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Science Assessment

SUMMARY OF KEY RESULTS

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While Canada has been very successful at reducing acid-causing emissions, acid deposition is still affecting the Canadian environment and the health of Canadians. Two methodologies, indicating best and worst case scenarios, were used to estimate the impact of acid deposition on Canada. According to these methodologies, approximately 21-75% of eastern Canada, corresponding to approximately 0.5-1.8 million km², continues to receive levels of acid deposition in excess of critical loads (i.e. the amount of acid deposition that a particular region can receive without being adversely affected). It is estimated that a further 75% reduction in sulphur dioxide (SO₂) emissions will be required from Canada and the U.S., beyond those agreed to in the Canada-U.S. Air Quality Agreement for 2010, in order to protect eastern Canadian ecosystems from damage by acid deposition. In eastern Canada, sulphur in deposition is still the predominant acidifying agent. However, it is possible that sustained high levels of nitrogen oxide (NO_x) emissions could result in the acidification of ecosystems in the future.

In western Canada (here defined as west of Ontario), there are large areas comprised of geology that is sensitive to acid deposition. These areas are located in northern and southeastern Manitoba, northern Saskatchewan, northeastern Alberta, Nunavut, the Northwest Territories and the coastal mountain ranges of British Columbia. At present, there is insufficient data on both the capacity of these ecosystems to safely assimilate acid deposition and levels of deposition. With a few exceptions, it is not possible to determine the extent to which acid deposition is affecting these potentially vulnerable ecosystems at this time.

In Canada and the U.S., major sources of acid-causing emissions are electric power generation, non-ferrous

mining and smelting, upstream oil and gas operations and transportation. Major Canadian emissions sources that impact eastern Canada are located in Ontario and Quebec. Major emissions sources in the U.S., that impact eastern Canadian ecosystems, are located in the states of the Midwest, Great Lakes, Ohio River Valley and East Coast. Major emissions sources that impact western Canadian ecosystems are located in Alberta, southern Saskatchewan and northern Manitoba.

There are several factors that are decreasing, or have the potential to delay, the efficacy of emission reductions. The concentration of acid-neutralizing base cations in soils is being depleted as acid deposition continues. Consequently, the capacity of soils to neutralize acids is declining, thereby increasing the susceptibility of many regions to acid deposition. As acid deposition decreases, sulphur stored in forest soils is being released into lakes and rivers adding to the acid burden of these ecosystems. Under periods of drought followed by rain, wetlands which store sulphur from deposition, release it into lakes and streams resulting in episodic acidification events. In a few locations, excess nitrogen is leaving watersheds and acting as an additional acidifying agent to surface waters.

Despite factors that are decreasing the efficacy of emission reductions, improvements in the acidification status of many lakes are being observed, particularly those located near smelters which have dramatically reduced emissions. The pathway to recovery in many of these lakes is complex and slow and may result in permanently altered biological communities. The capacity for many of these lakes to support aquatic biota is improving however, and increases in waterbirds such as the Common Loon have been observed.



Acid deposition is linked to many other environmental issues. Acid deposition shares precursor emissions (SO_2 and NO_x) with ground-level ozone and particulate matter (a.k.a. smog). The pollutants that cause acid deposition contribute to climate change and climate change has the potential to affect the geographic extent and severity of acid deposition and its effects. Furthermore, acid deposition exacerbates the conversion of relatively non-toxic elemental mercury to highly toxic and bioaccumulative methylmercury. Hence, mitigating acid deposition benefits many other environmental, economic and human health issues.

Due to the wide-ranging impacts of acid deposition on humans and their environments, there are potentially many socio-economic benefits from acid deposition mitigation. For example, the emerging science linking acid deposition to reductions in the productivity of forests suggests that reducing acid deposition could have significant economic benefits to the forestry sector.

Clearly, the problem of acid deposition is not yet fully addressed. In eastern Canada, on-going efforts to reduce acid-causing emissions and better understand the complex and long-term impacts of this pollution will be essential for effectively managing the issue into the future. The presence of acid-sensitive geology and increasing emissions of SO_2 and NO_x suggests that new monitoring efforts should expand into the western provinces to ensure that acid deposition does not damage ecosystems in this region.

The 2004 Canadian Acid Deposition Science Assessment has been prepared by researchers from the federal and provincial governments and academia. This assessment builds upon the results presented in the 1997 Canadian Acid Rain Assessment and presents the latest research related to the following:

- ⇒ progress towards reducing acid-causing emissions;
- ⇒ response of the atmosphere to past, present, and future changes in emissions;
- ⇒ new critical load estimates for aquatic and terrestrial ecosystems;
- ⇒ effects on forests, soils, aquatic ecosystems, wildlife, and human health;
- ⇒ recovery of aquatic ecosystems;
- ⇒ linkages to other environmental issues;
- ⇒ gaps in our understanding of the issue; and,
- ⇒ on-going efforts to quantify the costs and benefits associated with reducing acid deposition.

The assessment consists of two documents, the Summary of Key Results and the Assessment. The Summary of Key Results synthesizes the major findings of the Assessment in the context of ten questions and sub-questions put forth by the acid deposition policy and science communities. The Assessment presents a comprehensive review of acid deposition science in Canada.

The 2004 Canadian Acid Deposition Science Assessment represents two firsts: It is the first major synthesis of acid deposition science in Canada since the launch of the Canada-wide Acid Rain Strategy for Post-2000; and, it is the first comprehensive examination of atmospheric and ecosystem responses to sulphur dioxide (SO₂) emission reductions achieved under Phase I of Title IV of the 1990 U.S. Clean Air Act Amendments.

The fifth acid deposition science assessment in Canada in the last 25 years, this report arrives at an interesting time in the lifecycle of this issue. Since completion of the last assessment¹, compelling new science has emerged linking chronic acidification of soils to forest decline and delays in aquatic ecosystem recovery. Large increases in emissions of SO₂ and nitrogen oxides (NO_x) from oil sands operations in northern Alberta are raising concerns that acid deposition could potentially impact the west. Despite widespread misconceptions that the issue is solved, new research indicates that the problem could linger for another 60 years or more in eastern Canada². With public awareness and concern for the issue at low ebb, this is an opportune time to take stock and plan for the future.

What is acid deposition? Acid deposition is the end product of reactions between sulphur oxides (SO_x), nitrogen oxides (NO_x) and water in the atmosphere. Acid deposition reaches earth as precipitation (acid rain or fog) and as gases, acid aerosols and particles (dry deposition or sedimentation). The acidity (or pH) of acid deposition is influenced by atmospheric concentrations of sulphur- and nitrogen-derived acids and bases. Atmospheric levels of acids and bases are primarily

determined by anthropogenic emissions of SO_x, NO_x, ammonia and base cations from sources such as base metal smelting, thermal electric power generation, upstream oil and gas and transportation. In eastern Canada, SO₂ emissions account for the majority of acidity in deposition.

Pollutants that cause acid deposition can travel hundreds and even thousands of kilometres from the source of emission. Due to long-range transport and the destructive nature of acids, acid deposition has a wide range of impacts on humans, their environments and economy over a broad geographic range. Acid deposition affects lakes, rivers, soils, forests, buildings, and human health. Acid deposition reduces the biodiversity of aquatic ecosystems and has the potential to alter the composition of species in terrestrial ecosystems.

Acid deposition shares precursor emissions (SO_x and NO_x) with ground-level ozone and particulate matter (a.k.a. smog). Nitrogen oxides can contribute to the formation of ozone in the presence of volatile organic compounds (e.g., solvents) and sunlight. Sulphur and nitrogen oxides can react with other chemicals to form particulate matter (PM). Both PM and ozone are known to adversely affect the health of individuals. Furthermore, smog and some smog precursors scatter or absorb light travelling through the atmosphere, which affects visibility and contributes to climate change.

Long-range transport, combined with the proximity of major sources of SO_x and NO_x emissions in the U.S. to Canada, means that solutions to Canada's acid deposition problem require emission reductions from both countries. In Canada, the Eastern Canadian Acid

¹Environment Canada, 1998. 1997 Canadian Acid Rain Assessment. Vols. 1-5. ISBN 0-662-2598-6

²Based on forecast modelling of ecosystem response to optimistic emission reduction scenarios from Clair et al. (2003) for Nova Scotia and New Brunswick and Aherne et al. (2003) for Ontario. Studies assume that factors that would slow ecosystem recovery such as forest management practices, forest fires and nitrate leaching are not occurring.

Rain Program (ECARP) represented the first coordinated effort of the federal government and the seven easternmost provinces to address this issue. This program, launched in 1985, achieved its goal of reducing SO₂ emissions to 50% of 1980 levels by 1994. In the U.S., amendments were made to the U.S. Clean Air Act in 1990, which specified deep cuts in SO₂ emissions by 1997 (Phase I), further cuts by 2010 (Phase II) and reductions in NO_x emissions. The Canada-U.S. Air Quality Agreement (AQA), signed in 1991, reaffirmed the commitments of both governments to reduce SO₂ and NO_x emissions and consult on, and develop, the means to address other transboundary air pollution issues.

When the ECARP was developed, it was hoped that SO₂ emission reductions by Canada and the U.S. would reduce the deposition of sulphates from precipitation (i.e., rain and snow) from levels as high as 40 kg per hectare per year to no more than 20 kg per hectare per year. The 20 kg per hectare per year “target load”³, specified in 1983, was expected to protect aquatic environments that were moderately sensitive to acids. Although the 20 kg per hectare target is expected to be achieved by 2010, both the 1990⁴ and 1997⁵ Canadian Acid Rain Assessments concluded that many lakes and forests will continue to sustain damage from acid deposition. The 1990 assessment confirmed that a more meaningful measure of an ecosystem’s capacity to receive acid deposition without sustaining damage is the “critical load.” Critical loads are estimates of an environment’s assimilative capacity, that is, the amount of acid deposition that a particular region can receive without being adversely affected.

The 1985 ECARP was a first step towards solving the acid deposition problem in Canada. In 1994, the federal, provincial and territorial governments began developing a long-term acid deposition management strategy for Canada that would mitigate the environmental and human health effects associated with acid deposition and

acidifying emissions, respectively. Launched in 1998, the Canada-wide Acid Rain Strategy for Post-2000 (a.k.a. the Strategy) has a long-term goal “to meet the environmental threshold of critical loads for acid deposition across Canada.” The *Strategy* is currently being implemented. It consists of the following five commitments:

- ⇒ Pursuing further emission reduction commitments from the U.S.;
- ⇒ Establishing new sulphur dioxide (SO₂) emission reduction targets in eastern Canada;
- ⇒ Preventing pollution, and keeping “clean” areas clean;
- ⇒ Ensuring the adequacy of acid rain science and monitoring programs; and,
- ⇒ Reporting annually on SO₂ and nitrogen oxides (NO_x) emissions and forecasts, on compliance with international commitments, and on progress in implementing the strategy.

This assessment builds upon the results presented in the 1997 Canadian Acid Rain Assessment and presents our current scientific foundation for supporting the commitments of the *Strategy*. Preparation of this assessment began in 2001 with a series of workshops involving scientists and policy-makers from the federal and provincial governments and several universities. These workshops led to the development of a table of contents for the assessment as well as the following ten science questions that articulate the information needs of the science and policy communities:

1. Is acid deposition still affecting the Canadian environment and the health of Canadians? If so, where, how, and to what extent is it affecting these endpoints?
2. What are the current and forecasted trends in acid-causing emissions?

³In this case, target load is defined as an ecologically based objective that is less than the critical load and would thus allow some ecological damage. (Brydges, T. 2004. *Acid Rain in Story and Song*. Thomas and Marilyn Brydges Publ. Brampton, ON. Pp.131.)

⁴RMCC. 1990. *The 1990 Canadian Long-Range Transport of Air Pollutants and Acid Deposition Assessment Report*, Federal/Provincial Research and Monitoring Coordinating Committee.

⁵Environment Canada, 1998. *1997 Canadian Acid Rain Assessment*. Vols. 1-5. ISBN 0-662-2598-6

3. Where are the major industrial sources of acid-causing emissions that affect Canadian ecosystems?
4. Are further emissions reductions necessary in Canada and the U.S.? If so, by how much, and from where, do emissions need to be reduced?
5. Will NO_x reductions compensate for the need to reduce SO₂? Is nitrogen saturation a problem and how will changing NO_x emissions impact on Canadian ecosystems?
6. Are there other factors that might decrease the efficacy of emission reductions?
7. Are affected ecosystems recovering in response to past reductions in SO₂ emissions? If so, how is recovery proceeding? If not, why, when, and under what conditions, can we expect recovery to acceptable environmental objectives? What role do NO_x emissions play? And,
8. What are some of the socio-economic benefits of acid deposition mitigation?
9. What are the linkages and implications of other environmental problems with acid deposition, in particular, ozone and particulate matter formation, climate change and mercury?
10. Where do we need to continue atmospheric and effects monitoring? Where should we focus future research efforts for acid deposition?

The goal of this assessment is to synthesize the current state of knowledge on acid deposition in Canada. This knowledge is presented as answers to the ten questions and sub-questions in this Summary of Key Results. The full assessment provides a comprehensive examination of all aspects of acid deposition science and is published as a separate document. The full assessment and this report are available on the Environment Canada website (http://www.msc-smc.ec.gc.ca/saib/acid/acid_e.html) and from the Science Assessment and Integration Branch, Meteorological Service of Canada, Environment Canada, 4905 Dufferin Street, Downsview, Ontario, M3H 5T4.

1. Is acid deposition still affecting the Canadian environment and the health of Canadians? If so, where, how, and to what extent is it affecting these endpoints?

Acid deposition is still affecting the Canadian environment and the health of Canadians.

CANADIAN ENVIRONMENT

In Canada, the primary indicator of whether or not acid deposition is still affecting the environment is the occurrence of exceedances of critical loads. In this assessment, critical loads are defined as “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge”⁶. For the first time in North America, combined maps of the critical load values for both aquatic⁷ (i.e. lake) and terrestrial (i.e. upland forest soils) ecosystems have been produced for those regions where lake chemistry and/or soil chemistry and acid deposition data were available. The combined critical load maps take into account the acidity of wet and dry deposition derived from both sulphur and nitrogen pollutants and express critical loads as acid equivalents⁸ per hectare per year (eq/ha/yr). To produce these combined critical load maps, the most sensitive element of the environment - either the aquatic or terrestrial ecosystem - determines the critical load of a particular area (i.e. mapped grid

square). Two methods were used to calculate critical load exceedances for aquatic and terrestrial ecosystems. The first method, N-leaching, accounts for the acidity of wet and dry deposition of sulphur and only the component of nitrogen deposition that is estimated to be acidifying (i.e. not retained in the watershed). The second method, Steady-state, assumes that all sulphur and nitrogen deposition is acidifying.

N-leaching critical load exceedances best estimate the immediate impact on the environment of current levels of acid deposition. This measure is considered an “optimistic” indicator of impacts because ecosystems have yet to reach equilibrium with acid deposition. Steady-state critical load exceedances are considered a more accurate measure of the sustainable (long-term) impacts of current levels of acid deposition and may be considered a more “pessimist” measure of the short-term current impact. Exceedances of critical loads occur when levels of acid deposition exceed the level that the ecosystem can assimilate without significant harmful effects.

The results of this assessment confirm that although levels of acid deposition have declined in eastern Canada over the last several decades (e.g., Figures 1.1 and 1.2), approximately 21-75% of eastern Canada, corresponding to approximately 0.5-1.8 million km², continues to receive levels of acid deposition in excess of critical loads (Figures 1.3 and 1.4) according to best and worst case scenarios, respectively.

⁶Definition employed by the UN ECE (Nilsson, J. and Grennfelt, P. 1988. Critical loads for sulphur and nitrogen. Report from a workshop held at Skokloster, Sweden. Miljørapport 1988:15, Nordic Council of Ministers, Copenhagen, Denmark. 31pp.)

⁷Water chemistry data were compiled for 3130 lakes from all the Canadian provinces and territories (except PEI) to assess their current status. In the eastern provinces (defined as ON and eastwards), where lake chemistry is changing due to reductions in acidic deposition, the sampling period for these “current status” lakes was 1997 or later. This restriction was relaxed for the western provinces and territories. The compiled databases provide a sample population that is not a representative subset of the overall lake resource. Geographically, the lakes are irregularly distributed, often occur in clusters, and there are numerous areas where sample data are unavailable or too out-of-date. Lake samples in the eastern provinces tend to be located in acid sensitive terrain, and in both sensitive and insensitive terrain in the west and north. The available sample populations were skewed to larger lakes, and it is likely that many aquatic effects occur in the small lakes.

⁸Since S and N have different atomic weights, it is impossible to report combined critical load values on a mass basis (e.g., kg/ha/yr). Instead, combined critical loads must be reported on a charge equivalency basis, referred to as acid equivalents (e.g., eq/ha/yr).

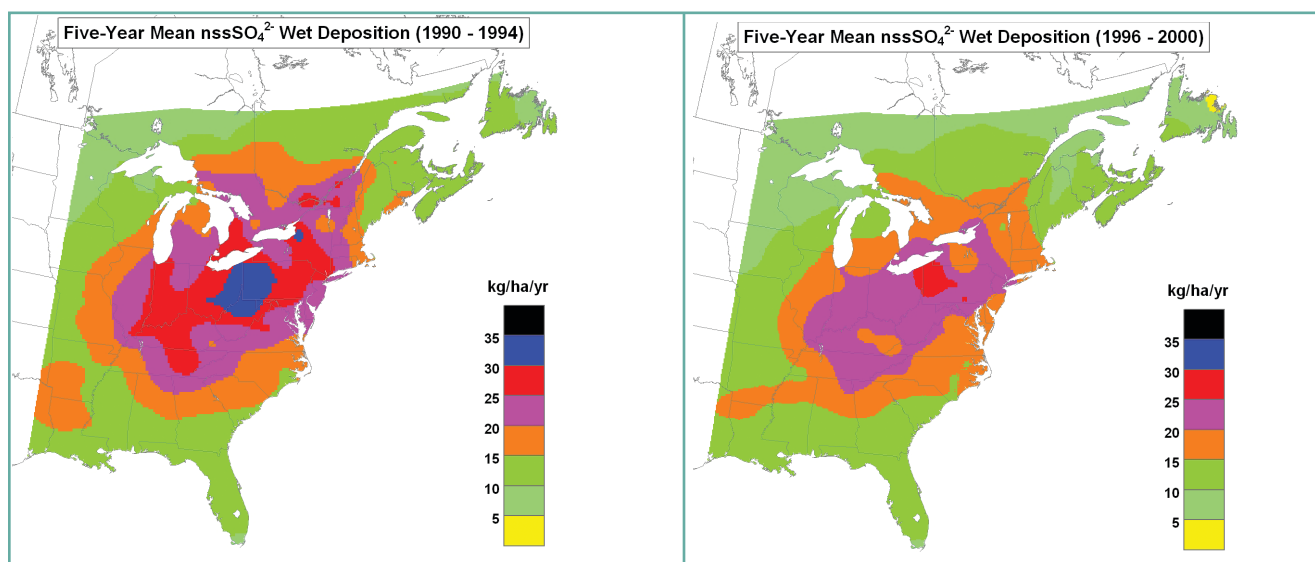


Figure 1.1: Changes to the spatial patterns of non-sea-salt-sulphate (SO_4^{2-}) wet deposition (in kg/ha/yr) in eastern North America from the early to late 1990s. The map on the left shows the 5-year-mean wet deposition pattern for the period 1990-1994 and the map on the right shows the 5-year-mean pattern for the period 1996-2000. A significant decrease in the area receiving deposition in excess of 20 kg/ha/yr has occurred in response to decreases in SO_2 emissions. (Note: 1 kg SO_4^{2-} /ha/yr is equal to 20.8 eq/ha/yr).

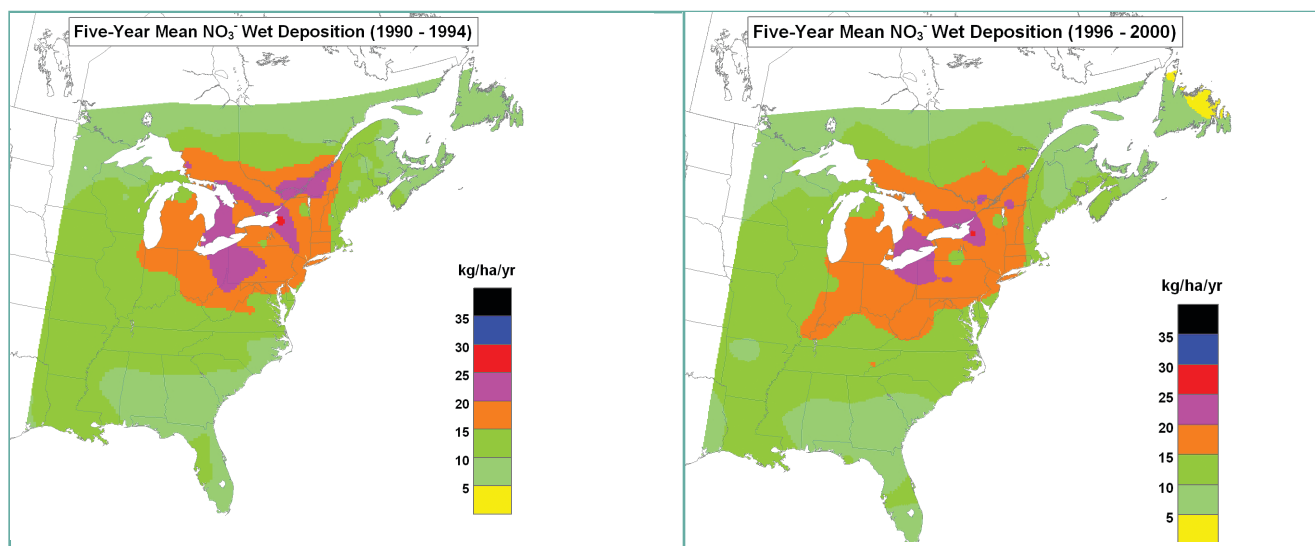


Figure 1.2: Spatial patterns of NO_3^- wet deposition over eastern North America in the early and late 1990s. The map on the left shows the 5-year-mean wet deposition pattern for the period 1990-1994 and the map on the right shows the 5-year-mean pattern for the period 1996-2000. In comparison to Figure 1.1, no major changes between the two sets of patterns are apparent; an observation that concurs with the relative constancy of NO_x emissions in this region over the same period. (Note: 1 kg NO_3^- /ha/yr is equal to 16.1 eq/ha/yr).

It should be noted that lake chemistry data are not available for sensitive terrain in some provinces, most notably northern and southeastern Manitoba, northern Saskatchewan, Nunavut, the Northwest Territories and the coastal mountain ranges of British Columbia. Hence, for these regions, the results presented in Figure 1.3 are unlikely to accurately represent the regional situation; however, there are no other independent critical load analyses to support (or refute) these values. In the other provinces, specifically Newfoundland and Labrador, Nova Scotia, New Brunswick, Quebec and Ontario, the spatial

coverage of lake chemistry data and, in some cases, the amounts of data are not adequate to represent the regional situation. It should also be noted that the critical loads for upland forest soils assume no forest harvesting and no forest fires. Since both harvesting and fires make forests more sensitive to acid deposition, the critical load values for forests reported in this assessment are if anything, too high. Furthermore, not all components of nitrogen in dry deposition are taken into account in the critical load exceedance calculations, hence, reported exceedance values are underestimates.

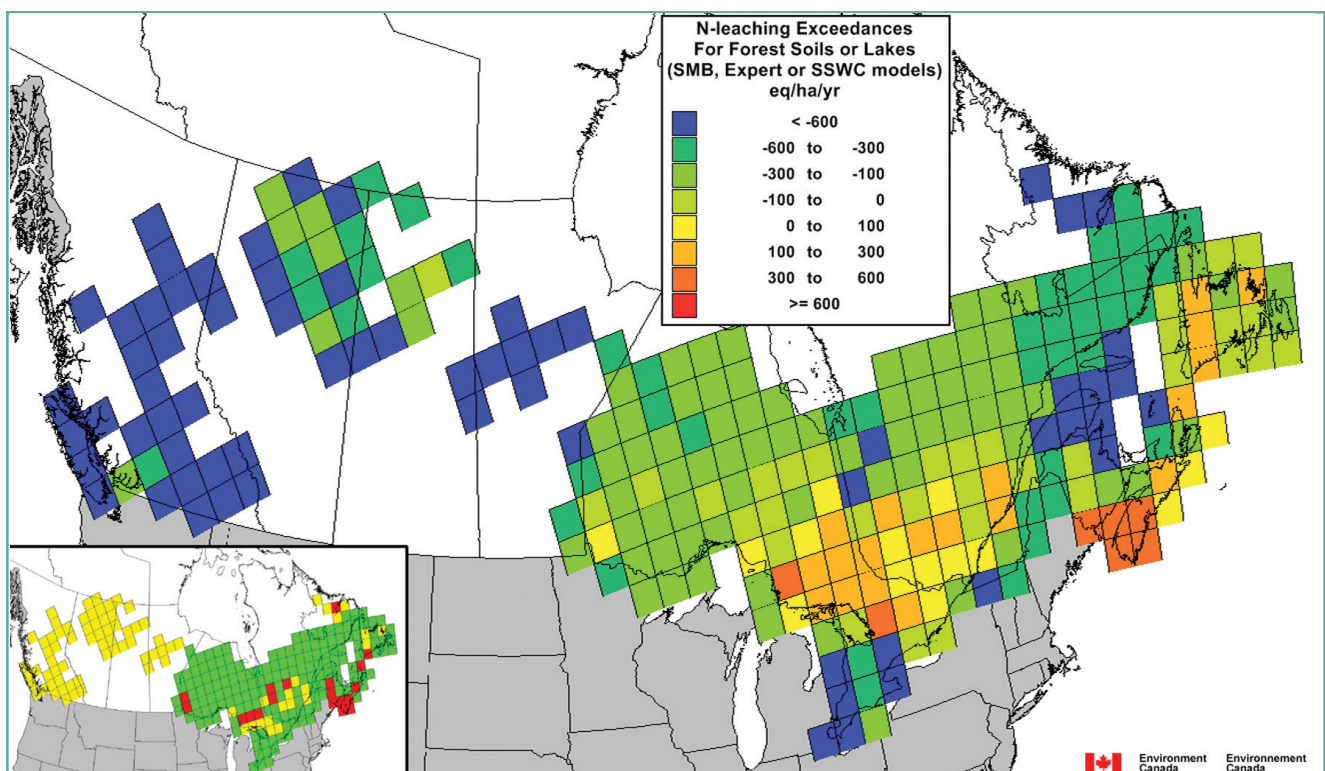


Figure 1.3: Aquatic or upland forest soil **N-leaching** critical load exceedances (wet + dry deposition in eq/ha/yr) for acidity (S+N) based on average deposition data from 1994-1998. Critical loads were calculated using either water chemistry models (i.e., “Expert” or “SSWC”) or a forest soil model (i.e., “SMB”). The critical load value for a given square is either the 5th percentile lake value or the 5th percentile soil polygon value. The index map (lower left) indicates the model selected for each grid square: red = Expert (aquatic), yellow = SSWC (aquatic), green = SMB (upland forest soils). The forest soil component was obtained by laying the grid over the soil polygon exceedance map. The forest critical load map was produced by the Forest Mapping Working Group of the New England Governors/ Eastern Canadian Premiers (NEG/ECP) Secretariat in cooperation with Ontario, Environment Canada and Natural Resources Canada – Canadian Forest Service.

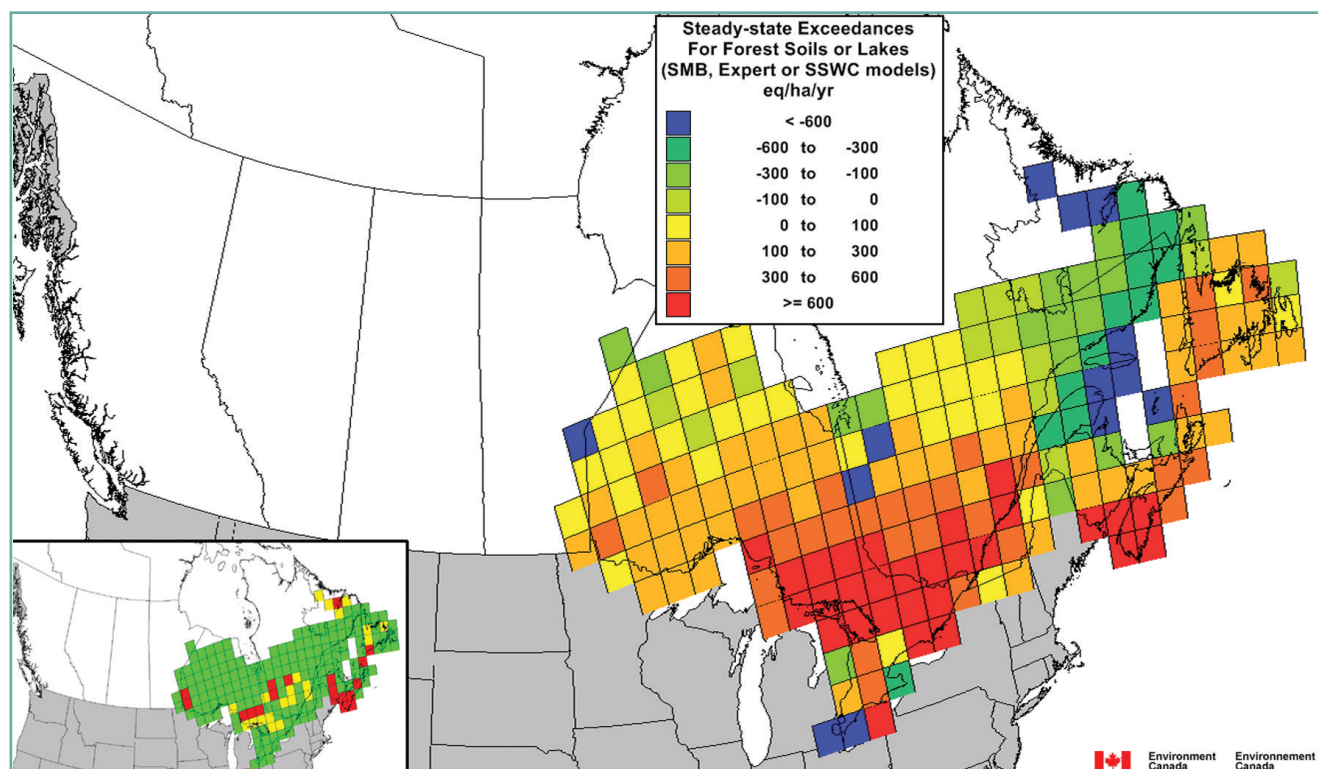


Figure 1.4: Aquatic or upland forest soil **Steady-state** critical load exceedances (wet + dry deposition in eq/ha/yr) for acidity (S+N) based on average deposition data from 1994-1998. Critical loads were calculated using either water chemistry models (i.e., “Expert” or “SSWC”) or a forest soil model (i.e., “SMB”). The critical load value for a given square is either the 5th percentile lake value or the 5th percentile soil polygon value. The index map (lower left) indicates the model selected for each grid square: red = Expert (aquatic), yellow = SSWC (aquatic), green = SMB (upland forest soils). The forest soil component was obtained by laying the grid over the soil polygon exceedance map. The forest critical load map was produced by the Forest Mapping Working Group of the New England Governors/ Eastern Canadian Premiers (NEG/ECP) Secretariat in cooperation with Ontario, Environment Canada and Natural Resources Canada – Canadian Forest Service.

In regions where the critical loads are being or have been exceeded, the following effects are being observed:

FOREST EFFECTS

Acid deposition is removing essential nutrients such as the base cations, calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+), from soils via leaching. This loss of nutrients is negatively affecting the health and growth of trees and depleting the capacity of soils to neutralize future loadings of acid deposition over much of eastern Canada. Net losses of base cations from forested watersheds in eastern Canada are widespread, particularly for Ca^{2+} . At a site in south-central Ontario, soil Ca^{2+} pools were reported to have declined by up to

30% since the early 1980s⁹. Recent declines in sulphate deposition have resulted in lower net losses of Ca^{2+} and, in turn, this has slowed down the rate of soil acidification; however, widespread net losses of Ca^{2+} (and in some cases Mg^{2+}) are still occurring in eastern Canada.

Although the rate of soil acidification has slowed down, further reductions in acid deposition are needed to meet critical loads for upland forest soils and prevent base cation levels in soils from falling below levels considered unsuitable for forest health and productivity. Currently, many areas in eastern Canada receive levels of acid deposition that exceed critical loads. In Ontario, sugar maple growth has been observed to be lower in areas

⁹Watmough, S.A., Dillon, P.J.. 2004. Major element fluxes from a coniferous watershed in central Ontario, 1983-1999. *Biogeochemistry* 67, 369-398.

where the critical load for soils is exceeded¹⁰. Analyses from the Research and Monitoring of Forest Ecosystems network in Québec show that, between the 1970s and the 1990s, hardwood and the coniferous stands located in areas where the critical loads were exceeded had a growth rate 30% lower than forest sites located in areas with no exceedances¹¹. Even in the event of large reductions in acidifying emissions, recovery of soils from acidification (i.e. replacement of base cations) is likely to be extremely slow because the most important process for replacing base cations – primary weathering of bedrock – is slow.

AQUATIC AND SOIL CHEMISTRY

Many lakes in southeastern Canada are still acidified (i.e. have lost some or all of their capacity to neutralize acids) and many do not meet the critical load pH condition of ≥ 6 ; a key threshold for the sustenance of fish and other aquatic biota. In eastern Canada, between approximately 25% (New Brunswick) and 40% (Ontario) of sampled lakes had pH levels less than 6. These percentages include those lakes that have been naturally acidified by organic acids associated with dissolved organic carbon (DOC). These types of lakes occur widely in Nova Scotia and to a lesser extent in Newfoundland but are not common in the other provinces. In Nova Scotia, 80% of sampled lakes had pH levels less than 6 and it is estimated that natural organic acids would leave approximately 40% of these lakes incapable of attaining a pH of 6 with significant reductions in acidifying emissions. In most provinces, however, the percentage of lakes with pH < 6 is a reasonable indicator of the effect of acidic deposition. Results from lake chemistry models suggest that approximately 500,000 - 600,000, or ~15%, of sensitive lakes in southeastern Canada (south of 52°N latitude) that were historically capable of having pH > 6 will have pH < 6 under levels of acid deposition similar to present conditions.

In many lakes, chemistry is responding to reductions in acidifying emissions (i.e. lakes are becoming less acidic) but several factors are acting to delay or diminish the

response. For example, there is mounting evidence that the size of acid-neutralizing base cation reservoirs in watershed soils determines the extent to which acid deposition acidifies surface waters. Net losses of base cations from forested watersheds in eastern Canada are widespread, particularly for calcium (Ca^{2+}). Hence, the capacity of watersheds to neutralize acid deposition is declining concomitant with the decline in the acidity of deposition.

In addition, the release of sulphate into surface waters exceeds the amount of sulphate received via acid deposition in most eastern Canadian forested watersheds. Likely sources of this “extra” sulphate are desorption of sulphate bound to soil, release of sulphate during the decomposition of organic matter, and drought-induced mobilization of reduced sulphur stored in wetlands or similar landscape features. All of these processes generate acids. The original source of much of this soil-bound sulphur is past inputs from acid deposition. Surface water critical load models, which are based solely on current sulphate inputs from deposition, underestimate critical load exceedances in those watersheds that exhibit substantial net losses of sulphate.

AQUATIC BIOLOGY

Algae, invertebrates and waterbird food chains continue to show acidification effects, particularly in lakes and rivers where fish communities have been impacted. Acidification effects often extend across trophic levels, altering the composition of biological communities and impacting ecosystem function. Impacts include direct acidity effects, metal toxicity, loss of prey, and reduced nutritional value of remaining prey. For example, most acid-sensitive invertebrate species are absent from lakes acidified below pH 6. Minnows and other small fish can be extirpated from small, acidified lakes and wetlands, causing important changes to the invertebrate food source of breeding waterbirds and other top predators. A general increase in the number of breeding fish-eating waterbirds (e.g. Common Loon, Common Merganser) was observed in much of southeastern Canada (i.e. Ontario,

¹⁰ Watmough, S.A.. 2002. A dendrochemical survey of sugar maple in south-central Ontario. *Water, Air and Soil Pollution* 136, 165-187.

¹¹ Quimet, R., Duchesne, D., Houle, D., Arp, P.A.. 2001. Critical load and exceedances of acid deposition and associated forest growth in the northern hardwood and boreal coniferous forests in Quebec, Canada. *Water, Air and Soil Pollution: Focus* 1, 119-134.

Quebec and Newfoundland). Recent observations from the Sudbury, Ontario region suggest that these increases may be related to improved habitat conditions in previously damaged lakes.

Elevated levels of mercury (Hg) in Common Loons, loon chicks and the fish they consume remain a cause for concern. Acidification of aquatic systems leads to increases in toxic methylmercury concentrations in water, sediment, and biota, and often results in elevated levels in the prey of fish-eating wildlife. Mercury concentrations in Common Loon adults, eggs, young and their fish prey tend to be higher in low pH lakes. Mercury concentrations in loons increase along a trajectory from west to east across southeastern Canada. High Hg levels in loons are associated with impacts to breeding productivity including reduced breeding success, reduced chick growth rates and modified chick behaviours which may increase mortality.

Atlantic salmon populations in rivers of the Southern Upland region of Nova Scotia continue to be severely impacted by acidification. Salmon in rivers with pH in the borderline toxicity range of pH 5.0 to 5.4 are at high risk of death due to sub-lethal effects which reduce feeding and growth, increase gill damage, and cause endocrine and osmoregulatory disruption. It is predicted that salmon from most Southern Upland Rivers will become extinct if adult survival rates remain at current low levels and pH recovery continues to be delayed.

HUMAN HEALTH

Recent epidemiological studies generally found small but significant associations between ambient aerosol acidity and the following outcomes: respiratory symptoms, impaired lung function, hospital admissions and emergency room visits, and premature mortality. Susceptible human sub-populations were identified for the different health outcomes. The toxicity of aerosol acidity might contribute to the associations between particulate matter (PM) and health effects. However, it is difficult to separate the effects of PM from that of aerosol acidity, because the measured components of PM were generally highly correlated with one another.

New clinical studies indicate that humans with asthma or allergies may be particularly sensitive to short-term exposure to acid aerosols alone, or to sequential exposure to sulphuric acid and ozone, compared with normal subjects. However, exposure levels in clinical studies were generally higher than levels measured in Canadian cities.

Results from recent animal toxicological studies suggest that exposure to acid aerosols can produce effects on immune defense mechanisms at concentrations close to those observed in eastern Canada. The effects of pollutant mixtures on human health endpoints can either increase or decrease compared with the effects of exposure to individual pollutants depending on the pollutants studied, the relative concentrations of individual pollutants in mixtures, and the endpoints measured.

2. What are the current and forecasted trends in acid-causing emissions?

SULPHUR DIOXIDE

In Canada, total emissions of sulphur dioxide (SO₂) declined by approximately 50% between 1980 and 2000 and are projected to decline by an additional 4% between 2000 and 2020 (Figure 1.5). These emission forecasts assume that no emission reductions are taken beyond those agreed to in Canada as of 2003. In eastern Canada, emissions of SO₂ declined by 53% between 1985 and 2000, while in western Canada, emissions of SO₂ declined by 6% during this period. Between 2000 and 2020, emissions of SO₂ are predicted to decline by 21% in eastern Canada and increase by 15% in western Canada. SO₂ emissions in western Canada are predicted to exceed emissions in eastern Canada by 2010.

In the U.S., total emissions of SO₂ declined by approximately 40% between 1980 and 2000 and are predicted to decline by approximately 38% from 2000 levels in 2020 (Figure 1.5). These emission forecasts assume that no emission reductions are taken beyond those described in the Canada-U.S. Air Quality Agreement and agreed to as of 2003.

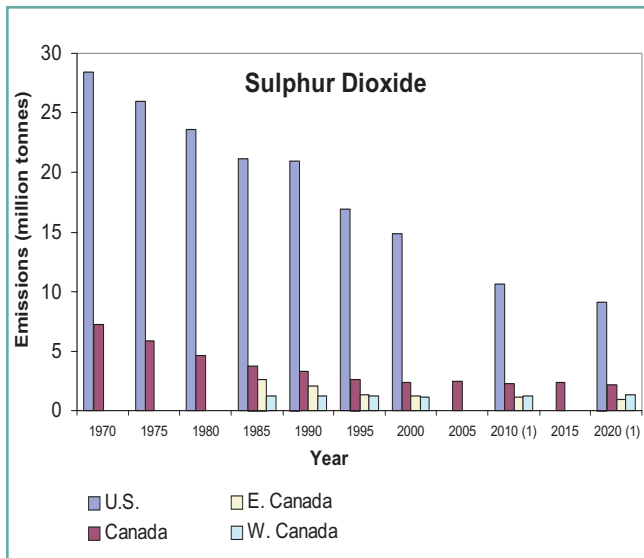


Figure 1.5: Estimated emissions of sulphur dioxide (SO₂) in the U.S. and Canada, including eastern (east of Manitoba) and western (west of Ontario) Canada. 1 - U.S. emissions forecasts are based on REMSAD emissions summaries.

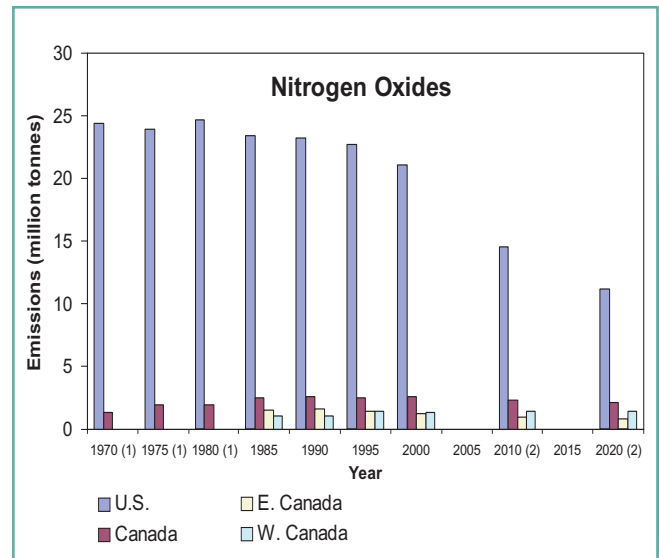


Figure 1.6: Estimated emissions of nitrogen oxides (NO_x) in the U.S. and Canada, including eastern (east of Manitoba) and western (west of Ontario) Canada. 1 - Canadian NO_x emissions for 1970 through 1980 are based on older methodologies and are not comparable to 1985 and beyond. 2 - U.S. emissions forecasts are based on REMSAD emissions summaries.

NITROGEN OXIDES

In Canada, nitrogen oxides (NO_x) emissions were approximately constant between 1985 and 2000 but are predicted to decline by approximately 17% between 2000 and 2020 (Figure 1.6). These emission forecasts assume that no emission reductions are taken beyond those agreed to in Canada as of 2003. In eastern Canada, emissions of NO_x decreased by 17% between 1985 and 2000 and are predicted to decrease by approximately 39% between 2000 and 2020. In western Canada, NO_x emissions increased by 29% between 1985 and 2000 and are predicted to increase by approximately 5% between 2000 and 2020. As of 2000, emissions of NO_x in western Canada surpassed emissions in eastern Canada. Western Canadian emissions of NO_x are predicted to continue to exceed emissions from eastern Canada to 2020.

In the U.S., NO_x emissions declined slightly between 1985 and 2000 and are predicted to decline by approximately 47% from 2000 levels in 2020 (Figure 1.6).

These emission forecasts assume that no emission reductions are taken beyond those described in the Canada-U.S. Air Quality Agreement and agreed to as of 2003.

3. Where are the major industrial sources of acid-causing emissions that affect Canadian ecosystems?

WHAT ARE THE MAJOR INDUSTRIAL SOURCE SECTORS OF ACID-CAUSING EMISSIONS IN CANADA AND THE U.S.?

In Canada, major source sectors of acid-causing emissions are non-ferrous mining and smelting, electric power generation, upstream oil and gas and transportation.

Sulphur dioxide and nitrogen oxides emission source sectors in eastern Canada are concentrated along the Windsor–Quebec City corridor with hotspots also found in central Ontario, central Quebec, south-central New

Brunswick, east-central Nova Scotia and Newfoundland (Figure 1.7 and 1.8). The Windsor-Quebec City corridor is highly urbanized and has emissions source sectors that include thermal electric power generation and on-road transportation. The hotspots in central Ontario and central Quebec are associated with non-ferrous mining and smelting operations. The hotspots in south-central New Brunswick, east-central Nova Scotia and

Newfoundland are associated with electrical power generation and other industrial emissions (e.g. mining and pulp and paper).

In western Canada, large SO_2 and NO_x emission source sectors are observed in Alberta and in defined hotspots in Manitoba and Saskatchewan. Emissions from Alberta are primarily from thermal electric power generation,

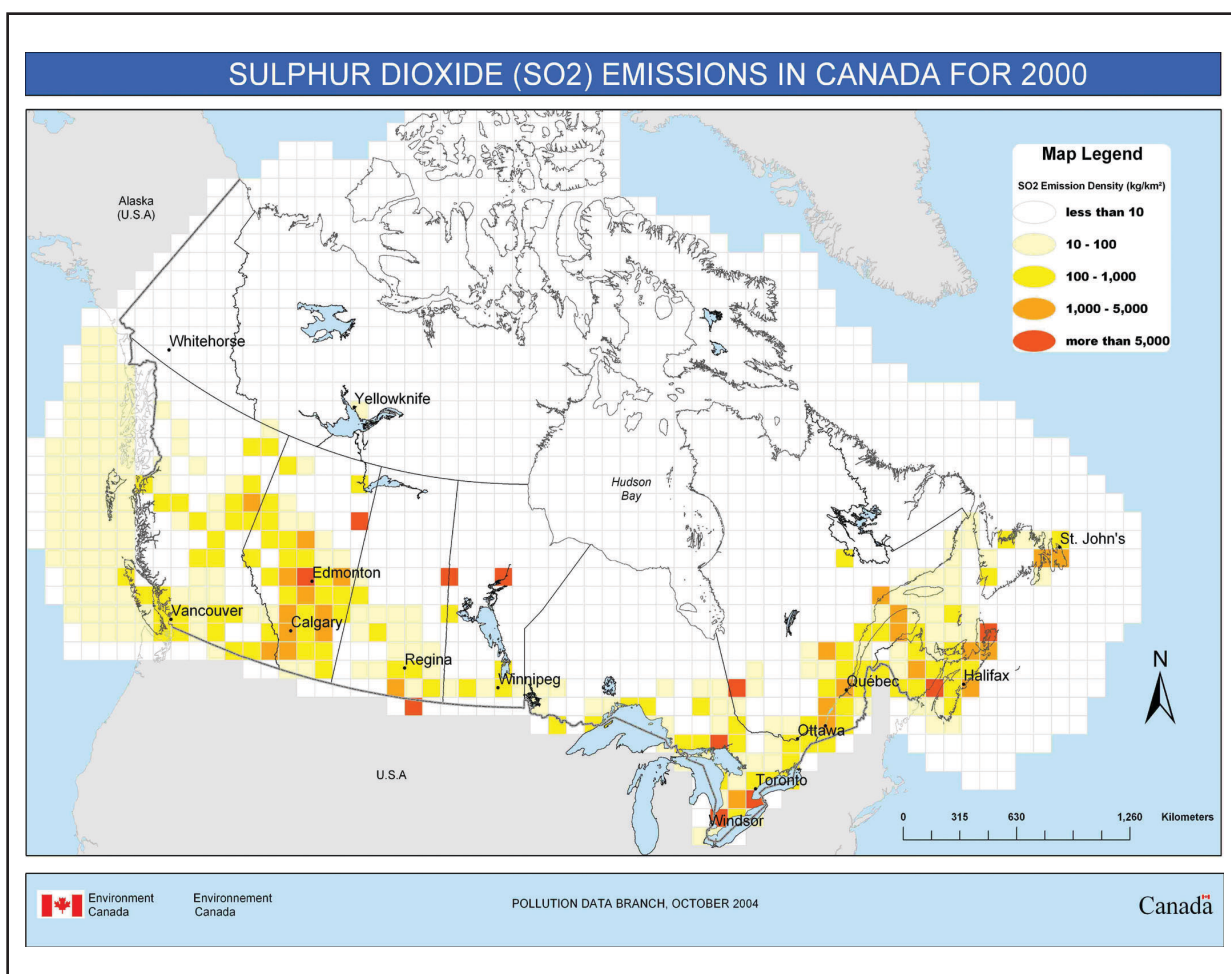


Figure 1.7: Distribution of sulphur dioxides (SO_2) emissions in Canada for 2000 (kg/km^2).

¹²Subcommittee on Scientific Co-operation (SC2) – Air Quality Committee (2004) Canada-United States Transboundary PM Assessment. 129pp.

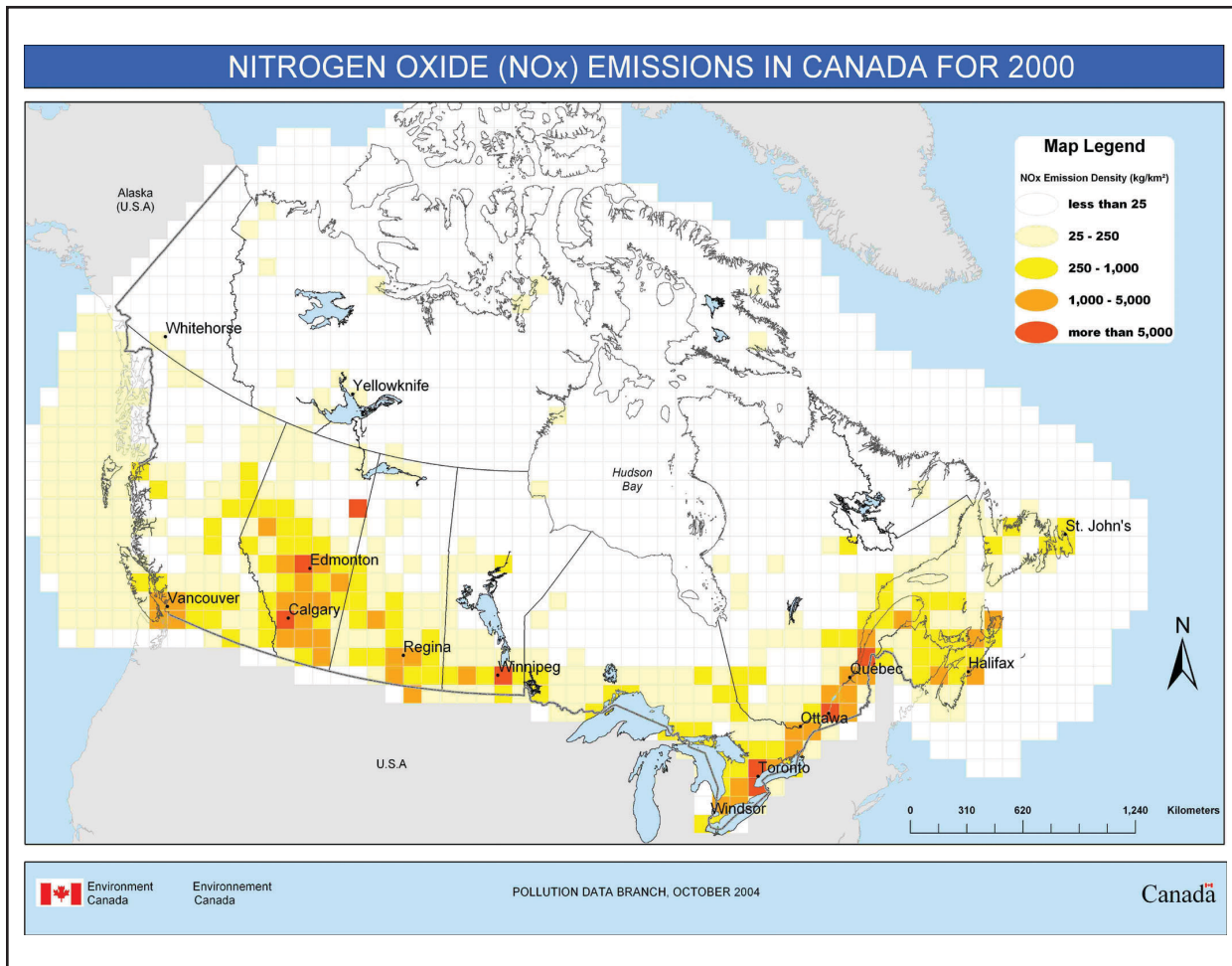


Figure 1.8: Distribution of nitrogen oxides (NO_x) emissions in Canada for 2000 (kg NO₂/km²).

upstream oil and gas and petroleum refining. High emission areas in Saskatchewan are sites of thermal electric power generation. High emission areas in Manitoba are associated with non-ferrous mining and smelting operations.

In the U.S., major source sectors of acid-causing emissions are electric power generation and on-road vehicles. Major sources of sulphur dioxide and nitrogen oxides emissions in the eastern U.S. are located in a highly industrialized and urbanized area from southeast Ohio to the western part of Virginia and western Kentucky to central Tennessee¹².

WHAT ARE THE MAJOR EMISSION SOURCE REGIONS THAT AFFECT CANADIAN ECOSYSTEMS?

Analyses of wet and dry deposition data, source attribution techniques and atmospheric models have enabled researchers to identify source regions of acid-causing emissions that affect Canadian ecosystems. Within the area of eastern Canada bounded by the Manitoba-Ontario border, Newfoundland, the Canada-U.S. border and 51° north latitude, Canadian sources emit less than 10% of total SO₂ and NO_x emissions in

eastern North America; however, that same area of eastern Canada receives roughly 30% of total sulphate and nitrate wet deposition in eastern North America (Figure 1.9). This large imbalance is due to long range transport and subsequent wet deposition of Midwestern and eastern U.S. emissions on eastern Canada. It is estimated that between 45 and 70% of sulphate and nitrate wet deposition in eastern Canada is attributable to emission sources in the eastern U.S.¹³.

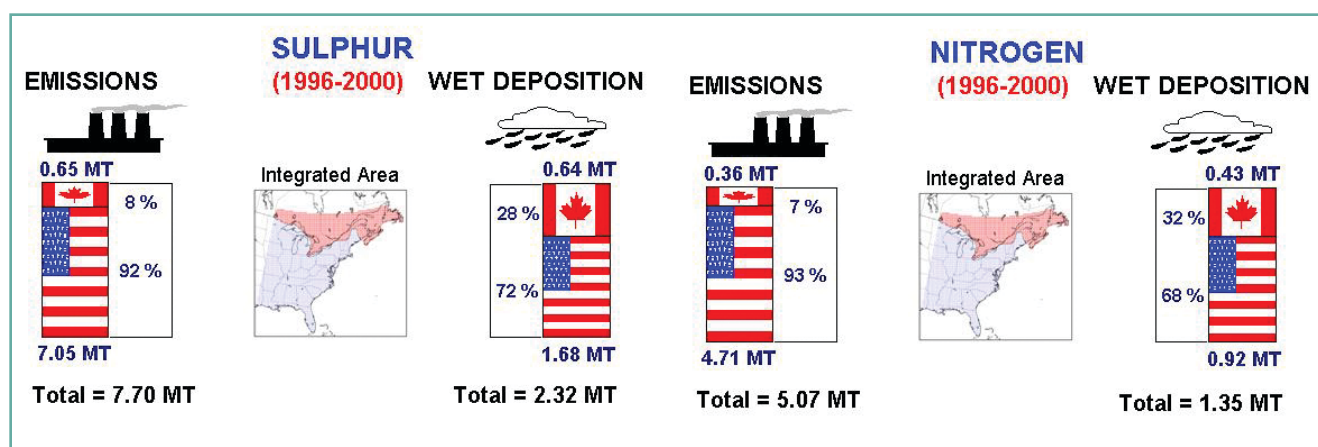


Figure 1.9: Five-year average (1996-2000) total emissions (megatonnes; MT) and wet deposition (MT) of sulphur and nitrogen over eastern Canada and the eastern U.S. (areas shown in map inset). The percentage values indicate the fraction of total eastern North American emissions and wet deposition in each country.

Wet and dry deposition data collected by the Canadian Air and Precipitation Monitoring Network (CAPMoN), combined with air mass trajectories, have been used to estimate the contribution of different emission source areas in North America to sulphur and nitrogen deposition at specific locations in Canada. In Ontario, Quebec and Nova Scotia, all CAPMoN measurement sites located within 200 km of the U.S. border are estimated to receive 50-70% of their sulphur and nitrogen deposition from emissions in the U.S. and from southern Ontario

and southern Quebec (Figure 1.10). The remaining 30 to 50% of the sulphate and nitrate at CAPMoN sites is attributable to Canadian sources to the north, west and east of the measurement locations; areas to the east of each measurement site make the lowest contribution to acid deposition at any given site. U.S. emission sources in the Great Lakes, Ohio River Valley and U.S. Midwest states appear to have the largest impact on wet and dry deposition in eastern Canada (Figure 1.10).

¹³Based on mass balance calculations.

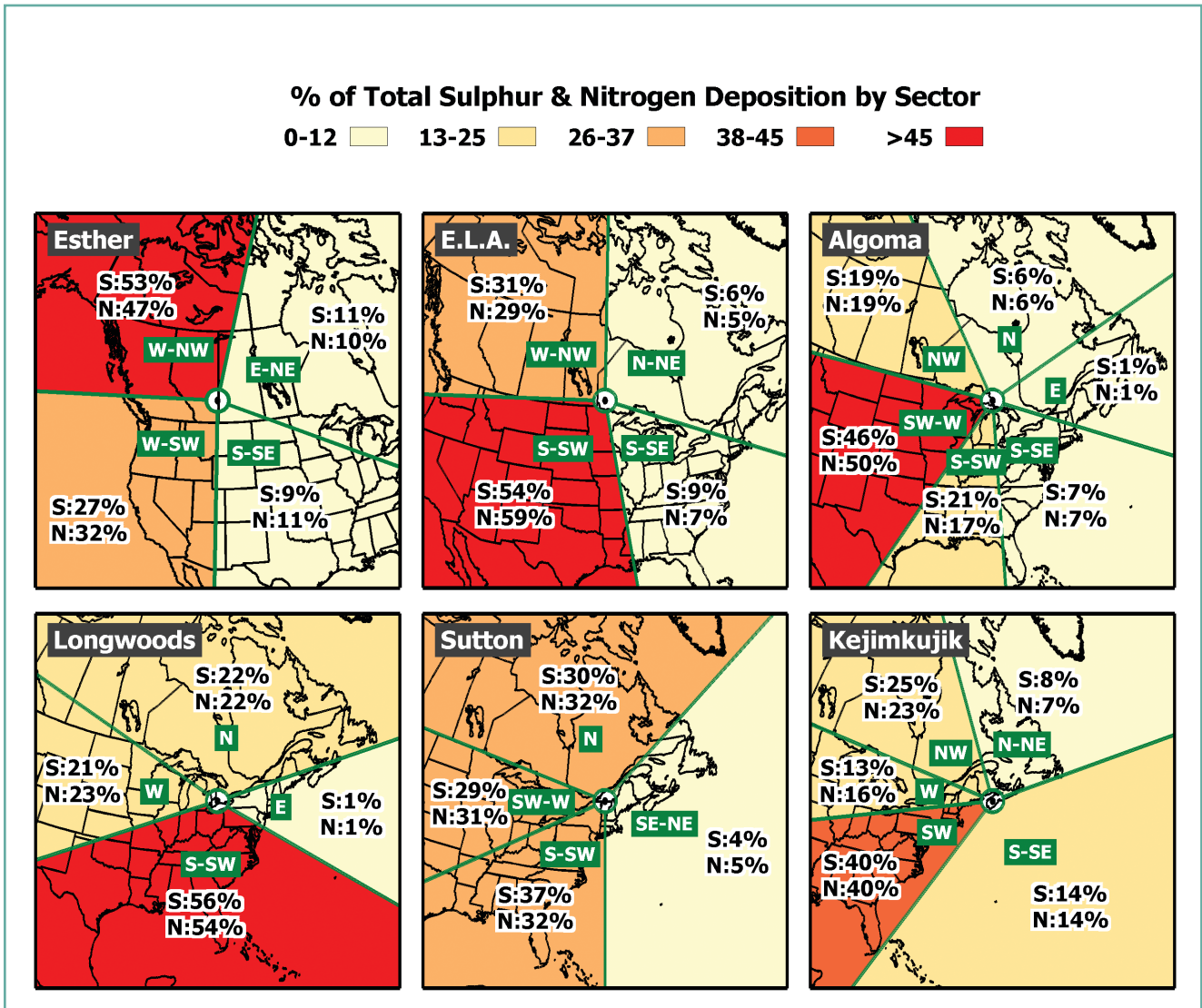


Figure 1.10: The percentage contribution of different source regions to total sulphur and nitrogen deposition at selected CAPMoN sites across Canada.

In western Canada, little measured data are available for estimating source attribution. At one measurement site in the prairies near the Alberta-Saskatchewan border, approximately 45-55% of wet and dry deposition is attributed to emission sources in central and northern Alberta/British Columbia (Figure 1.10). Sources in southern Alberta, southern BC and the northwest U.S. account for approximately 30% of the wet and dry deposition while sources east of the site account for

approximately 30% of the remaining wet and dry deposition.

Atmospheric chemistry models have been used to determine emission sources that affect Canadian ecosystems. For eastern Canada, results from the ADOM (Acid Deposition and Oxidant Model) suggest that SO₂ and NO_x emissions from both Canada and the U.S. contribute to acid deposition in eastern Canada. This

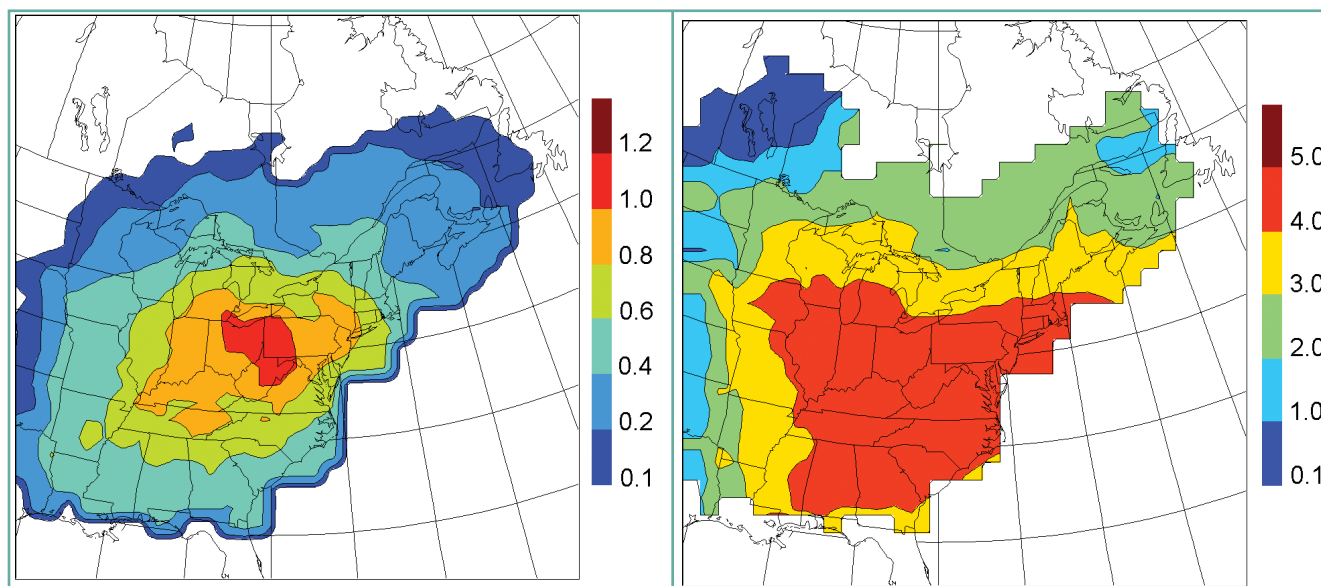


Figure 1.11: Plots of (a) actual difference and (b) percent difference in predicted annual sulphate wet deposition (units of $\text{kg SO}_4^{2-}/\text{ha}/\text{yr}$) between ADOM SO_2 emission control scenarios "PST2010A"¹⁴ and "PST2010B"¹⁵. Panel (b) was calculated as $(\text{PST2010A} - \text{PST2010B}) / \text{CCUSA2}$. The corresponding difference in U.S. SO_2 annual emissions between the two scenarios is 611 Ktonnes/yr, or 5% of U.S. emissions from "CCUSA2"¹⁶ scenario levels. (Note: $1 \text{ kg SO}_4^{2-}/\text{ha}/\text{yr}$ is equal to $20.8 \text{ eq}/\text{ha}/\text{yr}$)

conclusion is derived from comparisons of different emission scenarios for Canada and the U.S. For example, Figure 1.11 illustrates the change in sulphate wet deposition resulting from a further 5% decrease in U.S. SO_2 emissions from those projected for 2010 under the Canada-U.S. Air Quality Agreement (AQA) (reductions equal to 611 Ktonnes/yr) and no change in emissions from Canada beyond those described in the AQA. Annual sulphate wet deposition in eastern Canada is predicted to be reduced from over $0.8 \text{ kg SO}_4^{2-}/\text{ha}/\text{yr}$ in southwestern Ontario to $0.1\text{--}0.4 \text{ kg SO}_4^{2-}/\text{ha}/\text{yr}$ in the Atlantic provinces, central Quebec and Ontario. In percentage terms (Figure 1.11b), this corresponds to a 1-4% reduction in sulphate wet deposition in eastern Canada relative to the 2010 AQA scenario, with the largest percent decreases

occurring in southern Ontario, southern Quebec, New Brunswick, and Nova Scotia.

Figure 1.12, on the other hand, illustrates the change in sulphate wet deposition resulting from a 32% decrease in SO_2 emissions from Canada from projected 2010 levels (equal to 619 Ktonnes/yr) and no change in emissions from the U.S. For this scenario, annual sulphate wet deposition in eastern Canada is predicted to be reduced by $0.1\text{--}3.0 \text{ kg SO}_4^{2-}/\text{ha}/\text{yr}$ or by up to 15% in percentage terms, with the largest percentage decreases occurring along the Sudbury, Ont.-Rouyn, Quebec corridor and near Prince Edward Island. Decreases as large as 5% also occur in the northeastern U.S. as a result of the reduction in Canadian emissions. Since the actual total decrease in

¹⁴In scenario "PST2010A" the province of Ontario is assumed to reduce annual SO_2 emissions by a further 50% from the 1985 ECARP cap (885 to 443 Ktonnes SO_2/yr), the province of Quebec by a further 45% (500 to 275 Ktonnes/yr), and New Brunswick and Nova Scotia/PEI each by a further 25% (175 to 131 and 194 to 146 Ktonnes/yr, respectively). The United States is assumed to reduce its annual SO_2 emissions by a further 55% from 2010 levels described in the Canada-U.S. Air Quality Agreement (12,446 to 5,578 Ktonnes/yr).

¹⁵This scenario is very similar to the "PST2010A" scenario. The only difference is that U.S. SO_2 emissions are reduced to 40% of 2010 levels, that is, a 60% reduction, as compared to the 55% reduction considered in scenario "PST2010A".

¹⁶Scenario "CCUSA2" predicts levels of deposition in 2010 using SO_2 emission levels that would occur when the 1985 Eastern Canada Acid Rain Program (ECARP) and Title IV, Phases 1 and 2 of the 1990 U.S. Clean Air Act Amendments are fully implemented.

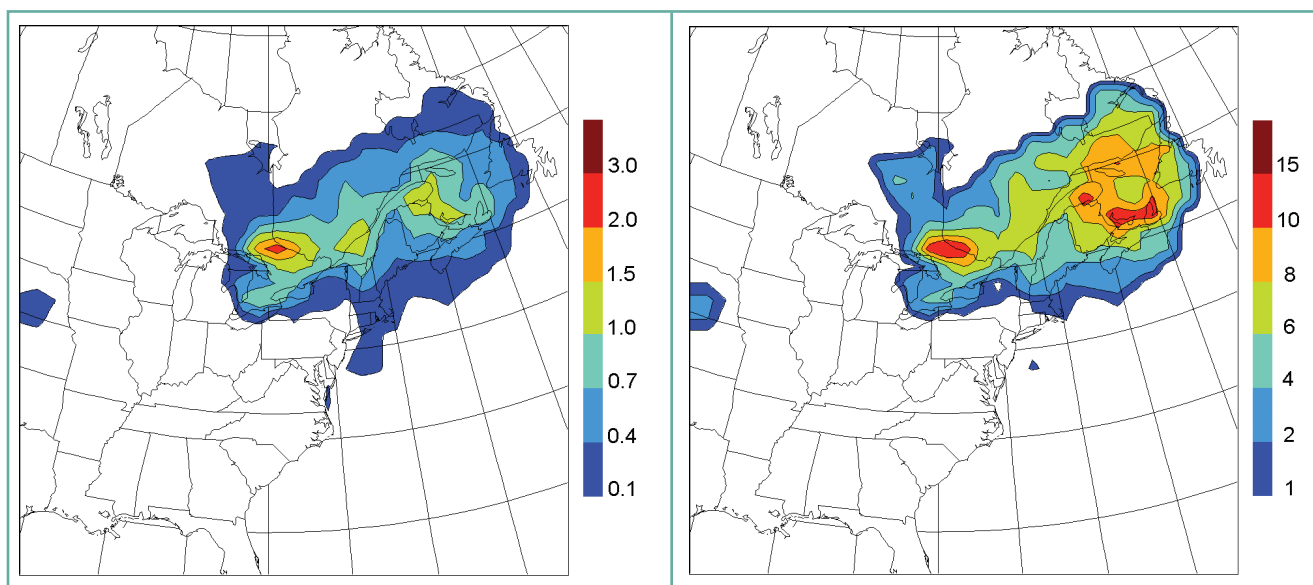


Figure 1.12: Plots of (a) actual difference and (b) percent difference in predicted annual sulphate wet deposition (units of $\text{kg SO}_4^{2-}/\text{ha}/\text{yr}$) between ADOM SO_2 emission control scenarios “CCUSA2” (see footnote 16) and “5CONLY”¹⁷. Panel (b) was calculated as $(\text{CCUSA2} - 5\text{CONLY}) / \text{CCUSA2}$. The corresponding difference in Canadian SO_2 annual emissions between the two scenarios is 619 Ktonnes/yr, or 32% from “CCUSA2” scenario levels. (Note: $1 \text{ kg SO}_4^{2-}/\text{ha}/\text{yr}$ is equal to $20.8 \text{ eq}/\text{ha}/\text{yr}$).

SO_2 emissions is nearly identical for these two scenarios, comparison of the corresponding responses suggests that a one tonne reduction of Canadian SO_2 emissions has a greater impact in Canada than a one tonne reduction in the U.S.

For western Canada, results of the REgional Lagrangian Acid Deposition (RELAD) and AES Lagrangian Sulphur Model (ALSM) models suggest that Canadian SO_2 and NO_x emission sources are the primary contributors to acid deposition. This conclusion is based on examination of continental emission maps and comparisons of model outputs to measured data. For

example, Figure 1.13 shows the 30-year mean annual sulphate and nitrate wet deposition fields predicted by RELAD based on 1995 emissions. From west to east, the local peaks in sulphate wet deposition, evident in Figure 1.13a, are associated with the Calgary-Edmonton corridor, the Fort McMurray area of Alberta, Flin Flon, Manitoba and Thompson, Manitoba. In contrast, peaks in nitrate wet deposition (Figure 1.13b) are predicted to occur in Alberta, along and to the east of the Calgary-Edmonton corridor, consistent with the different source types contributing to SO_2 and NO_x emissions in western Canada.

¹⁷This simple scenario is very similar to the “CCUSA2” scenario; the only difference is that Canadian SO_2 emissions in the eastern-Canada Sulphur Oxide Management Area (or SOMA) are rolled back by 50% from the provincial caps mandated under the 1985 ECARP. The ADOM domain approximates the SOMA for southeastern Canada.

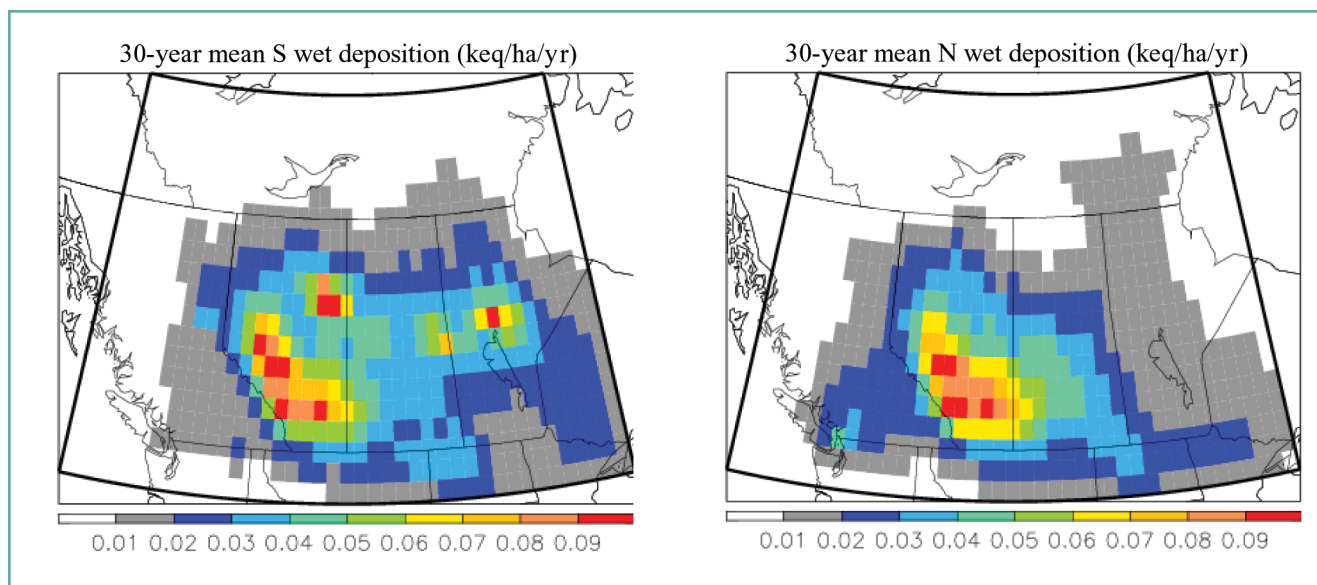


Figure 1.13: Wet deposition of sulphur (keq/ha/yr) and nitrogen (keq/ha/yr) predicted by RELAD based on the average meteorological conditions from 1971 to 2000 and Canadian emissions data from 1995. The RELAD domain is indicated by the dark black outline. Each grid cell is 1° of latitude by 1° of longitude in size. (Note: 1 keq/ha/yr of wet sulphur deposition is equal to 48.1 kg/ha/yr and 1 keq/ha/yr of wet nitrogen deposition is equal to 62.1 kg/ha/yr)

4. Are further emissions reductions necessary in Canada and the U.S.? If so, by how much, and from where, do emissions need to be reduced?

Since levels of sulphur and nitrogen deposition currently exceed critical loads for aquatic and upland forests over a vast area of eastern Canada, there is a clear need to further reduce SO₂ and NO_x emissions that impact this region. In western Canada, data on critical loads are insufficient to make specific conclusions about the need to reduce emissions that impact this region.

Using the most realistic future-year SO₂ emission scenarios data available to date, the ADOM model predicts that sulphate critical loads for aquatic ecosystems¹⁸ will still be exceeded in central Ontario and Quebec, even if SO₂ emissions from both Canada and the U.S. are reduced by a further 50% beyond what they have agreed to achieve in Canada-U.S. Air Quality Agreement (AQA) in 2010. This result is consistent with the predictions of a similar ADOM modelling scenario published in the 1997 assessment¹. Only for an SO₂

emission control scenario that constitutes a further 75% reduction in SO₂ emissions from those currently agreed to by Canada and the U.S. for 2010 in the AQA, are the 1997 aquatic critical load exceedances predicted to be completely eliminated in eastern Canada. It is important to note that the 1997 aquatic critical loads have been revised in this assessment and new critical loads have been estimated for both aquatic and upland forest ecosystems. These new critical loads are lower than those published in the 1997 assessment in many areas and higher in a few areas; hence, reductions in SO₂ emissions greater than 50% or 75% could be required to meet new, lower critical loads.

Finally, it is important to note that a 75% reduction in SO₂ emissions in eastern Canada and the eastern U.S. (needed to meet 1997 aquatic critical loads) translates into a greater reduction in SO₂ in terms of megatonnes (MT) from the U.S. than from Canada. This is because emissions of SO₂ from eastern Canada constitute only 9% of eastern North American emissions (based on 2000 emission estimates; see Figure 1.9).

¹⁸Using critical loads published in the 1997 Canadian Acid Rain Assessment.

The ADOM model results suggest however, that on a tonne-by-tonne basis, a reduction of one MT in emissions from eastern Canada would produce a larger reduction in deposition in eastern Canada than would a one MT reduction in emissions from the eastern U.S. This is because a larger proportion of each MT emitted by Canadian sources is deposited in Canada compared to a MT emitted by U.S. sources. Thus, although emissions from the eastern U.S. need to be reduced for critical loads to be met in eastern Canada (since 45% or more of sulphur deposition in eastern Canada is attributable to U.S. emissions), on a tonne-by-tonne basis, it is more efficient to reduce a tonne of emissions in Ontario and Quebec than a tonne in the Ohio River Valley or northeastern states. However, a very large percentage reduction in both countries is required reach the goal of entirely eliminating aquatic critical load exceedances in eastern Canada.

The deposition data analyses, although not able to estimate the level of SO₂ and NO_x emissions reductions needed to meet critical loads, are consistent with the ADOM modelling results. The analyses suggest that emission reductions are needed in eastern Canada, the Midwestern and eastern U.S. and western Canada to reduce acid deposition in eastern Canada. Within eastern Canada, the largest emission reductions appear to be needed in Ontario, and Quebec. In the U.S., the largest reductions are needed in the Midwest states in order to reduce deposition in northwestern Ontario, in the Great Lakes states and the Ohio River Valley in order to reduce deposition in the remainder of Ontario and Quebec, and in the states of the Ohio River Valley, and the East Coast in order to reduce deposition in Atlantic Canada. Complementary modelling results suggest that the most efficient place to reduce emissions that affect Canada would be in Canada, the northern tier of the Midwest, Great Lakes, Ohio River Valley, and East Coast states. In fact, emission reductions in the southern tier of the American states would have very little benefit to acid deposition levels in Canada.

5. Will NO_x reductions compensate for the need to reduce SO₂? Is nitrogen saturation a problem and how will changing NO_x emissions impact on Canadian ecosystems?

For watersheds in eastern Canada, sulphur deposition is still clearly the predominant acidifying agent; only a small number of watersheds demonstrate acidification that can be ascribed to nitrogen and recent trend information suggests that acidification at these sites may be declining. Critical load analyses, that separate the two acidifying components, show that there are some cases where reductions in sulphate deposition alone can be effective in decreasing exceedances, but in other cases, reductions in both sulphate and nitrogen deposition will be necessary (e.g. Muskoka River watershed in Ontario). Hence, according to our current understanding of the role of nitrogen in acidification, reductions in NO_x emissions will not compensate for the need to reduce SO₂.

Although nitrogen saturation is not a problem in most of eastern Canada, the capacity for terrestrial watersheds to retain nitrogen deposition is finite. It is reasonable to hypothesize that a dramatic decrease in nitrogen deposition may protect many sites from ever becoming nitrogen saturated. At this point in time, however, it is not possible to establish a particular threshold of nitrogen deposition that would prevent future nitrogen saturation in Canada.

6. Are there other factors that might decrease the efficacy of emission reductions?

There are several factors that might decrease the efficacy of emission reductions. These factors include the following:

- ⇒ Leaching of base cations decreases the capacity of soils to neutralize future acid loadings – i.e. increases the susceptibility of soils to acid deposition.
- ⇒ Under the oxygen-limited conditions that characterize wetland sediments, sulphate from deposition is converted to sulphides, which are stable storage products for sulphur. When the water level goes down during dry periods, oxygen penetrates into formerly anaerobic wetland soils

resulting in sulphur oxidation and release of sulphate. Hence, climatic changes can cause temporal variability in sulphate fluxes from wetland-dominated watersheds and confound the expected relationship between decreased sulphate deposition and sulphate concentrations in lakes and rivers.

- ⇨ Declines in inputs of sulphate to soils, as a result of reductions in acid deposition, are expected to cause the release (desorption) of sulphate previously stored in soils. The release of stored sulphate into lakes and rivers confounds the effects of SO₂ emission reductions. The amount of sulphate stored in soils and available for release is dependent on the characteristics of the soil and the concentration of sulphate in deposition. In watersheds, such as Plastic Lake in the Muskoka-Haliburton region of Ontario, stored sulphate is predicted to be released into surface waters for up to several decades¹⁹.
- ⇨ Mineralization (the transformation of organic sulphur into inorganic sulphate) and immobilization (the transformation of inorganic sulphate into organic sulphur) are microbial processes that occur concurrently within the soil. Mineralization may be a source of sulphate to drainage waters if sulphate release from organic sulphur compounds exceeds the rate of sulphate immobilization. A number of studies have suggested that mineralization is responsible for net sulphate export from watershed soils in Canada.
- ⇨ When terrestrial ecosystems become nitrogen saturated (i.e. receive more nitrogen than they can use), nitrogen forms acid which can leach from the soil and acidify surface waters.

7. Are affected ecosystems recovering in response to past reductions in SO₂ emissions? If so, how is recovery proceeding? If not, why, when, and under what conditions, can we expect recovery to acceptable environmental objectives? What role do NO_x emissions play?

At present, full scale chemical and biological recovery has not been observed in any ecosystem but there are encouraging signs of improvement.

Lakes in eastern Canada located near smelters, that have dramatically reduced their emissions for a significant period of time (e.g. at Sudbury and to a lesser extent at Rouyn-Noranda), provide the most definitive evidence of chemical recovery (increasing pH and/or alkalinity). Lakes in southeastern Canada that are predominantly affected by long-range sources of acid deposition show a general decline in sulphate but a relatively smaller compensating increase in pH and/or alkalinity. Factors such as declining base cations in precipitation and watershed soils, drought-induced mobilization of stored sulphur, and damaged in-lake alkalinity generating mechanisms are constraining (most likely delaying) chemical recovery; biological recovery will necessarily lag behind chemical recovery. In the end, lakes will probably recover to a state that is more dilute (lower ion concentrations and therefore more sensitive) than their pre-acidification state.

It is likely that many lakes will recover to a different state than their original one. Algae and zooplankton communities in some highly damaged lakes (e.g. Sudbury area) are responding to acidity reductions but recovery is constrained by metal toxicity and re-acidification events. Experimental acidification research shows that aquatic ecosystems can be resilient to acid-stress but that recovery will often be complex and slow and may result in permanently altered biological communities. The increases in numbers of loons and some other waterbirds breeding in southeastern Canada are encouraging signs of recovery but observations of declining loon breeding success will be cause for concern if trends continue and are widespread. Habitat suitability for waterbirds breeding in small lakes and wetlands of southeastern Canada is predicted to improve for fish-eating birds (e.g. Common Loon, Common Merganser) and small fish (e.g. minnows) and decline for some insectivorous diving ducks (e.g. Common Goldeneye), with the degree of change related to the prevalence and magnitude of chemical change.

With respect to soil chemistry, evidence of lake recovery in some regions supports the notion that soil chemistry may also be recovering because soil chemistry (i.e. base

¹⁹Eimers, M.C., Dillon, P.J., Schiff, S.L.. 2004. Sulphate flux from an upland forested watershed in south-central Ontario, Canada. *Water Air and Soil Pollution* 152, 3-22.

cation concentrations) largely controls the acidity of lake water. However, empirical and modelling evidence suggests that base cation reservoirs in soils throughout southeastern Canada continue to decline; a phenomenon which threatens the long-term sustainability of forests and impedes the recovery of lakes and rivers. In order to achieve recovery of terrestrial ecosystems, the level of acid deposition would need to decline to the point where inputs of base cations to soils from weathering of bedrock and deposition equals or exceeds the loss of base cations by acid leaching.

In terms of the role played by NO_x emissions, as mentioned previously, for watersheds in eastern Canada, sulphur deposition is still clearly the predominant acidifying agent (usually accounting for >90 % of acid leaching from soils). However, nitrate does contribute to soil acidification at a few sites such as the Muskoka River Watershed in Ontario.

8. What are some of the socio-economic benefits of acid deposition mitigation?

Acid deposition has negative impacts on lakes, rivers, soils, forests, wildlife, biodiversity, buildings, and human health. The socio-economic benefits of decreasing or avoiding these negative impacts could be significant. Furthermore, reductions in PM and ozone that accompany reductions in acidifying emissions would have a wide range of environmental, economic and human health benefits.

At current levels of acid deposition, it is estimated that over half a million cubic meters of wood is being lost from forests in Atlantic Canada each year due to soil nutrient loss. At market prices, the value of this lost wood is in the hundreds of millions of dollars per year. The decline in fish in lakes and rivers of eastern Canada has significant impacts on the fishing industry, particularly for Atlantic salmon. The effects of declining fish populations will also have non trivial effects for recreational fishermen who spent \$1.9 billion on fishing in 1996.

The corrosive impacts of acid deposition can be significant, particularly for electrical transmission towers.

Acid deposition can reduce the life expectancy of transmission towers by 50% and greatly increase repair frequency with an annual cost of thousands of dollars per tower.

There is some indication that damages to the overall integrity of the environment and ecosystem could be amongst the most economically significant impacts of acid deposition. In 1996, Canadians spent over \$12 billion on nature related activities. This \$12 billion in expenditures likely represents only the tip of the iceberg of the full value Canadians place on the environment.

Acid aerosols, PM and ozone can lead to a variety of adverse human health effects ranging from subtle changes and mild symptoms to hospital admissions and premature mortality. The elderly, children and people suffering from cardio-respiratory conditions such as asthma appear to be the most susceptible groups to the effects of outdoor air pollution. These impacts place a high cost on the medical system.

Reductions in emissions of SO_2 and NO_x will also have considerable benefits beyond acid deposition reductions (see below).

9. What are the linkages and implications of other environmental problems with acid deposition, in particular, ozone and particulate matter formation, climate change and mercury?

PARTICULATE MATTER

Particulate matter (PM) shares precursor emissions (SO_2 and NO_x) with acid deposition. The relationship between ambient levels of precursor gases and $\text{PM}_{2.5}$ is complicated. For SO_2 , long-term trends in ambient levels of $\text{PM}_{2.5}$, particle sulphate and SO_2 track each other closely. This suggests that reductions in emissions of SO_2 will lead to reductions in concentrations of $\text{PM}_{2.5}$.

The relationship between ambient levels of NO_x and $\text{PM}_{2.5}$ is also complicated; however, there is evidence that under NH_3 -limited conditions, reductions in SO_2 emissions with no concomitant change in NO_x and NH_3 emissions can result in an increase in PM levels due to the enhanced formation of ammonium nitrate particles.

Thus, SO₂ and NO_x emission reductions should occur at the same time in order to reduce PM.

OZONE

Tropospheric ozone (O₃) primarily shares the precursor emission of NO_x with acid deposition. The formation of tropospheric ozone occurs via a series of chemical reactions the most common of which involves nitrogen oxides, volatile organic compounds (e.g. solvents), and sunlight. In general, increases in the emissions of NO_x result in increases in concentrations of tropospheric ozone on the regional scale; however, in urban areas, ozone levels seem to be more influenced by VOC emissions (i.e. VOC emission controls are more effective for reducing ozone than NO_x emission controls) and increases in NO_x emissions lead to decreases in ozone levels, the so-called “NO_x disbenefit”. The non-linear relationship between concentrations of NO_x, VOCs and ozone production complicates the forecasting of NO_x emission reductions on ozone levels.

CLIMATE CHANGE

Acid deposition and climate change are linked in several ways: 1) Fossil fuel combustion is the primary anthropogenic source of carbon dioxide (CO₂), an important greenhouse gas, as well as SO₂ and NO_x which are precursors of acid deposition. Consequently, reductions in the use of fossil fuels will benefit both issues. 2) SO₂ and NO_x contribute to the formation of particulate matter and ground-level ozone which directly and indirectly impact on the radiation balance of the atmosphere (i.e. the amount of heat and light that are reflected into space or towards earth). For the most part, ground-level ozone is understood to exert a warming effect on climate and sulphate is understood to exert a cooling effect on climate at seasonal scales; 3) A changing climate may change the quantities and patterns of precipitation which could then affect the transport, dispersion, deposition and release of acid-causing pollutants; and, 4) a warmer climate may also increase biogenic emissions of NO_x, SO_x and VOCs. For example, increases in surface temperatures can stimulate increases in emissions of NO_x from soil bacteria. Despite the fact that acid deposition and climate change are linked, our capacity to predict the effects of increases or decreases in emissions of SO₂ and NO_x on climate is limited.

MERCURY

Emissions of mercury and other hazardous pollutants work in synergy with SO₂ and NO_x to enhance the deleterious effects of acid deposition on fish and wildlife. As levels of acidity in surface waters increase, the rate of conversion of mercury (Hg) into toxic and bioavailable methyl mercury (MeHg) increases. Recent studies have shown that significant declines in atmospheric deposition of sulphate and Hg are associated with declines in Hg levels in fish and fish-consuming wildlife such as the Common Loon. Thus, reductions in emissions of acid-causing emissions would benefit the mercury issue.

10a. Where do we need to continue atmospheric and effects monitoring?

Atmospheric monitoring needs to be continued at all current measurement locations and increased in both western and eastern Canada to continue to track the effectiveness of emission controls, provide data for the assessment of exceedances of critical loads, and to support human health studies. The highest priority for new deposition monitoring sites is in Ontario and Newfoundland since there are insufficient numbers of monitoring sites currently operating in these provinces. A high priority also needs to be given to the placement of sites in western Canada, where acid-causing emissions are projected to increase in the future but where very little deposition monitoring is taking place.

Aquatic and soil chemistry monitoring needs to continue and increase at sites that have exceeded, continue to exceed, or have the potential to exceed critical loads for acid deposition. Monitoring of surface waters (e.g. large and small lakes, rivers, wetlands) is necessary to determine trends in surface water chemistry such as pH, sulphate, nitrate and base cation concentrations. Data on these variables are essential for determining the extent to which ecosystems are being acidified, recovering from acidification, or are susceptible to damage from acidification in the future. Data on these variables also indicate the extent to which acid deposition is impacting or could impact biodiversity.

Monitoring of aquatic biota, wildlife and forests must continue in areas where critical loads are exceeded or have been exceeded. Integrated chemical and biological monitoring in these areas is necessary to determine how changes in surface water and soil chemistry are affecting biodiversity and ecosystem productivity and, if necessary, to support the development of management actions for ecosystem recovery.

10b. Where should we focus future research efforts for acid deposition?

EMISSIONS

Research needs to focus on the development of improved statistics, methodologies and emission factors to determine emissions from the on-road transportation, agriculture and residential wood combustion sectors.

Currently, a large percentage of the emission rates used to estimate emissions from industrial and non-industrial sources are based on measurements performed in the U.S. a number of years ago. There is a need to update these emission rates to reflect Canadian weather, fuels characteristics, operations, industrial processes, and emission control equipment and practices.

There is also a need to improve emission inventories for elements that govern total acidity of deposition. For some effects modelling, the controlling atmospheric input is not a particular acidifying species such as sulphate or nitrate but rather total acidity. Unfortunately, prediction of pH is particularly difficult because it requires the concentrations or depositions of all acidifying species to be estimated correctly, including total ammonia and base cations. Base cations pose a particular problem because they are present in crustal material (i.e. fugitive dust) in varying proportions and emissions of bulk crustal material are still not well characterized.

ATMOSPHERIC DEPOSITION MONITORING AND ANALYSIS

Future efforts in the area of atmospheric and precipitation monitoring should focus on improving the capacity to characterize total sulphur and nitrogen

deposition. Improvements are especially necessary for nitrogen because current dry deposition estimates are biased low in the absence of several unmeasured species. Although current acid deposition models predict both dry and wet deposition, it has not been possible until very recently to make measurement-based estimates of dry deposition on a routine basis at multiple sites. As a consequence it has not been possible to accurately assess the role of dry deposition in acid deposition, accurately determine the contribution of sulphur and nitrogen to total acidity, nor evaluate model predictions of dry deposition directly. The increased accuracy in the improved total deposition measurements will also enhance Canada's ability to determine when and where critical loads are being exceeded.

Future efforts should also focus on increasing the number of sites at which wet and dry deposition are measured in eastern and western Canada to permit accurate characterization of atmospheric deposition across the country. The increased number of sites would enable the determination of the spatial distribution of wet and dry deposition across all of Canada and, in combination with U.S. data, across all of North America. It will also allow us to fill large gaps in knowledge as to where critical loads are being exceeded and increase the capacity to assess human exposure to acid aerosols. It will also provide a stronger basis for determining whether emission reduction programs in Canada and the U.S. are being effective at reducing acid deposition where needed. This is particularly important in western Canada where, due to the paucity of measurements, such questions cannot be answered.

In addition, future research efforts should be focused on developing more sophisticated data analysis techniques to determine source-receptor relationships. This will improve our capacity to assess the efficacy of new emission reductions in Canada and the U.S.

FORESTS AND SOILS

The negative effects of decreasing soil fertility on forest health are becoming increasingly supported by recent studies. These observations are raising concerns about the effects of acid deposition on the productivity of Canadian forests located on poorly buffered soils.

Quantification of the relationship between acid deposition and forest health remains difficult, however. Further research is necessary to elucidate this relationship.

One of the major uncertainties, with respect to quantifying the time it will take for forest soils and surface waters to recover, is the rate of primary weathering and the size of the exchangeable pool of base cations. For this reason, determination and validation of these variables should be a focus of future research.

The release of excess sulphur from soils may be partly responsible for the lack of recovery observed in lakes and rivers in eastern Canada and is an additional source of acid that is not accounted for in critical load models. Consequently, future research should focus on elucidating the processes governing transformation and export of sulphur from terrestrial watersheds to surface waters in the context of decreasing sulphur deposition.

Finally, although nitrogen saturation does not appear to be a problem in eastern Canada, the capacity of forests to accumulate atmospherically deposited nitrogen is finite. Detection of nitrogen saturation in surface waters must be the subject of monitoring efforts in existing research sites in both eastern and western Canada.

AQUATIC CHEMISTRY

With respect to aquatic chemistry, future research should focus on implementing a robust survey framework across Canada and supporting research on soils.

Currently, our capacity to assess the status of lake chemistry in Canada is severely limited by the necessity of compiling existing monitoring data without regard to site selection. Ideally, a statistically-based regional survey of lakes such as the stratified random sampling designs that have been employed in the U.S. and Nordic Europe would be preferable to assess current status. Such a lake survey, if occasionally repeated (approximately once per decade – a rotating schedule of lake sampling would be instituted so that a tenth of the lakes were sampled every year) and integrated with an organized hierarchy of temporal monitoring and site-specific research, would provide all the information needed to accurately estimate resource-

level status and change, identify the causes of change, and predict future conditions.

AQUATIC AND TERRESTRIAL BIOTA

Ecosystem recovery is a primary objective of emission reductions. Understanding and predicting biological responses to emission reductions and consequent habitat recovery is necessary for evaluating the adequacy of controls and to direct conservation and management efforts. Identifying the nature and rate of biological recovery requires multi-disciplinary research, integrated habitat and biological monitoring, and robust predictive models. Information derived from these studies is essential for understanding how persistent biodiversity losses influence ecosystem function and for determining the emission reductions needed to meet ecosystem objectives.

The pace and nature of ecosystem recovery are influenced by many other environmental stressors. Future research efforts should include a focus on the interactions of acidification with other ecosystem stressors and those interactions should be integrated into model refinements. Relevant stressors include those related to atmospheric or climatic issues, metals and other toxics, land use/forest management practices and invasive species. Understanding the interactions between acidification and other stressors will provide more realistic predictions of ecosystem recovery.

A biomonitoring framework compatible with the lake chemistry survey described above would be the ideal foundation for estimating resource-level status and change and for predicting future biological conditions. With such a framework, efforts to understand biological recovery mechanisms could be specifically focused to investigate particular mechanisms and ecosystem stressors. The results of these more intensive investigations would be required to properly interpret observed trends and refine predictive models.

Acidification effects on terrestrial wildlife have received relatively little attention to date. Losses of available calcium sources have the potential to impact terrestrial invertebrates and the wildlife on which they depend (e.g. songbirds). Data-based investigations of potential effects

should continue but should be supplemented by targeted field investigations.

Options for managing or actively rehabilitating acidified lakes, wetlands and rivers should be identified and explored with regard to their effectiveness, costs and overall efficiency.

The Integrated Assessment Model (IAM) is used to predict chemical and biological responses to various scenarios of SO₂ emission reductions. This model is an important integrative assessment tool and needs to be maintained and improved to reflect the new knowledge developed above.

ATMOSPHERIC CHEMISTRY MODELS

For Canada, there are a number of areas in acid deposition modelling where further research is needed. Firstly, it has not been possible until very recently to evaluate directly the predictions of dry deposition by models. Efforts are needed to acquire appropriate data sets of sulphur and nitrogen dry deposition and use these to evaluate model predictions.

Some of the key properties of ammonia and nitric acid, needed to accurately predict wet and dry deposition and smog formation, require further investigation. The need for this information is becoming increasingly important as policy-makers seek scientifically defensible predictions of the consequences of changes in emissions of multiple pollutants (e.g., SO₂, NO_x, and ammonia) on air quality and acid deposition.

As emission control scenarios become more realistic, the level of effort required to prepare emissions data for acid deposition models becomes increasingly large. Consequently, there is a need for ready access to sophisticated and flexible emissions processing systems and, data on emissions of primary particulate matter including crustal material (i.e. dust).

To evaluate acid deposition model performance against newer sets of air chemistry and precipitation chemistry measurements, it is also necessary to compile year-long files of meteorological data for input to the acid deposition models.

All of the acid deposition models discussed in this assessment calculate deposition for grid widths ranging from 91 to 127 km. In some situations (e.g. near major sources of emissions), the use of smaller grid spacing and improved spatial resolution of emissions data would improve the accuracy of model predictions.

SOCIO-ECONOMICS

Although environmental economic research is evolving, there are still large gaps in our understanding of the nature and value of acid deposition impacts. Despite the fact that some economic-evaluation modelling capacity currently exists (e.g. the Environment Canada's Air Quality Valuation Model), economic-evaluation models for acid deposition do not adequately account for environmental benefits resulting from abatement. Hence, future research efforts should focus on quantifying the benefits and costs associated with acid deposition effects on forest growth and productivity, recreational fishing, wildlife consumption and biodiversity.

CONCLUSIONS

While Canada has been very successful at reducing acid-causing emissions, acid deposition is still affecting the Canadian environment and the health of Canadians. The results of this assessment confirm that although levels of acid deposition have declined in eastern Canada over the last several decades, approximately 21-75% of eastern Canada, corresponding to approximately 0.5-1.8 million km², continues to receive levels of acid deposition in excess of critical loads according to best and worst case scenarios, respectively.

It is estimated that on the order of a further 75% reduction in SO₂ emissions will be required from Canada and the U.S., beyond those agreed to for 2010, in order to protect eastern Canadian ecosystems from damage by acid deposition. At present, there is insufficient data on the capacity of western Canadian ecosystems to assimilate acid deposition without being harmed, hence, it is not possible to accurately assess the extent to which acid deposition is affecting ecosystems in the west.

Future research and monitoring will be required to verify the effectiveness of emission reductions and better understand the complex and long-term impacts of, in

some cases, irreversible damage caused by acid deposition. The presence of acid-sensitive geology and increasing emissions of SO₂ and NO_x suggests that new

monitoring efforts should expand into the western provinces to ensure that acid deposition does not damage ecosystems in this region.

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