FOREST HEALTH AND DECLINE

A report from the 2000 Muskoka Workshop and Field Tour of Experts

Executive summary

Forest decline has been observed and studied in the Muskoka area of Ontario for about 20 years. In the summer of 2000, a group of experts gathered for a workshop that focused on recent results and a field tour of damaged areas. This report summarizes the findings and conclusions from the information assembled at the workshop.

Six recent assessments and several scientific reviews of forest decline/health research and monitoring were examined. From these reports, the group found that acid rain and other air pollutants damage forests by a number of established mechanisms.

Nutrient deficiency in soils: A dominant mechanism for damages from sulphur and nitrogen deposition is nutrient deficiency caused by leaching of calcium and magnesium from the soil, leading to decreased growth, canopy decline, and increased tree mortality. Nutrient imbalance caused by leaching of calcium and magnesium from soils has been reversed in experiments conducted in Quebec, where dolomitic limestone was added to the soil under declining sugar maple trees. The experimental treatment increased tree growth rate within one year and stopped the progression of decline symptoms of the trees over the four-year study period.

Damage to vegetation by acidic fogs: Acid fogs have caused extensive dieback of white birch on the shores of the Bay of Fundy. Fog duration varies from year to year and there is a linear relationship between hours of fog from June to August and the mean percentage of foliar browning. Such fogs also prevent the germination of the pollen of white and mountain paper birch. Acid fogs reduce the frost hardiness of exposed red spruce.

Increased occurrence of insects and diseases: In a study of four areas of the northeastern United States, the areas with the greatest frequency of problems from forest insects and disease also receive the highest deposition of sulphur and nitrogen and/or have the highest annual exposure to ground-level ozone. Such a relationship is compatible with the role of strong anion deposition in depleting available pools of cations, notably calcium, from the relatively low soil pools in these forests.

Damage from nitrogen deposition: Nitrogen deposition can degrade forest ecosystems by increasing sensitivity to frost, reducing net primary production, and leaching of nutrients, especially in areas where soil nitrogen levels are high and have reached or are approaching saturation.

In addition to these mechanisms, other factors are cause for concern for the future of forests affected by acid rain.

Cumulative effects of stressors: For example, UV-B and acid rain act in concert to affect birch dieback in the Maritimes. Acid rain coupled with drought or frost has contributed to sugar maple decline in Quebec and Ontario.

Reduced earthworm diversity: A drastic reduction in earthworm diversity has been observed in acid rain-affected soils in Ohio compared to soils receiving lower cumulative dose in southern Illinois.

Shorter life span for forests: Increased tree mortality rates from 0.4–0.5% to 1.0–1.5% in hickory forests in eastern United States mean that the average life span of the forests would be reduced from about 200 years to about 150 years.

These findings are of particular importance to Canada for several reasons.

Ongoing damage: Acid rain has caused and is continuing to cause sugar maple decline at specific locations in the Muskoka area, and oak and several other tree species are also being damaged.

Acid deposition is still too high: Large areas of eastern Canada still receive sulphur and nitrogen deposition above the critical (protective) load for forest soils. While sulphur deposition has been reduced in North America, nitrogen deposition has not changed. When the current control programs were designed, it was known that the reductions would not be sufficient to eliminate all damage.

Large areas are being affected: It is estimated that 10 to15% of Canada's most productive forests are affected by acid rain. These forests have considerable ecological, social, and economic value and contain numerous federal and provincial parks and many recreational areas.

Major policy consequences: The growth and health of forests are becoming increasingly important for Canada as we embark on a policy of using forests as sinks within the national carbon dioxide budget. Credible projections of forest uptake of carbon dioxide for many years into the future are becoming quite problematic.

Table of contents

Introduction

In a very broad sense, a **healthy forest** may be considered as one that maintains and sustains ecosystem functions and processes. **Forest decline**, on the other hand, pertains to a continued and sustained deterioration of forest condition, ultimately ending in the death of trees. In operational terms, many monitoring and research programs are seeking to detect and explain unhealthy forest conditions, without clearly defining healthy forests. Recent reviews have summarized the observations and conclusions from studies in Canada, the United States, and Europe. These reviews discuss numerous cases of forest decline and impaired health that range from those associated with local industries to regional-scale occurrences and concerns for future threats to the health of forests.

Forest decline has been observed and studied in the Muskoka area of Ontario for about 20 years. In the summer of 2000, forest experts gathered for a workshop and field tour of damaged areas, monitoring plots, and research projects. This report summarizes the findings and conclusions from that workshop.

Findings from recent assessments

Health of North American forests

Hall et al. (1996) reported that defoliation and dieback of tree crowns were observed frequently and were caused primarily by insects, diseases, drought, and frost. Damages from acid fogs and ozone were recognized on several species in several biomes, indicating a potential for extensive damage in the absence of corrective action. Trees might also have been weakened or stressed by air pollution (classic symptoms were found in some forest ecosystems), a stress that may not yet be evident in the monitoring programs.

1997 Canadian Acid Rain Assessment, Volume One

Environment Canada (1998) concluded the following about the effects of acid rain on forests:

- Dry and wet acidic deposition alter the chemical and physical characteristics of the cuticle — the thin, waxy layer covering the surfaces of the leaves and needles. Cuticle damage accelerates natural aging and generally makes trees less vigorous. This, in turn, impairs the ability of trees to cope with other stressors, such as drought, insect infestations, disease, and increased ultraviolet-B (UV-B) radiation.
- Gaseous pollutants cause a decrease in net photosynthesis and nutrient uptake in mature red spruce trees. These effects increase with the amount of sulphur dioxide absorbed. Studies of lodgepole pine and trembling aspen showed that in areas of high pollution, annual tree growth was lower and the number of dead trees was higher than in areas of lower pollution.
- Acidic fog or mist, which is a common occurrence in eastern Canada, prevents germination of pollen in white birch and mountain paper birch. Acidic mists also reduce a tree's frost hardiness. In fact, there is a direct relationship between the amount of sulphate in a tree's leaves and its ability to withstand cold temperatures. In red spruce, for example, a 0.1% increase in the sulphur content of the leaves causes a 2.7% decline in frost hardiness. These trees are consequently more vulnerable to

climatic fluctuations and will remain so until further emission reductions are implemented (Eager and Adams 1992).
- Prolonged acid deposition alters the chemistry of forest soils, causing a loss of soil nutrients and increasing the concentration of aluminum, which interferes with the uptake of calcium and other nutrients by plants. Nutrient deficiencies result initially in slower tree growth and a consequent decline in the productivity of affected forests. More visible damage, such as defoliation, appears later. Declines of red spruce at high elevations have been strongly linked to imbalances in soil nutrients and high concentrations of aluminum in soil solutions.

Effects of acidic deposition on Canada's forests

Hall et al. (1998) discussed research addressing the effects of acid rain on Canadian forest ecosystems since 1990 — the year of the last national assessment of acid rain research. Above- and below-ground ecosystem linkages associated with acidic deposition are now better understood. Critical loads for certain forest soils have been postulated through modeling and research on critical loads for vegetation. The effects of control strategies on tree growth and soil quality can now be reliably predicted, and 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. The assessment concluded:

- Current target loads of acidic deposition (20 kg wet sulphate per hectare per year) are too high to protect sensitive forest ecosystems. However, since the current control programs were designed, it has been known that reductions to the target loads would not be sufficient to eliminate all damage (Bangay and Riordan 1983).
- 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, acid rain has accelerated the loss of base cations from soils. Growth of sugar maple is sensitive to increased levels of soil nitrate. As nitrogen deposition increases, a nitrogen/base cation imbalance in this species develops, resulting in reduced tree vigor. These effects are observed in many parts of eastern Canada.
- 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 frequent acidic coastal fogs.
- Data from the Acid Rain National Early Warning System (ARNEWS) plot network of Canadian Forest Service (CFS) have indicated that several 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 stresses, such as insect defoliation and extreme climatic events that 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 the 31 plots of the Réseau de Surveillance des Écosystèmes Forestiers (RESEF) have indicated that 19 of them 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 levels approach is useful in developing policies for air pollution control. Levels to protect vegetation are being developed for several 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.
- Decline is not limited to sugar maple as ARNEWS (Bowers and Hopkin1998) monitoring identified decline conditions for about a dozen tree species.

NAPAP Biennial Report to Congress: an integrated assessment

This report of the National Acid Precipitation Assessment Program (NAPAP) (National Science and Technical Council 1998) concluded for the United States that:
- Deposition of sulfur and nitrogen have caused adverse impacts on certain highly sensitive forest ecosystems in the United States. High-elevation spruce–fir forests in the eastern United States are the most sensitive.
- The gradual leaching of soil nutrients from sustained inputs of acid deposition could eventually impede forest nutrition and growth in several areas. Potential risk depends on numerous factors, including rate of cation deposition, soil cation reserves, age of forest, weathering rates, and species composition and disturbance history. Recent reductions in sulphur deposition should result in some near-term improvements in sensitive forests. Large improvements will occur at varying rates, depending on the factors listed above.
- Nitrogen deposition can significantly degrade forest ecosystems, especially in areas where nitrogen levels are already high and the soil has reached or is approaching saturation. However, some nitrogen-deficient forests may experience increased growth rates in response to continued elevated nitrogen exposure.

Forest health in Canada: an overview 1998

Canadian Forest Service (1999) concluded that of the nine Canadian forested ecozones, acid rain impacts adversely on growth and productivity of the eastern Boreal Shield, Atlantic Maritime, and Mixedwood Plains ecozones. This conclusion was reached through synthesis of several studies suggestive of impacts. The other six ecozones are relatively free from widespread air pollution. Key research results that form the basis of this synthesis included:
- There has been birch dieback along the fog belt of the Bay of Fundy coast of New Brunswick. Fog duration varies from year to year, and there is a linear relationship between the hours of fog from June to August and the mean percentage of foliar browning (Cox et al. 1996).
- Simulated acid rain experiments on Canadian tree species indicated a myriad of effects on tree physiology.
- Long-term nutrient loss at Hubbard Brook in the northeastern United States, as well as within the sugar maples stands of southern Ontario and Quebec.
- Soils that are common to large areas of Ontario and Quebec are receiving rates of acid deposition in excess of what they can buffer. Projections indicate forest decline of 30% to 40% for forest stands associated with these soils.
- Lakes associated with the eastern boreal forest and Atlantic Canada remain acidic despite reduced emissions. At least 13 500 populations of fish have disappeared from the 48 000 lakes in the Outaouais and Abitibi regions of Quebec.

- In Algonquin Park, black flies have increased almost 100 times compared to 50 years ago, the reason being that black-fly larvae can tolerate low water acidity better than their competitors and predators.
- Cumulative impacts of stresses appear to be more important than any one stress. For example, UV-B and acid rain act in concert to affect birch dieback in the Maritimes. Acid rain coupled with extreme weather conditions of either drought or frost has resulted in maple decline in Quebec and Ontario.

Forest condition in Europe 1999

The Federal Research Centre for Forestry and Forest Products (1999) concluded that a steady increase in defoliation of the main tree species had been occurring since 1988. The increase in defoliation was sharpest in European oak and other oak species, beech, and Maritime pine, and was attributed largely to natural stressors, such as pathogens and weather conditions. However, drought, ozone exposure, and to some extent soil chemistry were correlated with the crown condition.

Results from recent scientific journal publications

The workshop considered results from some recent research papers and noted the following.

Ryan et al. (1996) reported on a pattern of declining volume increments for sugar maple over its range in Ontario. After adjusting for tree age, rainfall, and temperature, the results indicated decreases in growth began around 1960 in areas of acid-sensitive soils. Growth in the southern part of Ontario, where soils are not affected by acid rain, had been relatively unchanged since the early 1900s. The authors proposed that the decreased growth was related to air pollution and possibly to decreased buffering capacity of the soils.

Vitousek et al. (1997) concluded that human domination of the nitrogen cycle has caused losses of soil nutrients such as calcium and potassium that are essential for long-term soil fertility.

The long-term negative effects of nitrogen accumulation in forest soils (from atmospheric deposition) has been investigated in a series of papers in the U.S. during the 1990s (Aber et al. 1998; Fenn et al. 1998). The hypothesis being tested holds that as soils approach nitrogen saturation (where nitrate release and associated leaching accelerate), fine root mass, foliar biomass, and net primary production all decline, eventually catastrophically. Detailed studies using long-term nitrogen fertilization plots and nitrogen deposition transects across the conifer and hardwood forests of northern New York and New England were used to explore the mechanisms of nitrogen sequestration in carbon depleted soils, and increased nitrification in mature forests, along with effects on foliar concentrations and fine roots. Fenn et al. (1998) summarized specific mechanisms by which, in a study in Vermont, all conifer stands showed large increases in nitrification and nitrogen leaching, and reduced growth or increased mortality. They noted that if nitrogen deposition and base cation leaching remained high, nutrient imbalances would continue to prevent stand recovery.

Briffa et al. (1998) reported on a study of trends in tree growth at 300 circumpolar sites in the Northern Hemisphere. Growth followed the expected temperature dependence for the first half of the 20th century, but for the second half, growth was less than predicted from temperature change. The cause of this was not known, but the authors suggested a combination of pollution and subtle climatic changes.

McLaughlin and Percy (1999) reviewed forest health and decline conditions in four North American case studies: northeastern hardwood forests; eastern spruce–fir forests; southwestern pine forests; and southeastern pine forests. Conclusions based on over 300 references included the following:

- Decreases in growth rates of red spruce in the Northern Appalachian Mountains that began in the 1960s were not due to climatic factors and regional scale air pollution played a significant role in the decline that was observed in the 1980s.
- In North America, the regional patterns of most frequent occurrence of major disease problems documented by forest surveys are spatially consistent with the patterns of highest levels of acidic deposition. Such a relationship was compatible with the role of strong anion deposition in depleting available pools of cations, notably calcium, from the relatively low soil pools in some northeastern forests.
- Acid rain, ozone, and increased deposition of nitrogen compounds factored into many manifestations of forest effects. However McLaughlin and Percy concluded that, "despite differences in species, levels and combinations of principal and secondary stresses and primary pathways of effects among the four case study forests, effects of air pollutants on the resources required for growth and defense are often similar. Reduced photosynthetic production in response to chronic pollution stress was found in all four systems examined."
- The authors further stated that a summary of the physiological changes induced by ambient air pollution in the four case studies indicates multiple pathways of effects on carbon, water, and nutrient resources required for forest health. The net effect of these process level effects has been multiple indications of reduced carbohydrate production by affected trees. Such changes typically lead to a shift in relative allocation of energy toward growth at the expense of reduced resistance to abiotic stress.

Driscoll et al. (2001) reviewed the deposition trends and effects of acid rain on lakes and forests in the northeastern United States. They reported that acidic deposition leaches cellular calcium from red spruce foliage, which makes trees susceptible to freezing injury, leading to over 50% mortality of canopy trees in some areas of the northeastern United States. They also noted that extensive mortality of sugar maple in Pennsylvania has resulted from deficiencies of calcium and magnesium. Acidic deposition has contributed to the depletion of these cations from soil.

This group of reports, which together incorporate a very large body of scientific publications, presents convincing documentation of damage to forests from acid rain (and associated precursors) and ozone. The dominant mechanism for acid rain-caused damage appears to be leaching of calcium and magnesium from the soil, leading to decreased growth, decline and reduced insect and disease resistance in forests. The direct effects of air pollution on foliage and stand aging can also be important causes of forest decline.

While sulphate deposition has been reduced in North America, it has been known since the current control programs were designed that the reductions would not be sufficient to eliminate all damage (Bangay and Riordan 1983). Large areas of eastern Canada still receive acid deposition above the critical (protective) load for forest soils (Arp et al.

1996). The area of exceedance was estimated at the workshop as being 10–15% of Canada's most productive forest. These forests have considerable ecological, social, and economic value and contain numerous federal and provincial parks and many recreational areas.

In addition, the reports raise concern for the future health of forests as they are being subjected to additional stressors such as increased UV-B radiation and climate change.

Workshop discussions

Workshop participants reviewed reports of particular relevance to eastern Canada and the Muskoka area.

A photographic record of maple forests in the Muskoka area taken every July since 1987 has shown a sustained deterioration of tree condition ending in the death of some of the trees. Figures 1, 2, and 3 show the results from one plot near Dorset, Ontario, in 1987, 1993, and 2001. Sustained loss of canopy is clear, with some trees having disappeared and the remaining large trees (notably the two on the right-hand side) still showing dieback at the ends of many branches. The understory has grown well and may indicate a long-term recovery of the forest. This area has experienced a decrease in acid deposition from about 30 (1980–1984) to about 15 (1995) kg per hectare per year of wet sulfate. Watmough et al. (1999), have reported on dendrochemical analyses of six of the trees in the photos. They found that a reduction in tree-ring width occurred in the 1940s but ring widths remained constant at the lower values after 1950. At a study plot 200 km farther north, that is still relatively free of decline symptoms, tree-ring widths experienced a similar decrease 20 years later. The authors ruled out insects and drought as the likely cause of the decreased ring widths and visible symptoms at the Dorset site. Concentrations of calcium and magnesium in the wood at Dorset since1947 are among the lowest reported in the literature. The authors noted that calcium and magnesium deficiencies appeared to be associated with the poor tree growth at both sites and are most likely responsible for the visible decline symptoms observed at the Dorset site. They further noted that other incidences of sugar maple decline in Ontario have been associated with calcium and magnesium deficiencies, and that the deficiencies observed at these two study sites are likely due to acid deposition.

Sager et al. (2000), conducted a dendrochemical analyses of mature hardwoods from eight sites from central Ontario, Quebec, Nova Scotia, and Prince Edward Island. They found that calcium concentrations in wood was lower at sites with more acidic soils and conversely, magnesium was higher in wood from the more alkaline soil sites.

In the 1980s, sugar maple decline was observed through its range in Quebec. While the majority of stands have recovered in recent years, some have continued to decline.

In a series of experiments, varying amounts of dolomitic lime (calcium and magnesium carbonate) were added to the soil surface under declining trees. After only one year, the foliar concentrations of calcium and magnesium increased and the radial growth rates of the trees increased. Four years after treatment, radial growth had increased by 45 to 90% depending on the amount of lime added. During the third and fourth years after treatment the liming had appeared to stop the progression of declining symptoms whereas the decline rate increased for the control trees (Moore et al. 2000). These results are consistent with earlier work by Ouimet and Fortin (1992), that showed improved foliar nutrient status and growth rates in declining maples following fertilization with potassium. Hendershot (1991) observed improved tree vigor in declining maples fertilized with calcium and magnesium.

Loucks (1998a) has published analyses showing an increase in mortality rate from 0.4–0.5% to 1.0–1.5% in hickory forests of the eastern United States. Such an increase means that the average life span of the forest would be reduced from 300 years to about 150 years. Loucks (1998b) also observed a drastic reduction in the earthworm numbers and overall soil invertebrate diversity in acid rain-affected forest soils of central Ohio compared to soils receiving a lower cumulative dose in southern Illinois.

In addition to published reports, workshop participants reviewed other observations on forest condition in the Muskoka and surrounding areas.

Symptoms of ozone damage, such as premature senescence, necrosis on leaf edges, and premature initiation of fall colours have been observed on sugar maples in the Minden area. Model calculations indicate that this area is likely to experience some of the highest ozone concentrations in Ontario.

Continuous records, since the 1950s and 1960s, of maple syrup production per tap, are available for four sugar bushes in central Ontario. Two forests showed no change while two have shown a statistically significant decrease in production. Given the economic incentive and availability of forest management advice, production would have been expected to increase.

Considerations of future trends in forest stress

The Technical Assessment Report of the Intergovernmental Panel on Climate Change **(citation??)** has made a number of statements regarding the future of forests with respect to nitrogen deposition effects, the interaction of increased CO_2 and ozone, and the adaptation of different genotypes to a warming climate. The workshop found that the following concepts warrant further consideration.

Nitrogen deposition effects

While nitrogen fertilization has an initial fertilization effect that increases growth, especially in nitrogen deficient forests, it also delays the twig and bud hardening-off process and causes increased levels of winter damage. If the combined effects of changing climate and deposition of nitrogen are considered, then the carbon stock of forests could be decreased over a 100 year period, since any increased growth from enhanced nitrogen is more than offset by forest decline and increased soil respiration. Under these processes, the potential for increased carbon sequestration under increased carbon dioxide availability and rising temperatures is unlikely. Many processes in forest ecosystems contribute to carbon balances, but they do not all work together to fix carbon (Makipaa et al. 1999).

Interaction of increased CO_2 and ozone

Forests have been predicted to grow faster under increased levels of carbon dioxide and so fix more carbon than possible under ambient conditions. However, along with the increasing concentrations of carbon dioxide in the atmosphere are increasing concentrations of tropospheric ozone. Ozone damages plant foliage and reproductive systems and adversely affects the growth processes. Current research suggests that the presence of elevated concentrations of ozone will likely negate the potential for increased grown and carbon sequestration from increased concentrations of carbon dioxide (Karnosky et al. 2000).

Adaptation of different trees species to a changing climate

Some assumptions have been made as to how tree growth will be affected by climate change, such as “global warming”. These have, on occasion, been built into national and global carbon budget models. A factor to be considered is that many trees and other organisms have adapted to the combination of site, climate, and day length where they now occur. When temperature is changed, it cannot be assumed that tree growth will increase or that the populations will remain optimally adapted to these sites. Analysis of seed source test data in the light of climate change projections indicates either no net growth increase from warming or small growth losses. This results from the maladaptation of the populations to the new conditions. Trees may also be under considerably more stress in a changed climate, leaving them more susceptible to insects and diseases than they are currently, thus reducing any net benefit of increased temperature on carbon sequestration in forests (Carter 1996; Matyas 1996).

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 pollutant load/level approaches that can be fully integrated into forest health monitoring programs in Canada. Decision support information on these questions is needed to provide reliable measurement and protection of forest sustainability. Maintenance of forest ecosystem health is essential to the sustainability of Canada's forests and the overall well being of the country’s economy.

The growth and health of forests will continue to be of critical importance for Canada as we embark on a policy of using forests as sinks in the national carbon dioxide budget. Making credible long-term projections of forest uptake of carbon dioxide will be quite problematic.

Conclusions from the Workshop

Recent forest research and monitoring have provided convincing evidence that acid rain and ozone have caused damage to forest health and forest decline in forest areas in eastern Canada, from Ontario to the east coast.

The area of forests currently subjected to damaging levels of air pollution, and where soils have been affected by decades of acid rain, was estimated to be 10–15% of Canada’s productive forests. The areas of forests affected by pollution have considerable ecological, social, and economic value, as they include some of the most productive forests in Canada and contain numerous federal and provincial parks and many recreational areas.

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