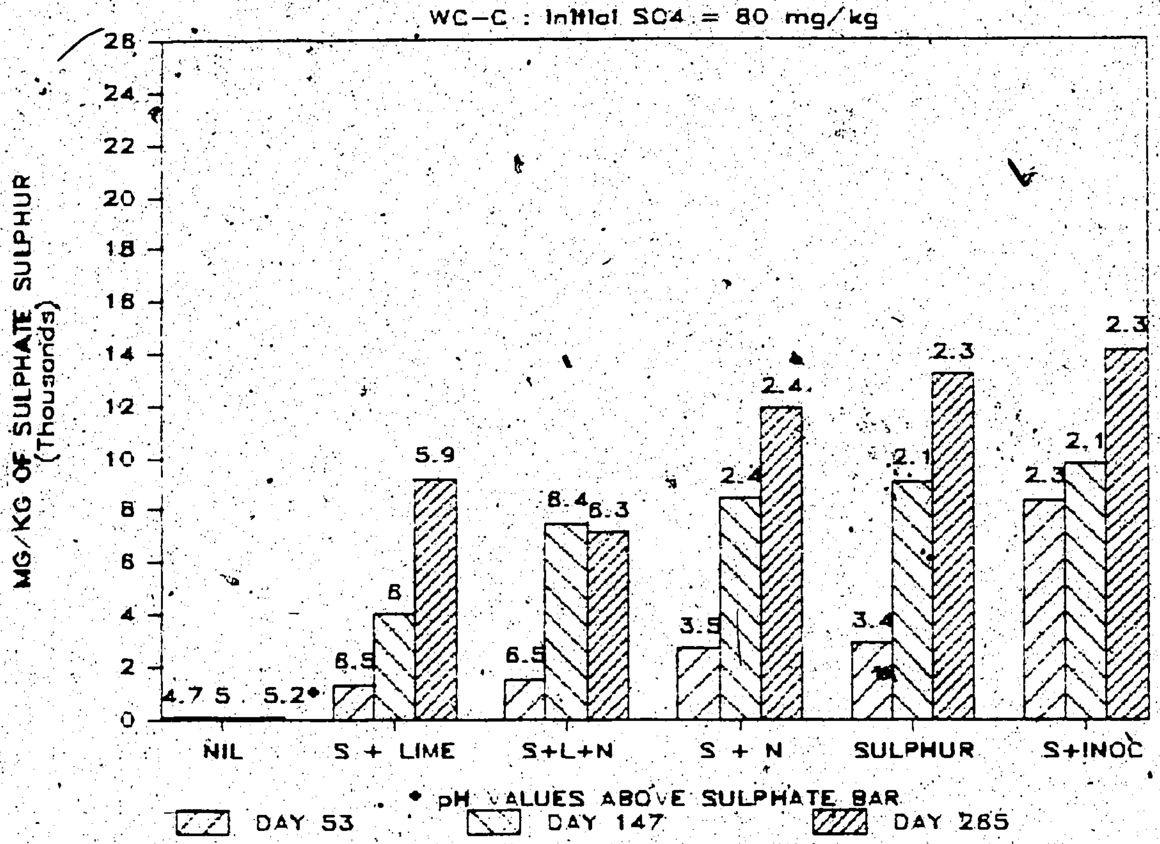

Figure 4.2a. Sulphate-sulphur values of forest litter soils (WC-C) which had been incubated after additions of nitrogen, lime and S^{O}. NIL: no additions; N: NITROGEN; L: LIME; S: S^{O}; S + INOC: S^{O} + Soil containing S^{O} oxidizing micro-organisms.

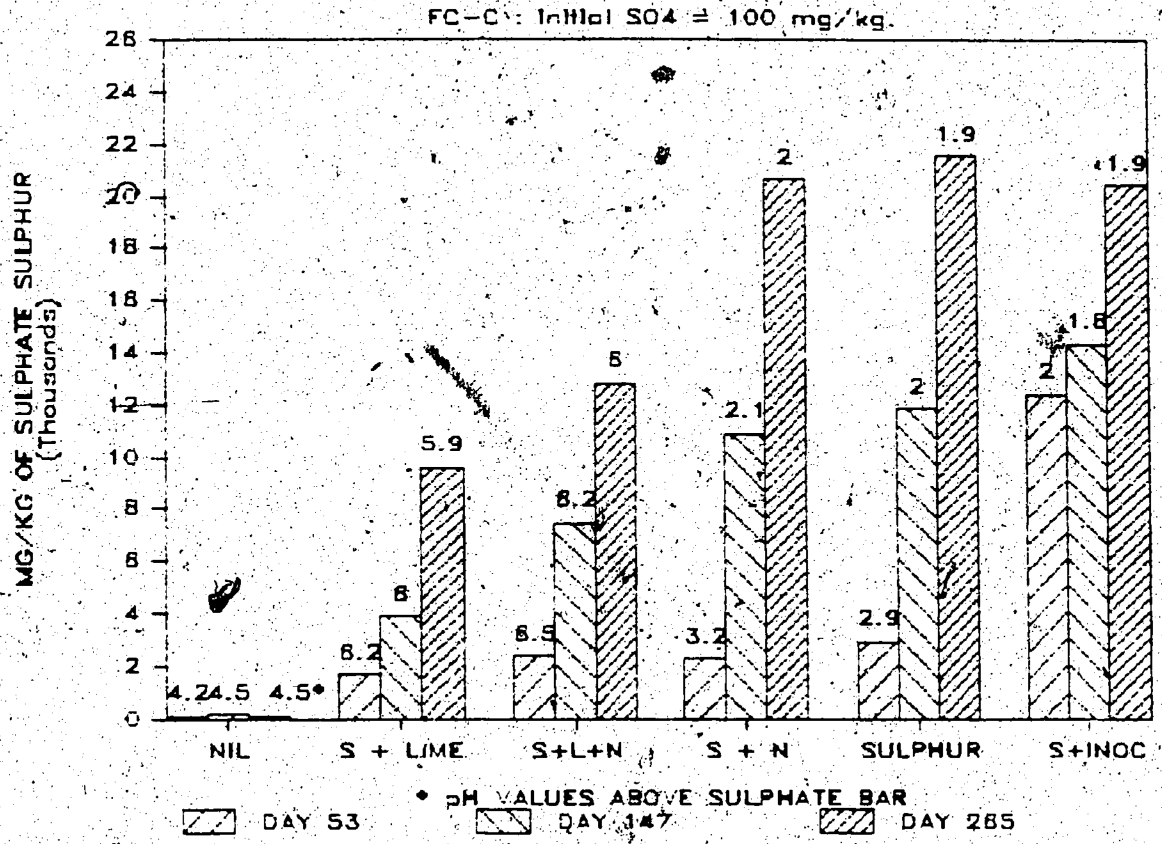

Figure 4.2b. Sulphate-sulphur values of forest litter soils (FC-C) which had been incubated after additions of nitrogen, lime and S^{O}. NIL: no additions; N: NITROGEN; L: LIME; S: S^{O}; S + INOC: S^{O} + Soil containing S^{O} oxidizing micro-organisms.

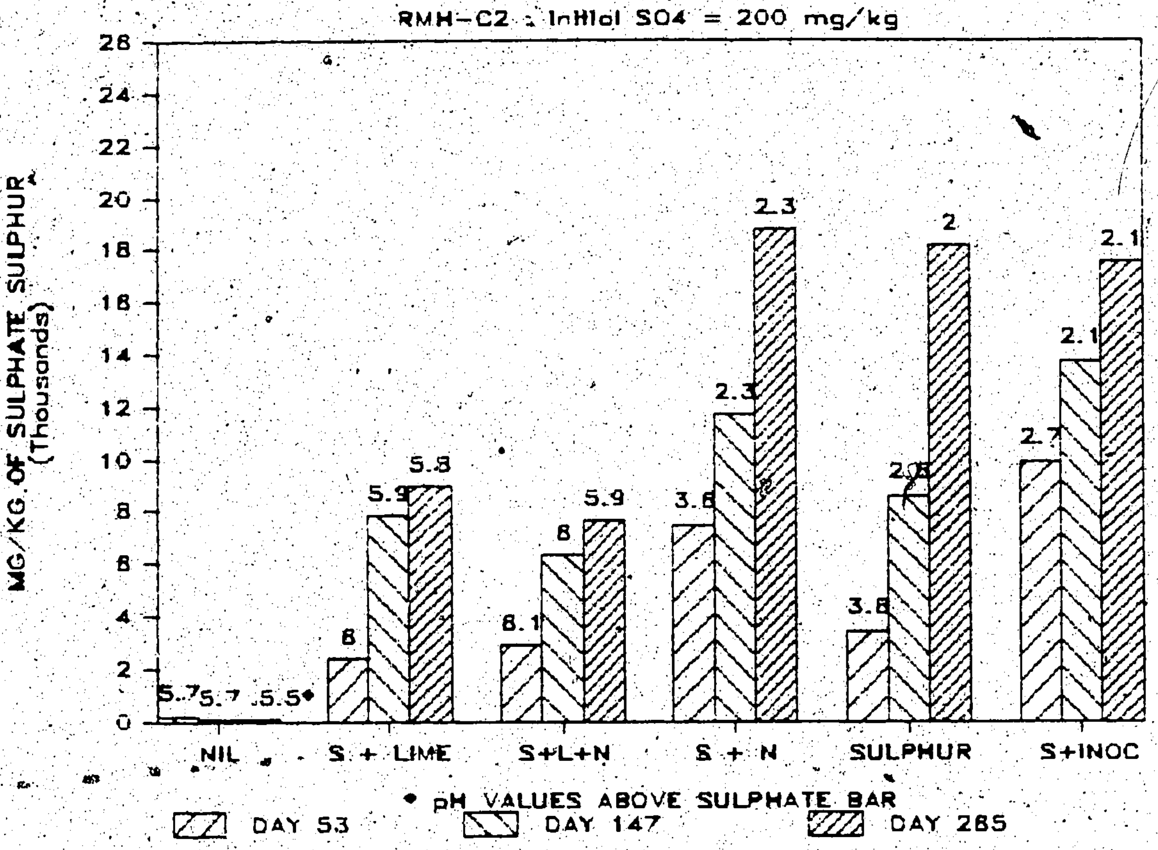

Figure 4.2c. Sulphate-sulphur values of forest litter soils (RMH-C2) which had been incubated after additions of nitrogen, lime and S^o. NIL: no additions; N: NITROGEN; L: LIME; S: S^o; S + INOC: S^o + Soil containing S^o oxidizing micro-organisms.

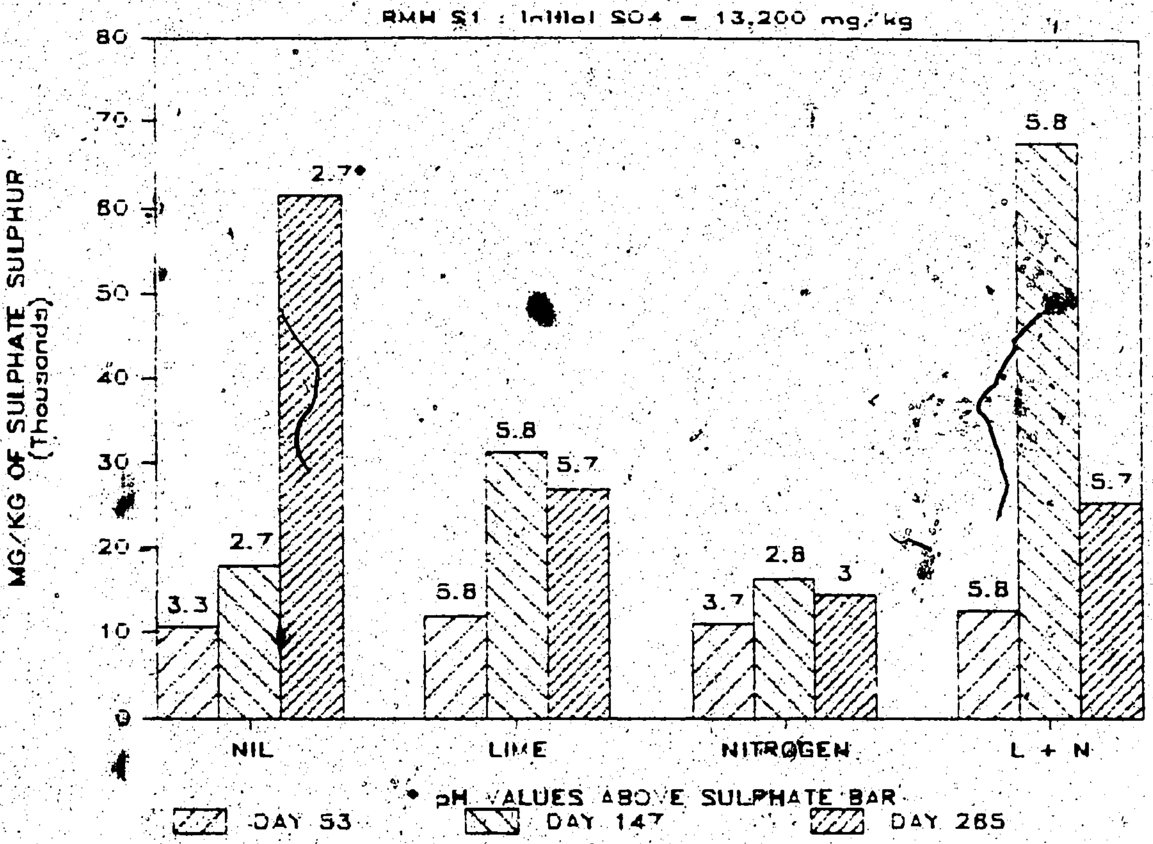

Figure 4.2d. Sulphate-sulphur values of forest litter soils (RMH-S1) which had been incubated after additions of nitrogen, lime and S^O. NIL: no additions; N: NITROGEN; L: LIME.

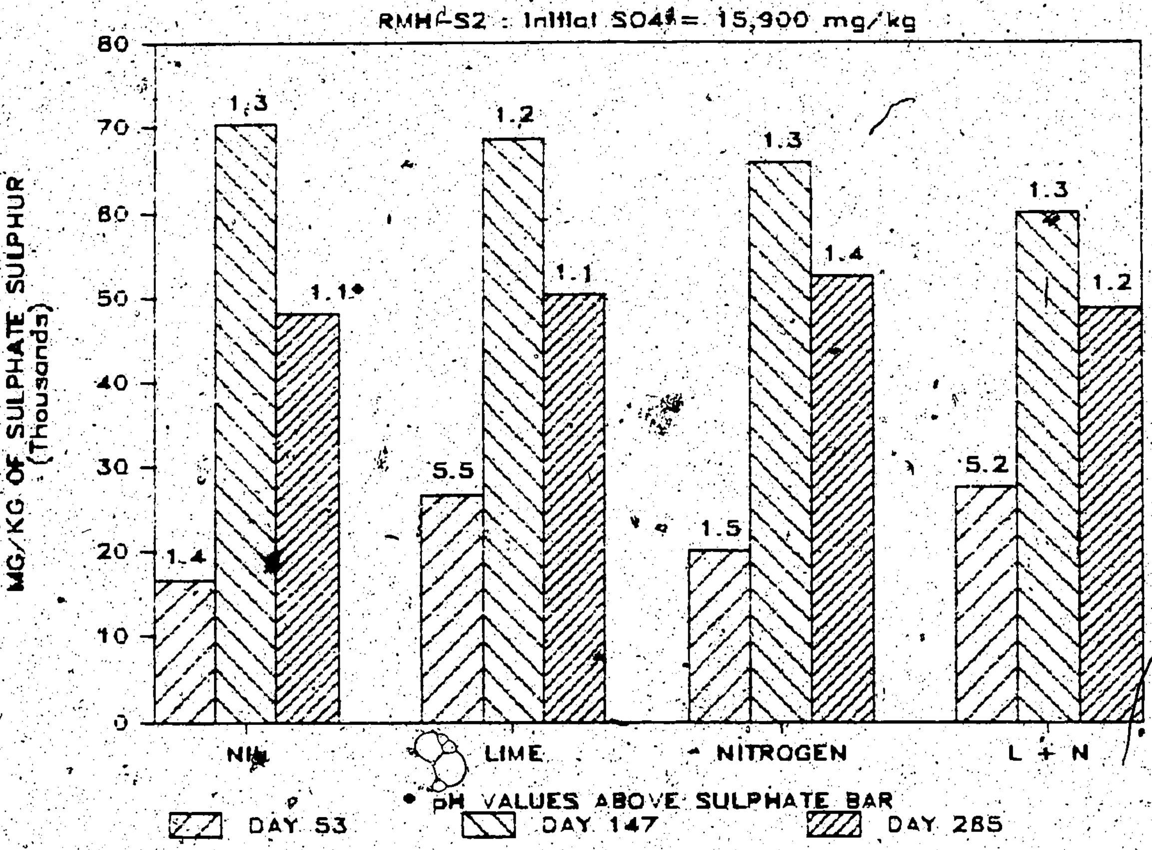

Figure 4.2e. Sulphate-sulphur values of forest litter soils (RMH-S2) which had been incubated after additions of nitrogen, lime and S^{O}. NIL: no additions; N: NITROGEN; L: LIME.

4.3.3 MPN of THIOBACILLUS

Those samples, where one g of soil was added to the medium, either remained at their original pH value or became slightly more alkaline. This indicated an inhibitory effect of organic matter to the growth of the sulphur oxidizing bacteria and the necessity of isolation through dilution.

The pH value for the first three weeks showed little change. Results were complete by the eighth week. More bacteria (10^5) were found in the leaf litter layers at Strachan than at the clean site. At Strachan, the FH layer had less T. thiooxidans than the L layer, while at the control, the numbers were greater in the FH layer (Table 4.3).

Table 4.3. The most probable number (MPN) of **Thiobacillus thiooxidans** (n=5) per g of soil for a sulphur dusted area (S1) and a control soil (C3).

SITE	LITTER LAYER (15cm X 15cm)	DEPTH (cm)	MPN PER g SOIL
STRACHAN (S1)	L	2.5	$> 10^5$
	FH	1.9	2.4×10^3
CONTROL (C3)	L	5.1	1
	FH	7.6	24

4.4 DISCUSSION

The rate of litter pH depression and of the conversion of S^o to SO_4^{2-}-S were rapid when S^o was added to the litter. The litter pH change varied with treatment (Table 4.4). Variability in the NIL treatments indicated a diversity of forest litter (heterogeneous combinations of needles, leaves and moss). On addition of S^o, the initial rate of decrease was 0.6 pH units per month. Addition of the inoculum increased the pH depression in the "controls", WC-C, FC-C, and RMH-C2. After two months, this rate dropped to 0.36 pH units per month. With the addition of Lime plus S^o, an initial increase of 1.0 pH unit per month for the first two months occurred, followed by a drop of less than 0.1 pH units per month. The response to lime was greater in soils that had a lower initial pH compared to more alkaline soils. In the case of S2, Day 147, addition of lime increased the oxidation of S^o as indicated by the increased rate of pH change. The response to NH_4NO_3 was minimal; however, repeated applications of N may have hastened and/or increased the oxidation of S^o.

On the addition of S^o to the three "controls", WC-C, FC-C, and RMH-C2, 10 to 20% of the added S^o was converted to SO_4^{2-}-S after 53 days of incubation (Figure 4.3a,b,c). After 265 days, 63 to 75% had been converted when S^o was added. With the addition of lime, less than 50% of the S^o had been converted to SO_4^{2-}-S by day 265. Addition of lime decreased

TABLE 4.4. pH change per month at various sites within two sampling intervals of litter samples from the oxidation experiment.

TREATMENTS	NIL	SLN	SL	SN	S	S+IN
SITE						
			DAY 53			
WC-C*	0.2	1.2	1.2	-0.4	-0.5	-1.2
FC-C*	0.1	1.4	1.2	-0.5	-0.6	-1.1
RMH-C2*	0.4	0.6	0.6	-0.8	-0.7	-1.3
RMH-S1+	-0.4	1.0	1.0	-0.2		
RMH-S2+	0.0	2.1	2.3	0.0		
			DAY 147			
WC-C*	0.1	0.0	-0.1	-0.3	-0.4	-0.1
FC-C*	0.1	-0.1	0.0	-0.3	-0.3	0.0
RMH-C2*	0.0	0.0	-0.1	-0.4	-0.4	-0.2
RMH-S1+	-0.1	0.0	0.0	-0.3		
RMH-S2+	0.0	-1.2	-1.4	0.0		

* non-sulphur dusted site

\+ sulphur dusted site

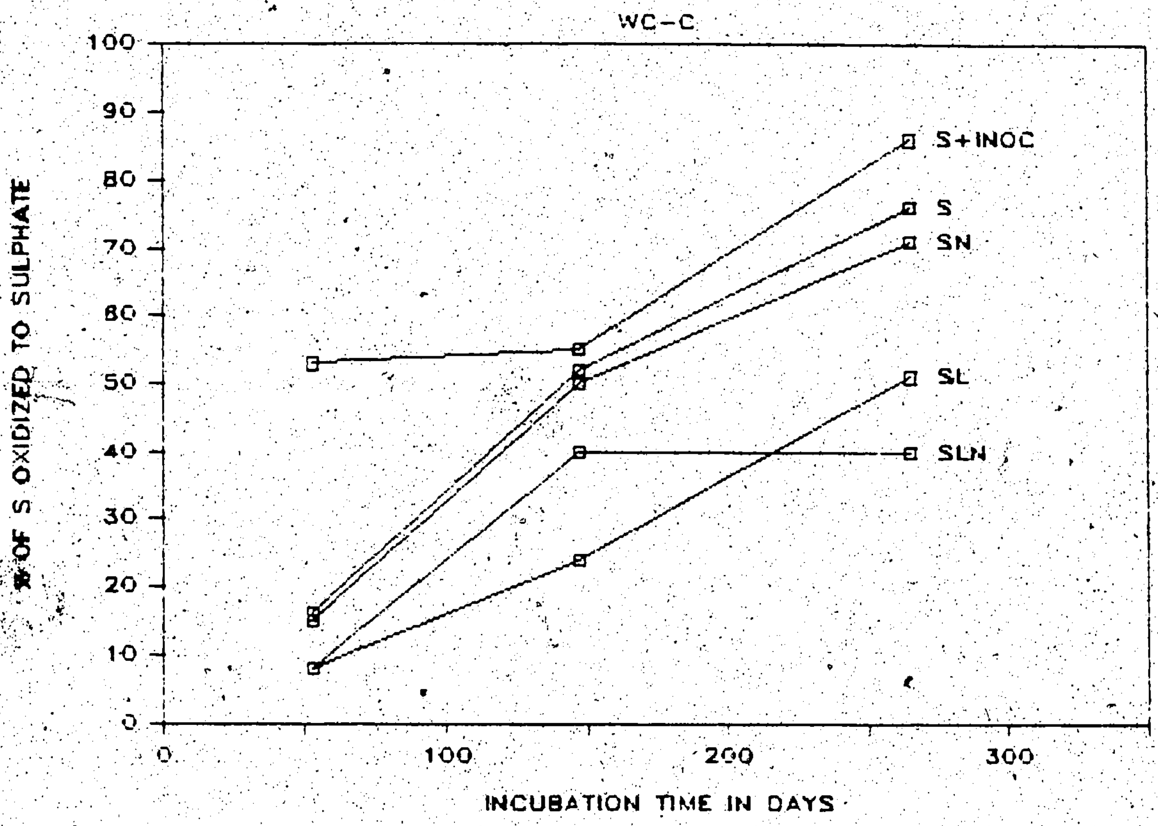

Figure 4.3a. Percent of S^o oxidized to sulphate for forest litter soils (WC-C) which had been incubated after additions of nitrogen, lime and S^o. N: NITROGEN; L: LIME; S: S^o; S + INOC: S^o + Soil containing S^o oxidizing micro-organisms.

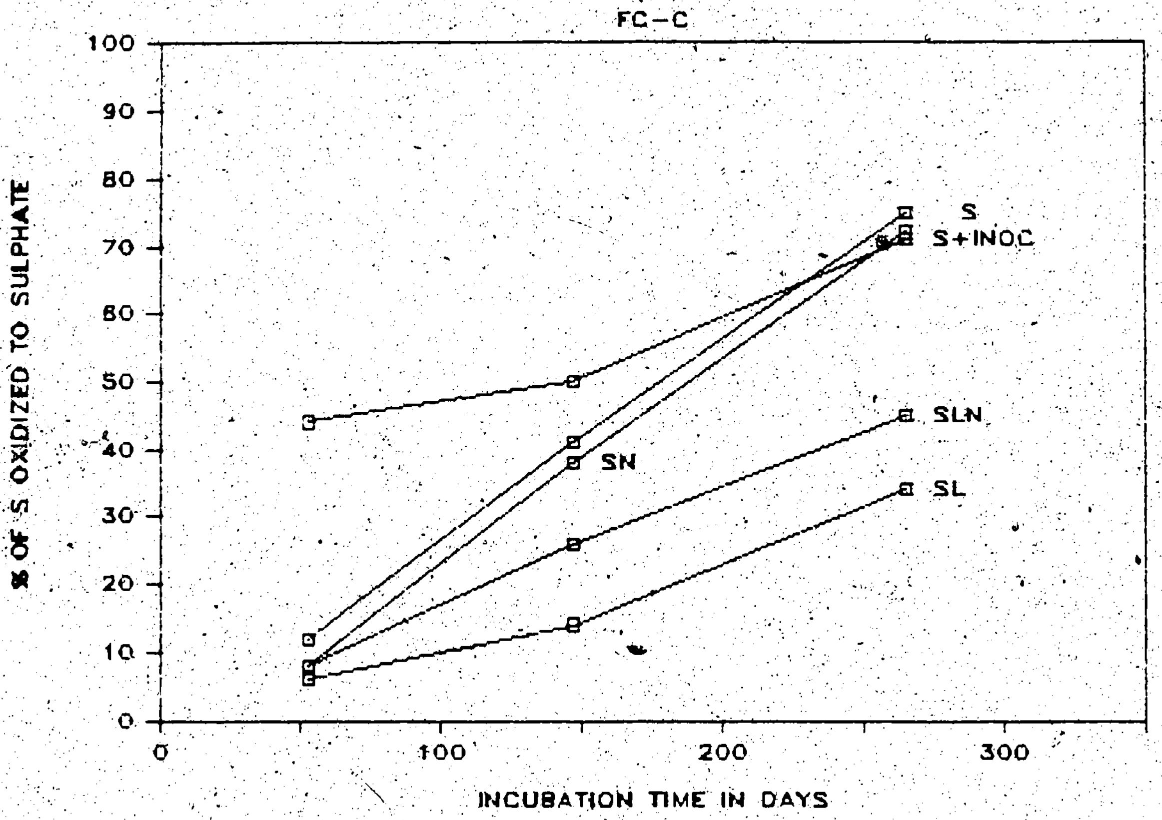

Figure 4.3b. Percent of S^o oxidized to sulphate for forest litter soils (FC-C) which had been incubated after additions of nitrogen, lime and S^o. N: NITROGEN; L: LIME; S: S^o; S + INOC: S^o + Soil containing S^o oxidizing micro-organisms.

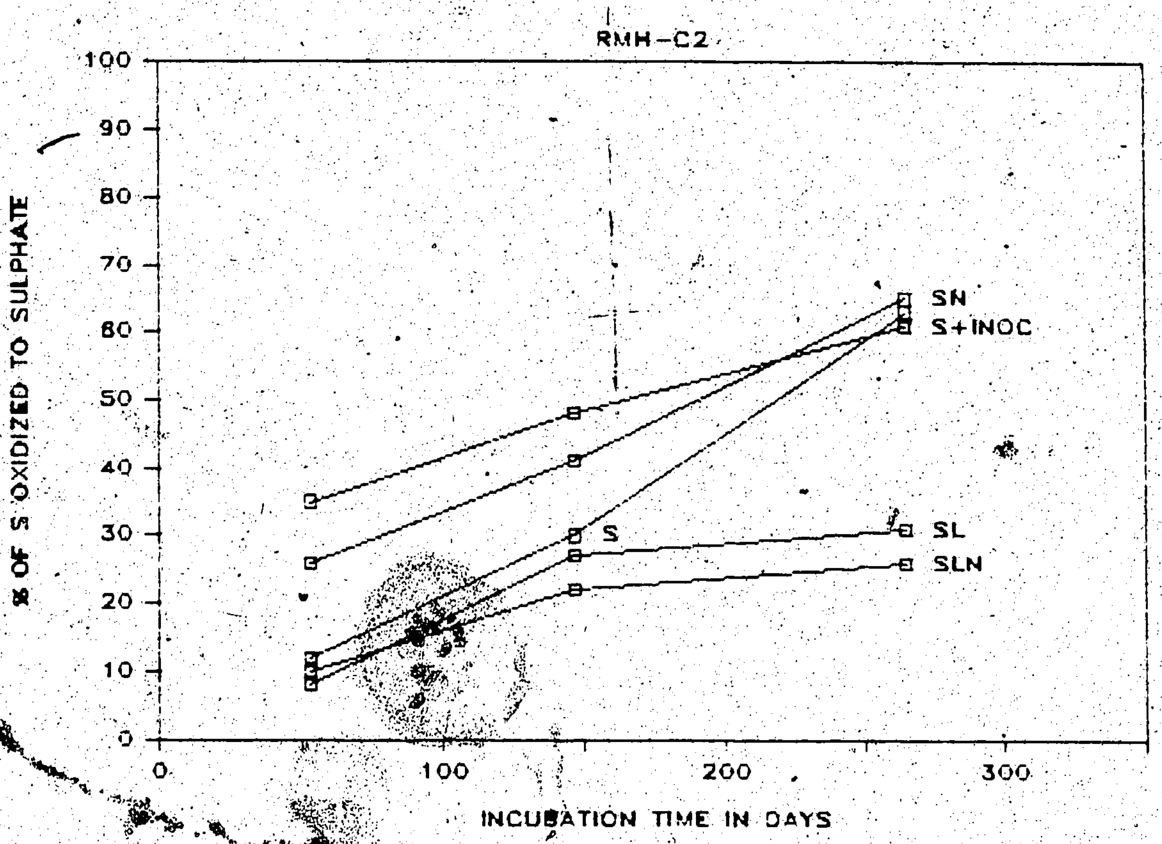

Figure 4.3c. Percent of S^O oxidized to sulphate for forest litter soils (RMH-C2) which had been incubated after additions of nitrogen, lime and S^O. N: NITROGEN; L: LIME; S: S^O; S + INOC: S^O + Soil containing S^O oxidizing micro-organisms.

the oxidation of S^o. The $SO_4{}^{2-}$-S increase and change in soil pH were well related on correlation analysis (Table 4.5).

The three "control" soils behaved similarly in the rate of soil pH depression and S^o conversion even though the samples were taken from distant locations under coniferous forest. Other published information for the litter layer under coniferous forest is lacking. The present work indicated that the application of S^o and a temperature of 20°C, soil pH was depressed by 0.6 units in the first two months, and more than 10 % of the S^o was converted within two months of application. Bertrand (1973), using Alberta soils, found more rapid pH depression and S^o conversion values than obtained in the present work, but his soils were agricultural Chernozems.

Kittams and Attoe (1965) found that oxidation rates were doubled, on the average, when soils were inoculated with a suspension of previously sulphured soil. The response to S^o plus inoculum was double that of S^o alone for the first 2 months. For the next three months the response was reversed: the S^o alone was greater than the S^o plus inoculum. This response may have been due to the rate of S oxidation being lower in a more acid soil (Nor and Tabatabai, 1977), and/or the lack of substrate for oxidation in the case of the S^o plus inoculum. Attoe and Olson (1966) found that liming a loamy sand increased the amount of added S^o oxidized by about 10 to 20 % over that of the unlimed

Table 4.5. The Pearson Product moment correlation coefficient (r) showing the measure of linear association between SO_4 and pH measurements with respect to treatments.

SITE	DAY¬ 53	DAY¬ 147	DAY¬ 265	DAYS¬ TOTAL	WITH LIME	NO LIME
			r			
WC-C	-0.72*	-0.62	-0.70	-0.59	0.52	-0.52
FC-C	-0.59*	-0.73	-0.71	-0.59	0.50	-0.87
RMH-C2	-0.86*	-0.76	-0.88	-0.78	0.46	-0.92
RMH-S1	0.96+	-0.36	0.79	-0.49	-0.58	-0.50
RMH-S2	0.98+	0.78	-0.40	0.13	0.36	-0.92

¬ with both lime and no lime treatments.

* with 6 treatments.

\+ with 4 treatments.

soil. Lettl et al. (1981) have shown that the process of sulphur oxidation [illegible]timulated by $CaCO_3$. However, in this study results w[illegible]eversed due to differing microbial populations in the forest soil.

The bacterium, **Thiobacillus thiooxidans**, is strictly autotrophic and aerobic with an optimum temperature of 28 to 30 °C and a growth range from 10 to 37 °C. The optimum pH is 2.0 to 3.5, with an upper limit of growth near pH 6.0 and a lower limit usually near a pH value of 0.5 (Buchanan and Gibbons, 1974). Laishley and Tyler (1978) found less than 300 "acidic" **Thiobacillus** per g dry weight of soil near "sulphur cement cylinders" placed in the soil at Lethbridge, Alberta. The maximum number of "less acidic" **Thiobacillus** was 3.3 x 10^5 per g dry weight of soil. The site at Strachan (S1) had > 10^5 **T. thiooxidans** per g dry weight of soil in the L layer of the leaf litter.

In conclusion, leaf litter from two coniferous areas of Alberta had similar pH responses to lime and S^o additions. Addition of lime decreased S^o oxidation. MPN of **T. thiooxidans** was greater in the L than in the FH of a S^o dusted forest soil.

5 NITROGEN FERTILIZER TRIALS

5.1 INTRODUCTION

Liming of soils, after deposition of S^o, overcomes soil acidity, but revegetation (artificially or naturally) may not be successful. Severe nitrogen deficiency occurred in barley plants grown on heavily limed soils, which had received S^o in greenhouse experiments with several Black Chernozemic soils (Nyborg, 1978). The nitrogen response was much less in the field (Nyborg, 1974). In a coniferous forest at Fox Creek, which had received S^o fallout and lime, nitrogen fertilization was needed for the growth of planted grasses. However, the recovery of the added nitrogen was less than 2% in the grasses (Nyborg, 1978). This study addresses the question of whether the unusual needs for nitrogen would occur in the coniferous forests at the Strachan (S1) and Ram River (S2) sites.

The objectives were 1) to determine the recovery, as mineral N, of NH_4NO_3 fertilizer added during a three-year period, 2) to determine the amount of N^{15}-tagged NH_4NO_3 fertilizer lost from the soil as total N, and 3) to determine the net rate of nitrification with and without liming.

5.2 EXPERIMENTAL PLOT LAYOUTS

5.2.1 Small N Plots

The plots at Strachan (S1) and Ram River (S2) were adjacent to Experiment #1 (Appendices IIi and IIii). The control site (C2) was situated halfway between the two gas plants, 200 m south of Highway 752 (Figure 2.1). Each plot was 6.1 m x 1.5 m in dimension. The treatment additions and sampling dates are listed in Appendix V. The fertilizer applications of 112 kg N ha^{-1} as NH_4NO_3 were begun in the fall of 1980. The situation with respect to S^o dust from adjacent sulphur blocks and aerial liming was:

C2 ....NIL
S1 ....LIME + S^o
S2 ....S^o

5.2.2 N^{15} Plots

The N^{15} fertilizer used in the following experiments was NH_4NO_3 labelled at 5.051 atom % abundance for both NH_4^+ and NO_3^- (Prochem, B.O.C Ltd., Deer Park Road, London).

In November 1981, a preliminary experiment (n=1) was begun adjacent the Big Plots at S1, S2, and C1. On analysis of soil samples taken the following July, little of the tagged N remained as mineral N (< 0.05 kg ha^{-1}) at the three sites. Recovery rates for total N^{15} were 90% for S2, and 55% for C1 and S1. On June 8, 1983, galvanized aluminum cylinders (38 cm in diameter and 23 cm in height at S1 and

S2; 30.5 cm in diameter and 17.8 cm in height at C1) were placed into the soil by gently prying the area around the cylinder with a shovel and forcing the cylinder down (on the NIL and LIME + S^o treatments within the Big Plots at sites C1, S1, and S2). S^o (2000 kg ha^{-1}) and $CaCO_3$ (technical grade) (5000 kg ha^{-1}) were added to the LIME + S^o treatment. N^{15}-tagged NH_4NO_3 (112 kg ha^{-1}) was sprinkled onto the litter and lightly washed (100 ml H_2O) into the litter layer. The soil was sampled July 11, 1983.

Moss bags have been used as a semi-quantitative monitor of airborne trace metals (Goodman and Roberts, 1971). In this study moss bags were used to detect gaseous loss of N. Nylon net bags (9 cm x 9 cm x 2 cm) filled with moss (23 g dry weight) from the forested area near C1 were suspended 0.3 m above cylinders at the C1 site, August 10, 1983. Lime (technical grade $CaCO_3$) was added (within cylinders) at 6430 kg ha^{-1} to the LIME + S^o treatment and S^o at 3120 kg ha^{-1} was added to the S^o and LIME +S^o treatments. N^{15}-tagged NH_4NO_3 (87.3 kg ha^{-1}) was added (within cylinders) to the NIL, S^o, and LIME + S^o treatments. Three control bags were hung at the far corners of the plot. The net bags were removed and the soils sampled within the cylinders, September 12, 1983.

5.2.3 Big Plots Plus LIME

Samples were taken from the NIL and LIME treatments (no fertilizer additions) of the Big Plots (Chapter 3) in July 1982 to observe the effects of liming on the mineralization of N in the field. The LIME treatment at C1 had received 6770 kg ha^{-1} of "feedgrade" limestone (Sep/81); S1 had received 5600 kg ha^{-1} of "glass rock" limestone (Sep/80); and S2 had received 9170 kg ha^{-1} of "feedgrade" limestone (Oct/80) (Appendix III).

5.3 SAMPLING AND ANALYSES

Two samples were taken from each treatment at each site at the following depths for the "small N plots":

1) Litter layer; A 15 cm x 15 cm area including both the undecomposed and decomposed portions of the LFH.

2) 0-15 cm mineral soil (3 cores).

3) 15-30 cm mineral soil (3 cores).

A "Lord" sampler with a core diameter of 1.9 cm was utilized for the mineral soils.

Samples were taken within the cylinders of the N^{15} experiments. The litter layer of the N^{15} experiment was sampled with the L and FH taken separately as a 15 cm x 15 cm square. The mineral soil beneath this square was obtained with a garden shovel down to a depth of 5 cm and then 10 cm. In the moss bag experiment, the cylinders were sampled as in the "small N plots", to a depth of 15 cm.

Samples were air dried. Litter was ground to pass through a sieve with openings less than 425 um in diameter and the mineral soil was ground to pass through a screen with openings less than 150 um. Total carbon was analyzed with a LECO gas induction furnace (Tabatabai and Bremner, 1970). Total nitrogen was determined by Bremner's "standard" micro-Kjeldahl method (Bremner, 1965a). The soil samples were pretreated with $KMnO_4$ and H_2SO_4 to oxidize nitrite to nitrate, and then reduced with Fe^{2+} to reduce nitrate to ammonium (Bremner, 1965b). Samples were digested for 1.5 hours at 220°C and 4 hours at 360°C in 250 ml tubes, cooled, diluted with 20 ml of distilled water and distilled with steam on a modified micro-distillation unit. The distillate was collected in 5 ml of 2% boric acid and titrated to a pH of 4.8 with 0.0250 M H_2SO_4 using a Mettler DL40 RC Memotitrator. Ammonium and nitrate were determined by steam distillation on 2 M KCl extracts as outlined in McKeauge (1978).

Titration samples that were labelled with N^{15} were acidified 0.2 ml of 0.5 M H_2SO_4 and dried in an 80°C sandbath. The salts were redissolved, transferred to disposable culture tubes and redried at 60°C. Ammonium was oxidized to N_2 using LiOBr according to the method of Porter and O'Deen (1977). The isotope ratio analysis was performed on a Micromass 602C double collector mass spectrometer using atmospheric N_2 as a reference (Fyles, 1984). The standard error of N^{15} abundance of $(NH_4)_2SO_4$ standards, run over a period of several weeks was 0.0002 of the mean (0.3655 abundance N^{15}).

5.4 RESULTS

5.4.1 Small N Plots

The control site (C2) had little mineral nitrogen in the soil at any sampling time (Table 5.1). In the fall of 1980, two months after the first NH_4NO_3 application to the S1 and S2 sites, more than 50 kg N ha^{-1} as NH_4 and NO_3 were found in the litter layers (Tables 5.2 and 5.3). However, in subsequent samplings little mineral N was found.

5.4.2 N^{15} in Big Plots

More total N was found in the NIL than in the LIME + S^o treatments (Table 5.4). This indicated a loss of N with the addition of lime to S^o dusted sites. The concentration of N^{15} (the ratio of total N^{15} to total N) was greatest in the NIL treatment of the control site, lower in the LIME + S^o treatments, and lowest in the NIL treatments of S1 and S2. Therefore, immobilization of N was found to be NIL > Lime + S^o > S^o (NIL of S1 and S2).

5.4.3 Moss Bag Experiment

The LFH, 0-15 cm mineral horizon, and moss from the net bags were analyzed for total N and tagged N. In the LFH, there was more total N and tagged N in the NIL treatment than in the S^o (Table 5.5). However, the S^o treatment had

Table 5.1. Mineral nitrogen (kg ha^{-1}) (n=2) found in the litter layers and mineral soil at different sampling dates in the 2N treatment of the Small N Plots at control (C1).

DATE	ACCUMULATE ADDED N KG HA^{-1}	LITTER		0-15CM		15-30CM	
		NH_4	NO_3	NH_4	NO_3	NH_4	NO_3
11/80	112**						
05/81	224						
07/81*		2	0	1	1	-2	4
07/81	336						
07/82	448						
09/82		5	2	3	3	-3	3
09/82	560						
06/83	672						
08/83	784						
09/83+		25	24	26	12	5	0

* Sampling occurred prior to fertilizer addition on the same day. The results are 2N minus the NIL treatment (net N mineralized).

\+ The sampling of Sep 83 was taken one month after the last fertilizer application. The NIL treatment was not sampled. These results are gross N mineralized.

** Each year there were two additions of NH_4NO_3. There had been a total of 784 Kg N ha^{-1} added by August 1983 (7 X 112).

Table 5.2. Mineral nitrogen (kg ha^{-1}) (n=2) found in the litter layers and mineral soil at different sampling dates in the 2N treatment of the Small N Plots at Strachan (S1).

DATE	ACCUMULATE ADDED N KG HA^{-1}	LITTER		0-15CM		15-30CM	
		NH_4	NO_3	NH_4	NO_3	NH_4	NO_3
09/80	112**						
11/80*		77	68	-7	0	10	1
11/80	224						
05/81		26	1	44	4	1	11
05/81	336						
07/81		11	0	14	1	2	1
07/81	448						
07/82	560						
09/82		4	16	2	1	0	-1
09/82	672						
06/83	784						
08/83	896						
09/83+		33	32	43	37	5	1

* Sampling occurred prior to fertilizer addition on the same day. The results are 2N minus the NIL treatment (net N mineralized).

\+ The sampling of Sep/83 was taken one month after the last fertilizer application. The NIL treatment was not sampled. These results are gross N mineralized.

** Each year there were two additions of NH_4NO_3. There had been a total of 896 kg N ha^{-1} added by August 1983 (8 X 112).

Table 5.3. Mineral nitrogen (kg ha^{-1}) (n=2) found in the litter layers and mineral soil at different sampling dates in the 2N treatment of the Small N Plots at Ram River (S2).

DATE	ACCUMULATE ADDED N KG HA^{-1}	LITTER		0-15CM		15-30CM	
		NH_4	NO_3	NH_4	NO_3	NH_4	NO_3
09/80	112**						
11/80*		65	71	3	1	3	0
11/80	224						
05/81		2	0	69	3	29	13
05/81	336						
07/81		0	0	49	1	7	9
07/81	448						
07/82	560						
09/82		19	27	27	30	1	0
09/82	672						
06/83	784						
08/83	896						
09/83+		23	22	39	12	4	1

* Sampling occurred prior to fertilizer addition on the same day. The results are 2N minus the NIL treatment (net N mineralized).

+ The sampling of Sep 83 was taken one month after the last fertilizer application. The NIL treatment was not sampled. These results are gross N mineralized.

** Each year there were two applications of NH_4NO_3. There had been a total of 896 kg N ha [illegible] added by August 1983 (8 X 112).

Table 5.4. Total nitrogen (mg kg^{-1}) (n=3) found in soil samples from C1, S1, and S2 which had been amended with 112 kg N ha^{-1} (NH_4NO_3 tagged at 5.05%). Placement was on June 8, 1983; sampling was on July 11, 1983.

SITE	TREATMENT			
	NIL		LIME + S^{o}	
DEPTH (cm)	N	N^{15}¬	N	N^{15}¬
	NITROGEN (MG KG^{-1})			
CONTROL (C1)	(4.4)*		(+)	
L	9960	1305	5362	504
FH	10596	568	9745	344
0-5	806	84	1018	41
5-10	603	8	589	6
STRACHAN (S1)	(2.9)		(6.6)	
L	10572	193	6160	576
FH	12189	178	7834	458
0-5	1174	59	1074	37
5-10	474	5	472	4
RAM RIVER (S2)	(2.7)		(5.1)	
L	8642	220	7315	472
FH	9606	165	9115	165
0-5	1325	85	1018	32
5-10	437	19	447	9

¬ Tagged fertilizer N

* pH value for the L litter layer June 1983 within the NIL and LIME + S^{o} treatments.

\+ missing data.

Table 5.5. Total nitrogen values (mg kg^{-1}) for soil samples taken from the big plot at the control site (C1). N^{15} labelled NH_4NO_3 had been added to all treatments at 87.26 kg N ha^{-1} on August 10, 1983. Values are means (n=3) taken September 12, 1983.

	TOTAL NITROGEN ($MG\ KG^{-1}$)					
TREATMENT	NIL		S^O*		LIME + S^O*	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
DEPTH (cm)						
TOTAL N						
LFH	13445	1745	8320	240	5390	1090
0-15	950	225	810	120	795	60
TAGGED N						
LFH	724	200	373	124	189	49
0-15	12	10	17	16	12	10
% RECOVERY	60		61		40	

* S^O was added at 3120 Kg ha^{-1} and $CaCO_3$ at 6430 Kg ha^{-1} to cylinders in the field.

more tagged N than the NIL treatment of the 0-15 cm mineral horizon. The LIME + S^o treatment had less total N and tagged-N in the LFH litter layer and the 0-15 cm mineral horizon than the S^o treatment and the NIL. The percent recovery was 40% of the tagged-N in the LIME + S^o treatment (calculations based on bulk densities listed in Appendix VIiii).

More N^{15} ($p<0.05$) was transferred from the soil to the suspended moss bags from the LIME + S^o treatment than from the S^o or NIL treatments (Table 5.6).

5.4.4 Big Plots Plus LIME

Mineralization increased with the addition of lime at the control site (Table 5.7). However, liming of the acid soils (S1 and S2) decreased NH_4^+-N in the LFH and 0-30 cm mineral horizon, and increased NO_3^--N.

5.5 DISCUSSION

Little of the applied fertilizer N was recovered as mineral N in the Small N Plots. Bosatta et al. (1980) found that mineralization was immediately balanced by root uptake in a Scots pine forest. In this study, mineralization increased with the addition of lime on the control site. Similar results were reported by Nyborg and Hoyt (1978) on incubation of soils from wooded sites from the Peace River Region. Ogata and Caldwell (1960) reported a positive effect

Table 5.6. Total nitrogen (mg kg^{-1}) (n=3) in moss bags suspended over treatments to which N^{15} labelled NH_4NO_3 had been added; initiated at C1, August 10, 1983; moss bags removed September 12, 1983. Lower case letters indicate significant differences ($p<0.05$) between treatments where the tagged fertilizer had been added.

	TOTAL N ($MG\ KG^{-1}$)			
	TOTAL NITROGEN		TAGGED NITROGEN	
TREATMENT	MEAN	S.D.	MEAN	S.D.
CONTROL*	6930	400	0.1	0.2
NIL	6845	1010	3.3 a	3.5
S^o	6550	1080	1.0 a	0.9
LIME + S^o	6610	820	115.6 b	95.0

* No fertilizer N added (background N^{15}).

Table [illegible]. Extractable mineral N values (mg kg^{-1}) (n=3) taken July 1982, from the NIL and LIME treatments (no fertilizer N), the Big Plots, at C1, S1, and S2.

	NITROGEN (MG KG^{-1})							
TREATMENT	NIL				LIME			
	NH$_4$		NO$_3$		NH$_4$		NO$_3$	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
SITE								
DEPTH (CM)								
CONTROL (C1)		(4.4)*				(6.8)		
LFH	54	28	2	2	85	22	23	18
0-15	4	0	1	1	6	1	2	1
15-30	6	3	2	1	5	2	2	1
STRACHAN (S1)		(1.7)				(3.2)		
LFH	303	155	7	5	146	65	17	8
0-15	4	6	2	1	5	1	2	0
15-10	3	1	1	0	3	1	3	1
RAM RIVER (S2)		(1.9)				(2.4)		
LFH	229	7	3	1	196	34	63	62
0-15	8	1	2	1	7	3	2	1
15-30	9	1	1	6	8	1	2	1

* pH value at time of sampling.

on the mineral N accumulation in the liming of acid soils. However, liming decreased net ammonification and increased net nitrification on the two S^{o} dusted sites, S1 and S2. Liming of raw humus from a podzolic soil developed beneath a mature stand of Norway spruce **Picea abies** (L.) Karst., depressed the accumulation of ammonium N (Nommik, 1968). Chase **et** al. (1968) reported that nitrifying bacteria increased in numbers in acid forest soils after liming.

The Small N Plots showed a 10% loss of fertilizer N at S2, and a 41% loss at C1 and S1 (Table 5.8). The 0-15 cm and 15-30 cm horizons had increased in their total N content after repeated applications of fertilizer N. S1 lost N in the LFH; however, C1 and S2 gained. The results at C1 and S2 are comparable to a study by Berg and Staaf (1980) who found that N was efficiently retained in litter when placed in a 60 year old stand of Scots pine. It should be noted that S2 had received heavy applications of S^{o} and S1 had received S^{o} and "glass rock" limestone.

The majority of the recovered N^{15} was found in the 0-5 cm mineral horizon (Table 5.9). Recovery of the applied N^{15}-tagged N ranged from 34 to 71%. Percent recovery was higher in the NIL than in the LIME + S^{o} at C1 and S2. The presence of **Petasites palmatus**, **Viola renifolia**, and **Lycopodium annotinum** indicated a moist site at C1 (Rowe, 1956). S1 was well drained and S2, imperfectly drained. Therefore, moisture regime may have contributed to the differences

Table 5.8. Total nitrogen (kg ha^{-1}) for soil samples taken from the Small N Plots (n=2)).

SITE	CONTROL (C1)		STRACHAN (S1)		RAM RIVER (S2)	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
SAMPLING DATES						
DEPTH (cm)	TOTAL N (KG HA^{-1})					
NIL JUL/81						
LFH	530	390	620	35	530	40
0-15	1220	40	1100	220	1340	6
15-30	920	120	870	1	870	40
2N SEP/83*						
LFH	540	50	455	135	575	60
0-15	1520	470	1600	70	1830	25
15-30	1075	255	1060	20	1140	+
TOTAL CHANGE WITH FERTILIZER ADDITIONS	465		525		805	
% LOSS	41		41		10	
pH NOV/80	+		4.0		2.5	
pH SEP/81	5.0		+		+	
pH JUN/83	+		3.0		2.7	

* The accumulated total of applied N as NH_4NO_3 for C1 was 784 kg N ha^{-1}, and for S1 and S2 was 896 kg N ha^{-1}, respectively.

\+ missing value.

Table 5.9. Tagged fertilizer N (Kg ha^{-1}) and percent recovery of tagged fertilizer N found in soil samples from C1, S1, and S2. Fertilizer addition (112 kg N ha^{-1}) on June 8, 1983; sampling on July 11, 1983. Different upper case letters indicate significant differences ($p<0.05$) in the amount of tagged N between sites and treatments at that depth (e.g. C1, S1, S2, NIL, and LIME + S^{O} are compared at FH).

DEPTH (cm)	TAGGED N (KG HA^{-1})	
	NIL	LIME + S^{O}
CONTROL (C1)		
L	18 C	12 BC
FH	13 B	13 BC
0-5	44 B	18 AB
5-10	5 A	4 A
TOTAL	80 B	47 AB
RECOVERY	71 %	42 %
STRACHAN (S1)		
L	4 A	12 B
FH	8 AB	17 C
0-5	31 AB	17 AB
5-10	4 A	3 A
TOTAL	47 A	49 AB
RECOVERY	42 %	44 %
RAM RIVER (S2)		
L	5 A	13 BC
FH	6 A	5 A
0-5	36 B	15 A
5-10	14 A	5 A
TOTAL	61 AB	38 A
RECOVERY	54 %	34 %

between S1 and C1 or S2. The differences between Small N Plots and the N^{15} experiment may have been due to the application time of the fertilizer N. For example, NH_4^+ was released from surface litter during summer, but effectively immobilised in autumn in a podzol in a Scots pine stand in Central Sweden (Bringmark, 1980). Experience with N fertilization of forest ecosystems indicates that the benefits from N fertilizers are transitory, usually lasting about 5 to 10 years (Mead and Gadgil 1978, Miller et al., 1976). It is normally assumed that the value of applied nitrogen ceases at the end of this response period because of the susceptibility of applied nitrogen to loss from the ecosystem through leaching, volatilization, denitrification, and immobilization (Wollum and Davey, 1975).

In the moss bag study, the NIL and S^o treatments showed little loss of gaseous N (< 3.4 mg tagged-N kg^{-1} retained in moss bags). Overrein (1969) found that denitrification was low in acidic podzolic soils. The largest losses of gaseous N occurred in the LIME + S^o treatment. The LFH of S1 (Small N Plot which had been S^o dusted and received aerial liming) had a depletion of 165 kg N ha^{-1} from 1981 to 1983. Sikora and Keeney (1976) removed nitrate from a nitrified septic tank effluent by employing the obligate chemolithotroph Thiobacillus denitrificans. This bacterium obtains energy by oxidizing reduced S compounds and passing electrons to NO_3^- in the absence of O_2. Columns were filled with a 1/1 mixture (wt/wt) of S^o (> 2 mm) and dolomite chips (1 cm) and pretreated by cycling an enrichment of T. dentirificans through the columns for 3 days. Continuous passage, through the columns, of septic tank effluent containing 40 ug NO_3^--N ml^{-1} removed NO_3^- in 3.3 hours at steady-state conditions (23°C). N_2 was present in highest concentration (on analysis of gases produced). The reaction would be similar to:

$$5S + 6KNO_3 + 2CaCO_3 \rightarrow 3K_2SO_4 + 2CaSO_4 + 2CO_2 + 3N_2 +$$ energy.

Bremner and Shaw (1958) found that denitrification increased with the addition of $Ca(OH)_2$. Tisdale et.al. (1985) reported that the percentage of free ammonia increases with rising pH. The gaseous N could have been N_2 and/ or NH_3. Examination of T. denitrificans would be of interest in the future on S^o dusted sites, under anaerobic conditions (high rainfall), with nitrate and lime present.

A normal forest tightly cycles N within its system (Bosatta, et al. 1980). In the present study, with the addition of S^o and/or lime, the following occurred:

1) an increase in mineralization with the addition of lime to the control site,

2) a decrease in ammonification and an increase in nitrification with the addition of lime to the previously S^o dusted site,

3) a greater retention of N fertilizer in the LFH and 0-30 cm mineral horizon of the control and S^o dusted sites than sites with lime plus S^o,

4) an increase in the loss of gaseous N (N_2 and/or NH_3) with the addition of lime plus S^o to the control.

6. VEGETATION

6.1 INTRODUCTION

Having examined the effects of lime and sulphur on pH, rate of acidification, and fate of fertilizer N of these forest soils, a study of the effects on vegetation was undertaken. The objective was to determine the effect of soil acidification, liming, and fertilizer application on natural vegetation and cultivated forages. Changes in vegetation were monitored by recording percent ground cover, and survival of sown seeds.

6.2 MATERIALS AND METHODS

Subtreatments of NIL, N, NPK, and 2NPK were superimposed on the NIL, LIME, S^o, and LIME + S^o main treatments of the Big Plots at the C1, S1, and S2 sites. NH_4NO_3 was added at 75 kg N ha^{-1}, P_2O_5 at 15 kg P ha^{-1}, and KCl at 20 kg K ha^{-1}. Some treatments had N added more than once in the initial year only. Additions began the spring of 1981 at S1 and S2 and in the fall of 1981 at C1 (Appendices VIIi to VIIv).

Seeding experiments were initiated in 1981 at S2-Experiment #2, in 1982 at S1-Experiment #2 and at S2-Experiment #1, and in 1983 at C1, S1-Experiment #1, and S2-Experiment #2 (Appendices IIi and IIii). The seed mixture consisted of brome grass, reed canary grass, timothy, and red clover with a Rhizobium inoculum (Appendix VIII). In the spring of 1982, new seed was obtained from Prairie Seeds, Edmonton, Alberta. At S2, the native ground cover was dead and the only green on the plot was due to the emergence of grass or clover seedlings. A subjective criterion was used based on percent cover, seedling height, and colour to determine emergence of the sown seed mixture.

An estimate of the plant species cover was taken in each sub-plot, July 1982 at C1, July 1983 at C1, S1, and S2, and August 1984 at C1, S1, and S2. The percent cover for one plant, fireweed (0.5 m tall) was calculated to be 0.50 percent. The calculated percent cover for one clump of grass (r=10 cm) was 0.40 percent (< 0.5 m tall) and 0.90 percent (> 0.5 m tall and heading). A percent cover of less than one was recorded as one percent. A one way analysis of variance was carried out between 1) lime and sulphur main treatments, and 2) fertilizer subtreatments, on grass, moss, and herbs, individually as well as the total of the three vegetation types.

6.3 RESULTS

6.3.1 EMERGENCE

In 1981 there was no emergence on S2-Experiment #2. In Sep/82, S2-Experiment # 1 which had been sown Aug/82, showed no emergence on either the NIL or S^o treatments (Table 6.1). The LIME treatment had poor to good germination. LIME + S^o

Table 6.1. An assessment of emergence completed September 18, 1982 for seed sown August 5, 1982 at Ram River S2-Experiment #1.

		TREATMENT			
	REPLICATE	NIL	LIME	S^{o}	$L + S^{o}$
SUBTREATMENT					
NIL	R1	0*	P	0	E
	R2	0	G	0	E
	R3	0	P+	0	G
NPK	R1	0	P	0	G
	R2	0	E	0	G
	R3	0	G	0	G
2N	R1	0	0	0	E
	R2	0	G	0	G
	R3	0	G-	0	E
3NPK	R1	0	G	0	G
	R2	0	G	0	G
	R3	0	G	0	G

* 0 = DEAD

P = POOR (YELLOWING OR PURPLING) < 10% COVER

G = GOOD (AVERAGE GROWTH) < 30% COVER

E = EXCELLENT (LUSH GROWTH) < 60% COVER

had good to excellent germination. Lime was needed for germination of these grasses. S1-Experiment #2 showed no emergence (1982).

In 1983, grass germinated best on the LIME and LIME + S^o treatments (Table 6.2a). However, on most sites native grasses possibly competed with the sown cultivars and in some instances it was difficult to differentiate between the two. Sites with a pH value less than 3.0 showed little or no emergence of sown grasses. At a pH of 5.0 or greater, emergence was good.

In 1984, grass germinated best on LIME + S^o treatments which had an excess of lime (Table 6.2b) and, in some cases with fertilizer additions. However, germination was negligible on S2-Experiment #2. At the Strachan site, Experiment #2 was furthest from the S^o block, while at Ram River, Experiment #1 was furthest (Figure 2.1). These two experiments had been seeded in 1982 while the remaining experiments and C1 had been seeded in 1983. On comparing the results from Table 6.1 and Tables 6.2a,b, the emergence of grass in the fall of 1982 at S2 followed the same trend in 1984; however, the percent cover of colonizers was much less.

Table 6.2a.- Average percent cover of grasses for each treatment (n = 3, 4 subtreatments). The seed mixture was sown June 15, 1983 at C1, S1-Experiment #1 and S2-Experiment #2, and the first week of August 1982 at S1-Experiment #2 and S2-Experiment #1. The percent cover was taken September 12, 1983. Numbers represent the percent of grasses which had recently emerged over the total percent of grasses which were not in head (the author was unable to distinguish the differences between native and sown grasses in some instances due to animal browsing).

SITE	C1	S1		S2	
EXPERIMENT		#1	#2	#1	#2
TREATMENT					
NIL	0/1 (4.4)¬	2/2 (2.9)	3/3	0/0 (2.7)	0/1
LIME	3/21	7/10 (6.0)	5/5	4/9 (5.5)	0/7
S^{o}	0/4 (2.2)	1/1	1/1	0/0	0/0
LIME + S^{o}	1/7	18/21 (6.6)	21/28	6/12 (5.1)	1/13

¬ pH values taken June 10, 1983.

Table 6.2b. Average percent cover of grasses for each treatment (n=3 and 4 subtreatments). The seed mixture was sown June 15, 1983 at C1, S1-Ex #1 and S2-Ex #2; and the first week of August 1982 at S1-Ex #2 and S2-Ex #1. Percent cover was taken August [illegible] 1984.

SITE	C1	S1		S2	
EXPERIMENT		#1	#2	#1	#2
TREATMENT					
NIL	6	1	2	0	0
LIME	10	7	8	5	0
S^o	2	1	1	0	0
LIME + S^o	8	10	22	9	1
NIL	2	7	4	7	0
NPK	4	3	14	3	0
2N*	9	6	7	3	0
2NPK+	9	4	7	2	0

* S1-#2 and S2-#2 are N

\+ S1-#1 and S2-#1 are 3NPK

6.3.2 VEGETATION, LIMING AND FERTILIZATION

Lime increased ($p<0.05$) the growth of moss (Table 6.3a), while S^o and fertilizer N decreased ($p<0.05$) the growth of moss. In the third year, 1984, the grass had increased ($p<0.05$) in the 2NPK subtreatment of the LIME + S^o treatment.

The percent herb cover increased ($p<0.05$) with LIME + S^o at S1 (Table 6.3b and 6.3c) and S2 (Table 6.3d and 6.3e) and with no fertilizer N at S1 (Table 6.3c). The moss cover increased ($p<0.05$) with the excess lime in the LIME + S^o treatment at S1 (Table 6.3c). At S2, grass increased ($p<0.05$) in percent cover with excess lime (LIME + S^o) and NPK (Table 6.3e). The moss and herb cover were alive at Strachan; whereas at Ram River the mosses were dead and the herbs were sparse.

pH values were not measured after 1982. At the control site (C1) percent moss cover increased when the pH value increased from 4.4 to 6.8. Percent cover decreased when the pH value dropped to 3.4 Table (6.3a). The herbs appeared to grow better at higher pH values; however, it would appear that some other factor is of greater importance (Table 6.3b for Strachan and Table 6.3d for Ram River) (i.e., pH of 6.0 does not ensure herb development).

Table 6.3a. Results from a one way analysis of variance for Control (C1) (Appendix IX). Different lower case letters indicate significant differences ($p<0.05$) in percent cover between lime and sulphur treatments for any year. Different upper case letters indicate significant differences ($p<0.05$) in percent cover between fertilizer treatments for any year.

FERTILIZER TREATMENTS	LIME AND SULPHUR TREATMENTS											
PLANT TYPES	1982				1983				1984			
	NIL	L	S	L+S	NIL	L	S	L+S	NIL	L	S	L+S
	4.4	6.8	3.4	6.5	4.4		2.2¬					
NIL												
GRASS												A
MOSS	ab	b	a*	a	b	cB	a	ab		B		
HERBS												
TOTAL					a	b	a	a	ab	b	a	ab
2N												
GRASS												AB
MOSS						A				A		
HERBS												
TOTAL									b	ab	a	ab
NPK												
GRASS												A
MOSS						A				AB		
HERBS									b	ab	a	b
TOTAL									b	b	a	ab
2NPK												
GRASS												B
MOSS						A				A		
HERBS									b	ab	a	b
TOTAL									ab	ab	a	b
TOTALS					ab	b	a	ab	b	b	a	b

¬ pH value

* "a" has a lower value than "b"

Table 6.3b. Results from a one way analysis of variance for Strachan (S1) Experiment #1 (Appendix IX). Different lower case letters indicate significant differences ($p<0.05$) in percent cover between lime and sulphur treatments for any year. Different upper case letters indicate significant differences ($p<0.05$) in percent cover between fertilizer treatments for any year.

FERTILIZER TREATMENTS / PLANT TYPES	LIME AND SULPHUR TREATMENTS 1983 NIL	1983 L	1983 S	1983 L+S	1984 NIL	1984 L	1984 S	1984 L+S
	2.8	6.0		6.6¬				
NIL								
GRASS					a	b	a	b
MOSS								
HERBS	a*	ab	a	b	a	b	a	b
TOTAL	a	a	a	b	a	b	a	b
2N								
GRASS								
MOSS								
HERBS					a	b	ab	c
TOTAL					a	b	a	c
NPK								
GRASS					a	ab	a	b
MOSS								
HERBS	ab	a	a	b	a	a	a	b
TOTAL					a	b	a	c
3NPK								
GRASS					a	a	a	b
MOSS								
HERBS	a	b	a	c	a	ab	a	b
TOTAL	a	ab	a	b	a	a	a	b
TOTALS	ab	b	a	c	a	b	a	c

¬ pH value

* "a" has a lower value than "b"

Table 6.3c. Results from a one way analysis of variance for Strachan (S1) Experiment #2 (Appendix IX). Different lower case letters indicate significant differences (p<0.05) in percent cover between lime and sulphur treatments for any year. Different upper case letters indicate significant differences (p<0.05) in percent cover between fertilizer treatments for any year.

FERTILIZER TREATMENTS	LIME AND SULPHUR TREATMENTS							
PLANT TYPES	------1983-------				------1984-------			
	NIL	L	S	L+S	NIL	L	S	L+S
NIL								
GRASS								
MOSS	a*	a	a	b	a	a	a	b
HERBS	a	a	a	bB	a	a	a	b
TOTAL	a	a	a	b	a	a	a	b
N								
GRASS					a	a	a	b
MOSS	a	a	a	b				
HERBS				A				
TOTAL					a	a	a	b
NPK								
GRASS								
MOSS	a	a	a	b				
HERBS				A	a	ab	a	b
TOTAL					a	a	a	b
2NPK								
GRASS	a	a	a	b	a	ab	a	b
MOSS								
HERBS				A				
TOTAL					a	ab	a	b
TOTALS	a	a	a	b	a	a	a	b

* "a" has a lower value than "b"

Table 6.3d. Results from a one way analysis of variance for Ram River (S2) Experiment #1 (Appendix IX). Different lower case letters indicate significant differences ($p<0.05$) in percent cover between lime and sulphur treatments for any year. Different upper case letters indicate significant differences ($p<0.05$) in percent cover between fertilizer treatments for any year.

FERTILIZER TREATMENTS PLANT TYPES	LIME AND SULPHUR TREATMENTS 1983 NIL	 1983 L	 1983 S	 1983 L+S	 1984 NIL	 1984 L	 1984 S	 1984 L+S
	2.7	5.5		5.1¬				
NIL								
GRASS								
MOSS								
HERBS	a*	a	a	b	a	a	a	b
TOTAL	a	a	a	b				
2N								
GRASS								
MOSS								
HERBS	a	a	a	b	a	ab	a	b
TOTAL	a	a	a	b				
NPK								
GRASS	a	ab	a	b				
MOSS								
HERBS	a	b	a	ab	a	b	a	ab
TOTAL	a	b	a	b				
3NPK								
GRASS	a	b	a	b	a	ab	a	b
MOSS								
HERBS								
TOTAL	a	ab	a	b				
TOTALS	a	b	a	c	a	b	a	c

¬ pH value

* "a" has a lower value than "b"

Table 6.3e. Results from a one way analysis of variance for Ram River (S2) Experiment #2 (Appendix IX). Different lower case letters indicate significant differences ($p < 0.05$) in percent cover between lime and sulphur treatments for any year. Different upper case letters indicate significant differences ($p < 0.05$) in percent cover between fertilizer treatments for any year.

FERTILIZER TREATMENTS	LIME AND SULPHUR TREATMENTS							
PLANT TYPES	1983				1984			
	NIL	L	S	L+S	NIL	L	S	L+S
NIL								
GRASS	a*	a	a	bAB	a	a	a	b
MOSS								
HERBS	a	ab	a	b	a	b	a	b
TOTAL	ab	b	a	cB	a	b	a	c
N								
GRASS	a	b	a	bA				
MOSS								
HERBS								
TOTAL	a	b	a	bAB	a	b	a	b
NPK								
GRASS	a	a	a	bB				
MOSS								
HERBS					a	ab	a	b
TOTAL	a	ab	a	bAB				
2NPK								
GRASS	ab	bc	a	cA	ab	b	a	ab
MOSS								
HERBS	ab	ab	a	b				
TOTAL	ab	bc	a	cA	ab	b	a	b
TOTALS	a	b	a	c	a	ab	a	b

* "a" has a lower value than "b"

6.4 DISCUSSION

Ground cover at the control site Sep/81 was diverse consisting of such species as **Pleurozium Schreberi**, **Cornus canadensis**, **Ptilium crista-castrensis**, **Hylocomium splendens**, **Linnaea borealis**, **Spiraea lucida**, **Antennaria neglecta**, **Arnica cordifolia**, and **Elymus innovatus**. With addition of lime, ground cover became more lush and heading of grasses increased with fertilizer treatment by Aug/84. In contrast, the S^o treatment showed a decrease in ground cover vegetation, mosses were brown in colour (indicating mortality) and the only species to survive were **Cornus canadensis**, (5%) a few grasses (5%), **Spiraea lucida** (5%), and **Linnaea borealis** (5%) (average percent cover values). In the LIME + S^o treatment, herbs and mosses were depleted (10%) with the grasses showing a 10% increase in percent cover.

At the Strachan site (S1) the ground cover was still healthy in the summer of 1981. The major species included **Cornus canadensis**, **Maianthemum canadense** var **interius**, **Linnaea borealis**, **Vaccinium myrtilloides**, **Ledum groenlandicum**, **Epilobium angustifolium**, **Pleurozium schreberi**, and **Ptilium crista-castrensis**. By Aug/84, with the addition of lime, grass cover increased with **Elymus innovatus** dominating. Percent cover of **Cornus canadensis** increased at Experiment # 1 but was 0 at Experiment # 2. **Epilobium angustifolium**, which normally establishes itself after fire or clear-cutting, was prominent. The S^o treatment had an average percent cover of 5%, with short grasses and **Epilobium angustifolium** as the major colonizers. In the LIME + S^o treatment, the diversity of species was maintained as in the summer of 1981, but percent cover of **Elymus innovatus**, **Linnaea borealis**, and **Epilobium angustifolium** increased.

The Ram River site (S2) had little ground cover in the summer of 1981. Moss cover was nil and species richness was low (**Cornus canadensis**, **Elymus innovatus**, and **Epilobium angustifolium**). By Aug/84, after addition of lime, percent cover of **Spiraea lucida** increased at Experiment # 2. In the S^o treatment, the vegetation was dead. In Experiment # 2, percent cover of **Spiraea lucida** increased in the LIME + S^o treatment as compared to the LIME treatment. In Experiment # 1, **Cornus canadensis** and **Epilobium angustifolium** were dominant. The grasses, **Elymus innovatus** and **Calamagrostis canadensis**, were found in clumps at both Ex # 1 and 2. S2 had less vegetative ground cover than S1. This can be attributed to the longer exposure to S^o dust and its breakdown products (ie., SO_4^{2-}-S).

In forests, uptake of nutrients occurs primarily from the surface soil organic layer (Cole, 1981). Trees that have evolved in a high NH_4^+-N, low NO_3^--N soil environment appear to take up NH_4^+-N over NO_3^--N, selectively. In this study, NH_4^+-N dominated the soil system on S^o dusted sites.

However, with the addition of lime, nitrification was increased.

In conclusion:

1) 6770 kg $CaCO_3$ ha^{-1} increased ($p<0.05$) growth of mosses (one year after application).

2) Two years after the application of 2280 kg S^o ha^{-1}, percent cover of mosses decreased ($p<0.05$).

3) Grasses were favoured by excess lime and NPK on a S^o dusted site.

4) Herb cover was maintained by excess lime without NPK on a S^o dusted site. Lime and fertilizer were needed to maintain vegetation at S2 while lime was needed at S1.

7. RECOMMENDATIONS

In an area where the possibility of S^o dusting exists, lime should be added immediately to retain the natural vegetation. Successive additions may be needed if S^o dusting continues over a long period of time. An excess of lime as $CaCO_3$ had no adverse affect on the vegetation. Therefore, more lime than required to neutralize a measured amount of acidification may be safely added if S^o dusting continues.

Once the ground cover has been depleted, NPK additions are needed to maintain grasses until natural vegetation can once again be established. Seeding of grasses (and clover) should be done when there is excess lime on the soil and rainfall is high to ensure germination and initial establishment of the seed mixture applied.

8. GENERAL DISCUSSION AND CONCLUSIONS

When the project was begun the "big" plots were designed with main treatments of NIL, LIME, Elemental Sulphur (S^o), and LIME + S^o and with subtreatments of NIL, N, NPK, and more than one application of N fertilizer in the first year. We hypothesized that on the main treatments, where soil had been made acid and barren of ground cover by S^o dust and subsequently limed, a mixture of cultivated grasses would take hold upon seeding. However, the hypothesis was incorrect as percent cover of the sown seed mixture was low (<10%). The soil of the Small N Plots (unseeded) was sampled twice yearly and mineral N determined. Mineral N from the applications of NH_4NO_3 quickly disappeared. However, 41% at C1 and S1 and 90% at S2, of the total applied, was retained in the soil down to a depth of 30 cm. The results of the Small N Plots indicated that mineral N would be insufficient for planted grasses.

NH_4NO_3, double tagged with N^{15}, was used to estimate the fate of applied N fertilizer. The recovery of total tagged NH_4NO_3 was 34% to 71% (to a depth of 10 cm) at two S^o dusted sites and one control site. The recovery was less on limed soil than on non-limed soil. When moss bags were hung 0.3 m over NIL, S^o, and LIME + S^o treatments, N^{15} was trapped in bags suspended over the LIME + S^o treatment. In the soil below the moss bags, recovery of total tagged nitrogen was 40% to 61%, with the lowest value obtained on the LIME + S^o treatment. Mineralization increased on the control site with the addition of lime. Ammonification decreased and nitrification increased with the addition of lime on two S^o-dusted sites. The N^{15} experiments indicated that in most cases half of the N^{15}-tagged fertilizer had disappeared from the soil. Applied nitrate may have been leached beyond the sampled layers. Denitrification of the nitrate or plant uptake may have occurred. Volatilization of ammonia from the applied ammonium nitrate was a possibility on treatments which received high rates of lime. The uptake of N by the moss bags hung over the LIME + S^o treatment, suggested that there was evolution of ammonia from that treatment and consequent fixation of ammonia by the moss. Normally, nitrification is slow when soils are acid (Bremner and Shaw, 1958). But sulphur oxidizing bacteria, e.g. **Thiobacillus denitrificans**, could have caused denitrification (Sikora and Keeney, 1976).

The "N^{15} in Big Plots" experiment was "wet" (170 mm; Jun/Jul 1983) as compared to the "Moss Bag Experiment" which was "dry" (35 mm; Aug/Sep 1983). The S^o treatment of C1 had a tagged-N recovery of 61% (Table 5.5) for the dry months, while for the wet months, the NIL treatment of S1 and S2 had a recovery of 42-54% (Table 5.9). **Thiobacillus denitrificans** may have been causing the loss of N during the wet months.

In this project, the shallow organic layers of the control site, which had not before received S^o, were made acid (pH 2.0) 21 months after S^o application. The mineral layers were not influenced. Application of lime, at the time of S^o application, resulted in higher soil pH which was maintained. Further, the ground cover survived. This finding indicated that lime application before S^o dust deposition will maintain the ground cover.

I used finely ground limestone in my field experiments, but in the extensive liming program by the two gas plants coarser "glass rock" limestone was spread from aircraft. The former is the conventional fineness of grind for liming farm soils and the "glass rock" is not considered fine enough to use on farm soils. The "glass rock" needs to be applied at much higher rates than finely ground limestone to achieve the same results.

Incubation experiments, with addition of S^o to the ground organic layers of soil from areas exposed to S^o deposition and from "clean" areas, showed a lag period in the "clean" samples for the oxidation of S^o and acidification of the soils. The MPN values of **Thiobacillus thiooxidans** were low for a "clean" site compared to a site which had received S^o. An increase in the **Thiobacillus** population was needed before a significant drop in the pH value could occur. In the field experiments and in the incubation experiments, S^o acidified each soil although the initial speed varied.

The pH of the leaf litter from the control site near the Ram River and Strachan gas plants was 4.4 in the L layer, 4.2 in the FH, and 4.5 in the 0-5 cm mineral horizon. Addition of 2280 kg S^o ha^{-1}, caused no pH response the first year, but by the second year the pH had dropped to 2.2 in the L layer, 1.8 in the FH, and 4.1 in the 0-5 cm mineral horizon. The ground cover vegetation, which was initially diverse and lush had become less diverse. The resulting vegetation consisted of **Cornus canadensis**, **Elymus innovatus**, **Linnaea borealis**, **Spiraea lucida**, and **Calamagrostis canadensis** (each with an average 5% cover value). Nine months after the addition of "feedgrade" limestone at 6770 kg ha^{-1}, the pH increased to 6.8 in the L layer, 5.5 in the FH, and 5.2 in the 0-5 cm mineral horizon. Moss cover increased ($p<0.05$) at this time. With the addition of 2280 kg S^o ha^{-1} and "feedgrade" limestone at 17700 kg ha^{-1}, the pH increased to 6.5 in the L layer, 6.1 in the FH, and 5.4 in the 0-5 cm mineral horizon. Moss cover decreased and herb cover increased.

In conclusion:

1) Sown cultivated grasses grew poorly on heavily S^o dusted areas which had been subsequently limed.

2) With the addition of nitrogen fertilizer on the LIME + S^o treatment the native grasses grew well.

3) Mineral N disappeared quickly from the plots, but a large

portion of the mineral N was immobilized in the LFH and the 0-15 cm mineral horizon.

4) There was a "lag" effect in oxidation of S^o in the organic layer in the field and in the lab in soils which had not been previously S^o dusted.

5) Acidification was shallow (down to a depth of 10 cm at S2) over the time period of the study.

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Appendix Ii. Soil profile description at the control site C1 (NOR-X-265; site # 9) (Addison et al., 1984).

SOIL DESCRIPTION

LOCATION............NW-18-37-12-W5
PARENT MATERIAL.....Eolian veneer/morainal till
ELEVATION (M).......1417
DRAINAGE............Moderately well drained
SLOPE & ASPECT......1.5% Northeast
CLASSIFICATION......Brunisolic Gray Luvisol
VEGETATION..........**Pinus contorta** var. **latifolia** was the dominant tree species with numerous **Abies balsamea** (stems < 5 cm in diameter). The ground cover was diverse with the major species being **Pleurozium schreberi**, **Cornus canadensis**, **Ptilium crista-castrensis**, **Hylocomium splendens**, **Linnaea borealis**, and **Spiraea lucida**.

HORIZON	DEPTH	COLOUR	TEXTURE	STRUCTURE
LF	4-0			
Ahe	0-5	10YR 4/1.5 (m) 10YR 7/2 (d)	L	structureless, massive
Bf	5-12	7.5YR 4/6 (m) 10YR 7/6 (d)	L	structureless, massive
IIBm	12-26	10YR 6/6 (m) 10YR 8/4 (d)	SL	very weak, medium subangular blocky

HORIZON	pH	ORGANIC C (%)	CEC (mmol kg^{-1})	BASE Sat. (%)	PARTICLE SIZE (%)		
					SAND	SILT	CLAY
LF	3.9						
Ahe	3.6	1.48	154		30	49	21
Bf	4.4	2.84	217	14	40	36	24
IIBm	4.4	0.60	93	29	52	30	18

SOIL CHEMISTRY

HORIZON	pH	TOTAL DIGEST (mg kg^{-1})		NH$_4$OAC EXTRACT (mg kg^{-1})		
		S	Ca	S	Ca	Al
LFH	4.5	1230	4190	190	4140	150
Ae1	4.7	210	3590	10	350	550
Bf	5.3	230	4190	20	550	900
Bm	5.4	210	1860	10	530	620

Appendix Iii. Soil profile description at Strachan (S1) (NOR-X-265; site # 1) (Addison **et al.**, 1984).

SOIL DESCRIPTION

LOCATION............	SE-35-37-09-W5
PARENT MATERIAL.....	Eolian veneer/morainal till
ELEVATION (M).......	1204
DRAINAGE............	Well drained
SLOPE & ASPECT......	1% Level
CLASSIFICATION......	Brunisolic Gray Luvisol
VEGETATION..........	There was a co-dominant stand of **Populus tremuloides** and **Pinus contorta** var. **latifolia** with a minor component of **Picea** sp. The ground cover was herb dominated by **Cornus canadensis**, **Maianthemum canadense** var **interius**, **Linnaea borealis**, and **Vaccinium myrtilloides**.

HORIZON	DEPTH	COLOUR	TEXTURE	STRUCTURE
[illegible]	5-4	10YR 2/2 (m)		
[illegible]	4-0	7.5YR 2.5/0 (m)		
[illegible]	0-3	10YR 5/2 (m) 10YR 7/2 (d)	SiL	structureless
Bm	3-11	7.5YR 4/4 (m) 10YR 7/6 (d)	SiL	structureless
Ae_2	11-21	10YR 6/3 (m) 10YR 9/2 (d)	SiL	moderate, medium platy

HORIZON	pH	ORGANIC C (%)	CEC (mmol kg^{-1})	BASE Sat. (%)	PARTICLE SIZE (%) SAND	SILT	CLAY
L	1.3						
FH	1.6						
Ae_1	3.2	1.52	210		27	59	14
Bm	4.6	1.81	220		26	54	20
Ae_2	4.9	0.29	130		18	63	19

SOIL CHEMISTRY

HORIZON	pH	TOTAL DIGEST (mg kg^{-1}) S	Ca	NH_4OAC EXTRACT (mg kg^{-1}) S	Ca	Al
LFH	2.5	58600	11700	11600	9540	300

Appendix Iiii. Soil profile description at Ram River (S2) (NOR-X-265; site # 15) (Addison **et al.**, 1984).

SOIL DESCRIPTION

LOCATION.............SW-01-37-10-W5
PARENT MATERIAL.....Eolian veneer/morainal till
ELEVATION (M).......1402
DRAINAGE............Imperfectly drained
SLOPE & ASPECT......Level
CLASSIFICATION......Gleyed Brunisolic Gray Luvisol
VEGETATION..........There was a co-dominant stand of **Pinus contorta** var. **latifolia** and **Picea** sp., with **Alnus crispa** as a shrub. The ground cover was sparse with **Cornus canadensis**, **Ledum groenlandicum**, and **Epilobium angustifolium**.

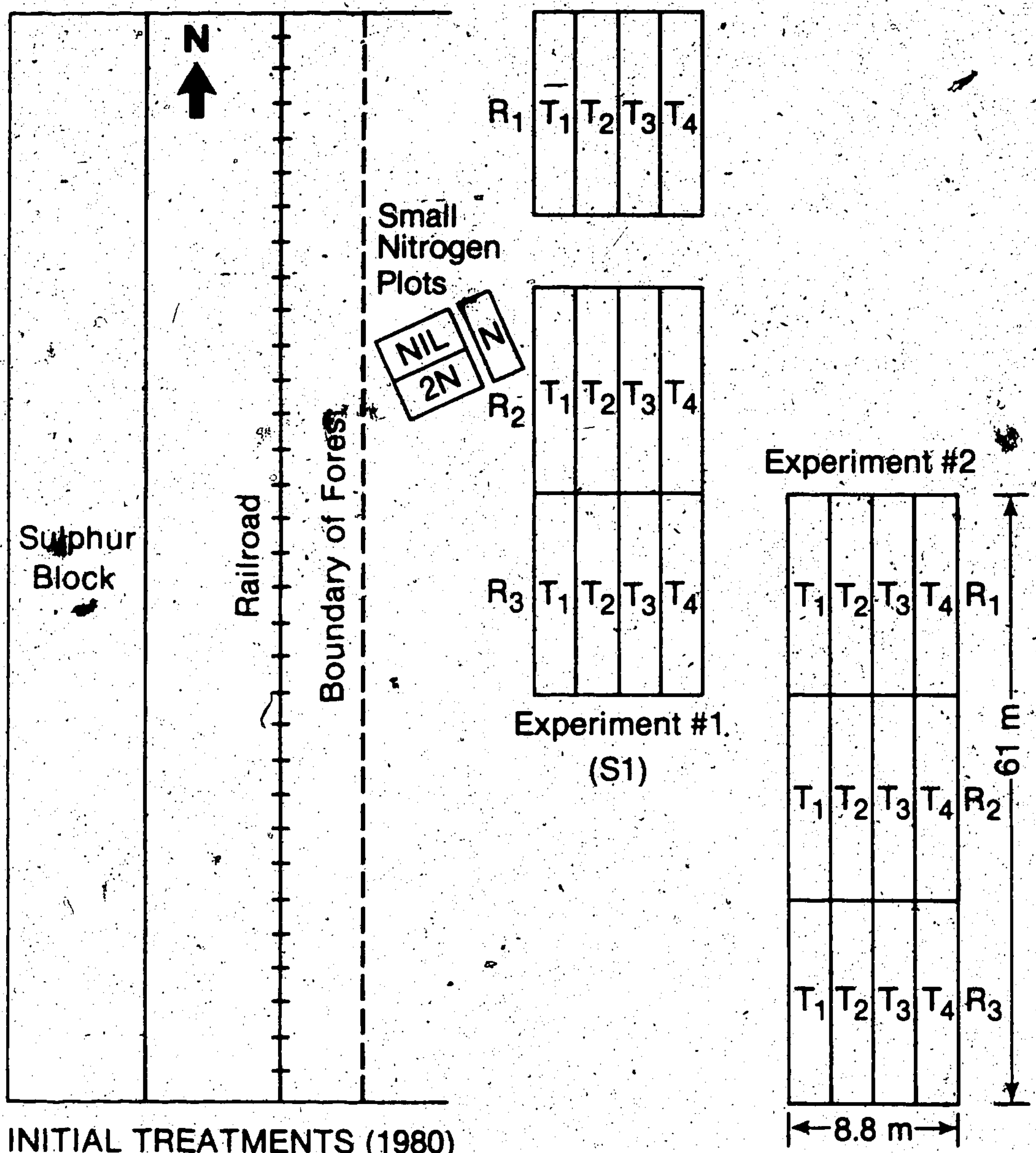
HORIZON	DEPTH	COLOUR	TEXTURE	STRUCTURE
L	8-5			
LFH	5-0			
Ahe	0-6	10YR [illegible]/2 (m) 10YR 7/2 (d)	L	structureless, massive
IIABgj	6-22	10YR 5/3 (m)	L	weak to moderate, fine to medium, subangular blocky

HORIZON	pH	ORGANIC C (%)	CEC (mmol Kg^{-1})	BASE Sat. (%)	PARTICLE SIZE (%)		
					SAND	SILT	CLAY
L	2.9						
LFH	2.0						
Ahe	3.3	1.50	220		29	49	22
IIABgj	4.1	0.64	130	40	32	44	24

SOIL CHEMISTRY

HORIZON	pH	TOTAL DIGEST (mg kg^{-1})		NH$_4$OAC EXTRACT (mg kg^{-1})		
		S	Ca	S	Ca	Al
LFH	3.0	36700	19300	13110	20200	390
Ahe	4.0	800	6120	540	1450	740
ABgj	4.5	560	3910	480	1090	800

Appendix II i) Field plan of plots at the Strachan Gas Plant (S1) which were situated 50 m east of the sulphur block. (Not drawn to scale)

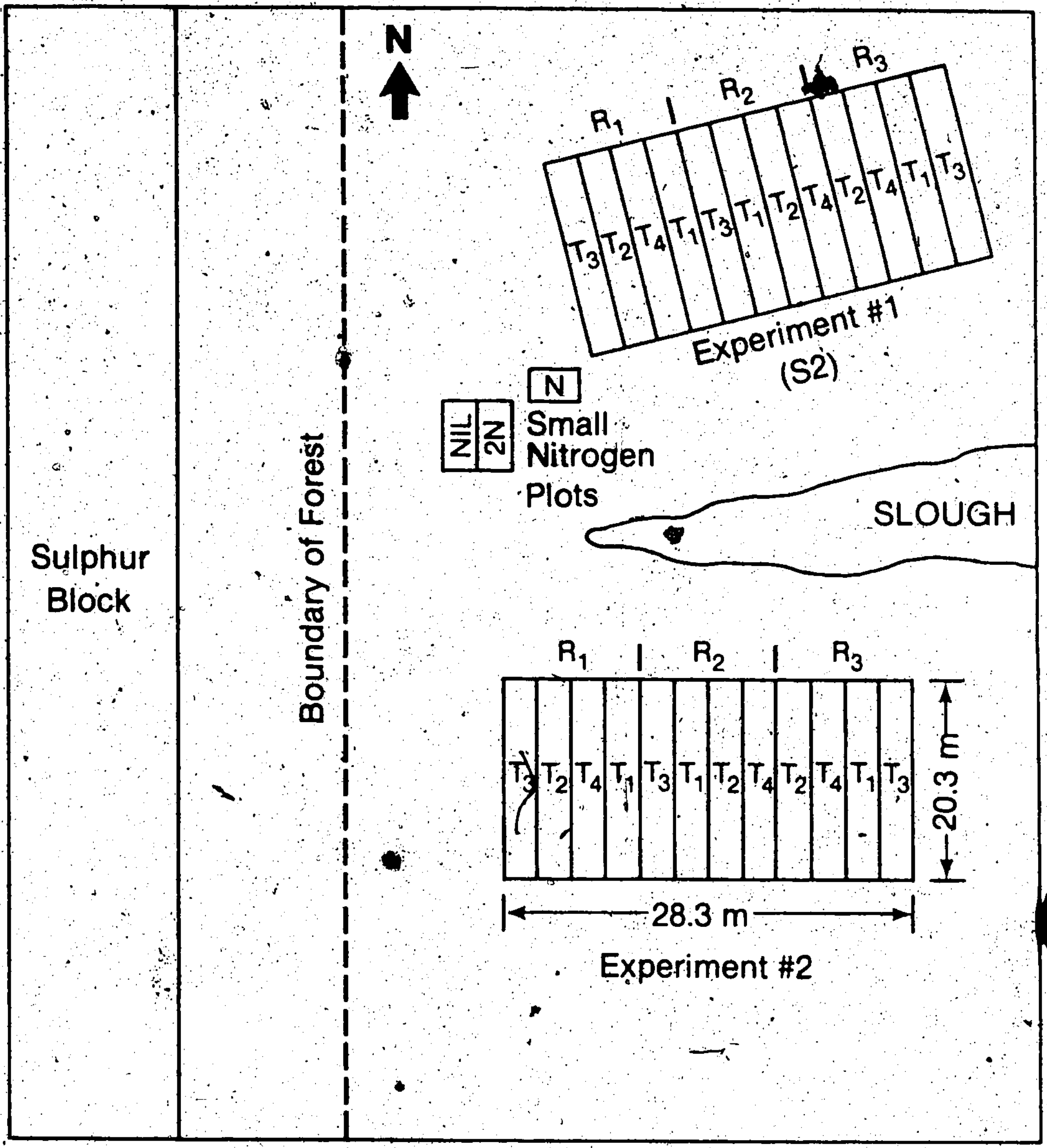


INITIAL TREATMENTS (1980)

1) NIL - covered.*
2) Air Applied LIME (5600 kg ha^{-1}).
3) Sulphur (2240 kg S° ha^{-1}) - covered. *
4) LIME (12080 kg ha^{-1}) + S° (2240 kg ha^{-1}) + Air Applied LIME (5600 kg ha^{-1}).

*sites were covered with polythene when lime was applied by air.

Appendix II ii) Field plan of plots at the Ram River Gas Plant (S2) which were situated 50 m east of the large sulphur block. (Not drawn to scale).



INITIAL TREATMENTS (1980)

1) NIL
2) LIME (9170 kg $CaCO_3$ ha^{-1})
3) Sulphur (2280 kg S° ha^{-1}).
4) LIME (18340 kg ha^{-1}) + S° (2280 kg ha^{-1}).

Appendix IIIi. The rates and dates of applications of lime and sulphur for the control site, C1.

TREATMENT	ADDITION	AMOUNT KG HA^{-1}	DATE
NIL	NONE		
LIME	FEEDGRADE LIMESTONE	6770	SEP 19 81
SULPHUR		2280	NOV 07 81
LIME + S^{O}	LIMESTONE	17700	NOV 07 81
	SULPHUR	2280	NOV 07 81
LIME	FEEDGRADE LIMESTONE	470	JUN 15 83
LIME + S^{O}	FEEDGRADE LIMESTONE	470	JUN 15 83

Appendix IIIii. The rates and dates of applications of lime and sulphur for the Strachan site (S1), Experiments # 1 and # 2.

TREATMENT	ADDITION	AMOUNT KG HA^{-1}	DATE
NIL	COVERED		
LIME	GLASS ROCK LIME - AIR	5600	SEP 15 80
SULPHUR	FINE S^O (COVERED)	2240	SEP/OCT 80
LIME + S^O	GLASS ROCK LIME - AIR	5600	SEP 15 80
	FINE $CaCO_3$	12080	SEP/OCT 80
	FINE S^O	2240	SEP/OCT 80
LIME AND LIME + S^O	FEEDGRADE LIMESTONE	3750	AUG 28 82
	LIME - AIR	5370	NOV/DEC 82
LIME AND LIME + S^O	FEEDGRADE LIMESTONE	4000	JUN 10 83
LIME AND LIME + S^O	LIME - AIR	11200	JUN/JUL 84

Appendix IIIiii. The rates and dates of applications of lime and sulphur for the Ram River site (S2), Experiments # 1 and # 2.

TREATMENT	ADDITION	AMOUNT KG HA^{-1}	DATE
NIL	NONE		
LIME	GROUND LIMESTONE	9170	OCT/NOV 80
SULPHUR		2280	OCT/NOV 80
LIME + S^{o}	LIMESTONE	18340	OCT/NOV 80
	SULPHUR	2280	OCT/NOV 80
LIME	FEEDGRADE LIMESTONE	2820	AUG 26 82
LIME + S^{o}	FEEDGRADE LIMESTONE	3750	AUG 26 82
LIME	FEEDGRADE LIMESTONE	4000	JUN 15 83
LIME + S^{o}	FEEDGRADE LIMESTONE	4000	JUN 15 83

Appendix IV. Site and sample descriptions from Rocky Mountain House and Fox Creek, Alberta.

SITE	DESCRIPTION	
	SITE	SAMPLE GROUND TO < 2 MM
WC-C	Whitecourt, mile post 102.5, closed stand of **Pinus contorta**. Oct 4/80. Shallow organic layer, 8 cm deep, little growing	greyish yellow brown, 4/2 10Y/R to brownish black 3/1 10Y/R, with few needles and few moss fragments, yellow 7/6 5Y.
FC-C	Fox Creek, 2.3 km north of plant, **Pinus contorta**, and **Picea glauca**. Oct 4/80. Very thin moss layer, organic layer, 10 cm deep	dark brown 3/3 10Y/R to brownish black 3/2 7.5Y/R with few olive yellow moss fragments 6/4 5Y.
RMH-C	Rocky Mountain House between S1 & S2, **Picea glauca** and moss. Oct 15/80. Undecomposed organic layer 15 cm deep with green moss	olive brown 4/3 2.5Y, olive 5/6 to yellow 8/6 5Y with many moss fragments and a few needles.
RMH-S1	East of Strachan gas plant, near Nipher, **Populus tremuloides**, **Picea glauca** and **Alnus crispa**. Oct 15/80. Decomposed organic layer 8 cm deep	brownish black 3/2 10YR and 3/2 2.5Y with yellowish brown 6/8 10Y/R needle fragments.
RMH-S2	East of Ram River gas plant, **Populus tremuloides** and **Pinus contorta**. Oct 15/80. Decomposed organic layer 7 cm deep	brownish black 3/2 10YR [illegible]/2 7.5YR with yellowish brown 5/8 10YR needles. Many dead needles S^{o} covered leaf fragments.

Appendix V. The application and sampling dates for the Small N Plots.

SITE	TREATMENT	AMOUNT ADDED KG HA^{-1}	DATE
S1, S2*	2N	112	OCT 13 80
C2	N	112	NOV 10 80
S1	N, 2N	112	NOV 10 80
S2	N, 2N	112	NOV 16 80
S1, S2, C2	N, 2N	112	MAY 23 81
S1, S2, C2	2N	112	JUL 23 81
S1, S2, C2	N, 2N	112	JUL 82
S1, S2, C2	2N	112	SEP 82
S1, S2, C2	N, 2N	112	JUN 15 83
S1, S2, C2	2N	112	AUG 10 83

SITE	TREATMENT	SAMPLING DATE
S1	NIL, 2N	NOV 10 80
S2	NIL, 2N	NOV 18 80
S1, S2	NIL, N, 2N	MAY 23 81
C2	NIL, N	MAY 23 81
S1, S2, C2	NIL, N, 2N	JUL 23 81
S1, S2, C2	NIL, N, 2N	SEP 09 82
S1, S2, C2	2N	SEP 13 83

*S1 - STRACHAN

S2 - RAM RIVER

C2 - CONTROL BETWEEN STRACHAN AND RAM RIVER

Appendix VIi. Calculation format for total N and tagged N.

AFTER DISTILLATION

Total N as mg kg^{-1} =

[(mls of sample - mls of blank) / sample weight] x .05 ' x

(14 "/ 1000) x 10^6

Tagged N as mg kg^{-1} =

Total N as mg kg^{-1} x (% abundance - % natural abundance) / 4.685*

Total N or tagged N as kg ha^{-1} =

mg kg^{-1} x g cm^{-2} x 10^{-1} ¬

' normality of H_2SO_4 used in titration

" molecular weight of nitrogen

* percent excess of tagged N fertilizer

¬ relative g cm^{-2} values are shown in Appendix VIii

Appendix VIii. The weight per area (g cm^{-2}) (n=3) of litter and mineral soil at different sites with various treatments.

	G CM^{-2}		
DEPTH	L	FH	0-15 CM
SITE TREATMENT			
CONTROL (C1)			
NIL	0.142	0.222	21.8
LIME	0.196	0.356	19.5
S^o	0.138	0.249	22.4
LIME + S^o	0.244	0.378	19.4
STRACHAN (S1)			
NIL	0.227	0.396	20.3
LIME	0.164	0.391	18.4
S^o	0.236	0.387	19.7
LIME + S^o	0.209	0.378	18.5
RAM RIVER (S2)			
NIL	0.258	0.400	19.5
LIME	0.231	0.364	20.3
S^o	0.240	0.253	19.5
LIME + S^o	0.276	0.298	18.9

Appendix VIiii. Average depth of litter (n=3) at C1, S1, and S2 for the NIL and LIME + S^O treatments, July 1982.

	DEPTH (CM)			
LITTER LAYER	L		FH	
SITE TREATMENT	MEAN	S.D.	MEAN	S.D.
CONTROL (C1)				
NIL	2.3 (0.058)*	0.4	3.0 (0.072)	1.9
LIME + S^O	3.0 (0.079)	0.7	3.2 (0.115)	1.7
STRACHAN (S1)				
NIL	1.9 (0.115)	0.6	3.2 (0.121)	1.9
LIME + S^O	3.2 (0.064)	1.7	5.5 (0.067)	4.1
RAM RIVER (S2)				
NIL	2.3 (0.104)	0.4	3.0 (0.107)	1.9
LIME + S^O	3.0 (0.112)	0.7	3.2 (0.092)	1.7

* AVERAGE BULK DENSITY (mg m^{-3})

Appendix VIIi. The rates and dates of fertilizer applications for C1.

FERTILIZER TREATMENT	ADDITION	AMOUNT (KG HA^{-1})	DATE
NIL	NONE		
2NPK, NPK, 2N	NH_4NO_3	N @ 75	SEP 20/81
2NPK, NPK	P_2O_5	P @ 15	SEP 20/81
2NPK, NPK	KCl	K @ 20	SEP 20/81
2NPK, 2N	NH_4NO_3	N @ 75	NOV 07/81
2NPK, NPK, 2N	NH_4NO_3	N @ 75	JUL 27/82
2NPK, NPK	P_2O_5	P @ 15	JUL 27/82
2NPK, NPK	KCl	K @ 20	JUL 27/82
2NPK, NPK, 2N	NH_4NO_3	N @ 75	JUN 15/83
2NPK, NPK	P_2O_5	P @ 15	JUN 15/83
2NPK, NPK	KCl	K @ 20	JUN 15/83

Appendix VIIii. The rates and dates of fertilizer applications for S1 Experiment #1.

FERTILIZER TREATMENT	ADDITION	AMOUNT $(KG\ HA^{-1})$	DATE
NIL	NONE		
3NPK, NPK, 2N	NH_4NO_3	N @ 75	MAY 22/81
3NPK, NPK	P_2O_5	P @ 15	MAY 22/81
3NPK, NPK	KCl	K @ 20	MAY 22/81
3NPK	NH_4NO_3	N @ 75	JUL 23/81
3NPK, 2N	NH_4NO_3	N @ 75	NOV 07/81
3NPK, NPK, 2N	NH_4NO_3	N @ 75	JUL 23/82
3NPK, NPK	P_2O_5	P @ 15	JUL 23/82
3NPK, NPK	KCl	K @ 20	JUL 23/82
3NPK, NPK, 2N	NH_4NO_3	N @ 75	JUN 14/83
3NPK, NPK	P_2O_5	P @ 15	JUN 14/83
3NPK, NPK	KCl	K @ 20	JUN 14/83

Appendix VIIiii. The rates and dates of fertilizer applications for S1 Experiment #2.

FERTILIZER TREATMENT	ADDITION	AMOUNT (KG HA^{-1})	DATE
NIL	NONE		
2NPK, NPK, N	NH_4NO_3	N @ 75	MAY 23/81
2NPK, NPK	P_2O_5	P @ 15	MAY 23/81
2NPK, NPK	KCl	K @ 20	MAY 23/81
2NPK	NH_4NO_3	N @ 75	JUL 23/81
2NPK, NPK, N	NH_4NO_3	N @ 75	JUL 23/82
2NPK, NPK	P_2O_5	P @ 15	JUL 23/82
2NPK, NPK	KCl	K @ 20	JUL 23/82
2NPK, NPK, N	NH_4NO_3	N @ 75	JUN 14/83
2NPK, NPK	P_2O_5	P @ 15	JUN 14/83
2NPK, NPK	KCl	K @ 20	JUN 14/83

Appendix VIIiv. The rates and dates of fertilizer applications for S2 Experiment #1.

FERTILIZER TREATMENT	ADDITION	AMOUNT (KG HA^{-1})	DATE
NIL	NONE		
3NPK, NPK, 2N	NH_4NO_3	N @ 75	MAY 23/81
3NPK, NPK	P_2O_5	P @ 15	MAY 23/81
3NPK, NPK	KCl	K @ 20	MAY 23/81
3NPK	NH_4NO_3	N @ 75	JUL 23/81
3NPK, 2N	NH_4NO_3	N @ 75	NOV 07/81
3NPK, NPK, 2N	NH_4NO_3	N @ 75	JUL 26/82
3NPK, NPK	P_2O_5	P @ 15	JUL 26/82
3NPK, NPK	KCl	K @ 20	JUL 26/82
3NPK, NPK, 2N	NH_4NO_3	N @ 75	JUN 15/83
3NPK, NPK	P_2O_5	P @ 15	JUN 15/83
3NPK, NPK	KCl	K @ 20	JUN 15/83

Appendix VIIv. The rates and dates of fertilizer applications for S2 Experiment #2.

FERTILIZER TREATMENT	ADDITION	AMOUNT (KG HA^{-1})	DATE
NIL	NONE		
2NPK, NPK, N	NH_4NO_3	N @ 75	MAY 23/81
2NPK, NPK	P_2O_5	P @ 15	MAY 23/81
2NPK, NPK	KCl	K @ 20	MAY 23/81
2NPK	NH_4NO_3	N @ 75	JUL 23/81
2NPK, NPK, N	NH_4NO_3	N @ 75	JUL 26/82
2NPK, NPK	P_2O_5	P @ 15	JUL 26/82
2NPK, NPK	KCl	K @ 20	JUL 26/82
2NPK, NPK, N	NH_4NO_3	N @ 75	JUN 15/83
2NPK, NPK	P_2O_5	P @ 15	JUN 15/83
2NPK, NPK	KCl	K @ 20	JUN 15/83

Appendix VIII. Seed mixtures, seeding times, and observation dates for field germination experiments.

SITE	SEED MIXTURE	AMOUNT ADDED (KG HA^{-1})	DATE SEEDED	DATE OBSERVED
S2	TIMOTHY	11.2	MAY 23/81	
EX #2	MANCHAR BROME GRASS	11.2		
	VANTAGE REED CANARY GRASS	11.2		
	RED CLOVER*	11.2		JUL 23/81
S1	TIMOTHY (CLIMAX)	5.4	AUG 1/82	
EX #2	TIMOTHY (ENGMO)	10.5		
	MANCHAR BROME GRASS	4.7		
	VANTAGE REED CANARY GRASS	7.5		
	RED CLOVER*	4.3		SEP 18/82
S2	TIMOTHY (CLIMAX)	10.8	AUG 5/82	
EX #1	TIMOTHY (ENGMO)	10.5		
	MANCHAR BROME GRASS	9.4		
	VANTAGE REED CANARY GRASS	11.3		
	RED CLOVER*	4.3		SEP 18/82
C1	TIMOTHY (CLIMAX)	2.7	JUN 15/83	
	TIMOTHY (ENGMO)	2.7		
	MANCHAR BROME GRASS	2.7		
	VANTAGE REED CANARY GRASS	2.7		SEP 12/83
	RED CLOVER*	6.7		AUG 02/84
S1	TIMOTHY (CLIMAX)	8.1	JUN 14/83	
EX #1	TIMOTHY (ENGMO)	9.6		
	MANCHAR BROME GRASS	6.8		
	VANTAGE REED CANARY GRASS	9.5		SEP 12/83
	RED CLOVER*	6.7		AUG 03/84
S2	TIMOTHY (CLIMAX)	8.1	JUN 15/83	
EX #2	TIMOTHY (ENGMO)	9.6		
	MANCHAR BROME GRASS	6.8		
	VANTAGE REED CANARY GRASS	9.5		SEP 12/83
	RED CLOVER*	6.7		AUG 02/84

* PLUS A RHIZOBIUM INOCULUM

APPENDIX IX.

Table i. An estimate of the plant cover (n=3) for each subplot at the control site (C1), taken July 27, 1982.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
TREATMENTS	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
PLANT TYPES								
NIL								
GRASS	3	1	11	17	2	3	4	5
MOSS	35	18	78	21	22	22	20	26
HERBS	13	14	41	39	20	13	18	9
TOTAL	51	7	130	72	44	12	42	38
2N								
GRASS	12	8	13	14	12	13	4	2
MOSS	47	45	30	13	13	23	55	23
HERBS	25	13	30	18	22	8	22	18
TOTAL	83	65	73	33	47	35	80	23
NPK								
GRASS	0	0	20	26	4	4	10	10
MOSS	33	23	42	42	48	44	15	15
HERBS	28	6	32	18	16	8	35	18
TOTAL	62	21	93	64	68	54	60	9
2NPK								
GRASS	8	10	25	22	23	20	43	32
MOSS	8	14	30	30	22	19	23	3
HERBS	15	10	12	11	25	5	23	15
TOTAL	32	15	67	53	70	44	89	49
TOTAL*	57	36	91	55	57	36	68	34

* mean of 4 main treatments plus standard deviation.

Table ii. An estimate of the plant cover (n=3) for each subplot at the control site (C1), taken July 25, 1983.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
TREATMENTS								
PLANT TYPES								
NIL								
GRASS	0	0	0	0	2	2	0	0
MOSS	22	16	50	5	1	1	6	4
HERBS	7	2	15	8	5	2	12	9
TOTAL	29	14	65	13	8	5	18	10
2N								
GRASS	12	8	18	19	2	0	20	26
MOSS	4	4	2	2	1	1	14	18
HERBS	19	11	9	1	7	4	10	5
TOTAL	35	16	29	18	11	5	44	47
NPK								
GRASS	1	1	31	43	4	5	12	15
MOSS	22	18	6	7	23	25	6	7
HERBS	29	20	16	17	2	2	29	~~19~~
TOTAL	52	35	53	44	29	28	47	30
2NPK								
GRASS	4	5	18	24	3	2	40	33
MOSS	10	11	14	12	3	4	1	1
HERBS	7	2	12	1	5	1	18	12
TOTAL	21	10	43	13	11	7	59	34
TOTAL*	34	21	47	26	15	15	42	32

* mean of 4 main treatments plus standard deviation.

Table iii. An estimate of the plant cover (n=3) for each subplot at the control site (C1), taken August 2, 1984.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
TREATMENTS								
PLANT TYPES								
NIL								
GRASS	2	3	8	8	1	1	3	4
MOSS	13	15	63	21	0	0	24	40
HERBS	46	21	67	37	5	1	50	36
TOTAL	61	23	138	29	6	1	77	73
2N								
GRASS	18	12	21	10	6	8	23	13
MOSS	28	18	13	6	0	0	18	18
HERBS	66	33	57	39	5	1	52	35
TOTAL	112	60	91	30	12	10	94	25
NPK								
GRASS	3	3	46	39	6	4	9	4
MOSS	40	36	27	25	0	0	5	3
HERBS	91	14	52	46	6	4	63	8
TOTAL	134	50	124	74	12	8	77	9
2NPK								
GRASS	11	11	33	22	8	8	40	13
MOSS	10	0	8	3	0	0	12	13
HERBS	60	28	40	22	6	4	65	23
TOTAL	81	36	82	44	14	11	117	20
TOTAL*	97	48	109	47	11	8	90	39

* mean of 4 main treatments plus standard deviation.

Table iv. An estimate of the plant cover (n=3) for each subplot at Strachan (S1) Experiment #1, taken July 25, 1983.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
<u>TREATMENTS</u>								
PLANT TYPES								
<u>NIL</u>								
GRASS	3	3	3	1	1	1	19	15
MOSS	0	0	0	0	0	0	1	1
HERBS	2	2	16	9	3	2	28	11
TOTAL	5	4	19	9	4	2	48	16
<u>2N</u>								
GRASS	7	6	12	16	2	2	30	48
MOSS	0	0	0	0	0	0	0	0
HERBS	5	5	13	3	6	7	33	26
TOTAL	12	10	25	14	8	9	63	40
<u>NPK</u>								
GRASS	3	3	1	1	2	2	26	38
MOSS	0	0	0	0	0	0	0	0
HERBS	9	8	7	3	3	3	22	9
TOTAL	12	11	8	4	5	3	48	34
<u>3NPK</u>								
GRASS	3	1	10	14	3	2	27	27
MOSS	0	0	0	0	0	0	1	2
HERBS	2	2	9	1	1	1	22	5
TOTAL	5	3	19	13	4	3	50	28
TOTAL*	8	8	18	11	5	5	52	27

* mean of 4 main treatments plus standard deviation.

Table v. An estimate of the plant cover (n=3) for each subplot at Strachan (S1) Experiment #1, taken August 3, 1984.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
TREATMENTS								
PLANT TYPES								
NIL								
GRASS	0	0	14	8	1	1	22	8
MOSS	0	0	0	0	0	0	0	0
HERBS	2	3	39	12	1	0	45	18
TOTAL	2	3	54	8	2	1	67	11
2N								
GRASS	3	4	29	23	1	1	38	27
MOSS	0	0	0	0	0	0	0	0
HERBS	1	1	21	5	1	0	47	17
TOTAL	4	5	50	27	2	1	85	13
NPK								
GRASS	1	2	11	5	3	3	35	23
MOSS	0	0	0	0	0	0	0	0
HERBS	3	2	12	6	1	1	72	23
TOTAL	4	3	23	1	4	3	107	3
3NPK								
GRASS	2	5	9	9	1	1	40	9
MOSS	0	0	0	0	0	0	0	0
HERBS	4	1	31	30	1	1	50	23
TOTAL	6	4	40	30	2	2	90	30
TOTAL*	4	4	41	21	2	2	87	21

* mean of 4 main treatments plus standard deviation

Table vi. An estimate of the plant cover (n=3) for each subplot at Strachan (S1) Experiment #2, taken July 25, 1983.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
<u>TREATMENTS</u>								
PLANT TYPES								
<u>NIL</u>								
GRASS	1	1	4	3	3	1	4	2
MOSS	0	0	0	0	0	0	4	2
HERBS	4	3	9	5	5	5	33	2
TOTAL	5	4	13	1	8	6	41	3
<u>N</u>								
GRASS	4	2	5	3	2	2	23	23
MOSS	0	0	0	0	0	0	3	1
HERBS	6	4	10	2	6	4	15	6
TOTAL	10	3	15	4	8	3	31	30
<u>NPK</u>								
GRASS	3	4	13	15	3	1	7	1
MOSS	0	0	0	0	0	0	3	1
HERBS	5	2	14	5	5	4	17	8
TOTAL	8	6	27	6	7	5	27	7
<u>2NPK</u>								
GRASS	4	2	4	0	0	0	9	4
MOSS	0	0	0	0	0	0	3	2
HERBS	11	13	12	0	5	3	14	3
TOTAL	15	14	16	0	5	3	26	9
TOTAL*	10	8	18	13	7	4	34	16

* mean of 4 main treatments plus standard deviation.

Table vii. An estimate of the plant cover (n=3) for each subplot at Strachan (S1) Experiment #2, taken August 3, 1984.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
<u>TREATMENTS</u>								
PLANT TYPES								
<u>NIL</u>								
GRASS	1	1	7	2	1	2	9	8
MOSS	0	0	0	0	0	0	19	15
HERBS	2	4	15	7	2	3	123	17
TOTAL	3	5	23	6	3	6	150	27
<u>N</u>								
GRASS	4	2	8	4	1	1	44	21
MOSS	0	0	0	0	0	0	3	5
HERBS	3	4	12	6	6	6	72	56
TOTAL	8	2	21	9	7	5	119	75
<u>NPK</u>								
GRASS	2	3	15	14	3	2	24	28
MOSS	0	0	0	0	0	0	2	2
HERBS	2	4	15	13	3	2	38	23
TOTAL	4	3	29	27	6	4	64	5
<u>2NPK</u>								
GRASS	1	1	7	1	1	1	37	29
MOSS	0	0	0	0	0	0	7	8
HERBS	2	1	13	7	4	5	46	35
TOTAL	3	2	19	16	5	6	90	63
TOTAL*	5	3	23	13	5	5	106	55

* mean of 4 main treatments plus standard deviation.

Table viii. An estim[illegible] the plant cover (n=~~3~~) for each subplot at Ram Ri[illegible]1) Experiment #1, taken July 25, 1983.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
TREATMENTS								
PLANT TYPES								
NIL								
GRASS	0	0	9	10	0	0	17	12
MOSS	0	0	0	0	0	0	0	0
HERBS	0	0	4	3	0	0	17	9
TOTAL	0	0	13	13	0	0	34	16
2N								
GRASS	0	0	10	16	1	1	24	14
MOSS	0	0	0	0	0	0	1	1
HERBS	1	1	2	0	0	0	14	5
TOTAL	1	1	12	16	1	1	38	7
NPK								
GRASS	0	0	16	11	1	1	26	14
MOSS	0	0	0	0	0	0	1	1
HERBS	0	0	6	2	0	0	2	3
TOTAL	0	0	22	11	1	1	29	11
3NPK								
GRASS	0	0	14	9	0	0	17	1
MOSS	0	0	0	0	0	0	1	1
HERBS	1	1	8	7	0	0	11	9
TOTAL	1	1	22	16	0	0	29	10
TOTAL*	1	1	17	13	1	1	32	10

* mean of 4 main treatments plus standard deviation.

Table ix. An estimate of the plant cover (n=3) for each subplot at Ram River (S1) Experiment #1, taken August 2, 1984.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
TREATMENTS								
PLANT TYPES								
NIL								
GRASS	0	0	12	16	0	0	21	25
MOSS	0	0	0	0	0	0	0	0
HERBS	0	0	2	2	0	0	14	8
TOTAL	0	0	14	18	0	0	35	30
2N								
GRASS	0	0	8	12	0	0	15	17
MOSS	0	0	0	0	0	0	0	0
HERBS	1	1	1	1	0	0	16	13
TOTAL	1	1	9	13	0	0	32	27
NPK								
GRASS	1	1	15	18	0	0	18	8
MOSS	0	0	0	0	0	0	0	0
HERBS	0	0	7	3	0	0	4	4
TOTAL	1	1	22	17	0	0	22	12
3NPK								
GRASS	0	0	5	2	0	0	11	5
MOSS	0	0	0	0	0	0	0	0
HERBS	0	0	5	6	0	0	14	19
TOTAL	0	0	10	8	0	0	25	19
TOTAL*	1	1	14	13	0	0	28	20

* mean of 4 main treatments plus standard deviation.

Table x. An estimate of the plant cover (n=3) for each subplot at Ram River (S1) Experiment #2, taken July 25, 1983.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
TREATMENTS								
PLANT TYPES								
NIL								
GRASS	5	3	6	4	0	0	21	4
MOSS	0	0	0	0	0	0	3	4
HERBS	1	1	12	9	0	0	24	8
TOTAL	6	4	18	9	0	0	49	5
N								
GRASS	1	2	15	8	0	0	17	1
MOSS	0	0	2	3	0	0	1	1
HERBS	0	0	12	7	1	1	11	9
TOTAL	1	2	29	11	1	1	29	8
NPK								
GRASS	1	1	13	11	1	1	29	5
MOSS	0	0	1	1	0	0	0	0
HERBS	1	2	6	8	0	0	12	6
TOTAL	2	3	20	18	1	1	41	11
2NPK								
GRASS	6	6	11	4	1	1	[illegible]	2
MOSS	0	0	1	2	0	0	[illegible]	1
HERBS	1	1	6	6	0	0	[illegible]	1
TOTAL	7	6	18	11	1	1	[illegible]	3
TOTAL*	4	4	22	12	1	1	36	12

* mean of 4 main treatments plus standard deviation.

Table xi. An estimate of the plant cover (n=3) for each subplot at Ram River (S1) Experiment #2, taken August 2, 1984.

	PERCENT COVER							
	NIL		LIME		SULPHUR		LIME + S	
	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
TREATMENTS								
PLANT TYPES								
NIL								
GRASS	1	1	1	1	0	0	9	1
MOSS	0	0	0	0	0	0	1	1
HERBS	1	1	11	7	0	0	13	5
TOTAL	2	1	12	7	0	0	24	4
N								
GRASS	0	0	10	13	0	0	9	2
MOSS	0	0	2	2	0	0	1	1
HERBS	0	0	9	8	0	0	12	10
TOTAL	0	0	21	14	0	0	22	9
NPK								
GRASS	1	1	7	6	1	2	25	26
MOSS	0	0	0	0	0	0	0	0
HERBS	1	1	6	6	0	0	12	7
TOTAL	2	1	13	12	1	2	37	32
2NPK								
GRASS	1	1	6	3	0	0	6	4
MOSS	0	0	1	1	0	0	1	1
HERBS	0	0	2	3	0	0	2	1
TOTAL	1	1	9	6	0	0	9	4
TOTAL*	1	1	14	10	1	1	23	18