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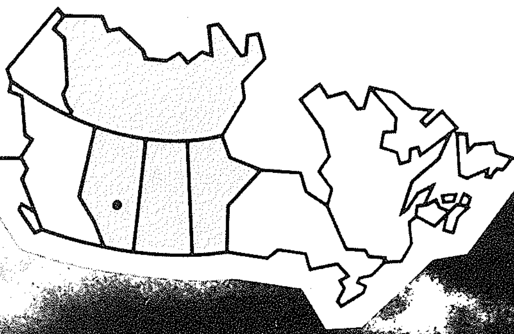

Information Report NOR-X-265
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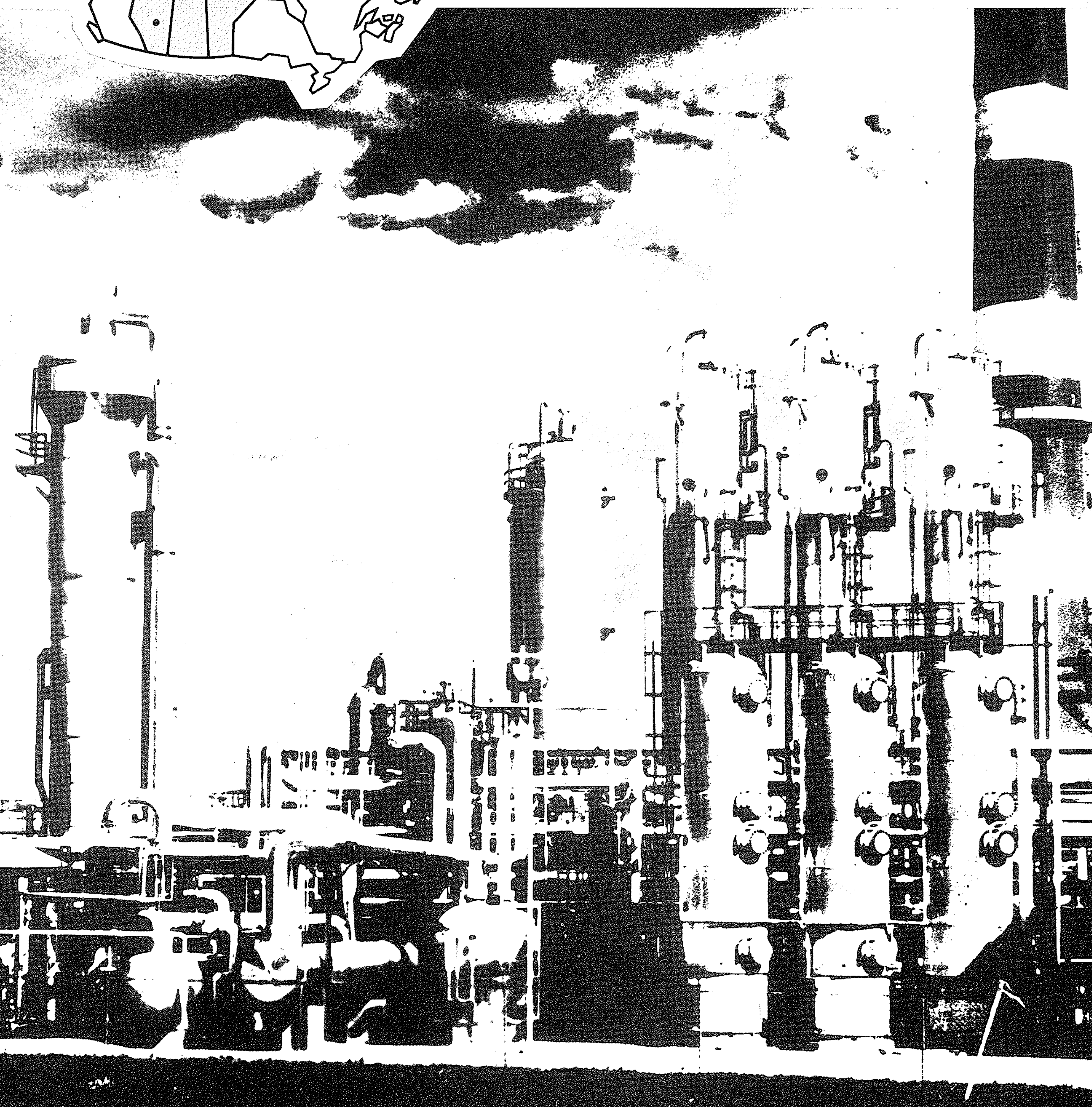

EFFECTS OF SOUR GAS PROCESSING ON A FOREST ECOSYSTEM IN WEST-CENTRAL ALBERTA

P.A. Addison, K.A. Kennedy, and D.G. Maynard

INFORMATION REPORT NOR-X-265

NORTHERN FOREST RESEARCH CENTRE
CANADIAN FORESTRY SERVICE
1984

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Catalogue No. Fo46-12/265E
ISBN 0-662-13628-4
ISSN 0704-7673

This publication is available at no charge from:

Northern Forest Research Centre
Canadian Forestry Service
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

Addison, P.A.; Kennedy, K.A.; Maynard, D.G. 1984. *Effects of sour gas processing on a forest ecosystem in west-central Alberta.* Can. For. Serv., North. For. Res. Cent. Edmonton, Alberta. Inf. Rep. NOR-X-265.

ABSTRACT

The impingement and impact of gaseous and particulate sulfur pollution from two sour gas processing plants on lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests in west-central Alberta were studied. Pollutants in the area were not evenly distributed. Elemental S (S^0) dust appeared to be limited to an area within 1.5 km of gas plant operations, but elevated sulfur gas concentrations extended 45 km northeast of the major pollutant source. The four sites impinged by S^0 had noticeable differences in several soil chemical properties. Plant response to soil changes was dramatic, although no change in growth or reproduction was observed in lodgepole pine. The normal concentration of sulfur gases did not have any measureable impact on the soils or vascular plants of the region. Lichen cover appeared to respond inconsistently to gaseous emissions.

RESUME

On a étudié les retombées de polluants soufrés, tant gazeux que particulaires, de deux usines de purification du gaz naturel acide et leurs effets sur les forêts de pin tordu latifolié (*Pinus contorta* Dougl. var. *latifolia* Engelm.) du centre-ouest de l'Alberta. La répartition des polluants dans la région n'était pas égale. La poussière de soufre élémentaire (S^0) semblait circonscrite à moins de 1,5 km des usines, mais on a observé une certaine concentration de gaz soufrés à 45 km au N.-E. de la principale source de pollution. Les sols des quatre stations réceptrices de S^0 possédaient des propriétés chimiques qui différaient notablement sur plusieurs points. La réaction des végétaux aux modifications pédologiques a été brusque, même si l'on n'a observé aucune modification de la croissance et de la reproduction du pin tordu latifolié. Les concentrations normales des gaz soufrés n'ont eu aucun effet mesurable sur les sols ou les plantes vasculaires de la région. Les lichens ont semblé réagir de façon incohérente aux émissions gazeuses.

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NOTE

The exclusion of certain manufactured products does not imply rejection nor does the mention of other products imply endorsement by the Canadian Forestry Service.

INTRODUCTION

The sour gas processing industry is the largest sulfur producer in Alberta. Although the overall recovery of sulfur is 97%, substantial releases of SO_2 (10^5 tonnes of S annually) occur owing to the very large volume (10^{11} m^3) of natural gas processed (Energy Resources Conservation Board 1982). In addition to stack emissions of SO_2, unknown quantities of H_2S, and other sulfur gases are also emitted.

Large amounts of elemental sulfur (S^0) are generated in the sulfur recovery operation, and prior to 1979 most of the S^0 was stored in blocks. The mechanical breaking of the blocks (i.e., by loaders and trucks) initially resulted in S^0 dust deposition in the immediate vicinity (1-2 km) of the processing plant.

Several studies have examined the impact of airborne pollutants on coniferous forest systems. The effect of acid deposition on both the European (Abrahamsen et al. 1977) and the eastern North American (Hutchinson and Whitby 1974; Freedman and Hutchinson 1980) boreal forest has been studied, as have the effects of O_3 on the San Bernadino forest system of California (Miller 1973), the effects of heavy metals and SO_2 on the boreal forest of northern Manitoba (Hogan and Wotton 1984), and the effects of SO_2 and particulates on a coniferous forest in northeastern Alberta (Addison 1980). In addition to these broad studies, there have been studies in the foothills region of Alberta on the effect of air pollution on ecosystem components such as tree physiology and growth (Legge et al. 1978), lichen communities (Skorepa and Vitt 1976), and soil chemistry (Baker 1977).

In 1981, a study was initiated with the support of Canterra Energy Ltd. (formerly Aquitaine Company of Canada) and Gulf Canada Resources Inc. to assess the impact of sulfur emissions from their two sour gas processing plants on the coniferous forest system in the area south and west of Rocky Mountain House, Alberta. The impact was determined by biomonitoring techniques that used the component parts of an ecosystem as indicators of both air pollution impingement (exposure) and impact (response). Many of the methods used in this study originated from the above-mentioned investigations and have proved effective in the quantification of ecosystem response to pollutant impact.

Ram River and Strachan are, respectively, the largest and tenth-largest sour gas processing plants in Alberta, and together they process approximately 13% of the province's natural gas. Since these plants became operational (Ram River in 1973 and Strachan in 1974), there has been a general decline in sulfur emissions from their incinerator stacks (Fig. 1). In 1981, Ram River and Strachan recovered over 98% and 97% of their inlet sulfur. Notwithstanding the high percentage of sulfur recovery from these processing plants, approximately 70 t d^{-1} of S was released as SO_2 in 1981 (Energy Resources Conservation Board 1982).

Significant S^0 dusting of the forest in the vicinity of sulfur blocks appears to have started at Ram River 1 to 2 years earlier (1978-79) than at Strachan (1980). At Strachan before 1980 virtually all sulfur was shipped as liquid, with the exception of a small amount of bagged prill (Fig. 1). At Ram River, shipping of formed sulfur commenced in 1976 and by 1979 approximately 2.5 Mt of sulfur had been reclaimed from the blocks. Since much of the initial reclaiming of block sulfur was by mechanical means, it is assumed that as the amount of formed sulfur increased, so did the amount of S^0 dust produced. As technology improved, *in situ* remelters largely replaced mechanical breakup and significantly reduced S^0 emissions. Currently both companies have remelters and prilling towers and minimize mechanical manipulation of formed sulfur, but even this technology does not completely eliminate sulfur dust emissions.

This report provides baseline information on the soils and vegetation southwest of Rocky Mountain House in Alberta and presents a preliminary assessment of the impact of sour gas processing on the forest ecosystem.

MATERIALS AND METHODS

Site establishment

A set of 26 sites was established in even-aged *Pinus contorta* Dougl. var. *latifolia* Engelm. stands in an area 30 × 30 km that had the two sour gas processing plants at the center (Fig. 2). The two gas plants, Ram River (Canterra Energy Ltd.) and Strachan (Gulf Canada Resources Inc.), are 13 km apart and are located about 45 km southwest of the town of Rocky Mountain House, Alberta. Site locations (Fig. 2) were based upon avail-

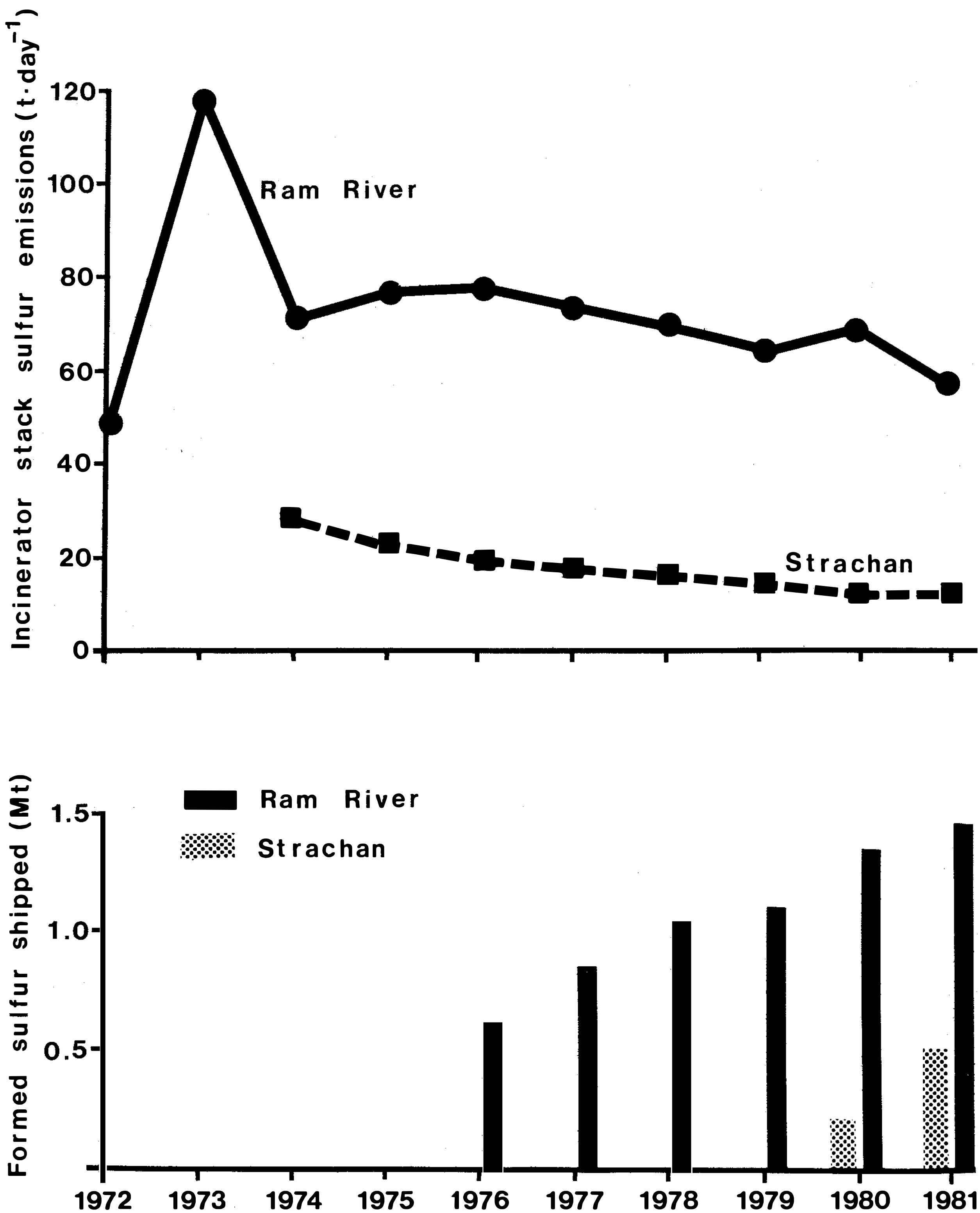

Figure 1. Sulfur dioxide emissions from incinerator stacks and formed sulfur shipped from Ram River and Strachan gas plants (1972-81).

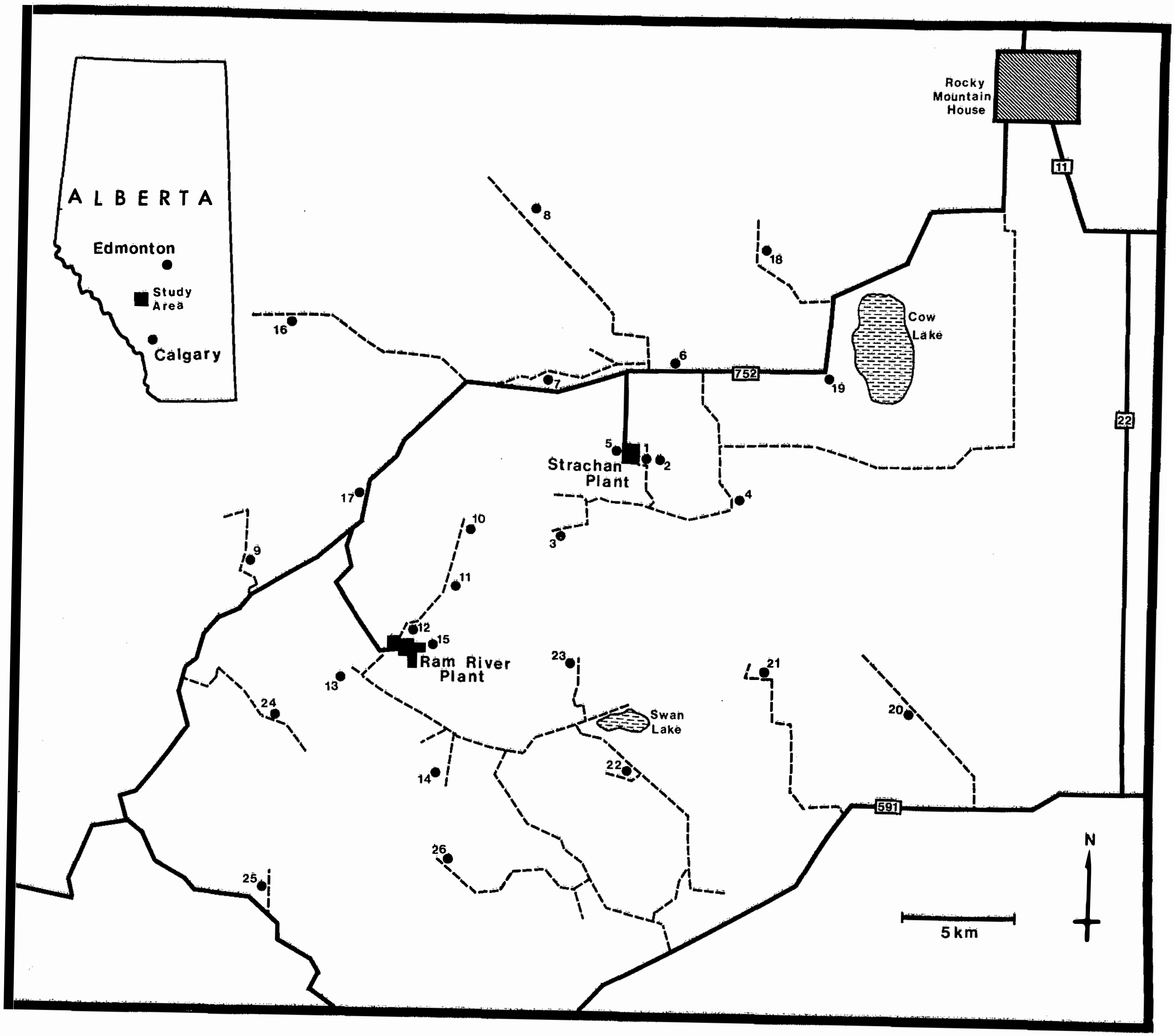

Figure 2. Location of biomonitoring plots and sour gas processing plants in west-central Alberta.

able air quality and airflow information, topography, logistics, and accessibility. The sites were subsequently divided into three groups: sulfur dusted, sulfur gas exposed, and background. Sulfur dusted sites had measurable (>100 mg kg^{-1}) of S^0 present. The sulfation isopleth of 0.05 mg dm^{-2} d^{-1} (SO_3) was chosen to delimit the area of S gas impingement. The threshold is arbitrary and is 10% of the provincial exposure guideline. Six of the ten sites in this area did not have measurable S^0. The specific sites were chosen primarily on the basis of the structure and species composition of the stands. There were three strata at all sites, but areas with a substantial cover of tall shrubs were avoided. The presence of plant species such as *Linnaea borealis* L. var. *americana* (Forbes) Rehd., *Vaccinium vitis-idaea* L. var. *minus* Lodd., *V. myrtilloides* Michx., *Pleurozium schreberi* (Brid.) Mitt., and either *Picea glauca* (Moench) Voss or *P. mariana* (Mill.) BSP was a prerequisite for the inclusion of any stand.

At each site, a 20 × 20 m plot was established with a north-south orientation, and a 1.5-m post was positioned at each corner. A 15-m band surrounding the plot was reserved for soil and plant sampling and lichen descriptions.

Sulfation plates

At each of the 26 sites, sulfation plates (PbO_2, 10 cm in diameter) were installed at a height of 1.5 m at five locations surrounding the plot. The plates were held upside down in a holder so that they would be exposed to the air but not to precipitation and were replaced every 1-2 months from July 1981 to June 1982.

In the laboratory, the PbO_2 plates were digested with a 2% Na_2CO_3 (w/v) solution at 50°C (Alberta Environment 1980). The concentration of sulfur in solution was measured with a vacuum inductively coupled argon plasma atomic emission spectrometer (ICAP-AES).

Soils

Soil description and classification

A soil pit at 21 of the 26 sites was dug, and the pedon[1] was classified according to the Canadian System of Soil Classification (Canada Soil Survey Committee 1978). Laboratory analyses were carried out to support the classification of the soils. There was no replication because the analysis was for descriptive and classification purposes only. The analytical methods used are those outlined in *Manual on Soil Sampling and Methods of Analysis* (McKeague 1974):

1. The pH measured in 0.01 mol $CaCl_2$, 2:1 solution to soil ratio for mineral soils, 4:1 solution to soil ratio for the organic horizons (Peech 1965).
2. Cation exchange capacity (CEC) and exchangeable cations—extraction with 1.0 mol ammonium acetate (NH_2OAc) at pH 7.0 (Chapman 1965). The ammonium (for CEC) was determined by macro-Kjeldhal distillation after displacement with 10% acidified NaCl. The exchangeable cations were determined using ICAP-AES analysis.
3. Organic C—modified Walkley-Black method (Allison 1960).
4. Pyrophosphate-extractable Fe and Al—0.3 g (100-mesh soil) was shaken overnight in 30 ml of 0.1 mol pyrophosphate (McKeague 1967); Fe and Al were determined by ICAP-AES.
5. $CaCO_3$ equivalents—modified pressure method using a pressure transducer was carried out on all mineral samples with a pH >6.5 (Skinner et al. 1959).
6. Particle size—hydrometer method with removal of organic matter by hydrogen peroxide in the Ae horizons (Bouyoucos 1962). No pretreatments were used for the remaining two horizons.

Soil chemical analysis

Five replicates from each of the four surface horizons were collected from all 26 sites. Subsamples were extracted with 1.0 mol NH_4OAc buffered to a pH of 4.8 with acetic acid at a 1:25 ratio of moist soil to solution for the determination of NH_4OAc extractable elements. The pH of the horizons was determined on a saturated soil paste (Richards 1954) also using moist subsamples. The remaining portion of the samples was air dried and ground to pass through a 100-mesh sieve. Subsamples were digested using an HNO_3-$HClO_4$-HF-HCl procedure modified from McQuaker et al. (1979) for total elemental analysis by ICAP-AES. The NH_4OAc solution and acid digests were analyzed for Ca, Mg, K, Al, Fe, Mn, S, P, and V (the latter two, total only) by ICAP-AES. All element contents were calcu-

[1] A pedon is the smallest three-dimensional unit or volume of soil that represents all the horizons of a soil profile. It is usually a horizontal, more or less hexagonal area 1 m^2 or larger.

lated on an ovendry weight basis. Cation exchange capacity was determined on air-dried samples for the four surface horizons by the same method outlined in the soil description and classification section (1.0 mol NH_4OAc extract pH 7.0). Subsamples of the LFH material were extracted with 100% acetone and were analyzed for S^0 spectrophotometrically.

The methods used in the classification of the soils conformed to standard methodology for the description of soil (i.e., 0.01 mol $CaCl_2$ for pH, and NH_4OAc extracts at pH 7.0 for CEC). A comparison of the pH and exchangeable cations for the detailed soil chemical analyses and those determined for classification purposes was not possible. The pH values in $CaCl_2$ are generally 0.5-0.9 pH units lower than the pH values in a water extract or paste (Russell 1977). Extraction of exchangeable cations with NH_4OAc at pH 7.0 rather than at pH 4.8 would probably result in higher exchangeable cations values, since at pH 7.0 a portion of the cations whose exchange is pH dependent would be removed (Coleman and Thomas 1967). Extraction at pH 4.8 (pH closer to that of the soil) would provide a measure of the effective exchangeable cations of these particular soils as defined by Coleman and Thomas.

Vegetation

Vegetation description

Twenty 1 × 1 m quadrats were randomly selected in the plot at each of the 26 sites, and the corners of each quadrat were permanently marked. An estimate of the plant species cover in each quadrat was recorded. Nomenclature for all species names follows Moss (1959) for vasculars, Conard and Redfearn (1979) for mosses, and Hale (1979) and Brodo and Hawksworth (1977) for lichens. Measurement of the 20 quadrats (5% of the total area) is considered sufficient for an adequate representation of the area (Mueller-Dombois and Ellenberg 1974). Ordination (Bray and Curtis 1957), cluster (Pritchard and Anderson 1971), and tabular (Ceska and Roemer 1971; Hill et al. 1975) analyses were used to synthesize the plant cover information. The diversity and abundance of trees, shrubs, herbs, and cryptogams were determined.

Arboreal lichens

Ten branches with luxuriant lichen cover were selected and labeled within the 15-m band that surrounded the plot at each site. The branches were photographed, and the cover of each easily recognizable lichen group was determined following the methods of Addison (1984).

Pine growth and reproduction

The first five *Pinus contorta* trees >10 cm diameter at breast height (dbh) east of each of the northeast and southeast corner posts of the plot were felled and sampled at each site. Measurements were made of the height, diameter, and length between terminal bud scale scars on the leader for the past 5 years. The top five branches more than 5 years old were harvested and separated into age classes. These samples were dried in the laboratory, and needle number, needle weight, stem length, and stem weight were recorded.

A basal disk was collected from each tree at 0.5 m height. In the laboratory, the disks were sanded, and the yearly growth increments from 1961 to 1980 were measured with a Digimicrometer Model MK-1B (Holman Electronic Controls Ltd.).

The age of the stand was determined by counting the rings on tree cores taken at stump height (30 cm) from 10 randomly selected pine trees greater than 10 cm dbh surrounding the plot.

A sample of cones (2-5 years of age) was collected from the 10 sample trees. A subsample of 100 cones was selected, and the seed was extracted, dewinged, cleaned, and counted. Five replicate samples of approximately 100 seeds were X-ray photographed with a Radiographic Inspection System (Tori/Scanray Corp.), and counts were made of the filled versus empty seeds. Empty seeds are not viable, and experience with other lodgepole pine seed sources indicates that the viability of the filled seeds would be about 97%.

Plant chemical analysis

Ten replicate samples from each of lodgepole pine (*Pinus contorta*), spruce (either *Picea glauca* or *P. mariana*), alder (*Alnus crispa*), twinflower (*Linnaea borealis*), and feather moss (*Pleurozium schreberi*) were collected from each site. Lodgepole pine samples were 1-year-old material taken from the leader of 10 trees harvested for growth and reproduction measurements. One-year-old samples from spruce were collected at a height of about 10 m from understory trees. These trees were permanently marked with tree tags. The other plant samples were collected from the 15-m band surrounding the plot at each site. Samples were taken in August with the exception of alder, which was taken in September.

The samples were dried, ground to pass through a 0.8-mm (20-mesh) screen, and digested with HNO_3-$HClO_4$-HCl. The solutions thus formed were analyzed for Ca, Mg, K, Fe, Mn, S, and P by ICAP-AES.

RESULTS AND DISCUSSION

The concentration of sulfur gases (H_2S and SO_2) as measured by Canterra Energy Ltd. and Gulf Canada Resources Inc. sulfation candles is not evenly distributed throughout the area. Sulfation rates ranged from 0.02 to 0.10 mg dm^{-2} d^{-1} (SO_3) in the area. These values are comparable with those from other gas plants but are lower than those in the oil sands area (Strosher 1978). All values were below the provincial SO_3 guideline of 0.50 mg dm^{-2} d^{-1}.

A distinct pattern of sulfation (7-year average, 1975-81) indicates that there is a prevailing southwest to northeast airflow and shows that the two sources share a common airshed (Fig. 3). The 0.04 mg dm^{-2} d^{-1} (SO_3) isopleth extended to the town of Rocky Mountain House and enclosed both sources. It should be noted, however, that the prevailing 10-m wind at Rocky Mountain House is north northwest (Atmospheric Environment Service 1982) and is perpendicular to the pattern. It is apparent that these wind data are not representative of the area surrounding the two gas plants. Wind direction appears to be controlled to a large extent by local topography and, even though the constant monitoring trailers close to the sources showed that 1981 winds were predominantly from the south and west (Canterra Energy Ltd. 1982), there were considerable differences among sites.

The influence of topography on airflow can be seen clearly in the pattern of sulfation (Fig. 3). There were extensions of higher sulfation northeast and southeast of Ram River, and both coincided with valleys. In addition to the channeling along valleys, high and exposed stations may also have high sulfation rates. Such was the case on a prominent nontreed ridge northwest of Ram River.

The magnitude of the two sources of gaseous pollutants can also be seen in the sulfation pattern. The area with elevated sulfation rates (greater than 0.05, 0.06, and 0.07 mg dm^{-2} d^{-1}) was substantially larger at Ram River than at Strachan.

Eight of the biomonitoring sites were located beyond the area monitored by the sulfation candle network. The sulfation rates at these sites as measured by sulfation plates in the forest (June 1981 to June 1982) were not correlated with distance from the gas plants (Table 1, r = 0.2). This indicates that local sources of S gas had little effect at these sites and that a sulfation rate of about 0.02 mg dm^{-2} d^{-1} (SO_3) represents the background level for this area. Closer to the source (<10 km), within-forest sulfation was significantly ($p < 0.05$) correlated with both distance from the closest gas plant (r = 0.7) and the sulfation rate measured in the open with sulfation candles (r = 0.8). Both variables were combined in a significant multiple regression (sulfation plate in mg dm^{-2} d^{-1} (SO_3) = 0.0023 + 0.5685 × sulfation candle in mg dm^{-2} d^{-1} (SO_3) — 0.0028 × distance in km; r^2 = 0.81). Attempts were made to include stand density, but the addition of this variable did not improve the fit of the curve.

The distribution of S^0 in the forest around the two gas plants has not been determined but can be inferred from the distribution of total soil sulfur in the area. Estimates based on 1981 and 1982 surveys of soil sulfur (Hardy Associates (1978) Ltd. 1981; Reid et al. 1982) indicated that S^0 had been deposited east of the sulfur blocks up to 1.5 km away at Ram River and 0.7 km away at Strachan.

Soils

Soil description and classification

Most of the sites lie within an upland physiographic district immediately east of the Outer Foothills region (Bostock 1970). The upland is similar to the O'Chiese and Wolf Lake Upland districts described in the Brazeau Dam report by the Alberta Soil Survey (Land Resource Research Institute 1981). The northeast section of the study area (one-half of the sites, including the Strachan sour gas plant) is located in an area that was previously surveyed (Peters and Bowser 1960). These soils were originally classified as Podzolic Grey Wooded soils (Brunisolic or Podzolic Gray Luvisols) and included the Prentice sandy loam, Lobley loam and heavy loam, Horburg sandy loam, and Caroline loam and sandy loam soil series.

Twenty-one of the 26 biomonitoring sites were described in detail and can be grouped into four general categories based on landform features:

Group A soils occur at the highest elevations (Sites 1, 2, 5, 9, 10, 11, 12, and 15) on nearly level to gently sloping topography of an undulating morainal plain or plateau.

Group B soils (Sites 3, 13, 14, 17, 20, 21, 22, 23, and 26) occur on irregular, usually complex, erosional slopes cut into the plain and are dominated by ice contact stratified (MFG) deposits.

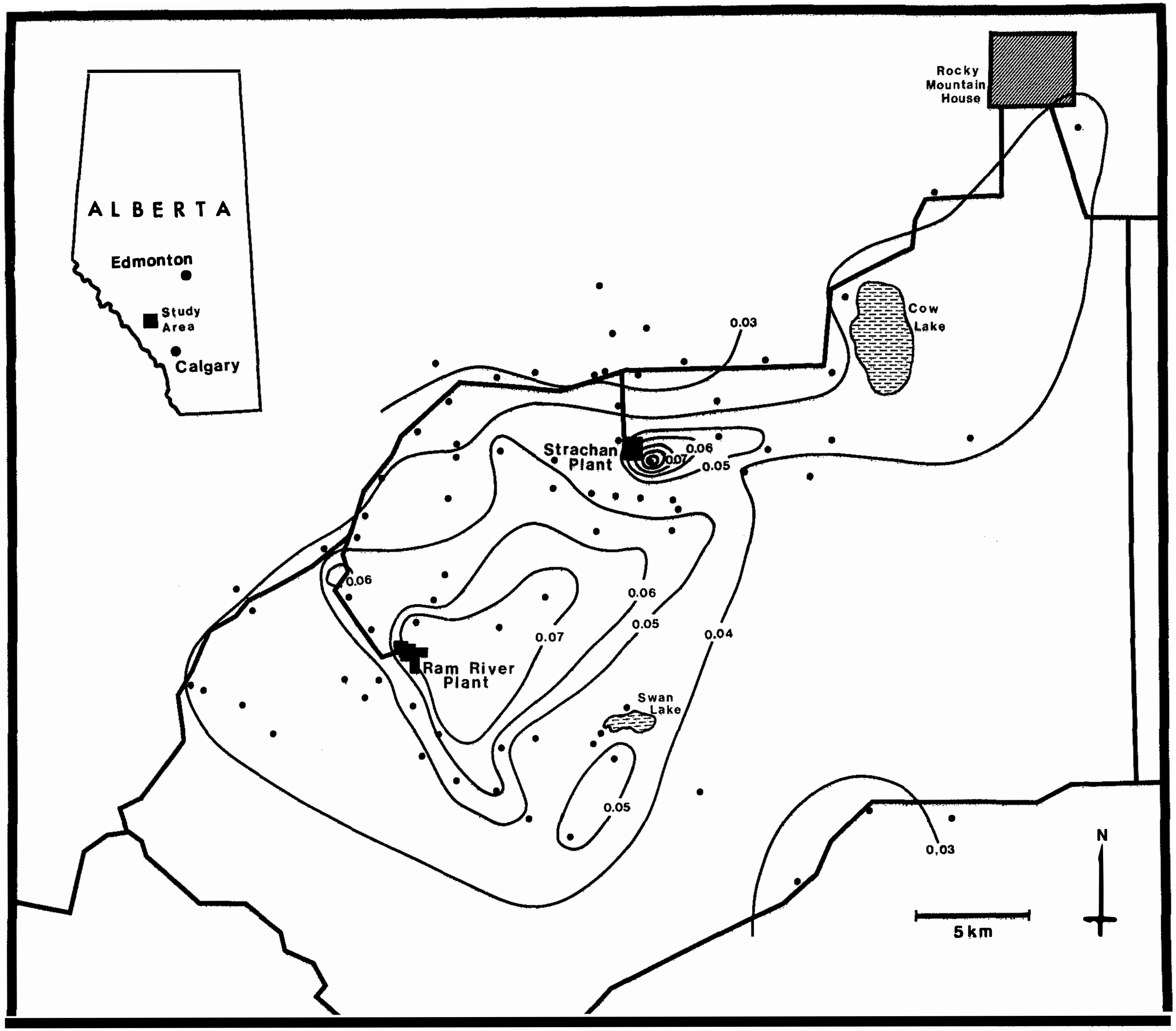

Figure 3. Isopleths of average sulfation rates (1975-81) in the vicinity of sour gas processing in west-central Alberta. Values are in mg dm^{-2} d^{-1} (SO_3).

Table 1. **Sulfation rates measured by plates and candles in the vicinity of Strachan and Ram River gas plants from June 1981 to July 1982.** Values are mg dm^{-2} d^{-1} (SO_3).

Site	Closest candle[a]	Distance from nearest gas plant (km)	Sulfation rate Plate	Sulfation rate Candle
1		0.50	0.104	
2	S 20	0.75	0.052	0.086
3	S 32	4.50	0.019	0.056
4	S 25	5.00	0.015	0.046
5	S 19	0.25	0.046	0.072
6	S 12	4.00	0.013	0.041
7		4.90	0.011	
8		11.40	0.007	
9	R 34	7.00	0.019	0.069
10	R 22	6.00	0.021	0.080
11	R 21	2.80	0.035	0.072
12	R 20	1.30	0.072	0.105
13	R 18	2.70	0.018	0.060
14	R 14	6.20	0.023	0.078
15		0.20	0.145	
16		15.00	0.017	
17	R 6	6.50	0.017	0.056
18		10.75	0.011	
19	S 14	9.50	0.018	0.042
20		16.00	0.017	
21		11.80	0.018	
22	R 35	12.50	0.016	0.085
23		7.35	0.025	
24	R 31	6.70	0.022	0.077
25		12.80	0.015	
26		11.25	0.024	

[a] S — Strachan.
R — Ram River.

Group C soils (Sites 4, 6, and 7) occur on glaciofluvial terraces on valley floors.

Group D soils (Site 19) occur on sand dunes.

Sites 8, 16, 18, 24, and 25 were not described in detail for classification purposes. Samples of the four surface horizons were collected, however, for detailed chemical analysis.

The majority of the 21 pedons (except Sites 21 and 26) are Brunisolic or Podzolic Gray Luvisols and are well to moderately well drained. Site 15 is an exception, and the sampled pedon was an imperfectly drained Gleyed Podzolic Gray Luvisol. The sola to depth are generally acidic, and the B horizons contain relatively high levels of pyrophosphate extractable Fe and Al (>0.06%). The formation of enriched Fe and Al B horizons in soils in the Canadian Rocky Mountains has been related to the weathering of the carbonate component of the shallow eolian deposits (Smith et al. 1983). The characteristics of each of the sites examined are presented in detail in a supplementary, unpublished document obtainable from the authors.

Soil chemical analysis

There was considerable variability in the concentration of total and NH_4OAC extractable elements and pH values of the four surface horizons both among and within sites. Differences in elemental concentrations (total and NH_4OAc extractable) were not related to the landform or parent material groups (as described earlier), with the exception of some elemental concentration at two sites located on the eolian sand dunes (Sites 18 and 19). Concentrations of S, Ca, Mn, Mg, and K in the mineral horizons were extremely variable owing to one of the five replicates at each site. Since neither of these sites is close to the gas plants, the variability appears to be a natural consequence of the composition and deposition of wind-blown material.

Sulfur: The biomonitoring sites were divided into two groups based on the presence of S^0. Since S^0 is not a naturally occurring substance in aerated soils, the presence of this material is a result of contamination owing to industrial activity. Sites 1, 2, 5, and 15 had detectable (>100 mg kg^{-1}) S^0 in the LFH horizons (Table 2). Elemental sulfur concentrations in the LFH horizons appear to be related to distance from the S^0 source. Sites 1 and 2 at Strachan are 60 m and 240 m from the S block, respectively, and Site 5 is located 960 m from the S^0 block at Strachan and 540 m from the prilling tower. Site 15 is the same distance from the S^0 block at Ram River as Site 2 is at Strachan (240 m).

Table 2. Elemental sulfur content of LFH horizon at selected biomonitoring sites. Values are means ± 95% confidence limits.

Site	Elemental sulfur (mg kg^{-1})
Sulfur dusted	
1	43 500 ± 12 700
2	14 600 ± 14 300
5	581 ± 452
15	11 700 ± 13 100
Sulfur gas[a] exposed	
3	B.D.[b]
11	B.D.
12	B.D.
13	B.D.
14	B.D.
23	B.D.
Background	B.D.

[a] The sulfur gas designation refers to sites that have 7-year mean sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).
[b] Below detection limit of the method. For litter material the detection limit of S^0 is 100 mg kg^{-1} soil.

The pattern of total S in the LFH (Site 1 > Site 15 > Site 2 > Site 5) was significant ($p < 0.05$) in a Sheffé Multiple Range Test. Only Site 5 was not significantly higher than the non-sulfur-dusted sites. In the mineral horizons, there were no significant ($p > 0.05$) differences among either the means of the four S^0 dusted sites or the S^0 dusted means and the background sites.

The NH_4OAc extractable S concentration in the various horizons of the S^0 dusted sites showed a different pattern than that of the total S (Table 3). In the LFH, only Sites 1 and 15 were significantly ($p < 0.05$) higher than the other sites. In the Ae_1 and B horizons, only Site 15 had greater ($p < 0.05$) NH_4OAc extractable S. Deposition at Site 15 has occurred over a longer period of time than at the Strachan sites (as indicated by the history of shipment of formed sulfur from the two gas plants; Fig. 1). The length of time of deposition would affect not only the total S deposition but also the amount of S^0 that was oxidized and the subsequent movement of SO_4 (end-product of S^0 oxidation) out of the LFH horizon.

In general, it is not possible to speculate on the relative magnitude of the S^0 deposition to Sites 1 and 15, but both of these sites had higher ($p < 0.05$) total and NH_4OAc extractable S contents than Sites 2 or 5. Although Site 1 had greater ($p < 0.05$) S^0 and total S concentration in 1981 than Site 15, Site 15 has had greater movement of S into the mineral horizons (Table 3). The differences between Sites 1 and 15 in the amount of S^0 transformed into the NH_4OAc extractable form and leached into the mineral horizons of the soil appear to be related to the time factor involved in the buildup of S^0-oxidizing bacterial populations in these sites. Sites 2 and 5 were less contaminated by S^0 and, other than the presence of S^0 in the LFH of Site 5, there were no significant ($p > 0.05$) differences in S content between Site 5 and the non-S^0 sites.

The variability of the S concentrations (total and NH_4OAc extractable) was generally higher at the S^0 sites than at background sites. This is not unexpected, because particulate deposition at the soil surface in a forest system is not uniform. It was necessary, therefore, to remove the S^0 dusted sites from the data set when examining the influence of S gas. The total and NH_4OAc extractable concentrations in the LFH of the S gas exposed sites (Table 3) were not significantly

Table 3. Total and NH_4OAc extractable sulfur concentrations (mg kg^{-1}) of the four surface soil horizons[a] at selected biomonitoring sites. Values are means ± 95% confidence limits.

Site	LFH		Ae_1		B		Ae_2	
	Total	NH_4OAc extract	Total	NH_4AOc extract	Total	NH_4AOc extract	Total	NH_4AOc extract
Sulfur dusted								
1	58 600 ± 12 900	11 600 ± 7 430	450 ± 111	216 ± 96	516 ± 104	266 ± 118	208 ± 66	65 ± 39
2	16 000 ± 11 600	2 070 ± 1 170	228 ± 24	45 ± 11	294 ± 78	74 ± 39	170 ± 58	31 ± 26
5	2 330 ± 624	865 ± 642	234 ± 62	26 ± 23	270 ± 32	57 ± 11	174 ± 14	16 ± 8
15	36 700 ± 9 780	13 100 ± 11 100	696 ± 200	544 ± 345	560 ± 228	481 ± 709	574 ± 442	250 ± 97
Sulfur gas[b] exposed								
3	1 150 ± 239	136 ± 59	192 ± 43	15 ± 5	174 ± 22	20 ± 18	154 ± 36	23 ± 12
11	1 000 ± 133	181 ± 68	280 ± 36	24 ± 7	342 ± 68	44 ± 38	200 ± 72	14 ± 6
12	1 010 ± 366	258 ± 144	294 ± 78	23 ± 4	268 ± 52	28 ± 8	168 ± 38	21 ± 8
13	919 ± 503	183 ± 52	78 ± 86	15 ± 5	74 ± 80	20 ± 10	40 ± 98	26 ± 16
14	1 075 ± 390	179 ± 64	216 ± 110	34 ± 15	158 ± 102	24 ± 4	178 ± 26	31 ± 9
23	1 270 ± 239	152 ± 70	220 ± 32	19 ± 5	256 ± 75	45 ± 19	187 ± 106	33 ± 22
All non-sulfur-dusted sites								
	1 060 ± 48	171 ± 8	225 ± 33	21 ± 5	245 ± 50	36 ± 7	200 ± 26	39 ± 20

[a] The exact horizon designation varies from site to site.
[b] The sulfur gas designation refers to sites that have 7-year mean sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).

Table 4. Total and NH_4OAc extractable Ca concentrations (mg kg^{-1}) of the four surface soil horizons[a] at selected biomonitoring sites. Values are means ± 95% confidence limits.

Site	LFH		Ae_1		B		Ae_2	
	Total	NH_4OAc extract	Total	NH_4OAc extract	Total	NH_4OAc extract	Total	NH_4OAc extract
Sulfur dusted								
1	11 700 ± 6 350	9 540 ± 6 800	6 550 ± 984	865 ± 302	5 540 ± 860	1 040 ± 312	3 908 ± 190	1 290 ± 489
2	12 900 ± 14 900	11 100 ± 13 700	5 330 ± 1 180	837 ± 408	5 080 ± 1 090	964 ± 471	3 530 ± 366	1 540 ± 1 430
5	12 700 ± 12 900	11 700 ± 13 900	5 220 ± 1 390	912 ± 850	4 690 ± 758	1 130 ± 586	3 510 ± 662	1 030 ± 455
15	19 300 ± 24 700	20 200 ± 36 900	6 120 ± 1 460	1 450 ± 521	3 910 ± 1 790	1 090 ± 544	3 130 ± 328	1 540 ± 572
Sulfur gas[b] exposed								
3	5 040 ± 2 000	4 150 ± 2 540	4 330 ± 1 280	897 ± 203	4 510 ± 2 000	1 270 ± 1 160	4 060 ± 1 300	1 720 ± 831
11	4 000 ± 1 470	3 590 ± 1 960	6 420 ± 1 380	787 ± 598	5 550 ± 2 820	512 ± 4 150	4 140 ± 4 150	513 ± 188
12	4 460 ± 2 409	4 840 ± 3 430	6 480 ± 1 030	830 ± 190	5 530 ± 1 230	810 ± 342	3 240 ± 342	1 200 ± 519
13	4 640 ± 1 880	4 730 ± 1 500	2 930 ± 944	714 ± 252	2 230 ± 1 310	695 ± 1 230	1 300 ± 1 230	1 480 ± 1 190
14	4 840 ± 1 480	5 760 ± 3 220	7 270 ± 746	1 320 ± 437	6 090 ± 3 140	1 220 ± 954	7 210 ± 954	1 900 ± 602
23	3 150 ± 964	2 330 ± 1 100	4 630 ± 439	429 ± 108	3 950 ± 1 870	271 ± 109	3 810 ± 2 950	1 150 ± 1 100
All non-sulfur-dusted sites								
	5 050 ± 411	4 810 ± 492	5 100 ± 489	838 ± 231	4 520 ± 784	942 ± 321	4 640 ± 1 750	2 010 ± 1 070

[a] The exact designation varies from site to site.

[b] The sulfur gas designation refers to sites that have 7-year sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).

($p > 0.05$) different from the remaining sites in any of the soil horizons.

Calcium and pH: Sites 1, 2, 5, and 15 were limed with $CaCO_3$ by the gas companies in 1979 and 1980. This has resulted in the total and NH_4OAc extractable Ca levels in the LFH horizon at these sites being considerably although not significantly ($p > 0.05$) higher than at any other site (Table 4). Since there was very little difference between total and NH_4OAc extractable Ca, the Ca in this horizon appears to be primarily on exchange sites or in a soluble form rather than in some insoluble mineral or organic form. Because Ca was in an extractable form, the high concentration in the LFH could be important in the release of other cations from this horizon. Saturation of the exchange sites with Ca could replace other cations, allowing them to be leached more readily. The elevated concentrations of Ca and S in the LFH horizon of Sites 1, 2, 5, and 15 (particularly Sites 1 and 15) indicate that $CaSO_4$ could be an important constituent of the soil at these sites.

No differences were observed in the concentrations of total and NH_4OAc extractable Ca among mineral horizons of the limed sites (1, 2, 5, and 15) and those of other sites (Table 4).

The pH of the LFH horizons at Sites 1 and 15 was lower than that at all other sites despite the addition of lime (Table 5). Although the differences in LFH pH between Sites 1 and 15 and the rest of the sites were not significant (Sheffé simultaneous test procedure), the means were more than 1.2 pH units lower than any other site. The large within-site variability of the pH data made it impossible to distinguish between sites on a statistical basis. In the mineral horizons, variability was also great, and no significant differences were seen among the sites. As with the S concentrations, pH differences were observed at a lower depth at Site 15 than at Site 1 (Table 5).

Other Elements: There was no significant ($p > 0.05$) reduction in any elemental concentration in the LFH at Site 1 (Table 6) compared with the non-S^0-dusted sites, even though S concentrations (S^0, total, and NH_4OAc extractable) were higher and the pH was reduced at Site 1. At Site 15, although there were no significant ($p > 0.05$) differences, the total concentration of Mg, K,

Table 5. The pH of the four surface soil horizons[a] at selected biomonitoring sites. Values are means ± 95% confidence limits.

Site	LFH	Ae_1	B	Ae_2
Sulfur dusted				
1	2.5 ± 0.2	4.1 ± 0.6	5.3 ± 0.4	5.1 ± 0.4
2	4.3 ± 1.1	4.7 ± 0.7	5.7 ± 0.6	5.4 ± 0.3
5	4.9 ± 1.1	4.6 ± 0.3	5.6 ± 0.2	5.5 ± 0.3
15	3.0 ± 1.9	4.0 ± 0.3	4.5 ± 0.1	4.4 ± 0.1
Sulfur gas[b] exposed				
3				
11	4.3 ± 0.2	4.5 ± 0.2	5.1 ± 0.4	5.4 ± 0.2
12	4.4 ± 0.6	5.1 ± 0.4	5.6 ± 0.2	5.5 ± 0.1
13	4.5 ± 0.3	4.5 ± 0.2	4.9 ± 0.2	4.9 ± 0.2
14	4.5 ± 0.2	4.7 ± 0.3	5.6 ± 0.4	5.7 ± 0.4
23				
All non-sulfur-dusted sites				
Range	4.2 — 5.5	4.0 — 5.5	4.9 — 5.6	4.9 — 6.2

[a] The exact horizon designation varies from site to site.

[b] The sulfur gas designation refers to sites that have 7-year mean sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).

Table 6. Total elemental concentrations (mg kg^{-1}) in the LFH horizon at selected biomonitoring sites. Values are the means ± 95% confidence limits.

Site	Elemental content (mg kg^{-1}) Mg	K	Mn	Fe	Al	P	V
Sulfur dusted							
1	735 ± 443	1 880 ± 624	660 ± 986	3 550 ± 2 390	8 070 ± 4 670	1 220 ± 343	14 ± 15
2	857 ± 435	1 880 ± 596	858 ± 884	2 130 ± 1 300	7 100 ± 2 750	1 100 ± 165	14 ± 15
5	958 ± 468	1 700 ± 628	614 ± 601	3 120 ± 1 890	6 560 ± 4 400	1 080 ± 298	11 ± 8
15	589 ± 204	986 ± 265	153 ± 92	3 060 ± 1 640	4 760 ± 2 420	817 ± 151	3 ± 2
Sulfur gas[a] exposed							
3	1 250 ± 367	2 030 ± 575	1 660 ± 1 670	4 130 ± 1 890	8 510 ± 2 680	1 090 ± 197	14 ± 8
11	1 070 ± 116	2 070 ± 172	1 290 ± 928	3 530 ± 625	8 730 ± 568	1 370 ± 292	9 ± 7
12	1 110 ± 524	2 090 ± 925	1 700 ± 1 690	3 830 ± 2 600	9 200 ± 50	1 220 ± 508	9 ± 5
13	918 ± 140	1 700 ± 367	458 ± 325	1 450 ± 651	5 160 ± 1 710	969 ± 202	7 ± 3
14	1 100 ± 643	1 800 ± 874	893 ± 537	3 220 ± 4 520	5 640 ± 4 020	820 ± 174	10 ± 10
23	798 ± 297	1 830 ± 737	1 130 ± 1 140	2 620 ± 1 060	6 480 ± 2 450	1 180 ± 353	6 ± 5
All non-sulfur-dusted sites							
	1 190 ± 80	2 160 ± 100	1 160 ± 222	3 730 ± 462	8 070 ± 590	1 080 ± 54	11 ± 1

[a] The sulfur gas designation refers to sites that have 7-year mean sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).

Mn, and Al in the LFH horizon were lower than the concentrations at all other sites. Lower Mn, Mg, and K levels appear to be a result of leaching from the soil horizon following increased acidification (Table 5) or replacement by Ca (Table 4). Magnesium levels at Site 15, for example, were lower than all other sites in the LFH but highest in the Ahe horizon.

NH_4OAc extractable Al in the LFH of Site 15 comprised a greater percentage of total Al than at all other sites (8.1% versus 2.1%). The greater percentage of extractable Al in these soils may be a result of the presence of the monovalent $AlSO_4^+$ in sulfate dominated soils that are dominated by sulfate (Singh 1982a, b). The low total Al in the LFH (Table 6) is probably a result of leaching of this more soluble form of Al. Total Al in the Ahe horizon at Site 15 was higher than at any other site.

There were no significant ($p > 0.05$) differences among sites in either NH_4OAc extractable or total concentrations of any element in the mineral horizons. The NH_4OAc extractable Mn in the three mineral horizons at Site 15, however, appeared to be elevated relative to the total concentrations (Table 7). The higher NH_4OAc extractable Mn concentrations could be due to the intense acidification of the LFH and subsequent solubilization and leaching of Mn into the mineral horizon. The data available to date, however, are not conclusive. Site 15 is imperfectly drained, and gleying occurs below 6 cm, indicating that reducing conditions occur during a portion of the growing season. Since Mn is more soluble under reducing conditions (Lindsay 1972; Russell 1977), the higher NH_4OAc extractable Mn concentration at Site 15 could be a result of the reducing conditions rather than the acidification of the LFH horizon.

Vegetation

Vegetation description

The vegetation of all the sites is characterized by a *Pinus contorta* stand with an abundant moss and lichen layer comprised of *Pleurozium schreberi*, *Ptilium crista-castrensis*, *Hylocomium splendens*, *Polytrichum* spp., *Tomenthypnum nitens*, and *Peltigera* sp. The ground shrub layer consists of *Rosa acicularis*, *Vaccinium myrtilloides*, *V. vitis-idaea*, and *Linnaea borealis*, and the herb layer contains *Epilobium angustifolium*, *Elymus innovatus*, *Calamagrostis canadensis*, *Cornus canadensis*, and *Maianthemum canadense*.

Table 7. **Total and NH_4OAc extractable Mn concentrations (mg kg^{-1}) in the mineral horizons[a] of Sites 1 and 15 as compared with background sites.** Values are means ± 95% confidence limits.

Site	Ae$_1$		B		Ae$_2$	
	Total	NH_4OAc extract	Total	NH_4OAc extract	Total	NH_4OAc extract
1	564 ± 364	77 ± 61	366 ± 94	34 ± 48	160 ± 22	3 ± 4
15	508 ± 458	70 ± 71	414 ± 250	38 ± 33	266 ± 54	18 ± 16
All non-sulfur-dusted sites	522 ± 109	25 ± 6	521 ± 86	5 ± 1	312 ± 51	4 ± 3

[a] The exact horizon designation varies from site to site.

Natural differences in the diversity, abundance, and species composition of the sites appear to be related to the elevation and age of the *Pinus contorta* stands. The sites were divided into five groups based on elevation and tree age: subalpine, high elevation old and young, and low elevation old and young (Table 8). Sites 1 and 15 were excluded since they were heavily impacted by gas plant activity. The groups were determined from tabular analysis. Ordination and cluster analyses were carried out but provided no further insight into the vegetational distribution than did the tabular analysis.

The subalpine group consists of Site 24 at an elevation of 1753 m. This stand has the fewest moss species as well as the lowest moss and herb covers (Table 8). In addition, *Juniperus communis, Vaccinium scoparium,* and *Rhododendron albiflorum* are found only in this stand. The short, cool growing season at this elevation probably accounts for the low diversity and cover.

The high (>1220 m), old (>80 yr) group of sites has the second-lowest mean diversity (23 species) compared with sites at lower elevations (34 species) and in younger stands (33 species). The percent cover of the understory, however, is similar to that at lower elevations and in younger stands (Table 8). The moss, herb, and shrub diversities in this group appear to be related to the influence of stand density on light penetration. The stands with the lowest stand densities (11, 12, and 22) have the greatest diversity and abundance of herbs. *Alnus crispa* is present only at these sites. The low moss cover at Sites 11 and 12 may be a response to shading by and litter-drop from the herbs and shrubs (Tarkhova and Ipatov 1975).

At high elevations (>1220 m), younger stands (<80 yr) have more diverse lichen, herb, and shrub components than older stands (Table 8). Variation within this group of sites appears to be related to both stand density and the moisture regime. The more open stand at Site 13 (925 stems ha^{-1}) had a much greater abundance of herbs and shrubs. Site 16 appears more moist than the others and has *Sphagnum* sp., *Ribes* sp., *Viburnum edule, Lonicera involucrata, Rubus pubescens, Viola renifolia, Lycopodium annotinum, Petasites palmatus, Gymnocarpium dryopteris,* and *Coptis trifolia,* which are mesophytic indicators (Rowe 1956). This site also has the highest moss cover of all the sites.

Species composition is the major factor that distinguishes high and low elevation groups. At high elevations a stand is composed of mainly coniferous species such as *Pinus contorta, Picea glauca,* and *Abies balsamea,* whereas at lower elevations a deciduous component, *Populus tremuloides,* is included.

At low elevations (<1220 m), the group of young sites has higher stand densities than the older group (Table 8), and *Alnus crispa* is present in each stand. The variation in most species groups was great, but much of it could be accounted for by Sites 19 and 5. The low moss and herb cover at Site 19 appears to result from drier soil conditions caused by the poor water retention of the sandy loam at this site. The presence of such xerophytic shrubs as *Shepherdia canadensis* and *Arctostaphylos uva-ursi* also indicate dry soil conditions (Rowe 1956). Site 5 is an anomaly. Although it has a closed canopy (>1500 stems ha^{-1}), it has diverse and abundant herb, shrub, and moss components. The high (30%) moss

Table 8. Diversity and cover of the understory components of *Pinus contorta* stands at the biomonitoring plots in the vicinity of the Strachan and Ram River gas plants

Group	Site	Elevation (m)	Stand age (yr)	Total diveristy (no.)	Total cover (%)	Lichen Total diversity	Lichen Total cover (%)	Moss Total diversity	Moss Total cover (%)	Herb Total diversity	Herb Total cover (%)	Shrub Total diversity	Shrub Total cover (%)	Tree density per hectare (dbh >10 cm)
Sulfur dusted	15	1402	76 ± 2	20	14	0	0	1	0.2	10	4	7	7	1350
	1	1204	49 ± 1	24	18	0	0	4	1	11	10	7	5	1250
Subalpine	24	1753	78 ± 3	22	21	4	0.5	6	3	3	1	7	12	1350
High old	10	1311	105 ± 3	21	48	4	0.5	5	34	4	2	6	7	2050
	11	1356	99 ± 3	26	39	1	0	5	7	12	21	7	9	875
	12	1372	95 ± 8	27	35	0	0	6	10	11	13	8	5	1025
	17	1250	101 ± 9	27	44	9	0.6	6	25	5	3	5	4	1600
	22	1295	115 ± 9	22	50	1	0.4	5	26	8	11	6	9	1000
	23	1295	106 ± 2	26	37	6	0.4	6	22	6	6	6	6	2050
	25	1478	134 ± 6	21	23	4	1.6	6	15	5	0.4	6	6	1500
	26	1295	105 ± 3	17	40	2	0.2	5	19	4	2	4	2	1800
Group avg		1332 ± 59	108 ± 4	23 ± 3	40 ± 7	3 ± 3	0.5 ± 0.4	6 ± 0.4	20 ± 7	7 ± 3	7 ± 6	6 ± 1	6 ± 2	1488 ± 396
Group total				55		13		6		22		10		
High young	9	1417	75 ± 2	33	32	10	0.5	7	18	11	7	3	3	1575
	13	1433	71 ± 5	33	56	6	0.4	6	15	11	17	8	23	925
	14	1295	78 ± 3	33	35	7	0.3	6	13	12	6	7	15	1525
	16	1341	51 ± 3	32	58	1	0	5	40	13	6	10	3	1400
Group avg		1372 ± 103	70 ± 4	33 ± 0.8	45 ± 22	6 ± 6	0.3 ± 0.3	6 ± 1	22 ± 20	12 ± 2	9 ± 9	7 ± 5	11 ± 16	1356 ± 472
Group total				56		11		8		22		12		
Low young	2	1204	73 ± 4	34	30	9	0.8	6	12	8	8	9	5	1725
	4	1082	60 ± 5	40	41	3	0.3	5	19	18	9	11	12	1125
	5	1204	75 ± 2	39	67	4	0.2	5	30	16	13	12	18	1525
	19	1036	78 ± 2	27	22	1	0	6	4	8	4	11	12	1400
	20	1158	53 ± 7	24	41	0	0	6	16	8	7	8	6	975
Group avg		1137 ± 93	68 ± 5	33 ± 4	40 ± 21	3 ± 4	0.3 ± 0.4	6 ± 1	16 ± 12	12 ± 6	8 ± 4	10 ± 2	11 ± 7	1350 ± 375
Group total				63		11		7		26		15		
Low old	3	1204	104 ± 3	38	44	8	0.6	6	19	13	9	9	10	1500
	6	1113	96 ± 5	33	57	1	0.1	6	32	18	11	7	7	1175
	7	1128	106 ± 5	33	44	2	0.1	6	27	15	9	9	8	975
	8	1128	80 ± 3	38	43	4	0.5	7	20	17	8	8	10	1325
	18	1021	88 ± 7	34	40	5	7.5	5	12	11	2	10	12	300
	21	1189	93 ± 19	27	36	2	0.1	5	13	10	8	9	10	1375
Group avg		1131 ± 68	95 ± 4	34 ± 4	44 ± 7	4 ± 3	1.5 ± 3.1	6 ± 1	21 ± 8	14 ± 3	8 ± 3	9 ± 1	10 ± 2	1108 ± 457
Group total				68		13		7		28		16		

cover is inconsistent with the large deciduous component in this stand. The reason for the diversity and abundance in the herb, shrub, and moss layers is not known but may be related to increased moisture in parts of the plot as evidenced by the presence of *Viburnum edule, Lonicera involucrata, Rubus pubescens, Viola renifolia, Lycopodium annotinum, Petasites palmatus,* and *Gymnocarpium dryopteris* (Rowe 1956). Site 4 also has a diverse herb layer, but some of these plants such as *Trifolium repens* appear to be a result of the grazing history of the site.

The group of old (>80 yr) sites at low elevations has the lowest stand density (1100 stems ha^{-1}) of all the groups but an understory cover comparable to those of more closed stands (Table 8). The closed canopy effect appears to be caused by the presence of a number of large *Picea glauca* individuals and is particularly pronounced at Sites 6 and 7, which have low stand densities (1175 and 975 stems ha^{-1}, respectively) but the greatest moss cover. Sites 18 and 21 vary from the norm. Site 18 has low herb and moss covers but the highest lichen cover (7.5%) of any site. This appears to be related to low soil moisture in the rapidly drained sand dune on which this stand is located. At Site 21, the diversity and cover of mosses and lichens are lower than in other stands in this group. This appears to be a response to shading by and litter-drop from *Alnus crispa* (Tarkhova and Ipatov 1975).

In general, the vegetation of the biomonitoring plots in this area appears uniform. The variation that does exist, however, can be broken down into two sources. Between-group variation appears to be related to the age and elevation of the stands, whereas within-group variation appears to result from differences in moisture regime and the interaction between species (e.g., *Alnus crispa* and moss).

Understory response

The understory vegetation at Sites 1 and 15 appeared to be affected by the deposition of S^0. Both sites had the lowest total diversity and cover of the elevational and age groupings to which they belonged (Table 8). The main difference between Sites 1 and 15 and their respective groups, however, was in moss cover. Site 1 had a moss cover of 1% compared with 16% for the low elevation, young sites. Site 15 appeared to be more greatly affected and had only 0.2% moss cover compared with 22% for the high elevation, young sites. In addition, Site 15 also appeared to have lower moss diversity (one vs. six species) and lower cover of herbs (4 vs. 9%) when compared with the high elevation, young group of sites. It is apparent that the response of the plant community to dusting by S^0 parallels that of both soil and plant chemistry. Only the sites (1 and 15) most heavily impinged showed an impact that could be attributed to this pollutant. Site 15 appeared to be affected to a greater extent than Site 1, and this can be attributed to the longer exposure to S^0 dust and its breakdown products.

Lichen response

The cover of *Usnea* and *Hypogymnia* appeared to be lower at the S^0 dusted sites and at Sites 12, 14, and 23 of the sulfur gas exposed sites (Table 9). Although the sites with lower *Usnea* and *Hypogymnia* covers appeared to coincide with those that had elevated S in plant tissue, there was no correlation between plant tissue S and lichen cover when all sites were considered. *Bryoria* and *Cetraria* did not show any differences between sites close to the gas plants and those at greater distance (Table 9). This was unexpected, since *Bryoria* has been demonstrated to be a sensitive species (Skorepa and Vitt 1976) and has been reported to be more sensitive to SO_2 than either *Hypogymnia* or *Cetraria* (Hawksworth 1973). *Bryoria* and *Cetraria* were both difficult to distinguish from the substrate using this photographic technique. The inherent errors in the measurement of lichen cover combined with the large within and between site variability made it impossible to make a definitive statement on the response of the lichen community to emissions from sour gas processing.

Table 9. Percentage cover of lichen groups at the biomonitoring sites in west-central Alberta. Values are means ± 95% confidence limits.

Site	*Usnea*	*Hypogymnia*	*Bryoria*	*Cetraria*
Sulfur dusted				
1	9 ± 2	2 ± 1	1 ± 0	3 ± 1
2	14 ± 4	2 ± 2	1 ± 0	3 ± 1
5	8 ± 4	3 ± 1	1 ± 0	2 ± 1
15	9 ± 1	2 ± 1	2 ± 0	1 ± 1
Sulfur gas[a] exposed				
3	28 ± 7	7 ± 2	2 ± 1	2 ± 1
11	18 ± 2	5 ± 2	1 ± 1	2 ± 1
12	7 ± 1	2 ± 1	2 ± 0	1 ± 1
13	29 ± 2	6 ± 2	3 ± 1	1 ± 1
14	15 ± 1	6 ± 3	2 ± 1	3 ± 2
23	12 ± 3	3 ± 2	1 ± 0	1 ± 1
All non-sulfur-dusted sites				
	22 ± 1	5 ± 1	1 ± 0	2 ± 0

[a] The sulfur gas designation refers to sites that have 7-year mean sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).

Pine growth and reproduction

The growth or reproduction of *Pinus contorta* at S^0 dusted and S gas exposed sites were not significantly different from those at any other site (Table 10). For all measurements, variability was great and apparently reflected the range of edaphic and biotic environments in this foothills region of Alberta. The only difference among the sites was that all of the S^0 dusted sites had lower than average needle retention than the background sites (Table 11). Since the S^0 dusted sites are also the sites with the greatest sulfation rates (Table 1), the reduction in needle retention may actually be due to SO_2, which is known to reduce tissue life span (Costonis 1970). The apparent reduction in needle retention has not affected growth rates.

Site 12 had the lowest growth rates (terminal and lateral) and seed production of any site (Table 10), although these differences were not significant. Since Sites 1 and 15 had higher sulfation rates a well as large amounts of S^0 deposition and still did not show any negative effects on the growth or reproduction of *Pinus contorta* (Tables 10 and 11), it is not possible to attribute the differences between Site 12 and the other sites to pollutant effects alone. Follow-up studies may help to quantify the contribution that air pollutants make to the characteristics of the pines at Site 12.

Sulfur dioxide has had an effect on the trees in the vicinity of sour gas processing. Acute SO_2 fumigations from fires on the sulfur block at Ram River in 1979 and 1981 have caused premature needle loss and almost total elimination of *Pinus contorta* in a 3 ha area south of Site 15. These fumigations may have been responsible for some of the reduction in needle retention at Site 15 and is the only definitive evidence of SO_2 damage to vegetation in the region.

Plant chemical analysis

Total Sulfur: The total S concentrations in the five plant species of the sites impinged by S^0 and in some plant species of sites close to Ram River were significantly ($p < 0.05$) higher than the total S concentrations of the remaining sites (Table 12). The magnitude of the increase in total S varied among the plant species and between the two groups of sites. At Sites 1 and 15 the total S concentration of *Pleurozium schreberi* (both in and on the tissue) was significantly ($p < 0.05$; Sheffé simultaneous test procedure) higher than that of the non-sulfur-dusted sites. The S concentrations of

Table 10. Characteristics of *Pinus contorta* at the biomonitoring sites. Values are means ± 95% confidence limits.

Site	Age (yr)	Height (m)	Growth rate: Leader (cm yr^{-1})	Growth rate: Lateral branches (cm yr^{-1})	Growth rate: Basal area (1972-81 cm^2 yr^{-1})	Ratio of basal area 1972-81/1962-71	Reproduction: Seed production (seeds/cone)	Reproduction: Viability (% filled seed)
Sulfur dusted								
1	49 ± 1	17.4 ± 1.2	27 ± 7	7.8 ± 0.7	85.8 ± 26.1	1.07 ± 0.26	22	86 ± 13
2	73 ± 4	20.3 ± 2.5	14 ± 5	5.3 ± 0.9	65.8 ± 37.7	0.97 ± 0.30	27	74 ± 15
5	75 ± 2	20.9 ± 1.2	14 ± 4	6.0 ± 0.6	64.8 ± 37.8	0.93 ± 0.31	29	86 ± 12
15	76 ± 2	20.3 ± 1.3	13 ± 3	5.3 ± 0.7	52.3 ± 22.8	1.29 ± 0.24	27	87 ± 12
Sulfur gas[a] exposed								
3	104 ± 3	22.4 ± 1.4	6 ± 1	3.1 ± 0.2	43.6 ± 20.3	1.09 ± 0.37	37	87 ± 17
11	99 ± 3	24.5 ± 1.9	8 ± 2	4.2 ± 1.0	104.0 ± 44.4	1.06 ± 0.22	35	75 ± 15
12	95 ± 8	22.6 ± 1.3	5 ± 3	2.8 ± 0.4	40.2 ± 17.1	0.89 ± 0.30	15	83 ± 17
13	71 ± 5	21.6 ± 0.8	18 ± 5	6.8 ± 1.4	137.0 ± 56.6	0.93 ± 0.12	28	39 ± 31
14	78 ± 3	22.2 ± 1.4	11 ± 3	4.0 ± 0.6	66.0 ± 29.4	1.27 ± 0.35	39	75 ± 13
23	106 ± 2	17.8 ± 1.3	10 ± 2	4.3 ± 0.3	35.8 ± 16.1	0.94 ± 0.23	30	84 ± 10
All sites								
	86 ± 8	19.2 ± 1.2	11 ± 2	4.5 ± 0.6	60.6 ± 13.0	1.01 ± 0.08	29 ± 2	80 ± 5

[a] The sulfur gas designation refers to sites that have 7-year mean sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).

Table 11. Needle production and retention of *Pinus contorta* (lodgepole pine) at selected biomonitoring plots. Values are averages or means ± 95% confidence limits.

Site	Needles produced in 1980 (g cm⁻¹ of stem)	1980 weight per needle (mg)	Weight of needles retained (% of 1980) 1981	1980	1979	1978	1977
Sulfur dusted							
1	0.85 ± 0.08	29.5 ± 2.1	84	100	87	80	41
2	0.86 ± 0.11	23.8 ± 2.0	70	100	78	89	52
5	0.68 ± 0.09	25.5 ± 2.7	72	100	92	85	34
15	0.83 ± 0.10	27.6 ± 2.1	74	100	68	69	48
Sulfur gas[a] exposed							
3	0.86 ± 0.08	25.2 ± 1.7	60	100	75	62	24
11	0.99 ± 0.14	32.3 ± 3.5	81	100	98	75	46
12	0.76 ± 0.12	22.2 ± 2.4	66	100	105	76	61
13	0.96 ± 0.11	28.0 ± 2.7	79	100	110	87	57
14	0.92 ± 0.08	26.1 ± 1.9	96	100	102	85	68
23	0.78 ± 0.10	26.4 ± 2.6	81	100	108	81	61
All sites							
	0.79 ± 0.05	26.1 ± 1.2	75 ± 5	100	95 ± 6	84 ± 6	55 ± 9

[a] The sulfur gas designation refers to sites that have 7-year mean sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).

Table 12. Total sulfur concentrations in plant tissue (mg kg⁻¹) at selected biomonitoring plots. Values are means ± 95% confidence limits.

Site	*Pinus contorta*	*Picea* spp.	*Alnus crispa*	*Linnaea borealis*	*Pleurozium schreberi*
Sulfur dusted					
1	2 460 ± 355	2 890 ± 235	10 600 ± 1 080	15 500 ± 2 580	79 100 ± 29 900
2	2 030 ± 229	1 770 ± 203	3 980 ± 397	6 400 ± 1 100	20 600 ± 5 020
5	1 460 ± 143	1 280 ± 108	2 750 ± 442	3 310 ± 330	9 880 ± 1 070
15	3 310 ± 391	3 620 ± 556	6 450 ± 768	33 900 ± 7 630	65 300 ± 11 700
Sulfur gas[a] exposed					
3	1 320 ± 150	1 160 ± 53	2 160 ± 299	1 450 ± 68	1 260 ± 96
11	1 300 ± 147	886 ± 78	1 610 ± 144	1 080 ± 53	1 250 ± 55
12	1 510 ± 247	1 040 ± 89	2 410 ± 308	1 670 ± 81	2 040 ± 82
13	1 380 ± 119	857 ± 61	1 730 ± 159	1 030 ± 50	1 110 ± 67
14	1 400 ± 168	1 180 ± 109	2 150 ± 273	1 550 ± 115	1 200 ± 108
23	1 040 ± 106	993 ± 11	1 480 ± 229	1 150 ± 39	1 250 ± 43
All non-sulfur-dusted sites					
	1 190 ± 29	952 ± 24	1 722 ± 53	1 190 ± 26	1 180 ± 32

[a] The sulfur gas designation refers to sites that have 7-year sulfation rates >0.05 mg dm^{-2} d^{-1} (SO_3).

P. schreberi at Sites 2 and 5, although not significantly different, were still 8 to 17 times higher than the S concentrations found on this species at the non-sulfur-dusted sites. A similar pattern in S concentrations was observed for *Linnaea borealis,* with Sites 1 and 15 significantly ($p < 0.05$) higher than all other sites. *Alnus crispa* showed a pattern in its S concentration that was similar to the soil S measurements. Site 1 had significantly ($p < 0.05$) higher S than Site 15, which was significantly higher than Sites 2 and 5. All four sites had significantly higher S in or on *A. crispa* than any other site.

Pinus contorta and *Picea* spp. at Sites 1, 2, and 15 also had significantly ($p < 0.05$) higher S concentrations in the 1-year-old tissue than at all other sites. These differences were small compared to the differences observed in the understory plants. At Site 5, the S concentration of the foliage was only slightly (250-300 mg kg^{-1}) higher than that of the background sites (Table 12), and these differences were significant only in *Picea* spp.

The elevated S concentrations in the plant tissue at S^0 dusted sites may be the result of three sources: elevated S^0 deposition on the surface of the vegetation, SO_2 or H_2S absorption, and uptake of S from the soil. It is not possible at this time to determine from what source the S originated; however, from the soils and sulfation data, field observations, and information in the literature it is possible to indicate the most probable source of S for a given plant species. The high concentration of S in *P. schreberi* samples appears to be the result of S^0 on the foliage. This species obtains virtually all of its nutrients from the atmosphere (Longton and Greene 1979). The magnitude of S gas uptake would be insignificant in comparison to the magnitude of the S^0 deposition on the moss at these sites. Uptake of S from the soil could be an important source of S for *A. crispa* and *L. borealis,* since they are rooted in soils with high concentrations of NH_4OAc extractable S, but it is not possible at this time to ascertain the contribution soil S makes to the S found in or on the foliage. Surface adsorption of S^0 is still probably the major source of S for *A. crispa* and *L. borealis* at the S^0 dusted sites. The increased tree S content at the S^0 dusted sites appears to be related to S uptake from the soil. The S concentration in the foliage at these sites follows a similar pattern to the NH_4OAc extractable S concentration in the LFH and Ae_1 horizons of these soils (Table 3). A similar hypothesis was suggested for increased sulfate concentration in the foliage of *Pinus* species adjacent to the West Whitecourt gas plant (Legge and Bogner 1982).

The S concentration of various plant species of the sulfur gas-exposed sites (sites with SO_3 sulfation of >0.05 mg dm^{-2} d^{-1} appeared to be higher than the average for the region as a whole. Owing to the tremendous added variance added by those sites exposed to S^0 dust, it was necessary to remove Sites 1, 2, 5, and 15 from the data set before statistical treatment.

Sites 12, 14, and 3 appeared to have elevated S content in the vegetation (Table 12). These sites were among the six sites with the highest total S for every species sampled. In addition, these three sites had significantly ($p < 0.05$; Sheffé simultaneous test procedure) higher *L. borealis* S content than all other sites and had the highest *A. crispa* S concentration, albeit not significantly different from that at several other sites. Site 12 had significantly ($p < 0.05$) higher *P. schreberi* S content and the highest *Pinus contorta* S content of all non-sulfur-dusted sites.

It was not possible to determine the source of the S in the foliage of the selected species. Sites 12 and 14 are close enough to the Ram River plant that they could be exposed to low levels of S^0 that were below the detection (100 mg kg^{-1}) of our analytical procedure. On the other hand, these sites were located in areas that had high sulfation rates (Fig. 3). Site 3 appears to be beyond the impingement of S^0. In general, therefore, it is felt that both particulate and gaseous sulfur emissions are responsible for the elevated total S concentration in plant tissue at sites up to 6 km from the two gas plants.

Calcium: Significantly ($p < 0.05$) elevated Ca concentrations of the foliage of *P. schreberi* were observed at Sites 2, 5, and 15 (Table 13). The Ca results were variable and were not in the same order of magnitude as the increased Ca concentrations in the LFH horizon of the soil. The reason for no significant ($p > 0.05$) increase in Ca concentration in *P. schreberi* at Site 1, which was aerially limed, is unknown. Considerable variability was found in Ca levels of the LFH where lime had been applied by air, and the apparent anomaly at Site 1 may simply be due to variability in the somewhat limited sample size (10). The lack of large increases in the Ca concentrations of the vegetation except for *P. schreberi* (where the majority of the Ca will be on the surface) suggests that the Ca was not readily available for plant uptake. It is possible that *Pinus contorta, Picea* spp., and *A. crispa* had the majority of their roots in the mineral horizons. Since elevated total Ca concentrations were limited to the LFH horizon and there were no significant differences in NH_4OAc extractable Ca among sites

Table 13. Element concentrations (mg kg^{-1}) in *Pleurozium schreberi* at selected biomonitoring sites. Values are means ± 95% confidence limits.

Site	Ca	Mn	K	Mg	P	Fe
Sulfur dusted						
1	4 880 ± 2 270	108 ± 56	2 610 ± 703	399 ± 68	1 220 ± 160	889 ± 230
2	13 000 ± 1 660	298 ± 69	5 940 ± 922	1 010 ± 494	1 520 ± 176	605 ± 154
5	10 600 ± 2 970	370 ± 56	5 380 ± 535	890 ± 72	1 340 ± 138	572 ± 47
15	10 400 ± 3 100	37 ± 17	744 ± 62	278 ± 41	719 ± 42	387 ± 190
All non-sulfur-dusted sites						
	3 740 ± 167	432 ± 22	5 470 ± 435	994 ± 35	1 305 ± 80	733 ± 56

(Table 4), the lack of pattern in plant Ca concentrations was not surprising. It is expected that, with time, Ca would become more available for plant uptake as more of it leached into the mineral horizons.

All plant species sampled, with the exception of *Pinus contorta*, had significant groupings of sites. These groupings appear to be the result of natural variability and not industrial activity. *Linnaea borealis*, however, had the highest concentrations of Ca at Sites 1, 2, and 5, but the grouping included Sites 17 and 21, which are distant from industrial activity.

Other Elements: The concentrations of K, Mg, and Mn in *P. schreberi* were lower at Sites 1 and 15 than at any other site (Table 13), but the differences were not statistically significant. These lower levels appeared to be related to cellular damage due to the end products of S^0 oxidation and the subsequent leaching of K, Mg, and Mn elements from the tissue. Elemental leaching (particularly K) has been shown to be an effective indication of pollutant damage to lower plants under laboratory conditions (Puckett et al. 1977). These elements and Ca are the most readily leached of the inorganic nutrients from plant tissue (Tukey 1970). The concentrations of K, Mg, and Mn in *P. schreberi* were lower at Site 15 than at Site 1 (Table 13), and Site 15 had the lowest Fe and P concentrations. Since Fe and P are leached from plant material with much more difficulty than K, Mg, and Mn (Tukey 1970), it appears that there has been a greater impact on this moss at Site 15 than at Site 1. This is consistent with observations of greater visible damage at Site 15 than at Site 1. The difference between the two sites appears to be related to the duration of exposure to S^0, since the pH of the LFH did not differ between the sites (Table 5).

The only other difference in the elemental concentrations of the plant tissue was observed at Site 15. Manganese levels were highest in the foliage of *Pinus contorta*, *Picea* spp., and *A. crispa* at Site 15 than at any other site (Table 14). A significant ($p < 0.05$) difference in the Mn concentration of *A. crispa* was observed at Site 15 as compared with all remaining sites. The differences between *Pinus contorta* and *Picea* spp. were not significant. The higher foliar levels are presumably a result of higher available Mn in the soil as indicated by the higher NH_4OAc extractable Mn concentration in the mineral soil at Site 15 (Table 7).

In general, only those sites (1 and 15) that were heavily impinged with S^0 dust showed any change in plant elemental content, with the exception of S. Elevated levels of S were found in certain plant species at sites outside the impingement zone for S^0 dust but close to the Ram River and Strachan gas plants. The higher S concentrations at these sites did not appear to influence the composition of other elements in plant tissue.

Table 14. Total Mn concentrations (mg kg^{-1}) in selected vascular plant tissue at Sites 1 and 15 as compared with background sites. Values are means ± 95% confidence limits.

Site	*Pinus contorta*	*Picea* spp.	*Alnus crispa*	*Linnaea borealis*
1	640 ± 87	998 ± 234	1 970 ± 166	330 ± 56
15	1 000 ± 185	2 230 ± 603	5 030 ± 577	502 ± 43
All non-sulfur-dusted sites	558 ± 29	1 110 ± 96	784 ± 71	339 ± 18

CONCLUSIONS

The four sites impinged by S^0 (Sites 1, 2, 5, and 15) had noticeable differences in soil chemical properties. These sites had higher total and extractable S in the LFH horizon, and at the most heavily impinged site (15), there were elevated S concentrations at depth. Also at this site, concentrations of Mg, K, Mn, and Al in the LFH were lower. Lower concentrations can be attributed to greater leaching caused by either acidification from S dusting or replacement of these elements by Ca from aerial liming.

The plant response to intense S^0 dusting was dramatic. Mosses appeared to be particularly sensitive, and their cover was substantially reduced at heavily impinged sites (1 and 15). In addition, there was a reduction in herb cover and moss diversity at Site 15. Trees, however, did not show either a growth or reproduction response, even through S concentration in tissue was elevated.

Several sites (12, 14, and 3) within 6 km of the gas plants had no measureable S^0 but had elevated S in plant tissue. It was not possible, however, to determine whether increased S was a result of very low levels of S^0 deposition or exposure to S gases. It is assumed that it was both.

ACKNOWLEDGMENTS

The authors would like to thank Canterra Energy Ltd., Gulf Canada Resources Inc., the Alberta Forest Service, Alberta Environment, and the Energy Resources Conservation Board for assistance in the planning of this study as well as for support in the form of information, access, logistics, and encouragement.

The financial assistance provided jointly by Canterra Energy Ltd. and Gulf Canada Resources Inc. is gratefully acknowledged. Field and laboratory assistance was provided by J.I. Ridgway and F. Radford with help from D. Carnochan, S. L'Hirondelle, C. McCall, and F. Theriault.

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