

NUTRIENT LEVELS IN RAINFALL, LODGEPOLE PINE
FOLIAGE, AND SOILS SURROUNDING TWO SULFUR
GAS EXTRACTION PLANTS IN STRACHAN, ALBERTA

BY

J. BAKER

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NORTHERN FOREST RESEARCH CENTRE
CANADIAN FORESTRY SERVICE
FISHERIES AND ENVIRONMENT CANADA
5320 - 122 STREET
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ABSTRACT

Analyses of rainfall, lodgepole pine tissues, and soils were carried out on samples from control and SO₂-impinged areas around two gas processing plants. Samples of rainfall from the more heavily exposed site contained greater amounts of SO₄-S than those from the control. Lodgepole pine needle and twig tissues contained varying amounts of cations and anions depending on the source of the material. Tissues from the sulfur-exposed sites contained greater amounts of sulfur and aluminum but less calcium, magnesium, and phosphorus than control tissues. Ionic composition of soil solutions and exchange complexes from the two general sample areas also differed. Samples from the more heavily impinged areas showed lesser amounts of basic ions (Ca, Mg, K, etc.) and larger amounts of acidic constituents (Al, S, etc.) even though the same general soil type prevailed over the entire study area.

RESUME

On a effectué des analyses d'eau de pluie, de tissus de Pin tordu et de sols sur des échantillons provenant de secteurs témoins et de secteurs en contact avec du SO₂, à proximité de deux raffineries. Les échantillons d'eau de pluie provenant de l'aire la plus exposée contenaient plus de SO₄-S que ceux provenant du secteur témoin. Les aiguilles et rameaux de Pin tordu contenaient diverses quantités de cations et d'anions, selon le lieu d'origine du matériel. Les tissus provenant des aires exposées au soufre avaient une teneur plus grande en soufre et en aluminium mais contenaient moins de calcium, de magnésium et de phosphore que les tissus témoins. La composition ionique tant chez les solutions du sol que chez les complexes d'échange provenant des deux

secteurs généraux d'échantillonnage, différait elle aussi. Les échantillons de sols des deux secteurs les plus lourdement chargés manifestèrent de moindres teneurs en ions de base (Ca, Mg, K, etc.) et de plus fortes teneurs en constituants acides (Al, S, etc.) malgré le fait que toute la région étudiée fût composée du même type général de sol.

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INTRODUCTION

A considerable number of the natural gas wells in Alberta are sour; that is, they contain hydrogen sulfide, H_2S . Since this gas is highly poisonous to animals and man, it must be converted into a nontoxic form, elemental sulfur. In the conversion of H_2S to elemental sulfur (S^0), much sulfur as sulfur dioxide (SO_2) escapes into the atmosphere. In 1975 over half a million tons of SO_2 were emitted into the atmosphere of Alberta (Baker *et al.* 1976). The effect of sulfur emissions on the acidity of precipitation was described by Nyborg *et al.* (1976).

Two large sources of SO_2 are the Gulf and Aquitaine gas processing plants located in the Strachan area of Alberta. These two plants, situated in forested areas and approximately 13 km apart, have been shown to have strong local influences on the total environment (Baker *et al.* 1973). Province-wide, however, damage from atmospheric SO_2 released by gas processing plants is negligible as yet. This report considers data on the chemical composition of rainfall, lodgepole pine foliage, and soil samples from sites surrounding the two gas plants.

METHODS AND MATERIALS

Earlier work* had delineated the zone of major SO_2 impingement. In this area five sites were selected for the installation of rainfall collecting apparatus:

1. Strachan Ranger Station--3.2 km northwest of Gulf Sulfur Plant
2. Gulf-Aquitaine Powerline--4.8 km south-southwest of the Gulf Plant and 6.4 km east-northeast of the Aquitaine Plant
3. Gulf Plant--1.0 km east of the Gulf Plant center
4. Aquitaine N.E.--3.2 km straight west of the Gulf Plant and 8 km northeast of the Aquitaine Plant
5. Two Dam Creek--6.4 km north of the Aquitaine Plant
6. Radiant Creek--19.2 km southwest of the Aquitaine Plant and 32 km southwest of the Gulf Plant

A diagram of sites selected for the permanent monitoring of sulfur impingement was given by Baker *et al.* (1976).

* Personal communication from D. Hocking, Northern Forest Research Centre, Edmonton, Alberta.

The Radiant Creek sampling site and the area west are protected from large-scale SO_2 impingement by Idlewilde Mountain on the immediate east. The entire area west of this point was thought to be relatively free from SO_2 contamination and was considered the "control" area. Since the Gulf Plant has been in operation for 8-10 yr the establishment of an uncontaminated control area was virtually impossible.

RAINFALL COLLECTION

At each site, rainfall collecting apparatus composed of V-shaped funnels 16 cm in diameter leading into covered 4.5-l plastic pails was set up. Fiberglass filters were placed in the neck of the funnels to remove solid debris. Two such collectors were installed at each site. Rainfall was collected throughout the entire 1976 growing season; samples were taken monthly for analyses. The total volume of precipitation collected over the entire period probably was in error from 10 to 15%. The fiberglass filter discs became clogged with debris, and thus in short but heavy rain storms the funnels would overflow and precipitation was lost. Since this difficulty was experienced equally at all collection sites, information obtained is assumed to describe the effects of SO_2 on rainfall at each site fairly well.

Rainfall data for each month included approximate volume, pH, sulfur ($\text{SO}_4\text{-S}$), calcium (Ca), magnesium (Mg), and potassium (K). Sodium (Na) was determined only for the last (Sept.) collection; results indicated that it should have been estimated routinely with the other cations. Both nitrogen ($\text{NH}_4\text{-N}$) and phosphorus (H_2PO_4^-) were sought in initial rainfall collections, but as these ions were negligible, estimations were discontinued.

SOIL AND FOLIAR ELEMENTAL ANALYSES

Foliar samples were taken in the general vicinity of the rainfall collection sites. Analyses performed on foliage were Ca, Mg, iron (Fe), aluminum (Al), K, Na, sulfur (S), phosphorus (P), and nitrogen (N). Analyses were carried out on samples that had been taken during the active growth season. The extreme 5- to 10-cm lateral tips of five to six

branches near the tree tops were used. Stand ages ranged from approximately 40 to 60 yr old. Phosphorus and nitrogen evaluations were carried out on wet ashed material; all other estimations were performed on dry ashed samples.

Chemical analyses of soil samples performed included the examination of both water- and NH_4Cl -extractable constituents. Samples were taken from the surface litter (L-F-H horizon), the 5- to 15-cm soil layer, and the 15- to 30-cm soil layer. Samples were stored in plastic airtight bags at 0°C , and thus the moist field condition was maintained. About 100-125 g of field-moist L-F-H sample and approximately 200-250 g of field-moist mineral materials from the 5- to 15-cm and 15- to 30-cm soil depths were placed in large plastic beakers. Distilled water was slowly added with mixing until a saturated paste was obtained. Samples in this saturated condition were allowed to stand 1 h, after which they were thoroughly mixed and transferred to pressure extractors. A portion of the paste was taken for moisture determinations before the transfer was made. Pressure to 100 kPa was applied to the extractors and permitted to act overnight. The water extracts taken were evaluated for Ca, Mg, Fe, Al, K, Na, S, and P. These constituted water-extractable ions. The extracted soil cake was then broken up and put through a 5-mm sieve, placed in a moisture can, and stored in a refrigerator. Five to seven grams of moist L-F-H and 10-15 g of mineral materials were weighed, placed in a funnel fitted with a wet No. 44 Whatman filter circle, and extracted with four 25-ml volumes of N ammonium chloride (NH_4Cl). Nômmik (1973) suggested that the use of N NH_4Cl was preferable in the determination of exchangeable cations in forest soils because exchange was more complete using the reagent. Each 25-ml volume was allowed a contact time of 1/2 h followed by a drain time of 1/2 h. Total extraction time was about 4 h. Extracts were made to 100 ml with N NH_4Cl and examined for Ca, Mg, Fe, Al, K, Na, S, and P. These constituted NH_4Cl -extractable ions. Extracted soils remaining in the filter papers were washed with 50 ml of distilled water, allowed to thoroughly drain, and then placed in a drying oven set at 105°C , and dried overnight. Oven-dry soil weights were obtained by subtracting the tare weight of the filter paper.

Physical analysis of the soils was not performed, nor were the soils classified. However, except for the Two Dam Creek site, where the soil appeared to be a silty loam, soils at all other sites were considered to be sandy loams. The depth of surface litter varied from site to site. Similar soils were classified as Caroline loam sands or sandy loams by Peters and Bowser (1957).

Cationic species Ca, Mg, etc., regardless of source (water, foliage, soil), were evaluated by atomic absorption spectrophotometry using an Instrumentation Laboratory model 251. Procedures suggested by the manufacturer were used throughout. Phosphorus was determined by the molybdenum blue method with a reductant of ascorbic acid, and total nitrogen by titration following digestion and distillation. Sulfur determination in the various materials was achieved by a modified Johnson-Nishita method as suggested by Carson *et al.* (1972). All soil pH measurements were made in 0.01 molar calcium chloride using the glass electrode. Exchange acidity was determined on the NH_4Cl extract by titration with standard NaOH using a Metrohm automatic titrator.

RESULTS AND DISCUSSION

RAINFALL

Rainfall collected at the control site contained the least sulfur, while that obtained at the Gulf plant site had the greatest amount (Table 1). All sites within the suggested SO_2 -impinged area exhibited sulfur fallout values in excess of that found for the control. That rainfall from the control site contained sulfur confirms the earlier statement that no area is entirely free of SO_2 impingement.

Other ions such as Ca, Mg, and K were also found in rainfall from the various sites. This suggests that the atmosphere contained these ions, but probably the rainfall was contaminated by drift and/or drip from vegetation, especially during wind storms.

Rainfall pH values from SO_2 -impinged sites were little different from those for the control site. The presence of sulfur appeared to have little effect on the pH of precipitation. The presence of contaminating

Table 1. Ionic constituents deposited by rainfall at test sites from June through September, 1976

	Distance from S plants km		pH	kg/ha				Volume ℓ
				S	Ca	Mg	K	
Gulf	1.0	Exposed	6.0	12.06	19.26	3.13	4.19	6.60
Strachan Ranger Sta.	3.2	Exposed	6.1	4.21	6.79	1.13	3.27	7.14
Aquitaine N.E.	3.2	Exposed	5.9	7.30	10.20	1.69	3.31	6.72
Powerline	4.8	Exposed	6.0	5.65	3.99	1.10	3.46	6.43
Two Dam Creek	6.4	Exposed	5.8	5.59	4.78	1.60	2.67	7.71
Radiant Creek	19.2	Control	6.1	2.57	7.50	2.96	1.69	5.67

ions, perhaps carbonates, may have prevented the full acid expression on the sulfur present. Similar results were observed in the Hinton area*.

Over the 4-mon summer period, rainfall at the Gulf plant site contained a total of 12 kg/ha of S and 19 kg/ha of Ca, while rainfall at the control site contained less than 3 and 8 kg/ha of these two ions. Additional small amounts of other constituents may have originated from the stacks of the two sulfur plants.

FOLIAGE

Sulfur and Al ionic contents in both needle and twig tissues from SO₂-impinged areas were substantially higher than in similar tissues from the control area (Table 2). However, levels of Ca, Mg, and P in the SO₂-exposed tissues were lower than those in tissues from the control sites. Tissues from both control and SO₂-impinged areas showed neither a consistent trend or large variation in the content of Fe, K, Na, and N present.

Mudd (1975) reported that atmospheric SO₂ may enter the plant system through the leaves, with the accumulation of SO₄-S as the major product. It may also enter the plant system by root absorption from the soil. Since S contents of rainfall and soils are greater in the SO₂-impinged zones, both mechanisms likely contribute to the elevated S contents of these needle and twig tissues. Higher twig S values may arise from the greater leaching loss from foliar than from more woody and bark tissues (Curlin 1968).

Ingestad (1960) suggested that foliar S at 400 ppm is deficient for pine seedlings. Consequently, lodgepole pine throughout the entire study area may be growing with only marginal levels of available S. If this is the case, then atmospheric SO₂ may be beneficial if levels can be controlled below those that cause damage.

Increased Al levels in contaminated tissues were also evident (Table 2). No recent information regarding the nutritional role has been

* Baker, J. 1976. File Report 162, Northern Forest Research Centre, Edmonton, Alberta.

Table 2. Average ionic contents (ppm) of actively growing lodgepole pine needle and twig tissues from sites surrounding two sulfur gas extraction plants. Approximate age of stands was 40 to 60 yr

Site	Tissue	Fe	Al	Mg	Ca	K	Na	S	P	% N
Control Sites (Far West)										
(Average for Control Sites)	needle	78.2	260.0	1354.0	2083.0	4582.0	33.4	364.0	1227.8	1.1
	twig	121.8	235.0	1686.0	1900.0	4446.0	33.6	450.4	1065.0	0.6
SO ₂ -impinged Sites										
(N-E of both Plants)	needle	81.3	540.7	1276.7	1825.8	4630.0	31.0	372.3	1159.8	1.1
	twig	135.5	412.5	1615.8	1833.3	4647.5	47.3	552.5	836.2	0.6
(Between both Plants)	needle	55.3	499.2	1075.8	1545.8	4435.0	34.0	454.7	1112.3	1.0
	twig	101.0	403.3	1580.8	1775.8	4570.8	45.2	517.3	733.0	0.5
(W & S of both Plants)	needle	67.4	430.0	1192.0	1982.0	4291.0	42.2	515.2	993.6	1.0
	twig	144.2	362.0	1670.0	1770.0	4273.0	51.6	554.0	839.0	0.5
(Average for Impinged Sites)	needle	68.0	490.0	1181.5	1784.6	4452.0	35.7	447.4	1088.6	1.0
	twig	126.9	392.6	1622.2	1793.0	4497.1	48.0	541.3	802.7	0.5

given for Al (Meyer *et al.* 1960). However, it is usually present in plant tissues in fairly large amounts, particularly in conifers. Raupach (1975) reported Al levels for coniferous needle tissues from 100 to 1200 ppm. The higher exchangeable Al values noted for SO₂-exposed soils (Table 4) probably contributed to the higher Al levels in SO₂-exposed tissues. Increased soluble Al usually is accompanied by increased soil acidity. This is confirmed by the slightly lower pH values for the SO₂-exposed soils (Table 3 and 4). While it appears that Al may not have a primary function in plant nutrition, Russell (1961) reported that excess soluble Al, particularly in acid soils, can and often does interfere with normal nutrition of plants, particularly by its reaction with P on root surfaces.

There was no consistent trend in Fe levels in tissues from both control and SO₂-exposed sites relative to the source of the materials. Iron contents in twigs exceeded those of needle tissues; this may be a function of the fact that this nutrient is among the least mobile, with little or no transfer between tissues (Meyer *et al.* 1960). Since Fe levels, especially in needle tissues, are sometimes controlled by Ca/K of the tissue (Russell 1961), soil Ca/K ratios probably contribute to the uptake and level of Fe in foliage. In any event, the levels present were well within those (30-324 ppm) suggested by Raupach (1975).

Nitrogen levels of both tissues from the two sources were virtually similar. The slight reduction noted in both needle and twig levels in tissues from the SO₂-exposed sites probably is not significant. However, it is not without interest that the lower average values were from the SO₂-exposed materials. However, values here compared closely with those of Beaton *et al.* (1965).

Sodium levels were extremely low compared to other nutrients and thus should be considered as a trace element. Nicholas (1975) reported that Na was essential in some crops alone and in conjunction with K, but whether it is essential in conifers is unknown. Average levels were only slightly higher in tissues from the SO₂-impinged sites. This may have resulted from the slightly higher soluble Na levels in the soil of exposed sites (Table 3).

Table 3. Water-extractable ions (average values) from soil samples of control and SO₂-impinged sites

Site	Sample Material	Ca	Ma	Fe	Al	Na	K	Cation Sum	P	S	pH 0.01 m CaCl ₂
		----- mg/kg -----						-----			
Control	Litter	731.0	132.0	10.4	19.7	21.5	358.5	1273.1	47.1	42.6	4.7
	5-15 cm	4.2	0.9	0.9	2.7	2.7	1.5	12.9	nil	1.2	4.9
	15-30 cm	2.6	0.7	3.4	7.0	2.9	1.4	18.0	nil	2.3	5.0
	Ave. to sampling depth	245.9	44.5	4.9	9.8	8.4	120.5	434.7	15.7	15.4	
	% of Total	56.7	10.2	1.1	2.3	1.9	27.8	100.0			
SO ₂ -exposed	Litter	60.3	25.7	4.2	10.3	22.2	96.4	219.1	18.3	37.1	3.8
	5-15 cm	1.1	1.0	0.1	0.3	5.1	1.9	9.5	nil	5.2	4.0
	15-30 cm	0.6	0.4	nil	0.1	3.4	0.6	5.1	nil	2.3	4.2
	Ave. to sampling depth	20.7	9.0	1.4	3.6	10.2	33.0	77.9	6.1	14.7	
	% of Total	26.5	11.6	1.8	4.6	13.1	42.4	100.0			

Table 4. Normal NH_4Cl -extractable ions (average values) from soil samples of control and SO_2 -impinged sites

Site	Sample Material	Ca	Mg	Fe	Al mg/kg	Na	K	Cation Sum	Exchange Acidity meq/100 g	pH 0.01 m CaCl_2	P	S
Control	Litter	9,766.4	1,184.9	11.0	26.3	26.9	1,028.9	12,044.4	0.4	4.7	47.5	3.9
	5-15 cm	2,180.8	272.3	1.2	49.6	22.1	200.3	2,726.3	0.5	4.9	nil	0.4
	15-30 cm	1,899.9	282.9	2.2	23.5	21.5	178.8	2,408.8	0.2	5.0	nil	0.4
	Ave. to sampling depth	4,615.7	580.0	4.8	33.1	23.5	496.3	5,723.8	0.4		15.8	1.6
	% of Total	80.6	10.1	0.1	0.6	0.4	8.2	100.0				
SO_2 -exposed	Litter	7,961.9	577.6	6.5	40.8	13.8	900.5	9,501.1	0.6	3.8	17.4	21.6
	5-15 cm	1,077.5	121.7	2.5	217.1	5.0	198.7	1,622.5	2.3	4.0	0.6	14.4
	15-30 cm	1,332.2	171.9	1.5	113.7	9.0	112.9	1,741.2	1.2	4.2	0.2	5.6
	Ave. to sampling depth	3,457.2	290.4	3.5	123.9	9.3	404.0	4,288.3	1.4		6.1	13.9
	% of Total	80.6	6.8	0.1	2.9	0.2	9.4	100.0				

Potassium concentrations (Table 2) showed little difference in both needle and twig levels in tissues from the two sample sources. Both tissues exhibit similar levels, which possibly is due to the high mobility of this ion. Concentrations of this nutrient appear adequate to meet growth demands, but since K is taken up by plants to a greater extent than others (Baker and Chesnin 1975), available soil levels also will have to remain high. Data (Tables 3 and 4) showed lower average levels of soluble and exchangeable K in soils from the SO₂-exposed areas. If these lower levels continued over a period of time, deficiencies in foliage could quite possibly appear.

Tissue levels (needle and twig) of Ca, Mg, and P were consistently lower in samples taken from within the SO₂-impinged sites. Possibly this is directly related to the available soil levels, particularly in the case of Ca and Mg.

Calcium and Mg make up a large proportion of the soil bases, and these elements are required in fairly large amounts (Baker and Chesnin 1975). These cations are also subject to removal, especially in acid soils. Likens (1976) reported that the impoverishment of soil bases due to increased soil acidities was likely to limit growth. Average soil pH values and Ca and Mg levels were lower in the soils exposed to SO₂ (Tables 3 and 4).

Both needle and twig levels of P appear to be adequate for growth at present (Beaton *et al.* 1965). However, the much lower P concentrations in both tissues in samples from exposed sites could become a problem if they continued for an extended period. Decreased soil pH values and increased available soil Al in SO₂-exposed soils (Table 4) may be responsible for lower P values. Russell (1961) reported phosphorus impoverishment in plants even where there was an adequate supply in the soil. He suggested that Al interfered with the translocation of phosphorus from roots to aerial parts of the plant by the formation of insoluble Al(OH)PO₄ on the root surfaces.

SOIL

Results (Tables 3 and 4) showed that most of the constituents removed to sampling depth (30 cm) were from the L-F-H horizon. The one

notable exception was exchangeable Al (Table 4). Both water- and N NH_4Cl -extractable cations generally exhibited the same trends, especially with reference to the major cationic nutrients Ca, Mg, and K (Tables 3 and 4). Lower amounts of these ions were found in samples from the exposed sites. NH_4Cl -extractable Al and exchangeable acidity also were greater in SO_2 -exposed samples (Table 4). Since the soils, with one exception, were of a sandy loam texture, these results suggest the possibility that atmospheric SO_2 (acid precipitation) may be impoverishing the soils of bases but at the same time increasing the available soil Al and exchangeable acidity (Table 4).

Tables 3 and 4 provide information on levels of individual cations for each of the three soil layers examined. Cation average values to sampling depth were also provided so that relative percentages of each major cation could be determined and that differences in ionic composition of soils from the two general sampling areas could be more readily observed.

Of the water-soluble cations, only Ca in the SO_2 -impinged samples showed a lower relative percentage compared to the values for the control samples. All other cations exhibited higher percentage values than the control. Although Fe and Al showed relatively larger percentage values in the SO_2 -exposed samples, these probably are not too significant since the magnitudes of these ions in exposed samples also are very small. However, Mg and K, whose magnitudes are greater, exhibited relative enrichment. Magnesium formed 11.6% of the total cations for the three layers in the exposed soils, or 1.4% over that in the control. Potassium composed 42.4% of the total cations in the exposed samples, which is 14.6% more than found in the control. Consequently, the composition of the soil solution was different in the two general sample sources. While Ca and Mg formed 67% of the soil solution in the control samples, in the exposed samples they constituted only 38%. On the other hand, K and Na, which made up about 30% of the cations in the solution of the control samples, formed about 55% of the total cations in the exposed soils. This difference in the cation composition of the

soil solution in samples from the two general sources probably played a role in the differential ion uptake pattern by the stand. The depressed uptake of Ca and Mg in the zones of SO₂ exposure noted earlier may in part be due to the well-known ion-antagonism among Ca, Mg, and K (Russell 1961).

Exchangeable cations (Table 4), especially Ca, Mg, and K, are more abundant in the soils than soluble constituents, but magnitudes found in the samples from the SO₂-contaminated areas were lower than those in soils of the control zone. An exception was exchangeable Al. Here again there was a difference in the relative percentage composition of the exchange complex of the samples from the two general sources. Calcium, which exhibited a substantial relative percentage difference in the water-soluble fraction in samples from both areas, showed no relative percentage change (Table 4). Magnesium, on the other hand, showed a lower relative percentage in the samples from the SO₂-contaminated sources (Table 4). Exchangeable K showed a slightly higher relative percentage in the samples from the SO₂-impinged areas. Exchangeable Al values, although small compared to Ca, Mg, and K in samples from the SO₂-exposed sources, showed a 2.3% relative percentage increase over that in the control samples. Thus, the relative percentage composition of the exchange complex was also different in samples from the two areas, although not as marked as that in the soluble cations. Again the samples from the SO₂-contaminated area showed a small relative percentage enrichment in alkali (K and Na) nutrients but a slightly lower alkaline earth (Ca and Mg) nutrient relative percentage content.

If SO₂ impingement was responsible for these differences, it is simple to explain the lower absolute and relative percentages of Ca and Mg but rather more difficult to account for the relative percentage enrichment of K. If the natural equilibrium in a soil is disturbed by some external pressure, such as acid precipitation, $\text{SO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{SO}_3$, the predominant ions of the exchange complex, usually Ca and Mg in north temperate soils, undergo the greatest displacement (Lyon *et al.* 1952). The fact that these two ions in both vegetation and soil samples from

the SO₂-exposed areas showed lower levels suggests that they may have been removed beyond the main rooting zone (30 cm). Potassium compounds are very soluble (Sisler *et al.* 1967) and readily displaced from the exchange complex also (Lyon *et al.* 1952); thus it was expected that K in SO₂-exposed soils would show the same pattern as Ca and Mg. However, this ion was enriched in samples from the exposed sources (Tables 3 and 4).

The fact that K is taken up by plants in greatest quantities (Baker and Chesnin 1975) may help to explain the apparent concentrating of K. Foliar and twig data (Table 2) showed that K magnitudes were greatly in excess of other cations. Potassium uptake by vegetation and its return to the forest floor by litter fall and mineralization during decomposition (nutrient cycling) possibly have kept this cation more concentrated in the surface soil than normally expected. In addition, luvisolic soils (gray wooded) are usually well supplied with degraded micas*, which are a good source of available K. This fact may also help to explain these high K values.

The suspension activity values for K in both control and exposed soil samples exceeded those suggested by Baker and Chesnin (1975). The contaminated samples, however, showed higher values than the control. The rather high K contents of these soils quite possibly could hinder the uptake of soil Ca and Mg so that even though the levels of Ca and Mg compare favorably with those suggested by Baker and Chesnin (1975), they may be only minimal so far as uptake is concerned.

Enrichment of an element (Smith 1976; Safaya 1976), whatever the cause, stimulates growth temporarily but at the same time places a greater demand on other nutrient elements whose levels remain fixed or become depleted. As a result, nutrient imbalance with accompanying deficiency or toxicity symptoms may develop. Accordingly, then, differences in the soil solution and exchange complex compositions observed in the soils from the two main sample sources may have played a role in determining the levels of nutrients in foliar and twig tissues.

Water-soluble sulfur showed little variation between samples from control or SO₂-impinged areas. While the sulfur in the litter of

* Personal communication, Hugh Gardiner, Soil Scientist formerly with the Soils Department, University of British Columbia, now with Oregon State University.

the exposed samples was somewhat lower than that from the control, the total amount extracted from the three layers was essentially the same for both areas. However, N NH_4Cl extracted considerably more sulfur from the three layers of SO_2 -impinged samples (Tables 3 and 4). Perhaps the more acid environment of the SO_2 -exposed samples rendered the soil sulfur compounds and minerals more susceptible to solution and removal by NH_4Cl . The lower soil pH values of the SO_2 -exposed soils (Table 4) probably increased the possibility of anion exchange of sulfate by chloride, which also may help to explain the higher S contents of the exposed samples. The higher level of S noted in the SO_2 -exposed samples could not have arisen as a result of microbiological activity, because Danforth (1976)* was unable to detect any evidence of oxidation of SO_2 or bisulfite by soil organisms. The presence of $\text{SO}_4\text{-S}$ in these soils probably was the result of photo-oxidation of SO_2 in the atmosphere (Fennelly 1976) and/or the oxidation of HSO_3^- in the soil.

Water-extractable P was found only in the litter samples of both exposed and control soils; mineral samples were devoid of water-extractable P. Twice the amount of P was removed from the litter material of the control than from the exposed source (Table 3). This suggests that some P in the SO_2 -contaminated soils may have been moved beyond the depth of sampling (30 cm). This postulation seems confirmed by the fact that small amounts of P were found in the underlying mineral layers (Table 4). Phosphorus is not usually considered a mobile ion in soils; however, since Alexander (1967) found that several forms of inorganic P in forest soils were readily available, these may be much more mobile than normally expected. The fact that P uptake by lodgepole pine was less under SO_2 -exposed than under control conditions suggests that lower pH values of SO_2 -exposed samples may have rendered soil P more soluble and thus more susceptible to movement within the solum.

* Danforth, J. 1976. Microbiological investigations of soils in selected areas west of Rocky Mountain House. File Report, Northern Forest Research Centre, Edmonton, Alberta.

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