EFFECTS OF OIL SANDS PROCESSING EMISSIONS ON THE BOREAL FOREST

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ABSTRACT

Between 1975 and 1985 a cooperative research program was carried out by the Canadian Forestry Service and Alberta Environment to determine the effects of emissions from oil sands processing on the surrounding boreal forest in the Athabasca Oil Sands area of northeastern Alberta. Fieldwork on vegetation, soil, and atmospheric deposition was performed at several research and biomonitoring sites dominated by jack pine (*Pinus banksiana* Lamb.). Significant uptake of industrial emissions by plants and soils was generally restricted to within 10 km of the major source, although some gradients extended up to 25 km. Lichens and mosses showed the greatest responses; changes in vascular plant communities could not be related to pollutant deposition. Numerous biochemical and physiological parameters were sensitive to SO_2 and other pollutants in the laboratory but showed no significant differences at the field sites. The results suggest that the low level and infrequency of pollutant episodes coupled with the assimilative capacity of the soil and the physiological resiliency of vascular plants have prevented damage to the trees.

RESUME

Entre 1975 et 1985, le Service canadien des forêts et le ministère de l'Environnement de l'Alberta ont collaboré à un programme de recherche visant à déterminer les effets sur la forêt boréale voisine des émissions provenant de l'exploitation des sables pétrolifères dans la zone des gisements de sables bitumineux de l'Athabasca dans le nord-est de l'Alberta. Des études de la végétation, du sol et du dépôt atmosphérique ont été effectuées à plusieurs stations de recherche et de biosurveillance où le pin gris (*Pinus banksiana* Lamb.) dominait. L'absorption significative de polluants industriels par les plantes et les sols était généralement limitée à un rayon de 10 km de la source principale, quoique certains gradients s'étendant jusqu'à une distance de 25 km aient été observés. Ce sont les lichens et les mousses qui ont fait voir les plus fortes réponses. Les modifications des groupements de plantes vasculaires n'ont pu être liées au dépôt de polluants. De nombreux paramètres biochimiques et physiologiques se sont révélés sensibles au SO_2 et à d'autres polluants au laboratoire, mais aucune différence significative n'a été observée sur le terrain. Les résultats obtenus semblent indiquer que la faible intensité et la fréquence peu élevée des épisodes de pollution, combinées à la capacité d'assimilation du sol et à la résistance physiologique des plantes vasculaires, ont empêché que les arbres subissent des dommages.

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NOTE

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

INTRODUCTION

The Canadian Forestry Service (CFS) has had a long-standing interest in industrial emissions and their effects on forest productivity. These effects have been actively investigated by the Northern Forestry Centre in Edmonton, Alberta, since the early 1970s. Initially, assessments were carried out by staff of the Forest Insect and Disease Survey, but as the number of sources and public interest in air pollution increased, specialists in air pollution research were recruited.

The first studies were impact assessments that relied almost exclusively on photographically recording the visible symptoms caused by specific pollutants. Several papers were published on the effects of pollutants, including a Northern Forestry Centre Information Report (Loman et al. 1972) and a more popularized version in a Forestry Report (Hocking et al. 1975). Much of the symptomology work was ultimately synthesized into a manual for the diagnosis of air pollutant and natural stress symptoms on forest vegetation in western Canada (Malhotra and Blauel 1980), so that Forest Rangers and other field personnel would have a tool to work with when dealing with pollution problems in forest systems.

With time, studies became more quantitative as a result of research efforts under two main programs: the Alberta Oil Sands Environmental Research Program (1975–81) and Alberta Environment's Research Management Division Mixed Pollutant Study (1982–85) that followed it.

ALBERTA OIL SANDS ENVIRONMENTAL RESEARCH PROGRAM

In 1974, a study was initiated by the CFS to monitor the impacts of emissions from oil sands operations on the forest system in the Athabasca Oil Sands area of northeastern Alberta. This study was incorporated into the Alberta Oil Sands Environmental Research Program (a joint Alberta-Canada research program), which started in 1975. Even though federal support for the program was withdrawn in 1979, work continued through 1981 because the Government of Alberta provided much of the operating budget.

Two studies evolved, each with specific objectives but so oriented that, when combined, an assessment could be made of the potential for forest impact caused by pollutants. The field study (biomonitoring) concentrated on the development and use of biomonitoring techniques for the detection of air pollutant effects. The laboratory study had two components. The biochemistry and cell physiology component attempted to determine the mode of action of pollutants such as sulfur dioxide (SO_2) in boreal forest plant species, whereas the whole plant physiology component looked at the influence of SO_2 on photosynthesis in a variety of native plant species to compare their sensitivities in air pollution. Despite the apparent compartmentalization of the research, each study relied on the other. The laboratory study relied on the field study in the selection of appropriate plant species and pollutant levels. The field study required the knowledge generated in the two laboratory studies to interpret field observations and to assess the potential for pollutant impact.

Biomonitoring and Physical Measurements

Many studies have examined the impact of air pollution on vegetation or its components such as tree growth or chemical composition. Almost all have dealt with severely degraded areas. In the Athabasca Oil Sands area, there appeared to be very little obvious damage to the forest ecosystem that could be attributed to air pollution (Addison and Baker 1979). The extraction of petroleum deposits has resulted in emissions of SO_2 and other pollutants from two megaplants, Suncor Inc. (formerly Great Canadian Oil Sands Ltd.) and Syncrude Canada Ltd. Suncor has been operating since 1967 and Syncrude since 1981. Since there was considerable potential for pollutant effects, given the emissions of existing oil sands extracting plants and the anticipated increase of these plants in number and in size, it was important to establish a network of sites in order to monitor the forest in the vicinity of both existing and proposed operations. In addition, it was necessary to assess a number of biological variables to determine their utility in biomonitoring.

Biomonitoring is a technique whereby biological variables are used as indicators of pollution impingement (deposition) and as measures of air pollution impact (response). Obviously, the health of any organism is the best measure of air pollution impact on that species. Biomonitoring may also utilize specific processes or formations of the ecosystem.

Several plant groups, particularly mosses and lichens, have been shown to be sensitive to pollutants as well as being very efficient in taking up and storing them (Clough 1974; Richardson and Nieboer 1981). If such ecosystem components can provide reliable and consistent measures of both impingement and impact of a specific pollutant or pollutant mixture in an area, the expense of establishing and maintaining high technology monitoring instrumentation can be eliminated in certain cases. It was the presence of several ongoing studies on pollutant dispersion, distribution, and deposition that made the Athabasca Oil Sands area ideal for evaluating the effectiveness of biomonitoring procedures.

This study was undertaken 1) to establish a network of permanent monitoring sites to evaluate the effects of airborne pollutants on the forest system in the vicinity of oil sands operations and 2) to select and evaluate various measurable biological variables for use in the biomonitoring of air pollution impacts.

Establishment of biomonitoring and technique sites

The approach of the Northern Forestry Centre was to work with well-defined, permanently marked and well-documented sites (Addison 1983). 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, because 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, discussion of the exposure of an organism to pollutants requires a measure of stand type and density, and plant pollutant content requires soil analyses and physical measurements of pollutant deposition before it can be interpreted.

3. It reduces the natural variability that has to be dealt with in all ecosystems by allowing measurements of the same site over time. Even careful selection of sites cannot eliminate the variability that often masks pollutant responses.

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 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 the 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.

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

A set of 13 jack pine biomonitoring sites was established in the Athabasca Oil Sands area in 1976 (Addison 1980a). Specific sites were selected based on the airshed characteristics and topography and were distributed as evenly as possible throughout the area (Fig. 1). These sites were sufficiently scattered to permit long-term biomonitoring of both present and proposed air pollution sources.

A series of techniques was evaluated for incorporation into the biomonitoring system. The techniques represent three types of measurements: physical collectors, soil parameters, and plant responses. A separate set of five technique sites was selected (Fig. 2) in a linear pattern south by southwest of the Suncor operations in 1977. These sites were 2.8 to 8.5 km from the pollutant source, were on level ground, and had similar jack pine communities (Addison 1983). It was anticipated that these sites, because of their proximity to the source, would show effects related to distance from the source (Addison and Baker 1979).

Site description

Description of each biomonitoring site consisted mainly of quantification of the vascular plant community with respect to both vegetational and soil components. Cover, frequency, and stand age of the plant community were measured in 1976, and elemental content of selected species was determined. Soils were classified and analyzed for S, Al, Fe, and several other elements. Lichens and mosses, because of their great sensitivity to air pollutants, were also described in terms of community composition and elemental content. Low-level aerial photography provided a baseline overview of tree crown condition near oil sands operations.

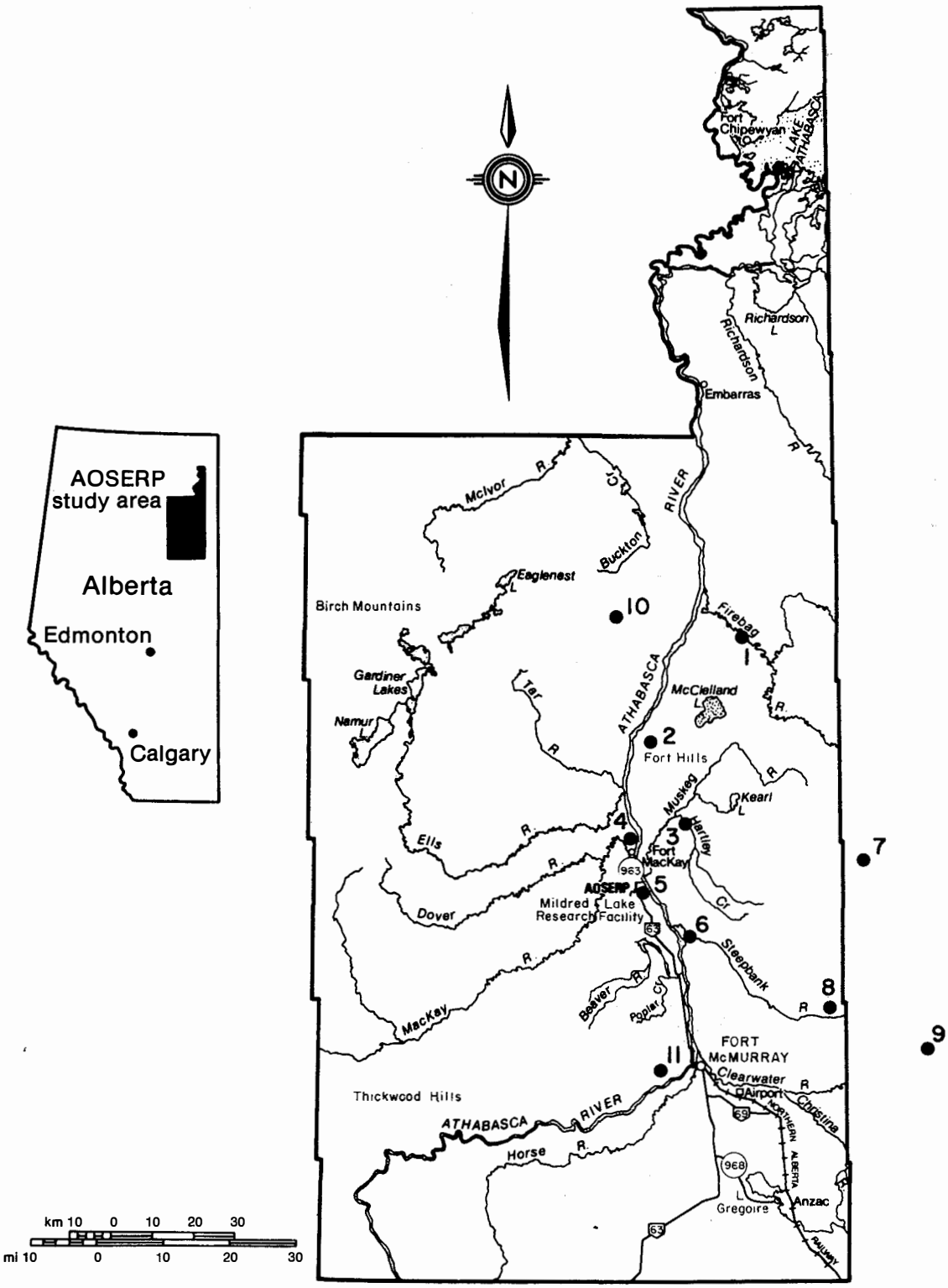

Figure 1. Location of permanent biomonitoring plots in the Athabasca Oil Sands area of northeast Alberta.

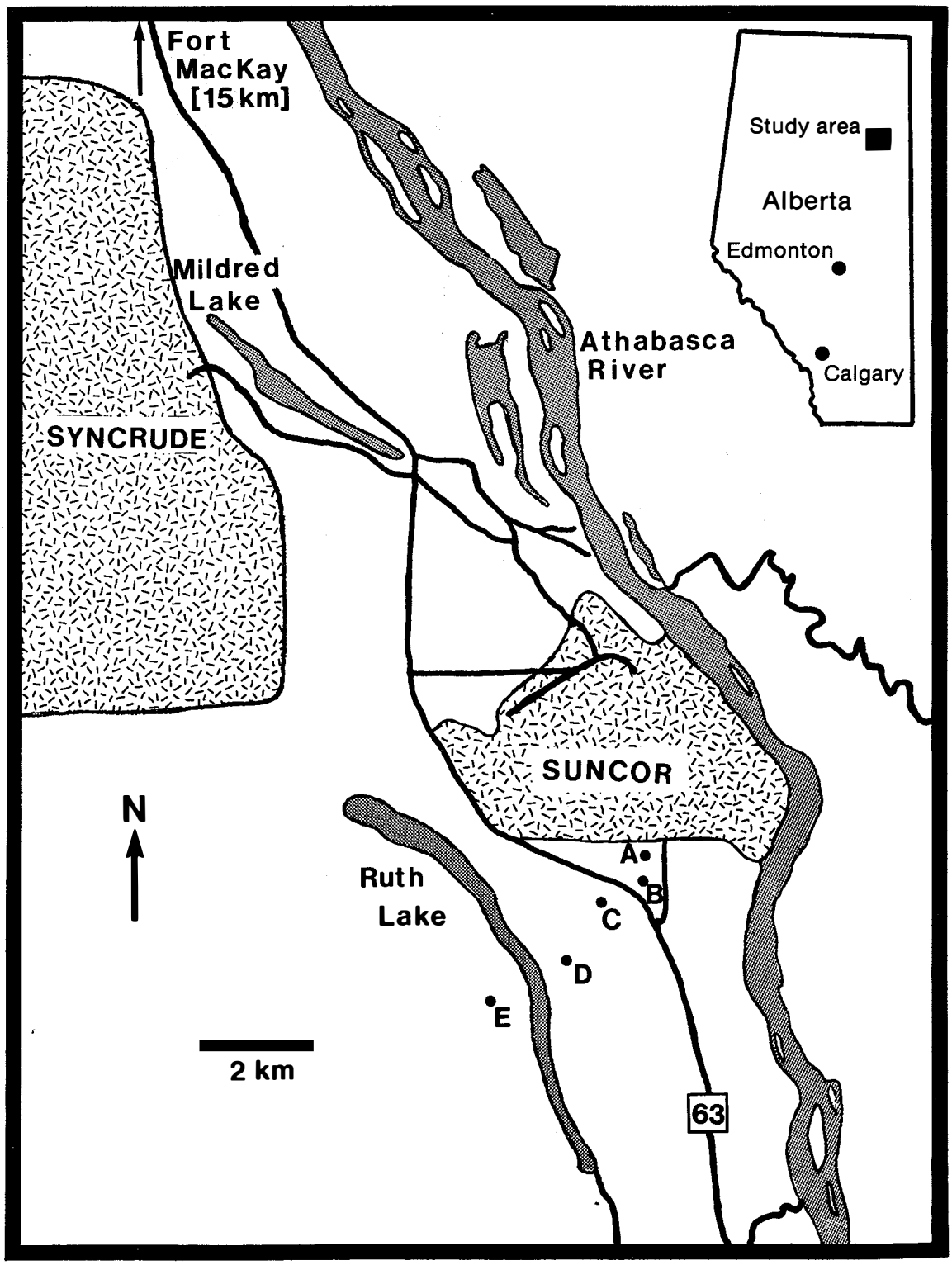

Figure 2. Location of technique sites in the vicinity of the Suncor operations.

Since natural variability, particularly in soil and plant elemental content was very high, the actual effects of the pollution source may have been masked; therefore, a follow-up examination of the plots was carried out in 1979 (Addison 1980b).

Physical collectors

Precipitation gauges: Precipitation collectors were installed at a number of sites. Initially (1977), four replicate collectors were placed on the ground in natural clearings at the five technique sites (Addison and Baker 1979). Precipitation samples were contaminated with insect and plant material even though attempts were made to ensure that only precipitation entered the gauge (screened opening). In addition, black bear interest prevented adequate replication. The next year, three replicate gauges covered with a fine mesh were placed at the top of the canopy at all biomonitoring sites (13) and were collected at the end of the summer.

Sulfation plates: Sulfation plates were used extensively in the study to determine the relative levels of S deposition at various sites. At each technique site, six 10-cm Huey plates were placed at 1.5-m height in three different microenvironments (in the open, under pine, and under spruce). Four sulfation plates were also placed at each of the biomonitoring sites at 1.5-m height in the open.

Soil parameters

Chemistry: In addition to the descriptive soil chemical data that comprised part of the base-line information about the biomonitoring sites (Addison and Baker 1979; Addison 1980a, b), some specific studies were carried out to assess the capability of the soil system to indicate pollutant impingement and impact. Baker (1980) examined the chemical composition of soils and jack pine foliage at two of the technique sites that were 2.8 and 5.3 km from the source. Soils were collected both under a pine canopy and in the open and were analyzed for S, P, Ca, Mg, K, Al, Fe, and Ti.

An attempt was made to determine the variability in elemental content of forest soils in the vicinity of oil sands operations (Addison, L'Hirondelle, and Maynard 1984). Twenty-five replicate samples of each of the three surface horizons (LFH, Ae, and Bm) were taken from a 5 × 5 m plot at the technique site 2.8 km from Suncor. The samples were analyzed for N, P, K, Ca, Mg, S, Fe, Al, Mn, Ti, Ni, Pb, Zn, V, Sc, and Se. In addition, the pH was measured in both water and in 0.01 M $CaCl_2$, and conductivity was determined.

Microbiology: A small-scale study was carried out on the potential for emissions to impact on the soil microbial populations[1]. Microbiological tests included total bacterial and total fungal counts and the most probable numbers of sulfur oxidizers, sulfate reducers, nitrifiers, and nitrogen mineralizers.

Plant responses

Vascular plants: Several growth and reproduction measurements were evaluated at the technique sites (Addison 1983). Basal area increment of jack pine was measured by taking two cores (south and west sides) from each of 10 trees at the five sites.

At one site close (2.8 km) to the pollution source and another about 10 km distant, five branches from the top of each of five jack pines were collected and used to determine shoot growth and needle retention.

Seed extracted from jack pine cones collected at sites ranging from 2.8 to 8.3 km from the source was used in germination tests.

Several biochemical and physiological measurements of field-collected jack pine and white spruce cut branches were carried out to detect air pollution effects on mature (30- to 50-year-old) trees in the oil sands area. Samples were examined for phosphatase and malate dehydrogenase activities, chlorophyll to pheophytin ratio, total S, net photosynthesis, and dark respiration.

Lichen studies: Several species of native lichens were used to estimate both pollutant impingement and impact. At 69 sites in the oil sands area, elemental content (Al, K, S, V, and Ti) was determined in *Evernia mesomorpha*[2], *Hypogymnia physodes*, and *Cladina arbuscula* (Addison and Puckett 1980). Transplanted lichen communities were used to detect changes owing to air pollutants by measuring percent cover and thallus chemistry (Addison 1980b).

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[1] Baker, J.; Danforth, J. 1976. Unpublished file report on the effect of oil sands emissions on microbial populations. Can. For. Serv., North. For. Cent., Edmonton, Alberta.

[2] Nomenclature follows Moss (1983) for the vascular plants, Conard and Redfearn (1979) for the mosses, and Hale and Culberson (1975) for lichens.

Results of biomonitoring and technique studies

Site description: There was no measurable impact of air pollutants on either vascular or cryptogamic (lichen) plant communities at the biomonitoring sites. Vascular plant communities in the area appeared to be patterned along a moisture gradient that was at least partially related to differences in stand density among the sites (Addison 1980a). Since little is known about factors that may have controlled the pattern seen in the branch-dwelling lichen communities, no explanation for that pattern was proposed. The crowns of various plant communities in the vicinity of Suncor (then called the Great Canadian Oil Sands plant) were examined using both color and infrared low-level aerial photography, but no pattern consistent with air pollution distribution was detected (Addison and Baker 1979).

At the biomonitoring sites, feather moss (*Pleurozium schreberi*) appeared to be the most effective species group in taking up and retaining aerial emissions (Table 1). Other species, particularly trees, showed a similar but less distinct pattern of pollutant content in leaf tissue with distance from the source. In general, significantly higher concentrations of emissions elements (i.e., sulfur) occurred in tissue less than 10 km from the pollution source, even though specific gradients in plant S content extended up to 25 km. In addition, the LFH horizon of the soil indicated that there were raised levels of S, V, and Ni close to the oil sands operations (Table 2) that could not be related to the mineral soil concentrations (Addison 1980b).

The attempt to use estimates of cover in the understory of jack pine stands to detect and quantify pollutant impact over time was not successful. In examining the 1976 and 1979 cover measurements at the biomonitoring sites, no relationship with distance from the source or direction could be detected (Addison 1980b). At five sites the cover measurements in 1979 were less than 85% similar to those in 1976, but none of the sites was close to the source. It was suggested that the variation between repetitive sampling of the vegetation was a result of errors in the measurement itself. A detailed study on the magnitude and nature of the errors in the estimation of cover in coniferous forests has been carried out as part of a study on sour gas plant effects in west-central Alberta (Kennedy and Addison 1986). This study demonstrated that the errors in the estimation of plant cover were indeed large (i.e., 20%) and ranged up to 100% for some species. It was not unusual to have control site similarity values vary by 15%, as was the case in the oil sands area.

Physical collectors

Precipitation gauges: No pattern of pollutant deposition could be detected in precipitation samples (Addison

Table 1. Element content (mg kg^{-1}; mean ± 95% confidence limits) of plant material from biomonitoring plots in the Athabasca Oil Sands area, 1979 (adapted from Addison 1980b)

Element and distance measured from Suncor (km)[a]	Jack pine	White spruce	Bearberry	Labrador tea	Ground lichens	Feather moss
S						
<10	870 ± 120	566 ± 78	564 ± 44	1 060 ± 137	327 ± 43	1 210 ± 146
10–25	705 ± 83 [b]	604 ± 65	482 ± 63	1 300 ± 143	255 ± 28	853 ± 96
>25	653 ± 42	412 ± 52	439 ± 48	985 ± 58	154 ± 17	682 ± 50
Al						
<10	702 ± 86	166 ± 30	308 ± 68	334 ± 52	484 ± 117	2 020 ± 358
10–25	624 ± 76	205 ± 99	237 ± 45	203 ± 37	341 ± 55	1 100 ± 121
>25	470 ± 33	48 ± 20	106 ± 24	107 ± 16	203 ± 23	730 ± 48
Fe						
<10	184 ± 36	99 ± 12	153 ± 21	203 ± 17	143 ± 26	1 110 ± 201
10–25	108 ± 30	108 ± 28	164 ± 38	152 ± 27	224 ± 58	798 ± 159
>25	60 ± 5	44 ± 5	68 ± 8	77 ± 5	107 ± 6	348 ± 22

[a] Three sites occurred within 10 km of Suncor, three sites were 10–25 km away, and seven sites were over 25 km away.
[b] Vertical lines indicate means not significantly different ($p < 0.05$) in a Student-Newman-Keuls test.

Table 2. Element content (mg kg^{-1}) of soils from the biomonitoring sites in the Athabasca Oil Sands area, 1979

Element and distance measured from Suncor (km)	Ammonium acetate extractable					Total				
	LFH	Ahe	Ae	Bm	C	LFH	Ahe	Ae	Bm	C
S										
<10	7 ± 14	1	1	3	1	629 ± 434	71 ± 29	39	42 ± 51	34 ± 70
10–25	7 ± 14	3 ± 6	ND[a]	2 ± 5	2 ± 5	585 ± 310	34 ± 1	ND	35 ± 56	40 ± 20
>25	8 ± 4	<1 ± 1	<1 ± 1	1 ± 1	1 ± 2	542 ± 200	106 ± 88	57 ± 47	81 ± 60	94 ± 72
Al										
<10	41 ± 93	32 ± 27	35	100 ± 22	37 ± 75	7 270 ± 792	6 580 ± 6 320	8 190	12 300 ± 6 320	8 540 ± 5 000
10–25	7 ± 16	34 ± 27	ND	55 ± 86	27 ± 60	4 730 ± 9 610	9 430 ± 9 530	ND	15 000 ± 14 700	13 400 ± 14 100
>25	28 ± 15	67 ± 56	72 ± 68	130 ± 105	68 ± 71	7 660 ± 3 470	11 800 ± 11 100	14 500 ± 10 300	21 200 ± 10 400	18 400 ± 10 800
Fe										
<10	20 ± 51	11 ± 19	16	32 ± 54	8 ± 16	3 510 ± 2 710	2 540 ± 2 620	3 350	6 820 ± 6 500	5 460 ± 5 380
10–25	6 ± 5	29 ± 58	ND	16 ± 18	6 ± 3	2 410 ± 1 890	2 830 ± 2 090	ND	6 500 ± 5 890	7 170 ± 4 090
>25	10 ± 4	23 ± 16	30 ± 24	28 ± 17	11 ± 8	3 210 ± 1 220	3 260 ± 1 230	4 370 ± 3 070	10 100 ± 5 060	8 280 ± 3 810
V										
<10	BD[b]	BD	BD	BD	BD	220 ± 360	25 ± 26	BD	26 ± 14	18 ± 39
10–25	BD	BD	BD	BD	BD	70 ± 62	13 ± 34	ND	25 ± 60	23 ± 49
>25	BD	BD	BD	BD	BD	35 ± 10	22 ± 16	25 ± 8	30 ± 12	28 ± 16
Ni										
<10	7, ± 12	1 ± 1	BD	BD	BD	105 ± 185	7 ± 5	5	4 ± 2	5 ± 2
10–25	2 ± 1	BD	ND	BD	BD	34 ± 16	2 ± 1	ND	7 ± 8	6 ± 9
>25	1 ± 1	1 ± 1	BD	BD	BD	24 ± 6	6 ± 8	7 ± 6	14 ± 11	11 ± 10

[a] Not determined.
[b] Below detection.

Table 3. Sulfur deposition as measured by sulfation plates at the technique sites in the vicinity of the Suncor operations in the Athabasca Oil Sands area in 1979 (adapted from Addison 1983)

Site	Distance and direction from Suncor	Sulfation (mg m^{-2} d^{-1}) May	June	July	August
A	2.8 km SSW	11.1	3.3	5.5	1.0
C	4.2 km SSW	5.2	4.0	3.5	1.4
D	5.3 km SSW	3.4	2.0	ND[a]	1.0
E	8.3 km SSW	2.3	1.2	1.1	0.9

[a] Not determined.

1980b). Several sites, however, had exceptionally high levels of certain elements such as Cu and Na relative to the rest of the sites. It is possible that these high levels may have been a result of sample contamination during preparation for measurement.

Sulfation plates: At four of the technique sites, it was possible to relate the pattern in sulfation rate as measured by sulfation plates (Table 3) to the pattern observed in the tissue S content (Table 4) of various plant species. Both patterns appeared to be linear with distance from the source but had differing regression coefficients (Addison and Baker 1979). When sulfation plates were placed at all 13 biomonitoring sites, there were substantial differences in sulfation between sites close to the Suncor operations and those at greater distances (Addison 1980b). Sulfation was negatively correlated with distance from the source and correlated with jack pine, white spruce, and feather moss tissue S concentrations. Sulfation rate was not related to the S content of the LFH horizon of the soil.

This technique appears to provide a reasonable estimate of gaseous S distribution and appears useful in providing a reference with which to compare biological response measures. Sulfation plates are currently being used to help evaluate the importance of fugitive emissions from oil sands operations in air quality modeling.

Soil parameters

Chemistry: Baker (1980) could not demonstrate any effect of S deposition on either soil or plant S concentrations at two sites near the source. The considerable variability in both soil and foliage elemental contents emphasized the need for more extensive sampling.

In the intensive soil variability study, it was found that 10 replicate samples from a 5 × 5 m plot could only show a 40% increase in S in the LFH with 90% certainty (Addison, L'Hirondelle, and Maynard 1984). It was concluded that in general, the routine measurement of soil chemical composition to detect deposition around sources with low emission levels is ineffective as a short-term monitoring tool. It is, however, necessary for initial site descriptions and to detect large or long-term changes.

Microbiology: In a study designed to determine the effects of oil sands emissions on the growth and activity of soil microflora, no difference could be detected between two soils adjacent (2.3 km) to and distant (10 km) from oil sands operations. Vanadium was shown to affect 20 bacterial isolates (identified as to family) from the native soils, and different groups had different tolerances to this metal in the laboratory. It was not possible, however, to

Table 4. Sulfur content (mg kg^{-1}; mean ± 95% confidence limits) of selected plant species at technique sites in the Athabasca Oil Sands study area (adapted from Addison 1983)

Site	Distance from Suncor (km)	Jack pine	White spruce	Bearberry	Labrador tea	Ground lichens	Feather moss
A	2.8	1 000 ± 48	918 ± 81	796 ± 71	1 410 ± 92	629 ± 38	1 290 ± 49
C	4.2	964 ± 28	735 ± 37	677 ± 28	1 150 ± 86	545 ± 27	1 420 ± 89
D	5.3	828 ± 30	691 ± 101	559 ± 23	1 180 ± 78	284 ± 25	1 200 ± 230
E	8.3	723 ± 40	496 ± 31	423 ± 76	1 054 ± 98	313 ± 74	928 ± 89

make the connection between laboratory and field samples that would permit interpretation of these findings in terms of field effects.[3]

Plant responses

Vascular plants: There did not appear to be any relationship between the cross-sectional area increment of jack pine and distance from the pollutant source (Table 5). Even though a form of self-standardization was used (taking the ratio of growth rate after oil sands operation to that prior to start-up) to eliminate some of the site-induced variability, it appears that growth changes still need to be large before they can be detected with any confidence (Addison 1980b).

Table 5. Ratio (mean ± 95% confidence limits) of wood cross-sectional area growth after (1968–77) versus before (1958–67) start-up of oil extraction operations in the Athabasca Oil Sands area (adapted from Addison 1980b)

Site	Distance and direction from Suncor	Ratio of wood area
A	2.8 km SSW	2.16 ± 1.26
Suncor	3.0 km N	1.15 ± 0.16
Steepbank	3.5 km ESE	1.02 ± 0.50
Fina	4.0 km ESE	1.62 ± 0.29
Mildred Lake	10.5 km W	1.48 ± 0.29

Over a 5-year period, jack pine shoot growth close to the Suncor operations was significantly larger than that >10 km distant and was consistent with basal area growth. Leaf number in the first 3 years also was higher close to the source than more distant from it, but in years 4 and 5 the pattern was reversed. It was felt that the reduction in needle number in years 4 and 5, although not statistically significant, may have been a result of premature aging and abscission caused by air pollutants. Because so many natural factors can influence needle retention, no definitive conclusion could be reached (Addison 1980b).

Germination in jack pine was reduced in seeds collected close to Suncor operations (Addison 1980b). The closest site had a significantly lower germination rate (81.5%) than the most distant of the technique sites (95.8%), whereas the other sites were intermediate and not significantly different from either of the end points.

Biochemical and physiological measurements of jack pine and white spruce branches did not prove to be useful as a biomonitoring technique in the oil sands area. Although these techniques had been used to detect pollutant damage around a smelting operation (Malhotra 1979), no significant differences in any of the metabolic responses measured were observed among the three sites sampled. This is discussed further in the section on analysis of field samples.

Lichen studies: Addison and Puckett (1980) in their study of the distribution of pollutants as measured by lichen element content found that 1) the pattern of elemental (S, Ti, Al, and V) deposition measured by lichen thallus concentration (Fig. 3) 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 wind-blown dust components; and 3) a single collection of lichen material can replace traditional physical monitoring methods in locations where only relative deposition estimates of pollutants are required. It was also possible to relate the condition of the *Evernia* thalli to the accumulated pollutant content to some extent. These data are currently being used to evaluate the magnitude and distribution of fugitive emissions from oil sands operations so that they may be incorporated into an air quality model.

The lichen community transplanting technique was useful in detecting changes in percent cover of certain species owing to pollutants. Addison (1984) showed that the errors owing to transplantation and to small change in habitat can be quantified and are not so large as to mask the effects of the pollution source. Effects on the cover of branch-dwelling lichens transplanted into the impingement zone could be seen to a distance of about 8 km from the Suncor operations.

[3] Baker, J.; Danforth, J. 1976. Unpublished file report on the effect of oil sands emissions on microbial populations. Can. For. Serv., North. For. Cent., Edmonton, Alberta.

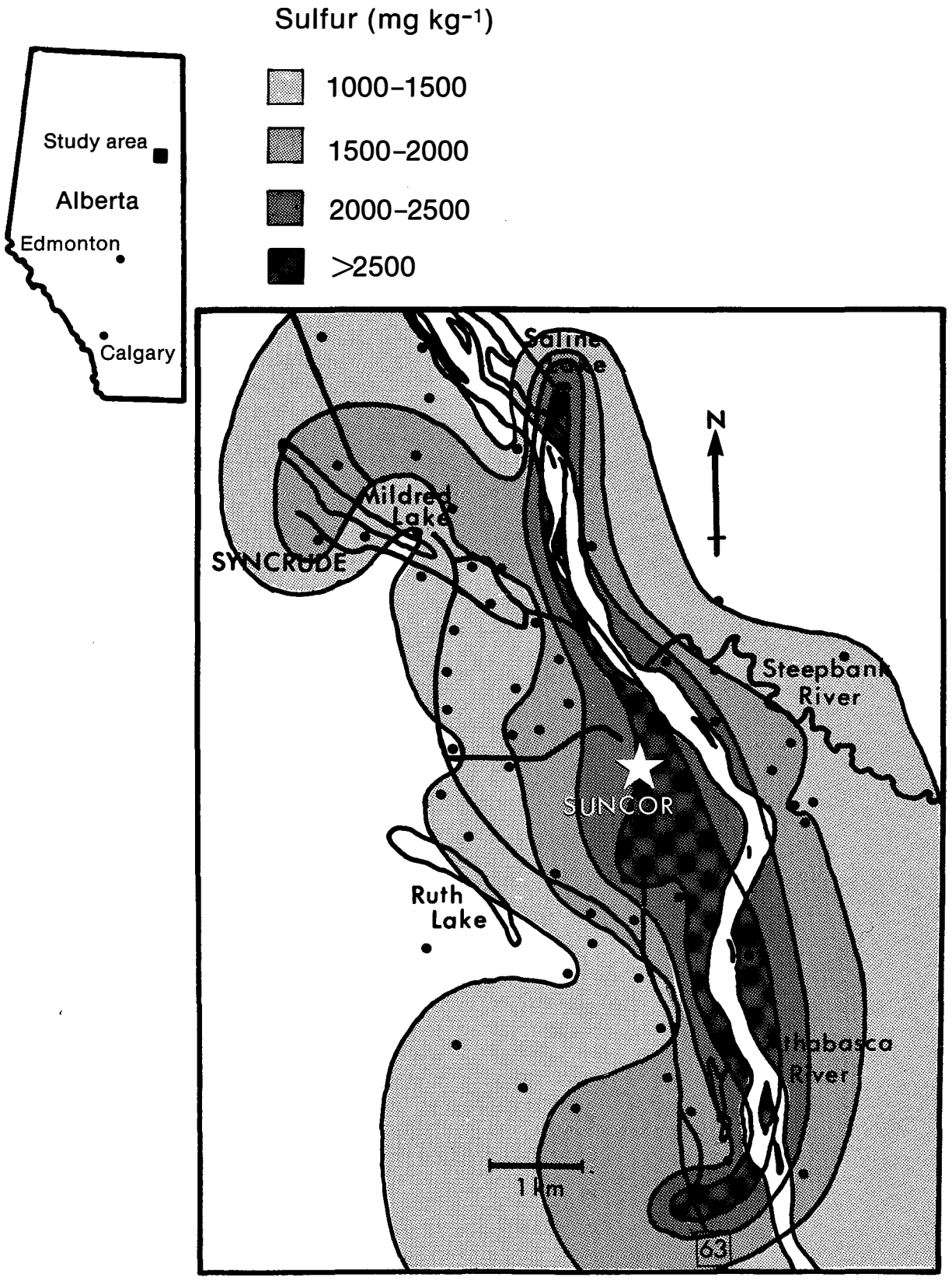

Figure 3. Sulfur content of *Hypogymnia physodes* in the vicinity of the Suncor operations in the Athabasca Oil Sands area. (Adapted from Addison and Puckett 1980.)

Investigations of pollutant uptake and chemistry of lichen thalli found that no pattern could be determined in K or Mg that could be related to pollutant content or the presence of the pollutant in the area (Table 6). During the first year after transplanting, S content increased in a dramatic and expected manner, but the exceptional losses in S in the second year were quite unexpected (Table 6). It appears that the uptake and retention of S in lichen material is complex and will require more work before it is understood. An examination of acid phosphatase activity, ^{14}C incorporation, and protein biosynthesis was not able to reveal any pattern that was consistent with pollutant impingement (Addison 1980b).

Table 6. Sulfur content and available-to-total ratios for K and Mg in *Evernia mesomorpha* material transplanted under jack pine canopies in May 1977 at the technique sites in the Athabasca Oil Sands area (adapted from Addison 1980b)

Element	Site	Time of sampling			
		May 1977	Sept. 1977	July 1978	July 1979
		S (mg kg^{-1})			
S	A	891	1 890	3 060	1 250
	B	624	1 200	2 020	1 260
	C	915	1 320	1 700	1 430
	D	931	1 700	1 620	1 560
	E	1 110	1 660	1 160	1 240
		Available-to-total ratio			
K	A	0.29	0.24	0.34	0.38
	B	0.28	0.18	0.19	0.37
	C	0.44	0.23	0.27	0.38
	D	0.36	0.20	0.24	0.25
	E	0.31	0.18	0.15	0.17
Mg	A	0.22	0.28	0.43	0.46
	B	0.24	0.19	0.34	0.62
	C	0.16	0.22	0.33	0.49
	D	0.17	0.23	0.49	0.16
	E	0.18	0.14	0.28	0.12

Biochemistry and Cell Physiology

Pollutants can have a deleterious effect on a variety of biochemical and physiological processes and on structural organization within cells. Following a pollutant episode, it is often assumed that there has been no injury to vegetation unless symptoms of phytotoxicity have developed. In many controlled environment studies, air pollutants have been shown to reduce the growth and yield of plants before any visible symptoms appeared. It is now commonly believed that injury initially takes place at the biochemical level (interference with photosynthesis, respiration, lipid and protein biosynthesis, etc.), subsequently progresses to the ultrastructural level (disorganization of cellular membrances), and then moves to the cellular level (cell-wall, mesophyll, and nuclear breakdown). Finally, visible symptoms develop (chlorosis and necrosis of foliar tissues) (Malhotra and Khan 1984).

A comprehensive literature review (Malhotra and Hocking 1976) pointed out that biochemical effects of SO_2 arise from its unique ability to act as an oxidizing or a reducing agent. Among some of the important metabolic effects are direct interference with photosynthetic CO_2 fixation (competitive inhibition of ribulose bisphosphate carboxylase by $SO_3^=$) and with energy metabolism (inhibition of mitochondrial adenosine triphosphate (ATP) production by $SO_3^=$). Many indirect effects result from formation of sulfites and organic sulfonates with other cellular constituents. These compounds can cause inhibition of a variety of metabolic enzyme systems. All these factors are probably instrumental in the gross disruption of chloroplast and mitochondrial ultrastructure. Injurious effects result when SO_2 is taken up in excess of the capacity of the tissue to incorporate sulfur into the normal metabolic activities.

The objectives of this project were 1) to study biochemical or physiological threshold levels of air pollution injury to boreal forest vegetation and 2) to develop sensitive and reliable methods for detecting air pollutant effects on forest vegetation prior to visual symptom development.

In order to estimate the phytotoxic effects of various pollutants, it was essential that the above objectives be tested first with each pollutant individually and then in combinations (Malhotra 1979).

Aqueous SO_2 effects

In the earliest phase of this program, facilities to fumigate plant material with pollutant gases were not available; consequently, research was carried out with aqueous SO_2 to understand the nature of phytotoxicity at the ultrastructural and biochemical levels.

The effects of aqueous SO_2 on the ultrastructural organization of pine chloroplasts and their photosynthetic

activity were determined under laboratory conditions (Malhotra 1976). At aqueous concentrations[4] of 100 and 500 μL L^{-1}, SO_2 caused swelling of thylakoid disks and disintegrated other intrachloroplast membranes, resulting in the formation of small vesicles. This damage was greater in older tissue than in younger needles. Biochemical observations such as decreases in Hill reaction activity of chloroplasts isolated from SO_2-treated pine needles were in good agreement with the cytological observations.

Photosynthetic pigments were also affected by aqueous SO_2 at similar concentrations (Malhotra 1977). Chlorophyll *a* was more sensitive to SO_2 than chlorophyll *b*. Quantitative determinations of various pigments suggested that SO_2 causes conversion of chlorophyll *a* into pheophytin *a* and conversion of chlorophyll *b* into chlorophyllide *b*. The suggested conversion of chlorophyll into chlorophyllide was supported by increased activity of pine needle chlorophyllase at low aqueous SO_2 concentrations. In addition, there was a decrease in the capability of pine needles to fix $H^{14}CO_3$. The effect of SO_2 on pigment breakdown and rate of photosynthesis was attributed to the direct action of SO_2 and not to increased acidity (Malhotra 1977).

The effect of aqueous SO_2 on the composition and concentration of lipids in pine needles was also explored (Khan and Malhotra 1977). Since lipids, mainly glycolipids, constitute about 50% by weight of chloroplast thylakoids, this was a natural follow-up to the study showing dramatic effects on thyalkoid ultrastructure (Malhotra 1976). The major glycolipids in pine needles were identified, and concentrations were found to be much higher in fully developed needles than in young tissue. Exposure of needles to aqueous SO_2 at 100 μL L^{-1} produced a considerable drop in linolenic acid content of all glycolipid fractions. The effects were more pronounced in the younger needles than in the older ones. Work continued on lipids, and a paper describing the characteristics of lipid biosynthesis in isolated jack pine chloroplasts was published (Khan and Malhotra 1978).

Gaseous SO_2 effects

Once a facility was available for gaseous SO_2 fumigations, a comparison was made on the effects of the two forms of the pollutant on the rate of lipid biosynthesis (Malhotra and Khan 1978). Treatment of the needle tissue with either gaseous or aqueous SO_2 markedly inhibited lipid biosynthesis. These effects were more pronounced in developing than in mature tissue. Fumigation with gaseous SO_2 showed that both concentration and duration of exposure affected the extent of lipid biosynthesis. These effects were more pronounced in developing than in mature tissue. Fumigation with gaseous SO_2 showed that both concentration and duration of exposure affected the extent of lipid biosynthetic inhibition. Lipid biosynthetic capacity partially or completely recovered when plants were removed from the SO_2 environment. Plants exposed to moderate SO_2 concentrations (0.18–0.20 μL L^{-1}) for a period of 24 h recovered faster than those exposed to near lethal SO_2 concentrations (0.34–0.37 μL L^{-1}) for only 1 h (Malhotra and Khan 1978).

Ribulose bisphosphate carboxylase and glycollate oxidase from jack pine were affected by both aqueous and gaseous SO_2 exposure (Khan and Malhotra 1982b). For both enzymes, $SO_3^=$ had a much greater effect than did $SO_4^=$. Fumigation of jack pine seedlings with 0.34 μL L^{-1} SO_2 for 24 and 48 h produced a considerable (10–30%) decline in the activities of these enzymes, but 1 h of fumigation produced no effect. It was suggested that the accumulation of $SO_3^=$ and $SO_4^=$ in the needles following SO_2 exposure influenced these enzyme activities.

Many other biochemical constituents or physiological processes were evaluated as possible indicators of gaseous SO_2 effects on jack pine and other boreal forest plant species. The effect of gaseous SO_2 on jack pine sugars and amino acid content was studied. Increasing concentrations of SO_2 caused an increase in reducing sugars and a decline in the nonreducing sugars in secondary needles of 5- to 6-month-old seedlings. This suggested a conversion from nonreducing to reducing sugars at high SO_2 concentrations (Malhotra and Sarkar 1979).

Fumigation of both jack pine and white birch with 0.34 μL L^{-1} SO_2 caused a marked increase in peroxidase activity and S content of foliage. These responses were more pronounced in white birch than in jack pine but were transitory in both species. The stimulation of peroxidase in SO_2-fumigated jack pine appeared to be due to increased production of the peroxidase isoenzymes rather than their activation (Khan and Malhotra 1982a).

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[4] These levels of aqueous SO_2 were selected because they represented approximately 0.1 and 0.5 μL L^{-1} of gaseous SO_2 (Hocking and Hocking 1977).

Fumigation of pine seedlings with gaseous SO_2 (0.34 μL L^{-1}) for 24 and 48 h markedly inhibited *de novo* protein biosynthesis in the cytoplasmic fraction and even more in the chloroplast fraction. The magnitude of inhibition was dependent on exposure time and appeared to be related to S uptake (Khan and Malhotra 1983).

In addition to the studies on vascular plants, metabolic processes such as photosynthetic CO_2 fixation and protein and lipid biosynthesis were found to be very sensitive to SO_2 in the epiphytic lichen *Evernia mesomorpha* (Malhotra and Khan 1983). Exposure of the lichens to 0.1 μL L^{-1} SO_2 for increasing durations produced a progressive reduction in these processes. Protein biosynthesis appeared to be the most sensitive process. The fumigations also inhibited acid phosphatase activity and caused an increase in S content of the thallus. During an SO_2-free period after fumigation, all processes recovered partially or fully in lichens exposed to 0.1 μL L^{-1} SO_2 but showed little or no recovery in lichens exposed to 0.34 μL L^{-1}.

SO_2 and heavy metal effects

Since SO_2 is not the only pollutant that is being released from oil sands operations, it was felt necessary to explore the effects of mixtures of SO_2 and several metals that were being emitted from the Suncor operations. Initially, the various compounds were tested individually (Malhotra and Khan 1980a) using acid phosphatase as an indicator of effect. Treatment of pine seedlings with 0.35 μL L^{-1} SO_2 inhibited acid phosphatase activity 40–50% after 24 h fumigation and 10–20% after 1 h fumigation. Upon removal of plants from the SO_2 environment, the inhibitory effects of SO_2 were completely reversed in plants exposed for short durations (1 h) but remained unchanged in the plants exposed for long durations (24 h). Individually applied F, Zn, As, Al, and Cu added to acid phosphatase extracts also considerably inhibited (20–80%) enzyme activity (Malhotra and Khan 1980a).

In a follow-up study, exposure of pine seedlings in solution culture to heavy metals (50 μL l^{-1} V and Ni) either singly or in combination with SO_2 resulted in the uptake of the metal, biochemical disturbances, and production of severe visual symptoms (Malhotra and Khan 1981). Individual pollutants such as SO_2, V, and Ni proved to be highly toxic to various metabolic processes (glyco- and phospholipids biosynthesis and activities of ribulose bisphosphate carboxylase, peroxidase, glycollate oxidase, and acid phosphatase). In general, the pollutant mixtures did not produce much additional response than that caused by metals alone. The response of various biochemical functions to each pollutant appeared to be related to the pollutant uptake by treated tissue.

Analysis of field samples

Assessment of air pollution injury to jack pine and epiphytic lichens at three sites in a southwest gradient from the Suncor plant (the two closest sites being in the impingement zone and the third in a relatively clean area) was carried out using some of the biochemical and physiological methods developed at the Northern Forestry Centre for detecting previsual injury from air pollution. Although these methods were able to detect previsual injury to greenhouse-grown plants, no significant differences in any of the metabolic responses were observed among the field sites. This may be due to either the relatively low levels of SO_2 experienced in these areas or the ability of the vegetation to recover its metabolic functions between the rare incidents of heavy fumigation. Sulfur levels in jack pine were shown to be near the lower end of the normal range for such species, and those in epiphytic lichens were also low but highly variable. Other reasons for not being able to detect injury to field specimens may be the low levels of tissue S and the transient nature of SO_2 injury probably brought about by the ability of the vegetation to detoxify the toxic species of S (conversion of HSO_3^- and $SO_3^=$ to $SO_4^=$ (Malhotra and Khan 1980b).

Whole Plant Physiology

This final component of the Alberta Oil Sands Environmental Research Program was an attempt to use Northern Forestry Centre laboratory facilities to provide information that could be used to interpret field observations. Since little was known about the sensitivity of native species in the area, it was essential that some type of ranking be carried out with which field studies could be compared. In addition, the reliability of visual symptoms could be ascertained.

The objectives of this study were 1) to describe visible effects of air pollutants on selected species from the Athabasca Oil Sands area in order to develop techniques to identify and assess the impact of air pollutants and 2) to determine in quantitative terms the threshold levels of air pollutant injury to species native to the Athabasca Oil Sands region.

The visual threshold level was defined as the time and concentration where foliar damage was first detected, and the physiological threshold level was defined as the time and concentration that reduced net CO_2 assimilation by 10% (Malhotra and Addison 1979).

The progress of this study was described in a series of Alberta Oil Sands Environmental Research Program reports (Malhotra and Addison 1979, Addison and Malhotra 1979; Malhotra et al. 1980), and the major findings have been published in the *Journal of Environmental Quality* (Addison, Malhotra, and Khan 1984).

The study was carried out on the influence of 0.34 $\mu L\ L^{-1}$ SO_2 (the Canadian maximum acceptable limit) on net CO_2 assimilation rate (NAR) and visible symptom development of several boreal forest woody species grown on a Brunisol soil or in oil sands tailings (which is the residue left after the oil has been removed by steam from the oil sands). Fumigation with SO_2 significantly reduced NAR in all species and produced visible symptoms of injury in 2 to 20 days (Table 7). The decrease in NAR of deciduous species such as aspen (*Populus tremuloides* Michx.), willow (*Salix* sp.), green alder (*Alnus crispa* (Ait.) Parsh), and paper birch (*Betula papyrifera* Marsh) was significantly more rapid than of conifers such as jack pine (*Pinus banksiana* Lamb.), white spruce (*Picea glauca* (Moench) Voss), and black spruce (*P. mariana* (Mill.) B.S.P.) or an evergreen angiosperm such as Labrador tea (*Ledum groenlandicum* Oeder) when grown on a fertilized Brunisol soil. Visible symptoms also appeared earlier in deciduous species but in all cases did not appear until NAR had decreased considerably. These metabolic and visible responses appeared to be related to differences in S uptake owing in part to higher gas exchange rates for deciduous species than for conifers.

Conifers growing in oil sands tailings responded to SO_2 with a significantly more rapid decrease in NAR compared with those growing in the Brunisol. Because both soils were fertilized, nutrient deficiencies were ruled out as a cause. It is suggested that the conifers obtained from the tailings dike were predisposed to SO_2 fumigation by either the presence of toxic material in the tailings or their history of exposure to moderate levels of SO_2 or to moisture stress. Jack pine collected from tailings sand had significantly lower prefumigation NAR than did jack pine grown on the Brunisol (Table 8). Sulfur uptake and visible symptom development were not different for any species grown on tailings as compared with on the Brunisol.

RESEARCH MANAGEMENT DIVISION MIXED POLLUTANT STUDY

Under field conditions, the impact of air pollutants on vegetation generally results from exposure to total emissions from an industry rather than an individual pollutant. The major pollutants in the oil sands area are SO_2, NO_X, and several heavy metals (V, Ni, and Al). Several studies have indicated that pollutant response differs when plants are exposed to two or more pollutants and may be additive, synergistic, or even antagonistic in nature. Very little or no information was available on the effects of pollutant mixtures on the species living in the vicinity of existing or proposed oil sands extracting facilities. Such information is a prerequisite for assessing the long-term effects of total industrial emissions on the environment.

The objectives of this project were 1) to determine the impact of pollutant mixtures on native soils and their ability to support vegetation (indirect pollutant effects) and 2) to determine the effect of pollutant mixtures on the previsible and visible symptoms of boreal forest plant species (direct pollutant effects).

Soil Core Experiments

In the first year of the study (1980–81), efforts were concentrated on objective 1, and an experiment was carried out to determine the influence of elevated levels of soluble pollutant mixtures on the capability of the soil to support jack pine. A method was developed to collect intact soil cores (15 cm diameter by 20 cm deep) for experimental purposes. The details of the methods used and specifics of the results are found in Addison et al. (1981, 1982).

The soil collected was a Degraded Dystric Brunisol (Canada Soil Survey Committee 1978), which is characteristic of jack pine stands in the oil sands area (Addison 1980a). Analysis of the total element content (Table 9) indicated slightly higher S levels than observed earlier (Addison 1980a), but the levels were well within the normal soil range (Chapman and Pratt 1961). The concentrations of other elements were also in the normal range for this nutrient poor and coarse-textured soil from this area (Turchenek and Lindsay 1978).

An experiment was carried out to determine the influence of the five major pollutants in the area (S, N, V, Al, and Ni). These elements were added to the cores in soluble forms (SO_4, NO_3, V_2O_5, $Al(NO_3)_3$, and $NiNO_3$, respectively) at concentrations that represented deposition equivalents of 13, 26, 52, and 104 years in the immediate vicinity of the Suncor operations (Barrie 1978). Jack pine seedling establishment, growth, and element content were recorded after 9 weeks (Table 10).

Table 7. Slopes of percentage change in net CO_2 assimilation rate with time, uptake, and time required for visible symptom development with SO_2 for woody plants growing in a Dystric Brunisol soil and in tailings sand (adapted from Addison et al. 1984b)

Species	Prefumigation slope	Fumigation slope[1]	S uptake (mg kg^{-1} d^{-1})	Visible symptom initiation
		Dystric Brunisol soil		
Willow	−1.1	−9.9*[2]	440 ± 230 b[3]	2 ± 1 a[3]
Paper birch	+1.7	−8.7*	660 ± 240 a	5 ± 2 a,b
Aspen	+2.1	−7.7*	260 ± 80 c	4 ± 1 a
Green alder	+0.2	−4.3*	480 ± 170 b	3 ± 1 a
Labrador tea	−3.2	−2.2*	270 ± 170 b,c	9 ± 3 c
White spruce	0	−2.1*	150 ± 60 c	21 ± 4 d
Black spruce	+0.5	−1.7*	80 ± 30 c	15 ± 5 c
Jack pine	+1.5*	−1.3*	90 ± 40 c	11 ± 2 d
		Tailings sand		
White spruce	+3.2	−5.2*	130 ± 20 c	15 ± 0 c
Black spruce	−6.3	−5.0*	110 ± 70 c	15 ± 0 c
Jack pine	−3.2	−6.5*	70 ± 70 c	13 ± 10 b,c

[1] Lines join slopes not significantly different ($p < 0.05$) by Simultaneous Test Procedure.
[2] Significant relationship between NAR and time ($p < 0.05$).
[3] Mean ± 95% confidence limits. Common letters indicate means that are not significantly ($p < 0.05$) different in a Student-Newman-Keuls test.

Table 8. Net CO_2 assimilation rate (mean ± 95% confidence limits) of woody plants before fumigation with SO_2 (adapted from Addison et al. 1984b)

Species	Net assimilation rate (mg g^{-1} h^{-1})	
	Dystric Brunisol	Tailings soil
Willow	19.0 ± 11.7	ND[a]
Paper birch	14.6 ± 2.8	ND
Aspen	17.7 ± 5.5	ND
Green alder	13.7 ± 2.2	ND
Labrador tea	7.6 ± 5.0	ND
White spruce	5.4 ± 0.8	6.1 ± 3.2
Black spruce	5.0 ± 1.5	6.1 ± 0.9
Jack pine	6.4 ± 1.5	2.9 ± 1.1

[a] Not determined.

Table 9. Chemical characteristics of a degraded Dystric Brunisol soil collected for soil core experiments from the Athabasca Oil Sands area. All concentrations are in mg kg^{-1} (means ± 95% confidence limits; n = 5). (Adapted from Addison et al. 1981.)

Element	Horizon				
	LFH	Ahe	Ae[a]	Bm	C
pH[b]	4.4 ± 0.2	4.2 ± 0.5	4.5	4.5 ± 0.1	4.6 ± 0.1
Cation exchange capacity[c]	390 ± 100	70 ± 40	20	20 ± 2	20 ± 1
S	583 ± 40	146 ± 44	111	105 ± 26	95 ± 24
Al	8 060 ± 1 600	8 750 ± 874	6 940	11 200 ± 1 950	9 190 ± 257
Fe	5 280 ± 728	6 330 ± 773	4 580	10 500 ± 1 900	6 660 ± 3 420
K	3 350 ± 755	3 950 ± 113	3 440	4 040 ± 921	3 660 ± 291
Mg	906 ± 163	526 ± 49	328	685 ± 117	566 ± 116
P	575 ± 189	331 ± 60	100	238 ± 124	138 ± 76
Ca	6 300 ± 1 860	2 170 ± 614	1 120	1 660 ± 334	1 450 ± 195
Mn	1 380 ± 310	764 ± 330	123	129 ± 25	118 ± 31

[a] Only two replicates.
[b] In $CaCl_2$.
[c] At pH 5.2.

Table 10. Plant response after 9 weeks to the addition of pollutants to native soil cores in the laboratory. Values are means ± 95% confidence limits; n = 5. Deposition concentrations represent equivalents of years of deposition in the immediate vicinity of the Suncor operations. (Adapted from Addison et al. 1981.)

Treatment	Deposition equivalents (Years)[a]	% establishment	Growth rate (mm d^{-1})	Element content in pine needles (mg kg^{-1})						
				S	P	Ca	Mg	K	Al	Ni
Al	13	43 ± 24	1.6 ± 0.2	884	1 900	1 430	1 210	9 050	240	3
	26	31 ± 27	1.6 ± 0.2	686	1 470	1 770	1 030	8 700	206	4
	52	66 ± 32	1.9 ± 0.3	687	1 600	1 200	880	8 080	220	3
Ni	13	32 ± 26	1.6 ± 0.2	786	1 500	1 280	930	9 030	250	7
	26	28 ± 11	1.5 ± 0.2	766	1 400	1 290	920	9 920	218	6
	52	13 ± 11	1.6 ± 0.3	ND[b]	ND	ND	ND	ND	ND	ND
SO_4	13	39 ± 20	1.9 ± 0.2	982	1 700	1 650	930	9 610	190	2
	26	32 ± 33	1.4 ± 0.2	566	1 340	1 340	922	11 000	250	2
	52	25 ± 12	1.7 ± 0.3	1 040	1 850	1 420	1 030	9 800	264	4
V	13	32 ± 14	1.8 ± 0.3	638	1 700	1 980	990	8 340	120	7
	26	36 ± 19	1.6 ± 0.2	656	1 880	1 310	1 130	9 890	313	13
	52	32 ± 20	1.7 ± 0.3	793	1 800	1 550	940	10 320	120	2
Ni + V	26	31 ± 18	1.6 ± 0.3	898	1 350	1 650	1 070	10 420	176	8
Ni + SO_4	26	23 ± 23	1.3 ± 0.3	1 060	1 600	1 650	1 220	10 500	280	4
V + SO_4	26	35 ± 30	2.0 ± 0.3	1 060	1 600	1 380	1 040	10 050	200	1
Ni + V + SO_4	26	28 ± 22	2.2 ± 0.3	1 010	1 600	1 700	1 000	11 440	120	3
Control		31 ± 8	2.0 ± 0.2	794	1 744	1 530	1 090	9 800	230	4

[a] Deposition rates from Barrie (1978) in mg m^{-2} a^{-1} are Al = 5.47, Ni = 4.09, S = 306.6, and V = 36.28.
[b] Not determined.

No significant differences in these responses could be detected even at the highest concentrations or with several pollutants present in mixtures.

Seedling establishment in all soil cores was exceptionally low, and to separate the effects of the core from those of the pollutants, seeds were exposed to various concentrations of the five pollutants in petri dishes. Germination was not greatly affected by up to 100 times the annual average concentration of pollutants (Table 11). Root growth, however, was significantly inhibited by the pollutants at high concentrations and low pH. The root response of the plants appeared to be almost totally controlled by pH, and with the exception of Ni, no response occurred above pH of 3.0. Soil pH in the cores was about 4.5; therefore, the poor germination and establishment in the microcosm experiment was related to factors other than pollutant concentration.

In 1981–82, experiments continued on the effect of adding pollutants to soil cores. Application of soluble forms of various pollutants and their mixtures to soil cores did not produce significant changes in either biochemical (peroxidase activity) or growth (weight) responses of jack pine seedlings grown in these cores (Table 12). Since some of these pollutants were shown to be phytotoxic to jack pine in hydroponic experiments (Malhotra and Khan 1979, 1980b), it appeared that at the concentrations used, the applied pollutants were rendered unavailable to the plant seedlings. There were no detectable levels of metal pollutants in the soil solution, which also indicated that the added soluble forms were converted to more insoluble forms. From these experiments, therefore, it appears that at the concentrations of pollutants used, the metals were effectively chemically bound with the soil material, as has been shown to be common by Schnitzer and Khan (1972). The importance of the LFH horizon in binding metals is well known (Chang and Broadbent 1982; Hogan and Wotton 1984).

Sulfate, which was not bound as were the metal pollutants, had the greatest effect on the chemistry of the soil core. The soil solution of the cores with added SO_4 had much higher levels of the major cations such as Ca and Mg (Table 13). This occurred without any apparent change in the pH of the soil solution. It has been shown that acid sulfate additions accelerate leaching of Ca and Mg from forest soils (Overrein 1977; Abrahamsen et al. 1977).

In order to evaluate the importance of the LFH horizon in protecting plants from metal loadings, an experiment was carried out to determine the response to soil pollutants of jack pine seedlings grown with and without an LFH horizon. Significant physiological effects were observed as a result of added pollutants in soils without the LFH horizon but not in soils with an intact LFH (Table 14). The LFH also had an obvious effect on jack pine seedling growth. Jack pine grown in a soil with an LFH horizon were significantly larger than those without an LFH and showed neither the negative effects of pollutant addition nor the stimulation of growth by the addition of SO_4 or NO_3.

Constant Fumigation Studies

Lichen studies

A study on the direct effect of pollutants on the lichen *Evernia mesomorpha* was initiated in 1981–82. Numerous studies have demonstrated that lichens are susceptible to atmospheric pollution, particularly SO_2 (James 1973). In spite of the number of studies that have been carried out on lichens and their recognized capability to act as biomonitors, comparisons between lichen response and responses of either a vascular plant or the ecosystem as a whole have not been made in any quantitative manner. This evaluation is only possible if one deals with the nature of the response itself and examines the influence of concentration and duration of exposure and their interaction.

Initial attempts to use ^{14}C incorporation to the lichen tallus as a measure of photosynthesis failed owing to excessive variation in the data set. An entirely new fumigation and measurement system was developed in 1984 using direct readings of CO_2 exchange in closed cuvettes following the method of Larson and Kershaw (1975). *Evernia mesomorpha* was shown to be particularly sensitive to short-term fumigations with low concentrations of gaseous SO_2 (Huebert et al. 1985). Net CO_2 assimilation rate (NAR) was significantly reduced after exposure to 0.085 $\mu L\ L^{-1}$ SO_2 for 1 h or more, and the reduction increased with increasing concentration (Table 15). Duration of exposure had no significant effect on NAR, indicating the importance of SO_2 uptake rate rather than the total amount absorbed. Respiration was significantly reduced after 4 h or more of exposure to 0.265 $\mu L\ L^{-1}$ SO_2 or higher.

Recovery of NAR after fumigation was dependent on both SO_2 concentration and durations of fumigation and on the time allowed for recovery. Virtually complete recovery occurred within 24 h after episodes with up to 0.355 $\mu L\ L^{-1}$ SO_2 for 1 h and 0.085 $\mu L\ L^{-1}$ for 4 h. Above these levels, recovery was incomplete or nonexistent after 24 h in clean air. The level of sensitivity found can be attributed to the environmental conditions during fumigation, which prevented thallus desiccation and inactivity.

Table 11. Percent germination and radicle length of jack pine after 10 days of exposure to various concentrations of pollutants. Values are means ± 95% confidence limits; n = 100. (Adapted from Addison et al. 1981.)

Pollutant		Treatment				
		Control	Annual average	10×	100×	1000×
Al	Length (mm)	26 ± 2	20 ± 3	25 ± 3	15 ± 2	1 ± 0
	% germination	90	72	72	82	80
	mg L^{-1}	0	0.011	0.11	1.1	10.8
	pH	5.0	3.9	3.5	3.0	2.0
Ni	Length (mm)	29 ± 1	26 ± 1	23 ± 3	22 ± 2	8 ± 1
	% germination	90	78	92	94	92
	mg L^{-1}	0	0.008	0.081	0.81	8.1
	pH	6.2	6.0	5.8	4.7	3.7
NO_3	Length (mm)	28 ± 2	27 ± 1	29 ± 2	12 ± 2	3 ± 0
	% germination	92	92	98	90	86
	mg L^{-1}	0	0.2	2.3	22.9	229.1
	pH	5.8	4.7	3.6	2.7	1.8
SO_4	Length (mm)	28 ± 2	28 ± 2	22 ± 3	4 ± 1	1 ± 0
	% germination	90	84	88	88	76
	mg L^{-1}	0	0.6	6.0	60.4	603.5
	pH	5.8	4.3	3.3	2.3	1.5
V	Length (mm)	26 ± 2	26 ± 1	18 ± 1	3 ± 1	0
	% germination	82	85	74	86	0
	mg L^{-1}	0	0.065	0.65	6.5	65
	pH	6.1	3.6	2.8	2.0	1.3
HCl	Length (mm)	30 ± 2	28 ± 2	27 ± 2	3 ± 1	0
	% germination	100	92	98	88	0
	pH	5.6	4.0	3.0	2.0	1.25

Table 12. Biochemical and growth responses of jack pine seedlings grown in soil cores after 23 and 40 weeks of exposure to a single deposition of various pollutants and their mixtures. Values are means ± 95% confidence limits; n = 5. (Adapted from Addison et al. 1982.)

Treatment[a]	Peroxidase (Units/mg protein)		Growth (g dry weight/seedling)	
	23 weeks	40 weeks	23 weeks	40 weeks
Control	2.8 ± 0.7	6.7 ± 2.1	0.35 ± 0.14	3.47 ± 1.53
V	2.6 ± 0.3	7.6 ± 3.9	0.15 ± 0.07	2.99 ± 1.64
Ni	2.9 ± 1.6	7.6 ± 2.2	0.19 ± 0.04	3.07 ± 0.96
SO_4	2.2 ± 0.4	8.5 ± 3.6	0.33 ± 0.11	3.23 ± 2.87
V + Ni	3.0 ± 1.1	8.2 ± 2.9	0.20 ± 0.10	2.48 ± 1.01
V + SO_4	ND[b]	6.9 ± 3.6	0.25 ± 0.01	3.28 ± 3.26
V + NO_3	ND	6.1 ± 4.1	ND	2.64 ± 1.26
Ni + SO_4	3.1 ± 1.0	8.2 ± 1.3	0.15 ± 0.05	1.91 ± 0.70
Ni + NO_3	ND	6.3 ± 1.2	ND	3.15 ± 1.89
SO_4 + NO_3	ND	7.7 ± 2.9	ND	4.07 ± 1.63
V + Ni + SO_4	2.9 ± 0.7	7.3 ± 2.1	0.26 ± 0.05	3.34 ± 1.07
V + SO_4 + NO_3	ND	6.7 ± 3.9	ND	3.39 ± 1.05
Ni + SO_4 + NO_3	ND	7.4 ± 2.5	ND	2.82 ± 1.45
V + Ni + SO_4 + NO_3	ND	6.3 ± 3.2	ND	3.12 ± 0.41

[a] Treatments represent a single application of the equivalent of 104 years of soluble deposition to the LFH horizon.

[b] Not determined.

Table 13. Effect of various pollutants and their mixtures on major cations and sulfur content in the soil solution of soil cores. Values are means ± 95% confidence limits; n = 5. Deposition concentrations represent equivalents of years of deposition in the immediate vicinity of the Suncor operations. (Adapted from Addison et al. 1981.)

Treatment	Deposition equivalents (Years)[a]	pH	Concentration (mg L^{-1}) Ca	Mg	K	S
Al	13	5.4 ± 0.3	6.7 ± 2.2	1.0 ± 0.4	5.4 ± 2.4	9.4 ± 5.0
	26	5.6 ± 0.2	6.8 ± 3.5	1.2 ± 0.8	5.9 ± 2.3	8.4 ± 3.5
	52	5.7 ± 0.6	6.6 ± 4.2	1.1 ± 0.6	6.7 ± 5.2	7.3 ± 4.9
Ni	13	5.7 ± 0.1	10.4 ± 7.1	1.7 ± 1.3	7.6 ± 4.2	15.6 ± 10.4
	26	5.2 ± 0.3	12.4 ± 10.0	2.3 ± 1.9	9.1 ± 7.5	18.5 ± 14.5
	52	5.7 ± 0.4	7.3 ± 3.6	1.4 ± 0.7	6.0 ± 2.7	10.7 ± 7.3
SO_4	13	5.5 ± 0.2	22.5 ± 10.0	4.2 ± 1.6	7.8 ± 3.1	29.8 ± 13.6
	26	5.3 ± 0.3	29.7 ± 14.6	6.2 ± 3.1	13.5 ± 9.7	33.4 ± 22.3
	52	5.1 ± 0.4	47.2 ± 29.1	11.4 ± 11.2	23.4 ± 15.3	70.7 ± 47.5
V	13	5.5 ± 0.1	6.5 ± 6.4	1.1 ± 1.6	5.4 ± 6.3	7.6 ± 7.2
	26	5.6 ± 0.4	8.4 ± 2.3	1.3 ± 0.8	7.6 ± 4.9	9.2 ± 4.6
	52	5.1 ± 0.6	7.3 ± 3.3	0.9 ± 0.4	9.6 ± 9.2	10.7 ± 4.9
V + Ni	26	5.5 ± 0.4	6.8 ± 6.7	1.2 ± 1.3	10.3 ± 9.6	9.8 ± 8.2
V + SO_4	26	5.2 ± 0.9	41.9 ± 17.9	8.3 ± 2.6	21.3 ± 7.7	44.1 ± 29.4
Ni + SO_4	26	5.3 ± 0.2	25.1 ± 23.8	6.2 ± 8.7	12.9 ± 6.3	37.0 ± 33.2
V + Ni + SO_4	26	5.4 ± 0.3	26.5 ± 15.6	5.2 ± 3.7	20.8 ± 10.3	30.7 ± 16.9
Control		5.5 ± 0.1	8.1 ± 1.9	1.4 ± 0.3	6.1 ± 1.3	10.6 ± 2.0

[a] Deposition rates from Barrie (1978) in mg m^{-2} a^{-1} are Al = 5.47, Ni = 4.09, S = 306.6, and V = 36.28.

Table 14. Effect after 15 weeks of various pollutants and their mixtures on growth and enzyme content of jack pine seedlings grown on soils with and without LFH. Values are averages of three replicates. (Adapted from Addison et al. 1981.)

Treatment[a]	Peroxidase (Units/mg protein)		RuBP carboxylase (Units/mg protein)		Growth (mg dry weight/seedling)	
	+ LFH	− LFH	+ LFH	− LFH	+ LFH	− LFH
V	5.8	5.4	6.0	1.7	189	49
Ni	4.4	3.5	8.0	4.5	219	63
SO_4	4.6	4.3	5.6	3.7	225	60
NO_3	4.6	5.8	8.0	5.8	212	98
V + Ni	4.3	4.1	6.8	5.4	170	85
V + SO_4	4.7	5.4	5.6	3.2	186	44
V + NO_3	6.2	5.7	7.8	5.3	181	105
Ni + SO_4	5.3	4.7	7.4	6.5	248	100
Ni + NO_3	3.7	5.2	7.0	4.1	166	81
SO_4 + NO_3	4.7	6.4	7.1	6.2	230	170
Control	4.7	4.5	7.7	4.8	208	56

[a] Treatments represent a single application of the equivalent of 104 years of soluble deposition to the LFH horizon.

Table 15. Response of *Evernia mesomorpha* to SO_2 fumigation in terms of net CO_2 assimilation rate and respiration rate, both in mg of CO_2 per dry weight per h; means ± 95% confidence limits[1]. In each cell, n = 16. (Adapted from Huebert et al. 1985.)

Duration (h)	Fumigation SO_2 concentration (μL L^{-1})					
	0	0.040	0.085	0.175	0.265	0.355
				Net assimilation rate		
1	1.6 ± 0.3 Aa	1.7 ± 0.5 Aa	1.0 ± 0.2 Ba	0.6 ± 0.2 Ba	−0.1 ± 0.2 Ca	−0.2 ± 0.2 Ca
2	1.7 ± 0.3 Aa	1.8 ± 0.4 Aa	1.1 ± 0.2 Ba	0.0 ± 0.2 Cb	−0.3 ± 0.1 Cb	−0.3 ± 0.1 Ca
4	2.0 ± 0.4 Aa	1.9 ± 0.3 Aa	1.0 ± 0.3 Ba	−0.2 ± 0.2 Cb	−0.2 ± 0.1 Cab	−0.3 ± 0.1 Ca
6	1.9 ± 0.5 Aa	1.6 ± 0.4 Aa	1.0 ± 0.4 Ba	−0.2 ± 0.1 Cb	−0.4 ± 0.1 Cb	−0.3 ± 0.1 Ca
				Respiration rate		
1	0.8 ± 0.1 Aa	0.8 ± 0.1 Aab	0.8 ± 0.1 Aab	0.8 ± 0.1 Aa	0.7 ± 0.1 Aa	0.6 ± 0.1 Aa
2	0.7 ± 0.1 Ba	1.0 ± 0.1 Aa	1.0 ± 0.2 Aa	0.8 ± 0.1 ABa	0.7 ± 0.1 Ba	0.5 ± 0.1 Ca
4	0.7 ± 0.1 Aa	0.8 ± 0.1 Ab	0.7 ± 0.1 Ab	0.8 ± 0.1 Aa	0.4 ± 0.1 Bb	0.3 ± 0.1 Bb
6	0.8 ± 0.1 ABa	0.7 ± 0.1 ABCb	1.0 ± 0.1 Aa	0.8 ± 0.1 ABa	0.6 ± 0.1 BCab	0.5 ± 0.1 Ca

[1] Across rows, cells with the same capital letter are not significantly different at $p < 0.05$. Down columns, cells with the same lower case letter are not significantly different. When comparing pairs of means, only differences greater than 0.2 exceed the error in measurement.

Based on this study, neither the concept of dose (concentration X time) nor that of threshold levels of SO_2 is supported for lichens. Peak exposures to SO_2 for short periods when lichens are active (moist) may be of primary importance in determining the survival of lichens in industrial areas and particularly around point sources such as oil sands plants.

Vascular plant studies

A similar approach (concentration X duration of fumigation matrix) was taken with the physiology of jack pine. A variety of physiological parameters was measured to determine the nature of the response of this species to SO_2 (L'Hirondelle and Addison 1985). Jack pine seedlings were exposed to a series of SO_2 concentrations (0.1 to 1.0 $\mu L\ L^{-1}$) and durations of fumigation (0 to 96 h) under controlled conditions. Leaf conductance, xylem tension, and fructose level decreased and S content increased as SO_2 concentration and duration increased (Table 16). Few significant changes were detected before visible injury occurred. Stomatal response was not rapid, and complete closure was found only at high concentrations and long durations. Xylem tension lagged behind leaf conductance in response, but the pattern was similar. Changes in fructose levels were small and gradual. Sulfur content increased significantly with SO_2 exposure after 10 h of fumigation.

Multiple regressions, used to describe three-dimensional response surfaces for each variable, all included a crucial interaction term. A plot of predicted response surface for leaf conductance is shown in Fig. 4. At the longest durations, there were steep declines with increasing concentrations. At the shortest durations, concentration had much less influence on leaf conductance. The predicted decreases were relatively steep in the first few hours of fumigation for all but the lowest SO_2 concentrations, and there were more-gradual decreases after 24 h duration. Although the regressions were highly significant, their predictive power was limited owing to the high natural variability in the seedlings.

In both lichen and pine fumigation experiments, attempts were made to determine in a quantitative manner the way in which the duration of exposure and the concentration interacted. The objective of this approach was to make the initial links between air quality modeling and biological responses. To date very few attempts have been made in this area, and it is felt that until a link between air quality and receptor response can be made, little consideration of the effects of air pollution will be given in decisions on industrial development.

Intermittent Fumigation Studies

In 1983–84, a redirection of the research efforts of the Northern Forestry Centre was made from the long-term objective of trying to link air quality modeling and biological responses to the more short-term objectives on pollution episodes required by Alberta Environment's Research Management Division.

The major objectives were 1) to determine the impact of various frequencies of exposure to a common episode of SO_2 fumigation on aboveground biomass production of greenhouse-grown jack pine and aspen and 2) to examine the influence of environmental history (long-term exposure to air pollutants) on the response of aspen and jack pine to episodes of SO_2.

An additional objective, carried over from the long-term objectives, was to study the distribution of pollutants within forest canopies.

Vascular plant studies

Field studies in the Athabasca Oil Sands area have consistently failed to show any physiological, biochemical, or biomass changes resulting from air pollution in several common boreal forest tree species (Malhotra 1979; Addison 1983). In contrast, laboratory studies have shown both aspen and jack pine to respond quickly to constant SO_2 fumigation (Karnosky 1976; Addison, Malhotra, and Khan 1984; L'Hirondelle and Addison 1985). The difference in tree sensitivity between field and laboratory fumigations may be largely due to the sporadic nature of the field fumigation episodes and the ability of plants to recover fully during periods of low or no SO_2 (L'Hirondelle et al. 1986).

In order to accomplish objective 1, 5-week-old aspen and 8-week-old jack pine seedlings were exposed to a 3-h SO_2 fumigation episode (peak = 0.78 $\mu L\ L^{-1}$, mean = 0.30 $\mu L\ L^{-1}$) zero, two, or five times per week. Intermittent SO_2 fumigation for 7 to 8 weeks had no consistent significant effect on aboveground biomass or prefumigation net CO_2 assimilation rate (NAR) and leaf resistance (R_L) of either species. A significant decrease (up to 47%) in biomass of fumigated jack pine seedlings was found at 6 weeks, but at 7 weeks the decrease was not significant (Fig. 5). There were, however, significant transient effects of SO_2 on NAR and R_L of both species. The maximum decrease in aspen NAR was 38% during fumigation and 13% immediately after fumigation. The maximum postfumigation NAR decrease for jack pine was 18%, and the mean decrease was 12% over 6

Table 16. Means ($\bar{Y}$) and predicted means ($\hat{\bar{Y}}$) of physiological responses of jack pine seedlings exposed to SO_2 (adapted from L'Hirondelle and Addison 1985)

Duration (h)	Concentration (μmol m^{-3})	Leaf conductance (cm s^{-1})		Xylem tension (kPa)		Fructose level (mg g^{-1} dry weight)		Sulfur level (mg g^{-1} dry weight)	
		$\bar{Y}$	$\hat{\bar{Y}}$[a]	$\bar{Y}$	$\hat{\bar{Y}}$	$\bar{Y}$	$\hat{\bar{Y}}$	$\bar{Y}$	$\hat{\bar{Y}}$
Control[b]		0.195[c]	—[d]	1 010	—	17.4	—	2.13	—
2	4	0.145[e]	0.158	980	1 040	16.9	16.5	1.78	1.75
2	16	0.161	0.139	940	970	15.3	15.8	2.02	1.98
2	23	0.144	0.132	830	940	15.9	15.6	2.02	2.03
2	39	0.074	0.119	850	880	14.0	15.1	2.30	2.12
6	4	0.164	0.170	1 070	1 030	16.5	15.9	1.92	1.83
6	16	0.149	0.122	850	830	14.2	14.6	2.21	2.22
6	23	0.198	0.104	830	760	14.7	14.1	2.37	2.31
6	39[f]	0	0.070	770	610	13.6	13.1	2.40	2.46
10	4	0.139	0.175	1 060	1 030	15.6	15.6	1.68	1.88
10	16	0.130	0.115	880	770	15.1	14.0	2.48	2.38
10	23[f]	—	0.091	790	670	14.5	13.4	2.47	2.51
10	39[f]	0.072	0.047	500	490	11.9	12.2	2.59	2.69
24	4	0.188	0.185	1 020	1 020	15.5	15.1	1.92	2.01
24	16[f]	0.158	0.101	700	670	13.2	13.0	2.75	2.78
24	23[f]	0.038	0.068	310	530	11.8	12.2	3.04	2.99
24	39[f]	0	0.008	230	280	11.1	10.7	3.11	3.27
30	4	0.187	0.187	1 040	1 020	14.0	15.0	2.00	2.06
30	16[f]	0.094	0.098	560	640	12.2	12.8	3.19	2.91
30	23[f]	0.016	0.062	410	490	11.0	11.9	2.84	3.14
48	4	0.194	0.192	1 000	1 010	14.3	14.7	2.11	2.16
48	16[f]	0.069	0.090	460	580	12.6	12.2	3.40	3.25
96	4	0.181	0.200	940	1 000	14.2	14.3	2.43	2.38
96	16[f]	0.117	0.080	710	500	11.2	11.4	3.95	3.91

[a] Calculated from multiple regression equations.
[b] No SO_2.
[c] Mean of 157 replicates (controls only).
[d] Cannot be calculated.
[e] Mean of 8 replicates (all SO_2 treatments). The 95% comparison intervals (minimum significant differences) are 0.080, 220, 3.4, and 0.58 for dependent variables leaf conductance, xylem tension, fructose level, and S level, respectively.
[f] Produced visible symptoms.

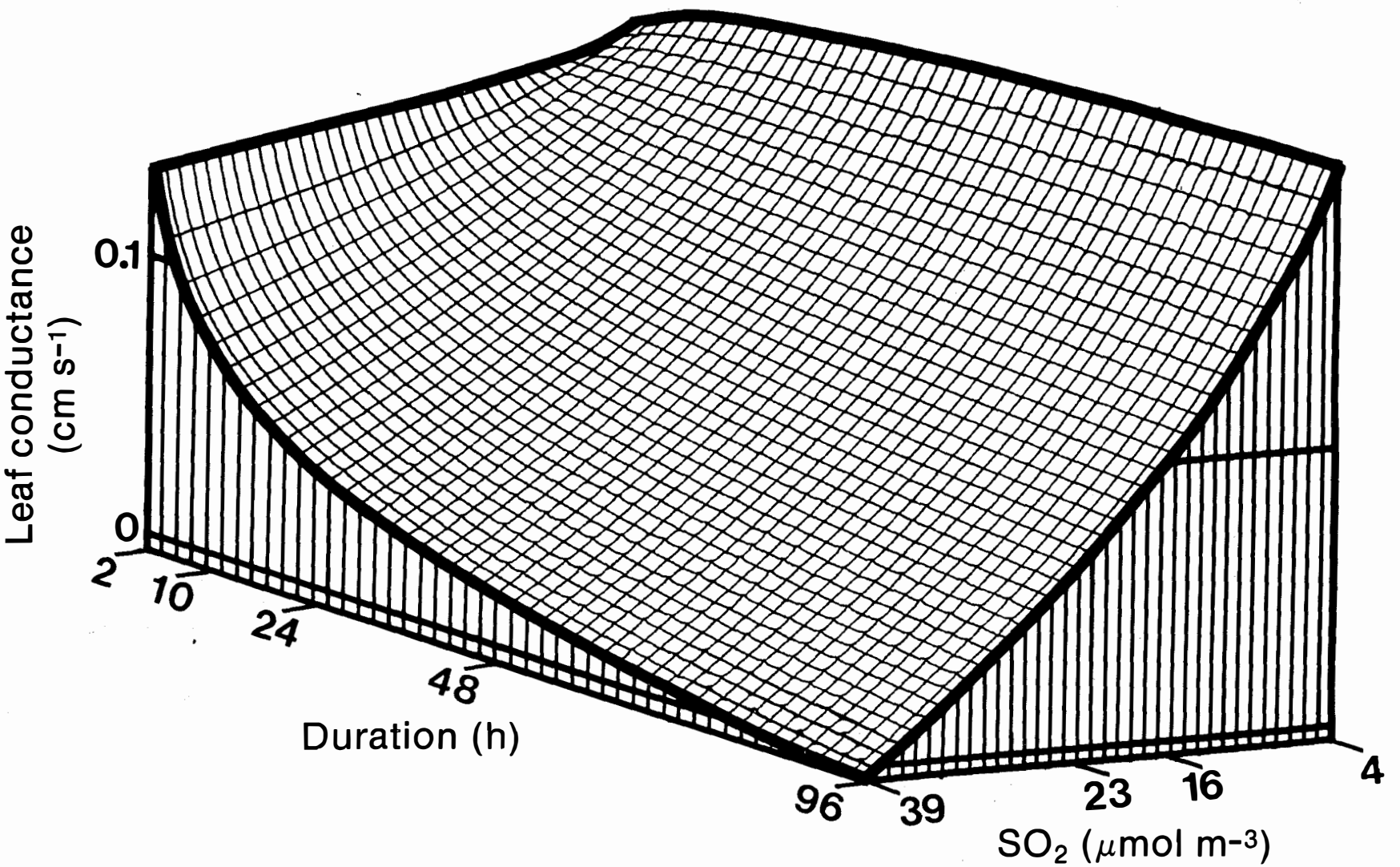

Figure 4. Predicted response for leaf conductance of jack pine seedlings exposed to SO_2. (Adapted from L'Hirondelle and Addison 1985.)

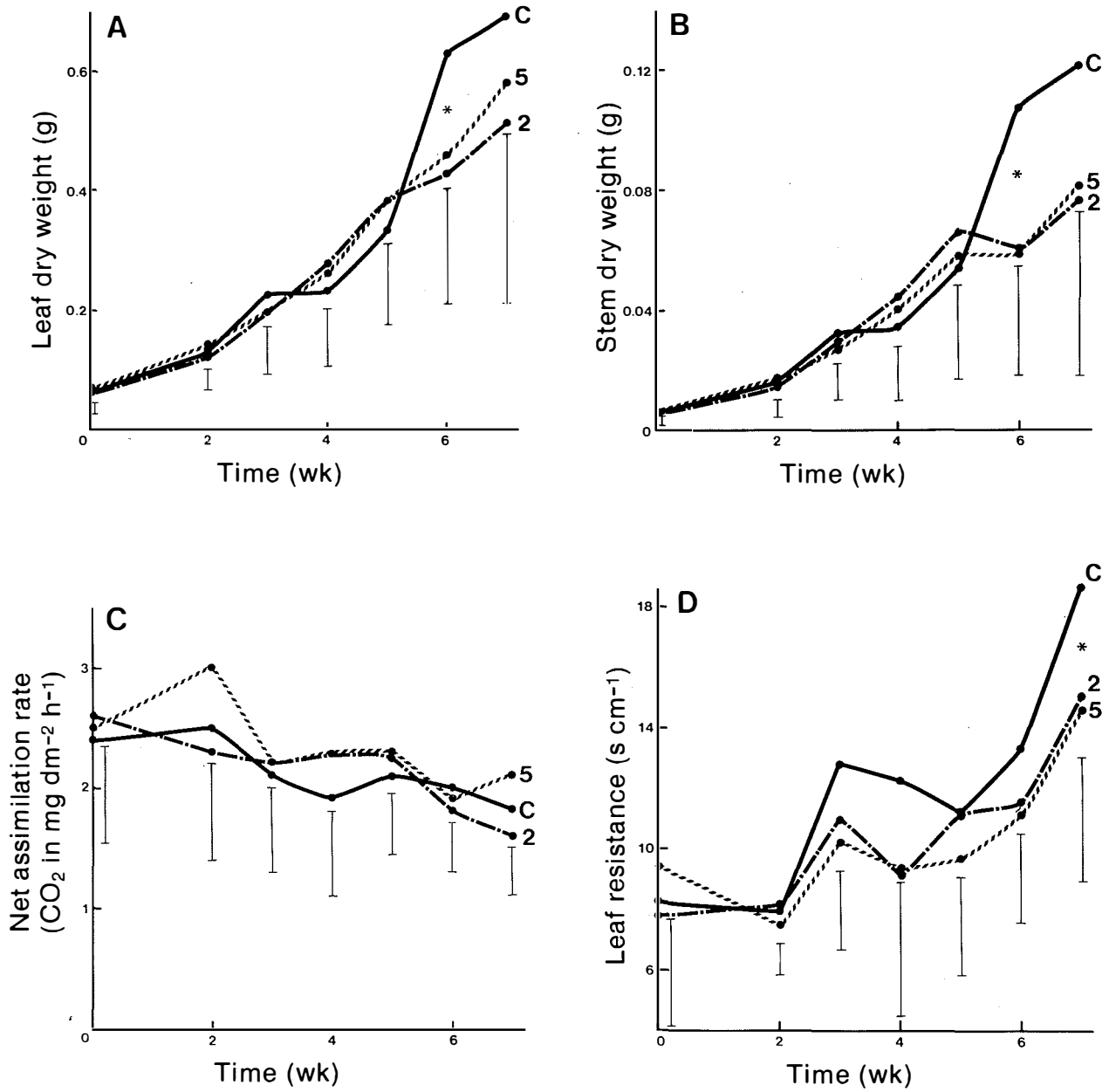

Figure 5. Effects of 3-h SO_2 fumigation episodes (peak = 0.78 μL L^{-1}, mean = 0.30 μL L^{-1} SO_2) given zero (C), two, and five times per week on *A* leaf dry weight, *B* stem dry weight, *C* net assimilation rate, and *D* leaf resistance of jack pine seedlings. At each harvest time, 95% confidence limits are shown by a line and significant differences ($p < 0.05$) are shown with an asterisk. (Adapted from L'Hirondelle et al. 1986.)

weeks. Aspen R_L increased up to 47% during fumigation and 20% after fumigation. Both species showed full recovery from transient SO_2 effects and no increased sensitivity to fumigation with time.

Laboratory work with field-collected cut branches of aspen showed significant responses of NAR and R_L to SO_2 fumigation (L'Hirondelle et al. 1986). Both sets of branches (from high and medium impact sites in the oil sands area) showed a 30% decrease in NAR after a 3-h episode. The differences in environmental history (frequency and concentration of SO_2) at the two aspen sites in the field apparently had no lasting effects on NAR since there were no significant differences in pre- or postfumigation NAR between the sites.

The low frequency of damaging SO_2 episodes in the field apparently allows full recovery of physiological processes between fumigations. In our laboratory study, there was recovery from even the highest fumigation frequency, which greatly exceeded the number of episodes recorded in the field. It is therefore not surprising that neither physiological (Malhotra 1979) nor growth changes (Addison 1983) have been reported near oil sands operations in northeastern Alberta.

Effect of Canopy Type

A study on the distribution of pollutants within forest canopies was initiated to make the connection between the output of the air quality models (ground level concentration, which is actually determined at the top of the forest canopy) and the concentrations to which various types of receptor plants are actually exposed.

Sulfation plates (six replicates) were maintained at six heights in three forest types for a period of 8 months. The vertical distribution of sulfation was highly dependent upon the type of forest stand (Fig. 6). A second-order polynomial was fitted to sulfation rate versus height for both pine and spruce stands. The amount of S deposition at 1.5 m in the pine stand was 40–45% of the above-canopy value, whereas in the spruce stand it was only 13–19%. The aspen stand showed a totally different pattern in that deposition increased with height from the ground surface, decreased with height into the tree canopy, and decreased above the canopy. This indicates penetration of the plume into the canopy similar to that observed by Legge et al. (1978) in an exposed lodgepole pine stand.

CONCLUSIONS AND RECOMMENDATIONS

It was possible to demonstrate through biomonitoring that pollutants characteristic of oil sands operations were not evenly distributed in the Athabasca Oil Sands of Alberta. Distinct gradients in lichen, moss, and vascular plant elemental content and in sulfation rate were observed in the vicinity of the Suncor operations during 1976–80. Plant responses such as vascular plant community changes and tree growth could not be related to pollutant deposition, whereas lichen community change and thallus condition, and jack pine seed germination, and needle retention appeared to be influenced by air pollution. Soil chemical measurements, although highly variable, showed indications of pollutant deposition. These measurements are essential for the characterization of the site and may help in monitoring if deposition is great or long-term.

In the laboratory, physiological and biochemical techniques were able to detect injury before the onset of visual symptoms. When these techniques were used in the field, however, no significant differences were observed in any of the physiological or biochemical responses. It appeared that the capability for plants to recover from episodes of SO_2 fumigation in the field is great and that both the concentration and the duration of exposures would have to increase substantially before gaseous effects on trees will be observed. There was no evidence for the sensitization of plants to the pollutant gases.

The level of pollutants found in the oil sands area appeared to be sufficient to cause the observed reduction in the lichen communities. Lichen response is most likely controlled by the occasional high (i.e., $>0.2\ \mu L\ L^{-1}$) and extended SO_2 fumigations that occur. It was not possible to link responses to SO_2 of lichens and vascular plants. Although there appeared to be similar responses of *Evernia mesomorpha* and jack pine in the laboratory, dramatically differing responses to environmental conditions makes it impossible to relate responses to pollutants in the field.

Soil core experiments showed that there was little likelihood of heavy metals from Suncor having a deleterious effect on jack pine stands. The surface organic horizon had a tremendous capability to bind even soluble metals, thus preventing them from entering the mineral soil and moving into plant roots. In addition, the levels of metals are very low and the natural variation in the soil system made it virtually impossible to detect metal deposition.

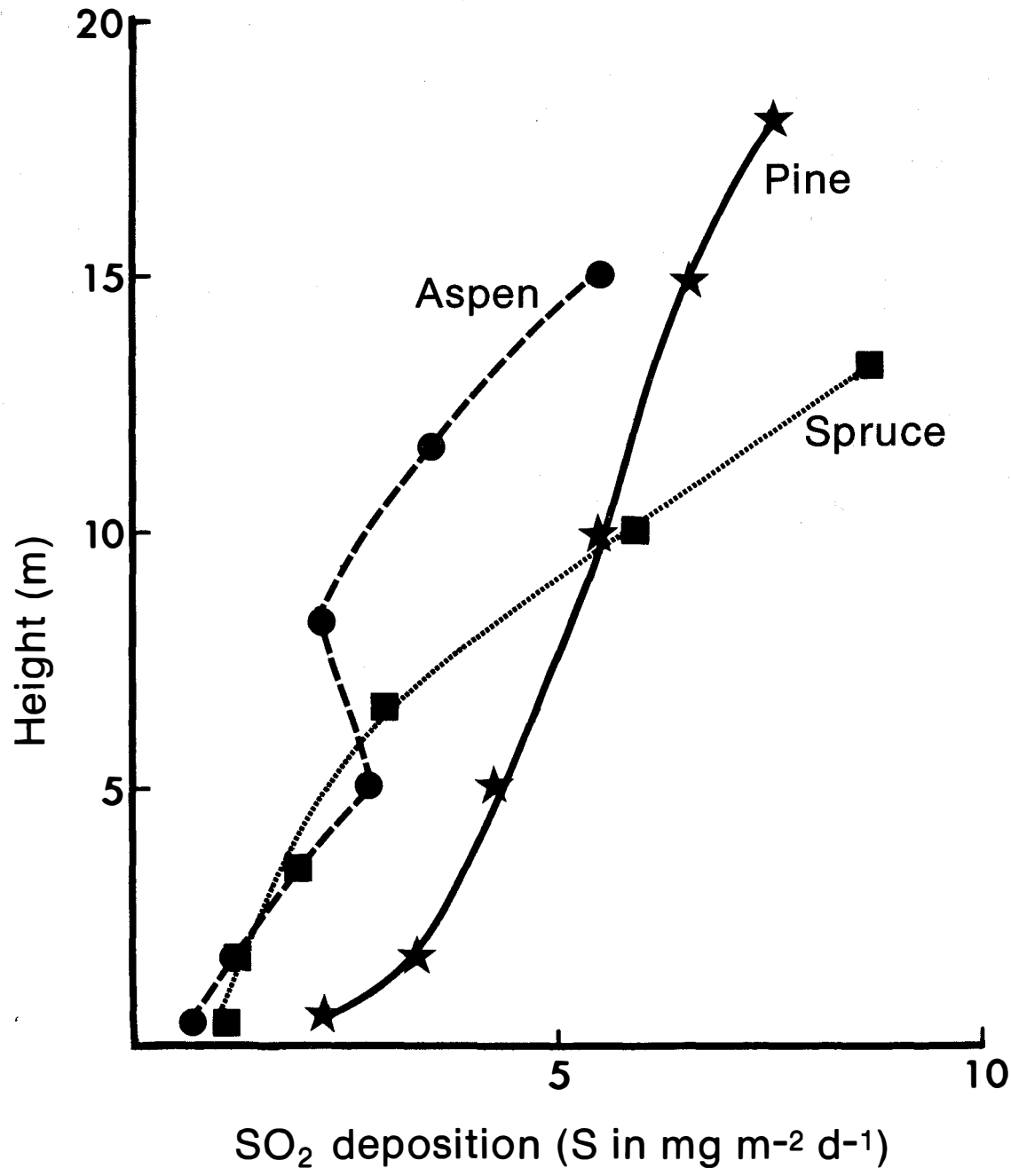

Figure 6. Profiles of SO_2 deposition to sulfation plates in three boreal forest stands in the Athabasca Oil Sands area. (Adapted from Addison 1983.)

The major recommendation coming from 10 years of work in the Athabasca Oil Sands area is that efforts should be made to link the output from computer simulations of air quality to biological responses. Unless biological responses can be related to air quality standards and the distribution of pollutants as predicted, they will not be considered in the process of locating new industrial developments. The job is ominous, since relationships between the so-called ground level concentrations at the top of the forest canopy and the concentrations to which the receptor organism is exposed must be determined. In addition, it is necessary to determine the complex relationships between concentration and duration of exposure and the role of environmental factors such as soil nutrients, moisture, temperature, and pathogens in modifying responses.

Having modelers and biologists working together would not be without benefits to modeling. Models are of no practical use without verification, and often biological measures can be used for that purpose as was done here. Checks in research are needed, because both biology and modeling are imprecise sciences.

In conclusion, there is a real need to study the mode of action of air pollutants in forest systems, and the dramatic impact that pollutants are having in Europe has driven that point home. It is apparent, however, that the Athabasca Oil Sands area of Alberta is not the area where that work should be done, unless researchers are willing to wait for potential long-term effects.

The following are specific recommendations arising from the 10 years of work reported here to ensure that any detrimental effects of oil sands processing can be detected.

1. Continue to maintain and monitor permanent biomonitoring plots where the elemental content and other physical characteristics of the soil and plants are determined every 5 to 10 years.

2. Occasionally (5–10 years) collect lichen samples (e.g., *Hypogymnia physodes*) for elemental analysis over the region as a whole to provide an update of the current pollutant distribution pattern without the expense of continuous monitoring.

3. Determine the relationship between ground level concentrations provided by computer simulations of pollutant distribution and the actual concentrations to which various receptor organisms in the dominant forest types are exposed.

4. Through a combination of existing networks of sulfation candles (industry and government), evaluate the effectiveness of the air quality models to predict the ground level concentrations in the area. Undoubtably these networks will need to be supplemented with some monitoring.

There are many reasons why one would *not* expect to see air pollution effects in the Athabasca Oil Sands area; however, the risk dictates that monitoring continue.

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