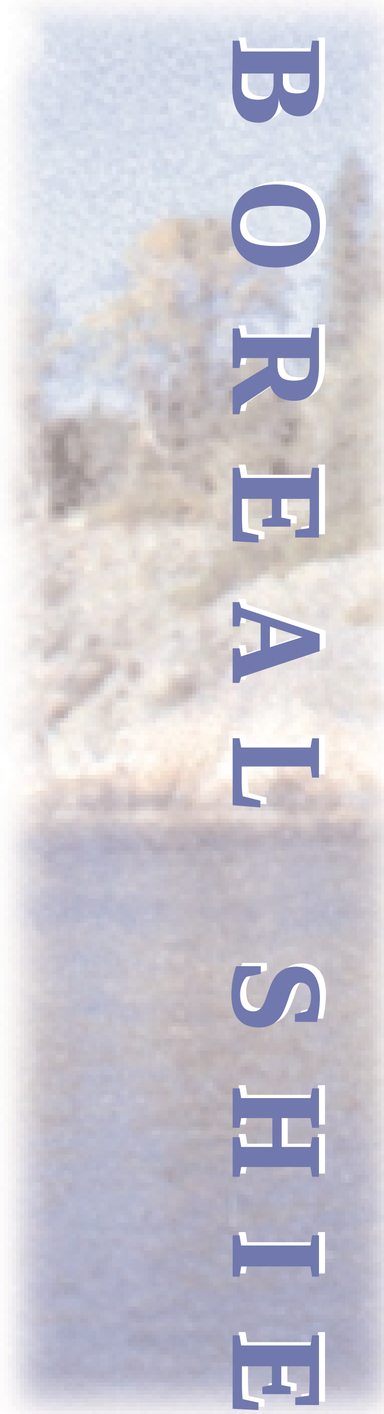
Ecological Assessment of the BOREAL SHIELD ECOZONE



BOREAL SHIELD

Environment Canada / Environnement Canada

Canada

Ecological Assessment of the BOREAL SHIELD ECOZONE

Edited by:

Natty Urquizo
Rainmakers Environmental Group

Jamie Bastedo
Cygnus Environmental Consulting

Tom Brydges
formerly EMAN Coordinating Office
Environment Canada

Harvey Shear
Ontario Region
Environment Canada

Canadian Cataloguing in Publication Data

Main entry under title:
Ecological assessment of the Boreal Shield ecozone

Issued also in French under title: Évaluation écologique de l'écozone du bouclier boréal.
Issued by the Indicators and Assessment Office.
ISBN 0-662-28679-0
Cat. no. En40-600/2000E

1. Environmental monitoring – Canadian shield.
2. Environmental indicators – Canadian shield.
3. Ecology – Canadian shield.
4. Canadian shield – Environmental aspects.
I. Urquizo, Natty.
II. Canada. Environment Canada.
III. Indicators and Assessment Office (Canada)

TD26.E32 2000 363.73'63'0971 C00-980110-3

Copies of this publication may be obtained free of charge from:
Indicators and Assessment Office
Environmental Conservation Service
Environment Canada
Ottawa, Ontario K1A 0H3

For more information:
Call 1-800-668-6767
E-mail enviroinfo@ec.gc.ca

This document is also available on the Internet at The State of Canada's
Environment Infobase (www1.ec.gc.ca/~soer/default_e.htm)

Table of Contents

Preface . . . ix

Highlights . . . xi

1. Introduction . . . 1
- 1.1 Purpose of the Assessment . . . 1
- 1.2 An Ecozone Under Stress . . . 1
- 1.3 The Role of Environmental Monitoring . . . 2

2. The Boreal Shield Ecozone . . . 5
- 2.1 Ecological Setting . . . 5
  - 2.1.1 Climate . . . 5
  - 2.1.2 Geology and soils . . . 5
  - 2.1.3 Vegetation . . . 6
  - 2.1.4 Water . . . 6
  - 2.1.5 Wildlife . . . 7
- 2.2 Socioeconomic Setting . . . 7
  - 2.2.1 Population . . . 7
  - 2.2.2 Labour and employment . . . 8
  - 2.2.3 Land use . . . 9

3. Environmental Stresses from Within . . . 11
- 3.1 Forestry . . . 11
  - 3.1.1 Forest resource use . . . 11
  - 3.1.2 Influence of harvesting and renewal practices on forest ecosystems . . . 12
  - 3.1.3 Forestry management . . . 14
- 3.2 Mining . . . 16
  - 3.2.1 Mineral resource use . . . 16
  - 3.2.2 Mining impacts . . . 17
  - 3.2.3 Mine management . . . 18
- 3.3 Hydroelectricity . . . 19
  - 3.3.1 Hydroelectric resource use . . . 19
  - 3.3.2 Impacts from hydroelectric development . . . 20

3.3.3 Hydroelectric management 22
3.4 Additional Land Uses 23
3.4.1 Peatland development 23
3.4.2 Cottage development 24
3.4.3 Protected areas 25

4. Environmental Stresses from Outside 27
4.1 Climate Change 27
4.2 Acid Precipitation 30
4.3 Ultraviolet-B Radiation 38
4.4 Long-range Transport of Pollutants 40

5. Selected Indicators of Change 41
5.1 Forest Fires 41
5.2 Insects 43
5.3 Mercury 45
5.4 Nonnative Species 46
5.5 Mammals and Birds 47
5.6 Plants and Lichens 48
5.7 Drought and Blowdown 49
5.8 Leopard Frog 49

6. Prognosis for a Healthy Ecozone 51

7. Conclusion 53

References 55

Appendix 1: Priorities for Environmental Monitoring of Acid Deposition 67

Appendix 2: Common and Scientific Names of Selected Species Referred to in the Report 69

Appendix 3: Units of Measure Used in the Report 71

List of Tables

Table 1: Economic importance of the Boreal Shield ecozone 8
Table 2: Trends in sulphur dioxide emissions for selected smelter locations. 17
Table 3: Some characteristic species of the Boreal Shield ecozone that are endangered or threatened 48

List of Figures

Figure 1: Map of the Boreal Shield ecozone and the Ecological Monitoring and Assessment Network (EMAN) sites included within it 2
Figure 2: Labour composition in the Boreal Shield ecozone 9
Figure 3: Mineral regions in the Boreal Shield ecozone, 1990. 17
Figure 4: Protected forest area in the Boreal Shield ecozone, 1970–1995 25
Figure 5: Annual duration of ice cover, Lake 239 of Ontario's Experimental Lakes Area, 1969/70–1996/97 29
Figure 6: Stream flow decrease in northwestern Ontario's Experimental Lakes Area 29
Figure 7: Relationship between the number of fish species and pH in 118 lakes from the Outaouais and Abitibi regions of Quebec 31
Figure 8: Mean annual dissolved organic carbon (DOC) concentration over time in three lakes at the Experimental Lakes Area 32
Figure 9: Five-year mean excess sulphate wet deposition patterns (in kg/ha per year) for 1980–1984 and 1991–1995. 34
Figure 10: Raw (dotted line) and annual average sulphate and calcium data (solid lines) . . . 35
Figure 11: Trends for alkalinity, calcium, magnesium, and sulphate in Pukaskwa National Park, Ontario, 1987–1995 36
Figure 12: Combined physical and chemical effects of acid deposition, climate warming, and stratospheric ozone depletion. 39
Figure 13: Annual area burned in the Boreal Shield ecozone, 1930–1992 42
Figure 14: Key insect disturbance trends in the Boreal Shield ecozone, 1980–1996 44

List of Boxes

Box 1: Canadian and international policy initiatives relevant to forestry management 15
Box 2: Regulatory and policy gaps hindering reduction of impacts from mining 19

Contributors

Allan, Rod J., National Water Research Institute, Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario
Bastedo, Jamie, Cygnus Environmental Consulting, Yellowknife, N.W.T.
Brydges, Tom, formerly EMAN Coordinating Office, Environment Canada, Burlington, Ontario
Hall, Peter, Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario
Hendrickson, Ole, Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario
Hopkin, Anthony, Canadian Forest Service, Natural Resources Canada, Sault Ste. Marie, Ontario
Rubec, Clayton, Canadian Wildlife Service, Environment Canada, Ottawa, Ontario
Shearer, John, Experimental Lakes Area Operations, Fisheries and Oceans Canada, Winnipeg, Manitoba
Stocks, Brian J., Canadian Forest Service, Natural Resources Canada, Sault Ste. Marie, Ontario
Urquizo, Natty, Rainmakers Environmental Group, Niagara-on-the-Lake, Ontario
Waite, Don, Prairie and Northern Region, Environment Canada, Regina, Saskatchewan
Wood, John A., Ecological Research Division, Prairie and Northern Region, Environment Canada, Regina, Saskatchewan

Reviewers

Bergeron, Yves, Boreal Shield (Quebec) Ecological Science Cooperative, Lac Duparquet, Quebec
Cole, Bill, Government of Ontario, Boreal Shield (Ontario) Ecological Science Cooperative, Swan Lake, Ontario
DeKimpe, Christian, Natural Resources, Agriculture and Agri-Food Canada, Ottawa, Ontario
Dillon, Peter, Ontario Ministry of Environment and Energy, Dorset Environmental Science Centre, Dorset, Ontario
Eros, Susan, Resource Conservation, Environmental Conservation Branch, Prairie and Northern Region, Environment Canada, Edmonton
Evans, Doug, Environmental and Resources Studies, Trent University, Peterborough, Ontario
Gagnon, Réjean, Université du Québec à Chicoutimi, Chicoutimi, Quebec
Gunn, John, Co-operative Freshwater Ecology Unit, Ontario Ministry of Natural Resources, Department of Biology, Laurentian University, Sudbury, Ontario
Hirvonen, Harry, Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario
Ironside, Gary, Indicators and Assessment Office, Environment Canada, Ottawa, Ontario
Jeffries, Dean, Atmospheric Contaminant Impacts, Environment Canada, Burlington, Ontario
Johnston, Vicky, Canadian Wildlife Service, Environment Canada, Yellowknife, N.W.T.
Kronberg, Barbara, Lakehead University, Thunder Bay, Ontario
Langford, Lynda, Ecosystem Management Special Project Manager, Saskatchewan Environment and Resource Management, Regina, Saskatchewan
LeHénaff, Annick, Indicators and Assessment Office, Environment Canada, Ottawa, Ontario
Maarouf, Abdel, Climate and Atmospheric Research Directorate, Environment Canada, Downsview, Ontario
McAfee, Brenda, Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario
Piche, E., Environmental Monitoring and Reporting Branch, Ontario Ministry of the Environment, Toronto, Ontario
Pinel-Alloul, Bernadette, University of Montreal, Montreal, Quebec
Quaile, Geoffrey, Environmental Advisor, Grand Council of the Crees of Eeyou Istchee, Quebec

Savard, Sylvain, Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario

Savidge, Rodney A., Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton, New Brunswick

Schindler, David, University of Alberta, Edmonton, Alberta

Snucins, Ed, Co-operative Freshwater Ecology Unit, Ontario Ministry of Natural Resources, Department of Biology, Laurentian University, Sudbury, Ontario

Streich, Laurie, Manitoba Environment, Winnipeg, Manitoba

Van dijk, Albert, La Mauricie National Park, Parks Canada Agency, Canadian Heritage, St-Mathieu du Parc, Quebec

Production

Crocodile Communications Inc., Ottawa, Ontario: design services and electronic page layout

Duggan, Doug, Indicators and Assessment Office, Environment Canada, Ottawa, Ontario: preparation of most figures

Ironside, Gary, Indicators and Assessment Office, Environment Canada, Ottawa, Ontario: coordination of final editing and production

Sheffer, Marla, Scientific Editing, Orleans, Ontario: copy editing

Preface

The Canadian environment, source of so much of the country's natural wealth, is under stress. Some of these stresses come from within, caused by forestry, mining, agriculture, hydroelectric generation, road construction, and other activities. Others come from outside the ecozone, often arising far away – climate change, stratospheric ozone depletion, acid precipitation, and the long-range air transport of pollutants, for example.

While some of these stresses, such as forest harvesting, cause immediate and obvious changes, others, such as the changing atmosphere, can result in long-term subtle ecosystem responses. Consequently, multiyear, multidisciplinary studies, supported by research and experiments, are needed to define ecosystem responses to these stresses and to design satisfactory environmental protection programs and resource management policies.

An urgent challenge now facing the scientific community is the need to mobilize efforts to understand and report on environmental changes in ways that contribute to improved decision-making. This is one of the main purposes of the Ecological Monitoring and Assessment Network, known as EMAN. The activities of EMAN are administered by the EMAN Coordinating Office of Environment Canada, in Burlington, Ontario. The EMAN Coordinating Office promotes the linking of ecological studies across Canada through workshops and national meetings. Preparing a directory of sites, describing their scientific studies, providing an inventory of researchers, and compiling bibliographies and data sets are among the many ways the EMAN Coordinating Office makes links with the wider world where land and water use decisions are made.

But the rate and magnitude of environmental changes we are now observing dictate that we must do much more. These organizational aspects are not sufficient to make EMAN as useful and as responsive to reporting on ecological concerns as it should be. While these projects were quite successful, they have yet to be fully applied in finding solutions to the multiple stresses now affecting Canada's rapidly changing environment.

In 1997, we initiated a pilot project to further develop the concepts and objectives of EMAN by contributing information from a number of EMAN sites to a multidisciplinary assessment report.

We decided that the boundaries of this project should be defined by one of Canada's 15 terrestrial ecozones. We chose the Boreal Shield ecozone for the pilot project, as it is of great economic importance to Canada and is subjected to all of the major stresses outlined above. There are 22 EMAN sites within this ecozone, some of which have the longest multidisciplinary monitoring data sets in Canada.

The Boreal Shield also represents an opportunity to study a number of stresses by comparing results at different sites. For example, acid rain affects the central part of this ecozone, with little effect in the extreme eastern and western areas, whereas increased ultraviolet-B radiation and atmospheric carbon dioxide concentrations may be more uniform across the ecozone. As well, average annual air temperature is increasing in the west and slightly decreasing in the east.

As a pilot project, this report may not be as complete and as detailed as possible, but, with the willing support of many scientists, we have assembled a substantial amount of information documenting the multiple stresses that now impinge upon the Boreal Shield ecozone.

Highlights

When the combined effects of climate warming, acid deposition, stratospheric ozone depletion and other human activities are considered, the boreal landscape may be one of the global ecoregions that changes the most in the next few decades. Certainly, our descendants will know a much different boreal landscape than we have today.

— D.W. Schindler, 1998

The Boreal Shield is Canada's largest ecozone, covering almost 20% of its land mass, containing 43% of its commercial forestland, and accounting for 22% of the country's freshwater surface area. The ecozone has a gross domestic product of almost $50 billion. Major contributors to the economy include hydroelectric generation ($16 billion), mining ($6 billion), and forestry ($5.85 billion from pulp and paper). The Boreal Shield is home to three million people and provides 15% of Canada's resource-based employment.

This assessment reviews findings and highlights current trends relating to environmental stresses on the Boreal Shield ecozone, provides direction to strengthen national programs aimed at addressing environmental concerns and developing remedial and preventative strategies, and, finally, focuses on the links of science with policy.

Ecosystem changes — links to stresses from within

Forestry

- Most indicators point to a net increase in wood harvested in the Boreal Shield over the past few years. The 1990s have also witnessed a rapid northward expansion of forestry-related activities.
- Clearcutting accounts for 90% of the 400 000 ha harvested annually in the Boreal Shield. The potential environmental impacts of clearcutting are well documented and include:
  - reduced biodiversity
  - loss or alteration of wildlife habitat
  - soil modification

- reduced water quality

- Although improved government regulations and technology have minimized environmental releases of mercury, dioxins and furans, and other organochlorines from pulp and paper mills in this ecozone, concerns persist about liver enzyme dysfunction in fish caused by mill effluents. As well, many pulp mills continue to release large quantities of dissolved organic matter such as tannins and other highly coloured humic substances.

Mining

- The Boreal Shield ecozone supplies 75% of Canada's iron, nickel, copper, gold, and silver.
- Northern Saskatchewan is the largest producer of uranium in the world, accounting for 34% of world production. Three new uranium projects are currently under development, and a fourth is expected to begin early in the next century.
- The primary impact of mines in the Boreal Shield is on aquatic biodiversity, caused by the discharge of mine effluents into water. Environmental problems created by abandoned mines also represent a major long-term hazard for the general health of the ecozone.

Hydroelectricity

- Canada is the largest producer of hydroelectricity in the world, accounting for approximately 15% of the world's total production. Thirty-nine per cent of Canada's hydroelectric capacity is located on rivers arising in or flowing through the Boreal Shield.
- Hydroelectric development has altered 85% of the drainage basins contained in whole or in part in the Boreal Shield – 77% contain major dams, 25% have major reservoirs, and 33% have rivers whose flow has been either augmented or diminished by water transfers.
- Impacts from hydroelectric development include:
  - loss of terrestrial habitats through dam construction and reservoir impoundment
  - shoreline erosion
  - wildlife and habitat disturbances associated with transmission corridors
  - altered competitive and predatory aquatic regimes due to increased water volume
  - increased turbidity
  - mercury release from the flooding of organic matter by reservoirs
  - release of carbon dioxide and methane from extensive flooding of land
- The long-term maintenance and reclamation of aging dams are emerging environmental concerns that have yet to receive significant scientific or policy attention from provincial governments.
- The negative impacts of hydroelectric projects have particularly affected the ecozone's native people because of their traditional pattern of settling, hunting, and travelling along the shores of rivers and lakes.

Additional land uses

- Widespread cottage development on Boreal Shield lakes has led to significant public concern about the eutrophication of recreational lakes. Another issue of concern is the removal of shoreline vegetation by cottage owners, resulting in local macrophyte population declines and disruptions to aquatic food chains.

- Although the Boreal Shield is the largest of Canada's 15 terrestrial ecozones, it has one of the lowest proportions of land – less than 3% – dedicated to protected areas in which all forms of industrial activity are prohibited.

Ecosystem changes — links to stresses from outside

Climate change

- Atmospheric models predict that Boreal Shield forests and wetlands are likely to be highly vulnerable to the effects of global warming. Small increases in temperature may give rise to large increases in biological activity, particularly in rates of plant growth and litter decomposition.
- Changes in lakes and rivers in the Boreal Shield have been recorded in response to changes in climate. At Ontario's Experimental Lakes Area, a temperature increase of 1.6°C and a 40% drop in precipitation were observed from 1970 to 1990, with the following results:
    - shorter ice cover periods for lakes
    - a nearly 50% increase in evapotranspiration
    - decreased dissolved organic carbon (DOC) and phosphorus in lakes
    - increased transparency, resulting in deeper penetration of ultraviolet-B (UV-B) radiation
    - decreased phytoplankton abundance in lakes with reduced phosphorus
- Climate change affects the life cycle, behaviour, and range of many Boreal Shield insect species.
- The Boreal Shield forests are a significant component of the global carbon cycle. The recent 20-year period of high disturbances in the Boreal Shield forests combined with warmer temperatures has resulted in a net loss of carbon to the atmosphere.

Acid precipitation

- Many fish and invertebrate populations from the Boreal Shield region have been lost as a result of acid precipitation. The poorly buffered lakes of the eastern half of the ecozone are particularly sensitive to acidification.
- Increased acidity is linked to high concentrations of mercury, cadmium, and lead in fish and can cause a loss of DOC in surface waters.
- The role of acid deposition in contributing to Boreal Shield forest declines has been widely studied. Some well-documented effects include:
    - decreased net photosynthesis and nutrient uptake
    - impaired germination
    - reduced frost hardiness
    - damage to protective leaves and needle cuticles
    - decreased ability to cope with other stressors, such as climate warming, drought, insect outbreaks, and disease

- Although sulphate deposition was reduced significantly over Boreal Shield regions between 1980 and 1993, atmospheric nitrate deposition remained constant or increased slightly during this period.
- Lake recovery following reduced acid deposition has been slow and uneven. Of 152 acidified lakes monitored in Newfoundland, Quebec, Nova Scotia, and Ontario from 1981 to 1997, only 41% became less acidic, 50% remained the same, and 9% became more acidic.

Ultraviolet-B (UV-B) radiation

- Very little is known about trends in UV-B radiation in the Boreal Shield ecozone, as the stressor is only beginning to be studied. Spectral measurements of UV-B radiation between 1989 and 1993 in Toronto, Ontario, just south of Boreal Shield latitudes, indicated that the intensity of light at wavelengths near 300 nm had increased by 35% per year in winter and 7% per year in summer. The trend at wavelengths between 320 and 325 nm, however, was essentially zero.
- Reduced tree vigour, reduced photosynthetic activity, sun scalding, and premature aging of needles are among the multiple impacts of rising UV-B radiation on coniferous trees.
- Stream invertebrates may be particularly sensitive to UV-B radiation, but even deepwater or bottom-dwelling organisms may experience adverse effects when they enter near-surface waters.

Long-range transport of pollutants

- Significant amounts of organochlorine pesticides are deposited into Boreal Shield lakes from long-range transport. While these quantities are not acutely toxic, their chronic effects are unknown. Studies suggest that persistent organic pollutants are accumulating in certain tissues of Boreal Shield invertebrates, fish, and higher vertebrates and may, over time, contribute to population declines and ecosystem malfunctions.

Indicators of ecosystem change

Disturbances

Forest fires

- Fire is a natural and dominant disturbance in the Boreal Shield ecozone. Fire is generally required for the adequate regeneration of most tree species.
- The annual area burned varies from 0.7 to 7 million hectares, averaging 2.9 million hectares annually. Fires are larger and occur with greater frequency in the Boreal Shield than in any other forested region of the country. Records reveal an upward trend in both fire occurrence and area burned in recent years.
- With present climate warming trends, larger fires are anticipated in northern parts of the ecozone. This could create undesired shifts in forest composition and age structure and negatively impact the global carbon budget.

Insects

- Insect outbreaks in forests have generally increased in area and duration over the past 25 years, possibly due to more intensive harvesting practices and fire suppression. The proportion of tree mortality due to insects is 1.5 times that due to wildfire and is equivalent to one-third of the annual harvest volume.

- The spruce budworm infestation that lasted from 1966 to 1996 resulted in 8.3 million hectares of balsam fir and white spruce mortality in Ontario, mostly in the Boreal Shield.
- The jack pine budworm range has been expanding eastward over the last 30 years, with outbreaks detected over large areas in central and eastern Ontario.The forest tent caterpillar, which is the most significant defoliator of hardwood trees in the Boreal Shield ecozone, recently defoliated 9.5 million hectares of birch and poplar forests in Ontario.

Contaminants

- Numerous fish species throughout Ontario and Manitoba contain dangerously high levels of mercury in their tissues, resulting in warnings regarding the amounts of fish that can be safely consumed by humans.
- Mercury contamination is a particular concern to Aboriginal people in this ecozone, many of whom give fish a central place in their diet.

Biodiversity

- The spread of exotic species that are harmful to native tree species is a growing concern for Boreal Shield forest managers.
    - The balsam woolly adelgid, an insect pest, is causing serious damage to balsam fir stands in Newfoundland, where it was accidentally introduced in the 1920s or 1930s.
    - The white pine blister rust, a tree disease caused by an introduced fungus, is also damaging trees in the Boreal Shield, particularly in southern parts of the ecozone.
    - In Manitoba, Ontario, and Quebec, purple loosestrife, a flowering plant, is a serious concern as it clogs streams and competes with native cattails and other aquatic plants important for wildlife.
- Most large mammal populations seem to be stable or increasing.
- Thirteen species of animals and plants in the Boreal Shield ecozone are listed as being at risk by the Committee on the Status of Endangered Wildlife in Canada.
- A globally rare lichen species, found in the remaining mature forests of Newfoundland, is vulnerable to timber extraction and highly sensitive to air pollution.
- Leopard frog populations have declined significantly over the past 20 years. Based on a survey of almost 100 wetlands within the ecozone, they have disappeared from an area north of Sault Ste. Marie to Nipigon.

Where do we go from here?

Resource management

- The National Forest Strategy, unveiled in the spring of 1998, provides a framework that will guide the policies and actions of the forest community over the course of the next few years in order to make the goal of sustainable forestry a reality. There will be a need for on-the-ground monitoring to determine how effectively its objectives are being met.
- Mine management will be improved through the development and implementation of a cooperative national environmental protection framework. This would include a revised federal effluent regulation, site-specific requirements, and environmental effects monitoring to provide information on the effectiveness of environmental protection measures.
- All provincial hydroelectric utilities and governments must give greater priority to ecosystem monitoring, hindsight assessments, and baseline research in order to answer the many environmental questions surrounding large-scale hydroelectric projects in the Boreal Shield.
- There is a growing public call for more coordinated management of Boreal Shield wetlands. To help address such concerns, the Federal Cabinet formally adopted the Federal Policy on Wetland Conservation in December 1991. The Policy was enhanced in 1996 with Guidelines for Federal Land Managers and has been complemented by provincial wetland policies.
- Additional studies are needed to better understand the full environmental impacts of recreational development and tourism in the Boreal Shield. Recent planning and policy advances in Ontario provide for improved site assessments and pollution controls for cottage developments.
- While the need to complete protected area networks in the Boreal Shield ecozone is well recognized, mounting resource development pressures are slowing movement towards this goal. Integrating an expanded protected area network with environmentally progressive land management practices is key to conserving biodiversity on an ecozone-wide scale.

Environmental monitoring

- Environmental monitoring programs in the Boreal Shield have shed much light on the severity of impacts of acidification on both terrestrial and aquatic ecosystems, the complexity of their interactions, and the dynamics of ecosystem recovery. Continued monitoring will be essential to gauge the effectiveness of future regulatory controls and to address the many unknowns raised by ongoing research.
- UV-B exposure is one of the most complex and least understood stressors now influencing the Boreal Shield ecozone. Continued monitoring of stratospheric ozone and incident UV-B radiation, and associated impacts on Boreal Shield ecosystems, will enable scientists and decision-makers to better understand the full significance of this stressor and determine how best to respond.
- The many unknowns and growing international concern regarding the long-range transport of persistent organic pollutants and heavy metals make enhanced monitoring of airborne contaminants imperative.
- Monitoring of the many indicators of ecosystem health – the severity and extent of insect outbreaks, mercury levels, and leopard frog numbers, for example – is essential to keep a pulse on the environmental health of the Boreal Shield ecozone.

1 Introduction

1.1 Purpose of the Assessment

The purpose of this assessment is to provide an overview of the broad ecological changes now occurring in the resource-rich Boreal Shield ecozone. What are the nature and cause of these changes? Why are they significant to Canadians? How are industry, resource managers, and policymakers responding to these changes? These are the kinds of questions addressed in this report. To answer these questions, this report has three main objectives:

1. To provide the most current scientific understanding on natural resource issues and trends affecting the Boreal Shield ecozone;
2. To communicate to Canadians the state of the Boreal Shield ecozone so that they can contribute to environmentally responsible decisions affecting its future; and
3. To demonstrate the importance of a long-term, multidisciplinary research and monitoring network in promoting science-based improvements to the way Canadians manage their natural resources.

1.2 An Ecozone Under Stress

One of the primary rules of ecology is that everything is changing all of the time. In nature, flux is the rule, and the Boreal Shield ecozone is no exception. Changes have been observed in practically every ecosystem component, ranging from the obvious, such as increased roads, hydroelectric lines, forest clearcuts, and forest fires, to the subtle, such as increased acid precipitation and ultraviolet-B (UV-B) radiation and reduced biodiversity. These changes are both natural and anthropogenic, that is caused by human activities.

Not all these changes are necessarily negative. For instance, most large mammal populations seem to be stable or increasing. Nonetheless, measured against the prospects of long-term ecological and economic health, the net effect of these changes on this vast, economically important ecozone points to a state of deterioration. The focus of this assessment report is to understand the multiple stresses causing this trend and to help set the stage for turning it around.

1.3 The Role of Environmental Monitoring

The ecological effects of localized, short-term stresses are well documented. For example, clearcutting a forest may reduce overall species diversity, cause siltation of water bodies, trigger insect outbreaks, and create soil erosion. All of these impacts can be mitigated with proper management. More widespread, long-term stresses associated with climate change or acid precipitation, for instance, can be much more difficult to measure, let alone control. Multiyear, multidisciplinary environmental monitoring studies are among the best tools for understanding these wider stresses and identifying science-based solutions for decision-makers.

Ecological indicators of stress are an important component of long-term monitoring. For instance, varying levels of sulphate deposited in the environment provide a good indicator of the relative severity of acid precipitation. The most useful indicators, like this one, are easily tracked, economically feasible to measure, and of use to a large number of scientific disciplines. Across the Boreal Shield, such indicators are now being monitored year after year at 22 sites (1 in Manitoba, 9 in Ontario, 10 in Quebec, and 2 in Newfoundland) linked through the Ecological Monitoring and Assessment Network (EMAN) (Figure 1). This assessment report draws heavily on the results of long-term monitoring studies undertaken at many of these sites.

The results of these long-term monitoring studies are not encouraging. Moreover, accelerating demands for natural resources, growing pollution and climatic stresses from afar, and prolonged lag times required for the environment to heal all suggest that, for the Boreal Shield ecozone, things will only get worse before they get better. But, in both the public and private sectors, many

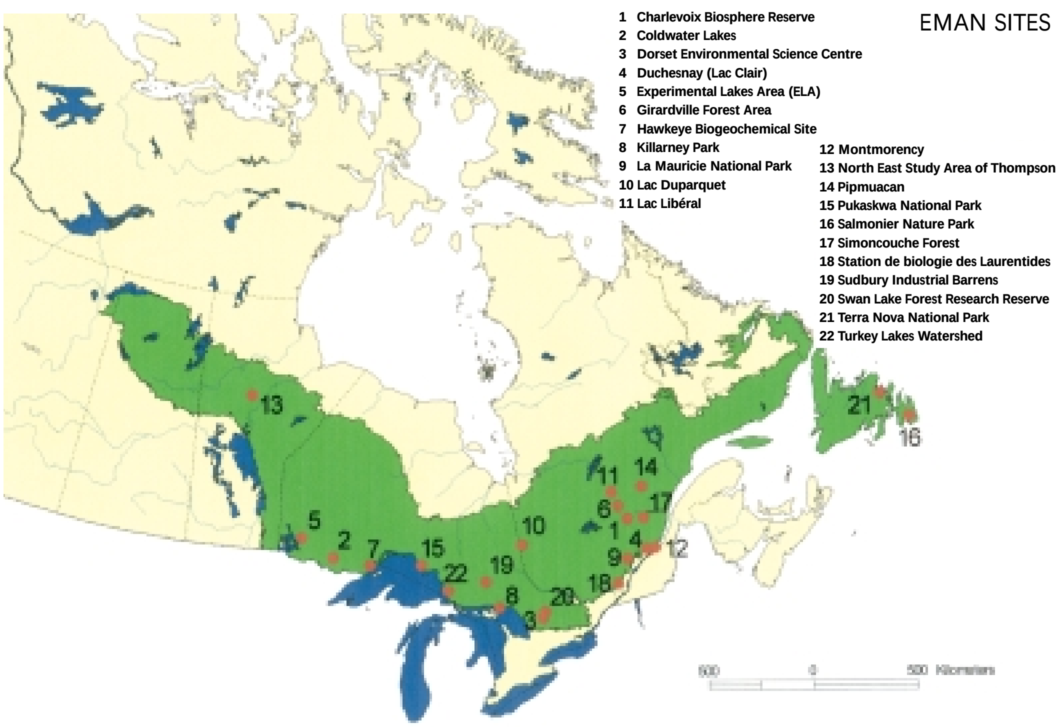


Figure 1: Map of the Boreal Shield ecozone and the Ecological Monitoring and Assessment Network (EMAN) sites included within it

Source: Indicators and Assessment Office, Environment Canada.

promising initiatives are already under way to help reverse some of the present trends towards environmental deterioration. True to the adage that "good science makes good decisions," a strong commitment to long-term environmental monitoring programs such as EMAN will be one of the best ways to reinforce existing and future initiatives to make things better.

2 The Boreal Shield Ecozone

2.1 Ecological Setting

The Boreal Shield ecozone stretches 3 800 km, from the eastern tip of Newfoundland to the northeastern corner of Alberta. This evergreen, granite-studded landscape is geographically defined by the overlap of the Canadian Shield and the boreal forest. The largest of Canada's 15 terrestrial ecozones, the Boreal Shield ecozone includes parts of 6 provinces, covers over 1.8 million square kilometres, encompasses almost 20% of Canada's land mass, and accounts for 22% of the country's freshwater surface area (Government of Canada, 1996). The ecozone displays a wide range of ecological diversity, reflecting coastal versus continental regimes, a broad range of growing season lengths, and variations in regional climate, soils, and vegetation patterns. In spite of this diversity, the Boreal Shield's character is fairly consistent from one end to the other.

2.1.1 Climate

The climate of this ecozone is generally continental, with long, cold winters and short, warm summers. Moist air masses over Hudson Bay bring relatively high levels of precipitation to much of the area, from 400 mm in the west to 1 000 mm in the east. The temperature averages -15°C in January and 17°C in July. Regions bordering the Great Lakes and the Atlantic Ocean tend to be warmed in winter and cooled in summer by the moderating effect of large water bodies. The average annual number of frost-free days ranges between 60 and 100, with some regions having fewer than 40. For many grain and other crops, a minimum of 100 frost-free days is needed for growth. Along with poor soils, this is one of the major factors limiting agriculture in the Boreal Shield ecozone.

2.1.2 Geology and soils

A landscape that once may have been crisscrossed by towering mountain chains is today a massive rolling plain of ancient bedrock. The foundation of much of this ecozone is metamorphic gneiss, a highly banded rock formed by intense crustal pressures and heat. Many of the minerals that contribute to the Boreal Shield's economy may have formed during geologically turbulent times over two billion years ago.

During the last ice age, which ended 10 000 years ago, the Shield was repeatedly scoured by advancing glaciers. While in retreat, they blanketed much of the landscape with coarse till released by torrential meltwater streams. Glaciation also had an important influence on the nature of today's soils, having scraped away much of the preglacial cover, often right down to bedrock. Not only are most soils here relatively thin, they are also high in acidity, low in nutrient availability, and cool. Organic soils underlying the expansive wetlands of this area further restrict plant growth by being oxygen poor and notoriously soggy. Although all of these qualities put severe restrictions on agriculture, the soils of the Boreal Shield are generally well suited for the growth of coniferous trees, as shown by the vast evergreen forests that now blanket much of this ecozone.

2.1.3 Vegetation

Cool temperatures, a short growing season, frequent forest fires, and acidic soils are among the many challenges faced by plant life in this ecozone. In spite of this, almost 85% of the ecozone is forest, of which 70% is considered productive for timber. The forest is dominated by a few highly adaptable tree species, such as black spruce, white spruce, jack pine, and balsam fir. Black spruce, the most common species, yields high-quality wood pulp and is therefore a prime species for Canada's growing paper industry.

Farther south there is a higher proportion of broadleaf trees, such as paper birch, trembling aspen, and balsam poplar, as well as other conifers, such as white, red, and jack pine. In southeastern parts of the ecozone, species characteristic of more temperate climates are common, including yellow birch, sugar maple, black ash, and eastern white cedar.

Throughout the Boreal Shield, these forests are mixed with innumerable bogs, fens, marshes, and other wetlands. Covering nearly 20% of the ecozone, these wetlands are among its most diverse and biologically productive ecosystems.

2.1.4 Water

The Boreal Shield is a well-watered landscape known and loved by many Canadians for its blue lakes and rocky shores. Intense glaciation over much of the area created thousands of disconnected dips, depressions, and furrows that are now filled with water. Throughout much of the area, crystalline bedrock – with its many faults, dikes, joints, and fractures – exerts an unyielding control over the flow of water. Hydrologists aptly describe the resulting drainage pattern as disrupted, disorganized – even deranged.

Since the days the first humans migrated into this ecozone, near the end of the last ice age, the Boreal Shield's sweeping network of rivers and lakes has served as a crucial means of transportation, a foundation for rich domestic fisheries, and a natural wellspring of fur-bearing mammals, which have long been central to the trapping economy. More recently, these waters have gained importance as a focus for outdoor recreation and the development of hydroelectric power.

To the east, the rocky shores of the Gulf of St. Lawrence and the coast of Newfoundland support diverse marine food chains and provide nesting grounds for many seabirds sustained by the sea's productivity.

2.1.5 Wildlife

Each spring, the abundance of water in the Boreal Shield ecozone attracts hundreds of thousands of ducks, loons, geese, and swans. They come here either to breed or to rest and feed before journeying onwards to more northerly nesting grounds. Among the more common waterfowl species that make this their summer home are the bufflehead, American black duck, wood duck, ring-necked duck, mallard, American wigeon, blue-winged teal, northern shoveller, and Canada goose. The boreal owl, great horned owl, evening grosbeak, blue jay, and white-throated sparrow are other representative birds.

Among the characteristic mammals of this ecozone are woodland caribou, white-tailed deer, moose, black bear, wolf, lynx, snowshoe hare, fisher, marten, and striped skunk. The ecozone's many wetlands, ponds, rivers, and lakes are important habitats for aquatic furbearers, such as beaver, muskrat, and mink.

In the Atlantic marine environment, typical mammals include grey, harp, and hooded seals and northern, bottle-nosed, sperm, killer, Atlantic pilot, fin, and blue whales. The endangered bowhead whale and threatened humpback whale are both found in this region. Inland, lake trout, lake whitefish, walleye, brook charr, and northern pike are among the most common fish species that thrive in the ecozone's multitude of lakes and rivers.

2.2 Socioeconomic Setting

The vast forests, rich mineral deposits, countless lakes, and abundant wildlife of the Boreal Shield ecozone are vital parts of Canada's natural resource base. This area ranks fourth among Canada's 15 terrestrial ecozones for its gross domestic product of approximately $50 billion. Although huge in area, its total income – at $41.8 billion – represents only 9% of Canada's wages. It also has a relatively low per capita income of $14 768 compared with the Pacific Maritime ecozone, which has a per capita income of $18 646 (Government of Canada, 1996).

2.2.1 Population

Ten percent of Canada's population – three million people – lives here, with most people gravitating to centres concentrated in southern and eastern portions of the ecozone. Overall, population density is quite low – about 1.5 people/km^2 – with the population roughly split 60/40 between urban and rural areas.

Most people live in settlements of between 1 000 and 30 000 residents. The largest urban centre is St. John's, Newfoundland, with a 1997 population of 175 000 people. Besides being relatively small, settlements are slow growing. Several single-resource towns, such as Flin Flon, Manitoba, and Schefferville, Quebec, show significant and often sudden declines in numbers resulting from the shutdown of local mines or mills. Some communities are seeking innovative ways to reverse this decline. For instance, after the closing of the uranium mine in Elliot Lake, Ontario, the town attracted several thousand people looking for a quiet, out-of-the-way community for retirement.

2.2.2 Labour and employment

The economy of the Boreal Shield is based strongly on its natural resources (see Table 1). About 15% of Canada's resource-related employment resides here. Of the natural-resource-based sectors, mining and forestry share top spot, with 5.4% of the total labour force, with fisheries and agriculture following with 2.5% and 2.2%, respectively (see Figure 2). Many people, particularly those of Aboriginal descent, are still involved in fishing and hunting.

Forestry	Mining	Hydroelectricity	Other
• 106 million hectares of timber–productive forestland, nearly half of Canada's total • 43% is commercial forestland, of which 70% is considered timber productive, compared with 59% of Canada's total forests • 400 000 ha harvested annually, twice as much as in the 1920s • forest sector in Quebec and Ontario produced $17.3 billion in 1996 exports, mostly in the Boreal Shield, and contributed $12.6 billion towards the balance of trade • 90% of harvesting is by clearcutting • supports logging for wood fibre, sawlog production, and pulp and paper mills • pulp and paper industry generates $5.85 billion annually	• generates an estimated $6 billion annually, supporting over 80 communities • over 50 mines, concentrated in Ontario and Quebec • produces 75% of total Canadian production of iron, copper, nickel, gold, and silver	• backbone of economic development within and outside of the ecozone • supplies energy for local wood and mineral processing as well as southern centres • 39% of Canada's hydroelectric capacity is in the Boreal Shield ecozone (24 574 MW), representing $16 billion annually • 279 large dams — 42% of the Canadian total — are located in the Boreal Shield, and there are many small dams as well; over 400 dams in Newfoundland alone • hunting, trapping, gathering (berries, fungi, medicinal plants), guiding, crafts, etc.	• agriculture (9% of total land area) restricted to clay belt area in north-central Ontario and Quebec; mainly livestock, with few hardy vegetables • commercial fisheries in Newfoundland and in lakes larger than 100 ha • lake fishing is important to Aboriginal peoples • tourism and recreation are increasing in economic importance and providing economic diversification; Ontario alone spent $462 million in 1996 on resource-based tourism activities • hunting, trapping, gathering (berries, fungi, medicinal plants), guiding, crafts, etc.

Table 1: Economic importance of the Boreal Shield ecozone

Source: Modified from Eaton et al., 1994; Ontario Ministry of Economic Development, Trade and Tourism, 1996; and Gibson et al., 1997.

From the mid-1980s to the mid-1990s, the trend in the primary (e.g., resource extraction) and secondary (e.g., resource processing) labour force has been downwards, while the tertiary (e.g., government, commercial services) labour force has swung upwards. The growing tertiary sector in this ecozone reflects general economic trends towards growth in the tourism and service sectors, technological change in resource extraction, and government decentralization initiatives (Government of Canada ,1996).

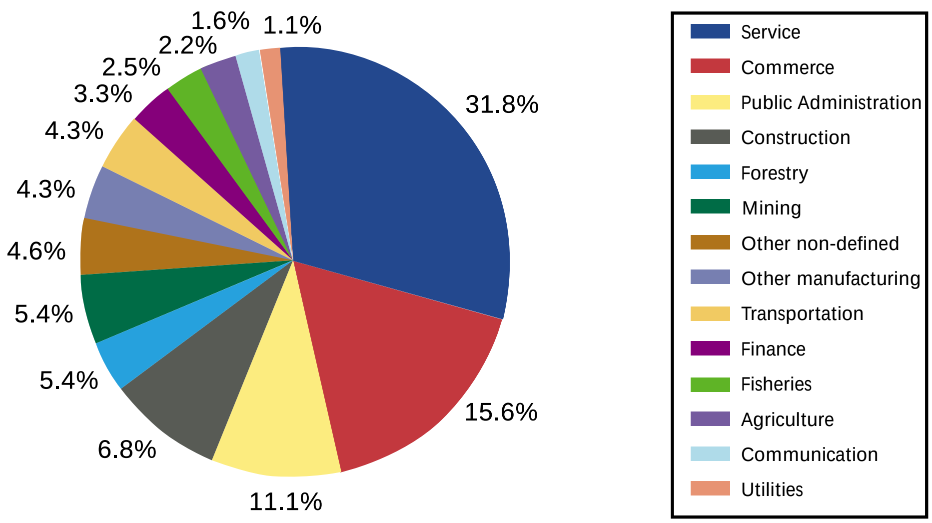


Figure 2: Labour composition in the Boreal Shield ecozone

Source: Manitoba Environment, 1997; Quaile, personal communication,1998.

2.2.3 Land use

Land use patterns in the Boreal Shield reflect the geographic distribution of resources found here as well as the evolution of its transportation systems. Its vast forests support such activities as logging, wood fibre and sawlog production, pulp and paper mills, and fibreboard production. Its wealth of minerals supports prospecting, mining, and smelting activities. Its plentiful waters support large-scale hydroelectric developments needed for southern urban and industrial centres, as well as wood and mineral processing within the ecozone. Its abundant wildlife and fish resources support subsistence, sport, and commercial harvesting activities, as well as a growing tourism industry (Ontario Ministry of Economic Development, Trade and Tourism, 1996).

Agriculture in the Boreal Shield ecozone is limited by the constraints imposed by a cool climate and poor, thin soils. Taking up only 9% of the total land area, most farming activities are restricted to the so-called “clay belt” area in south-central Ontario and Quebec. Limited agriculture occurs in scattered pockets throughout the ecozone where local climate and soils are favourable. Most farms are relatively small, producing livestock, dairy cattle, and hardy vegetables, fruits, and grain crops such as oats and barley. Wild rice, blueberries, cranberries, and peat are harvested from some wetland areas. Overall, agriculture is on the decline.

Commercial fisheries are locally important in Atlantic coastal regions of the Boreal Shield. However, since the early 1990s, fish populations have declined dramatically owing to intensive fishing, particularly around Newfoundland.

Transportation routes have been central to development of this large and remote part of Canada. Isolated road and rail networks link scattered resource towns to larger southern centres. The sporadic construction of new secondary roads continues to improve access to some regions. On the other hand, recent decreases in passenger rail, airline, and bus services to many smaller communities have had a reverse effect.

Like transportation corridors, the imprint of urbanized areas on this landscape is quite small – less than 350 km^2. Although much of the Boreal Shield ecozone remains in a relatively natural state, the reach of human activities extends far beyond the roadbed, railway tracks, or urban fringe.

3 Environmental Stresses from Within

3.1 Forestry

3.1.1 Forest resource use

The Boreal Shield ecozone, with 106 million hectares of timber-productive forestland, has close to half of Canada's total. On a per hectare basis, forest growth is not as vigorous as in many other parts of the country. But by its sheer size, this ecozone dominates the annual area harvested for Canada. This harvest supports 37 pulp and paper mills and numerous sawmills.

Most of the harvesting is carried out for pulp and paper production, although the fuelwood harvest within Newfoundland comprises approximately 25% of that province's total harvest. Quebec and Ontario contain the bulk of the timber forests of the Boreal Shield, including 40% of Canada's commercial forest, and account for 40% of the national allowable annual cut.

Approximately 400 000 ha of Boreal Shield forests are harvested each year. Although annual fluctuations in harvest levels reflect prevailing ups and downs in the economy, most indicators point to a net increase in wood harvested over the past few years. For example, the Compendium of Canadian Forestry Statistics (Canadian Council of Forest Ministers, 1995) shows that the net merchantable volume of softwood, most of which comes from the Boreal Shield, increased from 23.0 million cubic metres in 1990 to 29.0 million cubic metres in 1994. Over the same period, Ontario's softwood harvest increased from 19.3 million cubic metres to 20.8 million cubic metres. Saskatchewan showed a nearly twofold increase between 1990 and 1995, going from 2.8 million cubic metres to 4.9 million cubic metres.

Besides a net increase in forest harvesting, the 1990s have witnessed a dramatic northward expansion of forestry-related activities in the ecozone on various scales. These northward expansions have been facilitated by the consolidation of several small forestry companies and the opening and enlargement of several regional mills. At the same time, wood technology production has taken some major strides forward. New pulping techniques, oriented strand board processing, and wood chip production have encouraged the industry to harvest smaller trees and additional species such as poplar and birch that were formally considered uneconomical.

In Quebec, large-scale mills and new technology, plus a history of infrastructure subsidization (e.g., roads and mills), have allowed the forest industry to expand to the northern limits of the Boreal Shield ecozone. Quebec is currently in the final planning stages of allocating a major timber licence on a wildlife reserve northeast of Lake Mistassini, close to the extreme northern limit of the Boreal Shield ecozone. Forestry activities are also expected to soon expand into northern Saskatchewan, with increasing scarcities in world supplies and further northern infrastructure development (SERM, 1999).

Small-scale economic opportunism also contributes to increased harvesting pressures in northern portions of the ecozone. In northwestern Ontario, for example, commercial efficiency is being increased by granting licences to small operators with few or no other economic options. The need to enhance the income of hundreds of small operators in this situation is a key factor in continued forest fragmentation. Such socioeconomic conditions prevail throughout much of the northern Boreal Shield forest (Kronberg, personal communication, 1998).

3.1.2 Influence of harvesting and renewal practices on forest ecosystems

The rapid northward advance of forestry activities in the Boreal Shield raises several ecological concerns, because neither science nor forest management techniques have been able to keep pace with this expansion. Most of the science behind present forest management practices comes from research in southern areas of the ecozone, where ecosystems, growth rates, nutrient dynamics, etc. may vary considerably from those in northern portions of the Boreal Shield. The pattern of these harvest disturbances on the northern landscape has not been accurately mapped or quantified (SERM, 1999). Moreover, the long-term and cumulative impacts of intensified forestry on the fragile areas of the northern Boreal Shield are entirely unknown (Chambers, personal communication, 1998; Kronberg, personal communication, 1998).

Although many areas cut over by small northern operators are typically small, tree regeneration is often poor, as the operators do not have the capacity or the responsibility for replanting after harvest. As a result, these small harvest areas are often prone to soil erosion, especially on silt- and clay-dominated soils, because of the time lag between harvesting and revegetation (SERM, 1999).

Risks of soil modification in northern parts of the ecozone are heightened because of the dominance of boggy peatland soils. Because of their relatively high moisture content and weak structure, these soils are particularly sensitive to forestry activities that may cause compaction, puddling, remoulding, displacement, disturbance, and nutrient removal. McNabb (1992) observed that the use of low-ground-pressure machines and machines with wide tires does not necessarily reduce soil modifications in such terrain. This study concluded that forestry poses increased environmental risks when it occurs on wet northern soils. As forestry expands into the northern Boreal Shield, much of it is now occurring in expansive peatlands and spruce bogs with as yet undocumented impacts.

About 90% of all harvesting in this ecozone is carried out through clearcutting (Government of Canada, 1996). Most foresters argue that the poor quality and low volume of many of the mature stands make clearcutting the only economically viable choice for tree harvesting in the Boreal Shield forests. They maintain that this is the most ecologically sound system for even-aged boreal forest ecosystems and that it provides suitable conditions for regeneration in a cost-efficient manner. Clearcutting opponents suggest that the practice is not ecologically sustainable and can cause considerable loss of biodiversity and reduce soil and water quality (Government of Canada, 1996).

Although potential environmental impacts of clearcutting are well documented (e.g., DesGranges and Rondeau, 1992), a recent monitoring study of deforestation adjacent to three small (30 ha) Boreal Shield lakes northeast of Lake Superior showed some interesting results (Steedman and Morash, 1998). The experimental design consisted of five years of comprehensive pre-disturbance ecosystem monitoring, including climate, hydrology, physical and chemical limnology, and aquatic biota. Two years after clearcutting 70–80% of their catchments, the only notable impact shown by these lakes was weak evidence of nutrient enrichment. To date, they have not exhibited any measurable changes to stratification dynamics, oxygen depletion, or littoral fish populations.

Two clearcutting systems dominate forestry operations in the Boreal Shield: full-tree and tree-length. Under the full-tree harvest system (also called “whole-tree”), the cut tree, including limbs and foliage, is taken to roadside for delimbing. With the tree-length system, branches and foliage are removed at the original cutting site, and only the trunk is taken to roadside. This latter system removes less biomass and nutrients from the site. However, some argue that the dead material may impair regeneration. Ontario’s class assessment of the forest industry recommended site delimbing (tree-length technique) as a general policy. In contrast, many companies in Quebec routinely practise roadside delimbing. The relative impacts of both systems require further investigation, particularly since they have become enshrined in province-wide forestry policies (Quaile, personal communication, 1998).

Clearcutting and fire are the two most evident forces now altering the forests of the Boreal Shield. Many proponents of clearcutting suggest that this practice mimics the effects of wildfire. However, field research indicates that natural disturbances caused by fire are impossible to duplicate completely using commercial forestry practices. As well, fires do not leave roads, bridges, culverts, borrow pits, compacted landings, debris, etc. Most importantly, fires are not selective of older-age trees or particular tree species, as are most forestry practices in this ecozone (Chambers, personal communication, 1998). Recognizing that it is not possible to “mimic” all aspects of fire-caused changes, Ontario’s Ministry of Natural Resources has adopted the term “emulate natural disturbance,” promoting forestry practices that attempt to imitate natural disturbance wherever possible and practical (Cole, personal communication, 1998). Enhanced monitoring of forest fire effects could contribute to successful implementation of such policies.

Historically, the numerous pulp and paper mills of this ecozone have been major point sources of aquatic pollution by mercury, dioxins and furans, and other organochlorines (Rudd et al., 1983). Improved government regulations and technology have minimized these problems at most mills. For the most part, all mills are monitored and inspected on a regular basis. However, even with sophisticated effluent treatment systems, many pulp mills continue to release large quantities of dissolved organic matter such as tannins and other highly coloured humic substances. While these substances may not be acutely toxic, the long-term cumulative effects on Boreal Shield lakes and rivers are not well known.

According to Savidge (personal communication, 1998), the distribution and genetic diversity of Boreal Shield tree species are being severely altered by forestry activities. Genetic landscapes are being rearranged by extensive clearcutting and the planting of genetically altered trees. Many forest scientists are now raising concerns that "improved," fast-growing trees result in weaker wood and reduced resilience to environmental change. Further field research and monitoring will be required to fully validate these concerns and gauge their ecological and economic significance. Meanwhile, biotechnological researchers continue their quest for even faster-growing trees.

Socioeconomic impacts caused by forest harvesting in the Boreal Shield have been reported among the Moose River Cree. Extensive clearcutting has been linked to decreased trapping returns, destruction of traditional trails, significant noise pollution, and erosion of cultural values. Discharge from associated pulp and paper mills has contaminated the Cree's drinking water supplies and caused local declines in fish populations and harvest returns (EIP, 1997a,b).

3.1.3 Forestry management

In many parts of the Boreal Shield, monitoring the environmental effects of forestry and pulp and paper operations was formerly left almost entirely to the forest industry. There are also large differences in the extent to which monitoring is required by various provincial jurisdictions. Saskatchewan is leading the way to help correct this troublesome situation in which questions of accountability and conflict of interest often arise from the public (Chambers, personal communication, 1998). Saskatchewan Environment and Resource Management (SERM) is now implementing monitoring programs in partnership with industry and other interested organizations (Mclaughlan, personal communication, 1998).

Several jurisdictions within the Boreal Shield have recently introduced policies to help protect riparian zones and water bodies adjacent to forestry operations. To minimize siltation caused by logging, Newfoundland introduced strict buffer zones around streams and lakes in 1994. Special care is now paid to topography and soil conditions when building access roads to prevent soil degradation (Eaton et al., 1994). Newfoundland has also created special genetic reserves to protect remnant old-growth populations, many of which are found in riparian areas. For the past decade, Ontario has promoted the protection of riparian areas and fish spawning habitat with a policy that explicitly establishes a 30- to 90-m buffer zone around water bodies, depending on soil stability and slope (Cole, personal communication, 1998). Saskatchewan is currently developing improved standards and guidelines for the protection of riparian zones and associated fish and wildlife resources (SERM, 1999).

The impacts of pulp and paper mills in this ecozone were significantly reduced during the 1990s owing to a number of improvements in mill operations. These included putting a stop to log-driving activities, introducing secondary treatment of mill effluent, and switching over to more environmentally benign de-inking and bleaching processes. The first two improvements have been particularly helpful in decreasing biochemical oxygen demand (BOD) loadings in Boreal Shield rivers (EIP, 1997a). However, effects linger on from former practices, such as the clogging of rivers by thousands of logs and woody debris. Concerns persist about liver enzyme dysfunction in fish caused by mill effluents – even from those mills that no longer use chlorine bleaching agents (Munkittrick et al., 1994; Bezte et al., 1997). The continued presence of organochlorines such as polychlorinated biphenyls (PCBs) in aquatic systems has also been linked with liver enzyme dysfunction in fish. Recent research has identified highly toxic leachate from both hardwoods and softwoods that are stored near the water's edge.

With respect to Aboriginal issues raised by forestry activities, the framework of Criteria and Indicators of Sustainable Forest Management in Canada (Canadian Council of Forest Ministers, 1997), one of several policy initiatives designed to address the management and conservation of Canada's forest resources (see Box 1), includes indicators that promote Aboriginal participation in forest planning and management as well as related economic opportunities (McAfee, personal communication, 1998). There is also increasing recognition that traditional ecological knowledge, drawn from Aboriginals and other local residents, must play a more prominent role in forest planning within this ecozone (Welsh and Venier, 1996; Barsh, 1997; Lands for Life, 1998).

Canadian policy initiatives:

- National Forest Strategy 1998-2003 (Canadian Forest Service, 1998)
- Criteria and Indicators of Sustainable Forest Management in Canada (Canadian Council of Forest Ministers, 1997)
- Canadian Biodiversity Strategy (Environment Canada, 1995a)
- A Statement of Commitment to Complete Canada's Networks of Protected Areas (1992)
- A Wildlife Policy for Canada (Wildlife Ministers' Council of Canada, 1990)
- Canadian Species at Risk (Committee on the Status of Endangered Wildlife in Canada [COSEWIC]; updated annually)

International policy initiatives endorsed by Canada:

- Forest Stewardship Council Principles and Criteria (Forest Stewardship Council, 1995)
- Agreements arising from the 1992 Rio de Janeiro Earth Summit (UNCED, 1992):
  - Agreement on the Management, Conservation and Sustainable Development of all Types of Forests
  - Integrated Approach to the Planning and Management of Land Resources
  - Combating Deforestation

Box 1: Canadian and international policy initiatives relevant to forestry management

The National Forest Strategy (Canadian Forest Service, 1998), another policy initiative unveiled in the spring of 1998, provides a framework that will guide the policies and actions of the forest community over the course of the next few years. It outlines timber harvesting and silvicultural practices that must be followed to make the goal of sustainable forestry a reality. This strategy aims to reduce the loss of merchantable timber to fire, insect damage, and competing vegetation without disrupting natural ecosystem dynamics. There will be a need for on-the-ground monitoring to determine how effectively such well-intentioned objectives are being met.

To help address the many stresses caused by forestry in the Boreal Shield, innovative management approaches may be needed. For example, a new paradigm being considered for some portions of this ecozone is "mixedwood management" (MacDonald, 1995). Mixed-species forests comprise over half the total forests in areas such as northeastern Ontario, and timber harvest activities appear to be increasing this proportion (Hearnden et al., 1992). The mixedwood approach maintains that, for these areas, it is both biologically and economically better to manage natural regeneration of a variety of tree species than to attempt to convert all harvested areas to conifer plantations. The advantages of this approach must be balanced against the fact that successional processes following clearcutting may not retain preferred conifer species in their original proportions.

As popular as the term may be in theory, ecosystem-based forest management in practice is a major challenge that will require considerable flexibility, cooperation, and adaptiveness from the forest industry. Much-improved baseline information will be imperative. Choosing appropriate environmental indicators and monitoring programs to conserve forest biodiversity will be other top priorities. The Government of Quebec has established clear research and policy goals aimed at promoting the practice of ecosystem-based management in forests across the province (Gouvernement du Québec, 1996).

Several other recent policy initiatives hold promise for improved management and conservation of forest resources in the Boreal Shield ecozone. Many of these include provisions for setting aside representative natural areas, upgrading biological inventories, improving and sharing baseline data, enhancing biodiversity monitoring systems, and using traditional knowledge in the management of natural resources.

3.2 Mining

3.2.1 Mineral resource use

In the Boreal Shield ecozone, mining is concentrated in north-central Quebec and Ontario and in northern Saskatchewan and Manitoba (Figure 3; Government of Canada, 1996). The ecozone produces 75% of the total Canadian production of iron, copper, nickel, gold, and silver.

Northern Saskatchewan is the largest producer of uranium in the world. In 1997, the province's three operating mines, all located on the Boreal Shield, produced 14 200 t, accounting for 34% of world uranium production. Known uranium reserves in this province are sufficient for more than 30 years at the current rate of production (SERM, 1999). Three new uranium projects are under development at McClean Lake, McArthur River, and Cigar Lake, with a fourth, the Midwest property, expected to begin early in the next century. Other potential mineral resources in Saskatchewan's Boreal Shield include silica sand and building stone.

Figure 3: Mineral regions in the Boreal Shield ecozone, 1990

Source: National Atlas Information Service, Natural Resources Canada

3.2.2 Mining impacts

Metal smelters in the Boreal Shield are point sources of acid and heavy metal pollution that cause widespread aquatic contamination via atmospheric transport (Lockhart et al., 1993; Gunn, 1995; Rudd, 1995). Mercury and cadmium are released into the atmosphere through smelting and other industrial processes, then deposited across the landscape, including in Boreal Shield lakes. Once they enter the food chain, they accumulate in tissues of organisms and may reach toxic levels (Malley, 1993; Malley et al., 1996). Manitoba's Flin Flon smelter has been a chronic cause of environmental concerns and exceeds emission limits for an average of 150 hours per year (Gibson et al., 1997). Although eastern smelters have made significant acid emission reductions of over 75% over the past 20 years, Manitoba's reductions over the same period (Flin Flon and Thompson combined) have been only 24% (Table 2).

Sulphur dioxide emissions (kt)			
Smelter location	**1970**	**1992**	**1994**
Flin Flon, Manitoba	265	288	194
Thompson, Manitoba	485	267	194
Copper Cliff, Ontario	1 992	416[1]	162
Falconbridge, Ontario	342	54	54
Timmins, Ontario	N/A	4	2
Noranda, Quebec	1 619	170	156

N/A = no data available (smelter opened in 1972)

[1] Reduced by 30% in 1994.

Table 2: Trends in sulphur dioxide emissions for selected smelter locations

Source: Falconbridge Limited, 1992; Hudson Bay Mining and Smelting Co. Ltd., 1993; Noranda Minerals Inc., 1993; Manitoba Environment, 1995.

Ongoing mineral exploration tends to disturb more area than mining, primarily owing to the need to access large tracts of land to increase the chances of finding economic mineral deposits. For example, in Saskatchewan, exploration companies hold over 1 200 mineral leases or claims that cover more than 2.2 million hectares of the Boreal Shield ecozone (SERM, 1999). The traditional view is that impacts from road construction, line cutting, trenching, blasting, and exploratory drilling are temporary and localized. However, more information on such impacts is needed to confirm this view. Milling and processing require relatively smaller areas of land than exploration, but the mine site, tailings, and waste rock may have longer-term environmental impacts.

The primary impact of mines in the Boreal Shield is on aquatic biodiversity, caused by discharge of mine effluents into the water. The degree of impact on aquatic systems depends on the nature of the ore, its host rock, and the way that it is processed. Older mine sites and/or those with acid mine drainage typically create more significant impacts than newer sites. Mine effluents can contain high concentrations of heavy metals as well as cyanide, arsenic, or radioactive compounds. Effluent discharge also contributes to increased levels of suspended solids and may contain high levels of sulphide minerals, which, once oxidized, create sulphuric acid. Improper disposal of mine tailings and associated acid mine drainage has caused acute toxicity problems in localized areas (EIP, 1997a) and more widespread chronic effects downstream. Unless mine sites are properly rehabilitated, such impacts can continue for decades after a mine is abandoned. There are 6 000 abandoned mine sites in Ontario alone, only a fraction of which have undergone environmentally acceptable closures. Many of these are “orphaned” mines for which a property owner no longer exists. On the Boreal Shield of Saskatchewan, there is at least one orphaned uranium mine and several base and precious metal mines, all of which will remain a source of potentially serious water pollution until properly cleaned up.

3.2.3 Mine management

The mining industry, both through practices at operating mines as well as processes still occurring at closed or abandoned mine sites, continues to present a long-term strain on the Boreal Shield ecozone. The federal government's 1996 Assessment of the Aquatic Effects of Mining in Canada (AQUAMIN, 1996) identified several regulatory and policy gaps that currently hinder reduction of impacts from mining (see Box 2). AQUAMIN concluded that mining effluents continue to cause effects in aquatic ecosystems and recommended that a national cooperative environmental protection framework be developed for the mining sector. The framework would include: revised Metal Mining Liquid Effluent Regulations (MMLER); site-specific requirements, as needed, to protect local receiving environments; and environmental effects monitoring, which will provide information on the effectiveness of the other two components. The federal government is working with stakeholders to implement the AQUAMIN recommendations and to develop the environmental protection framework. A revised MMLER is expected to come into force in 2001 and will include a requirement for mines to conduct environmental effects monitoring at every mine in Canada.

The Assessment of the Aquatic Effects of Mining in Canada (AQUAMIN) identified several regulatory and policy gaps that currently hinder reduction of impacts from mining (AQUAMIN, 1996):

- The Metal Mining Liquid Effluent Regulations (MMLER) and other elements of the national environmental protection framework should be strengthened.
- Cyanide should be included in the MMLER.
- Additional metals, elements, and compounds, such as aluminum, cadmium, calcium, fluoride, iron, mercury, molybdenum, nitrogen compounds, and thiosalts, should be monitored. Mercury and cadmium must be reported on a regular basis, especially if they exceed a specific level.
- A monitoring program on environmental effects should be nationally consistent, site specific, and nonprescriptive. It must incorporate two phases: site characterization (full description of the operation) and field investigation and monitoring. Information obtained from both phases must be scientifically defensible.
- Acceptable and unacceptable effects of mining discharge should be reviewed periodically to take into account developments in environmental sciences and social values.
- Information on the biological availability of metals, their bioaccumulation, and their ecological effects is required for environmental regulations to be implemented.

Box 2: Regulatory and policy gaps hindering reduction of impacts from mining

Improved mine management policies must be supported by applied scientific research and monitoring. One example of such work comes from Quebec's Abitibi Lakes region, where scientists are studying the toxicological effects of metal contamination on native freshwater clams and other bivalves, long considered to be useful indicators of water pollution (Pinel-Alloul, personal communication, 1998). New approaches have been used to link metal concentrations in these species to deleterious effects at different levels of the organism (i.e., cellular, individual, population). This research is being jointly sponsored by an innovative partnership consisting of Noranda Mines, INRS-Eau at the University of Montreal, CANMET (Canada Centre for Mineral and Energy Technology) of Natural Resources Canada, and the Canadian Wildlife Service of Environment Canada.

3.3 Hydroelectricity

3.3.1 Hydroelectric resource use

Canada is the largest producer of hydroelectricity in the world, accounting for 62 722 MW of installed capacity and approximately 15% of the world's total production. Thirty-nine per cent of

Canada's hydroelectric capacity is located on rivers arising in or flowing through the Boreal Shield. Of Canada's 662 large dams, 279, or 42%, are located here (Government of Canada, 1996).

Major projects on the Boreal Shield include the Churchill Falls project (1971) in Labrador, the Lake Winnipeg Regulation and Churchill–Nelson Diversion (1976) in Manitoba, and the Island Falls Hydroelectric Station (1930) in Saskatchewan. The Churchill and Nelson river basin project is the largest of its kind in the Boreal Shield, extending across the northern half of Saskatchewan and Manitoba and generating 3 700 MW of power. Newfoundland has no hydroelectric projects of this scale but has over 400 small dams associated with hydroelectric development (Eaton et al., 1994).

Diversion projects consolidate water from two or more sources into one trunk line to increase the security and quantity of flow for hydroelectricity. Canada diverts more water than any other country in the world. Water diversions in the Boreal Shield account for 59% of the flow volume of Canada's major inter-basin diversions. Sixty per cent of this water (2 612 m^3/s) flows through the Boreal Shield (Day and Quinn, 1992). Unlike the United States, where water diversions are generally for the purposes of agricultural irrigation and water supply, water diversions in the Boreal Shield are intended to facilitate electricity generation.

Eighty-five per cent of the drainage basins contained in whole or in part in the Boreal Shield have been altered by hydroelectric development in one way or another. Seventy-seven per cent of the drainage areas contain major dams, 25% have major reservoirs, and 33% have rivers whose flow has been either augmented or diminished by water transfers (Government of Canada, 1996).

Although the main thrust of hydroelectric development in this ecozone is likely over, the prospect of revenue generation and foreign exchange earnings could lead to the development of hydroelectric resources that are of marginal value locally but that are attractive to potential customers in other provinces or the United States. Several potential dams in northwestern Ontario and northern Saskatchewan are currently on hold. In Manitoba, a further 1 100 MW may be added to the Churchill–Nelson system, pending the possible development of the Conawapa Generating Station (Environment Canada and Fisheries and Oceans Canada, 1992a). Meanwhile, Newfoundland is actively exploring the feasibility of additional small-scale run-of-the-river plants to meet local needs.

3.3.2 Impacts from hydroelectric development

Besides the obvious loss of terrestrial habitats through dam construction and reservoir impoundment, other land-based impacts of hydroelectric projects relate to soil erosion and transmission corridors. Shoreline erosion and scouring of river channels are common results of hydroelectric developments in the Boreal Shield. The amount of erosion and soil loss varies widely with soil type, the relative area flooded, and the range of fluctuations in water levels (Environment Canada and Fisheries and Oceans Canada, 1992a). For example, in the sensitive discontinuous permafrost terrain of northern Manitoba, significant flooding of South Indian Lake and the Rat and Burntwood rivers caused extensive shoreline erosion and thermokarst slumping (see photos).

Transmission lines from hydroelectric installations travel inside clearcut corridors through forests and wetlands. Their presence can reduce the wilderness character of remote regions, especially when they form long wide swaths through otherwise undisturbed terrain. Increased hunting access provided by transmission corridors may be linked to local depletions of wildlife. In addition, many corridors are treated with chemical herbicides, which may have localized impacts on food chains.

Collapsing shoreline at South Indian Lake caused by melting permafrost

Aquatic ecosystems are affected by hydroelectric development in several ways. For example, increases in water volume caused by the flooding of rivers and the creation of reservoirs often disperse existing species, resulting in altered competitive and predatory regimes. Lake trout and brook trout may abandon reservoir impoundments in part because of the rise in water levels, which adversely affects their spawning beds (Deslandes et al., 1994). Diversion of rivers can result in high levels of turbidity owing to increased flow rates and bank erosion. For instance, the diversion of the Churchill River augmented the flow of the Nelson River by about 37% (Wood, personal communication, 1997). High sediment loads resulted in increased turbidity of up to threefold, causing a significant decline in the health and abundance of downstream whitefish and pike populations (Bodaly et al., 1984; Environment Canada and Fisheries and Oceans Canada, 1992b).

Flooded shoreline at South Indian Lake

The flooding of organic matter by reservoirs results in the release of naturally occurring mercury, which may have toxic effects on both aquatic and terrestrial food chains (Bodaly et al., 1984; Rudd, 1995; St. Louis et al., 1995). Inorganic mercury, from either natural sources or aerial deposition, is combined with organic matter from the flooded vegetation and converted to toxic methylmercury by microbial activity. Predatory fish are particularly prone to methylmercury accumulation in their tissues.

Extensive flooding of land also causes the release of significant quantities of carbon dioxide and methane, two notorious contributors to climate warming. Studies from northwestern Ontario's Experimental Lakes Area (ELA) have demonstrated that decomposition of flooded wetland vegetation causes a dramatic release of these two gases to the atmosphere (Kelly et al., 1997). After flooding, these wetlands switched from being carbon sinks, taking in carbon at a rate of 6.6 g/m^2 per year, to carbon sources, releasing 130 g/m^2 per year. Future hydroelectric development projects in the Boreal Shield are more likely to be on wetlands, since most canyon-like areas are already developed. Consequently, carbon sources from this ecozone could significantly increase.

As a result of insufficient monitoring, many of these impacts are as yet poorly understood, particularly the dynamics of mercury release following reservoir construction. A comparison of hydroelectric reservoirs exhibiting high levels of mercury with those with lower levels indicates that certain areas of the Boreal Shield appear predisposed to mercury problems. Reservoirs in northern Manitoba, northern Ontario, and Labrador generally show higher mercury levels than those in Nova Scotia, New Brunswick, southern Manitoba, and British Columbia (Government of Canada, 1996).

The negative impacts of hydroelectric projects have particularly affected the ecozone's native people because of their traditional pattern of settling, hunting, and travelling along the shores of rivers and lakes (Environment Canada and Fisheries and Oceans Canada, 1992b). Unnatural water level fluctuations associated with these projects interfere with their subsistence fishing and hunting activities. Local declines in traditionally harvested fish and waterfowl populations have been directly linked to these fluctuations (EIP, 1997a). High water levels decrease shoreline trapping success. Traps become submerged in water, or, in some cases, native trappers return to find their traps far from shore as water levels decline. Like hydroelectric transmission corridors, the construction of access roads associated with dam developments has opened up areas previously inaccessible to nonnatives, leading to more competition for wildlife from sport hunters and anglers. Over the past 15 years, abrupt declines in moose and other large game animals have been linked to increased access associated with hydroelectric projects (EIP, 1997a). Among Quebec's Cree Nation of Eeyou Istchee, the situation has become so serious that the treaty-holding Cree are considering plans to invoke preferential rights on moose and ban sport hunting in an attempt to protect their traditional access to moose (Quaile, personal communication, 1998).

Many native people may have significantly decreased their fish consumption because of an actual or perceived increase in mercury contamination associated with hydroelectric development. This dietary change may result in an increase in obesity and diabetes in native populations as fish is replaced with less nutritious food (EIP, 1997a). Traditional native travel routes are also affected by hydroelectric activities. Routes can be flooded or dissected, making travel impossible. Navigation can also become hazardous, owing to tree stumps and logs not being removed from flooded areas. During winter, changing water levels have caused random ice thinning, preventing snowmobile travel over some traditional routes (EIP, 1997b).

3.3.3 Hydroelectric management

Mitigation of socioeconomic impacts on Aboriginal people as a result of hydroelectric projects is an ongoing issue in the Boreal Shield ecozone. For example, Saskatchewan Power continues to negotiate with both the Peter Ballantyne Cree and the community of Sandy Bay over impacts linked to the Island Falls Hydroelectric Station. To date, no settlements have been reached (SERM, 1999).

Many of the large-scale hydroelectric projects in the Boreal Shield may be approaching the end of their productive lives. Half the dams are at least 40 years old, and two-thirds of those in Ontario are over 50 years old. An increasing number of facilities will soon require major overhauls. Power upgrades to some of the ecozone's older hydroelectric plants may be accompanied by improved technology that minimizes environmental impacts. For example, hydroelectric turbines at the Island Falls plant in Saskatchewan were recently converted to greaseless bushings in areas of direct contact with water to prevent grease from entering the Churchill River (SERM, 1999). However, because of their age, hydroelectric corporations rarely, if ever, conduct environmental monitoring studies on existing dams. The long-term maintenance and reclamation of aging dams are emerging environmental concerns that have yet to receive significant scientific or policy attention from provincial governments.

Many environmental questions surround the history of large-scale hydroelectric projects in the Boreal Shield. Until all provincial hydroelectric utilities and governments give greater priority to ecosystem monitoring, hindsight assessments, and baseline research, many of these questions will go unanswered, and their potential value to future projects, both here and in other regions, may be lost.

3.4 Additional Land Uses

3.4.1 Peatland development

Climatic and physical conditions across much of the Boreal Shield ecozone are conducive to the accumulation of peat – partially decomposed mosses and other plant material associated with acidic, waterlogged soils. Vast areas of this ecozone are characterized by marshes, bogs, fens, swamps, and other muskeg terrain, all of which is underlain largely by peat. The rate of accumulation of carbon can be as much as 1–2 mm per year on some peatland sites, with an estimated annual accumulation of 14 million tonnes nationally (Tarnocai, personal communication, 1998).

In addition to carbon storage issues, the disturbance of wetlands raises many other ecological concerns, such as protection of wildlife habitat and rare or unusual plant species. Such issues are gaining public attention across the ecozone as these areas come under increasing pressure from various kinds of land use.

Hydroelectric projects have been the primary cause of wetland alteration or destruction in the Boreal Shield ecozone. Over the past 40 years, 900 000 ha of Boreal Shield peatlands were lost to flooding for hydroelectric reservoirs, with additional impacts to downstream coastal and estuarine wetlands. Virtually all of these changes occurred in the Boreal Shield ecozone. Current reservoir proposals could affect another one million hectares of wetlands by the year 2010.

Peatland forestry each year accounts for an estimated 18.4 million hectares of land, much of which is logged in the Boreal Shield ecozone (Dahl and Zoltai, 1996). The value of forest products derived from such peatlands may exceed $500 million annually (Rubec et al., 1988). Over the past 20 years, about 25 000 ha of peatlands have been drained to enhance tree growth and potential forestry operations. Most of these activities now occur in experimental or demonstration project areas. Pilot peatland forestry developments in Alberta, northern Ontario, eastern Quebec, and Newfoundland are being used to evaluate peatland drainage as a forest management tool. Such drainage is not yet common practice in this ecozone. However, several million hectares of forested peatlands are already harvested each year, often with little or no monitoring of impacts on wildlife, forest regeneration, or hydrology (Chambers, personal communication, 1998).

The harvesting of peat supplies is an expanding horticultural industry in North America. About 16 000 ha are used for horticultural peat or peat moss products (Keys, 1992). The annual value of peat products sent to market exceeds $200 million. In 1997, there were approximately 70 operations in Canada that produced horticultural peat. Major operations are located in southern and southeastern portions of the Boreal Shield ecozone, particularly in Quebec and Newfoundland. The Canadian peat industry is working closely with federal and provincial government agencies and university researchers to support restoration of peatlands on sites used for horticultural peat harvesting. The number of sites involved is quite small, and there is currently no threat to Boreal Shield peatland resources.

The use of peat as a fuel source is virtually nonexistent in Canada. However, peat power stations remain under active consideration, notably in Newfoundland. If such plans were implemented, they would require the consumption of large volumes of peat at unparalleled rates. Energy use of peat could contribute to problems associated with increased atmospheric carbon and particulate air pollution.

As peatlands come under increasing pressure from various land uses, there is a growing public call for more concerted attention and coordinated management of Boreal Shield wetlands (Chambers, personal communication, 1998). To help address such concerns, the Federal Policy on Wetland Conservation was formally adopted by the Federal Cabinet in December 1991. In 1996, this Policy was enhanced with Guidelines for Federal Land Managers. The federal policy has been complemented by provincial wetland policies in Alberta, Saskatchewan, Manitoba, and Ontario.

3.4.2 Cottage development

Over the past 30 years, construction of thousands of lakeshore cottages on Boreal Shield lakes and demand for more building lots on Crown land created significant public concerns about eutrophication of recreational lakes. This issue has been particularly acute in Ontario, where sewage disposal from lakeshore cottage developments remains a major concern.

Another common issue is the creation of “clean” shorelines by cottage owners who remove rooted macrophytes or “weeds” that tend to foul boat propellers and impede swimmers. These plant communities often provide critical rearing or feeding habitat for many invertebrates and fish. Removal of shoreline vegetation can result in local macrophyte population declines and disruptions to aquatic food chains. A shoreline monitoring study from the ELA in northwestern Ontario is evaluating the impacts of removing 50% of the macrophyte biomass on northern pike. Two years into the study, populations of northern pike and several prey species, such as yellow perch and pumpkinseed, have declined considerably (Mills, personal communication, 1997). More studies are needed to better understand the full environmental impacts of recreational development and tourism in the Boreal Shield.

In 1996, revisions to Ontario’s *Planning Act* transferred greater authority for site-specific environmental approvals from provincial to municipal resource planners. With this transfer came the need for clear guidelines to help rural communities manage shoreline development in Ontario's Shield lakes. The Ministry of Environment's proposed Lakeshore Capacity Guidelines provide for improved technical criteria to assess lakeshore capacities as well as revised water quality objectives to better control pollution from cottage developments.

3.4.3 Protected areas

Although the Boreal Shield is the largest of Canada's 15 terrestrial ecozones, it has one of the lowest proportions of land – 3% – dedicated to protected areas in which all forms of industrial activity are prohibited (see Figure 4). Approximately 5% of the ecozone includes additional protected areas where forestry, mining, and other activities may be permitted.

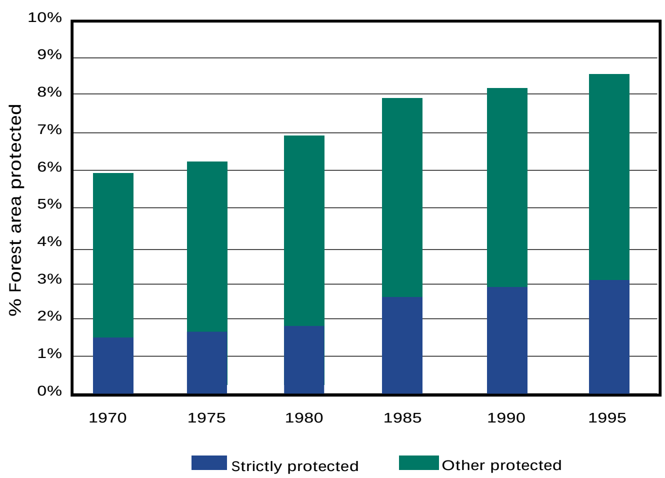


Figure 4: Protected forest area in the Boreal Shield ecozone, 1970–1995

Source: Environment Canada, 1997.

In an ecozone so large and subject to so many environmental stresses, the small percentage of strictly protected land is far from adequate to protect representative areas, provide ecological benchmarks, preserve areas of unique biological value, and ensure wilderness access to future generations (Kronberg, personal communication, 1998). The need to establish protected natural corridors for habitat and headwater conservation is a special concern in areas of the Boreal Shield subject to extensive forestry activities (Chambers, personal communication, 1998; Mclaughlan, personal communication, 1998).

To promote a broader base of public involvement in protected areas planning, both Ontario and Saskatchewan have adopted land allocation programs that include the formation of local and regional advisory groups to assist in the selection and management of parks. Ontario's Lands for Life program has been described as the most extensive and comprehensive public dialogue about land use planning in Ontario's history (Lands for Life, 1998). In the summer of 1997, this innovative program established three regionally based, multisectoral roundtables, two of which focused exclusively on Boreal Shield areas. Mandated to advise on the preparation of a regional land use strategy, each roundtable provided specific advice on the designation of lands for parks and protected areas as well as other land uses, such as tourism and forestry. The final report of the roundtables, completed in October 1998, articulates numerous recommendations to help the Ontario government fulfil its commitment to complete its system of parks and protected areas.

In Saskatchewan, local park advisory groups have been established, such as the one for Lac La Ronge Provincial Park on the Boreal Shield (SERM, 1997). As part of the Integrated Forest Land Use Management Planning Process now under way for Saskatchewan's Amisk-Atik region, community and regional advisory boards have been established to make land use recommendations, including the protection of special lands and waters (SERM, 1999).

While the need to complete protected area networks in this ecozone is widely recognized (Canadian Council of Forest Ministers, 1992), resource development pressures are slowing the achievement of this goal. For example, in spite of the impressive strides forward made by Ontario's Lands for Life program, forestry and mining interests continue to seek greater access to existing provincial parks (McAndrew, 1998). Integrating an expanded protected area network with environmentally progressive land management practices is seen by many as the key to conserving biodiversity on an ecozone-wide scale (Booth et al., 1993; Thompson and Welsh, 1993; Gauthier et al., 1996; Martin, 1996).

4 Environmental Stresses from Outside

The primary sources for many stresses affecting the Boreal Shield ecozone lie far beyond its boundaries, sometimes in other continents. These include climate change, acid precipitation, increased ultraviolet radiation, and long-range transport of atmospheric pollutants. Despite the remoteness of their source, these stresses could be devastating to the ecological integrity of the Boreal Shield. Ecologist David Schindler has been closely monitoring ecological changes to Boreal Shield systems for almost 30 years. He concludes that "when the combined effects of climate warming, acid deposition, stratospheric ozone depletion and other human activities are considered, the boreal landscape may be one of the global ecoregions that changes the most in the next few decades. Certainly, our descendants will know a much different boreal landscape than we have today" (Schindler, 1998).

The full magnitude and significance of regional and global stresses on this ecozone are only now dawning on both scientists and resource managers, thanks to long-term research and monitoring studies. Continued support for such studies is absolutely essential to help build the strong science base required to better understand these grave issues and devise appropriate management responses.

4.1 Climate Change

Over the relatively short span of two centuries, human activities have raised the level of atmospheric carbon dioxide by 30% through the burning of carbon-based fuels and disturbance of the earth's forests and peatlands that serve as giant reservoirs of stored carbon. More carbon injected into the atmosphere means more absorption of outgoing infrared energy. More energy absorption has already resulted in measurable increases in average global temperatures. Significant global warming and other climatic changes are forecast to continue at least up to the middle of the next century (Stewart, 1996).

Several atmospheric models suggest that the fastest, most pronounced global warming will likely occur in northern latitudes and that of all the world's major ecosystems, boreal forests and wetlands may be the most vulnerable (Woodwell et al., 1995). Many distinctive characteristics of this ecosystem are closely tied to climate, including plant productivity, carbon storage, insects, hydrology, and fish habitat. Environmental monitoring studies from across the Boreal Shield ecozone suggest that, in response to ongoing climate changes, many of these indicators are in turn changing in several dramatic ways. This complex mix of changes may cause severe malfunctioning of Boreal Shield communities and ecosystems in the future (Schindler, 1998).

Myneni et al. (1997) reported on satellite data from the 1981–1991 period showing increased plant productivity between 45 and 70°N latitude for areas where a net increase in spring temperatures was recorded. This study used a vegetation index that measures changes in absorption of photosynthetically active radiation. The greatest increase was observed in northwestern boreal regions, including a large portion of the Boreal Shield. These changes lagged behind recorded air temperature increases by about three years. The study concluded that small increases in temperature may give rise to large increases in biological activity, particularly in rates of plant growth and litter decomposition.

Changes in lakes and rivers in the Boreal Shield have been recorded in response to changes in climate. Ice studies from Boreal Shield lakes in northwestern Ontario observed a shift towards shorter ice cover periods through much of the 1970s and 1980s, followed by large year-to-year variability (Figure 5) (Dillon, personal communication, 1997; Shearer, personal communication, 1998). Schindler et al. (1990) observed the effects of climate warming in Ontario's ELA from 1970 to 1990. Over this 20-year period, annual air temperature increased by 1.6°C, precipitation decreased by about 40%, evapotranspiration increased by nearly 50%, recurrent forest fires removed significant organic matter from the soil, and wind velocities increased, possibly due to denudation of the landscape by intense fires. Among the many changes observed by Schindler and others (Snucins and Gunn, 1995; Dillon and Molot, 1997) in lakes and rivers of the Boreal Shield are:

- Decreased stream flow (Figure 6), resulting in decreased transportation of chemicals such as dissolved organic carbon (DOC) and phosphorus, important elements in food webs, to lakes from catchments. One study observed declines in total phosphorus concentrations by up to 40% between 1978 and 1993 (Dillon and Molot, 1997);
- Decreased phytoplankton abundance in lakes with lowered phosphorus concentration;
- Increased transparency – caused mainly by reduced DOC – resulting in deeper penetration of UV-B radiation;
- Increased use of thermal refuges such as groundwater outflows by lake trout and other cold-adapted fish;
- Deeper thermoclines, reducing habitat for cold-adapted invertebrates and fish;
- Increased accumulation of acid deposition in snow during the winter and decreased pH during the spring thaw; and
- Reacidification of streams owing to low water levels in catchment areas, which facilitated the oxidation of sulphur, producing sulphate.

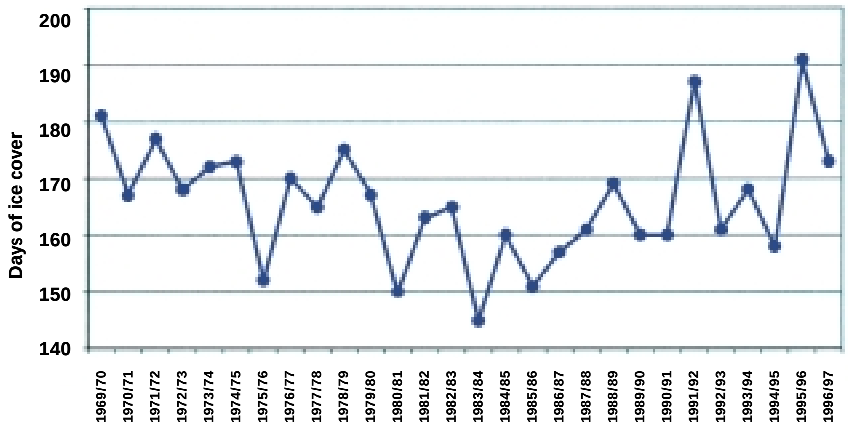


Figure 5: Annual duration of ice cover, Lake 239 of Ontario's Experimental Lakes Area, 1969/70–1996/97

Source: Shearer, personal communication, 1998.

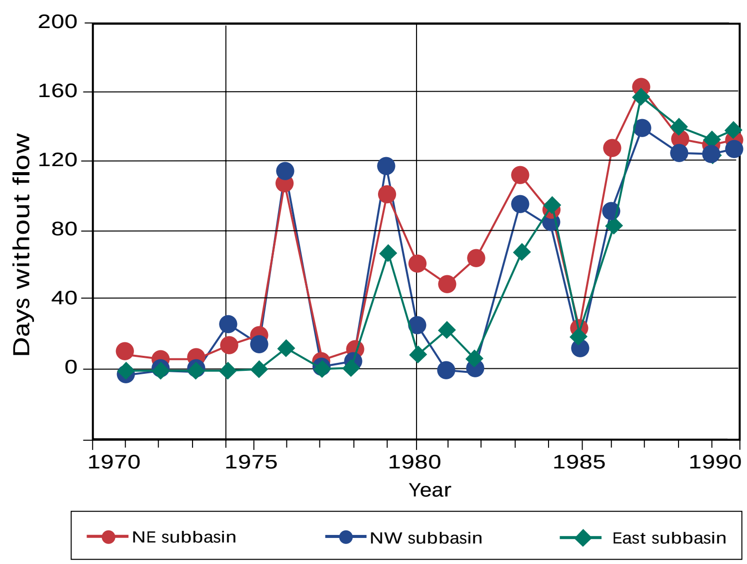


Figure 6: Stream flow decrease in northwestern Ontario's Experimental Lakes Area

Source: Schindler, 1998.

Together, these results suggest that profound alterations are occurring in many lakes and rivers in the Boreal Shield in response to changes in climate. The potential ecological and economic significance of these changes is still largely unknown but is under active investigation by several research groups (Schindler, 1998).

Fleming and Candau (1998) suggest that climate change is affecting not only aquatic systems but also the life cycle, behaviour, and range of many boreal insect species. Several other studies cite numerous examples of past and present insect outbreaks associated with warmer temperatures, often resulting in changes to tree species composition (Jardon et al., 1994; Daniels and Myers, 1995). Fleming and Volney (1995) observed that, over the past 25 years, spruce budworm have adapted to a net warming trend by advancing their flight periods by an average of 3–7 days.

The range of most boreal insects is controlled by low threshold temperatures. For instance, the balsam woolly adelgid does not survive below -34°C. Shaw (1997) suggested that current climate trends may remove this climatic control in some areas, resulting in longer, more widespread outbreaks of these insects.

A vital question is, how will future climate change affect carbon storage and cycling in forests of the Boreal Shield? The carbon budget of the Boreal Shield forests is not in equilibrium but changes from year to year, depending on productivity and disturbances such as fire, insects, diseases, and forestry practices. Moreover, the amount of carbon contained in the forest is strongly influenced by the age distribution of the forests. Hence, timing and rates of disturbances are important in determining whether Boreal Shield forests are sinks for or sources of atmospheric carbon.

Having studied the many complex factors influencing the Boreal Shield carbon cycle, Stewart et al. (1997) suggested that, even in the absence of climate change, the recent 20-year period of high disturbances in the boreal forest resulted in a net loss of carbon from the forest to the atmosphere. Factoring in current climate change scenarios, these authors predicted that this trend will continue over the next century, with forest regrowth unable to catch up to widespread natural and human-caused disturbances.

How to respond to the effects of climate change in the Boreal Shield ecozone is the question that forest managers in particular must ask themselves. Deciding what changes need to be made to forest management practices will require close monitoring of forests to determine what climate change effects are taking place and if thresholds for adjusting forestry practices have been reached. Only enhanced monitoring of carbon dynamics, adequate funding, and strong government and corporate support will make a positive difference in the long run.

4.2 Acid Precipitation

Acid precipitation, caused by human emissions of sulphur and nitrogen oxides to the atmosphere, has caused considerable stress to ecosystems throughout eastern North America. Thousands of fish populations and perhaps millions of invertebrate populations from Canada's boreal region alone have been lost as a result of acid precipitation (Schindler, 1998). The poorly buffered lakes of the eastern half of the Boreal Shield ecozone are particularly sensitive to acidification (Minns et al., 1990).

Chemical imbalances triggered by acid precipitation can have devastating impacts on sensitive lakes of this ecozone. As lake pH decreases below 5.5, populations of several aquatic species may start to decline or disappear, significantly altering aquatic food webs (Figure 7). By pH 5.0, most Boreal Shield fish species cease reproduction. At lower pH values, the lake biota becomes dominated by a few acid-tolerant algal species, bacteria, and insects. Some of these algal species (e.g., the filamentous green alga *Zygogonium* sp.) can foul beaches and other nearshore habitats, reducing recreational values and further altering natural species assemblages.

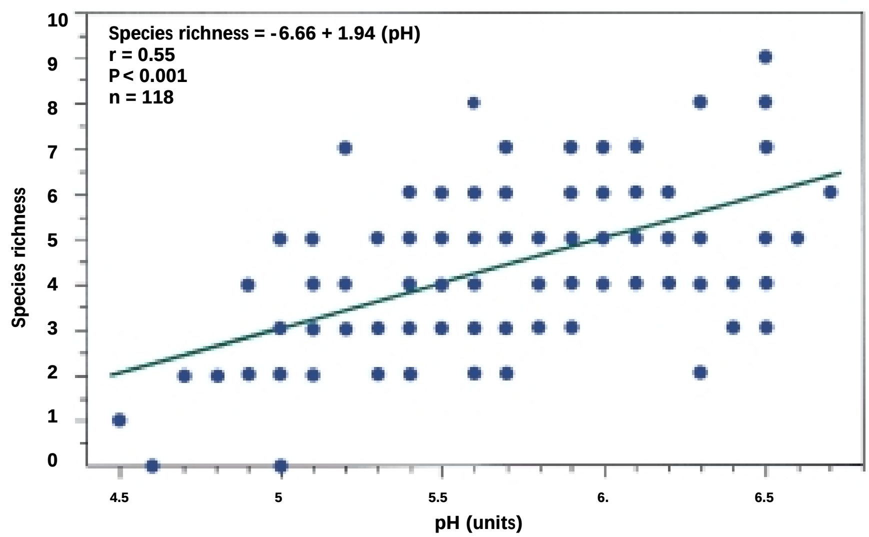


Figure 7: Relationship between the number of fish species and pH in 118 lakes from the Outaouais and Abitibi regions of Quebec

Source: Jeffries, 1997.

Recent aquatic studies on Boreal Shield lakes indicate that increased acidity (i.e., lowered pH) may contribute to increased mercury contamination in some boreal fish species (Scheuhammer and Blancher, 1994; McNicol et al., 1997). Besides limiting human consumption of fish, elevated mercury levels can impair reproduction in fish-eating birds, particularly the common loon, a problem estimated to affect fish-eating birds in up to 30% of Ontario's acid-sensitive lakes.

Low pH in lakes is linked not only to mercury contamination but also to high concentrations of cadmium and lead in fish (Scheuhammer, 1996). Acidification can also cause loss of DOC in surface waters (Figure 8). Reductions in DOC concentrations of up to 95% have been observed in acidified lakes, resulting in greatly increased penetration of solar radiation and pronounced thermal restructuring (Schindler, 1998). Such changes can have far-reaching impacts because of DOC's key role in the healthy functioning of Boreal Shield aquatic ecosystems – catalyzing microbial food chains, attenuating photosynthetically active sunlight, limiting harmful UV-B rays, and contributing to a number of important photochemical reactions.

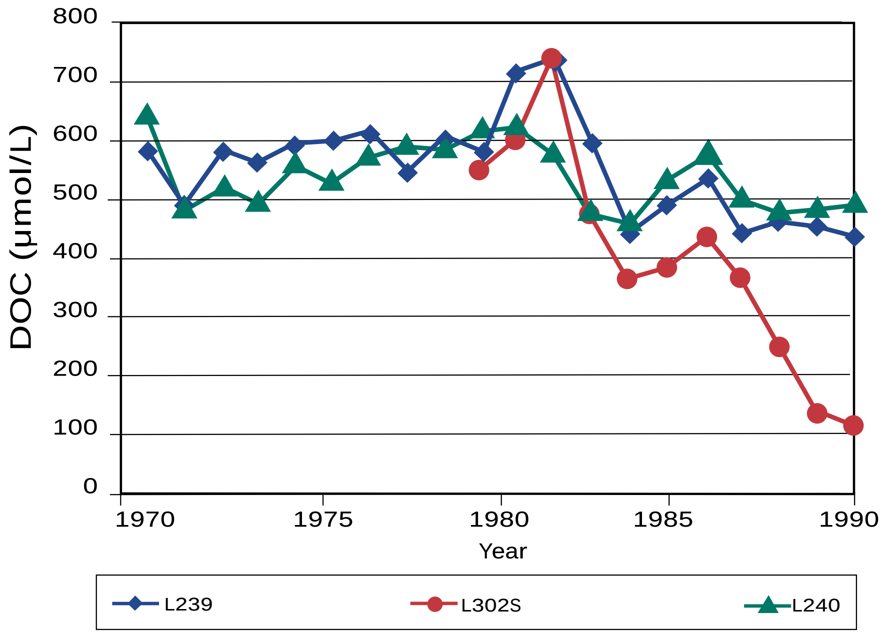


Figure 8: Mean annual dissolved organic carbon (DOC) concentration over time in three lakes at the Experimental Lakes Area

Source: Schindler, 1998.

On land, the role of acid deposition in contributing to boreal forest declines has been widely studied (Gagnon et al., 1994; McLaughlin et al., 1996; Acidifying Emissions Task Group, 1997; Hall et al., 1997). Some well-documented effects linked to acid deposition include:

- Damage to the tree's protective leaf or needle cuticle;
- Decreased net photosynthesis, nutrient uptake, and volume increments in mature red spruce trees;
- Impaired germination of paper birch and sugar maples;
- Reduced frost hardiness in leaves and needles;
- Acute tip dieback in sugar maples;
- Increased vulnerability to climatic perturbations; and
- Depletion in forest soil nutrients.

These impacts of acid deposition are extremely significant to the ecological and economic health of the Boreal Shield ecozone, since, acting in concert or alone, they could result in a much reduced productivity and vigour in the boreal forest over the long term. Moreover, the impacts of acid precipitation reduce the forest's overall ability to cope with climate warming, drought, insect outbreaks, disease, increased ultraviolet radiation, and other stressors. Widespread forest declines, growth reductions, and degraded soils have already been documented in southern regions of the Boreal Shield (Jeffries, 1995; Arp et al., 1996; Duchesne and Ouimet, 1996; Hopkin and Drummond, 1996; Houle et al., 1997; Watmough and Hutchinson, 1998).

Dendrochronology (tree ring) studies have been used to assess the long-term impact of acid deposition on hardwood forests of the Boreal Shield. Ryan et al. (1994) discovered pronounced growth declines beginning around 1960 in areas with acid-sensitive soils. In the Boreal Shield, the most severely affected regions were in northern Ontario (Hall et al., 1997). Similar dendrochronology studies are lacking for the ecozone's vast softwood forests of spruce and pine.

Continued forest monitoring is essential in order to assess long-term changes in forest ecosystem responses to acid deposition. The complexity of processes (soil fertility, forest growth and dynamics) necessitates continuing and, in some cases, such as dendrochronology, expanding research in these areas.

The practical and applied value of multiple, long-term monitoring sites is illustrated by their role in helping to determine appropriate threshold amounts for acid deposition. In the 1980s, a research group established under the 1984 Canada–U.S. agreement on acid rain drew heavily on field data from monitoring sites with long-term data sets on acid deposition. Using various environmental indicators, acid-sensitive sites receiving more than 20 kg wet sulphate/ha per year reported significant acidification damage. Thus, the 20 kg/ha per year deposition target was established as a general protection guideline. While this key threshold value was supported by mathematical models, it could only be defended against strong opposition to sulphur emission controls by comparing results from a number of on-the-ground sites. In this case, 15 sites were used, many of which were long-established EMAN stations in the Boreal Shield. These data continue to be used to upgrade deposition threshold values and advise decision-makers on the need for improved emission controls. For instance, Quebec recently announced its intention to lower sulphur dioxide emission limits (Fenech, personal communication, 1998).

Since 1980, emission controls have reduced atmospheric sulphur dioxide levels in Canada's seven eastern provinces by 53%, which is 13% more than the agreed-upon level (Environment Canada, 1996a). In the Boreal Shield, further reductions are likely once the United States completes Phase II of the *Clean Air Act* Amendment in 2010.

Wet sulphate deposition has diminished in the past 15 years. The area in Canada receiving more than the target load of 20 kg/ha per year decreased by 46% from the early 1980s to the early 1990s (Figure 9). Deposition changes resulting from pre-1995 emission reductions in the United States are not yet available. However, model predictions indicate that by 2010, when all of the provisions relating to the U.S. Acid Rain Program are in place, virtually all of Canada will receive less than 20 kg/ha per year.

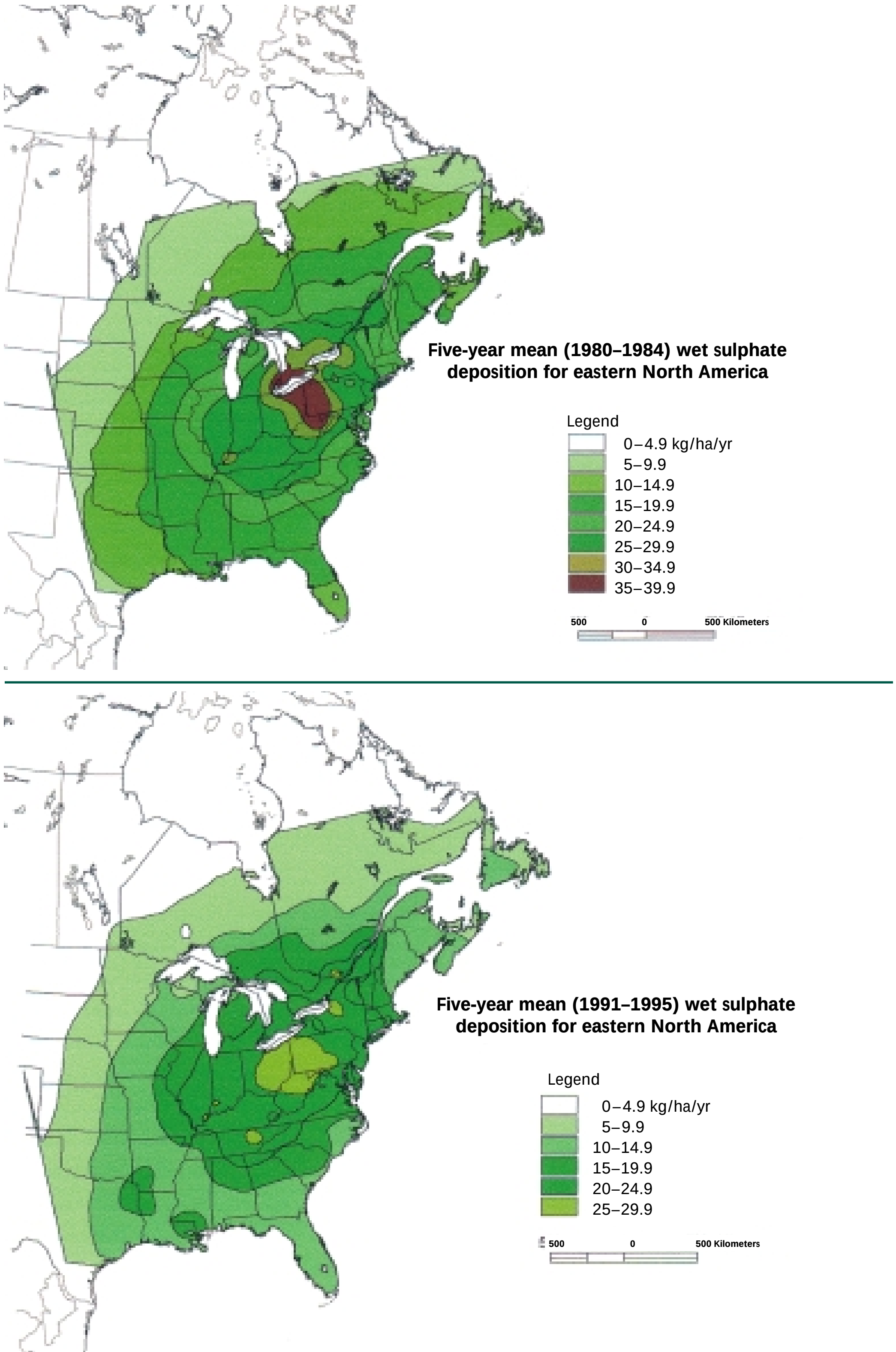


Figure 9: Five-year mean excess wet sulphate deposition patterns (in kg/ha per year) for 1980–1984 and 1991–1995

Source: Environment Canada, 1999a.

In the Boreal Shield, current deposition values of both sulphate and nitrate range between 10 and 20 kg/ha per year in a decreasing south–north gradient (Environment Canada, 1996b). Although sulphate deposition remains the number one acidifying agent in the Boreal Shield, nitrogen-based acidification has become a growing concern, particularly in southwestern parts of the ecozone. While sulphate deposition was reduced significantly between 1980 and 1993, atmospheric nitrate deposition has remained constant or increased slightly over boreal regions during this same period (Environment Canada, 1996b). The influence of nitrogen-based acidification on Boreal Shield lakes is not well understood. Nitrate shows greatest seasonal fluctuations, with average maximum values (~40 µeq/L) occurring in the spring. However, unless adequately controlled, the ongoing effects of nitrogen acidification will likely undermine the ecological benefits expected from recent reductions in atmospheric sulphur. Reductions of nitrogen oxide emissions were not required under the Eastern Canada Acid Rain Program, but may be considered in the National Acid Rain Strategy.

With a net downward trend in acid deposition loads on the Boreal Shield, the question remains, are there any hopeful signs of recovery? At the Turkey Lakes watershed in Ontario, the decrease in sulphate deposition has resulted in reduced concentrations of base cations in soil runoff and stream water (Figure 10). However, of 152 acidified lakes monitored in Newfoundland, Quebec, Nova Scotia, and Ontario from 1981 to 1997, only 41% became less acidic, 50% remained the same, and 9% became more acidic. Among the small fraction of Boreal Shield lakes that are recovering, this trend has not been even across the ecozone. The most dramatic recoveries were seen in lakes near Sudbury, Ontario, responding to reduced emissions from local metal smelters and long-range sources (Jeffries, 1997). A large number of lakes remain acidic, and further emission reductions are required if complete recovery is ever to occur. For example, critical load modelling of lakes in Killarney Park indicate that recovery and future protection will require no less than an additional 50% reduction in sulphate emissions beyond current legislated levels.

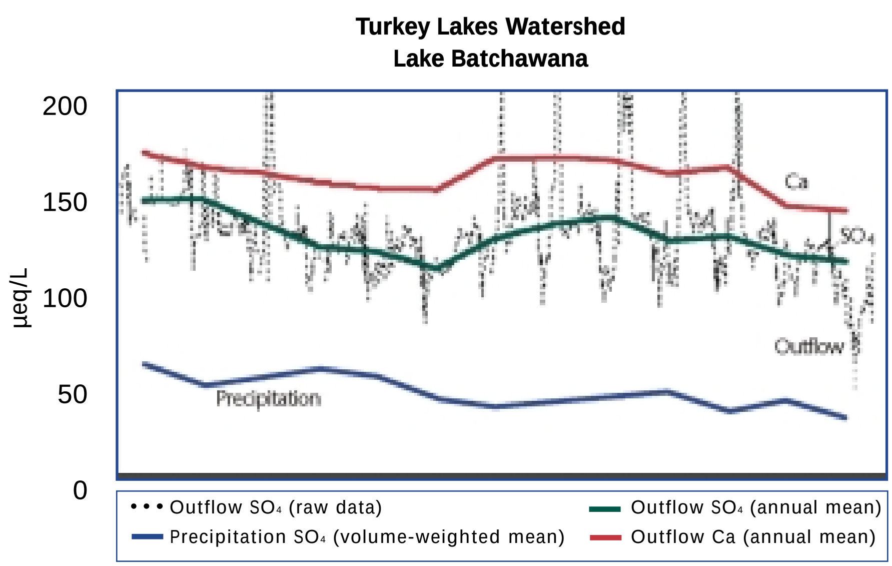


Figure 10: Raw (dotted line) and annual average sulphate and calcium data (solid lines)

Source: Weighted annual wet-only precipitation sulphate, Summers, 1995; Jeffries, 1998.

It is expected that the chemical and biological recovery of Boreal Shield lakes will lag far behind any reductions in acid deposition. There are many reasons for this lag time. First, reductions in sulphur dioxide emissions have been too recent to observe significant responses in many lakes. Second, drought induced by climate warming may negatively affect lake recovery (Bayley et al., 1986; Yan et al., 1996; Dillon et al., 1997). Third, during the recent period of reduced acid deposition, some lakes continued to exhibit water chemistry changes that severely damage their acid-buffering capacity, suggesting irrevocable damage to aquatic systems (Clair et al., 1995; Jeffries et al., 1995). Stream data which integrate several headwater lakes provide a good example of some of these changes (Figure 11). And fourth, as predicted by Minns et al. (1990), atmospheric inputs of strong acids are generally still too high to allow many acid-sensitive lakes to recover.

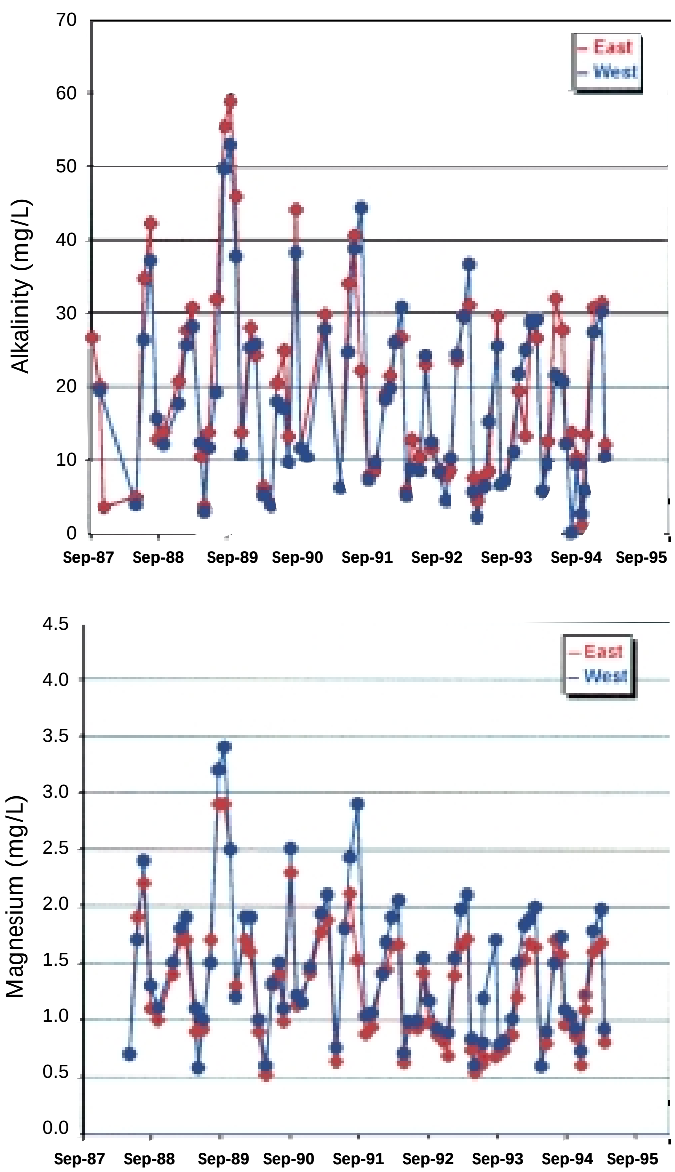


Figure 11: Trends for alkalinity, calcium, magnesium, and sulphate in Pukaskwa National Park, Ontario, 1987–1995

Source: McCrea and Burrows, 1998.

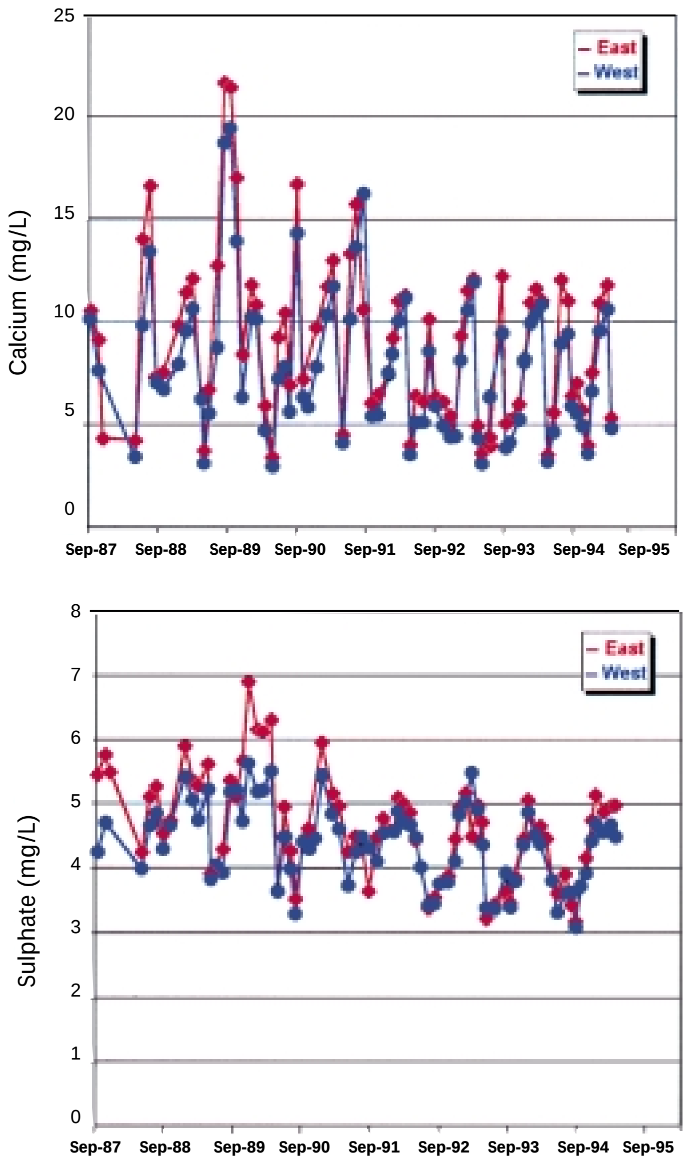


Figure 11: Trends for alkalinity, calcium, magnesium, and sulphate in Pukaskwa National Park, Ontario, 1987–1995

Source: McCrea and Burrows, 1998.

Environmental monitoring programs in the Boreal Shield have shed much light on the severity of impacts of acidification on both terrestrial and aquatic ecosystems, the complexity of their interactions, and the dynamics of ecosystem recovery. Continued monitoring will be essential to gauge the effectiveness of future regulatory controls and to address the many unknowns raised by ongoing research. An overview of recommended priorities for environmental monitoring of acid deposition is found in Appendix 1.

4.3 Ultraviolet-B Radiation

Canada is coming under increasing stress as a result of a dramatic rise in harmful ultraviolet radiation from the sun. Very little is known about trends in UV-B radiation in the Boreal Shield ecozone, as this stressor is only beginning to be studied. However, spectral measurements of UV-B radiation between 1989 and 1993 in Toronto, Ontario, just south of Boreal Shield latitudes, indicated that the intensity of light at wavelengths near 300 nm had increased by 35% per year in winter and 7% per year in summer. The trend at wavelengths between 320 and 325 nm was essentially zero (Kerr and McElroy, 1993). The full significance of this trend in Boreal Shield ecosystems will remain unknown until much more work is conducted on the biological effects of UV-B radiation. However, it is clear that many terrestrial and aquatic organisms are sensitive to this stressor (Bothwell et al., 1994; Vinebrook and Leavitt, 1996).

Monitoring studies from Ontario's Boreal Shield forests suggest that white pine and red spruce may be most sensitive to elevated UV-B exposure during the critical first six weeks of their growing season (Percy, 1997). Reduced tree vigour, reduced photosynthetic activity, sun scalding, and premature aging of needles are among the multiple impacts of rising UV-B radiation on coniferous trees. Percy (1997) recorded differences in sensitivities according to tree location. For example, high-elevation species seem more resistant to raised levels of radiation. This study also noted that UV-B-induced photosynthesis declines were more pronounced as temperatures dropped. Laboratory research indicates that elevated UV-B levels may reduce biomass production in most of the coniferous species found on the Boreal Shield. The long-term effects of increased UV-B exposure on the health and productivity of the ecozone's forests are unknown.

Ongoing Boreal Shield lake studies of possible harmful effects of UV-B radiation suggest that stream invertebrates may be particularly sensitive to this stressor (Schindler and Donahue, personal communication, 1997). Deepwater or bottom-dwelling organisms may also experience adverse effects of increased UV-B when they venture, or are carried, into the near-surface waters. Significant changes to the thermal characteristics of Boreal Shield lakes may also be associated with elevated UV-B levels.

DOC is the chief factor attenuating ultraviolet radiation in Boreal Shield lakes. DOC declines caused by climate warming or acidification result in greater lake transparency and, in turn, deeper penetration of UV-B rays. This increased exposure amplifies, by up to severalfold, the increase in UV radiation that is already stressing Boreal Shield lakes as a result of stratospheric ozone depletion (Schindler, 1998). Thus, Boreal Shield lakes are under a "three-pronged attack" from the combined effects of climate warming, acidification, and stratospheric ozone depletion, all of which contribute to increased UV-B exposure.

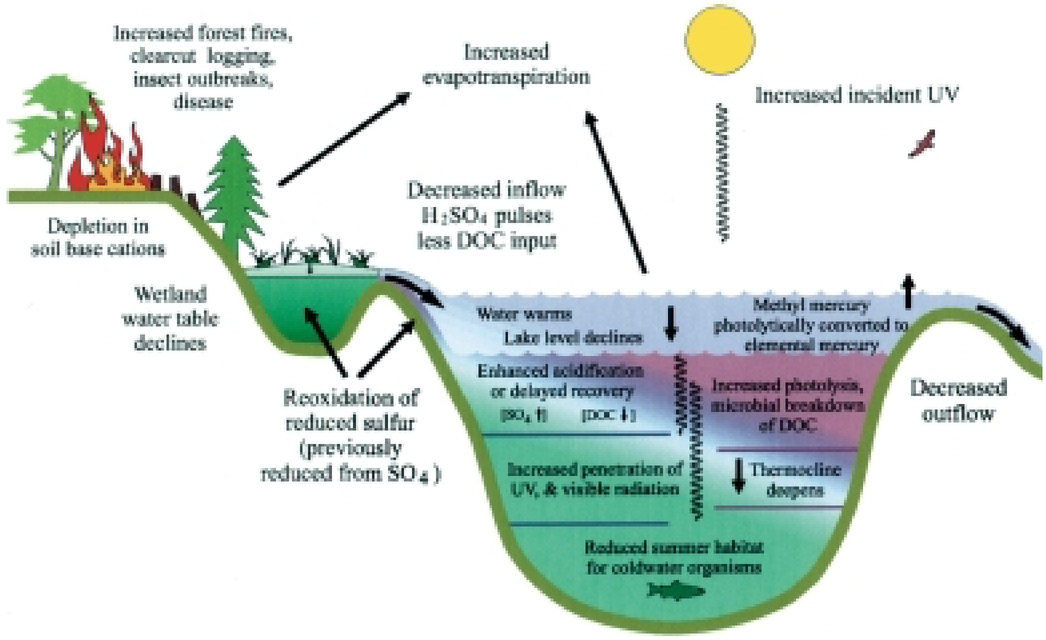


Figure 12: Combined physical and chemical effects of acid deposition, climate warming, and stratospheric ozone depletion

Source: Schindler, 1998.

The net decline in stratospheric ozone over mid-latitudes, where most of the Boreal Shield falls, was not detected until the late 1980s, thanks to long-term environmental monitoring. Wardle (1997) warns that if stratospheric ozone levels were to increase – with a consequent reversal of present UV-B radiation trends – there would likely be a time lag of many years before boreal systems might show any signs of recovery. Meanwhile, enhanced UV-B penetration in Boreal Shield lakes and rivers may continue – regardless of the state of ozone in the stratosphere – unless current acidification and climate trends are also reversed.

Clearly, increased UV-B exposure is one of the most complex and least understood stressors now influencing the Boreal Shield ecozone. Only with continued monitoring of stratospheric ozone and incident UV-B radiation, as well as associated impacts on Boreal Shield ecosystems, will scientists and decision-makers be able to understand the full significance of this stressor and, if possible, determine how best to respond. To this end, the following objectives should be given top priority in long-term UV-B research and monitoring programs:

- Determine which species are most sensitive and at what levels;
- Identify the biochemical and physiological attributes that contribute to sensitivity or resistance;
- Determine the effects on leaf cuticle, photosynthesis, DNA, and reproduction;
- Assess the potential for UV-B to alter biodiversity in forest ecosystems;
- Select forest health monitoring sites for continuous UV-B measurement; and
- Develop models of UV-B effects on tree seedling growth.

4.4 Long-range Transport of Pollutants

The worldwide use of pesticides and organochlorine chemicals over the past half-century has resulted in broad geographic dispersal of these persistent contaminants by long-range atmospheric transport. Monitoring at the ELA in northwestern Ontario indicates that significant amounts of organochlorines are being deposited into Boreal Shield lakes (Muir et al., 1990, 1996; Lockhart et al., 1993). While these quantities are not acutely toxic, the long-term, chronic effects are unknown. The ELA results suggest that persistent organic pollutants are accumulating in certain tissues of Boreal Shield invertebrates, fish, and higher vertebrates and may, over time, contribute to population declines and ecosystem malfunctions (Fairchild et al., 1992; Servos et al., 1992a,b; Thompson, 1996).

The environmental and toxicological importance of sublethal concentrations of trace organic compounds is a topic gaining increasing attention in the scientific literature. For example, some chemicals, although detected in minute quantities, may seriously disrupt ecosystem functions by catalyzing the actions of other chemicals. Many questions are being raised about the cumulative, synergistic, and antagonistic impacts of organic pollutants, as well as their interactions with acid precipitation, climate change, and other stressors. For much of Canada, including the Boreal Shield, such questions remain largely unanswered.

The many unknowns and growing international concern regarding the long-range transport of persistent organic pollutants, mercury, and other heavy metals make enhanced monitoring of airborne contaminants imperative. Research is also needed on the rate of increase of such pollutants and their effect on Boreal Shield ecosystems.

5 Selected Indicators of Change

5.1 Forest Fires

Fire is a natural and dominant disturbance in the Boreal Shield ecozone. Most tree species here are adapted to large, high-intensity, destructive wildfires, to the point where fire is generally required for adequate species regeneration – a classic example of a fire-dependent ecosystem. Fires are larger and occur with greater frequency in this ecozone than in any other forested region in Canada (Stocks et al., 1996). The annual area burned varies by an order of magnitude from 0.7 to 7 million hectares, the average being 2.9 million hectares.

Specific regional figures show that the average area burned each year generally decreases from north to south and from west to east, dropping from a high of 1.53% in northern Manitoba and Saskatchewan to 0.34% in northern Ontario and Quebec. Although climate differences may be a factor, the decrease from north to south is due primarily to increased fire protection in southern regions.

In spite of these regional differences within the ecozone, as a whole there appears to be a net upward trend in both fire occurrence and area burned. Figure 13 suggests that during the 1980s and 1990s, the frequency has been higher than during the previous 50 years.

Figure 13: Annual area burned in the Boreal Shield ecozone, 1930 –1992

Source: Environment Canada, 1995b.

Major fires, cycling naturally through the forest, remove tree cover and mineralize organic matter in soils, releasing nutrients. The short-term impacts of forest fires may be substantial, particularly on streams and shallow lakes. Two to six years after a major fire, runoff and stream bedloads can greatly increase (Bayley et al., 1992; Beaty, 1994). Reduced shade can also impact stream invertebrate and fish populations. All of these effects are part of a normal response to wildfire. Under natural frequencies, these fires have few short-term, and no significant long-term, effects on the freshwater systems themselves. In contrast, large, frequently recurring fires have been found to cause a net reduction in the area and density of black spruce. Although this species is well adapted to fire, it is unable to withstand a high frequency of fires and, under these conditions, tends to be replaced by other species, such as jack pine, paper birch, or trembling aspen (Gagnon, 1998).

With present climate warming trends, larger fires are anticipated in northern parts of Boreal Shield forests. This could create undesired shifts in forest composition and age structure and negatively impact the global carbon budget (Stocks et al., 1996; Bastedo, 1999).

For many years, both forest managers and scientists have been debating the ecological impacts of forest harvesting compared with those of wildfire on lake ecosystems. Several monitoring studies across the Boreal Shield are helping to shed light on this debate. Experimental harvesting of lake watersheds is being monitored at the Coldwater Lakes Research Project near Atikokan, Ontario, and at the TROLS (Terrestrial and Riparian Organisms of Lakes and Streams) project near Athabasca, Alberta. Comparative studies of water quality, biotic diversity, and structure in lakes impacted by wildfire and clearcutting are also under way near the Reservoir Grouin in Quebec (National Centre of Excellence in Sustainable Forestry). Together, these research studies suggest that, compared with harvesting, wildfires cause a relatively higher increase in inorganic nutrient inputs in lakes and in the abundance of chlorophyll and zooplankton. These studies also suggest that neither harvesting nor wildfire has significant impacts on species assemblages and biodiversity of lake plankton.

Studies from central parts of the ecozone suggest that a major shift from softwood to hardwood cover is occurring in areas where forest harvesting has replaced fire as the dominant disturbance (Hearnden et al., 1992; Carleton and MacLellan, 1994). Significant differences in the species composition of ground cover between cutover and burned sites may be associated with differing soil nutrient conditions (Johnston and Elliott, 1996).

5.2 Insects

Insects are an essential contributor to forest health in the Boreal Shield. In spite of the dominance of wind-pollinated coniferous trees, pollination by insects is as much a keystone process in this ecozone as elsewhere (Kevan et al., 1993). Besides aiding regeneration of the forest, insects also cause significant tree mortality through defoliation, one of the greatest contributors to forest change. The proportion of tree mortality caused by insects is estimated to be 1.5 times that due to fire and equivalent to one-third of the annual harvest volume (Hall and Moody, 1994). Although at times devastating, such natural disturbances are the drivers of forest diversity, structure, and function and are necessary for forest resiliency and long-term sustainability (Aber and Melillo, 1991; Haack and Byler, 1993; Attiwill, 1994).

On the Boreal Shield, there are four kinds of insects that may damage trees over large areas:

1. Spruce budworm on spruce and balsam fir;
2. Hemlock looper on balsam fir and eastern hemlock;
3. Jack pine budworm on pine species; and
4. Forest tent caterpillar on poplar species.

Major outbreaks of spruce budworm in the Boreal Shield often result in a reduced proportion of balsam fir in the forest canopy. While white and black spruce are less vulnerable to budworm attack, their reproduction is reduced as female flowers are eaten by budworms, resulting in fewer cones (Blais, 1985; Howse, 1997). In terms of area affected, outbreaks were generally greatest during the 1970s, possibly due to more intensive harvesting practices and fire suppression (Blais, 1983; Volney, 1988). For example, severe outbreaks of spruce budworm in Ontario and Quebec occurred in many areas where balsam fir had naturally replaced previously clearcut stands of black spruce (Quaile, personal communication, 1998). The most recent outbreak of spruce budworm in these provinces began around 1966. At its peak in 1975, 54 million hectares were moderately or severely defoliated (Davidson, 1976). By 1981, 300 million cubic metres of wood, or the equivalent of five years' harvest in eastern Canada, had been lost to this insect (Sterner and Davidson, 1981). The insect population declined slowly after 1981 but remained at high levels until 1996, 30 years after the outbreak began. By 1996, the gross area for which balsam fir and white spruce mortality had been recorded stood at 8.3 million hectares in Ontario, mostly in the Boreal Shield ecozone. During this same period, the outbreak also expanded rapidly into Newfoundland (Kondo and Taylor, 1985).

Consecutive years of defoliation result in decreased tree vigour, loss of volume increment, increased wood decay, tree deformities, and, ultimately, tree mortality. Tree mortality increases as the severity and duration of attack continue. Tree mortality also differs from stand to stand as well as according to the type of insect. For the spruce budworm, attacks begin to cause growth losses when defoliation reaches about 30%. In Ontario, consecutive years of defoliation resulted in 4 000 ha of tree mortality in 1998, for a total of 8.5 million hectares since the early 1980s (Howse and Scarr, 1998). Figure 14 shows key disturbance trends for spruce budworm and forest tent caterpillar in the Boreal Shield ecozone during the 1980s and the first half of the 1990s.

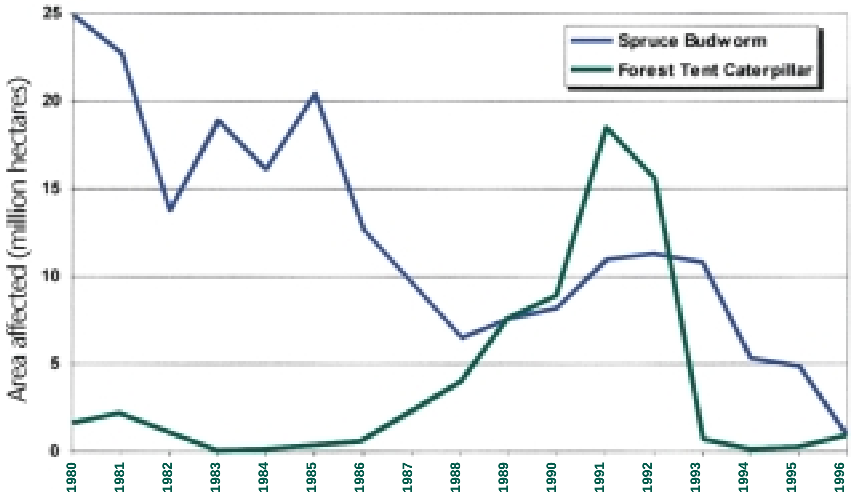


Figure 14: Key insect disturbance trends in the Boreal Shield ecozone, 1980–1996

Source: Environment Canada, 1999b.

The hemlock looper is another insect that affects the health of forests dominated by spruce or fir, particularly in Newfoundland and the Maritimes (Raske et al., 1995). As with spruce budworm, the looper mostly attacks mature to overmature balsam fir trees. Outbreaks of looper are usually localized, except in Newfoundland, where outbreaks damaging over 215 000 ha have been recorded (Kondo and Moody, 1987; Raske et al., 1995).

Although the jack pine budworm does not usually cause extensive mortality to its main host – the jack pine – its range appears to be expanding. This species' historic range included Saskatchewan, Manitoba, and northwestern Ontario, with only scattered outbreaks in southern and central Ontario (Cerezke, 1986; Howse, 1986). Over the past three decades, its range has been expanding eastward, with outbreaks detected over large areas in central and eastern Ontario (Howse and Meating, 1995). Meanwhile, the size of jack pine budworm outbreaks in the Prairie provinces is increasing, likely due to fire suppression practices that favour older stands more susceptible to insect attack (Volney, 1988).

The most significant defoliator of hardwood trees in the Boreal Shield ecozone is the forest tent caterpillar (Rose and Linquist, 1982; Ives and Wong, 1988). Although this species can cause considerable damage over large areas, it does not always kill the host tree (Howse, 1981; Moody and Amirault, 1992). Repeated defoliation results in growth losses, and several continuous years of defoliation result in mortality (Hall et al., 1998). A recent outbreak in Ontario defoliated 9.5 million hectares of birch and poplar forests (Moody, 1993). Increased fragmentation of aspen forest due to harvesting and land conversion may be increasing the severity and extent of forest tent caterpillar outbreaks in this ecozone (Roland, 1993).

Other insects provide further insights into the effects of forest change. For example, studies from the Abitibi region of Quebec suggest that the abundance and diversity of insect larvae are reduced by as much as 50% following clearcutting (Paquin and Coderre, 1997). On the other hand, a study from northwestern Ontario found that the diversity of wasps and bees increased following logging activity and budworm outbreaks (Fye, 1972). Northward range expansions of spruce budworm and some other insects are already occurring (Fleming, 1996; Bastedo, 1999).

Monitoring of changes in insect ranges, the severity and extent of insect outbreaks, and the abundance and diversity of insect species is essential to keep a pulse on forest health in the Boreal Shield ecozone.

5.3 Mercury

Mercury pollution is a characteristic problem of many forms of resource development on the Boreal Shield. This ecozone contains some of the largest metal mines, smelters, and pulp and paper operations in Canada, all of which are potential point sources of mercury release into the environment. Parts of the ecozone are quite high in naturally occurring mercury, especially areas dominated by shales and related Proterozoic bedrock. The flooding of organic matter by hydroelectric reservoirs and river diversions can result in the chemical release of natural mercury. Elevated mercury levels found in bottom sediments of remote Boreal Shield lakes, far from such point sources, may be due to the transport of atmospheric mercury from industries that lie well beyond the Boreal Shield. Mercury from any of these sources can be incorporated into both aquatic and terrestrial food chains, with potentially toxic effects.

Both soil and lake bottom studies within 80 km of the metal smelter at Flin Flon, Manitoba, show concentrations of mercury well above geological background levels. Recent improvements to metal processing at Flin Flon have significantly reduced mercury releases from this particular source.

Numerous fish species throughout Ontario and Manitoba contain dangerously high levels of mercury in their tissues, requiring detailed safety guidelines for limiting human consumption (Chambers, personal communication, 1998). In Ontario, the ministries of Environment and Natural Resources jointly monitor contaminants in sport fish, and a Guide to Eating Ontario Sport Fish is published biannually (Ontario Ministry of the Environment, various years). Based on the 1997/98 Guide, 44% of the fish tested in northern Ontario and 35% tested in southern Ontario had consumption restrictions in place. The Guide gives 13 550 consumption advisories, each one specific to one size of fish of one species from one location. For over 95% of the consumption restrictions for fish in Ontario's inland lakes, mercury was the principal contaminant of concern (Piche, personal communication, 1998). For example, about 80% of the population of large walleye in Ontario contained above 0.5 ppm mercury, and 10% contained above 1.5 ppm, a concentration well beyond recommended safe consumption levels (Mierle, 1997a).

Mercury contamination is a particular concern to Aboriginal people in this ecozone, many of whom give fish a central place in their diet. Blood tests indicate that they generally have higher levels of mercury than nonnatives. Moreover, some show levels above the threshold for mercury toxicosis. Although neurological examination of these individuals revealed no toxic effects, the margin of safety in such cases is nevertheless extremely small (Mierle, 1997b).

Although the effects of elevated mercury in humans have been thoroughly researched and monitored, very little is known about its effects on wildlife. Dose–response relationships have not been clearly established for any species of wildlife in the Boreal Shield ecozone. Nevertheless, a number of studies suggest that levels between 0.3 and 2.0 ppm would likely have toxic effects (Mierle, 1997b; Evans et al., 1998). A level of 0.9 ppm mercury was lethal to mink after about three months and caused emaciation in wild loons. At 0.6 ppm, the reproductive success of mallards was halted. McNicol et al. (1997) found lethal and sublethal effects of dietary mercury exposure in various birds at even lower concentrations. Such preliminary findings suggest that sensitivity differs widely among species and that human consumption guidelines (in the neighbourhood of 0.5 ppm) would in many cases offer little protection to wildlife. These results also suggest that the monitoring of mercury levels and their effects in wildlife deserves greater attention as a valuable indicator of ecological health.

5.4 Nonnative Species

The island of Newfoundland has only 14 native mammals, but its faunal diversity has been greatly increased through the introduction of nonnative species. The island now supports 150 000 moose, where a century ago there were none. Other introductions include fox, snowshoe hare, masked shrew, red squirrel, and, most recently, coyotes. The ecological impacts of these introductions are not well documented.

White-tailed deer have vastly increased their range in Manitoba and northwestern Ontario, possibly as a result of the proliferation of secondary roads. This expansion has raised concerns that a brain worm carried by white-tailed deer may infect woodland caribou populations where the two species overlap. Within the ecozone, there has also been a northern expansion in the ranges of magpies and cowbirds.

The spread of exotic insect species that are harmful to native tree species is a growing concern for forest managers in this ecozone (Armstrong and Ives, 1995). Species include the European spruce sawfly, European pine sawfly, spruce budworm, satin moth, mountain ash sawfly, birch leafminer, birch casebearer, larch sawfly, and balsam woolly adelgid. The latter species is among the most problematic. It is causing serious damage to balsam fir stands in Newfoundland, where it was accidentally introduced in the 1920s or 1930s; it has more recently spread to the mainland. The balsam woolly adelgid and a number of other nonnative species have been the subjects of biocontrol efforts involving the introduction of additional foreign predator or parasite species. These attempts have met with varying degrees of success. Although no effective control agent has been found for balsam woolly adelgid, a European parasite of mountain ash sawfly has provided good control of this insect.

Some introduced fungal pathogens, particularly the white pine blister rust, are also damaging trees in the Boreal Shield. This species now occurs throughout the range of its host species, causing significant mortality, particularly in southern parts of the ecozone (Lavallee, 1974; Gross, 1985; Castello et al., 1995). Invasion of the spiny water flea is decreasing biodiversity in some of Ontario's lakes (Yan and Pawson, 1997). One long-term monitoring study of a lake where this species was present found that although biomass remained the same, the lake's biodiversity dropped by almost 50%, from an average of 13 taxa per collection per year to a mean of 7.5 taxa. This dramatic fall in diversity has been linked directly to the introduced plankton species, since acid precipitation, climate patterns, thermal regime, and other factors remained relatively constant for this lake over the 20-year monitoring period.

In wetlands across Manitoba, Ontario, and Quebec, purple loosestrife is a serious problem that appears to be extending its range northward. This species clogs streams and displaces native cattails and other aquatic plants important for wildlife. It is now found as far north as The Pas and Snow Lake, the most northerly occurrences in North America (Chambers, personal communication, 1998).

Few studies have been done on the impacts of introducing exotic fish species through lake stocking programs or the use of live bait fish. One example from Quebec's La Mauricie National Park indicates that the introduction of minnows as live bait for salmonids has drastically changed the composition and abundance of native fish species (Pinel-Alloul, personal communication, 1998).

5.5 Mammals and Birds

Most large mammal populations in the Boreal Shield ecozone seem to be stable or increasing. For example, the woodland caribou herd in Newfoundland's Avalon Peninsula has recently stabilized from an earlier downward trend. The status of woodland caribou in other parts of the ecozone is less well documented and deserves more attention, given the species' sensitivity to timber harvest activities (Chubbs et al., 1993; Cumming and Beange, 1993; Racey and Armstrong, 1996). The original four moose introduced on the island of Newfoundland in 1904 provided the root stock for what is now the largest herd in the ecozone (LeHénaff, personal communication, 1998). The George River caribou herd recently expanded its winter range in northeastern parts of the ecozone. Quebec's Val-d'Or caribou herd is slightly decreasing (Government of Canada, 1996), as are woodland caribou in Manitoba (Chambers, personal communication, 1998). The accurate status of other economically important or ecologically threatened mammals is unknown as a result of limited monitoring. Up-to-date information on the pine marten, wolverine, and eastern cougar is especially scant. The eastern cougar has likely been extirpated from eastern portions of the Boreal Shield.

Compared with other ecozones, only a small number of forest species are listed as being at risk in the Boreal Shield by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 1997). However, some of these inhabit very large home ranges, posing difficult challenges for population monitoring and impact mitigation programs (Table 3). The Newfoundland pine marten was recently downgraded from threatened to endangered status in response to evidence of continuing population declines. One modelling study suggests that modified forestry practices could increase the availability of key habitat features for this species (Sturtevant et al., 1996). Strict protection of mature forests is particularly critical to the pine marten's survival (Thompson, 1991; Thompson and Colgan, 1994). Although it is not currently listed by COSEWIC, the red crossbill, another species associated with mature forests, is suffering a wide decline that is particularly pronounced in Newfoundland (Benkman, 1993a,b).

Endangered			
Group	**Species**	**Province**	**Reasons**
Mammals	Cougar (eastern)	Ont., Que.	Unknown, naturally rare
Fish	Aurora Trout	Ont.	Acidic deposition, pollution
Plants	Engelmann's Quillwort	Ont.	Habitat destruction, chemicals

Threatened			
Group	**Species**	**Province**	**Reasons**
Mammals	Newfoundland Marten	Nfld.	Habitat destruction (old growth forest)
Fish	Blackfin Cisco	Ont.	Exploitation by commercial fishing
	Shortjaw Cisco	Ont., Man.	Exploitation by commercial fishing
	Channel Darter	Ont., Que.	Sedimentation in aquatic habitat
Plants	Athabasca Thrift	Sask.	Habitat destruction following road construction
	Tyrell's Willow	Sask.	Habitat destruction following road construction
	Pitcher's Thistle	Ont.	Habitat destruction on sand beaches
	Blunt-lobed Woodsia	Ont., Que.	Habitat destruction

Table 3: Some characteristic species of the Boreal Shield ecozone that are endangered or threatened

Source: K. Ross, Canadian Wildlife Service, Ontario Region, personal communication.

5.6 Plants and Lichens

The management of old-growth pine stands is an ongoing source of concern and controversy across the ecozone. Both red and white pine continue to decline in Newfoundland. Overharvesting contributes to ongoing declines of white pine from Newfoundland to Manitoba. This problem is compounded by white pine blister rust, an introduced disease that interferes with the growth of young white pine (Gross, 1985). Red pine, on the other hand, adapts poorly to stand disturbance, perhaps as a result of its limited genetic diversity compared with most other Boreal Shield conifers (Mosseler et al., 1991; Mosseler, 1992). Boyle (1992) and Gordon (1996) discuss the role of genetic diversity in the decline of white spruce and other tree species in the Boreal Shield.

A lichen species not listed by COSEWIC but considered to be globally rare is the boreal felt lichen (*Erioderma pedicellatum*). In addition to being vulnerable to timber extraction, this lichen is highly sensitive to air pollution. Formerly common in Europe, one of the last strongholds of this species is now found in the remaining mature forests of Newfoundland.

5.7 Drought and Blowdown

Drought and blowdown can cause major natural disturbances within forests of the Boreal Shield. Most noticeable in sites with shallow soil, drought may directly harm trees and other plants. More often it acts in concert with secondary organisms to heighten mortality. Drought can also increase stress to defoliated trees during insect outbreaks, resulting in escalated damage. For example, in 1993, over 31 000 ha of jack pine died in Ontario's Boreal Shield as the combined result of drought, bark beetle damage, and root rot (Howse and Applejohn, 1993). Drought stimulates flowering of jack pine, which could result in higher damage during a jack pine budworm outbreak (Riemenschneider, 1985; Volney, 1988).

Blowdown caused by severe surface winds can uproot extensive areas of forest and significantly alter its structure (Flannigan et al., 1989). Blowdowns are common throughout the Boreal Shield but vary greatly in extent. In 1991, severe winds caused extensive damage to large tracts of forest in northern Ontario and Quebec. The largest tract of land was 164 000 ha, with a total 207 700 ha of uprooted and damaged trees (Sajan and Brodersen, 1992). Fire hazard can rise dramatically after a major blowdown. In 1973, an area of 40 000 ha in northwestern Ontario was severely damaged by wind, resulting in severe blowdown. The next summer, almost all of this blowdown area – 32 000 ha — succumbed to forest fires (Stocks, 1975; Flannigan et al., 1989).

5.8 Leopard Frog

Although the northern leopard frog has no economic profile to speak of, it has become an important ecological indicator of change throughout its Canadian range. Seburn and Seburn (1998) report that over the last 20 years, this species has declined significantly across western Canada, from British Columbia to Manitoba. In 1998, the British Columbia population of the northern leopard frog received endangered status, and the prairie population was designated as vulnerable (Seburn and Seburn, 1998; COSEWIC, 1999). Recent reports suggest that populations of leopard frogs in Manitoba may be experiencing a short-term rise (Chambers, personal communication, 1998; Roberts-Pichette, personal communication, 1998).

Leopard frogs appear to be on the decline in northern parts of Ontario. In the spring of 1996, Ontario's Ministry of Natural Resources conducted listening surveys from Sudbury to Nipigon, sampling almost 100 suitable wetlands that fell within a large area with historic records of leopard frogs. Leopard frogs were heard from Sudbury to Sault Ste. Marie. However, not one was heard north of Sault Ste. Marie all the way to Nipigon, east of Thunder Bay (Seburn and Seburn, 1997).

The relatively rapid disappearance of leopard frogs from parts of their historic range remains a mystery to science. Continued monitoring of this species may yet link it to other environmental changes or land use practices.

6 Prognosis for a Healthly Ecozone

By global standards, the Boreal Shield looks to be in pretty good shape environmentally. It is sparsely settled, with few roads and towns, isolated pockets of industry, and much biodiversity relatively intact. How could such a landscape be under any serious threat of environmental degradation?

This report shows that, on the surface at least, this granite-studded kingdom of spruce and pine does indeed retain many of its natural features and processes formed over thousands of years. Most of its myriad rivers run clear and free as always, forest fires have not lost their shaping influence on the landscape, bald eagles, moose, and caribou find all they could ever need on the Boreal Shield. But the insights provided by long-term environmental research and monitoring suggest that, below surface appearances, this ecozone is experiencing a period of ecological flux of unparalleled magnitude and pace.

The immense scale and complexity of many of the changes described in this report raise many questions that will take years to answer – if they are ever answered at all. For instance, there is a huge paucity of scientific knowledge on the cumulative effects of forestry, mining, and hydroelectric development in this ecozone. These are relatively localized activities that theoretically can be better managed once such key scientific blanks are filled in. As daunting as this task may seem, it may pale in comparison to the questions raised with respect to farther-reaching stresses, such as climate change, acid precipitation, and increased UV-B radiation. As Schindler (1998) emphasized, the “Big Three” stressors have cumulative and perhaps synergistic effects that may be radically altering the entire dynamic of this ecozone. Determining the ecological significance of these stresses, acting alone or in concert with one another, may well represent one of Canada’s major scientific challenges for the next century (Van dijk, personal communication, 1998).

Furthermore, the many unknowns associated with accelerated ecological change create new uncertainties in the region’s economy. For instance, in gauging the impacts of today’s environmental stresses on future forestry prospects in boreal regions, Stewart (1996) predicts that:

- future wood availability will be uncertain at best, based on current data, scenarios, and models;
- future wood production will be controlled by increases in climate-induced irregular and

large-scale mortality events, which cannot be simulated or predicted with current models; and

- large-scale mortality events (drought or insect related) will generate considerable surplus wood from salvage felling, but will severely decrease standing stock over the long term.

7 Conclusion

By illustrating the very complex nature of Boreal Shield forest ecosystems, the wide range of regional and local responses to various environmental stresses, and our current inability to either detect or forecast these intricate relationships, this report strengthens the rationale for a solid long-term monitoring network applicable to the entire ecozone.

The focus of this monitoring should be kept on the specific issues that require a large network for early detection of important but hard to detect ecosystem responses. For example, for the Boreal Shield, the issues of upslope clearcutting and downslope siltation – which are of major concern in mountainous regions – should be treated as localized problems that generally have preventative guidelines already in place (Cole, personal communication, 1998). Accordingly, monitoring for such processes would be strictly local in scale. The value of a regional or ecozone-based network is in tracking broader stresses, trends, and indicators – the kind described in this report.

Many promising resource management practices and policies are already being implemented to help reverse some of the present trends towards environmental deterioration in the Boreal Shield ecozone. Innovative partnerships for applied research have formed among corporate, public, and academic representatives who recognize a common interest in tackling these issues. But the full magnitude and significance of regional and global stresses on this ecozone are only now dawning on both scientists and resource managers, thanks to long-term research and monitoring studies. Strong, sustained support for such studies and wide dissemination of their results are absolutely essential to help build the broad science base required to better understand these issues and devise appropriate management responses.

References

Aber, J.D. and J.M. Melillo. 1991. Terrestrial ecosystems. Saunders College Publishing, Holt, Rinehart and Winston, Orlando, Florida. 429 pp.

Acidifying Emissions Task Group. 1997. Towards a National Acid Rain Strategy. Submitted to the National Air Issues Coordinating Committee, Environment Canada. 98 pp.

AQUAMIN (Aquatic Effects of Mining in Canada). 1996. Assessment of the aquatic effects of mining in Canada: AQUAMIN final report. Environment Canada, Ottawa, Ontario. 127 pp.

Armstrong, J.A. and W.G.H. Ives (eds.). 1995. Forest insect pests in Canada. Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario.

Arp, P.A., T. Oja, and M. Marsh. 1996. Calculating critical S and nitrate loads and current exceedances for upland forests in southern Ontario, Canada. Canadian Journal of Forest Research 26(4):696–709.

Attiwill, P.M. 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. Forest Ecology and Management 63:247–300.

Barsh, R.L. 1997. Forests, indigenous peoples, and biodiversity. Global Biodiversity 7(2):20–24.

Bastedo, J. 1999. Shield country — life and times of the oldest piece of the planet. Red Deer College Press, Red Deer, Alberta.

Bayley, S.E., R.S. Behr, and C.A. Kelly. 1986. Retention and release of sulfur from a freshwater wetland. Water, Air, and Soil Pollution 31:101–114.

Bayley, S.E., D.W. Schindler, K.G. Beaty, B.R. Parker, and M.P. Stainton. 1992. Effect of multiple fires on nutrient yields from streams draining boreal forest and fen watersheds: nitrogen and phosphorus. Canadian Journal of Fisheries and Aquatic Sciences 49:584–596.

Beaty, K.G. 1994. Sediment transport in a small stream following two successive forest fires. Canadian Journal of Fisheries and Aquatic Sciences 51:2723–2733.

Benkman, C.W. 1993a. Logging, conifers, and the conservation of crossbills. Conservation Biology 7:473–479.

Benkman, C.W. 1993b. The evolution, ecology and decline of the red crossbill of Newfoundland. American Birds 47:225–229.

Bezte, C.L., W.L. Lockhart, and S.B. Brown. 1997. Results from the biochemical and morphological analysis of white sucker downstream from the Pine Falls pulp mill and characterization of effluent toxicity and the effluent induced mixed-function oxygenase response (1993–1995). Final report on the effects of untreated effluent to the Department of Indian Affairs and Northern Development, Winnipeg, Manitoba. January.

Blais, J.R. 1983. Trends in the frequency, extent and severity of spruce budworm outbreaks in eastern Canada. Canadian Journal of Forest Research 13:539–547.

Blais, J.R. 1985. The ecology of the eastern spruce budworm: a review and discussion. Pages 49–59 *in* C.J. Sanders, R.W. Stark, E.J. Mullins, and J. Murphy (eds.), Recent advances in spruce budworm research. Proceedings of a Symposium, 16–20 September 1984, Bangor, Maine. Canadian Forest Service, Ottawa, Ontario.

Bodaly, R.A., R.E. Hecky, and R.J.P. Fudge. 1984. Increases in fish mercury levels in lakes flooded by the Churchill River diversion, northern Manitoba. Canadian Journal of Fisheries and Aquatic Sciences 41:682–691.

Booth, D.L., D.W.K. Boulter, D.J. Neave, A.A. Rotherham, and D.A. Welsh. 1993. Natural forest landscape management: a strategy for Canada. Forestry Chronicle 69:141–145.

Bothwell, M.L., D.J. Sherbot, and C.M. Pollock. 1994. Ecosystem response to solar ultraviolet-B radiation: Influence of trophic level interactions. Science 265:97–100.

Boyle, T.J.B. 1992. Biodiversity of Canadian forests — current status and future challenges. Forestry Chronicle 68:444–453.

Canadian Council of Forest Ministers. 1992. Sustainable forests: a Canadian commitment. Hull, Quebec.

Canadian Council of Forest Ministers. 1995. Compendium of Canadian forestry statistics, 1994. National Forestry Database. Available from Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario.

Canadian Council of Forest Ministers. 1997. Criteria and indicators of sustainable forest management in Canada. Available from Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario.

Canadian Forest Service. 1998. National Forest Strategy 1998–2003: Sustainable forests - a Canadian commitment. Natural Resources Canada, Ottawa, Ontario.

Carleton, T.J. and P. MacLellan. 1994. Woody vegetation response to fire versus clear-cut logging: a comparative study in the central Canadian boreal forest. Ecoscience 1:141–152.

Castello, J.D., D.J. Leopold, and P.J. Smallidge. 1995. Pathogens, patterns, and processes in forest ecosystems. Bioscience 45:16–24.

Cerezke, H.F. 1986. Impact studies of the jack pine budworm, *Choristoneura pinus pinus*, in Nesbit Provincial Forest, Saskatchewan. Pages 25–38 in Jack Pine Budworm Information Exchange, 14–15 January 1986, Winnipeg, Manitoba. Forest Protection Branch, Department of Natural Resources, Winnipeg, Manitoba.

Chambers, A. 1998. Personal communication. Vice-President, Canadian Parks and Wilderness Society, Manitoba Chapter.

Chubbs, T.E., L.B. Keith, S.P. Mahoney, and M.J. McGrath. 1993. Responses of woodland caribou (*Rangifer tarandus caribou*) to clear-cutting in east-central Newfoundland. Canadian Journal of Zoology 71:487–493.

Clair, T.A., P.J. Dillon, J. Ion, D.S. Jeffries, M. Papineau, and R.J. Vet. 1995. Regional precipitation and surface water chemistry trends in southeastern Canada (1983–91). Canadian Journal of Fisheries and Aquatic Sciences 52:97–212.

Cole, W. 1998. Personal communication, 2 October 1998, Government of Ontario: e-mail to A. Kerr, Indicators and Assessment Office, Environment Canada.

COSEWIC (Committee on the Status of Endangered Wildlife in Canada). 1997. Canadian species at risk — April 1997. Secretariat, Canadian Wildlife Service, Environment Canada, Ottawa, Ontario.

COSEWIC (Committee on the Status of Endangered Wildlife in Canada). 1999. Canadian species at risk — April 1999. Secretariat, Canadian Wildlife Service, Environment Canada, Ottawa, Ontario.

Cumming, H.G. and D.B. Beange. 1993. Survival of woodland caribou in commercial forests of northern Ontario. Forestry Chronicle 69:579–588.

Dahl, T.E. and S.C. Zoltai. 1996. Forested wetland resources: past, present and future. *In* Proceedings, International Symposium on the Ecology and Management of Northern Forested Wetlands, Traverse City, Michigan, 29–31 August 1994.

Daniels, C.J. and J.H. Myers. 1995. Climate and outbreaks of the forest tent caterpillar. Ecography 18:353–362.

Davidson, A.G. 1976. Forest insect and disease survey. *In* Annual report 1975. Canadian Forest Service, Ottawa, Ontario.

Day, J.C. and F. Quinn. 1992. Water diversion and export: learning from Canadian experience. Publication Series No. 36. Department of Geography, University of Waterloo, Waterloo, Ontario.

DesGranges, J.L. and G. Rondeau. 1992. Forest bird response to natural perturbations and silvicultural practices: does logging mimic nature? Pages 80–92 in D.H. Kuhnke (ed.), Birds in the boreal forest. Northern Forestry Centre, Forestry Canada, Northwest Region, Edmonton, Alberta.

Deslandes, J.C., S. Guénette, and R. Fortin. 1994. Evolution des communautés de poissons de milieux affectés par l'aménagement du Complexe La Grande, Phase I, 1997–1992. Joint report. Vice-Présidence Hydro-Québec and Université du Québec à Montréal. 89 pp.

Dillon, P.J. 1997. Personal communication, November. Ontario Ministry of the Environment, Dorset, Ontario.

Dillon, P.J. and L.A. Molot. 1997. Declines in phosphorus and dissolved organic carbon stream export and lake concentrations on the Precambrian Shield in central Ontario between 1978 and 1994. Unpublished manuscript. Trent University, Environmental and Resource Studies, Peterborough, Ontario.

Dillon, P.J., L.A. Molot, and M. Futter. 1997. The effect of El Niño-related drought on the recovery of acidified lakes. Environmental Monitoring and Assessment 46:105–111.

Duchesne, L. and R. Ouimet. 1996. Estimation préliminaire des charges critiques en dépôts atmosphériques de N et de S pour les forêts du Québec. Internal Report No. 410. Direction de la recherche forestière, Ministère des Ressources Naturelles, Gouvernement du Québec. 38 pp.

Eaton, P.B., A.G. Gray, P.W. Johnson, and E. Hundert (eds.). 1994. State of the environment in the Atlantic Region. Environment Canada. 457 pp.

EIP (Environmental Information Partnership). 1997a. Synthesis report of the information contained within the development reports catalogue pertaining to the Moose River Basin with particular reference to the aquatic environment. EIP Study Office, Ontario Government Complex, Timmins, Ontario. 173 pp.

EIP (Environmental Information Partnership). 1997b. Synthesis report of the information contained within the socio-economic catalogue pertaining to the Moose River Basin. EIP Study Office, Ontario Government Complex, Timmins, Ontario. 89 pp.

Environment Canada. 1995a. Canadian Biodiversity Strategy: Canada's response to the Convention on Biological Diversity. Available from the Biodiversity Convention Office, Environment Canada, Ottawa, Ontario.

Environment Canada. 1995b. Sustaining Canada's forests: timber harvesting. National Environmental Indicator Series, SOE Bulletin No. 95-4. State of the Environment Reporting Program, Indicators and Assessment Office, Environment Canada, Ottawa, Ontario.

Environment Canada. 1996a. Annual report on the federal–provincial agreements for the Eastern Canada Acid Rain Program. 4 pp.

Environment Canada. 1996b. 1996 progress report on the Canada–United States Air Quality Agreement. Report No. En40-388/1996F. 88 pp.

Environment Canada. 1997. Sustaining Canada's forests: Forest biodiversity. National Environmental Indicator Series, SOE Bulletin No. 97-1. State of the Environment Reporting Program, Indicators and Assessment Office, Environment Canada, Ottawa, Ontario.

Environment Canada. 1999a. Acid rain. National Environmental Indicator Series, SOE Bulletin. State of the Environment Reporting Program, Indicators and Assessment Office, Environment Canada, Ottawa, Ontario. In press.

Environment Canada. 1999b. Sustaining Canada's forests: timber harvesting. National Environmental Indicator Series, SOE Bulletin. State of the Environment Reporting Program, Indicators and Assessment Office, Environment Canada, Ottawa, Ontario. In press.

Environment Canada and Fisheries and Oceans Canada. 1992a. Federal Ecological Monitoring Program (FEMP) — Lake Winnipeg, Churchill–Nelson River System. Vol. 1.

Environment Canada and Fisheries and Oceans Canada. 1992b. Federal Ecological Monitoring Program (FEMP) — Lake Winnipeg, Churchill–Nelson River System. Vol. 2.

Evans, R.D., E.M. Addison, J.Y. Villeneuve, K.S. MacDonald, and D.G. Joachim. 1998. An examination of spatial variation in mercury concentrations in otter (*Lutra canadensis*) in south-central Ontario. Science of the Total Environment 213:239–245.

Fairchild, W.L., D.C.G. Muir, R.S. Currie, and A.L. Yarechewski. 1992. Emerging insects as a biotic pathway for movement of 2,3,7,8-tetrachlorodibenzofuran from lake sediments. Environmental Toxicology and Chemistry 11:867–872.

Falconbridge Limited. 1992. Report on the environment. Toronto, Ontario.

Fenech, G. 1998. Personal communication. Science and Policy Advisor, Science Assessment and Policy Integration Division, Atmospheric Environment Service, Environment Canada.

Flannigan, M.D., T.J. Lynham, and P.C. Ward. 1989. An extensive blowdown occurrence in northwestern Ontario. Pages 65–71 *in* D.C. MacIver, H. Auld, and R. Whitewood (eds.), Proceedings of the 10th Conference on Fire and Meteorology. Petawawa National Forestry Institute, Forestry Canada, Chalk River, Ontario.

Fleming, R.A. 1996. A mechanistic perspective of possible influences of climate change on defoliating insects in North America's boreal forests. Silva Fennica 30:281–294.

Fleming, R.A. and J.N. Candau. 1998. Influences of climatic change on some ecological processes of an insect outbreak system in Canada's boreal forests and the implications for biodiversity. Environmental Monitoring and Assessment 49:235–249.

Fleming, R.A. and W.J.A. Volney. 1995. Effects of climate on insect defoliator population processes in Canada's boreal forests: some plausible scenarios. Water, Air, and Soil Pollution 82:445–454.

Forest Stewardship Council. 1995. Forest Stewardship Council principles and criteria. Oaxaca, Mexico.

Fye, R.E. 1972. The effect of forest disturbances on populations of wasps and bees in northwestern Ontario (Hymenoptera: Aculeata). Canadian Entomologist 104:1623–1633.

Gagnon, G., C. Gravel, R. Ouimet, N. Dignard, R. Paquin, and G. Jacques. 1994. Le réseau de surveillance des écosystèmes forestiers (RESEF). II. Description des places d'étude et données de base. Research Report No. 116. Direction de la recherche forestière, Ministère des Ressources Naturelles, Gouvernement du Québec. 187 pp.

Gagnon, R. 1998. Nouveau modèle d'évolution des forêsts d'épinette noire. Carrefour de la recherche forestière 1997. Unpublished manuscript. Université du Québec, Quebec.

Gauthier, S., A. Leduc, and Y. Bergeron. 1996. Forest dynamics modelling under natural fire cycles: a tool to define natural mosaic diversity for forest management. Environmental Monitoring and Assessment 39:417–434.

Gibson, T., S. Nicol, and L. Streich (eds.). 1997. Moving toward sustainable development reporting — State of the environment report for Manitoba. State of the Environment Reporting, Manitoba Environment, Winnipeg, Manitoba.

Gordon, A.G. 1996. The sweep of the boreal in time and space, from forest formations to genes, and implications for management. Forestry Chronicle 72:19–30.

Gouvernement du Québec. 1996. Biodiversité du milieu forestier: bilan et engagements du Ministère des Ressources naturelles. Direction de l'environnement forestier, Ministère des Ressources Naturelles, Charlesbourg, Quebec.

Government of Canada. 1996. Boreal Shield ecozone. Pages 5-1 to 5-30 *in* The state of Canada's environment — 1996. Environment Canada, Ottawa, Ontario.

Gross, H.L. 1985. White pine blister rust: a discussion of the disease and hazard zones for Ontario. White Pine Symposium Supplement. Proceedings of the Entomological Society of Ontario 116:73–79.

Gunn, J.M. (ed.). 1995. Restoration and recovery of an industrial region. Springer-Verlag, New York, N.Y. 358 pp.

Haack, R.A. and J.W. Byler. 1993. Insects and pathogens — Regulators of forest ecosystems. Journal of Forestry 9:32–37.

Hall, J.P. and B.H. Moody. 1994. Forest depletion caused by insects and diseases in Canada, 1982–1987. Information Report ST-X-8. Canadian Forest Service, Ottawa, Ontario. 14 pp. [cited by Stewart et al., 1997].

Hall, P., W. Bowers, H. Hirvonen, G. Hogan, N. Foster, I. Morrison, K. Percy, I. Cox, and P. Arp. 1997. 1997 Canadian acid rain assessment. Vol. 4. The effects on Canada's forests. Environment Canada, Ottawa, Ontario. 46 pp.

Hall, J.P., W. Bowers, and H. Hirvonen. 1998. Forest insect and disease conditions in Canada: 1995. Forest Insect and Disease Survey. Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario. 72 pp.

Hearnden, K.W., S.V. Millson, and W.C. Wilson. 1992. A report on the status of forest regeneration. Independent Forest Audit Committee, Ontario Ministry of Natural Resources, Toronto, Ontario.

Hopkin, A.A. and T. Drummond. 1996. Hardwood tree condition in Ontario: results of FIDS unit surveys 1987–95. Frontline Technical Note No. 22. Canadian Forest Service, Natural Resources Canada, Sault Ste. Marie, Ontario. 4 pp.

Houle, D., R. Paquin, C. Camiré, R. Ouimet, and L. Duchesne. 1997. Response of the Lake Clair watershed (Duchesnay, Quebec) to changes in precipitation chemistry (1988–1994). Canadian Journal of Forest Research 27(11):1813–1821.

Howse, G.M. 1981. Losses from and control of spruce budworm and other insects in the boreal mixedwood forest. Pages 239–251 *in* R.D. Whitney and K.M. McClain (co-chairmen). COJFRC Symposium Proceedings O-P-9. Boreal Mixedwood Symposium, 1980, Thunder Bay, Ontario. Great Lakes Forest Research Centre, Canadian Forest Service, Environment Canada, Sault Ste. Marie, Ontario.

Howse, G.M. 1986. Jack pine budworm in Ontario. Pages 47–50 *in* Jack Pine Budworm Information Exchange, 14–15 January 1986, Winnipeg, Manitoba. Forest Protection Branch, Department of Natural Resources, Winnipeg, Manitoba.

Howse, G.M. 1997. Forest health conditions in Ontario. Great Lakes Forestry Centre, Canadian Forest Service, Sault Ste. Marie, Ontario. Online bulletin http://www.glfc.forestry.ca/english/onlinep/fhbfall.htm

Howse, G.M. and M.J. Applejohn. 1993. Forest insect and disease conditions in Ontario, summer 1993. Survey Bulletin. Forestry Canada, Sault Ste. Marie, Ontario. 14 pp.

Howse, G.M. and J.H. Meating. 1995. Jack pine budworm situation in Ontario 1981–1994. Pages 31–34 *in* W.J.A. Volney, V.G. Nealis, G.M. Howse, A.R. Westwood, D.R. McCollough, and B.L. Laishley (eds.), Jack pine budworm biology and management. Proceedings, Jack Pine Budworm Symposium, 24–26 January, Winnipeg, Manitoba. Information Report NOR-X-342. Canadian Forest Service, Edmonton, Alberta. 158 pp.

Howse, G. and T. Scarr. 1998. Status of important forest pests in Ontario in 1998. Report prepared for the 26th Annual Forest Pest Management Forum, 16–18 November, Ottawa, Ontario. Canadian Forest Service, Natural Resources Canada, and Ontario Ministry of Natural Resources.

Hudson Bay Mining and Smelting Co. Ltd. 1993. Annual report. Flin Flon, Manitoba.

Ives, W.G.H. and H.R. Wong. 1988. Tree and shrub insects of the Prairie provinces. Information Report NOR-X-292. Northern Forestry Centre, Canadian Forest Service, Edmonton, Alberta. 327 pp.

Jardon, Y., L. Filion, and C. Cloutier. 1994. Long-term impact of insect defoliation on growth and mortality of eastern larch in boreal Quebec. Ecoscience 1:231–238.

Jeffries, D.S. 1995. A preliminary assessment of nitrogen-based fresh water acidification in southeastern Canada. Water, Air, and Soil Pollution 85:433–438.

Jeffries, D.S. (ed.). 1997. 1997 Canadian acid rain assessment. Vol. 3. The effects on Canada's lakes, rivers and wetlands. Environment Canada, Ottawa, Ontario. 245 pp.

Jeffries, D.S., T.A. Clair, P.J. Dillon, M. Papineau, and M.P. Stainton. 1995. Trends in surface water acidification at ecological monitoring sites in southeastern Canada (1981–1993). Water, Air, and Soil Pollution. 85:577–582.

Johnston, M.H. and J.A. Elliott. 1996. Impacts of logging and wildfire on an upland black spruce community in northwestern Ontario. Environmental Monitoring and Assessment 39:283–298.

Kelly, C.A., J.W.M. Rudd, R.A. Bodaly, N.P. Roulet, V.L. St. Louis, A. Heyes, T.R. Moore, S. Schiff, R. Aravena, K.J. Scott, B. Dyck, R. Harris, B. Warner, and G. Edwards. 1997. Increases in fluxes of greenhouse gases and methyl mercury following flooding of an experimental reservoir. Environmental Science and Technology 31:1334–1344.

Kerr, J.B. and C.T. McElroy. 1993. Evidence for large upward trends of ultraviolet-B radiation linked to ozone depletion. Science 262:1032–1034.

Kevan, P.G., E.A. Tikhmenev, and M. Usui. 1993. Insects and plants in the pollination ecology of the boreal zone. Ecological Research 8:247–267.

Keys, D. 1992. Canadian peat harvesting and the environment. Sustaining Wetlands Issues Paper No. 1992-3. North American Wetlands Conservation Council (Canada), Ottawa, Ontario. 29 pp.

Kondo, E.S. and B.H. Moody. 1987. Forest insect and disease conditions in Canada 1986. Canadian Forest Service, Ottawa, Ontario. 128 pp.

Kondo, E.S. and R.G. Taylor. 1985. Forest insect and disease conditions in Canada 1984. Canadian Forest Service, Ottawa, Ontario. 76 pp.

Kronberg, B.I. 1998. Personal communication, 16 September 1998: letter to A. Kerr, Indicators and Assessment Office, Environment Canada.

Lands for Life. 1998. Consolidated recommendations of the Boreal West, Boreal East and Great Lakes St. Lawrence Round Tables. Website address: http://www.mnr.gov.on.ca/mnr/lfl/consolidated/report.html

Lavallee, A. 1974. Une réévaluation de la situation concernant la rouille vesiculeuse de pin blanc au Québec. Forestry Chronicle 50:228–232.

LeHénaff, A. 1998. Personal communication. Assessment Analyst, Indicators and Assessment Office, Environment Canada.

Lockhart, W.L., P. Wilkinson, B.N. Billeck, G.J. Brunskill, R.V. Hunt, and R. Wagemann. 1993. Polycyclic aromatic hydrocarbons and mercury in sediments from two isolated lakes in central and northern Canada. Water Science and Technology 28:43–52.

MacDonald, G.B. 1995. The case for boreal mixedwood management: an Ontario perspective. Forestry Chronicle 71:725–734.

Malley, D.F. 1993. Response of the population of crayfish Orconectes virilis *in* a Precambrian Shield lake to stress from cadmium at levels near the Canadian water quality guideline. Pages 389–392 in Proceedings of the 9th International Conference on Heavy Metals in the Environment, Vol. 1, 12–16 September 1993, Toronto, Ontario.

Malley, D.F., A.R. Stewart, and B.D. Hall. 1996. Uptake of methyl mercury by the floater mussel, *Pyganodon grandis* (Bivalvia, Unionidae) caged in a flooded wetland. Environmental Toxicology and Chemistry 15:928–936.

Manitoba Environment. 1995. Manitoba report of the Federal–Provincial Acid Rain Agreement, 1994. February 1995.

Martin, P.H. 1996. Will forest preserves protect temperate and boreal biodiversity from climate change? Forest Ecology and Management 85:335–341.

McAfee, B. 1998. Personal communication, September, Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario: letter to A. Kerr, Indicators and Assessment Office, Environment Canada.

McAndrew, B. 1998. Lands for Life or logs for jobs? The Sunday Star, 28 June 1998.

McCrea, R. and F. Burrows. 1998. Personal communication. Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario, and Pukaskwa National Park, Heron Bay, Ontario.

Mclaughlan, M. 1998. Personal communication, 30 September 1998, Forest Ecosystems Branch, Saskatchewan Environment and Resource Management: letter to A. Kerr, Indicators and Assessment Office, Environment Canada.

McLaughlin, D.L., J.C. Kinch, H. Liljalehto, and E. Boysen. 1996. Hardwood forest health surveys in Ontario - the first 10 years. Ontario Ministry of Environment and Energy/Ontario Ministry of Natural Resources.

McNabb, D. 1992. Planning harvesting operations to protect forest soils. Alberta Research Council, Edmonton, Alberta.

McNicol, D.K., M.L. Mallory, G. Mierle, A.M. Scheuhammer, and A.H.K. Wong. 1997. Leeches as indicators of dietary mercury exposure in non-piscivorous waterfowl in central Ontario, Canada. Environmental Pollution 95(2):177–181.

Mierle, G. 1997a. Mercury in Ontario's environment. SRQ Technical Bulletin No. AqSS-6, September. Aquatic Science Section, Standard Development Branch, Ontario Ministry of the Environment. 3 pp.

Mierle, G. 1997b. Mercury in Ontario's environment: Who is at risk? SRQ Technical Bulletin No. AqSS-7, September. Aquatic Science Section, Standard Development Branch, Ontario Ministry of the Environment. 4 pp.

Mills, K. 1997. Personal communication, May. Experimental Lakes Area fish populations scientist, Freshwater Institute, Department of Fisheries and Oceans.

Minns, C.K., J.E. Moore, D.W. Schindler, and M.L. Jones. 1990. Assessing the potential extent of danger to inland lakes in eastern Canada due to acidic deposition. III. Predicted impacts on species richness in seven groups of aquatic biota. Canadian Journal of Fisheries and Aquatic Sciences 47:821–830.

Moody, B.H. 1993. Forest insect and disease conditions in Canada 1990. Forestry Canada, Ottawa. 115 pp.

Moody, B.H. and P.A. Amirault. 1992. Impacts of major pests on forest growth and yield in the Prairie provinces and the Northwest Territories: a literature review. Information Report NOR-X-324. Northern Forestry Centre, Forestry Canada, Edmonton, Alberta. 35 pp.

Mosseler, A. 1992. Life history and genetic diversity in red pine: implications for gene conservation in forestry. Forestry Chronicle 68:701–708.

Mosseler, A., D.J. Innes, and B.A. Roberts. 1991. Lack of allozymic variation in disjunct Newfoundland populations of red pine (*Pinus resinosa*). Canadian Journal of Forest Research 21:525–528.

Muir, D.C.G., C.A. Ford, N.P. Grift, D.A. Metner, and W.L. Lockhart. 1990. Geographic variation of chlorinated hydrocarbons in burbot (*Lota lota*) from remote lakes and rivers in Canada. Archives of Environmental Contamination and Toxicology 19:530–542.

Muir, D.C.G., A. Omelchenko, N.P. Grift, D.A. Savoie, W.L. Lockhart, P. Wilkinson, and G.J. Brunskill. 1996. Spatial trends and historical deposition of polychlorinated biphenyls in Canadian mid-latitude and Arctic lake sediments. Environmental Science and Technology 30:3609–3617.

Munkittrick, K.R., G.J. Van Der Kraak, M.E. McMaster, C.B. Portt, M.R. van den Heuvel, and M.R. Servos. 1994. Survey of receiving-water environmental impacts associated with discharges from pulp mills. 2. Gonad size, liver size, hepatic EROD activity and plasma sex steroid levels in white sucker. Environmental Chemistry and Toxicology 13(7):1089–1101.

Myneni, R.B., C.D. Keeling, C.D. Tucker, C.J. Asrar, and R.R. Nemani. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature 386:698–702.

Noranda Minerals Inc. 1993. Environment report. Rouyn-Noranda, Quebec.

Ontario Ministry of Economic Development, Trade and Tourism. 1996. An economic profile of tourism in northern Ontario. Internal report. Tourism Policy and Research Branch. 12 pp.

Ontario Ministry of the Environment. Various years. Guide to eating Ontario sport fish. Published annually. Available from the Public Information Centre, Ministry of the Environment, 135 St. Clair Avenue West, Toronto, Ontario.

Paquin, P. and D. Coderre. 1997. Deforestation and fire impact on edaphic insect larvae and other macroarthropods. Pages 249–162 *in* Ecosystem effects of atmospheric change - sustainable development. Proceedings of a meeting held at Point Claire, Quebec, 5–6 March.

Percy, K. 1997. Forests. Pages 97–101 in D.I. Wardle, J.B. Kerr, C.T. McElroy, and D.R. Francis (eds.), Ozone science: A Canadian perspective on the changing ozone layer. Montreal Protocol, 1987–1997. Environment Canada, Ottawa, Ontario.

Piche, E. 1998. Personal communication, 29 September 1998, Environmental Monitoring and Reporting Branch, Ontario Ministry of the Environment: letter to A. Kerr, Indicators and Assessment Office, Environment Canada.

Pinel-Alloul, B. 1998. Personal communication, 30 October 1998, Directrice du Groupe de Recherche Interuniversitaire en Limnologie et en Environnement Aquatique, Université de Montréal: written comments to A. Kerr, Indicators and Assessment Office, Environment Canada.

Quaile, G. 1998. Personal communication, April. Grand Council of the Crees (of Quebec), Cree Regional Authority.

Racey, G.D. and E.R. Armstrong. 1996. Towards a caribou habitat management strategy for northwestern Ontario: running the gauntlet. Rangifer (special issue) 9:159–170.

Raske, A.G., R.J. West, and A. Retnakran. 1995. Hemlock looper Lambdina fiscellaria. Pages 141–147 in J.A. Armstrong and W.G.H. Ives (eds.), Forest insect pests in Canada. Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario.

Riemenschneider, D.E. 1985. Water stress promotes early flowering in jack pine. U.S. Department of Agriculture Forest Service Note NC-331.

Roberts-Pichette, P. 1998. Personal communication, 2 October 1998: written comments to A. Kerr, Indicators and Assessment Office, Environment Canada.

Roland, J. 1993. Large scale forest fragmentation increases the duration of tent caterpillar outbreak. Oecologia 93:25–30.

Rose, A.H. and O.H. Linquist. 1982. Insects of eastern hardwood trees. Technical Report 29. Canadian Forest Service, Department of the Environment, Ottawa, Ontario.

Rubec, C.A.A., P. Lynch-Stewart, I. Kessel-Taylor, and G.M. Wickware. 1988. Wetland utilization in Canada. Chapter 10 *in* Wetlands of Canada. Ecological Land Classification Series No. 24. Sustainable Development Branch, Environment Canada, Ottawa, Ontario, and Polyscience Publications Inc., Montreal, Quebec.

Rudd, J.W.M. 1995. Sources of methyl mercury to freshwater ecosystems: a review. Water, Air, and Soil Pollution 80:697–713.

Rudd, J.W.M., M.A. Turner, A. Furutani, A.L. Swick, and B.E. Townsend. 1983. The English-Wabigoon River system: I. A synthesis of recent research with a view towards mercury amelioration. Canadian Journal of Fisheries and Aquatic Sciences 40:2206–2217.
99

Ryan, D., O. Allen, D.L. McLaughlin, and A. Gordon. 1994. Interpretation of sugar maple (*Acer saccharum*) ring chronologies from central and southern Ontario using a mixed linear model. Canadian Journal of Forest Research 24:568–575.

Sajan, R.J. and H. Brodersen. 1992. Results of forest insect and disease surveys in the northwestern region of Ontario 1991. Miscellaneous Report No. 116. Forestry Canada, Sault Ste. Marie, Ontario. 32 pp.

Savidge, R.A. 1998. Personal communication, February. Professor of Tree Physiology, Biochemistry and Silviculture, Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton, New Brunswick.

Scheuhammer, A.M. 1996. Influence of reduced dietary calcium on the accumulation and effects of lead, cadmium and aluminium in birds. Environmental Pollution 94(3):337–343.

Scheuhammer, A.M. and P.J. Blancher. 1994. Potential risk to common loons (*Gavia immer*) from methylmercury exposure in acidified lakes. Hydrobiology 279/280:445–455.

Schindler, D.W. 1998. A dim future for the boreal waters and landscapes: Cumulative effects of climate warming, stratospheric ozone depletion, acid precipitation and other human activities. Bioscience 48(3):157–164.

Schindler, D.W. and W. Donahue. 1997. Personal communication, August. Department of Biological Sciences, University of Alberta, Edmonton, Alberta.

Schindler, D.W., K. Beaty, E.J. Fee, D. Cruikshank, E. de Bruyn, D. Findlay, G. Linsey, J.A. Shearer, M. Stainton, and M.A. Turner. 1990. Effects of climatic warming on lakes of the western boreal forest. Science 250:967–970.

Seburn, C.N.L. and D.C. Seburn. 1997. Northern Leopard Frog survey of northern Ontario: report on a declining amphibian. Unpublished report to the Wildlife Assessment Unit, Ontario Ministry of Natural Resources, Thunder Bay, Ontario.

Seburn, C.N.L. and D.C. Seburn. 1998. Status report on the Northern Leopard Frog, Rana pipiens, in Canada (Western populations). Report to the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). COSEWIC Secretariat, Canadian Wildlife Service, Environment Canada, Ottawa, Ontario.

SERM (Saskatchewan Environment and Resource Management). 1997. Saskatchewan's provincial parks: Directions for the 21st century. Regina, Saskatchewan.

SERM (Saskatchewan Environment and Resource Management). 1999. Saskatchewan's state of environment report 1999 — the Boreal Shield ecozone. Regina, Saskatchewan.

Servos, M.R., D.C.G. Muir, and G.R.B. Webster. 1992a. Environmental fate of polychlorinated dibenzo-p-dioxins in lake enclosures. Canadian Journal of Fisheries and Aquatic Sciences 49:722–734.

Servos, M.R., D.C.G. Muir, and G.R.B. Webster. 1992b. Bioavailability of polychlorinated dibenzo-p-dioxins in lake enclosures. Canadian Journal of Fisheries and Aquatic Sciences 49:735–742.

Shaw, R.W. (ed.). 1997. Climate variability and climate change in Atlantic Canada. Proceedings of a workshop, 3–6 December 1996, Halifax, Nova Scotia. Environment Canada, Atlantic Region, Bedford, Nova Scotia.

Shearer, J.A. 1998. Personal communication. Experimental Lakes Area Operations, Fisheries and Oceans Canada, Winnipeg, Manitoba.

Snucins, E.J. and J.M. Gunn. 1995. Coping with a warm environment: Behavioral thermoregulation by lake trout. American Fisheries Society 124:118–123.

Steedman, R.J. and P. Morash. 1998. Effects of forestry and forest regeneration on aquatic ecosystems. In B. Wagner and S. Columbo (eds.), Regenerating Ontario's forests. Fitzhenry and Whiteside, Markham, Ontario.

Sterner, T.E. and A.G. Davidson. 1981. Forest insect and disease conditions in Canada 1980. Canadian Forest Service, Ottawa, Ontario. 43 pp.

Stewart, R.B. 1996. Forests. Pages 187–196 *in* Ecosystem effects of atmospheric change—Sustainable development. Proceedings of a meeting held at Point Claire, Quebec, 5–6 March 1996.

Stewart, R., E. Wheaton, and D. Spittlehouse. 1997. Climate change: Implications for the boreal forest. Paper presented at the Air and Water Waste Management Association Symposium on Implications of Climate Change: What do we know?, 22–24 September, Calgary, Alberta.

St. Louis, V.L., J.W.M. Rudd, C.A. Kelly, and L.A. Barrie. 1995. Wet deposition of methyl mercury in northwestern Ontario compared to other geographic locations. Water, Air, and Soil Pollution 80:405–414.

Stocks, B.J. 1975. The 1974 wildfire situation *in* northwestern Ontario. Great Lakes Forest Research Centre Information Report O-X-232. Canadian Forest Service, Sault Ste. Marie, Ontario.

Stocks, B.J., B.S. Lee, and D.A. Martell. 1996. Some potential carbon budget implications of fire management in the boreal forest. Pages 8–96 in M.J. Apps and D.T. Price (eds.), Forest ecosystems, forest management and the global carbon cycle. NATO ASI Series, Subseries 1, Vol. 40, A global environmental change. Springer-Verlag, Berlin, Germany.

Sturtevant, B.R., J.A. Bissonette, and J.N. Long. 1996. Temporal and spatial dynamics of boreal forest structure in western Newfoundland: Silvicultural implications for marten habitat management. Forest Ecology and Management 87:13–25.

Tarnocai, C. 1998. Personal communication, April. Agriculture and Agri-Food Canada.

Thompson, H.M. 1996. Interactions between pesticides; a review of reported effects and their implications for wildlife risk assessment. Ecotoxicology 5:59–81.

Thompson, I.D. 1991. Could marten become the spotted owl of eastern Canada? Forestry Chronicle 67:136–140.

Thompson, I.D. and P.W. Colgan. 1994. Marten activity in uncut and logged boreal forests in Ontario. Journal of Wildlife Management 58:280–288.

Thompson, I.D. and D.A. Welsh. 1993. Integrated resource management in boreal forest ecosystems — impediments and solutions. Forestry Chronicle 69:32–39.

UNCED (United Nations Conference on Environment and Development). 1992. Agenda 21. United Nations Publications, New York, N.Y.

Van dijk, A. 1998. Personal communication, 28 September, La Mauricie National Park: letter to A. Kerr, Indicators and Assessment Office, Environment Canada.

Vinebrook, R.D. and P.R. Leavitt. 1996. Effects of ultraviolet radiation on periphyton in an alpine lake. Limnology and Oceanography 41:1035–1040.

Volney, W.J.A. 1988. Analysis of historic jack pine budworm outbreaks in the Prairie provinces of Canada. Canadian Journal of Forest Research 18:1152–1158.

Wardle, D.I. 1997. Trends in ozone over Canada, ozone depleting substances and the UV-B. Pages 66–74 in Proceedings of the International Specialty Conference: Emerging Air Issues for the 21st Century: The Need for Multidisciplinary Management — An International Management Conference, 20–24 September, Calgary, Alberta. Air and Waste Management Association, Pittsburgh, Pennsylvania.

Watmough, S. and T. Hutchinson. 1998. Final report on the dendrochemistry of declining sugar maple in central Ontario. Contracted project prepared for the Ecological Monitoring Coordinating Office, Environment Canada, Burlington, Ontario.

Welsh, D.A. and L.A. Venier. 1996. Binoculars and satellites: developing a conservation framework for boreal forest wildlife at varying scales. Forest Ecology and Management 85:53–65.

Wildlife Ministers' Council of Canada. 1990. A Wildlife Policy for Canada. Available from Canadian Wildlife Service, Environment Canada, Ottawa, Ontario.

Wood, J.A. 1997. Personal communication. Ecological Research Division, Prairie and Northern Region, Environment Canada, Regina, Saskatchewan.

Woodwell, G.M., F.T. Mackenzie, R.A. Houghton, N.J. Apps, E. Gorham, and E.A. Davidson. 1995. Will the warming speed the warming? Pages 393–411 in G.M. Woodwell and F.T. Mackenzie (eds.), Biotic feedbacks in the global warming climatic system. Oxford University Press, New York, N.Y.

Yan, N.D. and T.W. Pawson. 1997. Changes in the crustacean zooplankton community of Harp Lake, Canada, following invasion by *Bythotrephes cederstroemi*. Freshwater Biology 37:409–425.

Yan, N.D., W. Keller, N.S. Scully, D.R.S. Lean, and P.J. Dillon. 1996. Increased UV-B penetration in a lake owing to drought-induced acidification. Nature 381:141–143.

Appendix 1: Priorities for Environmental Monitoring of Acid Deposition

Several recent assessments and reports have identified research and monitoring priorities related to acid deposition.

The 1997 Canadian assessment of the effects of acid rain on Canada's forests (Hall et al., 1997) recommended the following:

a) Further analysis of sulphate and nitrate deposition is required, including enhanced modelling of critical loads and related exceedances.

b) Critical levels for pollutants that trees could tolerate without short-term and permanent damage should be developed.

c) Critical levels and areas of exceedance need to be mapped for forest ecosystems that are at high risk from acid rain.

d) Status and trend analysis of the health of Canada's forests requires inclusion of a broad spectrum of ecological attributes of forest ecosystems.

e) A comprehensive approach to assessment of forest health, which links stressors and their cumulative impacts, is needed.

f) 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.

The 1997 Canadian assessment of the effects of acid rain on Canada's lakes, rivers, and wetlands (Jeffries, 1997) made the following recommendations for future verification of recovery in response to emission controls:

a) Lake and/or river monitoring networks must be maintained throughout southeastern Canada at a level sufficient to detect temporal change in acidification status.

b) A small number of intensive, ecological monitoring sites across southeastern Canada must be maintained also, so that the cause of change can be identified.

c) On-the-ground verification of regional recovery can be accomplished only by resurveying lakes. Almost no lake surveys have been conducted since the late 1980s, and the regional database is becoming aged.

d) Canadian biomonitoring programs related to acidification either have ceased or may do so in the near future. They should be reinstated and/or maintained.

e) Whole-lake experimental acidification/recovery research is now funded at an ineffectual level, even though recovery is nowhere near complete. A reasonable funding level should be restored and the projects completed.

The knowledge gaps identified in the 1997 Canadian assessment of the effects of acid rain on Canada's lakes, rivers, and wetlands (Jeffries, 1997) are:

a) the influence of nitrogen-based acidification;

b) the erosion of the base cation pool in soils;

c) the lagging between ecosystem acidification and recovery pathways;

d) dissolved organic carbon as a significant controller of ecosystem responses;

e) effect of episodic acidification on aquatic biota;

f) interaction with other ecosystem stressors (e.g., climate, UV-B, mercury, etc.);

g) natural variability in aquatic communities at low pH;

h) the lag in biological recovery relative to chemical recovery;

i) biological makeup of recovering ecosystems and their long-term sustainability;

j) the role of acidification in the loss of primary production in sensitive ecosystems; and

k) the cumulative impact of acidification and other stressors on biological diversity.

Appendix 2: Common and Scientific Names of Selected Species Referred to in the Report

Species group	Common name	Scientific name
Vertebrate animals	Caribou, woodland Frog, northern leopard Loon, common Otter	*Rangifer tarandus caribou* *Rana pipiens* *Gavia immer* *Lutra canadensis*
Plants and kin	Alga, filamentous green Aspen, trembling Fir, balsam Hemlock, eastern Lichen, boreal felt Loosestrife, purple Maple, sugar Pine, jack Pine, red Pine, white Poplar, balsam Poplar species Spruce, black Spruce, red Spruce, white	*Zygogonium* sp. *Populus tremuloides* *Abies balsamea* *Tsuga canadensis* *Erioderma pedicellatum* *Lythrum salicaria* *Acer saccharum* *Pinus banksiana* *Pinus resinosa* *Pinus strobus* *Populus balsamifera* *Populus* spp. *Picea mariana* *Picea rubens* *Picea glauca*
Others (invertebrates, fungi, etc.)	Blister rust, white pine Budworm, jack pine Budworm, spruce Caterpillar, forest tent Looper, hemlock Water flea, spiny	*Cronartium ribicola* *Choristoneura pinus pinus* *Choristoneura fumiferana* *Malacosom disstria* *Lambdina fiscellaria fiscellaria* *Bythotrephes cederstoemi*

Appendix 3: Units of Measure Used in the Reports

Quantity	Symbol	Unit name
Area	ha	hectare
	km^2	square kilometre
	m^2	square metre
Concentration	µmol/L	micromole per litre
	ppm	part per million
Energy	MW	megawatt
Length	km	kilometre
	m	metre
	mm	millimetre
	nm	nanometre
Time	s	second
Volume	L	litre
	m^3	cubic metre
Weight	g	gram
	kg	kilogram
	kt	kilotonne
	t	tonne
Miscellaneous	µeq	microequivalent

ENVIRONMENTAL CHOICE · CHOIX ENVIRONNEMENTAL ·