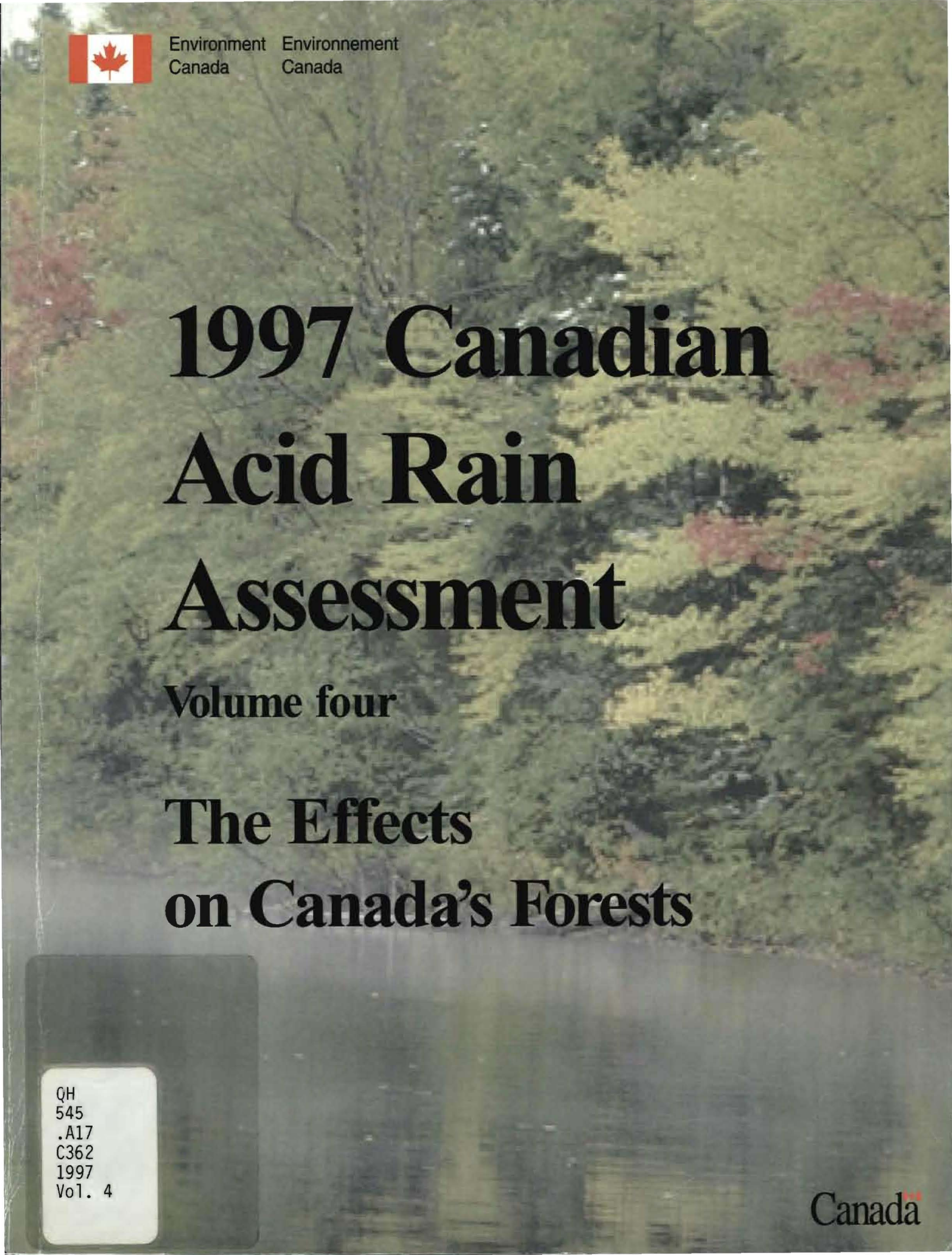
Environment Canada Environnement Canada



1997 Canadian Acid Rain Assessment

Volume four

The Effects on Canada's Forests

Canada

Published by the Authority of the Minister of Environment

1997 Canadian Acid Rain Assessment

Volume four

The Effects on Canada's Forests

Written by:

P Hall, W. Bowers and Harry Hirvonen
Canadian Forest Service
Natural Resources Canada
Ottawa, Ontario

Gary Hogan, N, Forster and I. Morrison
Canadian Forest Service
Natural Resources Canada
Sault Ste. Marie, Ontario

K. Percy and R. Cox
Canadian Forest Service
Natural Resources Canada
Fredericton, New Brunswick

Paul Arp
University of New Brunswick
Fredericton, New Brunswick

Acknowledgement Page

The 1997 Canadian Acid Rain Assessment is a federal and provincial project that had its beginning at a joint meeting of the Canadian Council of Ministers of Environment and Energy in November 1994. At that meeting, the ministers agreed to develop a national strategy for a long-term acid rain program that would begin after the year 2000.

According to the statement of intent to which the ministers agreed, this strategy was to be based on consultations with Canadians and the principles of co-operation on which the ministers agreed the year before in the Comprehensive Air Quality Management Framework for Canada. The strategy also was to be founded on a scientific assessment of the progress made in existing programs as well as the adequacy of Canadian and American programs to protect Canadians' health and the country's ecosystems. This is part of that assessment.

Contributors

Eric Allen
Canadian Forest Service
Natural Resources Canada
Victoria, British Columbia

James Brandt
Canadian Forest Service
Natural Resources Canada
Edmonton, Alberta

Robert Boutin
Canadian Forest Service
Natural Resources Canada
Ste-Foy, Quebec

Pierre DesRochers
Canadian Forest Service
Natural Resources Canada
Ste. Foy, Quebec

Antony Hopkin
Canadian Forest Service
Natural Resources Canada
Sault Ste. Marie, Ontario

Bruce Pendrel
Canadian Forest Service
Natural Resources Canada
Fredericton, New Brunswick

Tom Sterner
Canadian Forest Service
Natural Resources Canada
Fredericton, New Brunswick

Neil Cape
Institute of Terrestrial Ecology
Penicuick, Medlothian
United Kingdom

Guy Fenech
Atmospheric Environment Service
Environment Canada
Toronto, Ontario

David McLaughlin
Air Resources Branch
Ministry of Env. and Energy
Toronto, Ontario

Jean-Pierre Martel
Canadian Pulp and Paper Association
Montreal, Quebec

Rock Ouimet
Direction de la recherche
Ministère des ressources
Ste-Foy, Quebec

M. Germain Paré
Service de la recherche appliquée
Ministère des Forêts
Ste-Foy, Quebec

Wally Szumylo
INCO Ltd.
Copper Cliff, Ontar

Catalogue number – En56-123/4-1997E
ISBN number - 0662-25983-1

TABLE OF CONTENTS

Executive summary

The maintenance of the health of Canada's forest ecosystems is an important prerequisite to national and global forest sustainability. Remedial and preventative strategies formulated to address forest health must consider as a key factor the potential impacts of atmospheric pollution, particularly acid rain, on forests. This assessment reviews findings, highlights current trends and provides direction to strengthen national programs aimed at addressing acid rain issues; and focuses the links of science with policy.

Evidence for impact

The health of large portions of Canada's forests is being adversely affected through continuous exposure to a range of air pollutants. Air pollutants damage trees directly or influence ecological processes in a manner that impedes the development of a healthy forest ecosystem. Both managed and unmanaged forests are affected.

The range of impacts may be minimal or severe depending on the region of the country and on intensity and type of air pollutant. For example, in eastern Canada acid rain is extensive. Acid rain, used here as a generic term for all forms of precipitation including acid snow, acid fog, and acid vapour, damages the surfaces of leaves and needles and reduces a tree's ability to withstand cold and inhibit germination of pollen. Consequently, tree vitality and regenerative capability are reduced. In western Canada, acid rain is less widespread, with damaging pollutant levels being localized.

Forest ecosystem effects:

Dry and wet acidic deposition alters the chemical and physical characteristics of the leaf cuticle. - The cuticle is a thin, waxy layer covering the leaf and needle surface of trees. It protects the leaves and regulates many of the tree's functions. Alteration of the cuticle structure may result in acceleration of the natural ageing process and reduced tree vigour. In essence, the ability of the tree to cope with other stressors such as drought, insects and diseases and increased ultraviolet radiation is reduced.

Gaseous pollutants cause a decrease in net photosynthesis and nutrient uptake in mature red spruce trees; this effect increases with absorption of sulphate. - Other studies with lodgepole pine and trembling aspen near point sources of pollution showed more recently dead trees in areas of high pollution than in areas of less pollution. Volume increments also decreased. These results may be precursors of long-term trends in stand vigour attributable to continued pollution at the regional scale.

Acid fog or mist, with a pH below 5.6, prevents germination of pollen in white birch and mountain paper birch - Acid fogs are common along the Bay of Fundy where these trees are most impacted. Dieback within these species in this region is also extensive.

Acid mists also reduce a tree's frost hardiness - Studies associated with acidic fogs that regularly blanket high elevations of the Appalachian and Laurentian Mountains, show that a direct relationship exists between the amount of sulphate in the leaves and the ability of a tree to withstand cold temperatures. For example, in red spruce a 0.1 % increase in sulphur in leaves causes a 2.7°C decline in frost hardiness. With continued pollution, trees can be expected to become more vulnerable to climatic perturbations.

Red spruce decline at high elevations has been strongly linked to increases in aluminum/calcium ratio of woody tissues, and to increases in respiration. - The mobilization of aluminum through soil acidification impedes the uptake and transport of base cations by trees.

A continuing soil nutrient decline, due to acid rain, is occurring in certain forest ecosystems. - In Ontario, ambient levels of acid rain have accelerated the loss of base cations from soils that support sugar maple-dominated hardwood forest. Studies in Quebec indicate that the nutrient status of sugar maple seedlings declines as soil acidification increases and soil base saturation decreases. These effects likely will be sustained or increased at current deposition levels resulting in a long-term decline in forest ecosystem productivity.

Identifying areas at risk

Eastern Canada has extensive areas where sulphate and nitrate deposition exceeds the critical load. - These areas reflect forest ecosystems sensitive to acid rain. Critical load values provide useful information about sulphate and nitrate deposition that may lead to long-term damage of soils and forests. Preliminary modelling, based on the Acid Rain National Early Warning System of plots (ARNEWS), suggests that exceedances of critical loads of 1000 eq/ (ha year) would result in a 6-10% increase in mortality over a period of 11 years. Current exceedances are lower than this amount, but reach well above 800 eq/ (ha year) for portions of southern Ontario.

Areas with forest health problems coincide with areas where the annual rate of sulphate deposition exceeds the critical load. - Comparisons of maps outlining high exceedances of soil acidification with maps depicting symptoms of forest decline illustrate this relationship. For example, dieback of sugar maple in eastern Canada and the United States is higher in areas of exceedance than in areas of non-exceedance. In one study, through regression analysis, the rate of forest decline increased about 40% for an exceedance of 1000 eq/(ha yr).

Initial signs of damage from acidic deposition are evident in forest ecosystems characteristic of a harsh climate and soil conditions, - such as those ecosystems representative of nutrient-poor soils or of the northern edge of the growing range of tree species. Given that the effects of continuous sulphate and nitrate deposition are cumulative, decline in forest health may be more widespread in stressed ecosystems than currently documented.

Next steps

Further analysis of sulphate and nitrate deposition is required including enhanced modelling of critical loads and related exceedance. - If deposition continues to exceed critical loads, it poses a serious threat to the sustainability of forests in Ontario and large portions of the commercial forest in Quebec, Nova Scotia and New Brunswick. In some areas, reductions of either sulphate or nitrate deposition will minimize the threat. In other areas, both sulphate and nitrate deposition need to be reduced.

Develop critical levels for pollutants which trees could tolerate without short-term and permanent damage. - The UN-ECE has established critical levels for a number of pollutants, developed for a few sensitive tree species. Some regional work is underway in Canada. This effort needs to be expanded to include the major Canadian species under threat from acid rain.

Critical levels and areas of exceedance need to be mapped for forest ecosystems that are at high risk from acid rain: - for example, in regions of frequent acid fog or clouds. Models that relate concentrations of pollutants in fog or clouds to emissions need to be developed.

Status and trend analysis of the health of Canada's forests requires inclusion of a broad spectrum of ecological attributes of forest ecosystems. - Much research to date has been on effects of acid rain on forest trees and soils. Fauna and other flora, surface and subsurface waters among other attributes need to be incorporated.

A comprehensive approach to assessment of forest health, which links stressors and their cumulative impacts, is needed. - Acid rain must be considered and assessed together with other stressors such as UV-B, toxic chemicals and climate change. Such integrated assessment is key to determination of forest health.

Continued networks of baseline research and monitoring are essential to develop, enhance and monitor key indicators of forest health and to facilitate extrapolation of research results to regional and national scales. - Strong links need to be maintained between ecological science, monitoring and assessment.

1. Introduction

Canada is custodian to 10% of the world's forest resource. The nation's forests encompass 42% of our land area or 417.6 million hectares. They are an integral component of Canada's ecological mosaic. Forests continually respond to a combination of anthropogenic (i.e. air pollution, climate change, and enhanced UV-B radiation) changes and natural fluxes in the atmospheric environment. Public interest in the health of Canadian forests is high and there exists a lingering concern about anthropogenic influences on this health. The effects of air pollutants, particularly acid rain, are among the major issues. The term "acid rain" includes acidic precipitation in the form of rain, snow, mist and fog. Research indicates that ambient levels of acid rain are affecting managed and unmanaged forests in parts of North America (Taylor *et al.* 1994.). The determination of impacts of acid rain on forest ecosystems is a key component of a forest health assessment of Canadian forests

This Acid Rain Assessment reviews the state of the science as it has progressed since the last assessment carried out under the auspices of the Canadian Council of the Ministers of the Environment (CCME) in 1990. Considerable progress has been made in addressing issues identified in the 1990 Assessment and on issues that have emerged since. Some of the gaps identified in 1990 are addressed and the direction of future research is outlined. Where possible, results are based on peer-reviewed literature. The Assessment also highlights key policy issues and the uncertainties associated with addressing them.

Specifically, the following questions are addressed:

(a) What are the current effects of acid rain on forest trees, soils and ecosystems?

(b) What are the long-term effects of acid rain on forests?

(c) What policy actions will emerge from current science?

2. Acid rain and current forest decline

Forest decline denotes a continued and sustained deterioration of condition ending in the death of the tree (Manion and Lachance 1992). Decline may result from climatic events, anthropogenic influences such as air pollution, or insect and disease infestation indigenous to forests. These stressors may act singly or in consort to effect decline. In fact, declines are frequently initiated by one or more factors and these causal factors are often difficult to determine. In some instances, forest decline is part of the natural regenerative process for healthy forests. In other situations, anthropogenic stressors trigger decline. Determination of deterioration of forest health due to anthropogenic stressors from forest change due to natural disturbances is essential to forest health assessment. The role of air pollution including acid rain is a key element in this assessment. Current forest decline due to anthropogenic influences is evident in several forest ecosystems of eastern Canada and involves several tree species.

2.1 Coastal Birch forests

Historically, declines of birch have been associated with residual white birch stands subsequent to harvesting of other species. White birch has a shallow root system that is very sensitive to site disturbance. Studies of a protracted decline of yellow birch in eastern Canada, which began in the late 1920s and continued intermittently until the early 1950s, have revealed no definitive causes for the decline. Supposition is that it was triggered by winter climatic conditions (Braathe 1995; Cox and Malcolm 1997) which continued to impact adversely on the species at irregular intervals until a sustained recovery began in the early 1950s (Braathe 1995).

Currently, white birch and mountain paper birch decline is occurring in the Bay of Fundy area on Canada's east coast. This decline is widespread in relatively undisturbed forest stands that experience frequent fog. Observations since 1989 reveal a prevalent browning of leaves followed by premature leaf fall. Twig and branch death follows the browning often culminating in the death of the trees. Devastation by insects or diseases has been ruled out. Significantly, tree mortality in areas affected by acid fog is several times that of death rates in areas not characterized by acid fog. The degree of damage and rate of recovery over the years coincides with the frequency of these acid fogs. These facts clearly point to acid fog; a common occurrence in this area, as the causal factor of the decline (Cox *et al.* 1996.) Of the two impacted species, the foliage of mountain paper birch is more sensitive to acid fog, the tree crown condition is slower to recover, and as a result this species is more prone to mortality than white birch.

Wet deposition via fog in causing direct foliar damage differs from that of acid rain. With fog, acidic pollutants accumulate on leaf surfaces in higher concentrations because of almost instantaneous evaporation, and may remain longer before being washed off (Unsworth 1987;

Jacobson *et al.* 1990). Wetting and drying cycles exacerbate damage from acid fog as has been shown for red spruce, under laboratory conditions simulating acid rain. (Percy *et al.* 1990, 1992).

The birches of the Bay of Fundy area, as well as other tree species, are also subjected to elevated levels of tropospheric ozone from long range transport of gaseous pollutants (Cox *et al.* 1989, Williams 1994). Ozone causes carbon accumulations in the foliage at the expense of the roots (Temple and Riechers 1995). In addition, it damages cell membranes increasing permeability and nutrient leaching from foliage (Swanson and Thomson 1973). Ozone also increases the acidity of marine fogs as well as the water film on the leaf surfaces by the oxidation of sulphite to sulphate (Eatough *et al.* 1984). Ozone also plays a role in the region-wide alteration of needle surfaces (Percy *et al.* 1993; Cape and Percy 1996; Turunen *et al.* 1997; Cape and Percy 1997).

2.2 Sugar Maple forests

Extensive crown dieback and mortality of sugar maple occurred throughout Quebec during the early 1980s. Decline symptoms were evident across almost 2,000 km^2 of sugar maple forest by 1982 (Roy *et al.* 1985). A sustained recovery of these maples has been taking place since this time with mortality and dieback having reverted to historical levels.

Analysis of climatic data around the time of the decline suggested a strong link with winter weather conditions and the dieback. An unusual warming occurred in the affected area during February 1981 as regional temperatures hovered around 20°C resulting in a heavy snow melt leaving much of the ground snow free. Subsequently, temperatures dropped to levels normal for February and the ground froze to a depth of 1.0-1.5 meters. Snowfall again covered the ground. With the onset of the growing season, the trees became physiologically active. However, the roots were unable to tap water from the soil as it was still frozen. The lack of water and damage to the conducting vessels is postulated to have resulted in crown dieback and occasionally tree death.

To test the validity of these conclusions, similar frozen soil conditions were duplicated experimentally. Forest soils associated with sugar maple were allowed to freeze to comparable depths through the prevention of normal snow accumulation on the ground (Bernard *et al.* 1994). Maple decline symptoms resembled closely those of the sugar maple associated with the climatic anomaly of 1981. The experimental freezing resulted in a 27% increase in dieback three years after treatment and a 32% increase in canopy transparency one year following treatment. Sap flow was also impaired in the stressed trees; trees with greater than 50% dieback had a mean sap flow rate 12% lower than healthy trees associated with unfrozen spring soils (Robitaille *et al.* 1995). The experiment also revealed the development of smaller leaves on the stressed maples (Robitaille *et al.* 1996) These experimental results reinforce the conclusion that sugar maple decline of the early 1980s throughout southern Quebec was caused by abnormal climate conditions. The maples were also under additional stress from acid rain which, in consort with climate stress, undoubtedly resulted in more widespread damage than that attributable to weather alone.

Ryan *et al.* (1994) compared the specific volume increments of sugar maples over their range in Ontario. After adjusting for tree age, rainfall and temperature, the results indicate decline in growth beginning around 1960 in the areas of acid sensitive soils. Growth in the southern part of Ontario, where soils adequately buffer incoming acidic precipitation, has been relatively unchanged since the early 1900s. The authors propose that the decreasing growth on acid-sensitive soils is related to air pollution and possibly to reduced buffering capacity of the soils.

2.3 High elevation forests

Polluted cloud and rainwater is a threat to forest health at mid to high altitudes where forests are already under severe natural stress. Red spruce decline at high elevations in the Appalachian Mountains has been strongly linked to increases in the aluminum/calcium (Al/Ca) ratio of woody tissues, and to increases in respiration (Mclaughlin *et al.* 1991). High Al/Ca ratios were also found for red spruce root tips confirming that an increase in aluminum availability is associated with the decline (Smith *et al.* 1995).

The Chemistry of High Elevation Fog (CHEF) project began in late 1985 to study the chemical deposition by clouds to high elevation forests in southern Quebec. Initial sites for the CHEF project were located at Montmorency, Mt. Tremblant and Mt. Sutton . At present, only the latter two sites are still in operation. Researchers have examined trends (1985-91) in concentrations of sulphate, nitrate, ammonia and hydrogen ions. Consistent increases in several ions were found during winter while trends in the other seasons were variable. Significant nutrient leaching occurred from balsam fir foliage at one site during the winter when deposition was highest (Scheup and Hendershot 1989). Lin *et al.* (1995) have shown that trace metal deposition on balsam fir foliage is significantly enhanced by cloud and fog immersion at high altitudes. The chemistry of the acid rain and associated forest decline at Mt. Tremblant and Mt. Sutton is similar to the high elevation red spruce decline in the Northeastern United States (Eagar and Adams 1992).

3. Effects of acid rain on tree physiology

Acid rain affects trees directly by altering the physical and chemical characteristics of leaf cuticles, inhibiting reproductive processes, hampering the ability of trees to respond to low temperatures and by influencing tree physiology. Tree response to acid rain varies depending on dose-response relationships, and the pollutants and species involved.

3.1 Foliar surfaces.

The leaf surface is covered by a thin, waxy layer called the cuticle that has many essential protective and regulatory functions. Its integrity is vital to the maintenance of a healthy tree. This cuticle is exposed to the atmosphere and, as such, serves as the initial contact point between air pollutants and the tree. Its waxy layer has chemical (Percy *et al.* 1994) and physical (Huttunen, 1994) characteristics which can be deleteriously altered by dry and wet acidic deposition.

Under laboratory conditions simulating acid rain, the structure of the needle wax of red spruce and Sitka spruce degrades from a crystalline to an amorphous form at pH levels approximating ambient forest conditions (Percy and Baker 1990; Percy *et al.* 1990). This change is usually accompanied by alterations to wax chemical composition as air pollutants interact with chemicals that are naturally produced by the tree (Percy *et al.* 1992; Krywault *et al.* 1996; Bytnerowicz *et al.* 1997).

Once wax chemistry is altered, essential leaf surface properties are altered. Increased water loss results due to increased cuticular transpiration mainly at night. Decreased vigour in xerophytic species like spruce results. Also, an increase in leaf wettability takes place. As a consequence, water droplets spread more easily and cover a larger surface area of the leaf, putting more leaf epidermis in contact with acid in the precipitation than for an unaltered cuticle. An increased retention of solutes following droplet drydown occurs. This increased concentration of ions causes toxicity over localized areas of the leaf surface resulting in enhanced uptake of damaging ions (Percy and Baker 1991; Percy *et al.* 1992; Cape and Percy 1993, 1996). Increased water retention also leads to environments favourable for germination of fungal spores and for infection from foliar diseases.

The rate at which acid rain causes change in foliar chemistry is often rapid, less than six weeks in some instances, during the early part of the growing season (Huttunen 1994). Such effects are important measures of disruption. Consequently, cuticle change may serve as an indicator for determination of critical levels of acid rain for sensitive tree species (Cape 1994).

Similar cuticular changes have occurred on mature trees in the field. Epicuticular wax chemistry and needle/water droplet contact angles were altered to varying degrees related to deposition levels along gradients stretching more than 300 km (Percy *et al.* 1993; Turunen and Huttunen 1990; Turunen *et al.* 1997; Cape and Percy 1997). The degree of change was more severe on asymptomatic needles sampled from trees exhibiting decline, than on needles collected from "healthy" trees. In general, needle surfaces in the areas of higher acid rain "aged" at a more rapid rate than normal, often mimicking changes induced by natural factors (Hadley and Smith 1994; Hoad *et al.* 1994). Scientists are building on this research to develop the needle/droplet contact angle and epicuticular wax chemistry as early-warning indicators of tree decline due to acid rain (Meyer *et al.*, 1996; Cape and Percy 1996, 1997).

The role of altered epicuticular waxes, due to acid rain, in cuticular water loss is unclear (Rinallo *et al.* 1986, Barnes and Davison 1988). Internal tree water movement and transpiration in needle-leaved trees is unaffected by acid rain under conditions of normal water supply (Eamus *et al.* 1990). Cuticular water loss is more related to changes in the cuticular surface and than the stomata. As such, acid rain at ambient levels is unlikely to induce water loss of trees unless they are already water-stressed. Changes in needle surface characteristics due to natural environmental causes do correlate with changes in rates of needle water loss (Cape and Percy 1996).

Studies looking at relationships between acid rain and the foliar surfaces of deciduous species are limited. An increase in drought stress has been observed in white oak, when simulated acid rain was applied. However, this stress was attributed to adverse effects on root function rather than at the foliar surface (Walker and McLaughlin 1991).

3.2 Foliar leaching, nutrient concentrations and buffering capacity.

Acid rain increases foliar leaching which results in reductions of foliar nutrient concentration and growth unless compensated through increased uptake or internal redistribution (Morrison 1984; Hogan 1992). Increases in foliar nitrogen, and particularly sulphur, occur in response to uptake of sulphur from highly acid rains (Hogan 1996). Increases in foliar aluminum and, in some cases, calcium, can occur in response to nitrate and sulphate pollution, or through cation displacement brought about by soil acidification.

Base cations in foliage vary in their response to acid rain largely based on their physiological properties or location within the leaf. Unlike potassium and magnesium, calcium is readily leached from maple foliage over the range pH 5.0 to 3.0 (Wood and Bormann 1975; Hogan and Foster 1989; Hogan 1996). Potassium and magnesium are more often associated with intercellular structures of the leaf than is calcium. Estimates of leaching from the leaves of red maple exposed to pH 4.6 indicate that 1 to 22% of foliar base cations could be lost from this species during a growing season (Potter 1991).

Studies reveal that simulated insect damage to foliage increases the loss of potassium and magnesium, a finding that is noteworthy given that trees affected by pollutants are predisposed to secondary attack by insects and diseases (Cobb and Stark 1970; Smith 1981). As an example, Maynard *et al.* (1994) noted that trembling aspen, adversely affected by sulphur deposition, had increased incidences of *Armillaria* root rot and *Hypoxylon* canker.

External neutralization capacity (ENC) is a measure of the ability of the leaf to buffer acid rain while the buffering capacity index (BCI) is a measure of the ability of the leaf to resist internal acidification. ENC is related to foliar nutrient levels in a general way and BCI is correlated with magnesium, nitrogen and calcium (Liu and Coté 1993). Although preliminary, research with some native species suggests species-specific differences in these characteristics; an observation which may be used to assess species at risk. Generally, late successional species, such as sugar maple, have low ENC and BCI, which make them susceptible to acid rain. Early successional species like birch and largetooth aspen with higher ENC and BCI are less sensitive to acid rain when compared to these latter species. These traits establish a clear physiological basis for development of a range of measures of tree sensitivity to acid rain.

3.3 Photosynthesis and chlorophyll concentration

Studies with sugar maple and hybrid poplar, reveal that chlorophyll a and b concentrations are unaffected by increases in acidity of rain from pH 5.6 to 2.0 (Reich *et al.* 1986; Hogan and Taylor 1995; Neufeld *et al.* 1985). Certain findings indicate a natural selection for tolerance to pollutants. Adverse effects on photosynthesis are greater on pine clones originating from non-polluted areas than on clones growing in polluted areas (Charland *et al.* 1996). Similarly, white pine from Sudbury, Ontario is more tolerant to both sulphur dioxide and ozone than white pine from Acadia Forest Experimental Station, New Brunswick where ambient pollution is less.

A number of scientists have reported stimulation of net photosynthesis or no effect from acid rain with a pH 3.0 to 3.5 for a number of deciduous and conifer species (Norby *et al.* 1985; Taylor *et al.* 1986; Reich *et al.* 1987; Sasek *et al.* 1991; Seiler and Paganelli 1987; Barnes *et al.* 1990; Hogan and Taylor 1995). Studies with red spruce have revealed increases of net photosynthesis at rain acidities of pH 4.1 and no apparent effect at a mist of pH 3.6 (Taylor *et al.* 1986).

Exceptions to this body of research exist. A reduction in net photosynthesis after treatment with simulated acid rain at pH 3.0 occurred for yellow poplar (Roberts 1990). Also, Meng *et al.* (1994) reported a decrease in net photosynthesis and stomatal conductance for mature red spruce with increasing absorption of sulphate. Mclaughlin *et al.* (1992), reported that net photosynthesis for the same species decreased by 19% and dark respiration increased by 51% following 16 weeks of treatment by acid mist of pH 3.0. Increasing dark respiration is a common response of plants exposed to air pollutants and is considered a reliable indicator of stress.

3.4 Forest plant reproduction

Reproductive systems of wind-pollinated plants are vulnerable to atmospheric pollution. Changes in pollen structure may occur that affect the genetic composition of the progeny (Tanksley *et al.* 1981; Sarcy and Mulcahy 1985; Cox 1989). Natural selection for pollution-tolerant individuals may have occurred in white pine and red pine (Cox 1992). White birch and mountain paper birch near the Bay of Fundy frequently intercept acidic (pH <3.5) marine advection fogs. In both species, pollen germination and basic physiological responses are inhibited below pH 5.6 (Hughes and Cox 1994).

3.5 Frost hardiness

Several researchers have studied relationships between acid rain and changes in the inherent ability of trees to cope with natural stresses. In one study, red spruce was exposed to mist of varying acidity. A correlation was found between leaf sulphate content and frost hardiness. A 0.1% increase in foliar sulphur content caused a 2.7°C decline in frost hardiness (Sheppard 1994).

A toxic effect of sulphate on tree vigour occurs when other nutrients such as nitrogen are insufficient to direct the extra sulphate into protein synthesis for tree growth. Photosynthate production is reduced, and sugar amounts available for synthesis of anti-freezing compounds decrease, resulting in reduced frost hardiness. This process is likely responsible for large-scale decline of red spruce in the Appalachians (Eagar and Adams 1992). Sugar maple decline in Quebec and links' acid rain and frost hardiness are discussed in the section "Results of Forest Health Monitoring".

3.6 Tree growth and physiology

Studies carried out with red oak, sugar maple, hybrid poplar, and jack pine indicate that many growth parameters are not affected by acid rain at pH above 3.0 (Reich *et al.* 1986; Hogan and Taylor 1995). Among the growth parameters unaffected, except within extreme pH ranges, are height growth, number of leaves, stem diameter and leaf area.

In contrast, reductions in the growth rate of root biomass have been documented for white ash and jack pine following acid rain treatment at pH 3.0 (MacDonald *et al.* 1986; Chappelka and Chevone 1986; Amthor 1986). Another study revealed shifts in carbon allocation from coarse roots to a nutrient absorption function in fine roots on red spruce with application of simulated acid rain (Deans *et al.* 1990). These results need to be replicated under natural conditions.

3.7 Carbon exchange and storage

Carbon storage and storage products are reduced in a number of species due to acid rain. Jensen and Patton (1990) reported decreased starch in roots of yellow poplar treated with rains of pH 3.5 to 4.5. In another study, acid mists reduced levels of ethanol-soluble carbohydrates in current and two-year-old conifer needles (Barnes et al. 1990). Increased dark respiration rates have been measured within high elevation forests affected by high levels of acid rain resulting in carbon balances not conducive to sustained growth (Mclaughlin *et al.* 1993.)

4. Effects on soil chemistry

Strong acid anions, including sulphate and nitrate, deposited by acid rain, interact with forest ecosystems in both a beneficial and harmful manner. Both sulphur and nitrogen are essential to plants. Excess amounts however, hinder growth and vigour of soil biota, impede organic decomposition and nitrogen and sulphur cycling, and enhance base leaching and mobility of trace metals. Excess amounts of acid anions also weaken host tree species and cause deterioration of forest ecosystems leading to infestation by insects and diseases.

4.1 Soil biota, decomposition and nitrogen turnover

Increased acidity directly influences the soil nutrient cycle by reducing microbial diversity, nitrification, ammonia volatilization, and microbial respiration (Mahendrappa 1982, 1989, 1991). Microbial respiration and biomass carbon:organic carbon (C_{mic}/C_{org}) ratios are lowered in the litter and humus surface layers of the soil with application of sulphate singly or in combination with nitrate (Thirukkumaran and Morrison 1996). Continued reductions in these processes eventually reduce forest productivity. Acid rain at ambient rates on northern soils is probably not harmful to microbial processes in the short term. However, in areas of higher deposition, or long-term exposure, the possibility of ecosystem deterioration increases.

4.2 Soil acidification and base leaching

In northern Ontario, on nutrient-poor soils, most nitrogen from acid rain is absorbed by foliage or retained by the soil (Hazel *et al.* 1995). Retention of atmospheric nitrogen has a positive effect on tree growth, because much of the vegetative growth of the boreal forest is limited by lack of nitrogen. Vegetative uptake of nitrate helps to buffer soils against incoming acidity. Broadleaf trees neutralize up to 80% of rain acidity, compared to less than 50% for needleleaf trees (Mahendrappa 1983). However, the capacity for these sites to retain additional nitrogen is limited and continued deposition will lead to soil acidification and the eventual leaching of nutrients from the soil.

Any change in sulphate amounts in soil solution with nutrient-poor forest soils depends on the ability of the soil to retain it, which is, in turn, related to the amorphous inorganic aluminum content of the soil (Bhatti *et al.* 1997). At many nutrient-poor sites, the output of sulphate from the soil rooting zone is as great or greater than inputs from the atmosphere (Foster and Hazlett 1991; Mitchell *et al.* 1992).

Studies in Ontario indicate that ambient levels of acid rain have accelerated the loss of base cations from soils that support a sugar maple forest (Foster *et al.* 1992). Sugar maple is sensitive to levels of soil nitrate (Yin *et al.* 1993, 1994). An increase in nitrogen deposition may create nitrogen/base cation imbalances in this species. As an example of what can happen, on some ARNEWS plots in areas of high sulphate and nitrate deposition, depletion of base cations from forest soils is occurring and the prevailing thinking is that this leaching will increase as current deposition levels continue (Morrison *et al.* 1995).

Acid rain reduces concentrations of soil calcium, magnesium, and potassium. Effects are greatest where deposition is the highest (Morrison *et al.* 1995). The year-to-year supply of base cations to forest vegetation may be interrupted on sites where replenishment from the weathering of primary minerals is slow, or affected by natural disturbances such as drought, flooding, or severe frosts. Simulated long-term biomass projections, based on critical load research, suggest that when cumulative losses of base cations occur, forest productivity declines with continued sulphate and nitrate deposition (Arp and Oja 1992).

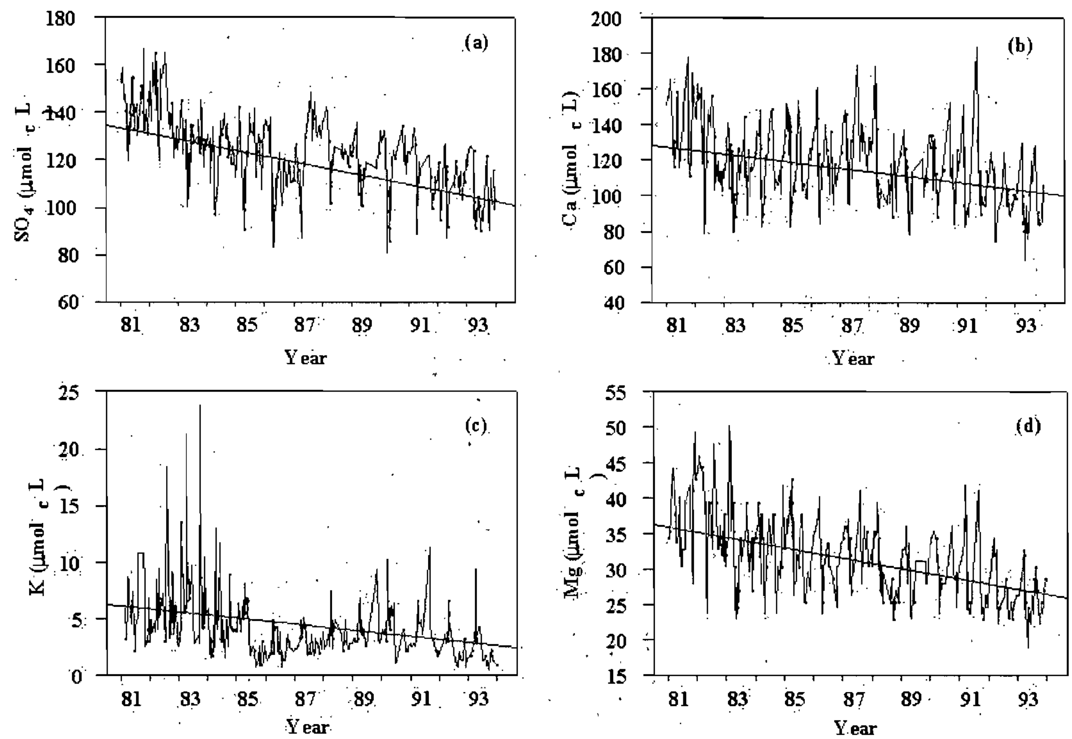
Based on analysis of nutrient fluxes, substantial losses of base cations linked to acid rain have occurred and are projected to continue at the Hubbard Brook Experimental Forest located in the northeastern United States (Likens *et al.* 1996). Continuous depletion of base cations from the forest floor layers has been documented at Hubbard Brook over a 30-year period. Depletion in this order has significant consequences for sustained growth. Sites of similar nutrient status without such an historical record could well be experiencing similar depletion of nutrients.

From studies in Quebec, foliar nutrient deficiencies in sugar maple have been linked with cation imbalances in soil. Specifically, soils associated with these stands have undergone reductions in calcium and potassium saturation, increased magnesium saturation and increased aluminum toxicity (Ouimet and Camire 1995). Growth and nutrient status of sugar maple seedlings decline with increased acidity and subsequent decreased soil base saturation. Overall, adverse impacts on ecosystem productivity are likely to worsen with continued inputs (Ouimet *et al.* 1996).

4.3 Ecosystem response to reduced acid rain

At the Turkey Lakes Watershed (TLW) in central Ontario, declining acidic concentrations in precipitation from 1981 to 1993 resulted in lower sulphate concentrations in soil runoff and stream water (Fig. 1a). Annual decreases in sulphate deposition of up to 31% reduced the concentrations and flux of sulphate in soil (Foster and Hazlett 1991). These decreases have slowed the rate of acidification of the nutrient-poor soils associated with the hardwood stands at TLW. Base cation concentrations in soil runoff and stream water have been substantially reduced (Figs. 1a-d). The increase in base cation levels in soil, in response to lower base cation leaching, however, may be less pronounced due to declining concentrations of base cations in precipitation across eastern North America (Likens *et al.* 1996)

Figures 1a – 1d. Trends in streamflow concentrations (charge mole basis) of sulphate (SO4), calcium (Ca), potassium (K) and magnesium (Mg) from basin 47 at the Turkey lakes Watershed research site from 1981-1993.



4.4 Interaction with other stresses.

Forest ecosystems are exposed to a myriad of natural and anthropogenic stresses. These stresses interact with each other and it is often the cumulative impact of more than one stress that results in reduced forest health. An example of interacting stresses was noted earlier with the decline of sugar maple in Quebec in the 1980s. The decline was triggered by extreme climatic conditions but exacerbated by ambient air pollution in the form of acid rain (Boutin and Robitaille 1995).

Acid rain also needs to be considered in association with other anthropogenic stressors such as ultraviolet radiation, toxic chemicals and climate change to understand cause and effect relationships with the health of forest ecosystems.

5. Results of forest health monitoring

During the late 1970s and throughout the 1980s, concerns regarding regional forest decline and the possible relationships with atmospheric pollutants were expressed in the popular literature, news media, and scientific publications. Much of the focus was on the forests of central Europe, the high elevation spruce forests of the northeastern United States, and the deciduous forests of eastern Canada and United States. In Canada, discussion centered primarily on white birch in New Brunswick and sugar maple in southern Quebec and south-central Ontario. It was during this period that initiatives in forest health monitoring within Canada were instigated.

Forests are monitored to explain the causes of observed changes. Tree condition can vary widely from year to year, and it is through long-term monitoring that trends in forest health can be detected. There are several forest health monitoring systems operated by federal and provincial governments.

5.1 Acid Rain National Early Warning System (ARNEWS)

The Canadian Forest Service (CFS) established the ARNEWS in 1984, in response to prevalent concerns about the impact of acid rain on the health of Canada's forests. Analysis of ARNEWS data strives to detect early signs of change or damage to forest trees and soils attributable to air pollution and not to damage associated with natural causes or management practices. Long-term changes in vegetation and soils attributable to acid rain and other pollutants are monitored. Symptoms of damage from air pollution are not obvious, and frequently resemble damage from natural causes. Experience of field professionals trained to distinguish these symptoms from abnormal climatic conditions, inherent nutrient deficiencies, and the effects of insects and diseases is crucial to ARNEWS.

Assessments of ARNEWS data indicate that there is no large-scale decline in the health of Canadian forests that can be directly attributed to atmospheric pollution (Hall and Addison 1991; Hall 1995a, 1995b, 1995c). However, on a regional scale damage from air pollution is evident for birch in the Bay of Fundy area of New Brunswick, certain high elevation forests and some red oak, red pine and sugar maple forests on acid-sensitive soils in Ontario and Quebec. Investigations into these declines are continuing. Air pollution may have a greater impact on forest stands weakened by other stressors such as climate extremes and insect defoliation.

Analyses of soils from ARNEWS plots were completed in 1985 and 1990, to examine changes in soil properties in relation to wet sulphate or wet nitrate deposition. Generally, no consistent changes in pH occurred over the 5-year period. There were reductions in concentrations of calcium and magnesium in the forest floor in areas of relatively higher acidic deposition. Trend analysis of soil chemistry within ARNEWS is ongoing.

5.2 North American Maple Project

In 1988, the North American Maple Project (NAMP), established a network of 166 monitoring sites in the northeastern United States and Canada covering most of the range of sugar maple. NAMP, jointly managed by the Canadian Forest Service and the United States Forest Service, currently is comprised of 233 plots. In Canada, 62 plots are monitored across three ecozones (Boreal Shield, 16 plots; Mixedwood Plains, 18 plots; and Atlantic Maritime, 28 plots), in both unmanaged stands and those managed for maple syrup production. .

The objectives of the NAMP program are to determine:

(i) the rate of annual change in sugar maple condition;

(ii) whether the rate of change in condition differs with the level of sulphate and nitrate wet deposition, between a sugar bush and undisturbed forest, and for various levels of initial stand conditions; and

(iii) the possible causes of decline.

From data compiled between 1989 and 1995, crown mortality was higher on plots in the Boreal Shield ecozone than in either the Mixedwood Plains or Atlantic Maritime ecozones (Bowers and Hopkin 1997). Moreover, McLaughlin *et al.* (1995) reported maple decline at locations on the Boreal Shield where shallow acid soils dominate. Some researchers have argued that these sites on the Precambrian Shield are poorly buffered against sulphate and nitrate and lower deposition levels can have a greater effect than on deeper and better buffered sites (Arp and Ouimet 1996). However, in earlier work, Basham (1973) had concluded that sugar maple in Ontario, within the Boreal Shield ecozone, is generally slower growing and contains more defects due to poorer site conditions.

Results from NAMP also indicate slightly higher levels of dieback in stands actively managed for sap compared to natural stands. This may be a factor of frequent incursions in sugar bushes causing more stress on the trees compared to unmanaged stands. This additional stress may originate from soil compacting, tree wounding, frequent light thinning, and tapping. Interactions with air pollutants cannot be discounted.

5.3 Québec monitoring networks.

The Réseau de surveillance des écosystèmes forestiers (RESEF) Network for the monitoring of forest ecosystems, was established in 1988 to collect information on climate, nutrient status of ecosystems, precipitation, and air quality. Linkages exist with other networks operated by the Departments of Agriculture and Environment and Wildlife of Québec, and the Canadian Air and Precipitation Monitoring Network (CAPMON) of Environment Canada. A total of 31 sites exist covering various ecological regions of Québec. The network compiles data on the effects of natural and anthropogenic stresses on forest ecosystems, particularly on their biological diversity and growth (Gagnon *et al.* 1994). Analyses of data have yet been published.

5.4 Forest health monitoring in Ontario

The hardwood forest of south-central Ontario receives the highest rate of acid rain and ground-level ozone in eastern Canada. In addition, much of the forest grows on naturally acidic, nutrient-poor, shallow soils characteristic of the Canadian Shield. This combination of high pollution loading and poorly buffered, acid-sensitive soils make a large portion of the hardwood forest in Ontario particularly susceptible to deterioration by acid rain.

In 1985, the Ontario Ministry of the Environment and Energy initiated a forest health survey of the tolerant hardwood forests in Ontario. The objective is to provide a province-wide database on the visual condition of the predominantly sugar maple forest. By periodically re-evaluating the same trees and comparing the results with earlier data, the intent is to identify trends in changing tree condition and allow comparisons between geographic areas across the province. The survey is based on plots containing over 14,000 trees across the range of sugar maple. The main visual symptoms of decline are pale green or yellowed foliage, small leaves, and dieback of the fine twig structure followed by the death of main branches.

Acid rain and ground level ozone, the two main regional air pollutants in Ontario, are highest in the southwestern portion of the province and decrease to the north and northwest. Analysis to date reveals a significant relationship between dieback and soil type. Plots on acidic, sandy soils have more dieback than plots on neutral-to-slightly-alkaline, loamy soils with carbonates in the surface horizons.

The fact that trees in the northern edge of their range and growing on sites with impoverished soils are in poorer condition then southern trees under less climatic stress and on better sites is not surprising. However, the soils of much of the northern hardwood forest are sensitive to acid deposition and pollutant levels are high enough to cause accelerated soil acidification. A statistically significant relationship exists between tree condition and soil pH, base saturation, and available aluminum on acid-sensitive sites. This significance is apparent even though the forest has been severely affected by natural insect and weather stresses. It is possible that air pollutants have altered the chemical cycles in the soil, thus predisposing this forest to devastation by natural stresses.

The average annual tree mortality over the ten-year survey period from all the plots was 1.2%. Results are consistent with other studies that confirm an average annual mortality in tolerant hardwood stands of approximately 1%. The first ten years of monitoring indicate that the hardwood forest in Ontario, on average, is healthy and stable. Annual fluctuations in tree condition are small and largely explainable in terms of known anthropogenic and natural stresses. Regional analyses, however, suggest deterioration in a few areas. Continued monitoring is necessary to determine if these regional trends are induced by air pollution or are longer-term fluctuations in natural forest cycles.

Turkey Lakes Watershed. - Studies carried out at Turkey Lakes Watershed from 1980-1996 indicate that atmospheric sulphur and nitrogen deposition produce an accelerated leaching of calcium, magnesium and potassium from soils. Since the soils are well buffered they have not been depleted of the nutrients necessary to support healthy tree growth. Simulated long-term forest productivity projections suggest that, when the cumulative loss of nutrients is taken into account, forest productivity will decline if sulphate and nitrate deposition continues (Oja and Arp 1997).

6. Critical loads / levels

The term "critical load" is defined as the "highest deposition of acidifying compounds that will not cause chemical changes leading to long-term harmful effects on the overall structure or function of the aquatic and terrestrial ecosystem". According to Nilsson and Grennfelt (1988), critical loads are quantitative estimates of an exposure to one or more pollutants below which significantly harmful effects on specified sensitive elements of the environment do not occur. Development of critical loads for atmospheric sulphur and nitrogen deposition allows the determination of whether or not current or anticipated sulphur and nitrogen deposition loads exceed such values (Arp et al. 1996).

In contrast, the "target load" is a political decision about risk and accepting change. The target load may be set above or below the critical load. The current Canadian objective to reduce acid rain is set at a target load of 20 kg/(ha yr) of sulphate in precipitation. This target was derived in the early 1980s from limited data, mainly based on the loss of sport fish, which occurs when pH in streams and lakes drops below pH 5.3. At that time, the assumption was that a reduction of atmospheric sulphur deposition to 20 kg/(ha yr) would protect moderately acid-sensitive waters. Sensitive terrestrial ecosystems were considered only in the sense of their buffering capacity to prevent leaching of nitrates and sulphates to receiving waters. In addition, not enough information was available to set target loads for protecting highly acid-sensitive areas. Thus, there exists a need to specify critical levels of wet and dry sulphate and nitrate deposition for forest ecosystems both in the short term (years to several decades) and in the long term (several complete stand cycles).

Existing guidelines (RMCC 1990) to protect surface waters suggest a range of target loads of 8 kg/ (ha yr) in some parts of Atlantic Canada, to more than 20 kg/ (ha yr) of sulphate in precipitation in some of the less acid-sensitive regions of Ontario and Quebec. The validity of these target loads in protecting sensitive forest ecosystems needs to be determined along with actual air pollutant loading for policy actions on pollution abatement strategies.

The determination of sulphur and nitrogen loads is critical to the management of forest ecosystems. The pulp and paper industry needs to know the levels of wet and dry sulphate and nitrate deposition that lead to unacceptable long-term effects on soils and forest growth. Similarly, the electric utility industry and regulatory agencies need such data to ascertain and prevent harmful levels of industrial sulphur and nitrogen emissions.

6.1 Case study -ARNEWS Network

A recent study has determined critical loads and related exceedances or non-exceedances for ARNEWS plots under current atmospheric deposition rates, from Newfoundland to Alberta (Moayeri and Arp 1997). ARNEWS sites in British Columbia will be incorporated into this study

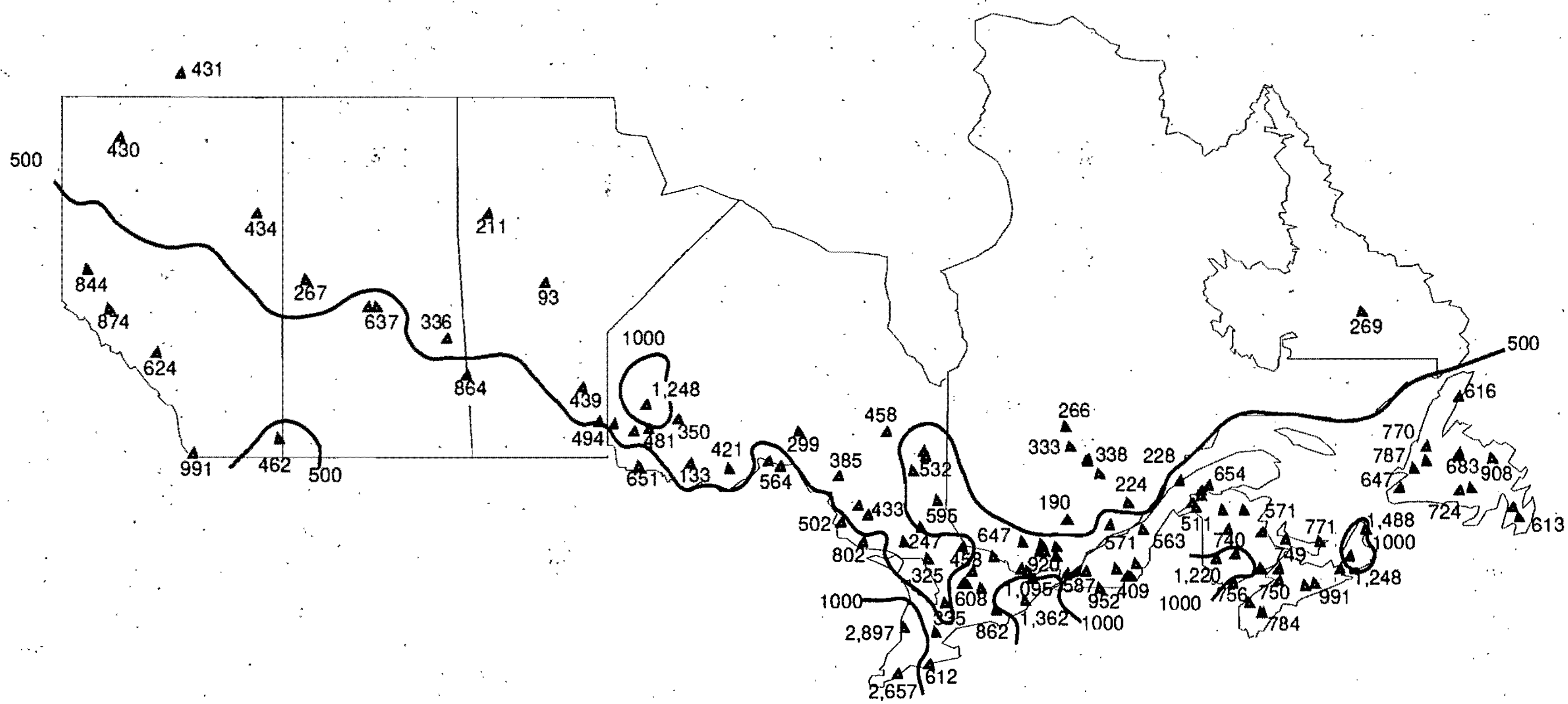


Figure 2. Critical acid deposition load assignments for ARNEWS plots (eq/ha yr). High critical loads correspond to occurrences of calcareous soils. Contours are based on plot-by-plot calculations. Finer resolution calculations will show a contour pattern much more intricate than the one depicted here.

as it evolves. Focus on ARNEWS plots offers several advantages for critical load assessments: plots are georeferenced, vegetation and soil within plots are monitored through common protocols and the monitoring effort is long-term having commenced in 1985.

Critical rates of soil acidification and related exceedances were calculated from the atmospheric acid deposition loads (wet sulphur, nitrogen, calcium, magnesium and potassium), and the capability of soil and vegetation to neutralize the incoming acidity. An aluminium/base cation ratio of 0.15 eq/eq served as the criterion for soil acidification. At this level, both topsoil and subsoil are considered protected against acidification and aluminium mobilization (Moayeri and Arp 1997). Exceedances were calculated by subtracting net acid neutralization rate from atmospheric wet nitrogen and sulphur deposition rates.

Model-calculated values for current critical acid deposition loads and for soil acidification exceedances are presented in Figures 2 and 3. Isolines drawn around these plots divide the regions into:

> a) areas of low and high soil sensitivity to acidification, as indicated by the critical load numbers. Areas with > 500 eq/(ha yr) are less sensitive than areas with < 500 eq/(ha yr);
>
> b) areas of exceedance and non-exceedance (negative numbers); and into areas of high and moderate exceedance, with the division line at 500 eq/(ha yr).

Critical acidic loads of < 500 eq/(ha yr) are prevalent in northern Ontario, Quebec, Alberta, Saskatchewan and Manitoba because of the presence of an acidic soil substrate (Figure 2). Areas in southern Alberta, Saskatchewan, Manitoba, Ontario, and Quebec, and many parts in the Maritime provinces, have high critical acidic loads because of calcareous soils. Acid sensitive areas tend to occur where the soils are derived from acid igneous or acid sedimentary bedrock.

Areas of non-exceedance characterize Alberta, Saskatchewan, and Manitoba due to low rates of acidic deposition (Figure 3). Likewise, exceedance levels are generally negative in Newfoundland and most of Nova Scotia, where acidic deposition tends to be moderate (exceptions occur along the Fundy coast and southwestern Nova Scotia). High exceedance areas are found in the mid-latitudes of Ontario and Quebec where acidic deposition is relatively high, and critical values are relative low.

Although only negative exceedances exemplify ARNEWS plots in northern and western Canada, these areas are not immune to soil acidification. Areas of local impact exist and are not included within the current analysis (i.e., down wind from smelters, and urban centres).

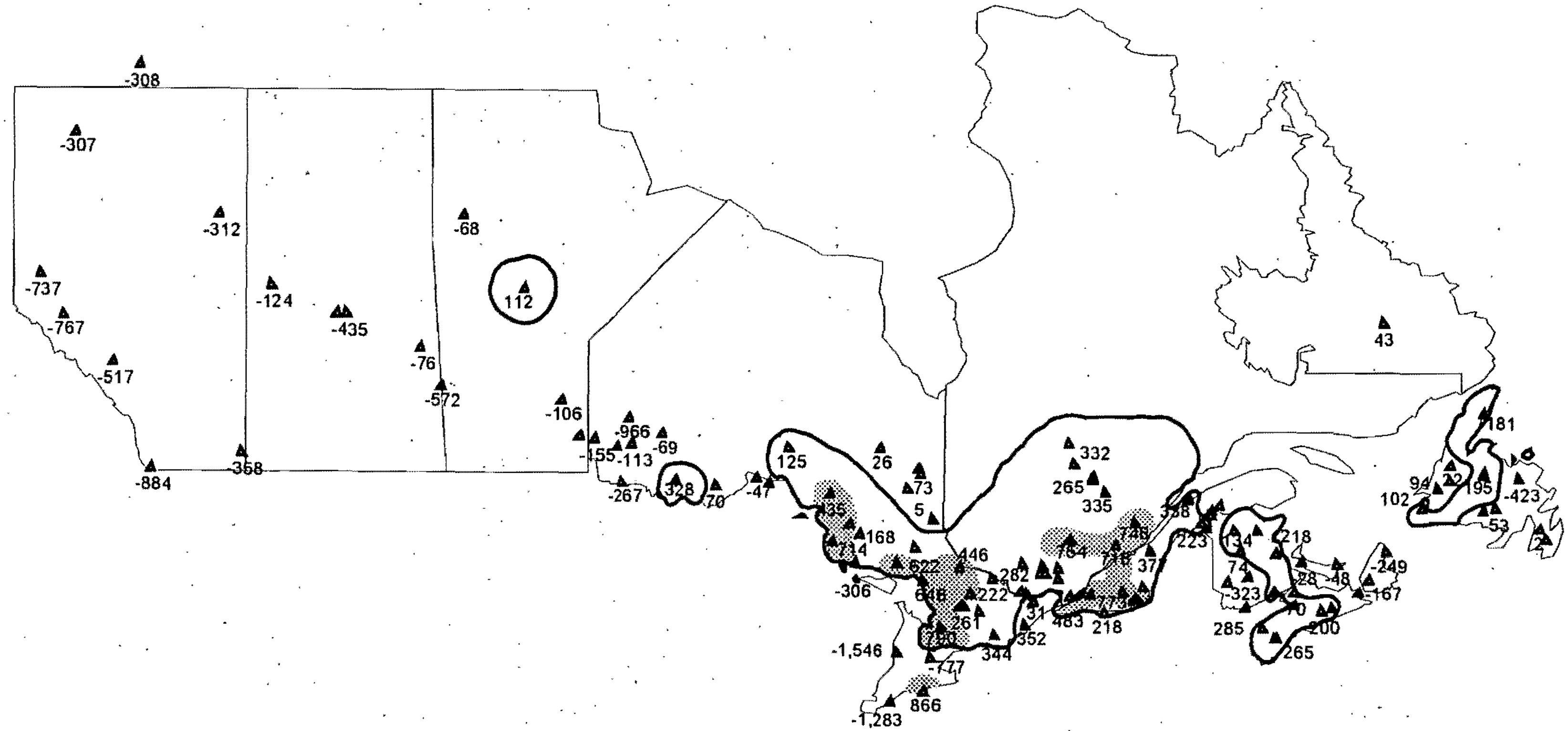


Figure 3. Exceedances of critical acid deposition (eq/ha yr), for ARNEWS plots. Bold line divides regions into positive (>100 eq/ha yr) and negative exceedance areas. Shaded area shows strongest exceedance (>500 eq/ha yr).

Areas with high exceedances are prone to forest decline, as observed for Ontario (Arp et al. 1996; Hopkin and Dumond 1996) and for Quebec (Ouimet *et al.* 1996). Moayeri and Arp (1997) found that defoliation levels correlated, in part, with calculated exceedance levels, critical loads for soil acidification, degree of insect damage and abiotic factors. With respect to defoliation, both the exceedance and critical load calculations factor strongly and positively across the ARNEWS plots. Preliminary analyses indicate that a 500 eq/ (ha year) exceedance is associated with an annual productivity loss of 10%. In terms of mortality, a 1000 eq/ (ha year) exceedance contributes to an 8 +/- 2% increase in mortality over a period of 11 years.

These exceedance numbers are underestimates since sulphur and nitrogen inputs from dry deposition have not been included. Fog inputs near the Great Lakes also aggravate the situation. To what extent exceedances of critical loads are deleterious to forest ecosystems is not known. Species shifts to nitrogen-loving flora would probably occur particularly in nutrient-poor ecosystems, such as peat bogs and heathlands.

6.2 Case study, Ontario

Atmospheric sulphur and nitrogen deposition varies across southern Ontario. Highest rates occur in the most southern parts; lowest rates occur in the northwest. Geologic substrates of the southern most parts are mostly limestone and dolomite. The soils derived from these substrates are well buffered, and therefore have high critical loads for soil acidification (Figure 2). Further to the north is the Canadian Shield, which is primarily igneous granitic. The soils derived from this substrate are generally poorly buffered, and therefore have low critical loads (Figure 2). Superposing current atmospheric deposition rates on the soil acidification potential by location and by way of the critical load calculations, indicates that the ability of the soils to buffer the incoming acidity is exceeded immediately north of the limestone/dolomite regions by at least 500 eq/(ha yr) in some cases (Figure 3, see also Arp et al. 1996). Comparing forest decline measures for sugar maple stands (e.g., % defoliation and mortality ratings) with calculated soil acidification exceedances for each stand location leads to a significant correlation: decline symptoms increase with calculated soil acidification exceedances (Figure 4).

Within the Canadian Shield, to reduce the greatest exceedance by about one-half, sulphate deposition rates would have to be reduced by 12 kg/(ha yr). The need for control of nitrogen is particularly strong in southern Ontario, because nitrogen eutrophication rather than soil acidification is likely to become a major concern on well-buffered soils.

Mean dieback levels of sugar maple, as measured by the NAMP, have been compared to critical loads maps (Arp *et al.*1996). Areas of critical load exceedances consistently have higher levels of dieback than areas of no exceedance. Other factors such as climate and ground-level ozone may also play a role.

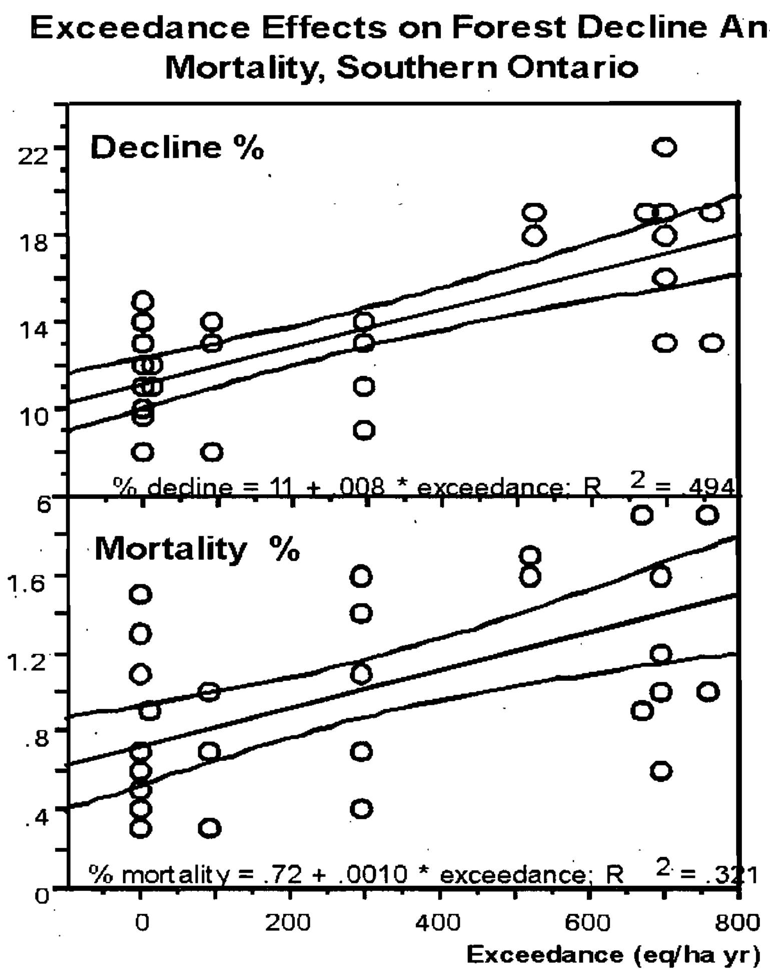


Figure 4. Percent decline and mortality observed for sugar maple stands in southern Ontario (MOE 1990), versus model calculated (Arp et al., 1996) soil acidification exceedances

6.3 Critical levels for vegetation

Levels to protect vegetation are usually developed for a few sensitive species or plant processes and applied to mapping at a regional scale in order to do risk assessment. The UN-ECE has established critical levels for sulphur dioxide, nitrous oxides, ammonia and associated ions in cloud/rain (Ashmore and Wilson 1995). These levels were based, to a large degree, on measurements of leaf surfaces (Cape 1993). The level is currently set at 0.3 mM (H+) for forests in cloud at least 10% of the time. The difficulty of measuring cloud water over large areas is overcome by modelling of particulate sulphate air concentrations and combining such data with climatological data or cloud occurrence (Cape 1993). In this way, critical levels may be mapped

for forest areas that are at greatest risk from acid rain.
Currently in Canada, some high elevation forests, particularly in the east, are blanketed in clouds over 30% of the time. As well, areas of white birch and red spruce decline along the eastern seaboard are typically inundated by acidic coastal fogs for long periods. Critical levels of acidity in both these situations may be exceeded over extended periods.

7. International linkages

International involvement and collaboration remain integral to Canada's Science and Technology program. This report provides the scientific underpinning for assessing the effects of acid rain on Canadian forests and builds on international efforts aimed at abatement of transboundary air pollution. Acid rain, the principal bilateral air quality issue, is the focus of research under the US/Canada Air Quality Accord. Both countries are making substantial progress in implementing their respective acid rain control programs. Canada continues to play a constructive role in promoting the activities of the International Co-operative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) of UN/ECE under the Convention on Long-range Transport of Air Pollution (LRTAP).

Fundamental research directed to effects of air pollution forms a scientific basis for development of indicators of forest sustainability under the Criteria and Indicators Initiative of the Canadian Council of Forest Ministers and the parallel international 'Montreal Process'. Development of the critical loads and estimations of exceedances of these loads enhance Canada's ability to measure and evaluate impact of pollution on forested ecosystems. Linking this approach to dynamic models also enhances predictive ability, minimizes uncertainties and contributes to international efforts on mitigation of acid rain impacts.

8. Research and information needs

A number of research needs arise from this assessment:

- Early warning systems that provide valuable information to resource managers on impending conditions require improvement. Specifically, thresholds and exceedance values for sensitive forest ecosystems are needed. Effective strategies to combat pollutants must be based on meaningful dose/response relationships.

- There is urgent need to determine the effects of air pollutants on forest soils and foliage and to make direct links between ambient levels of pollution and foliar damage. Again establishment of target loading, thresholds, exceedance values and determination of risks are needed. The assumption that the current target loading of 20 kg/(ha yr) of wet sulphate deposition provides reasonable protection for forest ecosystems is invalid. This level was derived for moderately sensitive aquatic systems and the level of risk it poses to terrestrial systems requires further resolution.

- Current negotiations and limits within the UN-ECE Long-Range Transport of Airborne Pollutants (LRTAP) Convention are based on calculation of deposition in excess of critical loads for forests soils. It is necessary to apply these principles to Canadian forests. Canadian efforts are constrained by the availability of data and modeling efforts. Current networks provide intensive data for only a small number of sites and need to be expanded to provide a comprehensive database.

- Current critical load assessment needs to be extended to include a greater range of tree species and to a much broader geographical area. In addition, research must be extended to examine the impact of exceedances on forest decline and tree mortality.

- There is a strong need for continued monitoring, research on methods, detection of symptoms, and cause and effect linkages. Increased understanding of basic mechanisms is required to understand air pollution behaviour and impact.

- Long-term chronic nutrient depletion is likely to continue and affect both forest function and structure. Research into the nutritional dynamics, status and stability of the forests should be extended. Specifically, protection against leaching of nutrients is needed, as is research to determine acceptable aluminium and nitrate concentrations for Canadian tree species and soils

- Greater focus overall needs to be placed on wet and dry forms of nitrogen deposition. As the sources are more diffuse, control of nitrogen emissions is more difficult. Moreover, regional deposition of ammonia and other forms of dry nitrogen will probably increase with the development of more intensive agricultural fertilization.

- New threats (ozone, UV-B, heavy metals, trichloroacetic and other acids) to forested ecosystems continue to emerge. These issues need to be addressed through the formulation of environmental objectives, guidelines and legislation. Interactions between air pollution and other influences must be better understood. Improved and heightened co-operation among all stakeholders is needed.

- Tropospheric ozone occurs in much of eastern Canadian forests where acidic deposition is high. Research on interactions between both pollutants and forest ecosystem processes is required.

- Assessment of the relationship between air pollution, forest health and economic ramifications is needed. Potential consequences from reduced forest health to Canada's competitive advantage in foreign trade and the protection of international market share may be substantial. Canada ranks first in the world in the export value of forest products and the forest sector is a key driver of the overall Canadian economy.

9. Conclusions

This report discusses progress on research addressing impacts of acid rain on forest ecosystems since 1990, the year of the last national Assessment of acid rain research. A better understanding of above and below ground ecosystem linkages associated with acidic deposition exists. Critical loads for certain forest soils have been postulated through modelling and research on critical loads for vegetation has begun. It is now possible to make reliable predictions on the impact of control strategies on tree growth and soil quality. Findings can also be linked to long-term strategies for forest management and sustainability. Uncertainty does exist and many gaps in knowledge remain but enough is known to provide some direction for the future.

- Current target loads of acidic deposition {20 kg wet sulphate/ (ha yr)} are too high to protect sensitive forest ecosystems. Projections show that forest decline is 30 to 40 % higher for forest stands for regions with exceedances 300 to 500 eq/(ha yr) than for less sensitive regions.

- In Quebec, foliar deficiencies in sugar maple stands are associated with cation imbalances in soil. In addition, growth and nutrient status of sugar maple seedlings decline as soil acidity increases, and soil base saturation decreases. These effects are likely to continue or worsen with continued inputs.

- In certain sugar maple forests within Ontario, acid rain at ambient levels has accelerated the loss of base cations from soils. Growth of sugar maple is sensitive to enhanced levels of soil nitrate. With increases in nitrogen deposition, a nitrogen/base cation imbalance in this species develops resulting in reduced tree vigour.

- In New Brunswick, areas of acidic fog are characterized by widespread birch decline which is expected to increase in severity and extent as current deposition levels continue. As well, red spruce decline in the Gulf of Maine/Bay of Fundy area is attributable to the frequent presence of acidic coastal fog.

- Data from the ARNEWS plot network of CFS indicate that a number of these plots are characterized by forest decline linked to air pollution. These sites, within the Boreal Shield, Mixedwood Plains and Atlantic Maritime ecozones are influenced by high levels of acidic deposition acting singly, or in combination with other stressors such as insect defoliation and extreme climatic events that serve to amplify the effects of pollutant exposure.

- In the northeastern United States (Hubbard Brook Experimental Forest), long-term data reveal that depletion of base cations from the forest soil has been occurring over a 30-year period and is continuing. Depletion of soil nutrients over such a long period results in reduced forest productivity. Although no such long-term data exist within Canada, similar ecosystems under similar acid rain scenarios do occur.

- Model calculations on plots of the Réseau de Surveillance des Ecosystèmes Forestiers (RESEF) indicate that of the 31 plots, 19 receive atmospheric acidic inputs in excess of their critical loads (67% and 42% of the deciduous and coniferous plots, respectively). In upland forests of the Canadian Shield of Southern Ontario, atmospheric deposition also exceeded critical loads. The critical level approach is useful in the derivation of policy for air pollution control. Levels to protect vegetation are being developed for a number of species, representing a range of sensitivities.

- Mapping of critical loads for Canadian forests at risk from acid rain is not currently available. Further definition of dose/response relationships is needed along with data on atmospheric anion concentrations for forests at greatest risk.

Continued scientific research is essential to assess the effectiveness of control strategies, to develop and implement a new generation of predictive models required to refine critical load/level approaches that can be fully integrated into forest health monitoring programs in Canada and to provide reliable measures of forest sustainability. The maintenance of forest ecosystem health is essential to the sustainability of Canada's forests and the overall well-being of the country.

APPENDIX 1

List of Tree Species Discussed in this Assessment

Jack pine	*Pinus banksiana* Lamb.
White pine	*Pinus strobus* L.
Lodgepole Pine	*Pinus contorta* Dougl. var. *latifolia* Engelm.
Ponderosa pine	*Pinus ponderosa* Laws.
Red pine	*Pinus resinosa* Ait.
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Red spruce	*Picea rubens* Sarg.
Trembling aspen	*Populus tremuloides* Michx.
White birch	*Betula papyrifera*, Marsh.
Mountain paper birch	*Betula cordifolia* Regel.
Red oak	*Quercus rubra* L.
White oak	*Quercus alba* L.
Sugar maple	*Acer saccharum* L.
White ash	*Fraxinus americana* L.

References

Amthor, J. S. 1986. An estimate of the "cost" of nutrient leaching from forest canopies by rain. New Phytol. 102: 359-364.

Arp, P.A.; Oja T. 1992. Estimating base cation losses and forest biomass response to acid sulfate/nitrate loading: A case study for maple sites within the Turkey Lakes (Algoma) and Harp Lake (Dorset) Watersheds. CEA No. 841-g-726, Joint CEA-CPPA-FC-EC Project: Tech. Rep., Part XVI.

Arp, P.A., Oja T., Marsh M. 1996. Calculating critical S and N loads and current exceedances for upland forests in southern Ontario, Canada. Can. J. For. Res. 26: 696 709

Ashmore, M. R.; Wilson, R.B. (*eds.*) 1995. Critical levels of air pollutants for Europe. London: Department of the Environment.

Barnes, J.D.; Eamus, D.; Brown, K.A. 1990. The influence of ozone, acid mist and soil nutrient status on Norway spruce *Picea abies* (L.) Karst. II. Photosynthesis, dark respiration and soluble carbohydrates of trees during late autumn. New Phytol. 115: 149-156.

Barnes, J. D.; Davison, A.W. 1988. The influence of ozone on the winter hardiness of Norway spruce (*Picea abies* L. Karst.), New Phytol. 108: 159-166.

Bertrand, A.; Robitaille, G.; Nadeau, P.; Boutin, R. 1994. Effects of soil freezing and drought stress on abscisic acid content of sugar maple sap and leaves. Tree Physiol. 14: 413-425.

Bertrand, A.; Robitaille, G.; Boutin, R.; Nadeau, P. 1995. Growth and ABA responses of maple seedlings to aluminum. Tree Physiol. 15: 775-782.

Bhatti, J.S.; Foster, N.W.; Evans, L.J. 1997. Sulphate adsorption in relation to properties of soils undergoing podzolization. Abst. 87th Ann. Mtg. Amer. Soc. of Agron. (in press).

Boutin, R.; Robitaille, G. 1995. Increased soil nitrate losses under mature sugar maple trees affected by experimentally induced deep frost. Can. J. For. Res. 25: 588-602.

Bowers, W. W.; Hopkin, A.A. 1997. Acid Rain National Early Warning System (ARNEWS) and North American Maple Project (NAMP) - 1995. Inf. Rep. ST-X- . Nat. Res. Can., Can. For. Ser., Sci. Dir., Ottawa (in press)

Braathe, P. 1995. Birch dieback - caused by prolonged early spring thaws and subsequent frost. Nor. J. Agri. Sci. Supp. No. 20. 1995.

Bytnerowicz, A.; Percy, K.; Padgett, P.; Krywult, M. 1997. Nitric acid vapour effects on forest trees- depositional and cuticular changes. Chemosphere (in press).

Cape, J. N. 1993. Direct damage to vegetation caused by acid rain and polluted cloud: Definition of critical levels for forest trees. Environ. Pollut. 82: 167-180.

Cape, J. N. 1994. Evaluation of pollutant critical levels from leaf surface characteristics. pp. 123-138 In Air Pollutants and the Leaf Cuticle (Percy, K.E., Cape, J.N., Jagels, R., and Simpson, C.J. Eds) NATO ASI Series G, Vol. 36, Springer-Verlag, Heidelberg.

Cape, J. N.; Percy, K.E. 1993. Environmental influences on the development of spruce needle cuticles. New Phytol. 125: 787-799.

Cape, J. N.; Percy, K.E. 1996. The interpretation of leaf-drying curves. Plant Cell and Environ. 19: 356-361.

Cape, J. N.; Percy, K.E. 1997. Needle epicuticular wax chemical composition in early diagnosis of Norway spruce, *Picea abies* L. Karst., decline in Europe. Chemosphere (in press).

Charland, M.; Malcolm, J.W.; Cox, R. M. 1996. Effects of Ozone and SO2 on Eastern White Pine Genotypes. Air Pollution & Multiple Stresses. Proc. 16th IUFRO Intl. Mtg. for Specialists in Air Pollution Effects on Forest Ecosystems, September 7-9, 1994. Fredericton, New Brunswick, Canada.

Chappelka III, A. H.; Chevone, B.I. 1986. White ash seedling growth response to ozone and simulated acid rain. Can. J. For. Res. 16: 786-790.

Cobb, W. F.; Stark, R.W. 1970. Decline and mortality of smog-injured ponderosa pine. J. For. 68: 147-149.

Cole, D. W.; Van Miegroet, H.; Foster, N.W. 1992. Retention or loss of N in IFS sites and evaluation of relative importance of processes. pp 196-199 *in* Atmospheric Deposition and Forest Nutrient Cycling. (D.W. Johnson and S.E. Lindberg. *Eds.*). Springer-Verlag, New York. Ecol. Studies 91. 707 pp.

Cox, R. M. 1989. Natural variation in sensitivity of reproductive processes in some boreal forest trees to acidity. pp. 77-88 The genetic effects of air pollution. Springer-Verlag, Berlin. 201 pp.

Cox, R. M. 1992. The Effects of Wet Deposition Chemistry on Reproductive Processes in Two Pine Species: Apparent Pollination Effectiveness in relation to species Pollen sensitivity. Water Air and Soil Pollut. 62: 213-226

Cox, R. M.; Lemieux, G.; Lodin, M. 1997. The Assessment and Condition of Fundy White

Birches in Relation to Ambient Exposure to Acid Marine Fogs. Can. J. For. Res. (In press).

Cox, R. M; Meng, F-R.; Charland, M.; Helleur, R.; Malcolm, J.W. 1997. Response of matue white pine foliage to tropospheric ozone. Proc. Ontario Climate Advisory Committee Workshop on Atmospheric Ozone: Issues, Science, Impacts, Programs. Downsview, Ontario, Sept. 30 - Oct. 1, 1996 (in press).

Cox, R. M.; Malcolm, J.W. 1997. Effects of winter thaw on birch die-back and xylem conductivity: An experimental approach with *Betula papyrifera* L. Tree Physiol. (in press).

Deans, J. D.; Leith, I.D.; Sheppard, L.J.; Cape, J.N.; Fowler, D.; Murray, M.B.; Mason, P.A. 1990. The influence of acid mists on growth, dry matter partitioning, nutrient concentrations and mycorrihizal fruiting bodies in red spruce seedlings. New Phytol. 115: 459-464.

Eager, C.; Adams, M.B. 1992. Ecology and Decline of Red Spruce in the Eastern United States. Ecological Studies 96. Springer-Verlag New York, U.S.A. 417 pp.

Eamus, D.; Leith, I.; Fowler, D. 1990. Water relations of red spruce seedling treated with acid mist. Tree Physiol., 5: 387-397.

Eatough, D. L.; Arthur, N.L.; Hill, M.N.; Mangelson, N.F.; Richter, B.E.; Hansen, L.D.; Cooper, J.A. 1984. Rapid Conversion of SO (g) to sulphate in a fog bank. Environ. Sci. Technol. 18: 855-859.

Foster, N. W.; Hazlett, P.W. 1991. The influence of reductions in atmospheric deposition on ion leaching from podzolic soils under hardwood forest, pp. 179-191 Acid Deposition. Origins, Impacts and Abatement Strategies .(J. W.. Longhurst, *Ed).* Springer-Verlag, New York.

Foster, N.W.; Morrison, I.K.; Yin, X.; Arp, P.A. 1992. Impact of soil water deficits in a mature sugar maple forest: stand biogeochemistry. Can. J. For. Res. 22: 1753-1760.

Gagnon, G.; Gravel, C.; Ouimet, R.; Dignard, N.; Paquin, R.; Jacques, G. 1994. Le réseau surveillance des Écosystèmes forestiers (RESEF) II Description des places d'étude et données de base. Gouvernement du Québec, Ministère des ressources naturelles, Dir. de la Recherche Forestière. Mémoire de recherche forestière No. 116. p.8.

Hadley, J. L.; Smith, W.K. 1994. Effect of elevation and foliar age on maximum leaf resistance to water vapour diffusion in conifers in the central Rocky Mountains, USA. pp. 261-268 Air Pollutants and the Leaf Cuticle (K. E. Percy, J. N. Cape, R. Jagels, and C. J. Simpson, *Eds.*) NATO ASI Series G, Vol. 36, Springer-Verlag, Heidelberg.

Hall, J. Peter. 1995a. Forest Health Monitoring in Canada: How Healthy is the Boreal Forest? Water Air and Soil Poll. 82: 77-85

Hall, J. Peter. 1995b. ARNEWS Assesses the Health of Canada's Forests. For. Chron. 71, No. 5: 607-613.

Hall, J. Peter. 1996. Forest Insect and Disease Conditions in Canada - 1994. Forest Insect and Disease Survey, Nat. Res. Can. Can. For. Ser. Ottawa. 112 p.

Hall, J. Peter; Addison, P.A. 1991. Response to air pollution: ARNEWS assesses the health of Canada's forests. For. Can. Sci. Dir., Ottawa, Inf. Rep. DPC-X-34. 42 p.

Hoad, S. P.; Jeffree, C.E.; Grace, J. 1994. Effects of wind and simulated acid mist on leaf cuticles. pp 225-237 Air Pollutants and the Leaf Cuticle (K. E. Percy, J. N. Cape, R. Jagels and C. J. Simpson, *Eds*) NATO ASI Series G, Vol. 36. Springer-Verlag, Heidelberg.

Hogan, G. D. 1992. Physiological effects of direct impact of acidic deposition on foliage. Agr. Ecosystems and Environ. 42: 307-319.

Hogan, G. D. 1997. Effect of simulated acid rain on physiology, growth and nutrient relations of sugar maple. Chemosphere (*in press*)

Hogan, G. D. Foster, N.W. 1989. Precipitation acidity and foliar cation losses from sugar maple. Proceedings of the symposium "L'atelier sur le dépérissment des érablieres" (G. Boudreault and Allard, G.B. *Compilers*). 23-24 Feb. 1989, Ste-Hyacinthe, Que., pp. 24-28.

Hogan, G. D.; Taylor, S.J. 1995. Effect of acidic deposition on hybrid poplar-primary or predisposing stress? Water, Air, Soil Poll. 85: 1419-1424

Hopkin, A. A.; Dumond, T. 1996. Hardwood tree condition in Ontario: Results of FIDS unit surveys 1987-95. Frontline Tech. Note 22.

Hughes, R. N.; Cox, R.M. 1994. Acid Fog and temperature effects on stigma receptivity in two birch species. J. Environ. Qual. 23: 686-692.

Huttunen, S. 1994. Effects of air pollutants on epicuticular wax structure. pp. 81-96 Air Pollutants and the Leaf Cuticle (K. E. Percy, J. N. Cape, R. Jagels, and C. J. Simpson, *Eds.*). NATO ASI Series G, Vol. 36. Springer-Verlag, Heidelberg.

Jacobson, J. S.; Bethard, T.; Heller, L.; Lassoie, J.P. 1990. Response of *Picea rubens* seedlings to intermittent mist varying in concentrations of acidity and sulphur and nitrogen-containing pollutants. Physiologia Plantarum, 78: 595-601.

Jensen, K. F.; Patton, R.L. 1990. Response of yellow-poplar (*Liriodendron tulipifera* L.) seedlings to simulated acid rain and ozone - 1. Growth modifications. Env. Exp. Bot. 30: 59-66.

Krywult, M.; Hom, J.; Bytnerowicz, A.; Percy, K.E. 1996. Deposition of gaseous nitric acid and its effects on foliage of Ponderosa pine (*Pinus ponderosa* L.) seedlings. pp. 45-51 In Air Pollution and Multiple Stresses (Cox, R. M.; Percy, K.E.; Jensen, K.F.; Simpson, C.J. *Eds.*), Proc. 16th Intl. Mtg. for Specialists in Air Pollution Effects on Forest Ecosystems, Fredericton, September 7-9, 1994. Nat. Res. Can., Can. For. Ser., Fredericton. 402 pp.

Lachance, D. 1985. Répartition géographique et intensité du dépérissement de l'érable à sucre dans les érablières du Québec. Phytoprotection 66: 83-90.

Lachance, D.; Hopkin, A.; Pendrel, B.; Hall, J. Peter. 1995. Health of Sugar Maple in Canada - results from the North American Maple Project, 1988-1993. Inf. Rep. ST-X-10. Nat. Res. Can., Can. For. Ser., Ottawa. 27pp.

Likens, G. E.; Driscoll, C.T.; Buso, D.C. 1996. Long-term effects of acid rain: response and recovery of a forest ecosystem. Sci. 272: 244-245.

Liu, G.E.; Cote, B. 1993. Neutralization and buffering capacity of leaves of sugar maple, largetooth aspen, paper birch and balsam fir. Tree Physiol. 12:15-21.

MacDonald, N. W.; Hart, J.B.; Nguyen, P.V. 1986. Simulated acid rain affects jack pine seedling establishment and nutrition. Soil Sci. Soc. Am. J. 50: 219-225.

McLaughlin, D.; Kinch, C.; Liljalehto, H.; Boysen, H. 1997. Hardwood Forest Health Surveys in Ontario - the first ten years: 1986 to 1995. (*in press*).

McLaughlin, S. B.; Andersen, C.P.; Hanson, P.J.; Tjoelker, M.G.; Roy, W.K. 1991. Increased dark respiration and calcium deficiency of red spruce in relation to acidic deposition at high-elevation southern Appalachian Mountain sites. Can. J. For. Res. 21:1234-1244.

McLaughlin, S. B.; Tjoelker, M.G.; Freer-Smith, P.H. 1992. Growth and physiological changes in red spruce saplings associated with acidic deposition at high elevations in the southern Appalachians, USA. For. Ecol. Man. 51: 43-51.

McLaughlin, S. B.; Tjoelker, M.G.; Roy, W.K. 1993. Acid deposition alters red spruce physiology: laboratory studies support field observations. Can. J. For. Res. 23: 380-386.

Mahendrappa, M. K. 1982. Effects of SO_2 pollution on nitrogen transformations in some organic soils of northeastern New Brunswick: ammonia volatilization. Can. J. For. Res. 12: 458-462.

Mahendrappa, M. K. 1983. Chemical characteristics of precipitation and hydrogen input in throughfall and stem flow under some eastern Canadian forest stands. Can. J. For. Res. 13: 948-955.

Mahendrappa, M. K. 1989. Impacts of forests on water chemistry. Water, Air, Soil Poll. 46: 61-72.

Mahendrappa, M. K. 1991. Acid rain effects on nitrogen availability from litter and organic matter decomposition. pp 209-229 In Effects of Acid Rain on Forest Resources (Robitaille, G.; Rennie, P.J. *Eds.*) Proc. Conf. 14-17 June 1983, Sainte-Foy, Que. For. Can., Ottawa, Ont. Inf. Rep. DPC-X-35. 655 pp.

Manion, P. D.; Lachance, D. (Eds.). 1992. Forest Decline Concepts. APS Press, St. Paul, Minn. 249 pp.

Maynard, D. G; Stadt, J.J.; Mallett, K.I.; Volney, W.J.A. 1994. Sulfur impacts on forest health in west-central Alberta. Nat. Res. Can., Can. For. Ser., Northwest Region, Inf. Rep. NOR-X-334. 51p.

Meng, F.R.; Cox, R.M.; Arp, P.A. 1994. Fumigating mature spruce with SO2: Effects on Net Photosynthesis and Stomatal Conductance. Can. J. For. Res. 24: 1464-1471.

Meyer, W. M., Jagels, R.; Carlisle, J.; Percy, K.E. 1996. Droplet contact angle as a biomonitor of air pollution stress: Variation in red spruce epicuticular wax wettability due to canopy position and diurnal cycles. pp 351-356 Air Pollution and Multiple Stresses (Cox, R.M., Percy, K.E., Jensen, K.F.; Simpson, C.J. *Eds.*) Proc. 16th IUFRO Intl. Mtg. for Specialists in Air Pollutant Effects on Forest Ecosystems, Fredericton, September 7-9, 1994. Nat. Res. Can., Can. For. Ser., Fredericton. 402 pp.

Mitchell, M. J.; Foster, N.W.; Shepard, J.P.; Morrison, I.K. 1992. Nutrient cycling in Huntington Forest and Turkey Lakes deciduous stands: nitrogen and sulfur. Can. J. For. Res. 22(4): 457-464.

Morrison, I. K. 1984. Acid rain. A review of literature on acid deposition effects in forest ecosystems. For. Abstr. 45: 483-506.

Morrison, I. K.; Fournier, R.E.; Hopkin, A.A. 1995. Response of forest soil to acidic deposition: results of a five-year resampling study in Canada. Air Pollution and Multiple Stresses (Cox, R. M; Percy, K.E.; Jensen, K.F.; Simpson, C.J. *Eds.*) Proc. 16th IUFRO Intl. Mtg. for Specialists in Air Pollutant Effects on Forest Ecosystems, Fredericton, September 7-9, 1994. Nat. Res. Can., Can. For. Ser., Fredericton. 402 pp.

Moayeri, M. H.; Arp, P.A. 1996. Assessing critical soil acidification load effects for ARNEWS sites: preliminary results. Draft Paper, Faculty of Forestry and Environmental Management, U. New Brunswick, Fredericton, N.B.

Neufeld, H. S.; Jernstedt, J.A.; Haines, B.L. 1985. Direct foliar effects of simulated acid rain. I. Damage, growth and gas exchange. New Phytol. 99: 389-405.

Nilsson, J.; Grennfelt, P. (Eds). 1988. Critical loads for sulfur and nitrogen. Nord 1988:97, Nordic Council of Ministers, Copenhagen, Denmark.

Oja ,T; Arp P.A. 1997. A forest soil vegetation atmosphere model (ForSVA), II: application to northern tolerant hardwoods. Ecol. Modelling 95:225-247.

Ouimet, R.; Fortin, J.M. 1992. Growth and foliar nutrient status of sugar maple: incidence of forest decline and reaction to fertilization. Can. J. For. Res. 22: 699-706.

Ouimet, R.; Camire, C. 1995. Foliar deficiencies of sugar maple stands associated with soil cation imbalances in the Quebec Appalachians. Can. J. Soil Sci. 75: 169-175

Ouimet, R.; Camire, C.; Furlan, V. 1996. Effect of soil base saturation and endomycorrhization on growth and nutrient status of sugar maple seedlings. Can. J. Soil Sci. 76: 109-115.

Percy, K. E.; Baker, E.A. 1990. Effects of simulated acid rain on epicuticular wax production, morphology, chemical composition and on cuticular membrane thickness in two clones of Sitka spruce *(Picea sitchensis* (Bong.) Carr). New Phytol. 116: 79-87.

Percy, K. E.; Krause, C.R.; Jensen, K.F. 1990. Effects of ozone and acid fog on red spruce needle wax ultrastructure. Can. J. For. Res. 20: 117-120.

Percy, K. E.; Baker, E.A. 1991. Effects of simulated acid rain on needle wettability and rain retention by two Sitka spruce *(Picea sitchensis* (Bong.) Carr). clones. Can. J. For. Res. 21: 694-697.

Percy, K. E.; Jensen, K.F.; McQuattie, C.J. 1992. Effects of ozone and acid fog on red spruce needle epicuticular wax production, chemical composition, cuticular membrane ultrastructure and needle wettability. New Phytol. 122: 71-80.

Percy, K. E.; Jagels, R.; Marden, S.;McLaughlin, C. K.;Carlisle, J. 1993. Quantity, chemistry and wettability of epicuticular waxes on needles of red spruce along a fog-acidity gradient. Can. J. For. Res. 23: 1472-1479.

Percy, K. E.; McQuattie, C.J.; Rebbeck, J.A. 1994. Effects of air pollutants on epicuticular wax chemical composition. pp. 67-79. Air Pollutants and the Leaf Cuticle. (Percy, K. E.; Cape, J.N.; Jagels, R.; Simpson, C.M. *Eds.*) NATO ASI Series G, Vol. 36 Springer-Verlag, Heidelberg.

Potter, C. S. 1991. Nutrient leaching from *Acer rubrum* leaves by experimental acid rainfall. Can J For Res 21: 222-229.

RMCC - Research and Monitoring Coordinating Committee 1990. The 1990 Canadian Long-Range Transport of Air Pollutants and Acid Deposition Assessment Report. Part I: Executive Summary. Ottawa, Ontario.

Reich, P. B.; Schoettle, A.W.; Amundson, R.G. 1986. Effects of ozone and acidic rain on photosynthesis and growth in sugar maple and northern red oak seedlings. Environ. Pollut. 40: 1-15.

Reich, P. B.; Schoettle, A.W.; Stroo, H.F.; Troiano, J.; Amundson, R.G. 1987. Effects of ozone and acid rain on white pine *(Pinus strobus)* seedlings grown in five soils. I. Net photosynthesis and growth. Can. J. Bot., 65: 977-987.

Rinallo, C.; Raddi, P.; Gellini, R.; di Lonardo, V. 1986. Effects of simulated acid deposition on the surface structure of Norway spruce and silver fir needles. Eur.J.For.Path. 16: 440-446

Roberts, B. R. 1990. Physiological response of yellow poplar seedlings to simulated acid rain, ozone fumigation and drought. For. Ecol. Manage., 31: 215-224..

Robitaille G.; Boutin, R.; Lachance, D. 1995. Effects of soil freezing stress on sap flow and sugar content of mature sugar maples (*Acer saccharum*). Can. J. For. Res. 25: 577-587.

Robitaille G.; Boutin, R.; Lachance, D. 1996. Effects of deep frost on sugar maple (Acer saccharum Marsh.): leaf dry weight and area. pp. 35-42. Air Pollution and Multiple Stresses (Cox,R.; Percy, K.E.; Jensen, K.F.; Simpson, C.J. *eds*.). Proc. 16th IUFRO Intl. Mtg. for Specialists in Air Pollutant Effects on Forest Ecosystems. Fredericton, Sept. 7-9 1994.

Ryan, D. A.; McLaughlin, D.L.; Gordon, A.M. 1994. Interpretation of sugar maple (*Acer saccharum*) ring chronologies from central and southern Ontario using a mixed linear model. Can. J. For. Res. 24: 568-575.

Sarcy, K. B.; Mulcahy, D.L. 1985. Pollen tube competition and selection for metal tolerance in *Silene Dioica* (Caryphyllaceae) and *Mimulus Guttatus* (Schrophulariaceae). Amer. J. Bot. 72(11): 1695-1699.

Sasek, T. W.; Richardson, C.J.; Fendick, E.A.; Bevington, S.R.; Kress, L.W. 1991. Carryover effects of acid rain and ozone on the physiology of multiple flushes of loblolly pine seedlings. For Sci. 37: 1078-1098.

Seiler, J. R.; Paganelli, D.J. 1987. Photosynthesis and growth response of red spruce and loblolly pine to soil applied lead and simulated acid rain. For. Sci., 33: 668-675.

Sheppard, L. J. 1994. Causal mechanisms by which sulphate, nitrate and acidity influence frost hardiness in red spruce: review and hypothesis. New Phytol. 127: 69-84.

Smith, W. H. 1981. Air Pollution and Forests. Springer-Verlag, New York.

Smith, K. T.; Shortle, W.C.; Ostrofsky, W.D. 1995. Aluminum and calcium in fine root tips of red spruce collected from the forest floor. Can J. For Res 25: 1237-1242.

Swanson, E. S.; Thomson, W.W. 1973. The effect of ozone on leaf cell membranes. Can. J. Bot. 51: 1213-1219.

Tanksley, S. D.; Zamir, D.; Rick, C.M. 1981. Evidence for extensive overlap of sporophytic and gametophytic gene expression in *Lycopersicon esculentum.* Sci. 213: 453-455.

Taylor, G. E. Jr.; Johnson, D.W.; Anderson, C.P. 1994. Air pollution and forest ecosystems: A regional to global perspective. Ecol. Applicat. 4(4): 662-689

Taylor, G. E.; Norby, R.J.; McLaughlin, S.B.; Johnson, A.H.; Turner, R.S. 1986. Carbon dioxide assimilation and growth of red spruce seedlings in response to ozone, precipitation chemistry and soil type. Oecologia, 70: 163-171.

Temple, P. J.; Riechers, G.H. 1995. Nitrogen allocation in ponderosa pine seedlings exposed to interacting ozone and drought stresses. New Phytol. 130: 97-104.

Thirukkumaran, C.; Morrison, I.K. 1997. Impact of simulated acid rain on microbial respiration, biomass and metabolic quotient in a mature sugar maple (*Acer saccharum* Marsh.) forest floor. Can J. For. Res. (submitted)

Turunen, M.; Huttunen, S. 1990. A review of the response of epicuticular wax of conifer needles to air pollution. J. Environ. Qual. 19: 35-45.

Turunen, M.; Huttunen, S.; Percy, K.E.; McLaughlin, C.K.; Lamppuu, J. 1997. Epicuticular wax of subarctic Scots pine needles: response to sulphur and heavy metal deposition. New Phytologist 96: (*in press*).

Walker, R. F.; McLaughlin, S.B. 1991. Growth and root system development of white oak and loblolly pine as affected by simulated acidic precipitation and ectomycorrhizal inoculation. For. Ecol. Manag. 46: 123-133.

Williams, T. P. W. 1994. Use of passive monitors to assess plant bioindicators for ground-level ozone. M.Sc. Thesis U. New Brunswick. pp 130.

Wood, T.; Bormann, W.H. 1975. Increases in foliar leaching caused by acidification of an artificial mist. Ambio, 4: 169-171.

Yin, X.; Foster, N.W.; Arp, P.A. 1993. Solution concentrations of nutrients below the rooting zone of a sugar maple stand: relationships to soil moisture, temperature, and season. Can. J. For. Res. 23: 617-624.

Yin, X.; Foster, N.W.; Morrison, I.K.; Arp, P.A. 1994. Tree-ring-based growth analysis for a sugar maple stand; relations to local climate and transient soil properties. Can. J. For. Res. 24(8): 1567-1574.

For copies of the 1997 Canadian Acid Rain Assessment please call Environment Canada's Enquiry Centre at 1-800-668-67667