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AN ACID DEPOSITION PERSPECTIVE

Contract Report No. 8

An Acid Deposition Perspective
for the Northwest Territories

by
S. R. Shewchuk

Saskatchewan Research Council
30 Campus Drive
SASKATOON, Saskatchewan

Prepared for the
Science Advisory Board
of the Northwest Territories
September 1983

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Table of Contents

List of Tables

List of Figures

Executive Summary

Acid deposition in the form of a wet and dry fallout from the atmosphere was reviewed for the Northwest Territories (NWT). Wet deposition at four sites in the Arctic is well documented. There is a great deal of variability in these data on a regional basis. Dry deposition is thought to be a significant atmospheric fallout mechanism in the NWT. Several studies of air pollution impacts have shown that air quality in the NWT is affected by long-range transport from continental sources. Most air pollutants impact on the Arctic in an episodic manner.

Due to lack of buffering elements, areas on the Precambrian Shield are highly sensitive to acid deposition. In general, most of the western portion of the District of Mackenzie has a low sensitivity to acid deposition. The possible impact of increased acid deposition on the Arctic islands is not addressed due to lack of baseline data. This issue must receive increasing attention due to the extent and persistence of an Arctic haze atmospheric layer present in late winter and early spring.

Within terrestrial systems, sensitivities of higher plants to acid deposition are not well understood. It is generally believed that for low levels of acid input plant communities receive little impact. However, lichen communities which are present on extensive areas in the NWT are known to be highly sensitive to even low levels of air pollutants. Hence, the impact of increased heavy metal and acid loading on lichen communities is considered an important issue for this region.

Firm data is sparse for the Northwest Territories on aquatic system sensitivities; however, most of the freshwater lakes on the extensive Precambrian Shield are probably highly sensitive to acid deposition.

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ᓄᓇᖓᓃᑦ ᑐᕐᑯᑎᕆᑦ ᐱᔾ ᔪᑎᒥᑦ ᓱᒥᑦ ᑭᓯᐊᓂ ᑕᐃᒪᓇᐃᕆᓕᖅ ᓄᓇᑦᓯᐊᕐᒥ ᑭᓯᐊᓂ
ᐃᒻᒪᖄ ᐅᐊᓕᓂᕐᒥ ᑲᒥᐋᓯ ᑯᖓᓂ (Mackenzie River-ᒥ).
ᖃᓄᐃᓕᒪᔭᕐ ᓂᖓ ᑕᒪᑐᒧᖓ ᒪᕐᑰᖃᑦ ᑕᖅᑑᑉ ᑑᔾ ᔮᒥᐅᑕᐅᑉ ᕿᑭᖅᑕᕆᓂᑦ ᐱᓕᑎᐊ-
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ᐅᐱᓐ ᖓᕐᔪᓕᓵᖅᑎᑦ ᓱᒍ.

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ᖃᐅᔨᒪᔭᐅᒪᑎᒃᐳᖅ ᑕᒪᒃ ᑯᐊ ᕐᑯᐋᐅᑏᑦ ᐃᒃ ᐱᑐᓯᒃ ᓴᖄᐃᓱᐊᕐ ᒪᑕ ᓯᑯᕐ ᓇᖅᑐᓂᒃ
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ᐃᒃ ᐱᒥᓴᖄᐃᓂᕆᑦ ᒪᕐᑯᑦ ᓱᕐ ᓂ ᐃᓯᒪᒥᔭᐅᓯᒪᔾᖅ ᐱᒻ ᒪᑎᐅᓂᖓᓄᑦ ᑕᒫᓂ
ᓄᓇᑦᓯᐊᕐᒥ.

ᖃᐅᔨᒪᓱᐊᕆᒃ ᑭᑦ ᓱᑎᒃ ᓄᓇᑦᓯᐊᕐ ᑕᓯᕐᑯᑎᕆᓂᒃ ᑕᒪᑐᒧᖓ ᒥᒃ ᓵᓄᑦ ᑭᓯᐊᓂ
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ᖃᐅᔨᒃ ᑲᓇ ᓂᑎᐊᖃᓪᒪᑎᒃᐳᑯᑦ ᓯᓕ ᑕᒪᑐᒧᖓ ᒥᒃ ᓵᓄᑦ.

NAIGLIHIMAYOK

HOGONGNAKTOK KATAGAGANGAMI NIPALUKHUNILUNIT KANIKHUNILUNIT HIOGAOPLUNILUNIT NAIMANAKHUNILUNIT IHIVGIOKTAOLIKTOK NUNATIAMI. NIPALUK HOGONGNAKTOK HITAMANI NUNANI KAOYIHAKTAOTTIAKHIMAYOK OKIOKTAKTOMI. PANIOMAYOKTAOK NIPALUNGNIK HOGONGNAKTOMIK NUNATIAMI KAOYIMAYAOYOKHAKTAOK. ILITOKHAINIKUT KANGIKHINAKTOK HOGONGNAKTON HILAMI NUNATIAMI TAIMAILIHIMAYOK HAVAKVIGYOANIT NUNANIT.

HOGONGNAKTOK KATAGAKPAKTOK ATYIKINGITOMIK KIHIMI MIKHAGUKPAKTOK HILAM. ILAINI NUNANI HOGONGNAKTOK NIPALUK MIKHIVAKTOK NUNAM ILUANITOINIT KIHIMI TAIMAINGITOK NUNATIAMI KIHIMI IMAKAK UATANI MACKENZIE RIVERM. KANUGINIA HOGONGNAKTOM NIPALUM OKIOKTAKTOM KIKIKTAINI HAVAKTAONGITOK ILITOKHAKHIMAINMAT HAMNALU KAOYIHAKTAOYOKHAK OKIOKTAKTOMI IHIGIAKPANGMAT OKIOMILU OPINGAKHAMILU.

KANNGUTAOVATOK KANUGIANIGUT HOGONGNAKTOM NIPALUKANGAMI NAPAKTONI KIHIMI KANGIKHIMAYAOYOK TAPKOA OKYOIT HOGOKPAKTON HILA HALUMAITKANGAT NAOTYUTIKHAKANGINAMIK NUNAM ILUANI TALVALU HILAMIT PILIKPAKAMIGIK NAOTIYUTIKHATIK TAIMAINAMI KANUGINIA HOGONGNAKTOM OKYOKUTIGUT IHOMAGIYAOVAKTOK HAMANI NUNAMI.

KANGIKHITTIAKTAOHIMANGITON TAOKA TAHIT NUNATIAMI UVUNA KIHIMI IHOMAGIYAOYOT TAHAPKOA TAHIT OGAYAHOKYOKAKTONI NUNANI HOGOKTAKTON HOGONGNAKTOMIK NIPALUKANGAT.

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Atmospheric Considerations

INTRODUCTION

Acid deposition deals with the transport, oxidation, and final deposition of emissions, primarily oxides of sulphur and nitrogen, onto ecosystems. Dry and wet deposition comprise the mechanisms through which such emissions are removed from the atmosphere. In dry deposition the gaseous pollutants are either removed directly from the air as SO_2 or NO_x and directly absorbed by the ecosystem, or they form particles which fall onto the various sytems. Wet deposition occurs when the oxidized gas is incorporated in the rain as an acid.

The long-range transport of air pollutants over international boundaries is today an accepted fact (Smith, 1981). Most effects have been discovered over the relatively pristine, remote areas of Norway, Sweden, the eastern United States and Canada where strong acids, such as sulphuric and nitric acid, have lowered the pH of rain and snow to between 4 and 5 (Overrein, 1977).

A program was conducted in Europe to determine the importance of local and distant sources of sulphur compounds in terms of their contribution to the air pollution over a specific region (OECD, 1977). The program confirmed that sulphur compounds do travel long distances in the atmosphere, often hundreds of kilometres. Measurable effects on the air quality of one country due to the emissions of another were reported.

Recent studies on a selected area of northeastern Alberta and northern Saskatchewan indicate that there are areas in western Canada that are highly sensitive to the long-range transport of air pollutants (Shewchuk, 1982).

ARCTIC AIR POLLUTION

Air pollution at mid-latitudes enters the North American Arctic during the winter and early spring (Barrie *et al.*, 1981). Aerosol concentration levels, determined by pollen counts, trace elements, and major ions all tend to confirm that the Arctic is receiving air pollutants from major source emitters. These aerosols are acidic. Maximum weekly-averaged-sulphate concentrations were found in the range 2-4 μgm^{-3}. Such values are within a factor of two of those observed at remote locations in central North America during winter (Barrie *et al.*, 1980). Pollutants reach the Arctic primarily because of an annual variation in scavenging rates. Barrie *et al*, (1981) showed that summer precipitation scavenging processes are much more effective removers of air pollutants than those in winter. Forty-nine pollen species were counted in suspended particulate matter at Mould Bay. It was reported that more than 80% were of non-Arctic origin. Species originating exclusively from eastern North American deciduous trees have been identified. Total pollen counts were highly episodic suggesting special trajectories were transporting air pollution to the Arctic.

Other studies in the Arctic (Rahn and McCraffrey, 1980; Rosen *et al.*, 1981) show the presence of large aerosol concentrations which significantly affect optical transfer through the atmosphere. The observation of substantial concentrations of particulate sulphur and vanadium at Barrow, Alaska has attracted some attention (Rahn and McCraffrey, 1980). Since graphitic carbon can only be produced from combustion processes, it can be a convenient tracer of anthropogenic activity. The graphitic content of Arctic aerosols shows significant increases from late fall to early spring (Rosen *et al.*, 1981), often reaching levels found in urban environments. Peak Arctic values in February are about an order of magnitude less than average levels found in New York City. Absorption coefficients of Arctic aerosols have been measured at Barrow, Alaska (Patterson *et al.*, 1982). These measurements show that the Arctic aerosol in winter has optical properties that are quite similar to those of an aged pollution-derived, mid-latitude, tropospheric aerosol.

Concerning the movement of polluted air into the Arctic, Carlson (1981) has suggested that the Arctic aerosol comes from regions north of the polar front, primarily from the Eurasian continent during the winter.

An episode has been documented in the Arctic that shows long-range transport in the order of 3,000 to 4,000 km from Eurasia to Iceland during the summer (Borys and Rahn, 1981). The cloud condensation nuclei concentration was found to increase in parallel with the pollution-derived fraction of sulphate in aerosols.

A series of airborne measurements into the Arctic in late March and early April of 1983 (Hileman, 1983) has shown the presence of an Arctic haze. The spatial extent of this haze is larger than had previously been suspected. The studies have suggested that the haze covers the entire ice cap area and often extends in a continuous manner up to the 3000 m level into the atmosphere. The effect of this Arctic haze structure is completely unknown; however, most immediate concerns deal with alterations of the earth-atmosphere radioactive balance processes.

REGIONAL EMISSIONS

The annual rate of sulphur dioxide emission to the atmosphere in eastern Canada is estimated at 4.2 x 10^6 tonnes (Voldner *et al.*, 1980). In the eastern U.S.A. an estimated 28 x 10^6 tonnes per year (Galloway and Whelpdale, 1980) are produced by fossil fuel combustion from power plants, industry, and other area sources.

Emission levels for Canada, by region according to a 1976 inventory prepared by the Environmental Protection Service for sulphur and nitrogen oxides, are shown in Figures 1 and 2. That inventory showed sulphur oxides emissions in the Yukon and the Northwest Territories as 3,118 tonnes per year. However, the figure failed to include the value for Giant Yellowknife mine. Hence it is generally agreed that 17,000 tonnes per year is more representative (Kent, 1982).

For the Yukon and Northwest Territories it is estimated that approximately 52,000 tonnes per year of NO_x, or 78% of the total nitrogen oxide emission, is caused by forest fires (National Emission Inventory, 1976). The remainder is generally believed to be of anthropogenic origin. The figures also show the general geographic distribution of the emissions. Areas to the south and east of the Northwest Territories represent a major source of sulphur and nitrogen oxides with respect to the NWT.

Industrial expansion in the Northwest Territories and nearby provinces is difficult to project. Most large metal smelters are fairly stable emitters and unless new mines appear, no significant changes are expected. However, a new large emitter in any province or the Northwest Territories could change the projections. The uranium industry emissions of northern Saskatchewan are likely to undergo only modest growth (Shewchuk *et al.*, 1981).

Emissions from the oil sands area are expected to increase within the next several decades, but the extent of the increase is a conjecture at this time. Present oil sands emissions are estimated to include 107,000 tonnes of sulphur dioxide per year. Projections in the order of 300,000 tonnes per year by 2006 have been suggested (Webber and Warne, 1979). Current emissions of nitrogen oxide from the oil sands area are in the order of 50,000 tonnes per year. Future increases are speculative.

ATMOSPHERIC FLOWS WITHIN THE NORTHWEST TERRITORIES

The air flow through the Northwest Territories is shown in Figure 3 using the 85 kPa (kilopascal) pressure level windrose patterns. The 85 kPa level is generally considered to be indicative of atmospheric movement of regional air pollutants. The data indicate that the predominant direction of motion is from a northwesterly or northerly direction. However, there are exceptions to this generalization and some stations should be discounted in this analysis since orographic effects are suspected at the 85 kPa level. These stations include Frobisher Bay, Eureka, Whitehorse, and Alert. The data were produced by Environment Canada for the single year 1974. Later, some considerable effort was spent to verify whether the data set is typical of other years (Hopkinson, 1982). It was noted that there are small but perhaps significant inclusions of air from the south into the Northwest Territories.

In western Canada emissions from northern Manitoba, Saskatchewan, and Alberta are all capable of penetrating the Northwest Territories. In 1977 the Alberta Oil Sands Environmental Research Program commissioned a study on forward air trajectories out from the Oil Sands region (Denison, 1977) using four years of data. Figure 4 shows the results of that study as they apply to the Northwest Territories. Three-day air trajectories were drawn originating from Fort McMurray. If it is assumed that the transport and subsequent deposition of pollutants from the atmosphere follows this airmass trajectory system, then Figure 4a shows that dry deposition will likely occur on the southern part of the NWT from this source. The most frequent category for trajectory classification was the occurrence of light precipitation (at Fort McMurray) as shown in Figure 4b. Here maximum occurrence of trajectory motion is near the Oil Sands region. However, areas of the Northwest Territories up to the islands of the Arctic may be considered as being influenced by these air motions. Figures 4c and 4d show that air trajectory motions initiated at the time of moderate and heavy precipitation do indeed penetrate into the Northwest Territories. Maximum impacts are likely to be concentrated in southern areas as shown. The study clearly shows that air originating in northern Alberta (with or without the occurence of precipitation) can penetrate a significant distance into the NWT over a period from several hours to several days. Long range transport of air pollution from the Oil Sands and other sources in western Canada has been modelled by others (Kociuba, 1982; Weisman *et al.*, 1982). Results generally confirm that air motion into the Northwest Territories can frequently originate from more southern regions.

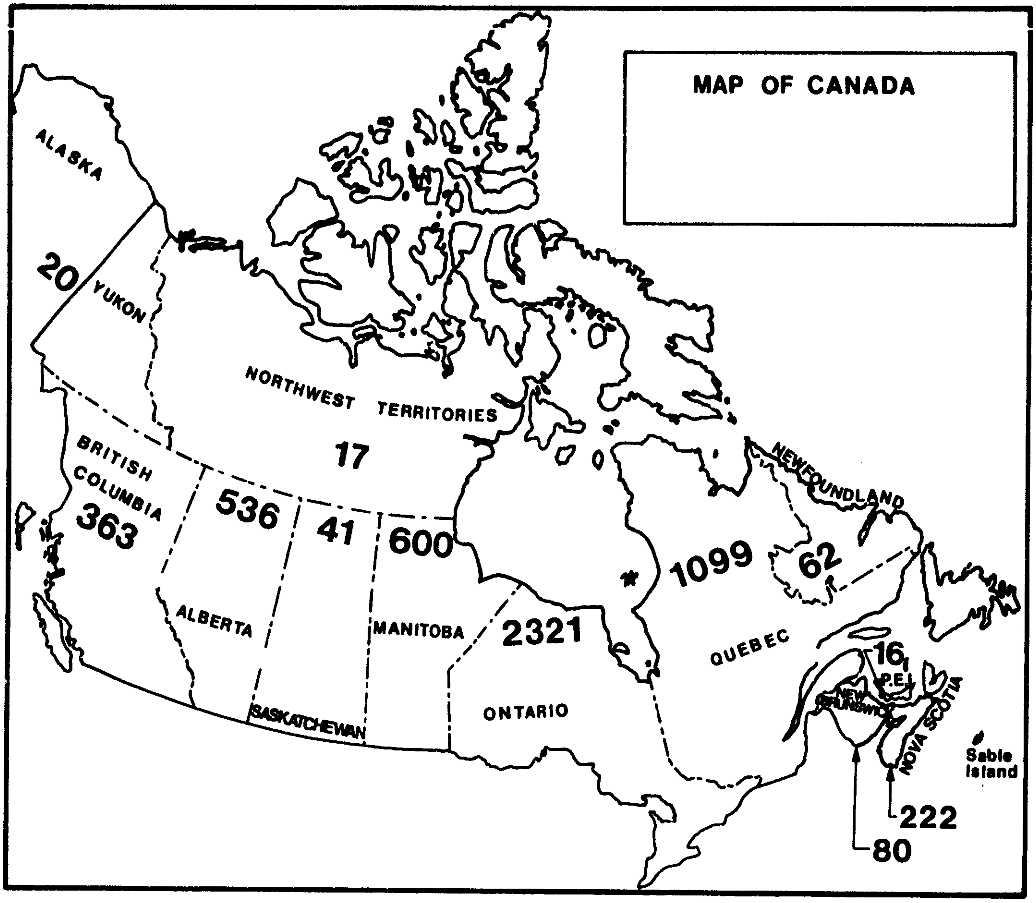

Figure 1 Annual SO_2 Emissions ($x10^3$ tonnes) from the Nationwide Inventory of Emissions of Air Contaminants (1976)

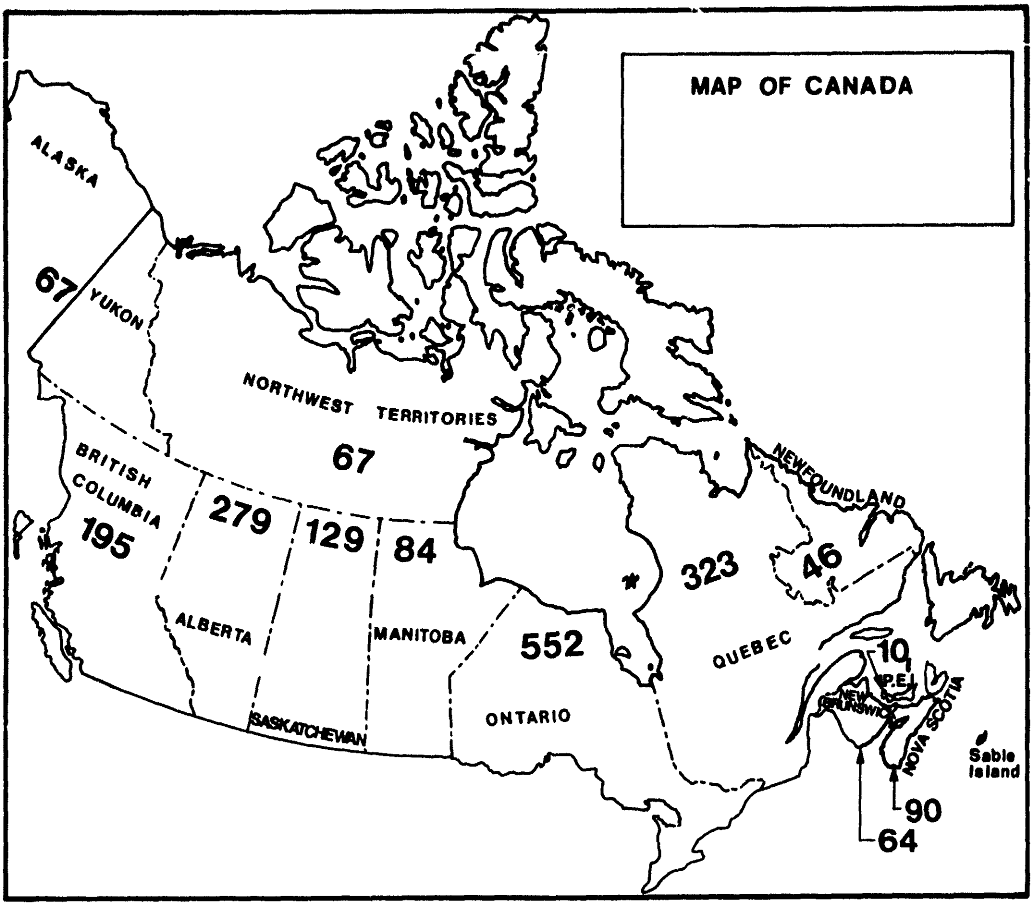

Figure 2 Annual NO_x Emissions ($x10^3$ tonnes) from the Nationwide Inventory of Emissions of Air Contaminants (1976)

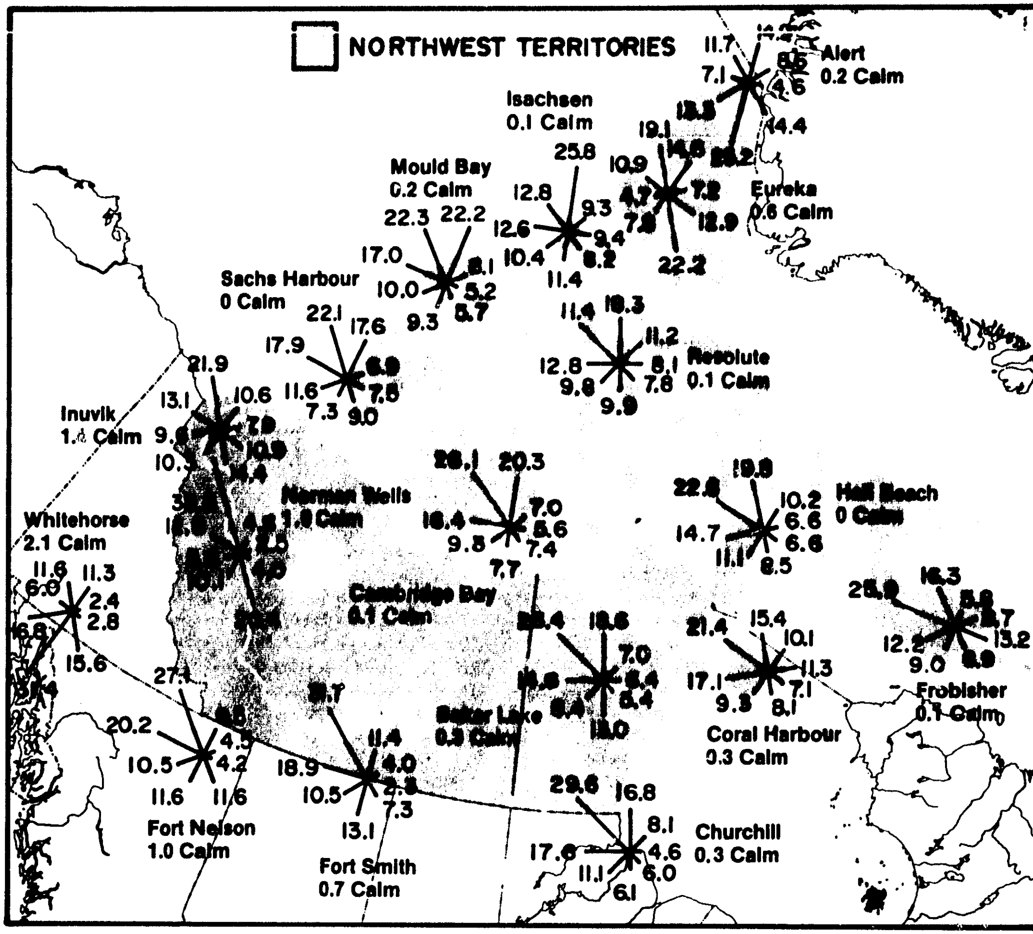

Figure 3 Annual 85 kPa windroses for the Northwest Territories in 1974 from the Atmospheric Environment Service (Hopkinson, 1982)

ACID DEPOSITION IN THE NORTHWEST TERRITORIES

WET DEPOSITION

For several years, Environment Canada has maintained a CANSAP (Canadian Network for Sampling Precipitation) network (Barrie *et al.*, 1980). Table 1 is a summary of the CANSAP results for the year 1980. Mean monthly sulphate and nitrate concentrations in the precipitation as well as the pH range are reported. Table 1 shows that stations which report the lowest mean sulphate also report the lowest mean nitrate. The pH is measured over a wide range of values. For comparison the sulphur content on ocean weather ships in the North Atlantic has been reported such that the normal global value of natural sulphate in precipitation can not be much larger than 0.3 mg/L. This value is given after the effects of sea-spray had been carefully discounted (Nyberg, 1977).

In southern Norway the large amount of acid deposition is mainly due to high precipitation values, not to the specific acidity of the rain water. The mean concentration of sulphate in the rain and snow was 2-3 mg/L (Rosenquist, 1978) for the U.S. compared to 1.5 mg/L for most of central Scandinavia. In the northernmost parts of Scandinavia, average values below 1 mg/L are found. In all areas a considerable part of the acid in both snow and rain was found to be precipitated during limited periods called "episodes".

In Canada, Maniwaki (Quebec) and Mount Forest (Ontario) data both show the presence of mineral acids in the rain. In the north, Fort Reliance values for sulphate are consistently low, with rather high hydrogen ion concentrations as measured by pH values. In these samples it is felt that pH is not a good indicator of acidity, due to the fact that in dilute precipitation solutions normal pH measurements are affected by unwanted electrode polarization potentials. In unbuffered low ionic strength solutions there can be significant effects from these unwanted potentials (Tyree, 1981).

Table 2 shows sulphur and nitrogen wet depositions for stations within the Northwest Territories and other select Canadian sites for 1980. Areas within the Northwest Territories where CANSAP data are regularly taken include Inuvik, Fort Reliance, Hay River, and Mould Bay. In that year NWT stations received annual sulphate wet depositions in the range of 0.65 to 2.17 kg/ha. For nitrogen as nitrate, the values ranged from 0.05 to 0.30 kg/ha. Several authors (Frantisak *et al.*, 1980; Almer *et al.*, 1978) generally concur that annual wet deposition of sulphur on a world-wide basis is likely near 2 kg/ha although this value is extremely difficult to quantify. The nitrogen wet deposition as nitrate is generally not known. Sulphur and nitrogen deposition levels reported in some CANSAP stations (Mount Forest and Maniwaki) are typical of wet deposition rates in areas where excess hydrogen ion is considered to present possible environmental effects.

Sulphur and nitrogen are reported in acid deposition studies since they are better, more stable indicators of acidity than electrode-derived pH measurements. Nevertheless, pH is included in the CANSAP network and given in this table because it is a relative indicator of acidity for the sample (Barrie *et al.*, 1980).

By way of comparison, studies of precipitation chemistry in Scandinavia have shown the mean annual wet deposition of sulphur (as sulphate) as kg/ha with an annual mean pH of 4.3 (Dovland *et al.*, 1976). The total annual deposition of sulphur as sulphate in precipitation in Central Alberta ranges from 2.2 to 4.4 kg/ha (Walker, 1969). The average value of annual wet deposition of sulphur in the eastern United States is estimated to be 11.9 ± 4.7 kg/ha (Galloway and Whelpdale, 1980). This latter value is based on 25 regionally representative sites.

The pH of atmospheric precipitation (Sequeira, 1982) at any given location depends on the chemical nature and relative proportions of the acids and bases in solution. The long-term free acid concentration depends on the temporal variability of natural and anthropogenic compounds in precipitation. The pH variation in nature may well be accounted for by variations related to changing alkali content relative to acid. However, sulphate and nitrate are not good quantitative indicators of acid deposition unless the relative alkali deposition is negligible or corrected for neutralization.

Further to assess the acidification of a rain sample one must study its entire ion balance. Table 3 shows the major ion concentrations in microequivalents per litre derived from the CANSAP data for the month of September, 1980. The hydrogen ion concentration of an air-polluted rain sample is difficult to determine and is not given. Man and nature both contribute to the ion balance of a rain sample, but it is generally believed that man's contribution of anions (primarily SO_4 and NO_3) far exceeds his contribution of cations. Man is adding emissions through industrial processes which are mainly acid-forming. Table 3 gives an indication of cation-anion availability in the precipitation collected at several stations of interest. Locations such as Inuvik, Churchill, and Kindersley all have significantly large amounts of cations. Consequently, the pH levels at these locations are predominantly alkaline.

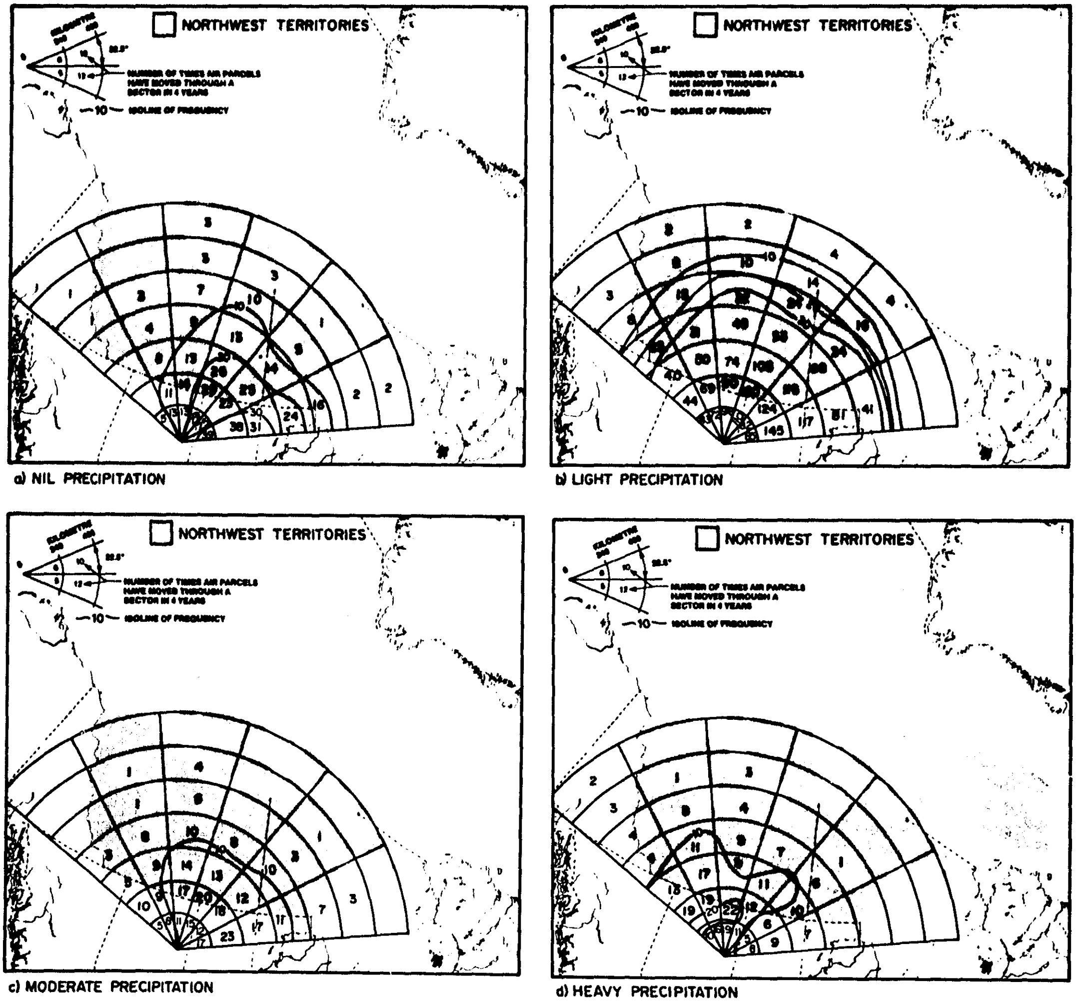

Figure 4 Frequency of air three-day parcel motions by direction "out from" the Alberta Oil Sands Area at 85 kPa (Denison, 1977)

Table 1

CANSAP SUMMARY 1980 FOR NORTHWEST TERRITORIES AND OTHER STATIONS

Location	Sulphate mean mg/L	Sulphate range mg/L	Sulphate No. obs	Nitrate mean mg/L	Nitrate range mg/L	Nitrate No. obs	pH range
Inuvik NWT	1.6	3.3-0.4	11	0.36	0.75-BD	11	7.5-6.5
Fort Reliance NWT	0.8	1.8-0.5	7	0.09	0.49-BD	8	6.1-4.3
Hay River NWT	4.0	6.7-0.4	8	0.46	1.86-BD	7	7.6-5.3
Mould Bay NWT	2.0	3.9-BD	5	0.44	0.76-BD	5	6.6-5.3
Fort Nelson B.C.	1.1	2.0-0.3	8	0.18	1.05-BD	8	7.0-5.9
Whitehorse Yukon	2.3	4.6-0.4	9	0.45	1.38-BD	6	6.9-4.9
Churchill Manitoba	4.5	5.4-3.6	2	0.18	0.22-0.13	2	6.9-6.7
Mount Forest Ontario	4.5	9.1-1.7	11	3.59	7.08-BD	11	6.3-4.4
Maniwaki Quebec	3.2	6.0-1.1	11	2.24	5.36-BD	11	4.7-4.1

BD below detection limit

Stations with a rather large amount of alkaline structure in the precipitation chemistry can buffer the sample much easier than stations with very little alkaline material in the precipitation. Locations in the former category include Inuvik and Churchill and locations in the latter category include Fort Reliance and Hay River.

DRY DEPOSITION

The best estimate approach for dry deposition is used in modelling long-range transport of air pollution. In most models the deposition velocities for particles range over three orders of magnitude while the deposition velocities for gases range over four orders of magnitude. Further, the dry deposition flux of pollutants to surfaces (i.e. water, snow, vegetation, or soil) has never been adequately quantified.

The atmosphere is continually cleansing itself by dry deposition processes. Wet deposition processes on the other hand operate by an intermittent mode of removal. Hence it has been suggested, that dry deposition is more important than wet deposition for removing airborne pollutants derived from anthropogenic sources (Sehmel, 1980).

Snow crystals falling directly below cloud base have been shown to efficiently collect aerosols in the size range 0.1 to 5 microns in diameter (Magono *et al.*, 1979). Apparent collection efficiencies were near unity. This suggests that snow crystals in the atmosphere would also be effective removal mechanisms for acid particles.

The contribution of both wet and dry deposition is referred to as total deposition. Several studies have been conducted

Table 2

ANNUAL WET DEPOSITION AT SELECTED CANSAP STATIONS 1980

Location	Rainfall (mm)	Sulphur (as $SO_4^=$) (kg/ha)	Nitrogen (as NO_3^-) (kg/ha)
Inuvik	245.1	1.31	0.20
Fort Reliance	237.5	0.65	0.05
Hay River	287.0	2.17	0.30
Mould Bay	99.0	0.65	0.10
Fort Nelson	445.9	1.59	0.18
Whitehorse	281.1	2.11	0.29
Mount Forest	849.6	12.67	7.02
Maniwaki	1016.9	10.64	5.24

on total deposition. The existence of permanent ice cores and prolonged winter periods lends itself well to the use of snow chemistry as an indicator of total deposition (Galvin and Cline, 1978).

Several snow cores have been taken from an area in central Antarctica (Delmas and Boutron, 1980) covering periods extending over the past one hundred years. Special emphasis was placed on the fluctuations observed in the sulphate concentration profile. It seems that anomalies in the profile can be explained by major volcanic eruptions. Acid concentration in ice (representing the past 5,000 years) from a surface-to-bedrock core on northern Ellesmere Island have recently been studied (Koerner and Fisher, 1982) and compared with snow deposited within the past 25 years at the same location. It is concluded that within the recent time frame snows have been increasingly acid in the NWT.

The use of a snowpack to study atmospheric pollution depositional processes was described for northern Saskatchewan (Shewchuk, 1982). The chemical balance in natural (and stable) snowpacks can be used to get some estimation of the total deposition of air pollution onto an ecosystem. Snow by virtue of its chemical and physical properties is an excellent preservation medium for chemical species. The northern Saskatchewan snowpack is quite stable during winter months. It is an ideal medium for acid depositional studies. Results of the study show that primarily the sulphur and nitrogen deposition on the Precambrian portion of the area was fairly uniform, indicating a natural distribution. However, near treelines, agricultural lands, and industrial emitters the sulphur deposited into the snowpack increased significantly, indicating that both natural and anthropogentic activity was influencing the snow chemistry.

Table 3

SEPTEMBER, 1980 CANSAP MICROEQUIVALENTS PER LITRE OF WET DEPOSITION

Location	pH	$SO_4^=$	NO_3^-	Cl^-	NH_4^+	Na^+	K^+	Mg^{++}	Ca^{++}
Inuvik	6.8	18.7	22.7	35.1	6.5	39.1	12.8	71.7	205.9
Fort Reliance	4.7	14.6	BD*	BD	BD*	BD	0.51	0.8	6.8
Hay River	5.8	22.9	BD	3.71	0.6	17.4	1.5	8.3	28.6
Churchill	6.7	7.5	3.9	384.8	0.6	439.1	11.5	124.2	130.4
Fort Nelson	6.3	12.5	BD	BD	BD	0.87	6.77	7.50	16.4
Kindersley	7.1	83.3	71.2	12.0	BD	30.4	6.9	133.3	279.5
Mount Forest	5.0	70.8	56.4	11.7	41.8	4.4	1.5	24.2	39.1
Maniwaki	4.2	81.3	45.4	BD	21.8	4.4	2.1	5.8	15.5

BD below detection limit.

Ecosystem Considerations

GEOLOGY AND SOILS

Little work has been done on the interrelationship of geology to acid deposition. However, most studies categorize bedrock and surficial geology in terms of buffering capacity, which is primarily the presence or absence of carbonate material. The pertinent geology of the Northwest Territories is shown in Figure 5.

Systems with low sensitivity are associated with carbonate-rich areas. Such areas of low sensitivity occupy the western portions of the Northwest Territories and contain mainly sedimentary and volcanic rocks. The carbonate nature of the bedrock results in high buffering capacity. The highly sensitive area comprises a vast portion of the eastern part of the Northwest Territories. Here, the bedrock consists of primarily plutonic rocks such as granite and granodiorite. Several areas in the District of Mackenzie are highly sensitive as well, being similar in geologic structure to the Athabasca Sandstone basin of northern Saskatchewan. The quartzitic sandstone of this region has little carbonate buffering capacity.

The impact of acidic deposition on soils is dependent upon such soil properties as the amount of exchangeable cations and the proportion of those cations other than hydrogen. Holowaychuk *et al.*, (1981) have established a classification of soil sensitivities for northern Alberta and Saskatchewan based on these criteria.

A soil map for the Northwest Territories is seen in Figure 6. Soil sensitivity to acid deposition is based on criteria similar to those used in geology because many of the soil constituents are derived from the underlying geology. The term sensitivity refers mainly to the degree of susceptibility of the soil to changes in pH in response to acid inputs. However, consideration must also be given to the possible influence that soild may have on the quality of effluent water. The rock, peat, and podzolic soils of the Mackenzie District likely contain some degree of limestone or carbonate as a buffer. They can be tentatively classified as possessing low sensitivity to acid deposition. However, there are vast areas in the eastern Arctic that consist primarily of tundra soils and permafrost. These areas are lacking in carbonate and consequently can be tentatively classified as possessing high sensitivity to acid deposition.

TERRESTRIAL AND WILDLIFE SYSTEMS

In Canada few studies have attempted to relate acid deposition to plant damage in the field. Adverse effects on woodland areas of Canada are expected to be extremely variable, but long-term decreases in forest growth due to acid precipitation have yet to be demonstrated (Tamm, 1976).

The principal vegetation zones of the Northwest Territories are shown in Figure 7. The lower Mackenzie is occupied by predominantly boreal forest type, while much of the central portion of the territories consists of forest and barren land. The northern sections of the Territories consists of Arctic and alpine tundra.

A computerized environmental data base has been utilized to summarize quantitative information on soil type, vegetation, and surficial geology for areas in Canada receiving acidic deposition (Rubec, 1981). Poorly buffered, acidified podzolic and bare rock were considered as highly sensitive to acidic deposition. Approximately 30% of the area north of 60° latitude has a high sensitivity to increased acidic deposition.

Determining the effects of acidic deposition on the flora and fauna of the Northwest Territories is a complex task. The poor quality of much of the information makes only preliminary evaluations possible. However, mixed and hardwood forests have low sensitivities but such areas may have lichen species that are highly sensitive. Above the treeline, despite low levels of total annual precipitation, effects may be significant on the sensitive lichen communities in the NWT (Rubec, 1981).

Much of the recent air pollution research on plants is focussed on experiments designed to simulate low SO_2 concentrations over prolonged periods of time. The effect of low concentrations of SO_2 on trees has been studied at Whitecourt area of Alberta (Legge *et al.*, 1980). This work showed that there has been a definite reduction in basal area increment in lodgepole pine trees since emissions from gas plants began. This effect progressively declined to zero several tens of kilometres from the source. It is believed that sulphur dioxide acts through a depression in the net assimilation rate (Bell *et al.*, 1979).

In agricultural crops, SO_2 pollution may be beneficial. Sulphur is an essential plant macronutrient and plays a major role in the synthesis of proteins and chlorophyll. Maugh (1979) found that near a coal-burning power plant in an agricultural zone of the United States as much as 40% of the plant-accumulated sulphur was derived from the sulphur

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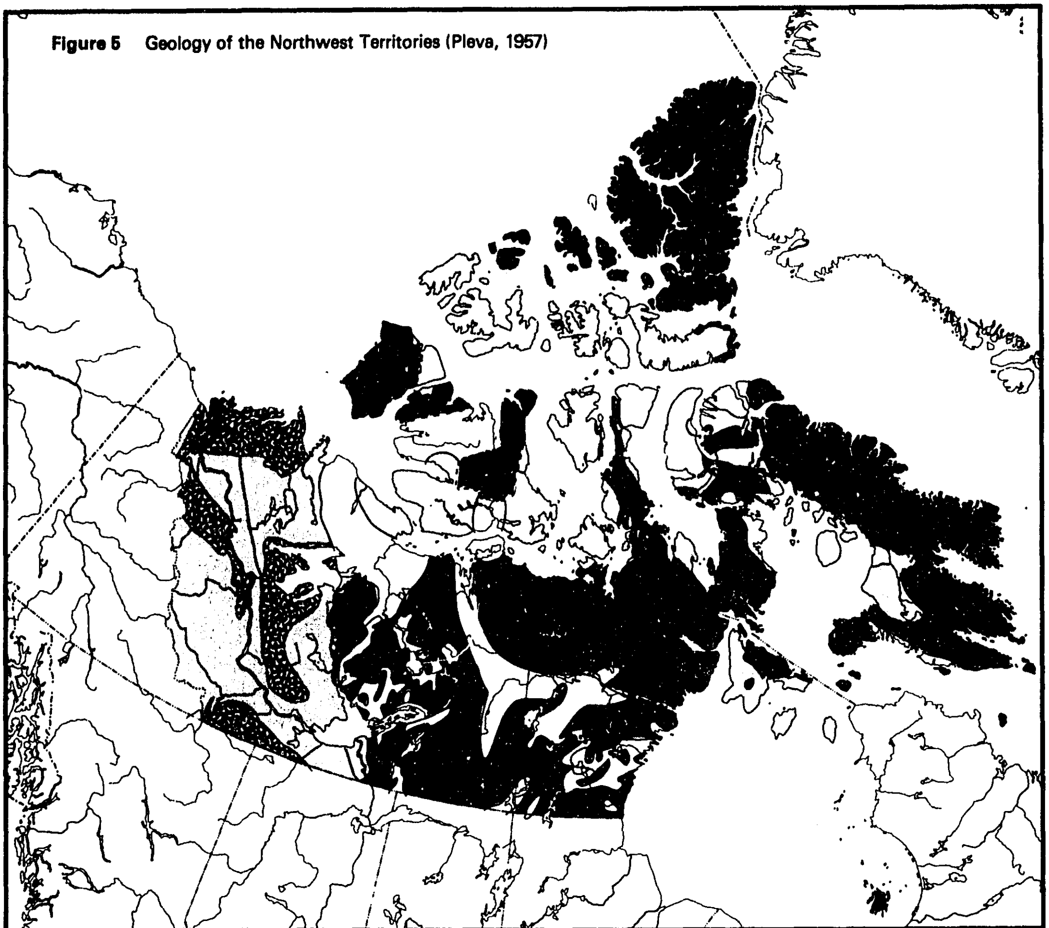
Figure 5 Geology of the Northwest Territories (Pleva, 1957)



CENOZOIC, Sedimentary & Volcanic Rocks

- PLEISTOCENE and RECENT. Alluvium, glacial drift. (All Canada was affected by Pleistocene glaciation.)
- PALAEOCENE, EOCENE, OLIGOCENE. Sedimentary rocks (sandstone, shale, conglomerate, coal measures).
- TERTIARY. Volcanic rocks (basalt, andesite) associated with sedimentary rocks (sandstone, shale, conglomerate, coal measures)

MEZOZOIC, Sedimentary & Volcanic Rocks

- CRETACEOUS. Mainly sedimentary rocks (sandstone, shale, conglomerate), oil and natural gas, coal, tar sand, bentomite

PALEOZOIC, Sedimentary & Volcanic Rocks

- UNDIVIDED
- CARBONIFEROUS and PERMIAN. Mainly sedimentary rocks (sandstone, limestone, shale, conglomerate), some volcanic rocks; coal measures, oil and natural gas, gypsum.
- DEVONIAN. Sedimentary and volcanic rocks (shale, limestone, dolomite, conglomerate, sandstone; volcanic rocks), salt, oil and natural gas.
- SILURIAN. Mainly sedimentary rocks (sandstone, shale, limestone, conglomerate, dolomite), some volcanic rocks; gypsum, salt; oil and natural gas.
- ORDOVICIAN. Sedimentary rocks (limestone, dolomite, shale, argillite, sandstone, quartzite, grit), oil and natural gas
- CAMBRIAN. Sedimentary rocks (dolomite, limestone, shale, chert, quartzite, sandstone, conglomerate).

PRECAMBRIAN, Sedimentary & Volcanic Rocks

- PROTEROZOIC. Mainly sedimentary and volcanic rocks and derived metamorphic rocks (shale, argillite, slate, chert, limestone, dolomite, sandstone, quartzite, arkose, greywacke, conglomerate; schist, gneiss, greenstone, andesite basalt, trachyte, tuff, volcanic breccia; iron formation).
- ARCHEAN. Mainly sedimentary and derived metamorphic rocks (argillite, slate, arkose, quartzite, greywacke, conglomerate, sedimentary gneiss and schist). Associated with areas mainly volcanic and derived metamorphic rocks (andesite, dacite, basalt; rhyolite, trachyte, volcanic breccia and tuff; greenstone schist, hornblende gneiss; iron formation).

INTRUSIVE ROCKS

- ARCHEAN and/or PROTEROZOIC. Mainly acid rocks (granodiorite, granite, quartz diorite, granite gneiss), including some granitized sedimentary and volcanic rock. Some areas of basic and ultrabasic rocks (anorthosite, gabbro, diabase sills and dykes)

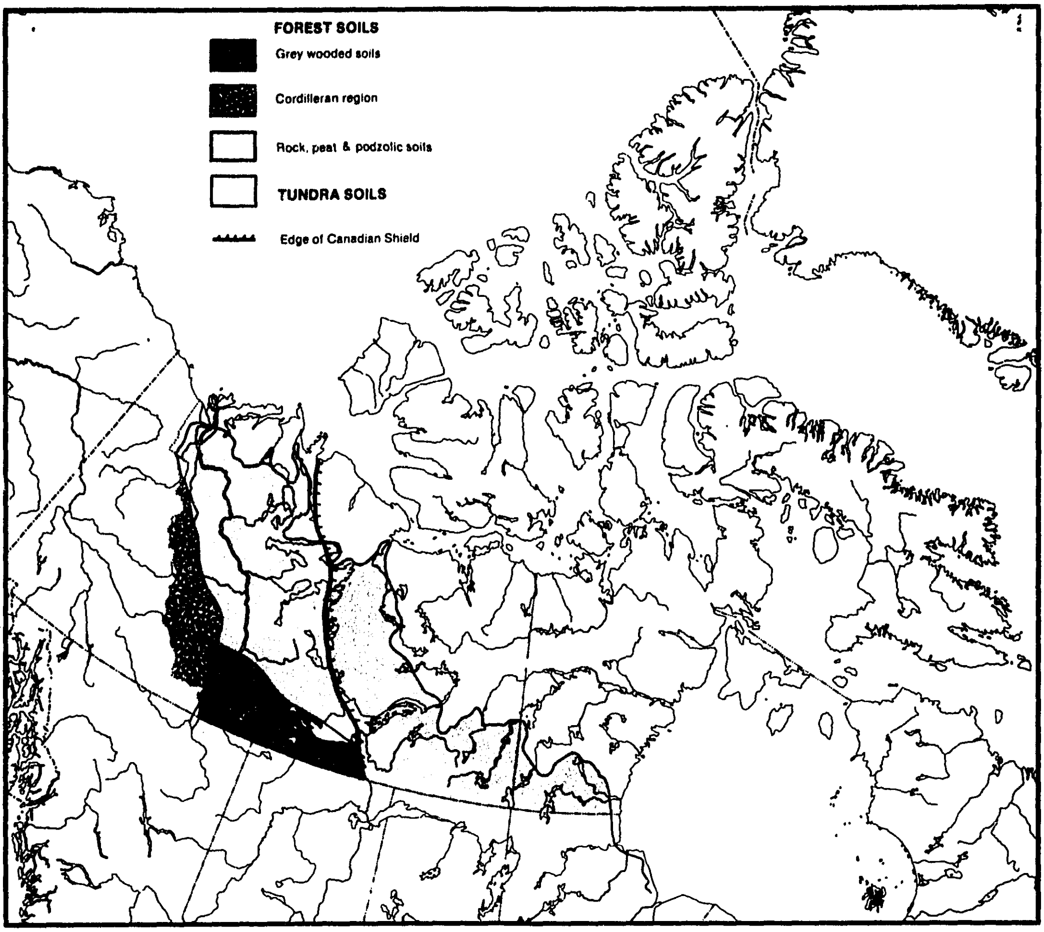


Figure 6 Soils of the Northwest Territories (Pleva, 1957)

dioxide absorbed directly from the air. In a study to determine the relative sensitivity of major United States crops to sulphuric acid rain Lee *et al.* (1980) found foliar damage effects evident at pH values below pH 4.0. However, foliar injury was not correlated with yield effects.

Lichens are useful biological indicators of pollution (Connor, 1979). This is due to their ability to accumulate many elements. Leaching of dry deposited sulphur on lichen tissue by rain is a major source of this nutrient. Most sulphur dry-deposited on a tissue surface remains there (Raybould *et al.*, 1977). Lichen sensitivity to pollutants including acid deposition (Robataille, G., 1980) is considered to be extremely variable. Compared to higher plants they have increased sensitivity due to the absence of a cuticle, (pollutants accumulate over the exterior surface), the absence of roots (depends on atmospheric deposition for nutrients), and the absence of water retention (thallus water content varies with that of the surroundings). Epiphytic lichens can be particularly sensitive to small changes in wet and dry deposition. As wet deposition accumulates on lichens, the flow bathing the thalli and the bark (or rock base) becomes more acid. Salts will be leached out of the substrate (bark or rock), thus impairing its buffering capacity. Consequently, the buffering capacity of the lichen thalli may also be affected.

Many studies have dealt with the effects of pollution on lichens. Most of the studies to date have focussed on heavy metals such as copper, mercury, and others (Puckett, 1979). Field and laboratory studies have shown that lichens have the capacity to accumulate high levels of potentially toxic metals.

On the island of Hawaii, Connor (1979) found that the increased ambient air quality values within a 3 km zone about a natural volcano had an effect upon heavy metal accumulations in plants and lichens. Selenium in leaves was low in trees growing at the edge of the "volcanic thermal zone". Samples of lichens *(Cladonia skottsbergii)* confirmed changes in selenium levels both inside and outside the power plant's zone of influence.

The photosynthetic capacity of the caribou lichen *(Cladina stellaris)* was studied in an experiment where simulated acid precipitation (pH equal to 4.0 and a sulphate concentration equal to 10.00 mg/L) was deposited on the lichen tissue (Lechowicz, 1982). Its maximum photosynthetic capacity was lowered by 27% from normal levels. In addition, the lichen in its dry state took 14% longer after wetting to attain this reduced rate of photosynthesis.

Element accumulations in lichens were studied in the Athabasca oil sands area of Alberta (Addison and Puckett, 1980) in relation to both gaseous and particulate pollution. The pattern of element deposition measured on lichen thallus appeared similar to the distribution pattern of elements as measured by physical and chemical means. Elements that were considered in this study included sulphur, vanadium, and aluminum. Highest concentrations occurred within 10 km of the source and a gradient in plant element content was evident for up to 25 km. In general, lichens accumulate elements in the thallus by both wet and dry deposition. The thallus will intercept particulates and gases through impaction, sedimentation, and molecular diffusion.

In winter, pollution is removed from the atmosphere by wet (snowfall) and dry deposition. Spring thaws release deposited elements in an episodic manner. This provides an "acid shock" to the ecosystem. Such pollution releases will stress the lichen in numerous ways (Niebor *et al.*, 1978). A survey of the element content of lichens collected from the Northwest Territories was reported by Puckett and Finegan (1980). Fourteen lichen species were collected from 45 sites and analyzed for 20 elements. Aluminum, chromium, iron, sodium, titanium, and vanadium had enrichment factors in the range 1-5. These values indicate that there was no enrichment in the lichens above the crustal rock value. For other elements, such as chlorine, lead, and sulphur, consistently higher enrichment factors were obtained. The higher values were thought to have resulted from both natural and anthropogenic sources.

Migratory barren ground caribou *(Rangifer groenlandicus)* inhabit the Canadian mainland between the Mackenzie River and Hudson Bay. These caribou have apparently declined in number since 1958 (Kelsall, 1968). In 1977, the estimate was about 600,000 (Calef, 1978) but the 1982 estimate is only 300,000 to 400,000 (Thomas, 1981). Although the animals commonly eat many plants, a staple of the caribou diet is lichen. Species such as *Cladina stellaris* are favoured winter food for caribou (Bergerud, 1977). In Alaska, Hanson *et al.* (1975) found that in winter a free-roaming female caribou could ingest as much as 5 kg (dry weight) of lichens per day.

All vertebrates and many microorganisms require selenium in their diets. Insufficient dietary selenium results in "nutritional myopathy" in domestic animals. Selenium deficiencies have been associated with reduced levels of selenium found in forage vegetation which was grown in soils low in plant-available selenium. Although most selenium deficiencies in livestock can be remedied by dietary supplements, for wildlife the situation is considerably more complex (Shaw, 1981). Sulphur and selenium, which have similar biochemistry in the living organism, may substitute for one another in some biochemical reactions. At the cellular level it is thought that the sulphur and selenium compete for the same uptake sites (Leggett and Epstein, 1956). Most plants do not seem to require selenium as an essential growth element; rather, the

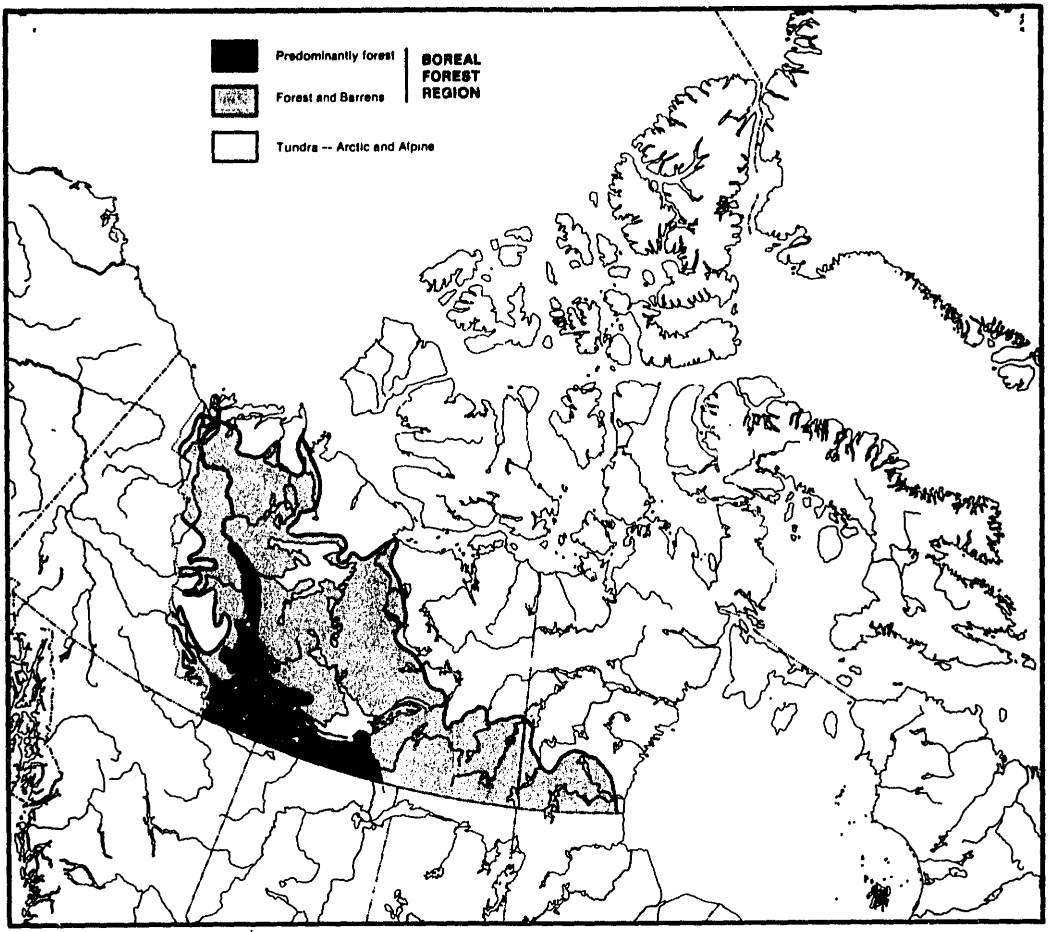


Figure 7 Vegetation of the Northwest Territories (Pleva, 1957)

plant acts as a carrier for selenium, transmitting it to animals. The importance of selenium in animal nutrition has been appreciated only in recent years (MacDonald and Klemm, 1973).

Under acid soil conditions selenium is found mainly in highly insoluble ferric oxide-selenite complexes which are largely unavailable to plants (Oldfield, 1972). Hence, soil which becomes increasingly acidic may lock up the selenium in a form not available to plants. Such selenium-deficient plants may, in turn, affect ungulates. White muscle disease, which results from selenium deficiencies, has been implicated in wildlife deaths in the northwestern part of the continent, but was never proven (Stoszek *et al.*, 1978).

In laboratory experiments Shaw (1980) found that exposure to low levels of SO_2 (0.2 ppm) significantly reduced the selenium uptake by plants. Kurkela (1979) found that selenium concentration in reindeer muscle was reduced to 0.34 ppm when 30% of the diet (normally lichens) consisted of barley. Barley and hay have relatively low concentrations of selenium, in the order of 0.007 ppm and 0.015 ppm respectively. Lichen selenium levels are usually between 0.1 to 0.2 ppm (Westermarck and Kurkela, 1979). Selenium concentrations in muscle of reindeer feed on a 100% lichen diet was 2.21 ppm.

Experiments are being conducted in the field to determine whether SO_2 related selenium-depression in plants of nutritional significance to wild herbivores occurs under field conditions (Shaw, 1982). These results should be closely monitored, given the importance of ungulates to residents of the Northwest Territories.

Sulphur-selenium relationships in major moose browse such as *Salix, Bebbiana, Planifolia* and dogwoods in winter should be studied, particularly in the Mackenzie Valley area as they may be similarly stressed by elevated SO_2 levels.

AQUATIC SYSTEMS

Acidification of freshwaters first became apparent in the 1940s when brown trout populations decreased in a number of lakes in southern Norway (Wright and Snekvik, 1978). Later, this acidification was related to acid precipitation which resulted from the emission, oxidation, and long-range transport of sulphur and nitrogen oxides from densely populated Europe (Barrett and Brodin, 1955). In Canada, acidic deposition from the atmosphere is presently causing the deterioration of susceptible lakes and rivers in south-central Ontario and elsewhere. This acid stress has led to loss of fish populations. Measures of fish tolerance to an increasing acid environment in the La Cloche Mountains of Ontario indicate that lake trout are among the most sensitive while lake herring and white fish are much less sensitive (Harvey, 1979).

In the Sudbury region, fallout of sulphur oxides has been shown to be responsible for damage to vegetation, lakes, and fishes (Beamish, 1976). Increased acidification of lake water was shown to reduce spawning incidence and disturb the normal serum calcium levels. In addition, evidence from a number of laboratory and field studies indicates that low pH could increase susceptibility to disease, change predator-prey relationships, and increase the availability of toxic substances (Fritz, 1980). In the Experimental Lakes Area in northwestern Ontario, snow has been recorded to contain excess particulate material and sulphate concentrations 5 to 10 times greater than measured in previous samples (Barica and Armstrong, 1971). Since there were no major industrial emitters in the vicinity, it seems that the atmospheric fallout may have originated in the north-central part of the United States.

A massive fish kill in the Tovdal River in southern Norway (Leivestad *et al.*, 1976), during the spring run off of 1975, provided an opportunity to investigate physiological changes. In the spring, pollutants released in the first phases of the snow melt produced a pH shock in the rivers and upper layers of the lakes. Lakes and rivers on geological and soil substrates that were poorly buffered were most subject to this stress.

Studies were conducted on a small lake in south-central Norway. Langtern, an acid lake that lost its fish population in the early 1960s (Henrikson and Wright, 1977), has a watershed of 4.8 km² and a surface area of 0.23 km². It is underlain by a granitic rock. Studies showed that the net inputs of all major ions equal the outputs, except for H^+ and NO_3^-, which are accumulating. Acid precipitation is probably responsible for the acidification of this freshwater. Rosenquist (1978) suggests however that not all the acidity of freshwaters is coming from the atmosphere. Part results from a natural cycle whereby acids reach freshwater systems as a result of ion-exchange reactions in the raw humus of the catchment areas. Hence the increased biomass and sub-fossil humus due to changes in agriculture, farming and forestry is also an important factor.

A study on the natural acidification of an ecosystem in the NWT has been reported (Havas and Hutchinson, 1983). The spontaneous burning of shales has produced acidic deposition that has strongly influenced local ecosystem structure. The combustion is produced by an exothermic reaction which is produced when sulphur comes into contact with bitumen. The smoke consists of sulphur dioxide, sulphuric acid aerosols, and steam. It is carried by local advection winds across the tundra into nearby areas with alkaline ponds with pH values typically above 8.0 in a natural setting. The acidic deposition from this source base acidified many ponds to values of pH below 2.0.

Under the U.S.-Canada Memorandum of Intent, current literature regarding long-distance pollutant transport and its effects on water systems has been reviewed (Glass *et al.*, 1981). The study discusses processes by which acidic inputs to watersheds can produce effects, surveys the geographical extent of water quality changes, and evaluates the data on the mechanisms of acidic deposition.

A set of criteria has been proposed to assess the sensitivity of water to acidification (Altshuller and McBean, 1979). The criteria are based on the calcium and bicarbonate content and conductance as shown in Table 4.

Table 4

CATEGORIES OF WATER SENSITIVITY TO ACIDIFICATION
(Altshuller and McBean, 1980)

Sensitivity	Ca (mg/L)	HCO_3 (mg/L)	Conductance (µmho/cm)
Highly sensitive	0-4	1-12	0-30
Moderately sensitive	4-8	12-24	22-70
Least sensitive	>8	>24	> 60

These criteria were applied to a series of lakes in northeastern Alberta and northern Saskatchewan (Shewchuk *et al.*, 1981). It was found that many waters within the Precambrian Shield structure in Alberta and Saskatchewan were highly sensitive to increased acid deposition. The extension of this study to the Precambrian Shield of the Northwest Territories has not occurred. However, extrapolation of the sensitivities of other systems suggests that the Precambrian Shield portions of the NWT would be equally sensitive. Preliminary work done by Armstrong and Schindler (1971), shown in Table 5, tends to confirm that waters on the Precambrian Shield of the NWT are dilute solutions of various ions, including carbonates.

Table 5

IONIC COMPOSITION OF DILUTE LAKES IN THE NORTHWEST TERRITORIES
(Armstrong and Schindler, 1971)

Location	Ca (mg/L)	HCO_3 (mg/L)	Conductance (µmho/cm)
McLeod Bay, (Gt. Slave L.)	2.8	11.6	28
Large lakes (Precambrian)	2.0	9.1*	20
South of Gt. Slave (small lakes)	7.8	30.0*	–
Christie Bay, (Gt. Slave L.)	16.7	76.2	180
Gt. Bear L.	16.2	68	155
Nettilling L. (Baffin Is.)	1.6	40.2	–

* calculated by difference

The table shows that fringe Shield lakes such as Great Bear and Great Slave, contain a degree of buffering capacity. The high bicarbonate of Christie Bay and McLeod Bay is considered to represent anomalies within the region (Atton, 1982). The Precambrian "Large Lakes" are considered more typical of the highly sensitive area. "Large Lakes" represents a summary of data taken at the following locations: Mackay Lake, Obre Lake, Casmir Lake, Angikuni Lake, and Snowbird Lake.

Conclusions and Recommendations

CONCLUSIONS

Air pollution is being transported into the NWT. Most emission sources in Canada are located in the southern portion of the provinces and, because wind systems move primarily in a northwest to southeast direction, most Canadian pollutants will advect away from the NWT. Air pollution events in the NWT are mainly of an episodal nature where frequency is determined by season and air mass trajectory from the point of origin. Acidic deposition in a likewise manner is episodal in nature. A small frequency of storm systems can deposit a large fraction of total annual acid.

The regional emissions and depositions for the eastern portion of the United States and Canada are significantly greater than those of the west, including the Northwest Territories. Some portion of the current acid deposition observed in the Northwest Territories may be attributed to anthropogenic sources. However, wet deposition of both sulphur and nitrogen oxides is low in comparison to the rest of Canada. Air pollution does reach the NWT from industrial areas that are widely distributed. Winter time air pollution occurrences are particularly noteworthy due to the fact that longer atmospheric residence times are involved. The origin and importance of the vast areas of Arctic haze reported in the late winter and early spring seasons remain largely unknown. It is likely that transcontinental emissions within the Arctic Circle should be considered.

Lichens can accumulate significant quantitites of sulphur, vanadium, nickel, lead, and other elements by dry deposition processes. Some model air trajectory studies show that under specific conditions it is possible to have dry deposition impact upon the Precambrian Shield of the Northwest Territories. The lichen-herbivore relationships in the NWT may be of concern.

This results from the fact that lichens are rather efficient accumulators of dry particle deposition and may concentrate sulphur in their tissues. This may cause selenium deficiencies in the ungulates which depend on lichen. It is possible to envisage an increase in the current acid depostions within the NWT, as more industrial projects come on stream. Their effect on lichen communities is not known at the present time.

On the Precambrian Shield many of the freshwater lakes have alkalinities that make them highly sensitive to acid deposition. However, the western portion of the Northwest Territories possess sufficient carbonate structure so that it is moderately sensitive to acidic deposition. An exception might be the mixed woodland and organic soils of the Mackenzie Valley. Here, poorly buffered glaciofluvial and moraine deposits with lichen vegetation may be significantly affected by even low annual inputs of acidic deposition. Effects of acid deposition on the sensitive soils and tundra vegetation have not been documented to date.

Numerous knowledge gaps exist in regional sensitivity of the Northwest Territories to the impact of long-term deposition trends. Improved information as to the nature of the associated biological effects and modelling the dose/response relationships is required. Unless significant water quality and biological monitoring programs are in place, there will be little capability in the future to quantify results of either reduction or increases of ecosystems to acidic deposition.

RECOMMENDATIONS

1. *It is recommended that the current CANSAP network be maintained and that a new series of locations be established in the Keewatin, particularly at Baker Lake or Ennadai Lake. A precipitation chemistry program should be considered for the Arctic Islands.*

A strong statistical base is needed for precipitation chemistry as episodic transports into the region are responsible for much of the air pollution. The current CANSAP data do not adequately address the deposition rates of the eastern portion of the Precambrian Shield. Fort Reliance cannot be considered a typical station for the study of acid deposition in sensitive areas of the NWT. More attention should be paid to event samples and less attention given to monthly integrated composites. Acidic precursors are transported to the NWT in the air, rain, and snow. It is natural that first efforts at quantification begin here.

It would be quite useful to establish precipitation chemistry studies in the High Arctic. Locations such as Alert should provide more knowledge on the atmospheric depositional processes involved with the Arctic haze phenomenon.

Since there are few alkaline ions in the structure of the Arctic atmosphere to neutralize the input acidity of sulphate, the question of possible impacts of acidic deposition in late winter or early spring must be of primary concern.

2. *It is recommended that dry deposition receive more attention in environmental monitoring and research studies, that increased research on snow chemistry studies is a particularly useful way, in part, to accomplish this end.*

Sulphur and heavy metal transport to the Arctic takes place because deposition processes generally involve slow removal mechanisms. Dry deposition is a difficult parameter to measure effectively. However, there are methods available that could be used to determine the relative importance of this deposition indirectly. A detailed snow chemistry survey for the entire mainland portion of the Northwest Territories based on a 100 km-square grid would be highly desirable. However, the area of the NWT Precambrian Shield should receive the greatest attention.

Snow is an effective accumulator of atmospheric fallout. By monitoring changes in snowpack chemistry over a long period of time the importance of total deposition may be assessed.

3. *It is recommended that emissions grids for sulphur and nitrogen oxides be maintained for the areas located near the Northwest Territories.*

It is likely that within the NWT over the next several decades emissions will not increase significantly over the present value. However, present emissions and future growth scenarios are in place for many of the provinces and countries near the NWT. The modelling of the long-range transport of these pollutant emissions into the NWT will give some direction as to where impacts are expected. The emissions from eastern North America, Europe, and Russia must not be discounted in this inventory.

4. *It is recommended that increased modelling of long-range transport of air pollution be undertaken and that particular importance be given to modelling deposition onto sensitive ecosystems.*

The annual frequencies of wind patterns show that circulations from the northerly sectors are predominant. Major emitters in southern Canada are shown to have possible impacts in the Northwest Territories by way of episodic intrusions. However, the persistence and frequency of circumpolar air masses is likely to be far more important to the area, this is particularly true for the islands of the Canadian High Arctic. Depositions scenarios for the periods during March and April should receive the greatest attention.

5. *It is recommended that special studies be initiated to explore the possible link between increased sulphur deposition episodes and selenium deficiencies in wild herbivores, particularly the barren ground caribou.*

Knowledge is incomplete on the environmental variables that influence growth rates of lichens and annual production rates. A great deal more information is needed on the influence of atmospheric fallout of industrial wastes on lichen growth rates and species susceptibility. Selenium is an important trace constituent of animal diets. Since caribou depend heavily on lichen in their diet it is recommended that the importance of selenium leaching from lichen tissue be addressed in field experiments.

Research into SO_2 effects on herbivore food quality should proceed along two lines. The collection of baseline data at permanent locations throughout the mainland Northwest Territories should be initiated and their response to low levels of SO_2 should also be conducted. In addition, considering the possibility of the depression of the photosynthetic capacity of lichens wetted by acid deposition, it is essential that the implications of long-term reductions in lichen biomass in northern ecosystems receive further study.

These studies must also include the effects of acid deposition on arctic and Sub-Arctic soils. Little is known of possible impacts here. Increasing the current acid-loading may well lead to significant alteration of much of the Arctic environment due to the fact that many systems at present are existing under marginal conditions.

6. *It is recommended that an alkalinity baseline be established for small lakes on the vast Precambrian Shield of the NWT.*

First effects of acid deposition are seen in lightly buffered freshwater systems. Such systems exist on vast areas in the Northwest Territories. A representative number of small lakes covering mainly the Precambrian Shield in the NWT are recommended for this study.

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