BIOMONITORING IN THE ATHABASCA OIL SANDS AREA OF ALBERTA: PROGRESS AND PITFALLS

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ABSTRACT

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1. INTRODUCTION

Biomonitoring is a technique whereby biological samples are used both as indicators of pollution impingement and as a measure of air pollution impact. Obviously, the state of health of any organisms is the best measure of air pollution impact on that species. Biomonitoring also may utilize specific processes or formations of the ecosystem. As with an organism, a process such as decomposition of a plant community response may be the most effective way to assess pollutant impact to these ecosystem components.

Several plant groups, particularly mosses and lichens, have been shown to be sensitive to as well as very efficient in taking up and storing pollutants (Clough 1974; Richardson and Nieboer 1981). If the ecosystem in an area can provide a reliable and consistent measure of both impingement and impact of a specific pollutant or pollutant mixture, and if this is the objective, the expense of establishing and maintaining high technology monitoring instrumentation can be eliminated. This does not mean that air quality measurements will be out of date, quite the opposite. These types of measurements along with deposition studies will still be essential for pollution regulation and testing the reliability of biomonitoring techniques.

Several studies have attempted to use components of the terrestrial ecosystem as indicators of pollution deposition and impact in the Athabasca Oil Sands area. These studies have included the examination of particular groups of organisms such as insects (Hilchie and Ryan 1980) or lichens (Douglas and Skorepa 1976; Addison and Puckett

1980) as well as soils (Takyi and Nyborg 1977; Baker 1980) and vegetation (Addison 1980a; 1980b). The Athabasca Oil Sands area is northeastern Alberta is of particular interest in biomonitoring technique development owing to both the potential for long-range transport of air pollutants to the Province of Saskatchewan and the large amount of information on air quality and pollution deposition that has been generated by the Alberta Oil Sands Environmental Research Program.

This report describes biomonitoring techniques using soils and vegetation in the Athabasca Oil Sands area from 1975 to 1981. It is hoped that the information describing responses to air pollution in the vicinity of Suncor Inc., will serve as an indication of soil and plant monitors that have, and have not proved successful. This is important, particularly at this time when the Research Management Division of Alberta Environment is embarking on a biomonitoring research program. It is expected that with the history of biomonitoring in the area, the program concentrating on technique development may produce an effective biomonitoring system that can be used throughout much of this province and elsewhere.

1.1 STUDY AREA

All work was carried out in the study area as defined by the Alberta Oil Sands Environmental Research Program (Figure 1). The sites selected for detailed examination and manipulation were as close as possible to Suncor Inc., with a reference site at Fort MacKay, about 25 km north of the source (Figure 2). Sites included the five gradient sites (A to E), Fina Airstrip (F), Steepbank (G), Suncor Clearcut (H), Syncrude Turnoff (I), Mildred Lake Research Facility (J) and Fort MacKay (K). A substantial amount of time was spent in an attempt to select sites that were as similar as possible. Stand densities, types, and physical characteristics of soils as well as the composition of the vegetative components of these sites showed minor variation. It was imperative, however, to assume that the sites

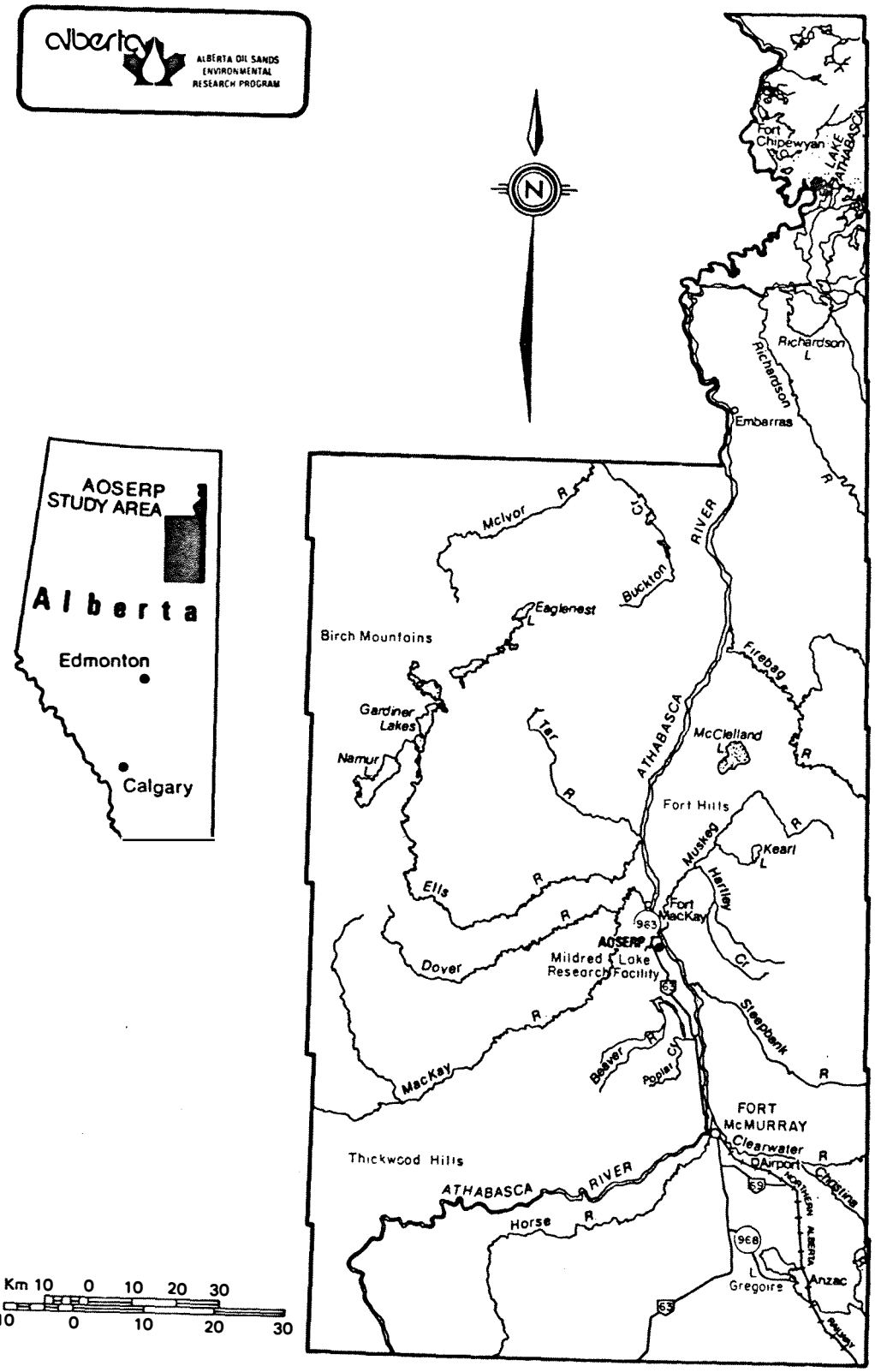

Figure 1. Location of the Alberta Oil Sands Environmental Research Program study area.

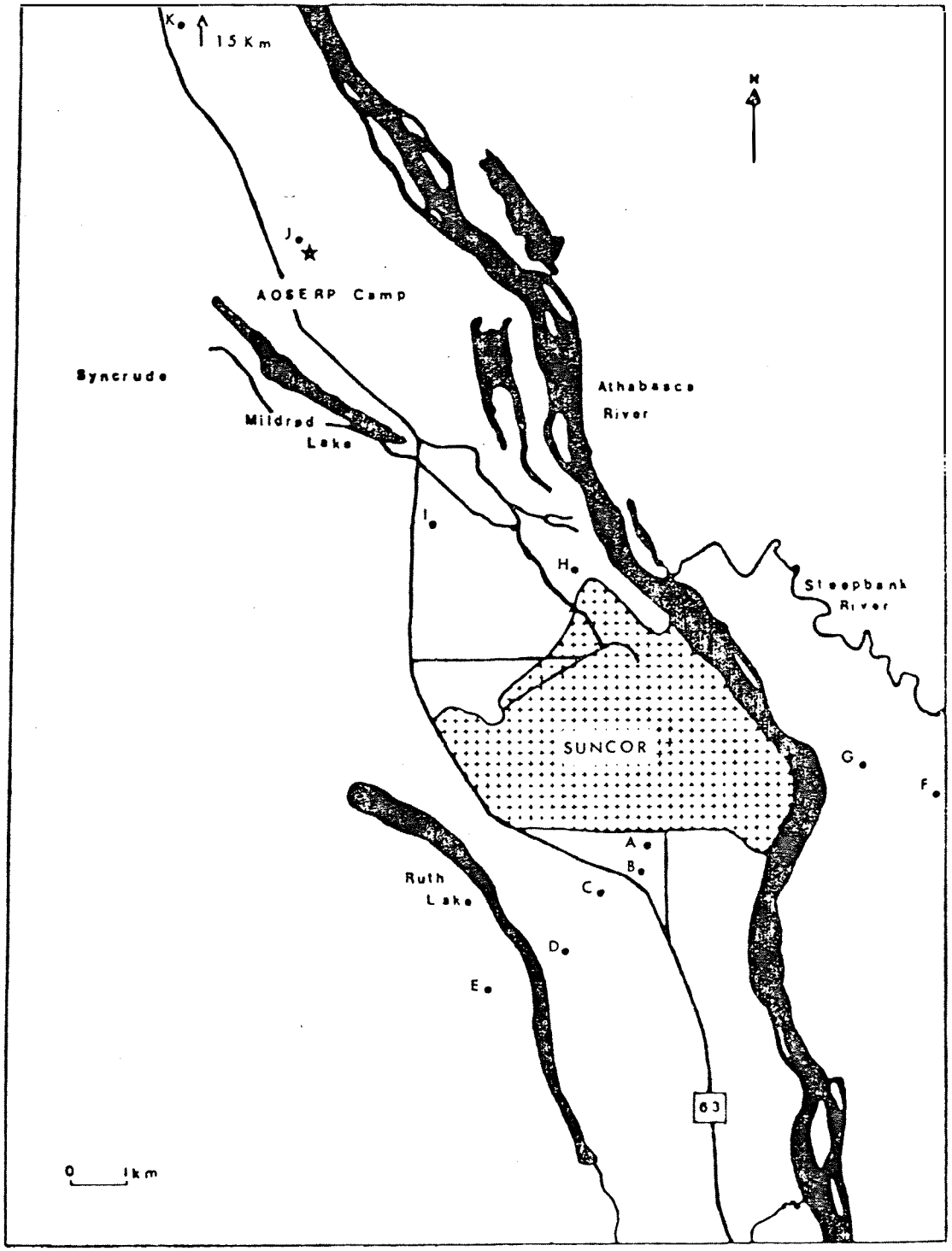

Figure 2. Location of gradient sites and other specific sites used to test biomonitoring techniques.

were different and to quantify the differences that did exist. This was done to avoid the pitfall of making the unjustified and the theoretically unsound assumption that any two forest stands were identical.

2. METHODS AND MATERIALS

2.1 MEASUREMENT OF DEPOSITION

2.1.1 Physical Collectors

2.1.1.1 Precipitation. Three methods were used to monitor deposition of pollutants by both dry-fall and precipitation at sites A to E. In 1977, six cylindrical collectors (20 cm in diameter x 50 cm long) were placed in natural clearings at each site. Mineral oil was placed in each collector to prevent evaporation of the collected precipitation and the trapped material was collected monthly. In 1978, triplicate collectors were placed at the top of the canopy. In this case, a funnel was used to channel precipitation and particulates to a fibre-glass filter and then through a column of two ion exchange resins (one for cations and one for anions). The liquid was then trapped in a reservoir and the entire collector was retrieved after four months. In 1979, the same collector and locations used in 1978 were established with the exception that both the filter and the two exchange resins were eliminated. Samples were collected after four months and concentrated before analysis.

2.1.1.2 Sulphation. Huey plates, 10 cm in diameter, were placed, in duplicate, in three microenvironments (in the open, under jack pine and under white spruce) at sites A to E in the summer of 1977 and at sites A to G (excluding B), J and K from May 1978 to September 1979. Plates were mounted upside down to shield the reactive lead dioxide surface from precipitation. Plates were replaced and analyzed approximately monthly in the summer and every second month in winter.

Sulphation plates at a site close to Suncor Inc. (A) were placed in three different forest stands (jack pine, aspen, and black

spruce). Duplicate plates were situated 3 m above the canopy, at the top of the canopy and at various heights (10, 5, 1.5, and 0.7 m). Plates were replaced on a 1 to 2 month interval.

2.1.2 Native Plants

Six species or species groups were sampled at sites A to E and analyzed for S, Al, Fe, P, and K. The species included jack pine (*Pinus banksiana* Lamb.), white spruce (*Picea glauca* (Moench) Voss), common labrador tea (*Ledum groenlandicum* Oeder), common bearberry (*Arctostaphylos uva-ursi* (L.) Spreng.), ground lichens (mainly *Pleurozium schreberi* (Brid.) Mitt.). These six species were selected because they demonstrated the greatest uptake of S close to the pollution source of the 15 species analyzed in 1976 (Addison, unpublished). These species also represented both dry and moist microenvironments. Five replicates were collected for each species. Pine and spruce samples consisted of 1-yr old material collected 7 to 10 m above ground, whereas other samples were of indeterminant age. Duplicate plant samples were passed through a 20 mesh screen and mineralized using an oxygen flask combustion technique (Chan 1975). Element analysis was carried out as described below.

2.1.3 Soils

Duplicate soil samples were collected from each horizon of the profile at each site. The soils were oven dried (105°C for 24 h) and digested using an aluminum block digester (Technicon Inc.) and teflon beakers. Samples (0.5 g) were predigested in 10 mL of 16N HNO_3 and 2 mL of 10N $HClO_4$ for 1.5 h at 70°C. Silica was then driven off with 20 mL of 29N HF at 150°C. The sample was taken to near dryness, dissolved into 1 mL of 12N HCl and brought to 50 mL with glass distilled water. Digests were analyzed for Al, Fe, and K with an atomic absorption spectrophotometer (Instrumentation Laboratories #251), P with an autoanalyzer, and S using a modified Johnson-Nishita method (Carson et al. 1972).

2.2 MEASUREMENT OF RESPONSE

2.2.1 Growth and Reproduction of Jack Pine

2.2.1.1 Basal Area. Radial increment growth of jack pine was determined at five sites (A, G, H, J, and K; Figure 2) by taking two cores from the south and west sides of trees (5 to 10) at each site. The increment for each of the previous 20 years was measured with an Addo-X Tree Ring Measuring Instrument, and the data from the two cores were averaged. Age (taken at 30 cm above the ground) of the trees sampled was also determined. Only cores that went through the centre of the tree were retained.

2.2.1.2 Shoot Length and Leaf Number. At a site close to the pollution source (Site A) and at Site J, about 10 km distant, five branches from the top one-third of each of five trees were collected. The length (distance between bud scale scars in mm) and the number of needles were determined for each of five age classes on each branch.

2.2.1.3 Seed Germination. The effect of air pollutants on jack pine seed viability was determined by collecting and testing seeds from mature (i.e., 35 year old) trees at sites A to E. Seed germination tests were carried out in the laboratory by placing 3 to 5 replicates of 50 seeds on moist filter paper at 20°C (day) and 16°C (night) fluctuating temperatures in the light. Germination was recorded after three weeks.

2.2.1.4 Biochemistry and Physiology. On several occasions during the summer of 1977, triplicate samples of both jack pine and white spruce branches were collected at sites A, C, and E and brought to the laboratory for biochemical and physiological investigation. The tissue

was examined for phosphatase and malate dehydrogenase activities, chlorophyll/phaeophytin ratio, total sulphur content, net photosynthesis, and dark respiration. Methods followed were those of Malhotra and Khan (1979).

2.2.2 Plant Community

At each gradient site (A to E) in 1977, a 20 x 20 m plot was established and stand density and age as well as the cover and frequency of the lower stratum vascular plant species were determined. The lower stratum was quantified using 20 1 x 1 m quadrats that were randomly selected from a 20 x 20 matrix of the plot. The sample area represented 5% of the total and quadrat size was greater than the minimum sampling area required as defined by Cain and deCastro (1959). All quadrats were mapped so that future measurements of the site would be as close as possible to the first.

In 1979, these sites were re-examined and the cover of each species in the same quadrats was again estimated. Sites were subsequently compared with themselves and the change over time recorded.

2.2.3 Studies of Naturally Occurring Lichen

2.2.3.1 Condition and Element Content. Samples of *Evernia mesomorpha* and *Hypogymnia physodes* were collected from 69 locations in the vicinity of Suncor Inc. operations (Addison and Puckett 1980). These two species were selected because they were the most common corticolous lichens in the area and represented foliose and fruticose growth forms. Samples of both species were collected from the bark of *Picea mariana* (Mill.) BSP. For each site, only material in the best physical collection was collected. A qualitative estimate of thallus condition on a scale of 1 (least) to 5 (most luxuriant) was made on the samples of *E. mesomorpha* collected for analysis. No such estimate was attempted for *H. physodes* since changes in this lichen morphology and colouration were too subtle

to quantify. Tissue samples were oven dried at 80°C to constant weight (24 h). No attempt was made to remove surface deposits on the lichens, but all remnants of the substrate were removed.

All lichen material was frozen in liquid nitrogen and ground to pass through a 60-mesh sieve. Approximately 0.1 g of material was mineralized using oxygen flask combustion and S was determined as above. Potassium was determined on the same samples by atomic absorption. Aluminum, titanium, and vanadium contents were determined on ground, non-ashed samples by instrumental neutron activation analysis.

2.2.3.2 Biochemical Condition. Samples of *E. mesomorpha* were collected in September from sites A, C, E, J, and K (Figure 2). Samples were almost dry at the time of collection in the field. They were brought to the laboratory and kept at -15°C in the dark in polyethylene bags until analysis of acid phosphatase, protein biosynthesis, and ^{14}C bicarbonate incorporation.

2.2.4 Studies of Lichen Transplants

2.2.4.1 Community. A branch lichen transplant study was initiated in 1976. Branches of black spruce were collected at Fort MacKay and relocated in five microsites at each of four locations (Sites H to K, Figure 2). Two branches were placed in a clearing and under jack pine, white and black spruce, and aspen at a height of 1.5 m. Quantification of the cover and frequency of the species groups present were accomplished using a 15 x 20 cm gray card and photographs. Each branch was marked and labelled and the lichens moistened slightly so that they were pliable. Spruce branches are oriented mainly on a plane and, hence, there was no difficulty in placing the quadrat below the branch. Lichens normally grow on the top and sides of branches and, hence, the entire stand was included in a photograph taken from directly above the branch.

Analysis of the photographs was done by projecting the transparency onto a 45 x 60 cm rear projection screen. The screen was divided into 100 units and the presence of each lichen species or species group was recorded for each unit. A correlation was made based on the average cover that each species had when it occurred in a unit.

Lichen community transplants were established at sites A to E in 1977 under spruce trees and the transplants (10 at each site) were quantified in the same manner as described. All transplants were re-examined each year between 1976 and 1980.

2.2.4.2 Element Content and Physiology. Pine branches bearing mainly *Evernia mesomorpha* were placed under jack pine trees. Six replicates were used at each site and material was collected from these transplants, brought into the laboratory and analyzed for total sulphur and available and total K^{+} and Mg^{++}. Available K^{+} and Mg^{++} was extracted by 1N HCl during shaking for 1 h. Analyses were done by atomic absorption spectrophotometry.

3. RESULTS AND DISCUSSION

3.1 DEPOSITION

3.1.1 Physical Collectors

3.1.1.1 Precipitation. Not one of the attempts to measure deposition through the collection of precipitation was successful. In 1977, damage to the collectors by bears was so extensive that, on several occasions, it was not possible to find a single collector intact after one month. The few samples that were collected were not analyzed since it would serve little purpose with the amount of missing data.

In 1978, collectors on the top of trees resolved the animal damage problem. In spite of much testing in the laboratory and a demonstrated capability of the exchange resins to trap and hold the elements of interest, it was not possible to rely on the results from this collector. After four months of exposure in the field, the resins showed some breakdown and released some of their trapped elements as well as some resin components.

In 1979, no pattern of pollutant deposition could be detected using samples of precipitation collected at the top of the forest canopy throughout the snow-free period (Addison 1980b). Several sites, however, had high levels of certain elements such as copper and sodium relative to the rest of the sites indicating contamination of the sample during processing. Further work is required on this technique before reliable results can be assured.

3.1.1.2 Sulphation Plates. Sulphation plates demonstrated that both distance and the type of canopy were important in determining the amount of SO_2 present at any location. At all sites, plates located in the open absorbed the greatest amount of SO_2, followed by those located under pine. In most cases, the amount of SO_2 absorbed by the plate under spruce was half to two-thirds that absorbed in the open (Table 1). The effect of canopy was significant ($p < 0.05$) in all months.

Table 1. Sulphur deposition ($mg.m^{-2}.d^{-1}$) in the vicinity of the Suncor Inc. operations in the Athabasca Oil Sands area in 1979.

Site	Distance (km) and Direction from Suncor		Open				Under Pine				Under Spruce			
			May	June	July	Aug	May	June	July	Aug	May	June	July	Aug
A	2.8	SSW	11.1	3.3	5.5	1.0	8.1	4.2	2.2	1.2	7.0	2.3	1.9	0.8
G	3.1	ESE	6.2	6.8	8.1	0.9	4.9	5.4	11.3	0.8	2.2	4.0	4.4	0.7
F	4.0	ESE	1.8	4.2	7.4	0.6	1.2	2.8	12.2	0.8	0.9	1.7	-	0.5
C	4.2	SSW	5.2	4.0	3.5	1.4	7.9	2.7	4.0	0.5	2.8	1.8	2.6	0.4
D	5.3	SSW	3.4	2.0	-	1.0	3.4	2.1	0.9	1.0	2.5	1.5	0.8	0.7
E	8.3	SSW	2.3	1.2	1.1	0.9	3.2	2.7	1.4	0.8	2.9	0.8	1.3	0.8
J	10.5	NW	0.3	1.3	1.5	1.4	0.9	1.4	1.8	1.3	0.7	1.3	0.9	0.9
K	23.7	NNW	0.4	0.3	1.2	1.5	0.5	0.5	0.9	1.0	0.1	0.1	0.7	0.9

Sulphur dioxide concentration appears to be highly dependent upon time of year, presumably as a result of changes in the prevailing wind direction. In general, the sites closest to the source had the greatest deposition at all times of year, and the two most distant sites represented background SO_2 levels for the area as a whole.

Sulphation plates placed at various heights in jack pine, black spruce, and aspen canopies substantiated the statement that the type of canopy is important to SO_2 deposition in forested areas (Figure 3). The open jack pine stand had a SO_2 deposition profile that would be expected in open areas with a sink of SO_2 at the ground surface. It mirrors the expected wind speed profile upon which it is at least partially dependent.

The other two profiles indicated the canopy structure. The black spruce stand became progressively more dense close to the surface whereas the aspen stand had a dense tree stratum separated from the high shrub stratum by about 3 m (3 to 6 m) of only the boles of the trees.

The importance of wind speed cannot be understated since it may be the primary factor causing the measured deposition profiles. Wind profiles are necessary before an assessment of the influence of the various plant species can be made. In spite of this limitation, it is apparent that SO_2 deposition to forested canopies of varying composition cannot be assumed to be the same.

3.1.2 Native Plants and Soils

Chemical analysis of selected plant species at sites A to E showed a substantial increase in S content at sites close to the pollution source (Table 2). Labrador tea and feathermoss had the highest S levels at all sites but the difference in S between sites A and E were similar for all species. Since there were substantial differences in S concentration between species at each site, no direct

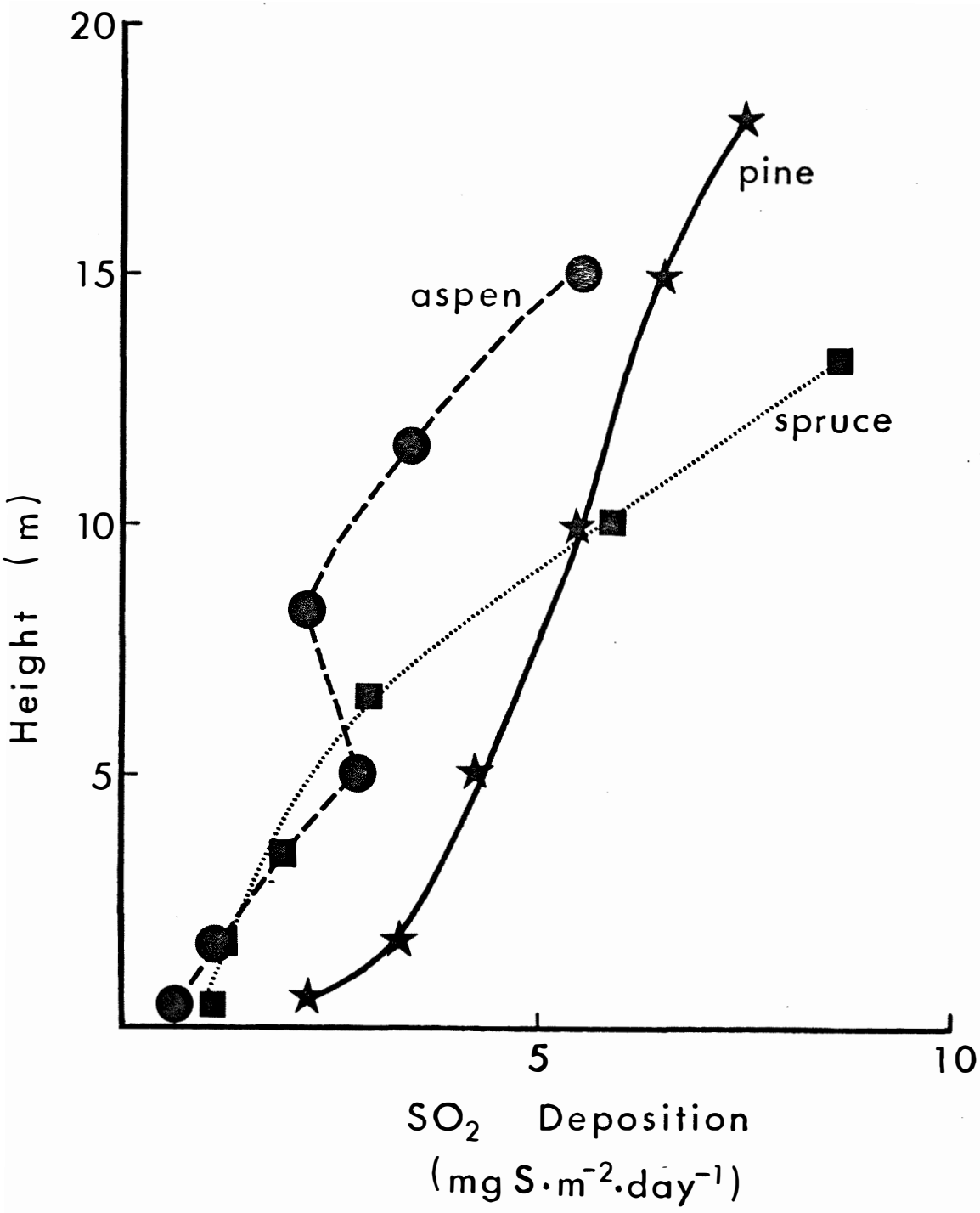

Figure 3. Profiles of SO_2 deposition to sulphation plates in three boreal forest stands in the Athabasca Oil Sands area. Values are averages of four measurements.

Table 2. Selected element content (ppm) of certain plant species at gradient sites in the vicinity of oil sands operations. Mean ± 95% confidence limits. Samples taken in 1977.

Site	Distance from Suncor (km)	Dry Phase			Moist Phase		
		Pinus banksiana	*Arctostaphylos uva-ursi*	Ground Lichens	*Picea glauca*	*Ledum groenlandicum*	Feather-moss
Sulphur							
A	2.8	1002 ± 48	796 ± 71	629 ± 38	918 ± 81	1409 ± 92	1289 ± 49
B	3.4	940 ± 60	601 ± 34	439 ± 51	718 ± 41	1288 ± 64	1434 ± 54
C	4.2	964 ± 28	677 ± 28	545 ± 27	735 ± 37	1146 ± 86	1419 ± 89
D	5.3	828 ± 30	559 ± 23	285 ± 25	691 ± 101	1180 ± 78	1195 ± 230
E	8.3	723 ± 40	423 ± 76	313 ± 74	496 ± 31	1054 ± 98	928 ± 89
Aluminum							
A	2.8	643 ± 60	397 ± 70	738 ± 369	303 ± 195	399 ± 54	2150 ± 1089
B	3.4	480 ± 83	549 ± 62	1051 ± 609	182 ± 46	473 ± 107	4772 ± 2162
C	4.2	626 ± 122	268 ± 54	620 ± 221	97 ± 31	203 ± 49	1294 ± 407
D	5.3	655 ± 100	196 ± 35	386 ± 181	253 ± 92	350 ± 76	2073 ± 262
E	8.3	668 ± 88	261 ± 54	392 ± 120	162 ± 21	276 ± 25	1528 ± 95
Iron							
A	2.8	191 ± 18	215 ± 31	293 ± 127	125 ± 34	248 ± 20	753 ± 373
B	3.4	199 ± 31	207 ± 32	417 ± 142	173 ± 26	475 ± 81	1093 ± 591
C	4.2	156 ± 30	162 ± 19	243 ± 73	102 ± 15	150 ± 24	715 ± 215
D	5.3	120 ± 25	190 ± 27	168 ± 61	300 ± 169	412 ± 78	2341 ± 338
E	8.3	331 ± 69	254 ± 49	241 ± 125	215 ± 31	338 ± 51	2165 ± 145
Phosphorus							
A	2.8	966 ± 129	1169 ± 145	382 ± 118	922 ± 90	1216 ± 94	494 ± 155
B	3.4	814 ± 105	848 ± 118	273 ± 86	1058 ± 102	1022 ± 79	754 ± 274
C	4.2	789 ± 80	960 ± 91	164 ± 41	919 ± 49	976 ± 125	620 ± 160
D	5.3	765 ± 48	821 ± 66	221 ± 41	763 ± 72	1061 ± 45	1060 ± 192
E	8.3	892 ± 19	958 ± 58	151 ± 30	1139 ± 80	1136 ± 113	1091 ± 56
Potassium							
A	2.8	3322 ± 432	4633 ± 231	489 ± 112	4199 ± 560	4063 ± 156	2093 ± 776
B	3.4	3186 ± 408	3616 ± 332	546 ± 227	3785 ± 430	3502 ± 236	3408 ± 1229
C	4.2	3556 ± 306	4691 ± 608	444 ± 122	3782 ± 228	4125 ± 509	2488 ± 714
D	5.3	3020 ± 429	4904 ± 77	398 ± 90	3011 ± 382	3988 ± 473	4111 ± 1228
E	8.3	3631 ± 289	4756 ± 359	321 ± 71	5115 ± 404	3439 ± 414	5675 ± 519

comparison could be made. Regressions were constructed for the S concentration of each species versus distance from Suncor Inc. and the Y intercept in each case was considered as maximum S content (100%). Regression coefficients were determined for relative S contents and this gave a measure of the decrease in S content with increasing distance.

Similar values were calculated for sulphation plates and for arboreal lichen S content (Table 3; Addison and Baker 1979).

Higher S levels close to the pollutant source did not appear to be related to soil S content and there was little difference among sites in the rhizophere (Ah, Ae, and Bm horizons; Table 4). The LFH horizon did show a distinct gradient in S either as a result of direct long-term deposition or because of addition by leaf-fall, or both.

Understory plant species in dry locations had a much greater increase in S with decreasing distance from the processing plant than did those related to the difference in stand density and the lushness of the lower stratum of the community. The dry sites were far more open than the moist ones and, hence, the pollutant could enter the stand and fumigate the ground vegetation much more readily. White spruce from moist sites on the other hand, had a greater rate of increase in S content than jack pine. In this case, both samples were collected well up the tree where SO_2 could easily impinge on the tissue. It is felt that the differences between these two species may be related to the resistance to entry of the gas imposed by the stomata.

3.2 MEASUREMENT OF RESPONSE

3.2.1 Growth and Reproduction of Jack Pine

3.2.1.1 Basal Area. There did not appear to be a relationship between the cross-sectional area increment and distance from the pollutant source (Table 5; Addison 1980b). There was actually greater growth in the last 10 years relative to the previous 10 years close to Suncor Inc. than at 10 km distance. Even though this form of self-standardization (comparing each tree's increment with itself before industrialization) can eliminate much of the site-induced variability, it appears that growth changes still need to be very large before they can be detected with any confidence.

Table 3. Regression coefficients of relative sulphur content versus distance from Suncor Inc. for selected plant species and sulphation plates (1977).

Material	Microsite		Regression Coefficient
	Type	Location	
jack pine	dry	canopy	-4.5
bearberry	dry	ground	-6.5
ground lichens	dry	ground	-7.4
white spruce	moist	canopy	-6.3
labrador tea	moist	ground	-3.7
feathermoss	moist	ground	-5.1
sulphation plates	both	1.5 m	-8.2
arboreal lichens	dry	1.5 m	-9.6

Table Total element content (ppm) of the primary soil horizons at the gradient sites in 1977. Values are averages of 2 to 4 samples.

Site	Distance from Suncor (km)	LFH	A Ah,Ae,Ahe	Bm	C
Sulphur					
A	2.8	634	207	35	87
B	3.4	-	91	15	5
C	4.2	498	35	9	9
D	5.3	128	108	44	33
E	8.3	68	13	25	33
Aluminum					
A	2.8	7300	8849	16364	11863
B	3.4	-	8223	18374	12434
C	4.2	7688	7348	10063	12841
D	5.3	4714	9773	18424	14271
E	8.3	6636	6709	14251	6401
Iron					
A	2.8	3718	3427	12240	7999
B	3.4	-	1875	8673	4157
C	4.2	2977	2530	6478	6422
D	5.3	1605	2473	13186	5686
E	8.3	2865	1983	11893	6326
Phosphorus					
A	2.8	956	246	339	111
B	3.4	-	417	565	297
C	4.2	878	320	623	310
D	5.3	541	102	262	93
E	8.3	1024	179	846	364
Potassium					
A	2.8	2162	4593	5892	5417
B	3.4	-	3571	6580	4703
C	4.2	2196	2661	2823	3932
D	5.3	1575	5337	5896	6387
E	8.3	1912	2627	4272	2996
Calcium					
A	2.8	732	261	147	142
B	3.4	-	216	105	83
C	4.2	543	113	77	103
D	5.3	199	192	124	147
E	8.3	571	80	120	85
Magnesium					
A	2.8	870	521	1024	764
B	3.4	-	414	1131	562
C	4.2	623	330	456	660
D	5.3	219	374	1140	749
E	8.3	800	259	868	467

Table 5. Ratio of wood cross-sectional area growth before versus after start-up of Suncor in the Athabasca Oil Sands area in 1966.

Site	Distance (km) and Direction from Suncor		Ratio of wood area 1968-77 ÷ 1957-67 (mean ± 95% confidence limits)
A	2.8	SSW	2.16 ± 1.26
H	3.0	N	1.15 ± 0.16
G	3.5	ESE	1.02 ± 0.50
F	4.0	ESE	1.62 ± 0.29
J	10.5	NW	1.48 ± 0.29

3.2.1.2 Shoot Length. Over the past 5 years, the jack pine at Site A produced significantly ($p < 0.01$) longer leaders of the lateral branches than did jack pine at Site J (Table 6; Addison 1980b). This observation concurs with the basal area growth measurements that showed over twice the radial growth at Site A ($435\ mm^2 \cdot yr^{-1}$) than at Site J ($215\ mm^2 \cdot yr^{-1}$). The differences seen in Table 6 are presumably a result of substantially better growing conditions at Site A that have not been significantly affected by the presence of air pollutants.

3.2.1.3 Leaf Number. The needle number of the most recent three age classes indicated that jack pine sampled at Site A produced more needles than did those at Site J (Table 6; Addison 1980b). This is consistent with both the leader length and basal area measurements that also showed greater growth at Site A than at Site J. In years 3 and 4, however, there were fewer needles per age class at Site A (Table 7), although the differences were not significant. It is thought that the reduction in needle number in years 3 and 4 may be a result of premature aging and abscission of leaves caused by air pollutants. Because so many natural factors may influence needle retention, no definite conclusion is possible. It should be noted, however, that even if premature needle drop does occur in the vicinity of Suncor, there is no evidence that it detrimentally affects plant growth and survival.

3.2.1.4 Seed Germination. The jack pine seed germination rate appeared to be reduced close to Suncor operations (Table 8; Addison 1980b). Site A had significantly ($p < 0.05$) lower germination rate than Site E, whereas the other sites were intermediate and were not significantly different from either A or E. There was also a significant correlation of seed germination with distance from the source ($p < 0.05$). Seed germination rate did not appear to be related to tree age (Table 8).

Table 6. Leader length of lateral branches of jack pine at Site A and at Mildred camp (J) in the Athabasca Oil Sands area. (mean and 95% confidence limits)

Age Class	Distance between Bud Scale Scars (cm)	
	Site A	Mildred J
Current	21.2 ± 2.2	15.8 ± 1.4[a]
1 year	24.0 ± 2.5	19.3 ± 2.2
2 year	23.4 ± 2.2	17.5 ± 1.9
3 year	27.6 ± 2.5	17.9 ± 1.6
4 year	25.4 ± 2.9	21.2 ± 1.9

[a] There are significant ($p < 0.05$) differences between sites for each age class.

Table 7. Number of needles per age class on the lateral branches of jack pine at Site A and Mildred (J) in the Athabasca Oil Sands area (mean ± 95% confidence limits).

Age Class	Number of needles		
	Site A	Mildred J	Significance
Current	115 ± 10	104 ± 8	NS
1 year	119 ± 11	100 ± 9	0.05
2 year	132 ± 13	93 ± 8	0.001
3 year	58 ± 22	63 ± 13	NS
4 year	14 ± 10	22 ± 10	NS

Table 8. Jack pine seed viability of trees from the gradient sites in the Athabasca Oil Sands area.

Site	Distance (km) from Suncor	Tree Age (y)	Seed Germination (%)
A	2.8	54.6	81.5[a]
B	3.4	33.6	89.4
C	4.2	29.1	90.9
D	5.3	40.0	94.2
E	8.3	42.0	95.8

[a] Lines join means that are not significantly different ($p < 0.05$) in a Student-Newman-Keuls test.

3.2.1.5 Biochemistry and Physiology. No significant differences in any of the metabolic responses measured were observed among the sites sampled. This may be owing to either the low concentrations of SO_2 experienced in these areas or the ability of spruce and pine to recover their metabolic functions between pollutant episodes. The concentrations of S in tissue (Table 2) were in the normal range for these species and it is felt that this, along with the plant's capability to detoxify the toxic species of sulphur (conversion of HSO_3^- and $SO_3^=$ to $SO_4^=$), that is responsible for the lack of response (Malhotra and Khan 1980). It should be pointed out that several of the biochemical and physiological responses measured here have been used to detect air pollution injury to plants near Flin Flon, Manitoba (Malhotra and Khan unpublished). This pollution source has been operating for a considerably longer period of time and releases both greater amounts of SO_2 and more persistent pollutants (heavy metals; particularly zinc) than oil sands operations.

3.2.2 Plant Community

The jack pine stands at the gradient sites (A to E) were selected because of their similarity. In spite of this, in 1977, there was considerable variability in species composition and cover of the lower stratum plants (Table 9), This variability did not appear to be related to either gaseous pollutant deposition (Table 1) or distance from Suncor Inc. The community structure and composition therefore, provided no evidence that the Suncor processing plant was having an effect on jack pine stands in the immediate vicinity of oil sands operations (i.e. < 8.3 km).

Measurements of the same sites in 1979 permitted direct comparison of each site with itself over a two year period. Changes in the stands could not be related to pollutants. It is thought that some of the changes in cover (Sorenson's index) at these sites were as a result of error in the placement of quadrats during repetitive

Table 9. Association table of cover values of the vascular plants in the lower strata of jack pine stands (A to E) in the Athabasca Oil Sands area (July 1977).

Species	Sites				
	E	D	A	C	B
Trees					
Picea glauca	0.03				
Pinus banksiana	0.03		0.03		
Populus tremuloides	1.45	0.35	0.05		
Shrubs					
Alnus crispa		8.50	0.13	8.20	
Amelanchier alnifolia			0.08		0.45
Prunus virginiana			0.05	4.13	
Rosa acicularis			0.08		
Ledum groenlandicum	0.30	2.08			
Vaccinium myrtilloides	6.13	9.78	11.70	7.05	2.55
Ground Shrubs					
Arctostaphylos uva-ursi	0.85	2.05	12.95	14.15	27.40
Vaccinium vitis-idaea var. *minus*	2.93	10.48	1.23	1.98	2.45
Linnaea borealis var. *americana*		0.75	0.50	0.50	0.85
Herbs and Grasses					
Unidentified Grass	0.53	0.50	0.53	0.53	0.60
Lilium philadelphicum var. *andinum*		0.18			
Maianthemum canadense	0.55	0.98	0.95	0.28	0.50
Comandra pallida	0.03	0.05	0.60	0.58	0.50
Geocaulon lividum	0.03				
Potentilla tridentata		0.13	0.28		
Viola nephrophila			0.03		0.05
Epilobium angustifolium	0.03	0.13		0.35	0.33
Aralia nudicaulis				1.28	
Cornus canadensis	0.53	1.80	0.18		
Pyrola secunda					0.05
Apocynum androsaemifolumi				0.03	
Mertensia paniculata				0.03	
Melampyrum lineare	0.23	0.23	0.10	0.18	0.18
Campanula rotundifolia			0.03	0.03	
Solidago decumbens				0.03	0.10
Pteridophyte					
Lycopodium complanatum		0.03		0.98	2.70
Total Cover					
Vascular Plants	13.65	38.02	29.50	40.31	38.71
Lichens	76.90	36.55	50.28	50.63	33.03
Mosses				0.25	0.05
Stand Density (stems/ha)	100	175	150	75	400

sampling. Individual quadrats were mapped but not permanently marked and, hence, errors in repositioning may have been responsible for some of the changes seen in Table 10. In addition, the amount of natural change that goes on at these sites is unknown.

Table 10. Similarity in Sorenson's index between 1977 and 1979 sampling times of jack pine stands A to E .

Site	Distance from Suncor (km)	Percent Similarity
A	2.8	88.4
B	3.4	-
C	4.2	83.6
D	5.3	85.3
E	8.3	84.5

3.2.3 Studies of Naturally Occurring Lichens

3.2.3.1 Condition and Element Content. Detailed results and discussion of the survey of lichens in the vicinity of Suncor Inc. have been reported elsewhere (Addison and Puckett 1980). The conclusions from this study indicated that: (1) the pattern of element deposition measured by lichen thallus concentration appeared to be related to the distribution pattern of elements as measured by physical and chemical methods; (2) the accumulation of elements by *Evernia mesomorpha* and *Hypogymnia physodes* could be related to both gaseous and particulate emissions from industrial sources and to localized windblown dust components; (3) a single collection of lichen material can replace traditional physical monitoring methods in locations where only relative deposition estimates of pollutants are required. The use of lichens in this manner also permits a measure of biological response that can be partially related to the content of specific elements in the thallus.

3.2.3.2 Biochemical Condition. No pattern that could be related to pollutants was observed in any of the metabolic processes examined (Table 11). Only the healthiest material from each site was used in the analyses and, therefore, it appears that the lichens that do exist close to the pollutant source are metabolically active. It is felt that impact to lichens occurs on an event basis when environmental conditions and pollutant levels interact to damage parts of the thallus. This hypothesis would resolve the apparent inconsistency between the metabolic and the field survey and transplant studies.

3.2.4 Studies of Lichen Transplants

3.2.4.1 Community. Lichen community response to air pollutants characteristic of oil sands operations, has been demonstrated by

Table 11. Metabolic activity of *Evernia mesomorpha* from sites in the Athabasca Oil Sands area. Values are means of three replicates ± standard deviation.

Site	Distance from Suncor (km)	Acid Phosphatase units/g dry wt	^{14}C incorporation 10^5 cpm/g dry wt	Protein Biosynthesis 10^5 cmp/g dry wt
A	2.8	1.7 ± 0.2	70.9 ± 2.9	13.3 ± 1.5
C	4.2	3.1 ± 0.2	55.7 ± 4.1	22.9 ± 0.9
E	8.3	1.8 ± 0.3	62.6 ± 6.2	17.3 ± 3.6
J	10.5	–	–	15.0 ± 3.0
K	23.7	–	–	13.9 ± 3.3

Addison (1980b). Response of transplanted lichens in the immediate vicinity of Suncor appeared to be the result of a complex of factors that include several pollutants as well as natural environmental factors. The importance of several factors in lichen response was demonstrated by Addison and Puckett (1980). Since changes in lichen condition of transplants were consistent with changes occurring on non-transplanted branches in areas of low or negligible pollutant deposition, the concern that small changes in microenvironment may dramatically affect lichen community composition and cover on a short-term basis appears unfounded.

3.2.4.2 Element Content and Physiology. Available to total ratios of K and Mg in transplanted *Evernia mesomorpha* appeared to be unrelated to air pollution (Addison 1980b). Variability of all measurements was great and it is clear that, in its present form, the introduction of lichen material for detailed examination of sulphur uptake or changes in physiological condition is inadequate as a biomonitoring tool. The technique, however, may be effective if more meaningful biological measurements are made and greater replication is ensured.

4. BIOMONITORING APPROACH

To date, our approach has been to work with well-defined, permanently marked and well-documented sites. The advantages of this approach are as follows:

1. It permits simultaneous assessment of numerous factors that may respond to pollutants. This results in greater reliability as it substantially reduces the possibility of a chance occurrence being interpreted as a meaningful response.
2. It permits the interpretation of one factor through the use of others. For example, a discussion on the exposure of a target organism in a forest without a measure of stand type and density would be meaningless, as would a discussion of plant pollutant content without soils analyses and physical measurements of pollutant deposition.
3. It reduces the natural variability that has to be dealt with in all ecosystems by allowing measurements of the same site over time.
4. It permits the establishment of a system that takes into consideration different types and rates of response. Biomonitoring, if it is to be used as a method to provide early warning of pollutant injury to the forest, must use a combination of techniques of differing sensitivities with known relationships between them so that both questions, What has happened? and What will happen?, can be answered.
5. It permits comparison of different types of responses and allows testing of the reliability and reproducibility of specific techniques.

The approach, however, is not without disadvantages. Only a small number of sites (< 30) can be handled since the technique is labour intensive. Sites must also be representative of the area. This is a particularly difficult requirement to satisfy in heterogeneous areas. A team approach which is often difficult to maintain is essential owing to the multidisciplinary nature of the work.

In general, this approach when applied to the Athabasca Oil Sands area of Alberta met with mixed success. It was possible to demonstrate that pollutants characteristic of oil sands operations were not distributed evenly. Distinct gradients in soil LFH horizon, native plant element content, and sulphation plates were observed in the vicinity of Suncor Inc. It is expected that precipitation measures would also show the same pattern if it were not for the technical problems encountered.

Demonstration of plant response to the deposited pollutants was much more difficult. Long-term measures such as vascular plant community change, soil nutrient change, and tree growth could not be related to pollutant deposition. Some plant responses such as lichen condition and pollutant content, jack pine seed germination and lichen community change appeared to be influenced by Suncor, but the magnitude of response is not great enough to be of alarm. Physiological responses of vascular plants and lichens that were expected to be very sensitive were far too variable to be useful without further refinement.

Many other biomonitoring techniques in a wide variety of disciplines warrant examination. Support of both government and industry proposed for the next few years shall provide biological tools for the detection of airborne pollutant effects on terrestrial ecosystems.

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