EFFECTS OF AIR POLLUTANTS ON THE FOREST ECOSYSTEM: A REVIEW

by

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EXECUTIVE SUMMARY

Air pollution and its effects on various ecosystems has been a subject of increasing controversy. The European forest damage situation has heightened the public's awareness of the problem.

Historically, the observed pollution damage was believed to be due mainly to sulphur dioxide pollution. Recent research has indicated that other factors including nitrogen oxides, ozone and other photo-oxidants, and various climatic conditions contribute to the problem. The possibility of a multiple-pollutant effect is recognized and is leading to a more multi-disciplinary approach to the study of the effects of air pollution on forest ecosystems.

In Canada, research has centred around the higher emission areas in the eastern part of the country. In the western provinces, there is a concern that the forests may be adversely affected in the long term. Alberta is in a fortunate situation because most of its soils are underlain by calcareous bedrock and can, therefore, neutralize in-coming acids more efficiently than areas covered by the Canadian Shield. However, sensitive areas do exist, and the long-term impact of continuous inputs into the system is not yet fully understood.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

Figures

Maps

LIST OF TABLES

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1. INTRODUCTION

1.1 Purpose of Report

This report provides a summary of information of the effects of air pollution on the forest ecosystem and a list of reference material on this topic. It is intended for use primarily by Alberta Forest Service staff. The Technical Development Section carried out a review of scientific literature available within the branch as well as interviews with key persons involved in this field in Alberta.

1.2 Present Concerns

Emissions of air pollutants into the atmosphere eventually return to the earth as wet or dry deposition. These pollutants include sulphur compounds, nitrogen oxides and heavy metals, and their adverse effects on some ecosystems has drawn world-wide attention. Ozone, although not emitted into the atmosphere, can be formed in the presence of sunlight by a chemical reaction between nitrogen oxides and various hydrocarbons. It is a component of photochemical smog and has, therefore, been considered a major cause of plant injury in some areas (Sub-Committee on Acid Rain 1981). Historically, public concern has been predominantly in the area of human health. More recently, impact on wildland recreation and forest decline have become a concern, and the latter is the focus of this report.

1.3 Acid Rain

By definition all natural rainfall is acidic, in the range of pH 5.5 to 6.0, but with the addition of sulphur and nitrogen oxides, it can acidify to pH 3.0 or more.

Acidic waters and loss of fish come to mind when acid rain is mentioned. The term acid rain has negative connotations when considered in relation to the forest ecosystem and fisheries resources. Air pollutants have been identified as a cause of damage to forests in several countries, but the severity of the impact depends on site-specific factors. These include the amount of atmospheric input, nutrient status of the soil (Johnson et al, 1982), elevation and climatic factors.

The popular term acid rain implies only part of the problem, for precipitation is only one mode of depositing these compounds, and not all deposits are acids. Rather, the term air pollution is preferred and is used in this report.

Air pollution, and the associated increased levels of acidic deposition, is a world-wide concern, but each portion of the globe can be affected differently by emissions. Owing to its uniqueness in terms of atmospheric, geologic and geographic location, the Alberta scenario is discussed here with emphasis on the productive forests.

2. THE WORLD SITUATION

2.1 Europe

2.1.1 Water Bodies

Acidification of water courses has been a major problem in Europe since the 1920s, but only recently has acidic deposition been identified as the cause. It is now estimated that 18 000 of Sweden's lakes are acidified; of these, approximately 2 500 are totally devoid of fish (Anon. 1983). The reduction of fish population has also been recorded in other European countries, including Norway, Scotland and parts of England and Wales (Anon. 1983). Liming of lakes is the only method of treating these waters and saving sensitive species of fish. However, the treatment is costly and is temporary if pollutants continue to be deposited.

2.1.2 Forests

In the past, death of trees near major sources of SO_2 emissions was understood, but today, die-back and decline are occurring at a slower rate in forests farther away from major sources of air pollution (Tomlinson 1983).

For example, in West Germany in 1982, it was estimated that forests covering 560 000 ha had been damaged to varying degrees, and SO_2 emissions and their reaction products were identified as the primary cause (Tomlinson 1983). One year later, a second survey concluded that forests on 2.5 million ha were damaged (Postel 1984). Czechoslovakia is the second largest producer of SO_2 in the world, and its forests too have been seriously affected. The Czechoslovak Academy of Scientists

(CSAV) has predicted that "if present trends continue, half of the woodland in Czechoslovakia will be severely damaged or destroyed by the end of the century" (Csepel 1984). Forests in Poland, too, have been severely damaged. If present industrialization plans materialize and increased burning of high-sulphur brown coals takes place, scientists fear the destruction of up to 3 million ha of forest by 1990 (Postel 1984).

Tree injury in Germany as well as in Czechoslovakia has been found in places where SO_2 concentration was lower than that deemed safe. Although several causes such as climatic extremes, insects and pathogens contribute to this injury, the fundamental cause is believed to be air pollutants (Tomlinson 1983). Crown die-back has been observed in France, Switzerland, Yugoslavia and Poland, and the drying out of foliage and loss of needles have been reported in parts of Scandinavia (Livingston 1982). Monitoring of emissions and studying their effects has been done for several years in these countries. The possibility that heavy metals play an important role in the observed tree decline is being investigated.

2.2 North America

2.2.1 Water Bodies

Water bodies have a certain buffering capacity, which is a measure of the potential of the water to neutralize incoming acids. Water bodies with a low alkalinity have a limited buffering capacity, and are, therefore, particularly sensitive to continual acidic deposition. This poses a problem for sport fishing since fish populations are greatly reduced when the pH of the water is below 4.5 (Sub-Committee on Acid Rain 1981).

In Northern Ontario, a region dominated by the Canadian Shield, many lakes have become acidified, and tourism, a major source of income for the people, is declining. The salmon fishery of Atlantic Canada is also threatened.

In the United States, the problem centers around the Adirondacks, where many lakes are acidified.

2.2.2 Forests

In the United States, forest growth has declined in several areas, mainly in those areas east of the Mississippi in the mountains of Pennsylvania, New York and New Hampshire (Sub-Committee on Acid Rain 1981). One of the most heavily damaged areas is Vermont, where it is estimated that nearly half the spruce trees have died, and seedling reproduction has also decreased by about half since 1965 (Anon. 1984; Vogelmann 1982). The Sierra Nevada Mountains of California have also been seriously affected. It is believed that the high mountain forests receive three to four times as much acidic deposition as those in lower elevations (Postel 1984).

In Canada, the major resources threatened by air pollution - sport fishing, tourism and the forest products industry - generate 8 per cent of Canada's Gross National Product (Anon. 1984). Forestry alone contributes $22 billion to the Canadian economy (Livingston 1982 and Sub-Committee on Acid Rain 1981). The areas most seriously affected in this country are Southern Ontario, Quebec and Atlantic Canada. INCO Ltd.'s smelting plant in Sudbury, Ontario is the largest point source sulphur dioxide emitter in North America (Wilson 1984). In the Sudbury smelting area, over 256 km^2 is almost devoid of vegetation and damage is visible over approximately 4 600 km^2 (Shewchuk et al 1981). The Noranda Mines Ltd. smelter in Rouyn, Quebec is the second largest emitter of the continent.

In Atlantic Canada, both New Brunswick and Nova Scotia have sources that produce significant amounts of air pollutants. Prince Edward Island has many areas that are sensitive to acidic deposits. The problem is complex because affected areas do not necessarily create their own problems. For example, Newfoundland is not a large producer of air pollution, yet its resources are in danger because the province lies in a path of prevailing winds and other weather systems which flow from the industrialized areas of northeastern and central North America (Sub-Committee on Acid Rain 1981).

Part of Canada's acidic precipitation originates in the U.S. because of the long-range transport phenomenon (Sub-Committee on Acid Rain 1981). For example, the Muskoka-Haliburton region of Ontario is particularly sensitive and American sources contribute up to 70 per cent of the emissions (Sub-Committee on Acid Rain 1981). Although it is difficult to link episodes of atmospheric deposition with any point source, the transboundary flow of air pollution is widely accepted. The prevailing winds are such that they tend to transport emissions from the U.S. into Canada (Sub-Committee on Acid Rain 1981). Co-operation between both countries is needed to find solutions to this problem.

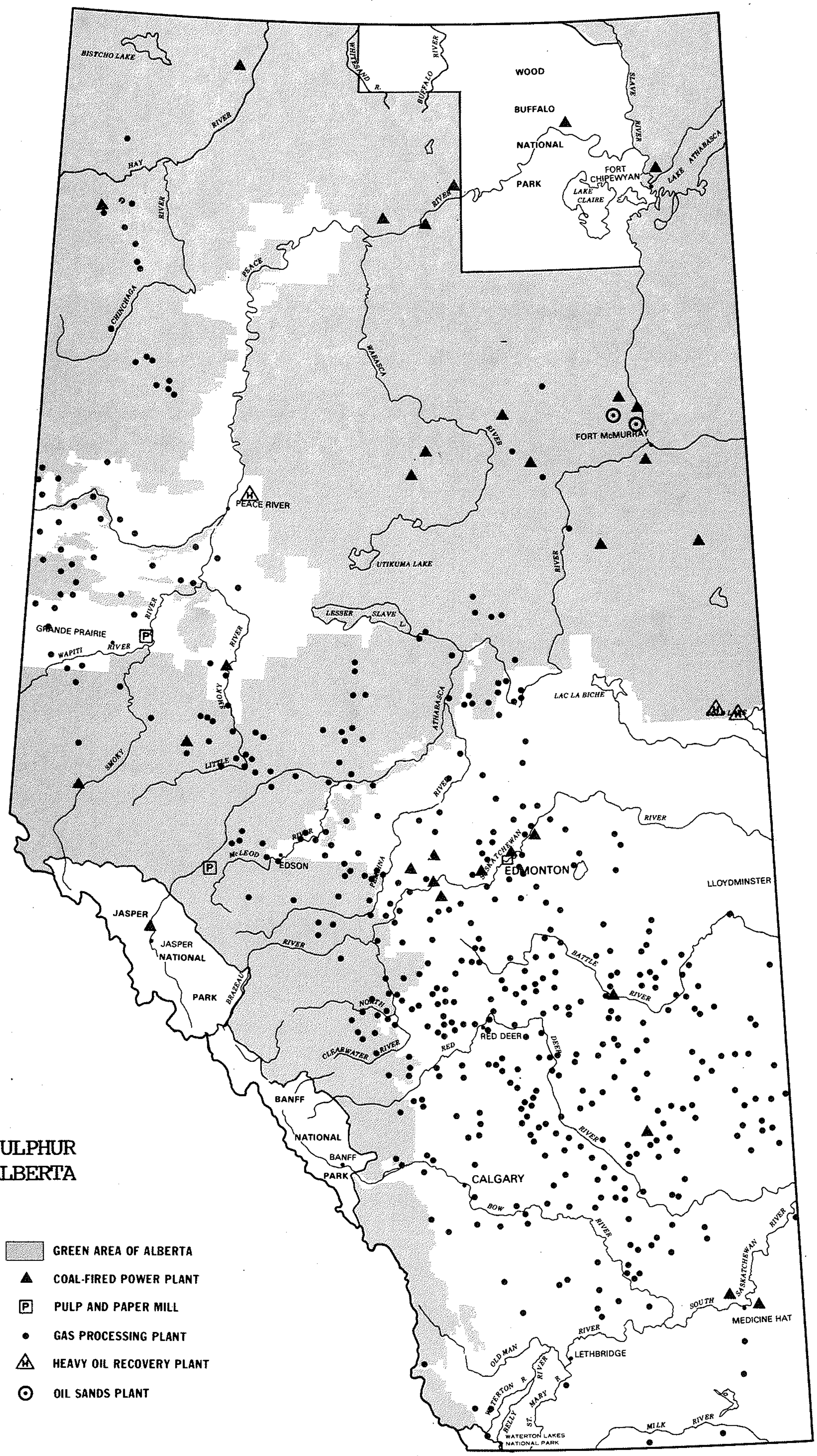
3. THE ALBERTA SITUATION

3.1 Emission Sources

The emission sources of sulphur compounds in Alberta's Green Area are: sour gas processing plants, oil sands plants, coal-fired power plants, sour oil production facilities, pulp and paper mills and heavy oil recovery plants. The majority of the sour gas plants are in the sour-gas corridor which runs northwest from Calgary to Grande Prairie (see Map 1). Another area with relatively large amounts of SO_2 emissions is the oil sands area near Fort McMurray.

The major source of nitrogen oxides emissions is automobile exhaust. Power plants (other than coal-fired) are also significant contributors. For this reason, the important source areas are the urban airsheds of Edmonton and Calgary. Since nitrogen oxides are precursors in the formation of ozone, these same areas will generally have the higher concentrations of ozone.

Alberta has relatively low emissions of air pollutants when compared to the rest of Canada (see Table 1). It does, however, have the highest emissions in the West. It cannot be concluded at this time that air pollution in Alberta has caused chronic damage of forest vegetation (Sandhu et al 1980), however, biological results of stress may take up to several decades to become identifiable (Sub-Committee on Acid Rain 1981).



MAP 1

LOCATION OF SULPHUR EMITTERS IN ALBERTA

TABLE 1

ANNUAL EMISSIONS OF SULPHUR DIOXIDE
AND NITROGEN OXIDES IN CANADA
BY PROVINCE - 1978

Province	Sulphur Dioxide	Nitrogen Oxides	Total Acid-Forming Emissions
Newfoundland	58.4	30.5	88.9
Prince Edward Island	5.7	6.8	12.5
Nova Scotia	187.0	85.1	272.1
New Brunswick	179.0	59.5	229.5
Quebec	1 119.4	331.7	1 451.1
Ontario	1 614.5	531.5	2 146.0
Manitoba	499.0	79.8	579.4
Saskatchewan	56.7	148.6	205.3
Alberta	526.4	377.7	904.1
British Columbia	236.0	172.5	408.5
Northwest Territories and Yukon	2.7	26.3	29.0
Total	4 484.8	1 850.0	6 326.4

Unit: thousands of tonnes

Source: Environment Canada 1983

3.2 Ecosystem Sensitivity

3.2.1 Water Bodies

It is not expected that water bodies in Alberta will be significantly damaged by air pollution. Except for the northeast corner of the province, Alberta waters have a high buffering capacity, and would therefore neutralize any anticipated acidifying deposits.

3.2.2 Soils

Soils have an important role in the determination of whether an area is susceptible to pollution damage. Holowaychuk and Lindsay (1982) define sensitivity of soils as "an expression of the susceptibility of different soils to relative degrees of change in their pH, base saturation and mobilization of exchangeable cations in response to given inputs of acidity". They stated that the buffering capacity (BFC) of a soil is the best indicator of its sensitivity and that the cation-exchange capacity (CEC) serves as a good index of the BFC.

It is generally accepted that the moderately-acid soils with a low CEC (and thus low BFC) are most susceptible to acidification by atmospheric deposits (Johnson et al 1982). Except for the northeastern corner of the province, most Alberta forest soils are calcareous, and thus have relatively high buffering capacity (Canadian Petroleum Association 1983). A soil sensitivity map is not yet available, but it can be generalized that areas with more acidic sandy soils and low organic matter have greater potential for being affected by atmospheric deposition than those soils with high clay and high organic matter content (Map 2 shows the distribution of the major soil groups in Alberta).

3.2.3 Vegetation

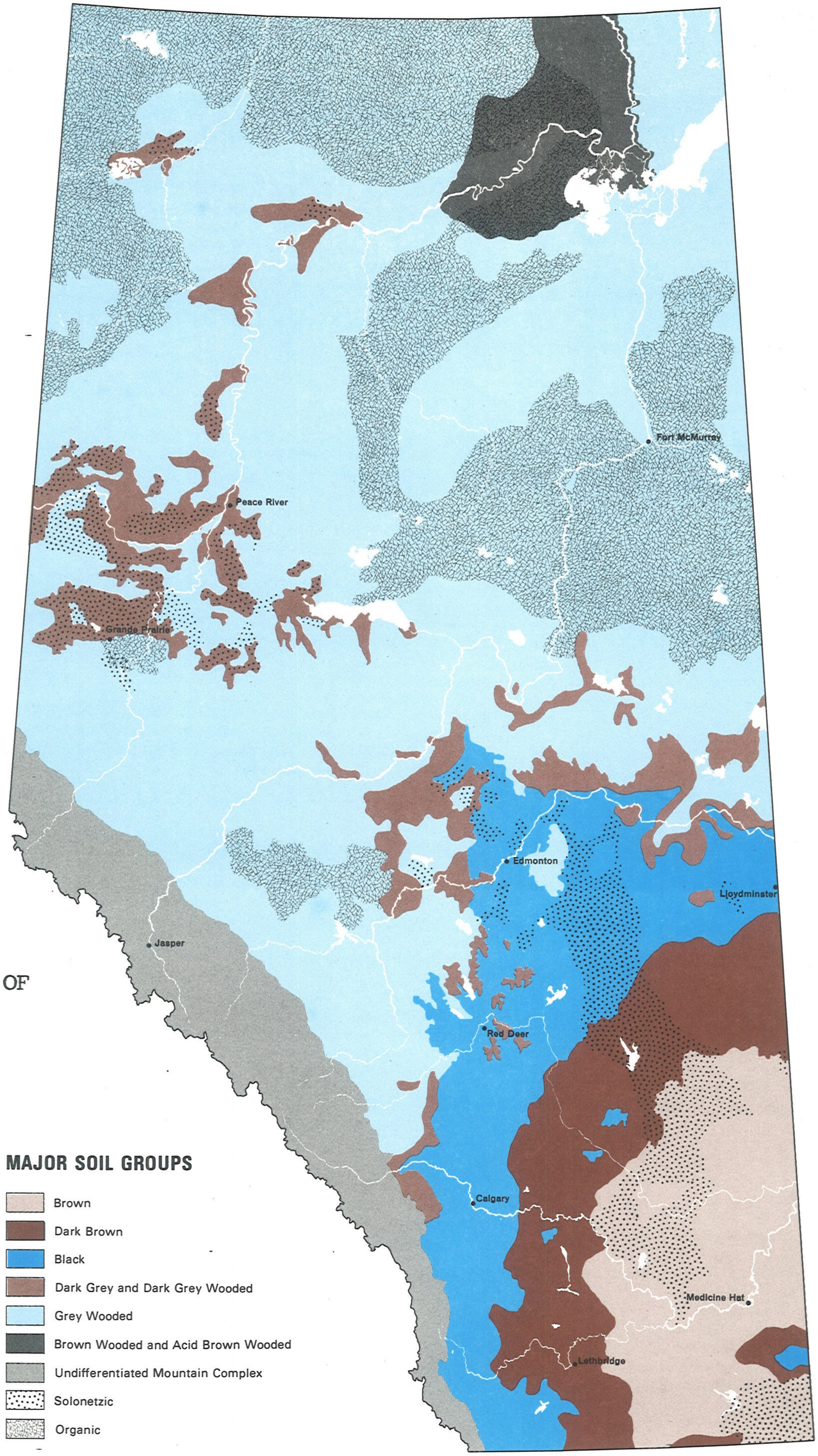
Air pollution damage to vegetation is a result of either direct or indirect effects. The former includes damage to foliage and inhibition of seed germination. The latter are considered to be of greater importance and are the result of nutritional effects on a plant which may cause stunting and a generally weakened tree (Johnson et al 1982).

Different tree species have different sensitivities to atmospheric pollution. Shewchuk et al. (1981) state that coniferous trees appear to be more tolerant of acidic precipitation than broad-leaved deciduous trees. However, there appears to be some controversy on this subject for some evidence suggests that conifers would be more susceptible to long-term damage than deciduous trees because of longer foliage retention time. As yet there is no satisfactory rating system available for species sensitivity to different air pollutants, but Table 2 shows the sensitivity of some Alberta species to SO_2 fumigation.

3.3 Air Quality Standards

The current pollution standards are established by a federal/provincial committee that periodically reviews existing scientific literature and sets the standards based on health and environmental protection objectives.

"The Alberta Ambient Air Quality Standards for sulphur dioxide are at present identical to the Federal 'Maximum Desirable Level', the most rigorous of the National Ambient Air Quality Levels for sulphur dioxide" (Loman 1982). Damage to vegetation is expected when this level is doubled. Our air quality standards are high, however, it is important to keep in mind that these levels do not guarantee that there will be no effect on the environment from air pollution. As has been seen in Germany and Czechoslovakia, damage was detectable when SO_2 levels were deemed safe.



MAP 2

SOIL ZONES OF ALBERTA

TABLE 2

SENSITIVITY OF SOME ALBERTA PLANT SPECIES TO FUMIGATION BY SO_2

VEGETATION TYPE	COMMON NAME	LATIN NAME
TREES		
Most Sensitive: (to foliar injury)	Balsam Poplar	Populus balsamifera L.
	Alder	Alnus tenuifolia Nutt.
	Trembling Aspen	Populus tremuloides Michx.
	White Birch	Betula papyrifera Marsh
	Willow	Salix spp.
Least Sensitive: (to foliar injury)	White Spruce	Picea glauca (Moench) Voss
SHRUBS		
Most Sensitive:	Wild Raspberry	Rubus strigosus Michx.
	Wild Gooseberry	Ribes lacustre (Pers.) Poir.
	Wild Rose	Rosa avicularis Lindl.
	Honeysuckle	Lonicera involucrata (Richards.) Banks
	Dogwood	Cornus stolonifera Mischx.
	Saskatoon	Amelanchier alnifolia Nutt.
	Low Bush Cranberry	Viburnum edule (Michx.) Raf.
	Bog Birch	Betula pumila L. var. glandulifera Regel
	Wolf Willow	Elaeagnus commutata Bernh.
Least Sensitive:	Bear Berry	Arctostaphylos uva-ursi (L.) Spreng.
HERBS		
Most Sensitive:	Fireweed	Epilobium angustifolium L.
	Sweet Coltsfoot	Petasites palmatus (Ait.) A. Gray
	Bunchberry	Cornus canadensis L.
	Wild Strawberry	Fragaria virginiana Dcne.
	Arnica	Arnica mollis Hook.
Least Sensitive:	Wild Aster	Aster ciliolatus Lindl.

Source: Hocking 1975 as cited by Sandhu et al 1980.

3.4 Overview

To date, several province-wide monitoring projects have been considered:

1. Canadian Forest Service proposed program - Acid Rain National Early Warning System (ARNEWS).
   Status - Program initiated in 1985. Five sites in the Green Area; will probably add two more in 1986.

2. Canadian Forestry Service - Long-range Transport of Air Pollutants (LRTAP).
   Status - Tentative initiation in Alberta in 1986 depending on funding. Sites have not yet been selected.

3. Alberta Environment - Pollution Control Division - Air Quality monitoring program
   Status - All sour gas plants in the Green Area are required to conduct monitoring in accordance with the Clean Air Permit.

4. Alberta Environment - Earth Sciences Division - Soil monitoring program
   Status - Alberta Environment has established long-term soil monitoring plots with one location in the Green Area (Athabasca Forest).

5. Alberta Forest Service - Timber Management Branch - Permanent Sample Plot program.
   Status - Sixteen PSPs in the Athabasca Tar Sands area were included in the Alberta Environment Research Division Program. This is being reviewed.

4. BACKGROUND INFORMATION

4.1 Air Pollutant Sources

4.1.1 Anthropogenic Sources

4.1.1.1 Sulphur Compounds. Table 3 lists sulphur emission sources in Alberta and amounts emitted per day.

To date, there have been no large-scale major impacts in Alberta due to medium- and long-range transport of sulphur emissions, but there is evidence of sulphur impingement on the ecosystem. As well, severe local effects due to elemental sulphur being wind-blown from near-by stockpiles have been observed (Sandhu et al 1980).

In a sour gas plant, SO_2 is emitted into the atmosphere from three main sources - the tall (incinerator) stack, the flare stack, and the compressors. The latter is often referred to as "fugitive sources". The tall stack is the source of low-level but steady emissions of SO_2 whereas the flare stack is used in an emergency to burn excess quantities of gas (Legge et al 1981).

Hydrogen sulfide (H_2S) is the main sulphur compound in sour gas. In a gas plant with a sulphur recovery unit, the H_2S undergoes several chemical reactions and is removed as elemental sulphur. Any H_2S not converted is incinerated in excess air and methane in a furnace at high temperatures, and is oxidized to SO_2.

Acidic deposits are the main concern of air pollution. Sulphur dioxide will react with water in the atmosphere to form weak sulphurous acid. If further oxidation takes place and sulphur trioxide reacts with water,a stronger compound, sulphuric acid, is formed. These reactions usually occur between water and oxides of sulphur; reactions involving sulphates may also occur (Canadian Petroleum Association 1983). The following reactions illustrate the above:

TABLE 3

SULPHUR EMISSIONS (OBSERVED VS. LICENSED IN TONNES/DAY) FROM VARIOUS FACILITIES OPERATING IN THE GREEN AREA OF ALBERTA FROM 1977 - 81*

SOURCE	1977	1978	1979	1980	1981
GAS PROCESSING PLANTS (with sulphur recovery)	261.1 (475.2)	256.0 (475.7)	259.1 (486.5)	250.6 (472.8)	212.8 (472.1)
GAS PROCESSING PLANTS (without sulphur recovery)	8.6 (20.5)	10.6 (31.0)	9.5 (26.5)	9.0 (25.2)	9.2 (38.4)
OIL SANDS PLANTS	112.3 (176.8)	147.4 (322.8)	124.8 (322.8)	201.8 (322.8)	193.6 (322.8)
COAL-FIRED POWER PLANTS	2.8 (4.7)	2.8 (4.7)	4.8 (9.2)	7.1 (9.2)	6.3 (9.2)
SOUR OIL PRODUCTION FACILITIES**	N/A	54.7 (N/L)	x51.2 (N/L)	x45.0 (N/L)	x41.0 (N/L)
PULP AND PAPER MILLS	21.3 (7.7)	18.7 (7.7+)	3.9 (7.7+)	9.8 (7.7+)	8.1 (7.7+)
HEAVY OIL RECOVERY PLANTS	N/O	N/O	0.0 (28.9)	3.2 (30.5)	3.9 (30.5)

* - Sulphur, not sulphur dioxide emission
- All figures are based on 365 days
- Terms in parentheses are licence values
- Plants with licence limits of less than 0.1 tonnes/day are not included in the list
- N/A - Not available, N/L - No licence required, N/O - Not in operation

** - This estimate was provided by the Energy Resources Conservation Board considering 324 batteries in 1978. Since 1979, 24 sour oil pools have been included in gas conservation schemes
- Taken directly from reference; not known how many of the batteries are in the Green Area

x - Only those facilities emitting 0.1 tonne/day or more were considered

Source: Industrial Sulphur Emissions for Alberta 1977-1981. Alberta Environment - Pollution Control Division

a) oxidation of H_2S by:

i) $$2H_2S + 3O_2 \longrightarrow 2H_2O + 2SO_2$$
ii) $$H_2S + O_3 \longrightarrow H_2O + SO_2$$

b) Hydrolysis of SO_2 by:

i) $$H_2O + SO_2 \longrightarrow H_2SO_3 \text{ (Sulphurous acid)}$$
ii) $$SO_2 + 2O_3 \longrightarrow 2SO_3 + O_2$$
$$H_2O + SO_3 \longrightarrow H_2SO_4 \text{ (Sulphuric acid)}$$

4.1.1.2 Nitrogen Oxides. The main sources of nitrogen oxides in Alberta occur in the White Area. Emissions from thermal power plants and the large source areas of Edmonton and Calgary are most significant (Legge et al 1980). Emissions from the Alberta Oil Sands plants are significant due mainly to power generation at the sites (Legge et al 1980; Peters and Sandhu 1980).

Although urban sources are greatest, effects are not limited to a city or its immediate area. In the Eastern U.S., the movement of pollutants from cities to rural areas several hundred kilometres away has been reported (Legge et al 1980). Similar possibilities exist in Alberta.

Tables 4 and 5 show emission sources and amounts emitted per year.

In high temperature reactions such as those occurring at industrial plants, nitrogen oxide (NO) is emitted to the atmosphere where it is oxidized to nitrogen dioxide (NO_2). If initial NO concentrations are low, photochemical reactions dominate.

TABLE 4

NITROGEN OXIDE EMISSIONS (tonnes/year)
FROM MAJOR SOURCES IN ALBERTA*

Source	1976	1977	1978	1979
INDUSTRIAL PROCESSES				
Fertilizer Plants	4 500	10 643	8 248	8 174
Chemical Plants	3 370	3 340	3 460	4 420
Refineries	1 893	1 917	1 933	1 949
Natural Gas Processing	127 960	133 387	132 133	116 696
Oil Sands Plants	N/A	16 000	8 600	16 000
Subtotal	137 723	165 287	154 374	147 239
FUEL COMBUSTION				
Power Plants	28 935	30 289	35 584	39 876
Residential	2 397	2 513	2 867	3 034
Commercial	3 508	3 698	4 083	4 292
Industrial	10 956	10 074	9 602	10 572
Heating	420	608	254	1 087
Subtotal	46 216	47 182	52 390	58 861
TRANSPORTATION				
Gasoline & Diesel Motor Vehicles	74 127	81 657	88 400	96 171
Railways	11 201	10 921	11 881	12 302
Subtotal	85 328	92 578	100 281	108 473
TOTAL	269 267	305 047	307 045	314 573

* Estimated as NO_2
N/A = Not Available

Source: Peters, R.R. and H.S. Sandhu 1980.

TABLE 5

NITROGEN OXIDES EMISSIONS (tonnes/year) FROM NATURAL GAS PROCESSING PLANTS IN ALBERTA*

Source	1976	1977	1978	1979
Compressors				
Sweet Plants	38 561	40 161	39 819	35 245
Sour Plants	80 247	83 880	83 049	73 409
Subtotal	118 808	124 041	122 868	108 654
Heaters and Boilers				
Sweet Plants	8 735	8 723	8 648	7 507
Sour Plants	597	623	617	535
Subtotal	9 332	9 346	9 265	8 042
TOTAL	128 140	133 387	132 133	116 696

* Estimated as NO_2.

The estimates are based on fuel data taken from Statistics Alberta (1976-79) and fuel usage fractions (percentage of plant fuel used for compressors and heaters and boilers) obtained from Dr. M. Winning (personal communication, Shell Canada Ltd. 1980). Plant fuel is defined by Statistics Alberta as coming from: (1) field, (2) gathering system, (3) injection, and (4) plants. Flared quantities are not involved in any of the data.

Source: Peters, R.R. and H.S. Sandhu 1980.

Nitric acid (HNO_3) is formed when NO_2 reacts with water in the presence of ozone (O_3).

$$\text{i)}\quad O_3 + H_2O \longrightarrow 0\ O_2 + 2(OH)$$
$$\text{ii)}\quad 2NO_2 + 2(OH) \longrightarrow 0\ 2HNO_3$$

Although nitrogen oxides are usually the reactants, reactions with nitrates may also take place.

4.1.1.3 Ozone. Ozone is abundant in the troposphere because it is the product of many reactions that nitrogen oxides undergo when producing photochemical smog. It also occurs in the stratosphere as a product of naturally occurring photochemical reactions. Concentrations are highest in stagnant air masses during the summer (Kulp 1985). City size, topographic and climatic features contribute to its high incidence. The reactions that involve ozone may take a long time, therefore, ozone and its precursors may be transported over long distances, although the major areas where it occurs as a pollutant are in urban center airsheds (Legge et al 1980).

Stratospheric air also contains Be^7, a radioactive isotope that exists in almost constant ratio with ozone, thus tracing stratospheric O_3 in the troposphere is relatively easy (Kulp 1985).

Ozone has been considered the most serious air pollutant, causing reduction in photosynthetic productivity of crops, and deterioration and death of trees in Europe and North America (Kulp 1985).

Nitrogen oxides play an important role in the photochemical formation of ozone. Nitrogen dioxide absorbs light and passes energy through various chemical processes. The concentration of ozone is, therefore, dependent on two things:

a) the intensity of sunlight, and
b) the ratio of NO_2:NO

The following reactions show the principles involved (Legge et al 1980).

i) NO_2 + light ⟶ $O(^3P)$ + NO
ii) $O(^3P) + O_2 + M$ ⟶ $O_3 + M$
where $M = N_2$, O_2 or other molecule
iii) $NO + O_3$ ⟶ $NO_2 + O_2 + e$

In the first two reactions ozone is produced, and in the third, it is consumed. Many other pollutants such as peroxyacetyl nitrate (PAN), and hydrocarbons are present in a polluted atmosphere, but a discussion of their significance is beyond the scope of this report.

Ground level concentrations of ozone at cities such as Edmonton and Calgary are low when compared with other Canadian cities but occasionally, the air standards (50 ppb) are exceeded (Legge et al 1980).

As sources, these two cities are unlikely to have a significant effect on the Green Area because of prevailing winds.

4.1.2 Natural Sources

4.1.2.1 Sulphur Compounds. Natural sources of atmospheric sulphur dioxide are mainly due to the death and decay of organisms and land vegetation as well as plankton from the oceans. Active volcanoes also release SO_2 to the atmosphere. Sulphur released in the form of H_2S will be oxidized to SO_2 in the atmosphere.

4.1.2.2 Nitrogen Oxides. Bacterial action produces 90 per cent of nitrogen oxides (NO_x) emitted into the atmosphere (Legge et al 1980). Nitrous oxide (NO) is the main product of biological activity that occurs in the soil and because it does not enter into the formation of photochemical smog, it is not considered an atmospheric pollutant. Nitrous oxide and dinitrogen oxide (N_2O) are naturally present in the stratosphere and are significant when considered as a source of NO_x to the troposphere. Although this contribution would be small, it is relevant since the NO_x can undergo reactions with O_3.

4.1.2.3 Ozone. Ozone is produced naturally in the stratosphere and can then be transported down to the troposphere. Several chemical reactions can also occur in the troposphere, resulting in both the production and consumption of ozone.

4.1.2.4 Other Sources. Hornbeck (1981) lists sources of natural air pollution as "sprays from oceans and lakes, particulates and gases from wildfire and volcanic eruptions, products of biologic reactions such as methane and hydrogen sulfide, and organic particles such as pollen and spores". There is also a background low level of pollutants of anthropogenic sources contributed by global effects.

The breakdown of organic matter by soil microfauna releases organic acids which may also acidify the soil. Sulphur is stored in organic matter as SO_4^{-2} and through the process of mineralization, is released (Hausenbuiller 1972).

4.2 Plume Dispersion

4.2.1 Long-Range Transport

Sulphur dioxide emissions are capable of travelling hundreds of kilometres before becoming completely oxidized. The weather patterns in eastern North America enable pollutants in the atmosphere to move over great distances, both within each country, and across the international boundary (Sub-Committee on Acid Rain 1981). There has been little research of this type conducted with respect to Alberta, therefore, the total amount of sulphur compounds being transported into and out of this province is not well-known (Sandhu et al 1980). However, photographic records of plume dispersion are available and a plume model has been applied to the province (Sandhu et al 1980).

4.2.1.1 Stack Height. Rowe (1974) defines small-scale plume dispersion as travelling up to 10 kilometres in distance and one kilometre in height, and meso-scale as up to 100 kilometres in distance and 10 kilometres in height. In the former, he states that both stack height and plume rise are important parametres to consider, whereas, in the latter, only the emission rate of SO_2 needs to be known.

Sanderson (1984) defines long-range transport as pollutants travelling more than 100 kilometres, and states that it is favored when pollutants are emitted from taller stacks (also Sub-Committee on Acid Rain 1981). In such a case, the pollutants are emitted high enough into the atmosphere to be picked up by the wind stream and deposited far from their source. If emissions have a long lifetime in the atmosphere i.e., more than several hours, they can travel considerable distances before being removed.

4.2.1.2 Meteorological Conditions. The distance that pollutants are transported in the atmosphere depends on wind and temperature conditions (McMillan 1981). The long-range transport of NO_x is not yet clearly understood (Sub-Committee on Acid Rain 1981); more work has to be done on the transport of these compounds.

Whether pollutants are incorporated into stagnant high pressure systems such as those which commonly occur in summer, or are carried by a brisk wind, affects their atmospheric lifetime (Sanderson 1984). In the first case, the emissions will accumulate in the air mass and become well-mixed through convection. They will then move away from the high pressure area and affect distant areas (Committee on the Atmosphere and Biosphere 1981 as cited by Sanderson 1984). This statement is supported by McMillan (1981) who reported that "pollutants emitted into stable air will not diffuse rapidly and may be carried for long distances." In the second case, when winds are strong, the plume rise and reaction time are reduced, and emissions are removed close to the source area (Sanderson 1984).

There are problems in studying winds and the long-range transport of atmospheric pollutants. Specifying the wind field, especially as it pertains to acidic precipitation, is difficult since rain is most often associated with air fronts. For modelling of long-range transport, winds are often reconstructed from pressure fields. However, it is important to note that with present methodology, the rapid changes in both wind and temperature at fronts cannot be accurately estimated (McMillan 1981).

Temperature also plays an important role in long-range pollutant transportation. The following information is from McMillan (1981).

> The planetary boundary layer undergoes a diurnal variation dependent on radiation. During the day, the sun heats the ground causing vigorous convection pushing the mixing depth higher. At night, radiative cooling occurs and the inversion forms at lower elevations as the turbulent motion dies out and the air becomes more stratified. This diurnal variation can have an influence on pollutant transport since pollutants emitted into stable air will not diffuse rapidly in the vertical and may be carried for long distances . . . . It is apparent that stack height can influence the dispersion of pollutants because of atmospheric stratification . . . . Clouds can extend to a height of 15 km and since they have updrafts associated with them, they can suck pollutants to these altitudes.

Pollutants may be incorporated into clouds either as gases or solids. Solid removal of pollutants from the atmosphere is possible but is not as effective as rain. The highest acidity is associated with cold-front and air-mass-type storms (McMillan 1981).

4.2.2 Short-Range Transport

Sanderson (1984) defines short-range transport as the removal of pollutants from the atmosphere less than 100 kilometres from a source.

Acute injury commonly results from short-range transport such as is the case with sulphur block fires.

4.2.2.1 Gases and Aerosols. Gases and aerosols emitted into the atmosphere can be removed in either the wet or dry form at distances less than 100 kilometres. Both vegetation and soils are capable of absorbing gases directly. Dry deposition is becoming increasingly important, particularly in Alberta where precipitation rates are generally low.

4.2.2.2 Elemental Sulphur. There has been an increase in demand for elemental sulphur (S°) for export, particularly to Japan for fertilizer production. In sour gas plants, sulphur is recovered and large quantities have been placed in storage as sulphur blocks. Nyborg (1978) has reported that wind-blown S° may be deposited at 1-100 tonnes per hectare in the vicinity of the sulphur-handling operation. Also, S° may be deposited on soils and on vegetation while in transit (Sanderson 1984). Although these deposits may be heavy, they are usually localized, and remedial action through liming is possible and effective, at least in the short term (Nyborg 1978; Sanderson 1984).

4.3 Modes of Deposition

Once in the air, particles are removed through wet or dry deposition. Because meteorological conditions vary so much from region to region, local data is needed to determine deposition rates. Extensive research of this type has not yet been done in Alberta (Sandhu et al 1980) but there has been a modelling study done for the area. It concludes that annual deposition rates, in both wet and dry form, from sulphur extraction gas plants should not exceed 10 kg/ha (Western Research and Development Ltd. 1978).

Since precipitation rates are generally low in Alberta, dry deposition is of major significance in predicting the overall effects of atmospheric deposition on the forest ecosystem.

4.3.1 Wet Deposition

4.3.1.1 Precipitation. Overrein (1977) defines wet deposition simply as "removal by precipitation of gas and aerosols". This will include hail, sleet, fog, and snow, as well as rain. Since the process of wet deposition is determined by precipitation, large local variations are expected. Precipitation is also episodic, therefore deposition of pollutants by wet forms may be large during limited time periods (Overrein 1977). The main ion present in polluted precipitation is sulphate (SO_4^{-2})but others such as hydrogen (H^+), ammonium (NH_4^+) and nitrates (NO_3^-) are also common (Overrein 1977).

One of the fates of SO_2 when it is emitted into the atmosphere is to combine with cations such as calcium (Ca^{++}) or amonium ($NH4^+$) to form sulphates. These compounds are more or less neutral but may acidify land when they settle (Nyborg 1978).

The contribution of wet deposition to the overall atmospheric deposition problem in Alberta varies every year according to location and amount of precipitation. Walker (1969) found that deposition rates for sulphur in precipitation in high emission source areas such as central Alberta, was only 2-4 kg/ha. Nyborg et al (1977) then concluded from this figure that the movement of air masses are transporting the pollutants long distances, perhaps even out-of-province, before they are removed from the atmosphere.

Fogs occurring on mountain tops can be 100 times more acidic than normal rain (Vogelmann 1982). This is known as acid mist and has been observed to be a problem in the high mountain forests of the United States and Europe.

Intercepted precipitation can be either as throughfall - that which is first trapped by the canopy, or stemflow - that which flows down the stem of the tree (Parker 1983). Both are major pathways for the recycling of nutrients but throughfall is the largest pathway by which sulphur is returned to the forest floor. Parker (1983) has estimated sulphur contributions to the forest floor by throughfall to be 35.5 per cent of total annual sulphur fall. Contributions made by stemflow are less, but stemflow does deliver a substantial amount of water and nutrients to the forest floor (Parker 1983).

In forested areas far from point sources of air pollutants, the rain that is intercepted by conifers will have a lower pH than that which falls directly on bare ground; rain intercepted by deciduous species will usually have a higher pH than free-falling rain (Morrison 1984). This can be clearly seen in Table 6. In industrial areas with high SO_2 emissions, the pH of precipitation is also more acidic than in more remote areas (Parker 1983; Nyborg 1978).

Precipitation intercepted by a forest canopy was found to contain up to four times the sulphur content of free wet rain (Nyborg et al 1977). The exact mechanism by which throughfall and stemflow in coniferous forests becomes lower in pH and higher in sulphur content is not yet fully understood (Nyborg 1978).

TABLE 6

SULPHUR DEPOSITION BY RAIN AND BY SPRUCE THROUGHFALL

Location	Sulphur deposition	($kg\ ha^{-1} mo^{-1}$)
	Rain	Throughfall
Control (2 sites)	0.1	0.2
*Exposed (3 sites)	0.7	2.6

* Within 8 km of oil sands extraction plant.
Source: Nyborg et al 1977.

"Foliar leaching is concluded to be the major process controlling throughfall and stemflow enhancement for nearly all elements, though foliar uptake and canopy filtration of dusts, aerosols and gases is important in particular situations" (Parker 1983). Nyborg et al, (1977) support this statement by saying that one of the major mechanisms of sulphur deposition in Alberta forests is by washout from trees that have intercepted sulphur from the atmosphere.

<u>4.3.1.2 Snowpack.</u> In areas of sulphur accumulation in the snow pack, concentrated sulphur is released during the snowmelt period resulting in a sudden drop in pH of surface waters and soils (Cowling and Dochinger 1980; Kling and Grant 1984). A three-year study in Michigan showed that release of strong acids occurred during the early snowpack melt period (Cadle et al 1985).

The sulphur content in Alberta snow is generally very low. Even in areas close to SO_2 emission sources, the sulphur content in snow is less than 1 kg/ha (Nyborg et al 1977). This is supported by Caiazza et al (1978) in their findings that "concentrations in snow were significantly lower than those in rain for N, SO_4^{-2} and silica." In Alberta, the ground is often covered with snow for almost half the year, and it is believed that during this period the SO_2 emissions are transported out of the province (Nyborg et al 1977).

4.3.2 Dry Deposition

Dry deposition is defined as "dry fallout consisting of solid particles, aerosols, and gases between precipitation events" (Helvey et al 1982). "The forest acts as an efficient filter for contaminated air. The total dry deposition will be a function of air concentration, wind velocity and turbulance, character of the forest (e.g., partially open, variable height, different species, hardwood/softwood ratio and time since the last rain)" (Kulp 1985). Few studies have been done to quantify amounts of dry versus wet deposition. Nyborg et al (1977) found that in Alberta, particulates contribute 0.32 kg S/ha/wk - up to three and a half times as much sulphur as rain does. Direct sorption of gases and particulates containing sulphur are major sources of S deposition, along with rainfall intercepted by trees (Nyborg 1978).

4.4 Effects on Vegetation

4.4.1 Direct Effects

The main entrance points for air pollutants into vegetation are the stomata, therefore, the times of high susceptibility to SO_2 are when the stomata are open (Linzon 1971). The SO_2 gas that is absorbed undergoes assimilatory reduction (Loman et al 1972). This reduced form is then toxic to the mesophyll cells. Kozlowski (1980) describes the order to injury to broadleaved plants as:

1) collapse of spongy mesophyll cells (and lower epidermis),
2) chloroplast destruction and injury to pallisade layer, and
3) collapse of the upper epidermis

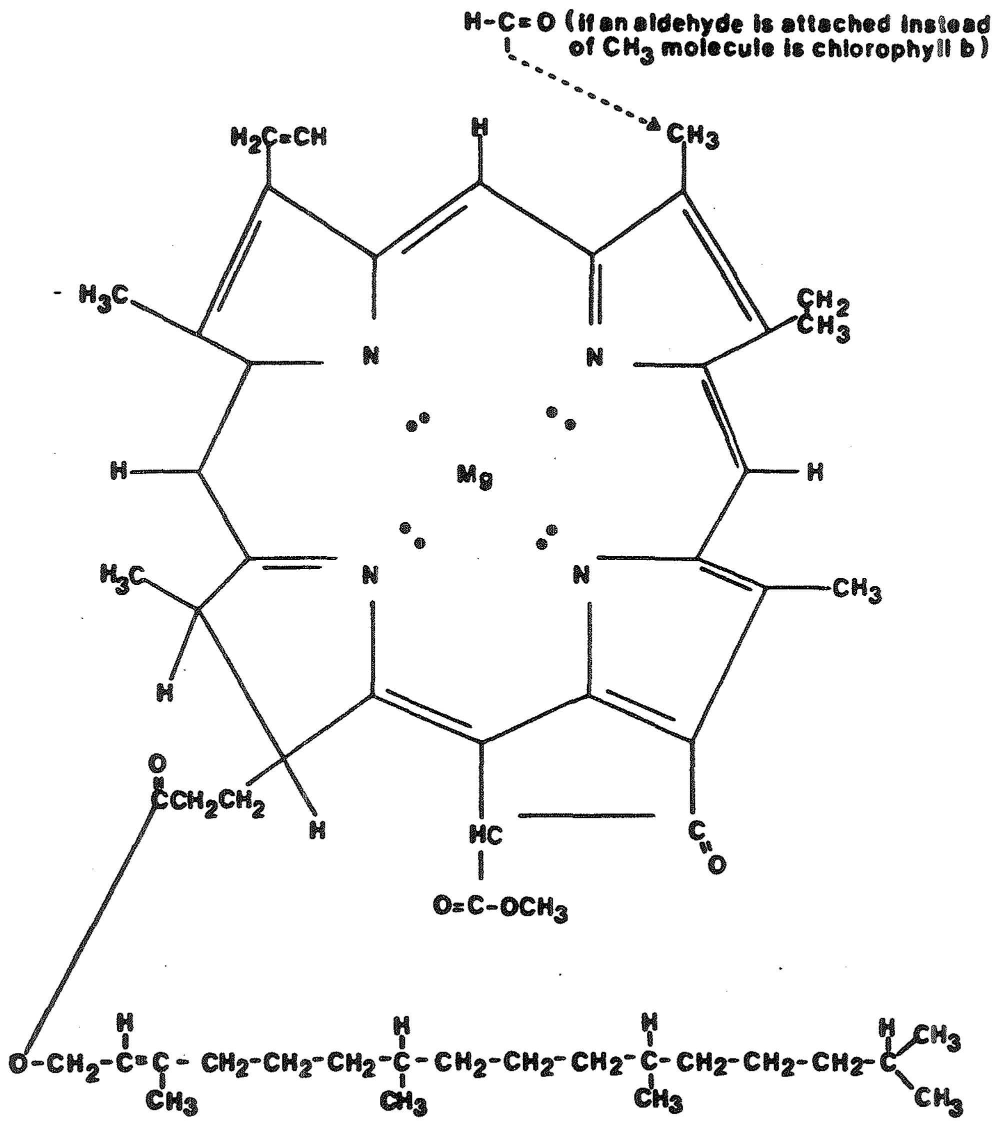
Lichens and bryophytes are most susceptible to air pollution damage since a large part of their nutrition is derived directly from the air. Lichens, especially, have been extensively used in biomonitoring programs because of their extreme sensitivity to air pollutants.

4.4.1.1 Trees Foliar damage is of special importance because it is directly related to productivity. Lower quantity and quality of leaves has a negative effect on fibre yields and thus lowers productivity (Malhotra and Blauel 1977). Damage to leaves usually starts as chlorosis and may progress to complete necrosis of the affected tissue.

Chlorosis: Sulphur dioxide is converted to bisulfite (HSO_3) in the cells and causes chlorophyll destruction by inhibiting photosynthesis (Salisbury and Ross 1978). Magnesium (Mg) is a structural component of the chlorophyll molecule (see fig. 1). Malhotra and Blauel

FIGURE 1

CHLOROPHYLL MOLECULE (a)



Source: Salisbury and Ross 1980

(1977) state that SO_2 acts upon the pigment by releasing the Mg, thereby, destroying the chlorophyll molecule. Their research has confirmed that chlorosis is not a result of high acidity but is in fact caused by SO_2 (see table 7). They have also found that damage caused by exposure of plants to SO_2 concentrations meeting air quality standards was reversible; within 24-28 hours, there was practically complete recovery.

TABLE 7

THE EFFECT OF VARIOUS CONCENTRATIONS OF SO_2 ON TOTAL CHLOROPHYLL CONTENT OF PINE NEEDLES

TREATMENT	pH of INCUBATION MEDIUM	CHLOROPHYLL CONTENT (mg/L)	% of CONTROL
Control	7.20	65.27	100.00
10 ppm SO_2	7.18	64.13	98.25
25 ppm SO_2	7.13	63.50	97.29
50 ppm SO_2	7.10	63.82	97.78
100 ppm SO_2	7.00	63.38	97.10
250 ppm SO_2	6.60	47.98	73.51
500 ppm SO_2	3.95	34.69	53.15
HCl control	3.95	62.71	96.08

Source: Malhotra and Blauel 1977.

Chlorosis, whether reversible or not, is indicative of an interruption in photosynthesis and can be used as an early warning signal.

Inhibition of Germination

Riding and Boyer (1983) conducted experiments with red pine (*Pinus resinosa* Ait.) and jack pine (*Pinus banksiana* Lamb). They found that the effects of SO_2 on seed germination varied with species and season. The germination of red pine seeds was shown to decrease consistently; the results for jack pine were not so clear. It was concluded that the response of jack pine depended on the season. During the summer, SO_2 stimulated germination, perhaps due to increased microbial activity in the duff layer.

4.4.1.2 Understory Vegetation. To date there appears to be little research done on the effects of air pollutants on shrubs and herbs. This is perhaps due to the fact that the major concern to the general public is forest productivity. Another possibility is that the work may be too recent to be documented. Refer to table 2, page 13 for the sensitivity of various shrubs and herbs to SO_2.

Mosses and lichens are highly sensitive to air pollution, and both have been used extensively as biomonitoring tools to detect atmospheric pollution. As Skorepa and Vitt (1976) state, "a given lichen flora reflects the average, cumulative effects of air pollution over a long period of time." Both wet and dry deposition add elements to the thallus of lichens. "Thalli will intercept particulates and gases by impaction, sedimentation, and Brownian movement. Similarly, wet deposition will result in the availability of water-soluble and insoluble particulates and dissolved gases" (Addison and Puckett 1980). Winner et al (1977) conducted experiments on understory canopy coverage of white spruce stands. They found that the SO_2 stress gradient, as shown by effects on the understory, are related to the dispersion of the SO_2 plume. Also in areas of SO_2 emissions, S can be found in the native mosses. The relative health of the understory vegetation is inversely related to the amount of S found in the mosses. Therefore, epiphytic lichens and bryophytes can be used as early warning monitoring tools for the decline in vigor and productivity of higher vegetation.

4.4.2 Indirect Effects

The indirect effects on vegetation due to deposition of atmospheric pollutants are many and complex. Since the forest ecosystem is being dealt with as a whole, the interrelationships among the many components need to be considered. This makes it difficult to report on any component in isolation. This section deals with those indirect effects on vegetation that result from effects on pathogens and insects, as well as the positive and negative effects on growth, both above- and below-ground.

4.4.2.1 Pathogens There are two factors to consider in terms of the effects of air pollutants on pathogens. First, the effect on the host (i.e., tree), either beneficial or detrimental; second, the effect on the disease, or the interrelationship between host and pathogen.

It is commonly thought that air pollutants will weaken a tree and thus predispose it to attack by pathogens (Treshow 1975). This hypothesis is certainly valid in some cases, however, the converse may also be true, i.e., the pollutants may be more toxic to the pathogen than to the host (Kozlowski 1980; and Treshow 1975). In this instance, some disease control may be achieved when the concentration of the pollutants is high enough to restrict the development of the pathogen but low enough not to reach the threshold injury level of the host (Kozlowski 1980).

SO_2: Sulphur dioxide has been reported (Treshow 1975) to weaken a tree to the point that it predisposes it to infection by fungi. Infection by aerial pathogens is facilitated possibly through the effect SO_2 has on increasing stomatal aperture (Unsworth et al 1972; Williams et al 1971 as reported by Treshow 1975). Treshow (1975) conducted an experiment by exposing several fungal species to different concentrations of SO_2 for increasing periods of time. He showed that spores are five to six times more susceptible to disease than mycelia, which in turn is more sensitive than sclerotia. Treshow concluded that SO_2 had varying effects on different species of fungi. On some species, it exerted a toxic effect; others were slightly stimulated, and some were not altered. For example, he cited research that reported SO_2 at 4 ppm was toxic to species of Rhizoctonia when the fungus was exposed for 16 hours. Penicillium sp. were "slightly stimulated in nutrient solutions that contained the equivalent of 90 ppm SO_2". Absence of powdery mildew in areas of heavy SO_2 pollution is very noticeable and was reported first by Koch in 1935. Similar results are also expected with some other foliar diseases (Treshow 1975).

Several studies have been done on the effects of air pollutants on Scleroderris canker on red pine caused by Gramminiella abietina. One such study by Bragg and Manion (1983) was undertaken because the outbreak of the disease in the Adirondack Mountains of New York coincided with the acidic deposition problem. They concluded that acidic deposition was not a major environmental factor in the development of the disease. Laurence et al (1983) arrived at the same conclusion and went on to state that "in several cases it did appear that SO_2 inhibited infection by G. abietina. This was apparent in non-inoculated plots, where the natural rate of infection of SO_2-treated trees was probably due to the high disease intensity resulting from a heavy inoculum load. The protective effect was transistory, since it was much less apparent in the summer of 1981, one year after fumigation."

Treshow (1975) reported that Pseudomonas phasiolicola was incapable of infecting either healthy bean leaves or those already injured by acidic precipitation, if kept in an environment of pH 3.2 for at least two hours.

In conclusion, the response of pathogens to air pollutants is highly variable; some diseases are intensified because of atmospheric pollutants, others are eliminated, and some are not affected.

Ozone: Treshow (1975) observed that while ozone tended to suppress aerial growth of fungi, it did not affect subsurface growth. He also noted that "infection was frequently observed to originate in ozone-injured leaf areas." The necrotic lesions caused by ozone pollution (and SO_2) actually create infection courts that can increase the chances of pathogen penetration into the host. Once penetration is complete, the pathogen became less susceptible to ozone. Wearing away of the plant's protective cuticle by acidic deposition also facilitates penetration.

At times, low concentrations of certain pollutants will tend to enhance the metabolism of the host, thereby enabling the development of those parasites (i.e., viruses and obligate parasites) that grow best in active tissue (Treshow 1975). The virus-host relationship is an interesting one especially in areas where ozone is a major pollutant (Treshow 1975). Ozone injury is often prevalent in areas with vegetation previously infected by certain viruses. Treshow (1975) considers the following in such a relationship:

1) sensitivity of the host to ozone,
2) concentrations and durations of ozone exposure,
3) specific viruses, and
4) phase of growth at which ozonation occurs.

Parasites also appear to be affected by acidic deposition. Penetration and establishment by facultative parasites is enhanced by acidic precipitation (Treshow 1975) while obligate parasites are somewhat inhibited by a stressed plant.

A tree that has been weakened due to air pollution may also become more susceptible to root diseases. If carbohydrate availability is reduced, the tree roots will lose their vigor and become more prone to attack by rot pathogens (McLaughlin et al 1982). One such common disease is root rot caused by <u>Armillaria mellea</u> (Treshow 1975).

<u>4.4.2.2 Insects</u> The weakening effect of air pollutants on forest trees may facilitate attack by some insects, especially bark beetles

(Kozlowski 1980). The Ponderosa pine (Pinus ponderosa Laws.) in the San Bernardino Mountains in California were studied by Kozlowski (1980). He found those trees with advanced symptoms of oxidant injury were the ones most frequently attacked and killed by pine bark beetles (Western Pine Beetle: Dendroctonus brevicomis, and Mountain Pine Beetle: D. ponderosae). Another study conducted by Dahlsten and Rowney (1980) concluded that "bark beetles (assuming no deleterious effect of air pollution), should increase in areas with high ozone damage, and thus, tree mortality will also increase."

4.4.2.3 Tree Productivity

Increased Growth: The nitrogen and sulphur found in acidic precipitation are plant nutrients. When plants take up sulphates and nitrates in salt form, they have a higher tolerance level than if they were to take up the nutrients as acids (Black 1981). Sulphur is a constituent of proteins, vitamins and ferrodoxin. Through a complex enzyme system, green plants reduce and assimilate SO_2 and SO_4^{-2} as long as the plant's threshold level for these compounds is not exceeded (Loman et al 1972). The S-deficient regions in Alberta are not extensive and acidic precipitation provides no amelioration since the S-content in rain is so small (Nyborg 1978). Nitrogen as a component of proteins, nucleic acids and chlorophyll molecules is also very important to plants. Many soils in Alberta are nitrogen-deficient (see map 3). Although the amount of N supplied by acidic deposition is small, it may reduce the need for fertilizer on some crop land (Black 1981).

Cowling and Dochinger (1980) state that for many forest trees and herbaceous plants, a significant portion of their nutrition is absorbed directly from the atmosphere. Acidic deposition, then, may be beneficial to the plant if nutrient elements are absorbed.

There is some claim that if NO_3^-, NH_4^+ and SO_4^{-2} are deposited on soils that are deficient in these nutrients, they may act as fertilizers and actually enhance the productivity of the forest

(Environmental Resources Ltd. 1983). Rates of deposition in Alberta are believed to be too low to be of any benefit to soils (Nyborg 1978).

Decreased Growth: Reduced pine growth is evident in Canada when SO_2 concentrations reach 45 ug/m^3 (Environmental Resources Ltd. 1983). Riding and Boyer (1983) reported a decrease in height of established pine seedlings due to SO_2. Chronic injury and cumulative responses of trees to air pollutants is expected since trees are perennials (Cowling and Dochinger 1980). Tomlinson (1983) reports that the common cause of reduced above-ground growth of trees is primarily a damaged root system. A low ratio of calcium to aluminum (Ca:Al) or a decrease in Ca will reduce nutrient assimilation in the roots. Aluminum toxicity may also destroy the finer roots. Eventually, the tree becomes unable to absorb water from the soil and the moisture content of the tree lowers significantly even though drought conditions are not prevalent in the soil. A damaged root system thus results in a slowing of the growth rate (Tomlinson 1983).

Abrahamsen (1980) states that when Mg and potassium (K) are the growth-limiting factors, reduced growth due to air pollutants is expected. Legge (1980) agrees and states that nutrient cycling is the most important process affected by air pollution.

It has been shown that ozone influences not only growth of forest trees but also tree species composition. In the U.S., research into the extensive die-back of Ponderosa Pine supports the theory that succession will take place toward species that are more tolerant to ozone (Smith 1984). Smith (1984) further explains that:

> "Most woody plants susceptible to ozone injury are generally species of an early successional stage. Most trees having intermediate or high tolerance to ozone stress are typically mid- or late-successional stage types . . . Mature ecosystems are typified by processes that may increase their inertia (resistance) to air pollution stress. Low net production

> may reduce the potential importance of restrictions imposed on photosynthesis by air contaminants. Closed and slow nutrient cycle may make nutrient capital less liable to loss by the influence of air pollutants."

The potential for a reduction in net productivity in the absence of visible tissue damage exists. Legge (1980) reported effects on vegetation in the Whitecourt area. He found that (lodgepole x jack) pine hybrids affected by SO_2 initiated photosynthesis later in the spring than unaffected trees. In addition, a decrease was found in the basal area increment when correlated with SO_2 emissions after taking site differences into account.

Air pollutants are not expected to drastically decrease tree productivity in Alberta, however, impact signs on vegetation have been observed and the long-term effects may be more serious than anticipated.

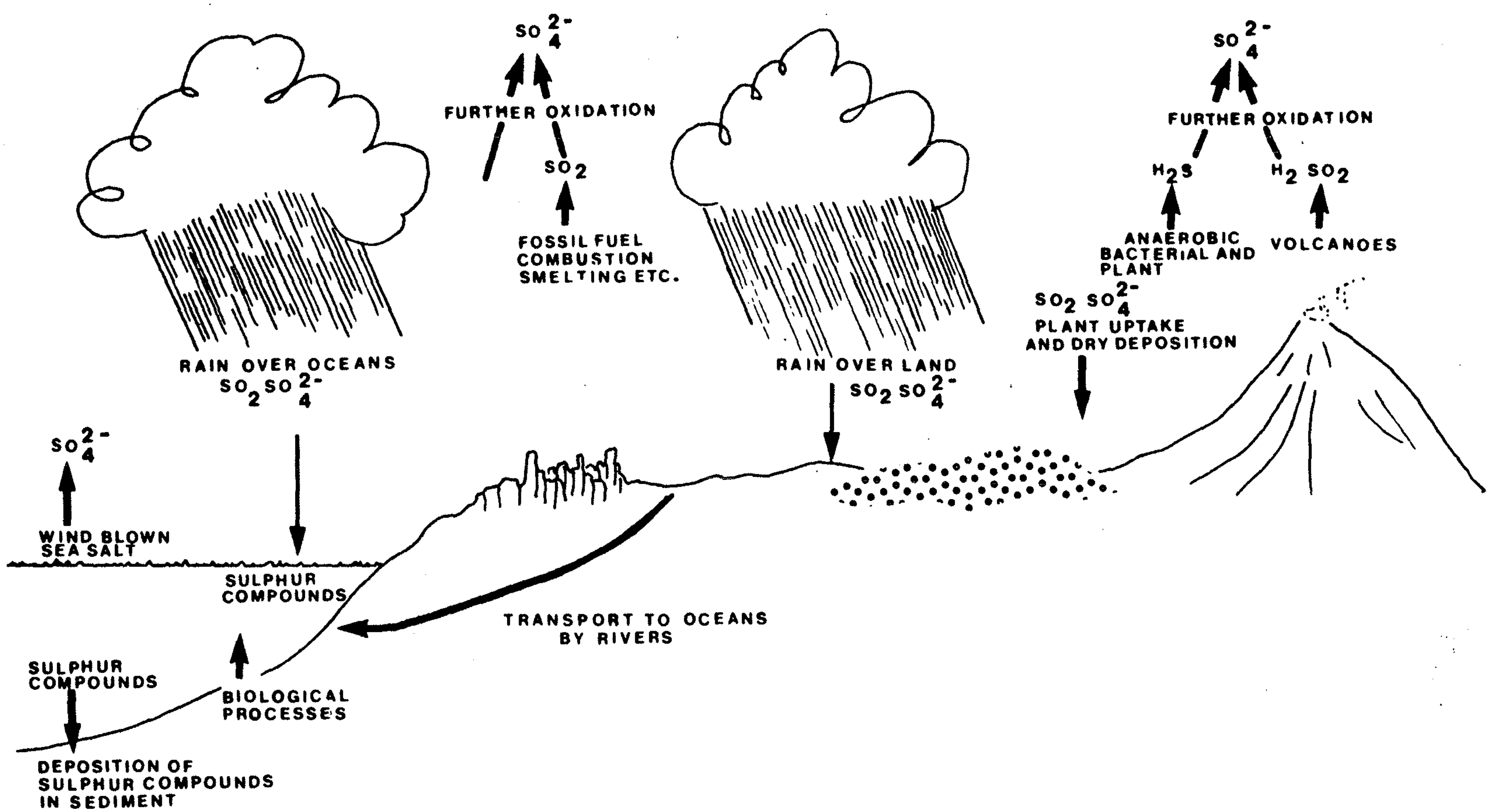
4.5 Effects on Soils

4.5.1 Fate of Atmospheric Deposits in the Soil

4.5.1.1 Sulphur. Sulphur can be absorbed directly by a soil as SO_2 and H_2S or it can enter the soil system in solution via wet deposition. When elemental sulphur is deposited, it can be oxidized by micro- organisms. The sulphur cycle is shown on figure 2 and demonstrates the fate of sulphur once it reaches the soil. Approximately 95 per cent of the S in soils is held in organic matter with the remainder being held in salts such as $CaSO_4$ and Na_2SO_4 (Nyborg 1978). Approximately 1-3 per cent is mineralized to inorganic SO_4^{-2} and about the same amount is immobilized to organic matter. Therefore, the mineralizable S is usually not a good indicator of the total S content of soils (Nyborg 1978).

FIGURE 2

THE SULPHUR CYCLE



Source: Rennie 1980

When SO_2 is first sorbed by a soil, it has two possible paths. Most forms sulfite (SO_3), then undergoes quick oxidation to form SO_4^{-2}. The other possibility is for the SO_2 to react with organic matter and form non-extractable, apparently organic, S (Nyborg 1978). If there are not enough bases to buffer the reaction, the soil will become acidified (Nyborg 1978).

In anaerobic soils, the resulting sulfates are reduced to sulfides. This is accomplished by the action of two genera of bacteria: *Desulfovibrio* and *Desulfotomaculum*. In aerobic soils, elemental sulphur is oxidized by *Thiobacillus* sp. to H_2SO_4. This bacteria can operate under extreme acidity and its processes result in further increases in soil acidity.

Nyborg (1978) states that sulphur pollution of soils may result from the following processes:

1) oxidation-reduction of sulphur
2) mineralization-immobilization of soil organic sulphur
3) sorption of SO_2
4) formation of H_2SO_4 by some S fertilizers and by SO_2 emissions
5) retention and leaching of sulphates in soils

Sulphur pollution of soils is not an effective means of correcting sulphur deficiency since much of the sulphur in soils is not present in a form available to plants (Walker 1969; Nyborg 1978). In the extreme case, both sulphur deficiency and sulphur pollution may occur in the same soil (Nyborg 1978). Walker (1971) states that with present levels of deposition, most soils are not benefiting through a fertilization effect.

Nyborg (1978) lists the disadvantages of relying on atmospheric deposits of sulphur for crops as:

1) unreliability of the amount of S from year to year

2) losses through leaching if the S is deposited when the crop is not growing
3) greater combination with soil organic matter

4.5.1.2 Nitrogen. The processes that nitrogen undergoes when it is in the soil are many and complex. Figure 3 shows that nitrogen can undergo mineralization, immobilization, denitrification, fixation by Rhizobium sp., oxidation and volatilization. The nitrate ion (NO_3) and the ammonium ion NH_4^+ are the forms taken up by plants. The former is preferred by dicots and the latter by monocots and seedlings. Nitrification of NH_4^+ is accomplished by two genera of bacteria - Nitrosomonas and Nitrobacter. Ammonia (NH_3) is essentially basic but is converted to nitric acid in the soil.

Most soils of temperate forests, including Alberta, are nitrogen-deficient. The nitrogen supplied in precipitation, however, is not believed to have much of a fertilizing effect on forest trees because it is supplied in small amounts.

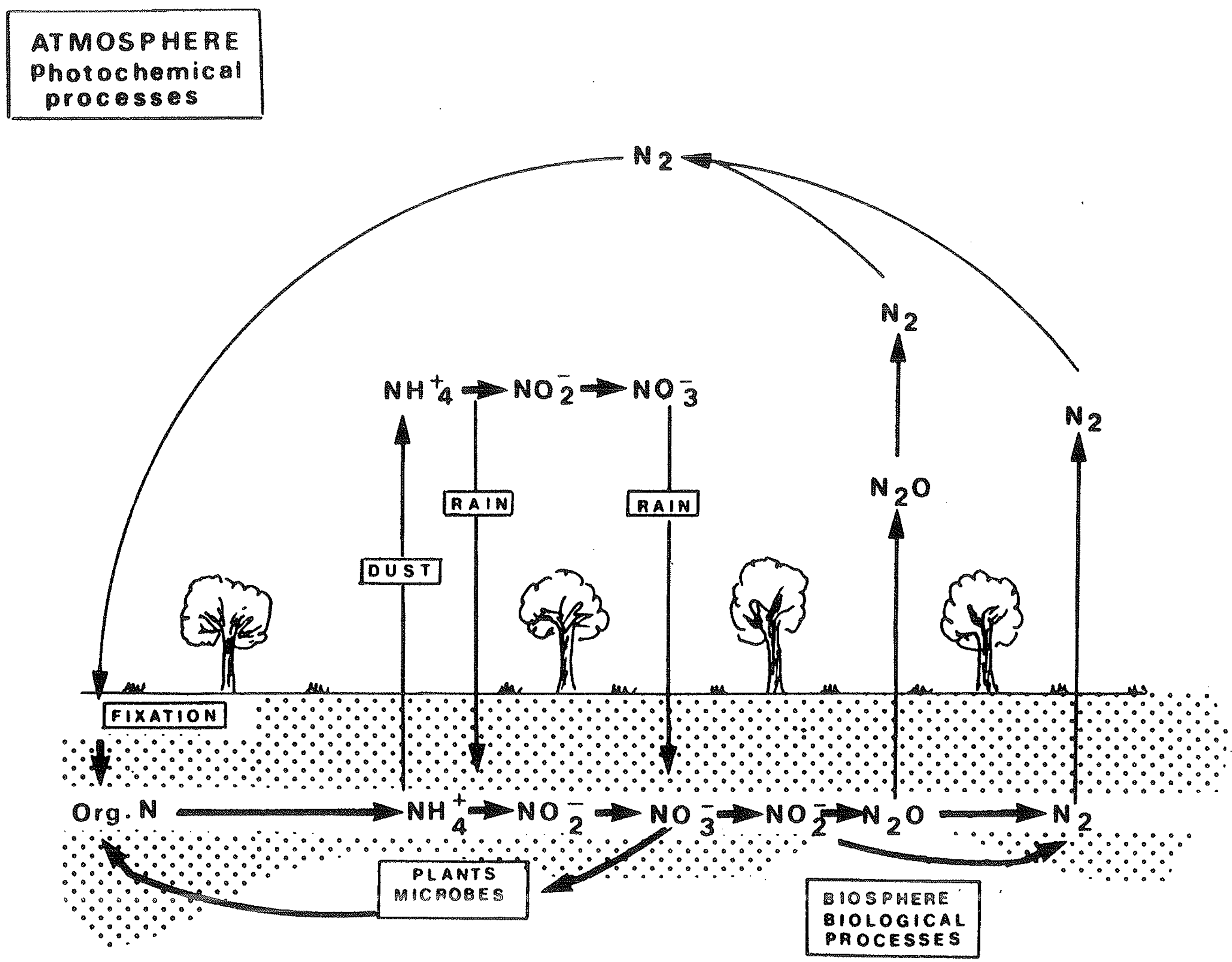
4.5.2 Increased Acidity

The most basic concern of atmospheric deposition on soils is the acidification it causes and its consequences. Increased acidity (i.e., decreased pH) due to atmospheric deposition has several adverse effects on the soil-plant system. The surface horizons of the soil are usually most affected by acidification (Ulrich 1980). Soil response to acidification includes decreased nutrient availability, mobilization of toxic ions, changes in the microbial population and a change in the rate of soil processes. Many soils can resist these changes for a certain time.

4.5.2.1 Nutrient Availability. Acidic deposition on soils can increase base cation leaching if the associated anion is also mobile in the soil (Johnson et al 1983). Sulfuric (or nitric) acid in the soil causes an exchange in the cation complex by releasing the anions SO_4^{-2} (or NO_3^-).

FIGURE 3

THE NITROGEN CYCLE



Source: Richards 1974

(Overrein et al 1980). These anions then attach themselves to base cations such as Ca, Mg, Na, or K and leach downward through the soil profile (Baath et al 1980; Nyborg 1978). The base cation is replaced by H^+ or H_3O^+ and acidity is increased (Overrein et al 1980).

Baath et al (1980) found lower levels of Mn, P, K, Ca and Mg in soils with lower pH and concluded that cation leaching can be accelerated by atmospheric deposition.

Johnson et al (1982) cites that soils sensitive to leaching by H_2SO_4 as those that are low in free Fe and Al oxides. Soils with an abundance of N are sensitive to leaching by HNO_3.

<u>4.5.2.2 Mobility of Toxic Ions.</u> One result of increased soil acidity is the release of Al^{3+} ions, which, when in soil solution, can be extremely toxic to plants (Nyborg 1978). Work done with agricultural crops has shown that root growth of some crop species is impeded when the Al^{3+} concentration in the soil solution is 1 ppm (Voigt 1980).

To counteract the acidity of the upper soil horizons, weathering of the mineral substratum will commence. "Very early in the weathering process, hydrolysis of the silicon-oxygen-aluminum linkage occurs, releasing Al and other soil constituents to the soil solution" (Voigt 1980). Aluminum in the soil solution will decrease the pH by the following reaction (Holowaychuk and Lindsay 1982):

$$Al^{3+} + 2H_2O \longrightarrow AlH_2O^+ + 2H^+$$

Acidity may also cause increased levels of Fe and Mn in solution which will be toxic to certain plant species (Voigt 1980).

Under acidic conditions, aluminum will combine with phosphorus to form a complex and result in a phosphorous deficiency (Voigt 1980). Nyborg (1978) has reported that phosphorous availability is not as high in acid soils as in neutral soils.

4.5.2.4 Microbial Changes. Acid deposition may have an adverse effect on the soil microfauna of the forest floor (Voigt 1980), however, the interactions between pollutants and soil micro-organisms are so complex that much more research needs to be done (Baath et al 1980). Studies done thus far show that some microbial processes are reduced, but the nature, rate, and extent of the effects are not yet fully understood (Francis 1982). Addison (1984) has concluded that Collembola species would be the best to use in biomonitoring studies of sulphur pollution. She has found pollutant gradient effects on species number, species diversity, and total numbers.

Baath et al (1980) reported that soil microflora are sensitive to acidification in varying degrees. They reported a reduction in fungal hyphae and bacterial biomass, and a change from a dominant bacterial community to one mainly of spore-formers. They found that microbial biomass is a good indicator of soil acidification stress.

It may take many years for atmospheric deposition to change the soil pH significantly. The microbial population may adapt rapidly to a change in pH; this would make impact assessment very difficult in the short run (Francis 1982).

4.5.2.5 Changes in Soil Processes. Nitrification rates have been shown to decrease when the pH decreases (Voigt 1980). Nitrogen fixation and nitrogen mineralization are also adversely affected (Tamm 1977). Voigt (1980) also reported a decrease in the decomposition of organic matter exposed to SO_2.

4.5.3 Buffering Capacity

The buffering capacity of a soil is, very generally, the ability of that soil to resist change in pH. It is "inversely related to the magnitude of pH decrease in response to a given increase in soil acidity" (Holowaychuk and Lindsay 1982). The buffering capacity of a soil in a given climatic regime (and therefore, its ability to resist change due to acid precipitation) depends mainly on the characteristics of the mineral substratum. Weathering of this layer releases ions into the soil solution to neutralize some of the acidity caused by atmospheric inputs (Voigt 1980). Soils differ in their capacities to absorb sulfate. For example, those with a higher absorption capacity have lower sulfate mobility, and therefore there is less removal of base cations and a higher buffering capacity (Voigt 1980).

Bache (1980) stated that the depth of a soil is an important factor when considering buffering capacity. A deep soil will have a higher buffering capacity than a shallow soil that overlies hard rock.

<u>4.5.3.1 Acidic Soils</u>. Since pH is a measure on a logarithmic scale, inputs of H^+ to an already acid soil will not yield big changes in that soil's pH (Tamm 1977). Moderately acid soils are more susceptible to anthropogenic S inputs as they will usually have low exchange capacity and low buffer capacity (Malmer 1974 Wiklander 1974 as cited by Tamm 1977). Reuss (1977) states that "as acidity increases due to anthropogenic S inputs, the ability of the soil to hold the SO_4^{-2} ion through the absorption mechanism would also increase. Slightly alkaline soils would have a higher percentage of base saturation, and therefore, a higher capacity to neutralize increased acidity.

<u>4.5.3.2 Calcareous Soils</u>. Soils with a high base saturation respond differently to atmospheric inputs than those slightly acid soils with many H^+ as exchangeable ions (Tamm 1977). When inputs of SO_4^{-2} are accompanied by basic cations such as Ca, Mg, N and K a marked change in soil pH would not be expected (Reuss 1977).

In calcareous soils, neutralization of H^+ by the free carbonates in the soil can occur at a fast enough rate, by the reaction described below, to maintain equilibrium (Ulrich 1980; Holowaychuk and Lindsay 1982).

$$(CaCO_3 + H_2O \longrightarrow Ca^{++}HCO_3^- + OH^-)$$

Acidic deposits high in SO_4^{-2} would dissolve the $CaCO_3$ and gypsum would precipitate out. Changes in the plant community might result if the plants normally growing in the area could not adapt to increased levels of gypsum (Reuss 1977).

Nyborg et al (1977) considered the buffering capacity of Alberta soils and conclude that "the deposition of 50 kg S/ha annually would result in a drop in pH of 0.5-1.5 units in the top 15 cm of soils after a period of 10-20 years. Returning the soils to the original pH would need about 2t of lime per ha." Liming, however, is not considered a practical method for reclaiming forest soils except on limited areas.

4.6 Impact Signs on the Forest

4.6.1 Commercial Tree Species

This section deals mainly with visual symptoms of cumulative SO_2 emissions on commercial tree species. It is believed that once the impact signs are present damage has already progressed extensively throughout the tree. Malhotra and Blauel (1980) have stated that initial injury occurs at the biochemical level, hence, processes such as photosynthesis and respiration are interrupted. Injury then progresses to the ultrastructural level causing disorganization of cellular membranes, then to the cellular level and, finally, visual symptoms can be observed. It may be difficult to assess pollutant damage as such and differentiate it from damage caused by other factors such as adverse climatic conditions, nutrient deficiency, insects and pathogens. However, if the impinged area is near an SO_2 emission source and relevant observations and data were taken on the above-mentioned factors, relevant conclusions about the effects of pollutants on vegetation can be drawn. The defence mechanism of vegetation may become so weakened by unfavorable environmental conditions that it becomes more susceptible to air pollution damage (Malhotra and Blauel 1980).

It is important to note that symptom development progresses at different rates depending on several factors, such as tree species and age of the needles (see table 8). Old needles are more sensitive to pollution damage since their metabolic rate is low and they cannot assimilate SO_2 as quickly as younger (but mature) needles. However, the immature flush is most sensitive (Malhotra and Blauel 1980).

4.6.1.1 Injury Symptoms.

In general, forest ecosystem damage results from:

1) chemical acidification of soils,
2) soil nutrient depletion due to increased nutrient solubility and consequent leaching,
3) change in soil microflora due to increased acidity, and
4) release of phytotoxic elements under acidic conditions.

Two types of injury can result from direct impact of sulphur dioxide on vegetation. Acute injury occurs when vegetation is exposed to lethal doses of SO_2 (or other pollutants) for a relatively short period. Chronic injury results from exposure to sub-lethal doses (steady but low emissions) for relatively long periods of time (Linzon 1971; Barfield et al 1982). Table 9 lists the symptoms of both acute and chronic SO_2 injury on coniferous and deciduous trees. For more detailed information, refer to the publication by Malhotra and Blauel (1980) which can also be used as a field guide.

TABLE 8

RANKING OF BOREAL FOREST TREE SPECIES
BY SENSITIVITY TO SO_2

Highly Sensitive	Moderately Sensitive	Less Sensitive
Alpine fir	Balsam poplar	Black spruce
Balsam fir	Jack pine	White spruce
Green alder	Lodgepole pine	
Tamarack	Trembling aspen	
White Birch	Willow	

* Trees are listed alphabetically.

Source: Malhotra, S.S. and R.A. Blauel 1980.

TABLE 9

VISUAL SYMPTOMS OF SO_2 INJURY
ON COMMERCIAL TREE SPECIES.

	Coniferous Species	Deciduous Species
Acute Injury	- current year pine needles chlorotic needle browning, dessication, and necrosis - in young, mature needles, discoloration at tips progressing toward base - chlorosis near necrotic zone - injury bands if affected by periodic SO_2 fumigations - premature drop of old needles - dead buds	- light interveinal chlorosis to complete interveinal necrosis - wetting of leaf undersurface - premature leaf drop
Chronic Injury	- varying degrees of persistent foliar chlorosis - stunted growth, reduction in yield - reduction in needle retention time if exposure is extensive	- water-soaked appearance of leaf undersurface, followed by severe chlorosis and necrosis at the edges and between the veins - leaf curling and shrivelling - premature leaf drop

Source: Malhotra, S.S. and R.A. Blauel 1980.

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