

**Assessment of Forest Sensitivity to Nitrogen and Sulfur Deposition
in New England and Eastern Canada**

**Conference of New England Governors and Eastern Canadian Premiers
Forest Mapping Group Pilot Phase Report**

8 September 2003

Table of Contents

1. Executive Summary	1
2. Background	4
3. Atmospheric Deposition	5
4. Forest Nutrient Requirements	7
5. Soil Mineral Weathering	7
6. Forest Sensitivity Assessment	8
7. Impacts on Forest Ecosystems when the Deposition Exceeds the Critical Load	13
8. Stakeholder Consultations	14
9. Conclusions	14
10. Acknowledgments	15
11. Members of the Forest Mapping Working Group Pilot Phase Technical Group	16
12. References	16

List of Figures

1. Critical load of sulfur + nitrogen deposition to upland forested areas of (a) Vermont and (b) Newfoundland.	2
2. Forested Areas of (a) Vermont and (b) Newfoundland that are sensitive to the negative effects of combined atmospheric sulfur and nitrogen deposition.....	3
3. Growth rates of northern hardwood and boreal coniferous forest stands relative to the deposition index.....	5
4. Average annual atmospheric deposition of sulfur and nitrogen to (a) Vermont (1996-1999) and (b) Newfoundland (1994-1997).	6
5. The deposition index for atmospheric sulfur and nitrogen deposition to Vermont (1996-1999) with respect to forest ecosystem critical loads.	10
6. The deposition index for atmospheric sulfur and nitrogen deposition to Newfoundland (1994-1997) with respect to forest ecosystem critical loads.	11
7. Predicted improvement (a) and deterioration (b) in forest condition with changes in atmospheric deposition of S + N to Vermont; improvement (c) and deterioration (d) in forest condition with changes in atmospheric deposition of S + N to Newfoundland.	13
8. Status of the Forest Mapping Project.....	15

1. Executive Summary

Acidic Deposition in Northeastern North America

Although sulfur emissions have decreased as a result of SO₂ control programs, projected emissions of acidifying sulfur and nitrogen compounds are expected to have continuing negative impacts on forests. These emissions present some of the most serious long-term threats to forest health and productivity in northeastern North America. Excess sulfur and nitrogen deposition may reduce the supply of nutrients available for plant growth. Nutrient depletion leads to increases in the susceptibility of forests to climate, pest and pathogen stress which results in reduced forest health, reduced timber yield, and eventual changes in forest species composition.

Forest Sensitivity Mapping Project

Conceived by the Conference of the New England Governors and Eastern Canadian Premiers (NEG/ECP), under the direction of its Committee on the Environment, their 1998 Acid Rain Action Plan called for the formation of a Forest Mapping Working Group to conduct a regional assessment of the sensitivity of northeastern North American forests to current and projected sulfur and nitrogen emissions levels. This group is charged with identifying specific forested areas most sensitive to continued sulfur and nitrogen deposition and estimating deposition rates required to maintain forest health and productivity.

How Was This Assessment Done?

Evaluating forest sensitivity to acidic deposition requires information on: pollution loading to forest landscapes; the interaction of pollutants with forest canopies; plant nutrient requirements; and the ability of soils to buffer acid inputs and replenish nutrients lost due to acidification. Recent scientific advances in estimating each of these factors have made it feasible to produce maps of forest sensitivity to acid inputs from atmospheric nitrogen and sulfur. An integral part of this project was an open dialog with scientists, air resource specialists, foresters, and members of provincial, state and federal governments about data, methodology, and interpretation of results. The development of appropriate methods, models and mapping techniques, and the identification of data requirements, have been completed and are reported in this Pilot Phase Report for one state (Vermont) and one province (Newfoundland).

The approach we have used to determine acceptable levels of deposition is an ecological assessment based on a steady-state, ecosystem mass balance for nutrient cations (calcium, magnesium, and potassium). Two metrics (*critical load* and *deposition index*) express the result of this assessment. The *critical load* of sulfur + nitrogen is the level of deposition below which no harmful ecological effects occur for a forest ecosystem (Figure 1). The *deposition index* is the difference between the critical load and current deposition (Figure 2) and is used to identify sensitive forest ecosystems. The magnitude of the deposition index indicates the severity of nutrient depletion caused by sulfur and nitrogen deposition. When exports of these nutrient cations are greater than inputs to an ecosystem, a condition known as *cation depletion*, inadequate levels of nutrients may develop in both soils and plants. Inadequate nutrient levels have been linked to a wide range of forest health problems, reduced growth rates, and increased mortality.

Forest Sensitivity Assessment Metrics

Critical load of sulfur + nitrogen is the level of deposition below which no harmful ecological effects occur for a forest ecosystem.

Deposition index is the difference between the critical load and current deposition and is used to identify sensitive forest ecosystems.

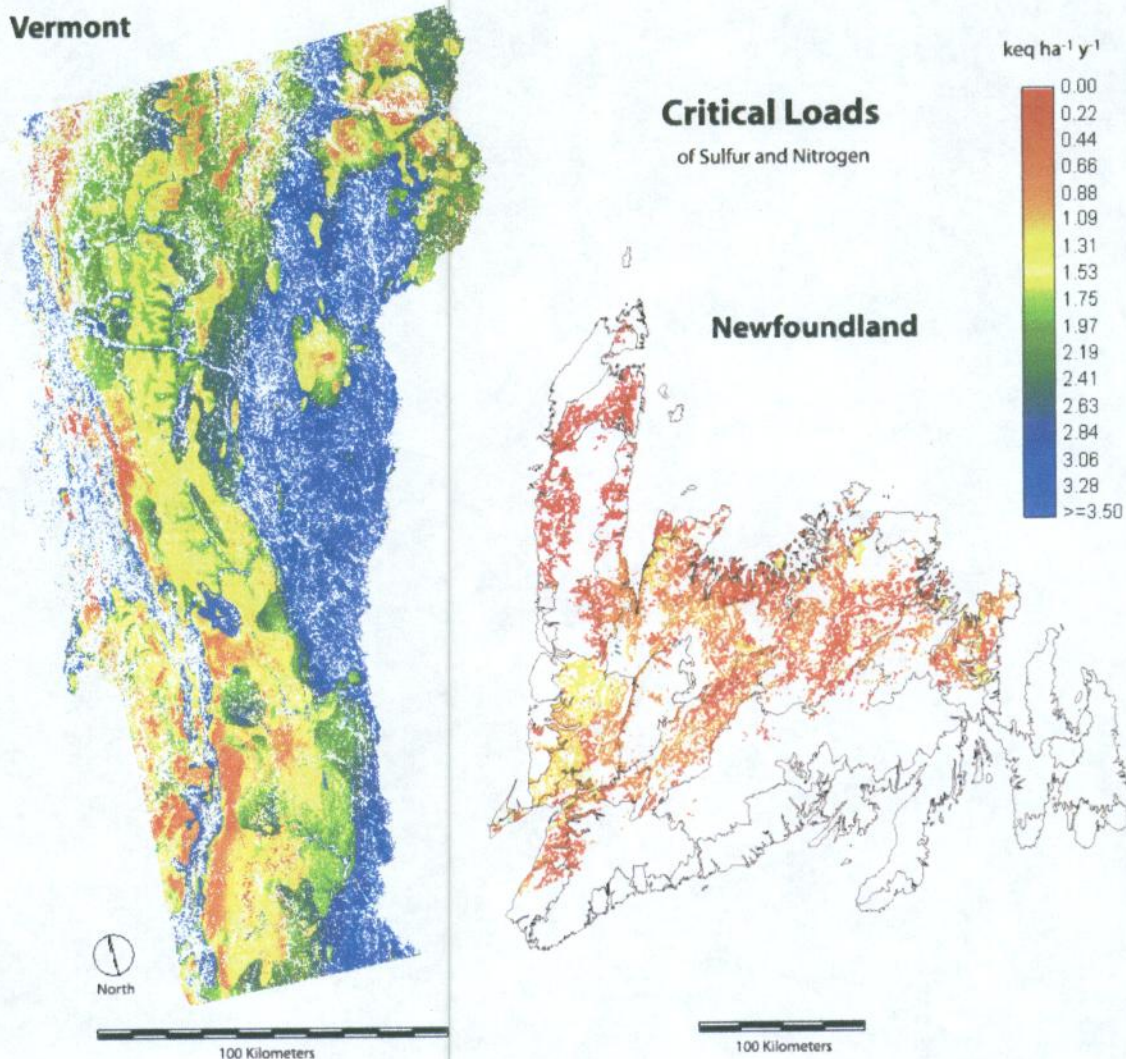


Figure 1. Critical load of sulfur + nitrogen deposition to upland forested areas of (a) Vermont and (b) Newfoundland. Sulfur + nitrogen atmospheric deposition rates higher than the critical load result in greater exports of nutrient cations (Ca^{2+} , Mg^{2+} , K^+) than inputs and eventual deterioration of soil fertility, forest health, and forest productivity. Critical loads are expressed in kilo-equivalents per hectare per year; nitrogen deposition includes both ammonium + nitrate forms.

Forest Sensitivity Findings

Sensitive forest areas were mapped in both Vermont and Newfoundland under the current emissions levels of sulfur and nitrogen (Figure 2). In Vermont, current levels of S + N deposition create the conditions for cation depletion in 31% of upland forests (561,127 ha). In Newfoundland, it is predicted that current levels of sulfur + nitrogen deposition are causing cation depletion in 23% of upland forests (456,845 ha).

Sensitive Forest Area Results:

- 31% of Vermont forests
- 23% of Newfoundland forests

Factors that increase forest sensitivity include: high levels of nitrogen and sulfur deposition, low mineral weathering rates, and tree species with high nutrient demands. High elevation forests and areas closest to emission sources experience the highest levels of nitrogen and sulfur deposition. Low mineral weathering rates occur in association with particular geologic and climatic factors. Requirements for soil nutrients vary according to the species currently growing in a forest, because tree species have different nutrient requirements for health and growth. Sugar maple trees, for example, have a high demand for calcium.

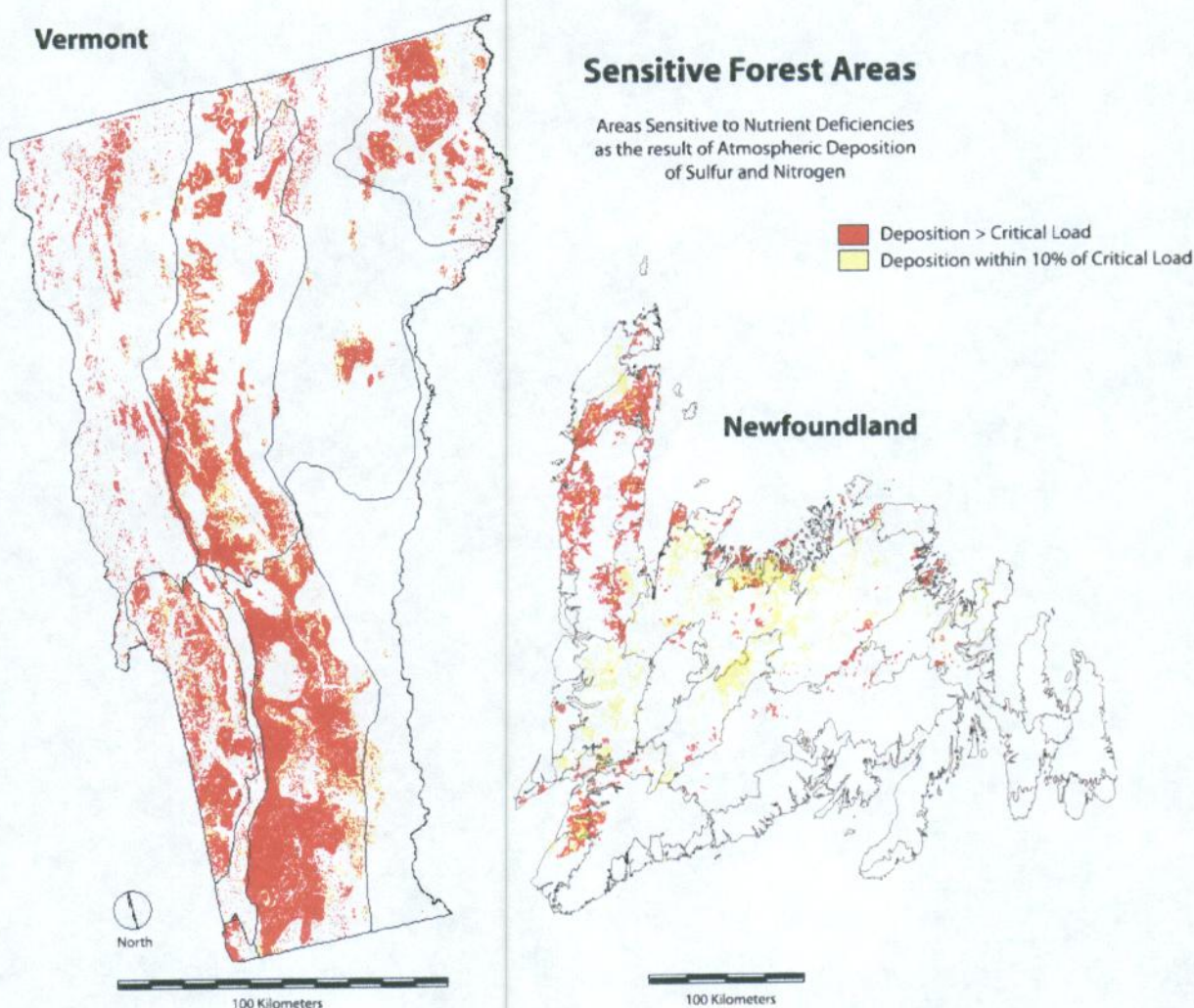


Figure 2. Forested Areas of (a) Vermont and (b) Newfoundland that are sensitive to the negative effects of combined atmospheric sulfur and nitrogen deposition. Red areas indicate current sulfur and nitrogen atmospheric deposition rates greater than the critical load. Yellow areas indicate current atmospheric deposition rates within 10% of the critical load.

Independent ecological indicators have been used to demonstrate that the assessment results are consistent with tree health observations from the region. Forests classified as sensitive by this approach exhibited crown health problems across Canada and in Vermont and lower tree growth in stands in Québec.

Projected Sulfur and Nitrogen Emission Levels and Future Forests

Modifications in pollutant emissions and deposition can affect the area and distribution of sensitive forests. We estimate that a 50% reduction in combined sulfur and nitrogen deposition would remediate the nutrient depletion problem on 78% of the sensitive forest area in Vermont and 68% in Newfoundland. Conversely, a 10% increase in combined sulfur and nitrogen deposition would cause an additional 12% and 8% of the currently unaffected forests to be classified as sensitive in Vermont and Newfoundland, respectively.

Solutions Are Possible:

A 50% reduction in N & S deposition can reverse forest effects by 78% in Vermont and 68% in Newfoundland.

Completing Forest Sensitivity Maps for Northeastern North America

Results of this pilot project provide compelling motivation to complete forest sensitivity maps for the entire New England and eastern Canada area. During the second phase of this project, regional data will be compiled to develop these valuable maps. Assessment components will be added to more accurately estimate the time span until forest health and productivity are compromised. Final maps for the region will be developed by the end of 2004, contingent upon funding.

Phase II will complete maps for all New England States and Eastern Canadian Provinces by 2004.

2. Background

Although sulfur emissions have decreased as a result of SO₂ control programs, projected emissions of both sulfur and nitrogen compounds are expected to have continuing negative impacts on forests, presenting some of the most serious long-term threats to forest health and productivity in northeastern North America. Anthropogenic sulfur and nitrogen deposition can cause excessive nutrient cation (calcium, magnesium, and potassium) leaching, reducing the supply of nutrient cations available for plant growth, a process called *cation depletion*. Inadequate nutrient supplies frequently lead to increased susceptibility to climate, pest and pathogen stress, and result in reduced forest health, reduced timber yield, and eventual changes in forest species composition. For example, forest growth is significantly lower in Québec forest stands where current deposition exceeds the critical load (Figure 3). The approach we have used to determine acceptable levels of deposition is an ecological assessment based on a steady-state, ecosystem mass balance for nutrient cations¹ (NEG/ECP-FMG, 2001). Two metrics (*critical load* and *deposition index*) express the results of this assessment. The *critical load* of sulfur + nitrogen is the level of deposition below which no harmful ecological effects occur in a forest ecosystem. The *deposition index*² is the difference between the critical load and current deposition and is used to identify sensitive forest ecosystems³. The deposition index provides information to policy makers about present and potential future status of forests and provides a useful general target for understanding what deposition levels might be deleterious to forest ecosystems.

This report provides a summary of the results of the Pilot Phase of the Forest Mapping Project. The purpose of the Pilot Phase, which included Newfoundland and Vermont, was to

¹ Base cations were evaluated individually to determine whether there was an insufficient supply of any individual base cation. If there was an inadequate supply of any one base cation, the ecosystem was considered sensitive to the current levels of S+N deposition. The critical load was, therefore, calculated based on the most limiting nutrient cation.

² Deposition index = Critical Load - Current Deposition.

³ A positive value of the deposition index indicates the additional deposition that can be tolerated by the forest ecosystem. A negative value of the deposition index indicates the magnitude of deposition reduction required to eliminate all cation deficits (ensuring an adequate long-term nutrient supply).

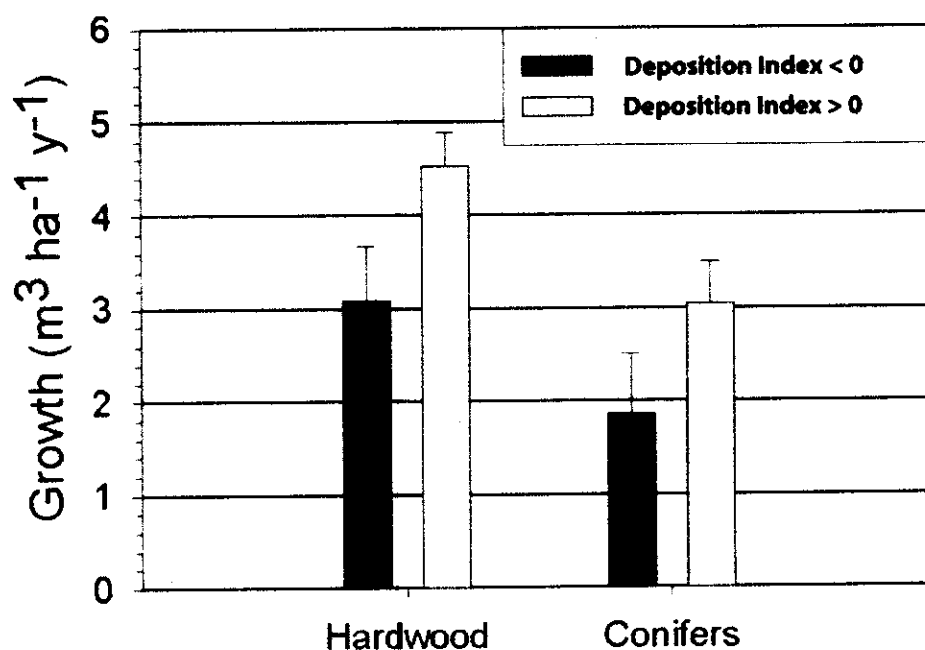


Figure 3. Growth rates of northern hardwood and boreal coniferous forest stands relative to the deposition index. Forest growth was significantly lower over a 19-year period at hardwood and softwood stands in Québec where current deposition levels exceed the critical load (deposition index < 0) than at sites where deposition is less than the critical load (deposition index > 0). Data presented are means adjusted for plot initial volume and stand age. Error bars represent standard errors of the adjusted means (Ouimet et al., 2001).

develop and evaluate the approach for assessing forest sensitivity to acidic deposition in order to refine it, as necessary, prior to developing maps for the whole region. The report describes how atmospheric deposition, forest nutrient demand associated with growth after harvest, and soil mineral weathering rates were estimated for the region and provides a discussion of the forest sensitivity assessment, the relationship of forest health indicators to forest areas identified as sensitive, and a summary of the working group's interactions with stakeholders.

3. Atmospheric Deposition

Atmospheric deposition of sulfur (S), nitrogen (N), chloride (Cl), calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) representative of recent conditions was estimated for the study regions using the best available data for each state or province. We used a 4-year average (VT: 1996-1999; NL: 1994-1998) in order to provide some smoothing of year-to-year variations in patterns of atmospheric transport. Total deposition, including precipitation, cloud droplet interception, and dry deposition, was estimated for Vermont (Figure 4.a.), while precipitation plus dry deposition was estimated for Newfoundland (Figure 4.b., fog capture in coastal areas was not assessed). Total deposition to VT was modeled at a 30-m ground resolution using atmospheric chemistry data from the US NADP, CASTNet, and NOAA-AirMon deposition monitoring networks and the High-Resolution Deposition Model (Miller, 2000; NEG/ECP Forest Mapping Group, 2001). A spatial-database of wet deposition to Newfoundland was provided by

Environment Canada at 45-km resolution. Dry deposition to Newfoundland was estimated to be 20% of wet deposition based on observations of both wet and dry deposition at the nearest representative locations. Deposition monitoring sites are sparsely distributed in the study areas (VT: 3 wet, 3 dry; NL: 2 wet, 0 dry) and factors affecting deposition rates are highly variable, particularly in mountainous regions (e.g. Miller et al., 1993), thus the deposition estimates carry some unquantifiable uncertainty.

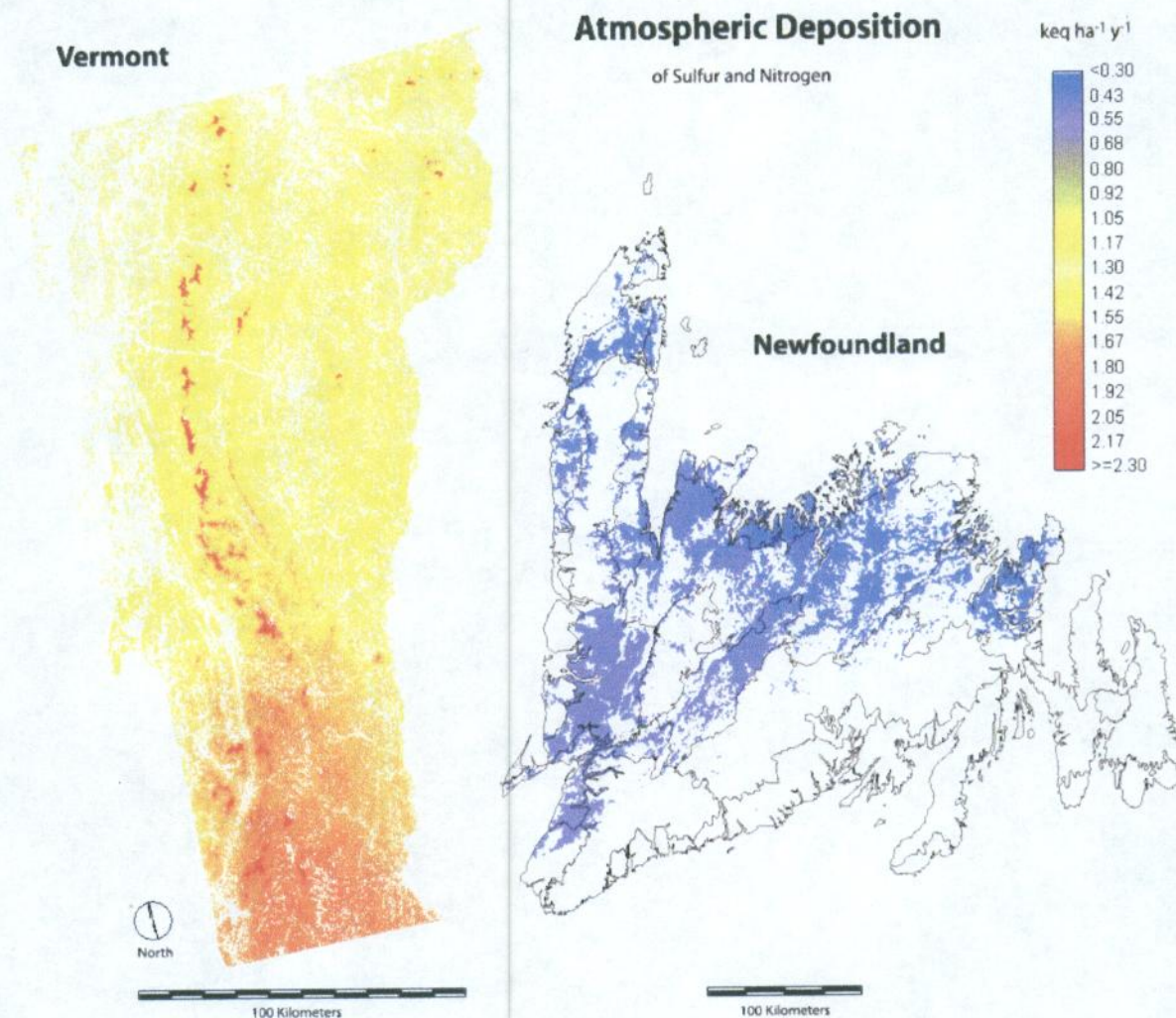


Figure 4. Average annual atmospheric deposition of sulfur and nitrogen to (a) Vermont (1996-1999) and (b) Newfoundland (1994-1997). Total deposition (particle + SO_2 + precipitation + cloud water [VT only]) expressed in terms of the kilo-equivalents of charge per hectare per year; nitrogen deposition includes both ammonium + nitrate forms. This represents the total base-neutralizing and cation-leaching power of S and N atmospheric deposition.

4. Forest Nutrient Requirements

Forest nutrient demand was quantified as part of the mass balance (NEG/ECP-FMG, 2001). In undisturbed forests that have reached their climatic potential biomass there is no *net* annual requirement for nutrients because nutrients in dead trees are recycled into new forest growth. When forests are burned or harvested, part of the nutrient capital of the stand is removed with the ash or timber. The amount removed depends on the intensity of the fire or harvest and the parts of the tree that are removed. In order to calculate a critical load that will adequately protect the working forest, it is necessary to quantify the demand for nutrients required for growth after fire or harvest. Forest trees species and communities vary substantially in their inherent growth rates, demand for specific nutrients, fire recurrence interval, and level of forest management activity in different parts of the study regions. There are also variations in harvesting rates and practices on privately and publicly owned lands and in different jurisdictions. For these reasons, we characterized the rate of nutrient extraction associated with fire or harvest by forest type, land-ownership category⁴, and location.

Distribution of Forest Types

For Vermont, a 30-m resolution spatial data layer describing the distribution of 9 major forest types was produced by determining the probability of forest type occurrence as function of climate, and using the USEPA/USGS National Land Cover Data to discriminate between evergreen, deciduous or mixed forest types that could potentially occupy the same climatic conditions. A ground truth survey determined that the forest type map was 75% accurate overall, with higher accuracies for the dominant forest types. For Newfoundland, the geospatial distributions of the main forest species groupings were available in the form of provincial forest inventory maps at 1:50,000 scale.

Nutrient Exports Associated with Fire and Harvesting

In Vermont, land-ownership category, county, and forest-type specific estimates of timber extraction rates were used together with wood nutrient content by forest-type to estimate the nutrients required to grow the biomass exported via harvesting. Annual biomass extraction (averaged over 1999-2001) was tabulated by county, land-ownership category (public, private) and gross forest type (softwood, hardwood, mixed) from forest inventory and harvest survey data provided by the Vermont Agency of Natural Resources and land ownership data assembled from state and federal sources. Fire recurrence intervals in Vermont average tens of thousands of years, so losses due to fire were ignored. In Newfoundland, most of the forests are softwoods or fast-growing hardwoods that are clear-cut by stem-only harvest methods and fire is more common. Forest growth rates after harvest or fire disturbance were derived from provincial forest inventory data and combined with forest-type specific biomass chemistry to estimate nutrient export. In both Vermont and Newfoundland, nutrient concentrations for each species for healthy foliage, branch, bark, and stem wood were compiled from the literature.

5. Soil Mineral Weathering

The chemical breakdown of rock-forming minerals and their conversion to soil minerals, termed *soil mineral weathering*, is the primary means of replenishing the nutrients Ca, Mg and K that are lost from soils via acidic deposition-induced leaching and/or biomass removal. The

⁴ The public and private land ownership categories refer to all lands where harvesting would be permissible. There is no harvesting from private, state and federal reserves or wilderness areas.

landscape and geologic factors that control the rate of weathering are: 1) mineral assemblage, 2) climate, and 3) physical properties of the soil. Common minerals that may co-occur in the same rock or soil may have widely varying Ca, Mg, and K contents and inherent rates of chemical breakdown that could vary by up to 8 orders of magnitude. Thus, the proportion (by mass) of easily weathered minerals (which are often the highest in Ca and Mg) exerts the dominant control on the overall soil weathering rate. The mineral assemblage is governed by the geologic history of a site including the bedrock mineralogy, transport of minerals to the site by water or glaciers, and the length of time the assemblage has been subject to weathering. Weathering rates increase with increasing temperature and water flux through a soil. The more mineral surface area that is exposed to water, the higher the weathering rate and this factor is governed by soil texture and climate. The depth to which roots can penetrate the soil (a function of both plant and soil characteristics) and the presence or absence of a fluctuating water table at this depth influence the volume of soil over which weathering is relevant to plant nutrition. Not surprisingly, the weathering rate is a highly localized parameter and very difficult to estimate on a regional basis given the complexity of factors involved and data required. The approaches described below provide estimates of the average weathering rate for upland soils (NEG/ECP-FMG, 2001). Local weathering rates may depart substantially from the averages derived, but the estimates provide a rational basis for differentiating the ability of different areas within Vermont and Newfoundland to replenish lost nutrients.

Data availability and landscape characteristics dictated different approaches to estimating mineral weathering rates in Vermont and Newfoundland. The mountainous landscape, range of climate, diverse bedrock geology, glacial history, and lack of any data that were scale-appropriate, for the entire state in Vermont presented a series of challenges. Through a combination of field studies, modeling, and literature review we: 1) resolved a debate on the directions of glacial transport, 2) developed an empirical model describing the glacial transport of minerals in the <2mm size fraction, 3) developed a comprehensive state-wide database of bedrock mineralogy to be used with the glacial transport model, 4) developed landscape context sensitive empirical models of key climatic factors and soil characteristics, and 5) modified the PROFILE (Sverdrup and Warfvinge, 1993; see also NEG/ECP-FMG, 2001) weathering rate model to process this information stored in a geographic information system.

For Newfoundland, a spatially comprehensive database of soil chemical and physical properties (CANSIS: <http://sis.agr.gc.ca/cansis/>) was available, but this database lacked key variables needed for the PROFILE model. Instead, soil depth, soil clay content and a soil parent material classification method were used to estimate soil-weathering rates. The parent material classification was based on the local bedrock geology as follows: (1) mostly silicaceous – low weathering rate, (2) mostly mafic – moderate rate, (3) intermediate between (1) and (2), and (4) calcareous – high rate, after deVries (1991).

6. Forest Sensitivity Assessment

Forest areas sensitive to current levels of S + N deposition were identified by computing the steady-state mass balance for sources and sinks of acidity in a forest ecosystem (NEG/ECP-FMG, 2001). Briefly, we evaluated whether the base cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+) lost in conjunction with leaching of SO_4^{2-} and NO_3^- from the ecosystem and via harvesting or fire can be replaced on an ongoing basis by base cations released into the soil by mineral weathering reactions and those deposited from the atmosphere. Mass balances for Ca, Mg, K, and Na were evaluated

individually⁵. If the steady-state mass balance for any one individual cation is negative, the ecosystem is considered to be sensitive to the effects of current levels of S and N deposition over the long term. A negative mass-balance for Ca, Mg or K indicates a long-term nutrient limitation. If all cation mass balances are positive, this indicates the system has the capacity to tolerate additional S or N deposition.

Critical loads of S + N ranged widely in Vermont ($0.1 - 11.8 \text{ keq ha}^{-1} \text{ y}^{-1}$) as a result of the diverse geology and climate of the state (Figure 1.a.). The vast areas of Ca-rich rocks and soil materials found in the Lake Champlain Valley and east-central part of the state support the highest critical loads, often in excess of $3 \text{ keq ha}^{-1} \text{ y}^{-1}$. The lowest critical loads were found along the spine of the Green Mountains and other high-elevation areas of the state where soils are developed in tills derived from metamorphic rocks such as quartzite, slate, schist and gneiss. These soil parent materials are poor in Ca, Mg and K and comprised of minerals that are generally resistant to weathering. Because of their chemical and physical durability these are the rock types that form the spine of the Green Mountains and other high-elevation areas of the state.

Atmospheric deposition (Figure 4.a.) also ranges widely in Vermont. Sulfur deposition ranges between 6.2 and 24 (median 8.1) $\text{kg ha}^{-1} \text{ y}^{-1}$ and nitrogen deposition (ammonium + nitrate) ranges between 10.7 and 33 (median 13) $\text{kg ha}^{-1} \text{ y}^{-1}$, producing an aggregate acidifying and nutrient leaching potential of 1.1 to 4.0 (median 1.5) $\text{keq ha}^{-1} \text{ y}^{-1}$. The highest elevation areas receive the highest S + N deposition due to orographically-enhanced precipitation and cloud water inputs. Deposition is also high in the southwestern part of the state due to proximity to emission sources.

The convergence of low critical loads and high atmospheric deposition along the Green Mountains and in the southwestern highlands create conditions where combined S and N deposition frequently exceeded the critical load (Figure 5). Critical loads were exceeded in approximately 31% of the forested area of Vermont. An additional 8.4% of the forested area experienced deposition within 10% of the critical load and was potentially vulnerable.

Forest tree species occupy different portions of the landscape as a function of climate, soil conditions and land-use history. This distribution results in some types of forests being more severely impacted than others by the nutrient cation depletion caused by S + N deposition. For example, critical loads are exceeded in 73% of Vermont's red spruce and balsam fir forests, but in just 20% of the state's northern hardwood forests. This is because balsam-fir and red spruce stands (1.7% of total forest area) tend to occur in the high elevations on poor soils. The northern hardwood forest (25% of forest area) occurs widely and at the mid to lower elevations. Sugar-maple dominated stands (27% of forest area) occupy mid-elevation sites and have the highest Ca-requirement of the state's forests. We estimate that the critical load is exceeded in 44% of Vermont's sugar-maple stands and deposition is within 10% of the critical load in an additional 8%.

Typically, Newfoundland forests are part of a morainal landscape that alternates between harvestable forests and, heathlands, peatlands, and rocklands. Of this, only about 18% is harvestable. Nine percent of the productive forest land exists in protected areas (parks). Upland forest cover is mainly black spruce (41%), balsam fir (56%), and white birch (2.6%). Balsam fir and white birch dominate the northwestern portion. Black spruce and white birch dominate the northeastern parts of the island.

⁵ Individual cation balances were evaluated in Vermont. This method will be used in the other states and provinces. Due to lack of adequate data, only the aggregate cation balance was evaluated in Newfoundland for this pilot study.

Deposition Index Vermont

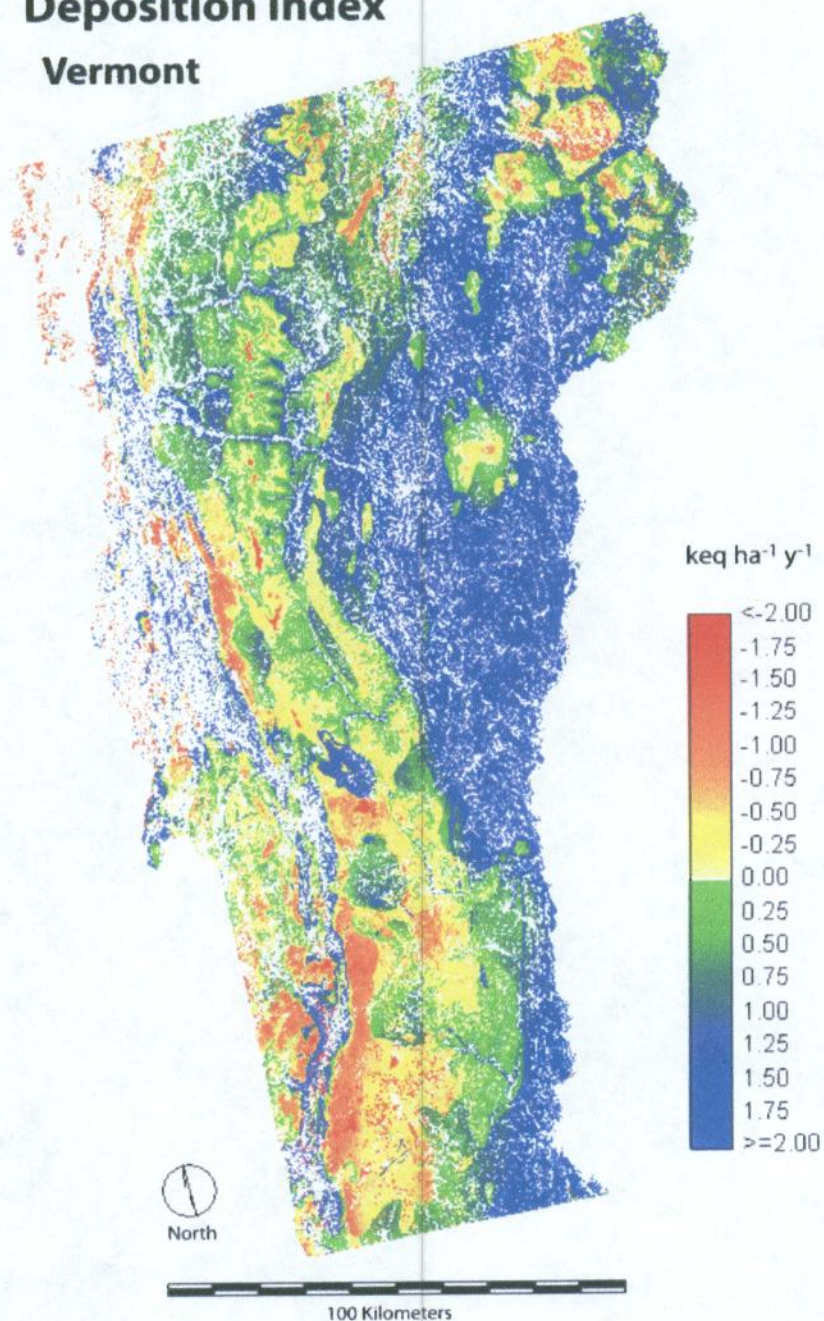


Figure 5. The deposition index for atmospheric sulfur and nitrogen deposition to Vermont (1996-1999) with respect to forest ecosystem critical loads. Positive values of the deposition index reflect the capacity of a forest ecosystem to tolerate additional acidic deposition. Negative values of the index correspond to the reduction in S and N deposition required to eliminate present or deter the development of future nutrient limitations. Red areas indicate current sulfur and nitrogen atmospheric deposition rates greater than the critical load. The deposition index is expressed in terms of the kilo-equivalents of charge per hectare per year. Nitrogen deposition includes both ammonium + nitrate forms.

Deposition Index

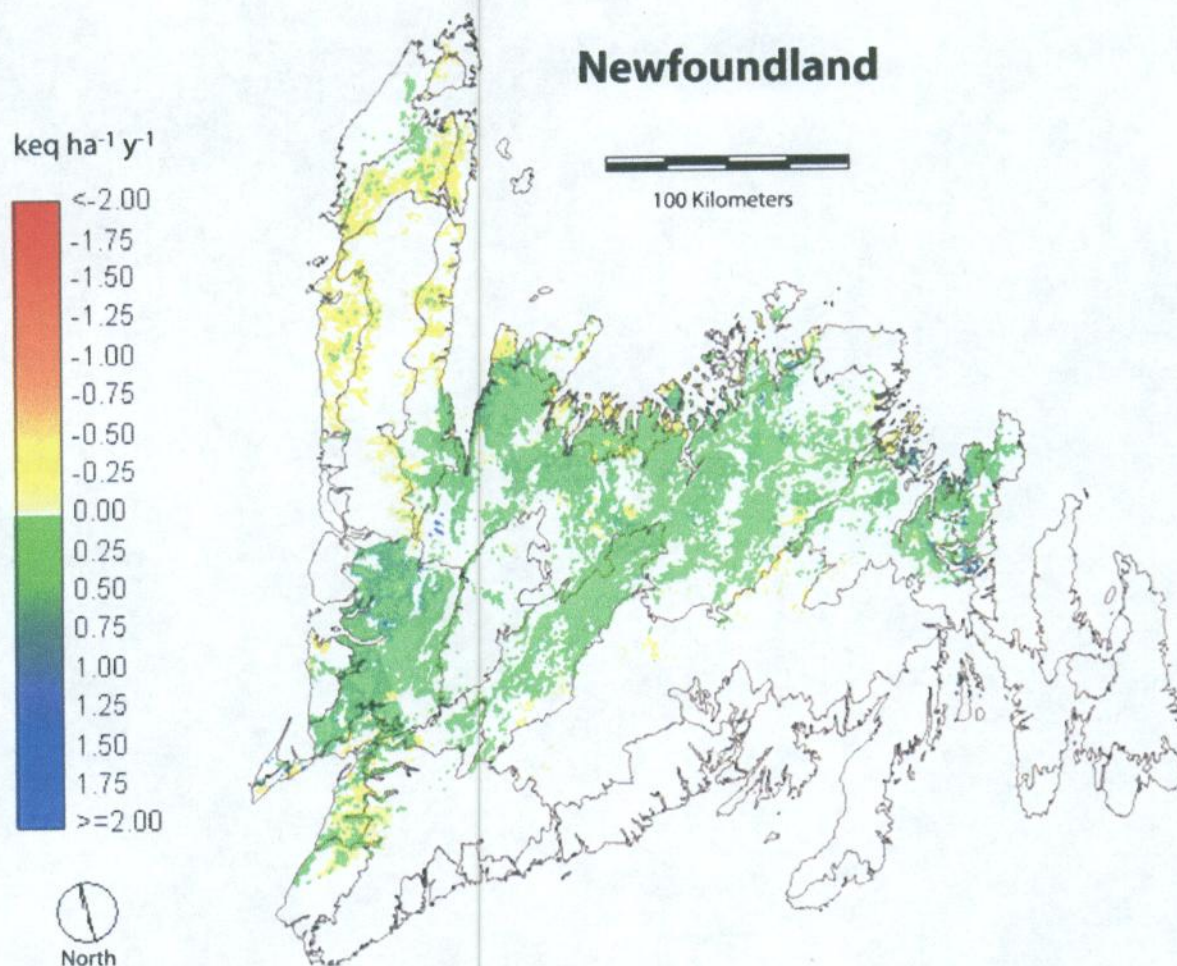


Figure 6. The deposition index for atmospheric sulfur and nitrogen deposition to Newfoundland (1994-1997) with respect to forest ecosystem critical loads. Positive values of the deposition index reflect the capacity of a forest ecosystem to tolerate additional acidic deposition. Negative values of the index correspond to the reduction in S and N deposition required to eliminate present or deter the development of future nutrient limitations. Red areas indicate current sulfur and nitrogen atmospheric deposition rates greater than the critical load. The deposition index is expressed in terms of the kiloequivalents of charge per hectare per year. Nitrogen deposition includes both ammonium + nitrate forms.

Atmospheric S deposition ranges from 3.1 to $4.7 \text{ kg ha}^{-1} \text{y}^{-1}$ and N deposition ranges from 1.8 to $3.0 \text{ kg ha}^{-1} \text{y}^{-1}$. Atmospheric deposition is highest in the southwest and lowest in the northeast, in parallel with total precipitation. The lowest critical loads and lowest deposition index values (Figure 6) are mainly associated with rocky, coarse and predominantly siliceous soils, which occur throughout the region. Critical loads range from $0.15 \text{ keq ha}^{-1} \text{y}^{-1}$ on shallow rocky

soils to $2.6 \text{ keq ha}^{-1} \text{ y}^{-1}$ on soils enriched with carbonates and other easily weathered soil minerals. Atmospheric deposition from 1994 to 1998 exceeded critical loads for about 23%, of the forested area and was within 10% of the critical load in an additional 7.1%. Critical loads were exceeded in 34% of balsam fir forests, but in only 8.7% of black spruce and birch forests. The lowest deposition index values of about $-0.26 \text{ keq ha}^{-1} \text{ y}^{-1}$ occurred in forests that grow on shallow and rocky soils.

The difference between the critical load and current atmospheric deposition (Figure 5) indicates the severity of the current nutrient imbalance (negative values) or the capacity to tolerate additional deposition (positive). At sites where the deposition index is negative, the time required for the manifestation of declines in forest health and growth rate is governed, in part, by the size of the soil-exchangeable pool of nutrient cations. Exchangeable cations are those that are loosely retained in the soil, and can be thought of as the short-term supply of nutrients, while soil mineral weathering provides the long-term supply. If the exchangeable pool is large, the forest may be able to buffer a small nutrient input-output imbalance for tens to hundreds of years, delaying the onset of health and growth limitations. This buffering period allows time for the implementation of air-pollution emissions reductions.

The size of the exchangeable cation pool is governed by a variety of factors including soil depth, texture, organic matter content and the history of nutrient input-output imbalance or surplus. This is an extremely local condition. It is not possible to estimate the size of exchangeable nutrient pools on a regional basis. Observations at specific sites indicate exchangeable cation pools in the general range of 2 to 80 keq ha^{-1} . Frequently, sites with low weathering rates and a history of nutrient depletion will also have small exchangeable pools of cations. Thus, we can generally assume that where the critical load is exceeded today (negative deposition index), it was also exceeded in the recent past (1960's to present) and the buffering capacity of the exchange pools at such sites has already been somewhat diminished. Whereas, at sites with a positive value of the deposition index, exchangeable cation reserves are increasing. Therefore, the deposition index also provides an indication of the time to the onset of problems. Where the index is strongly negative, health problems and growth declines should be evident now (e.g. Figure 3) or within decades. Where the index is only slightly negative, problems may take 100 to several hundred years to develop.

Information on the spatial distribution of atmospheric deposition rates and critical loads can be used to estimate the impact of potential changes in atmospheric deposition rates. We estimate that a 50% reduction in combined sulfur and nitrogen deposition would remediate the nutrient depletion problem in 78% of the forested area where critical loads are currently exceeded in Vermont (Figure 7.a.). The remaining sensitive forest areas (67,335 ha) would primarily be high-elevation balsam-fir and red-spruce and sugar maple forests near their elevational limit to growth. Conversely, only a 10% increase in combined sulfur and nitrogen deposition would jeopardize the nutrient supplies of an additional 152,018 ha of forest, primarily sugar maple and northern hardwood stands (Figure 7.b.). In Newfoundland, a 50% reduction in acidic deposition would eliminate nutrient depletion problems in 68% of the potentially impacted area. A 10% increase in combined sulfur and nitrogen deposition would put an additional 8.3% (150,670 ha) at risk of nutrient depletion. From this analysis (Figure 7.b.,d.) it is clear that reductions in S deposition already achieved since the mid 1970s (NSTC, 1998) have prevented vast areas of forest from developing nutrient limitations to growth.

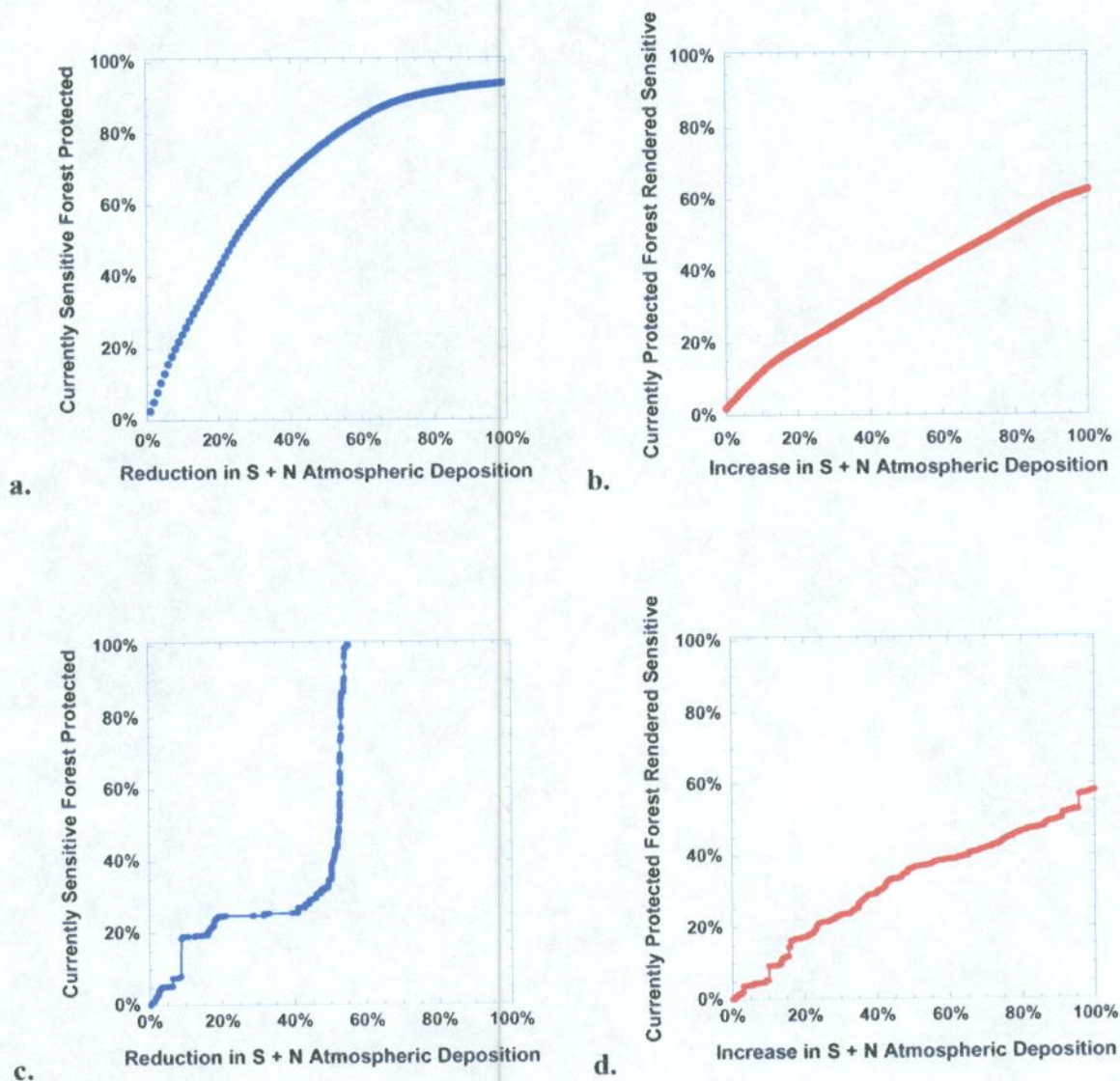


Figure 7. Predicted improvement (a) and deterioration (b) in forest condition with changes in atmospheric deposition of S + N to Vermont; improvement (c) and deterioration (d) in forest condition with changes in atmospheric deposition of S + N to Newfoundland. Improvement refers to the percentage of forest area with deposition currently greater than the critical load that would have deposition less than the critical load with a given percentage reduction in atmospheric deposition. Deterioration refers to forests that currently experience deposition rates less than the critical load that would experience deposition in excess of the critical load with a given increase in atmospheric deposition.

7. Impacts on Forest Ecosystems when the Deposition Exceeds the Critical Load

Excess acidic deposition to forest ecosystems can adversely affect forest growth and productivity. Forest health consequences of elevated nitrogen and sulfur deposition have been documented in the literature and are variable depending on many site-related characteristics. In

general, acidic deposition can cause soil and surface water acidification, increase soluble soil aluminum to toxic levels, and lead to a depletion of soil base cations, especially those required for plant growth (Ca, Mg and K). The symptoms of plant nutrient deficits manifest themselves at the cellular level, but also become visible as primary indicators of tree health. Notable tree health problems include increased susceptibility to winter injury, increased crown dieback, and increased proliferation of insect or disease activities. All of these may reduce forest growth and increase mortality. Over time, stand productivity may decrease, and the accumulation of health problems may lead to shifts in species composition and diversity.

Provincial, state, and federal agencies routinely measure established indicators of ecosystem health throughout the study area. These ecological indicators are used in this project for several purposes. First, comparison of the deposition index with independent indicators demonstrated that our assessment is consistent with region-wide tree health data. For example, Figure 3 shows the association between tree growth of hardwood and softwood stands in Québec, and the plot-specific deposition index. Similar associations were obtained between the deposition index and crown dieback (in Vermont) and canopy transparency (across Canada from Newfoundland to Alberta). The second phase of the project will include assessment of the deposition index against a broad array of ecological indicators of tree health (e.g., tree condition, growth, mortality, canopy transparency, and incidence of insect and disease) across all states and provinces within the study area. Comparison of the magnitude of the deposition index with ecological indicators will also aid in refining estimates of the time to development of forest health problems associated with different values of the deposition index. If forest health is already compromised in large areas with a negative deposition index, then this may emphasize an urgent need to accelerate on-going regional, national and international air quality policy discussions.

8. Stakeholder Consultations

The maps and products relating forest sensitivity to acidic deposition are new tools for eastern North American resource managers. While their primary purpose is to guide the development of policies focused on acidic deposition control, they also provide valuable information pertinent to state and provincial air quality standards, local forest management, and future land-use assessments. Interactions with stakeholder groups have been an integral part of the development of this project, including data compilation, developing methods and processes of using multi-disciplinary data, and interpreting the results. During this pilot project, regional experts from all areas of forest ecosystem science have been consulted, both individually and in groups. State, provincial, and federal government employees from air resources and forestry have also been involved at numerous stages of the pilot project. Private forest landowners and forestry professionals had additional opportunities for input. While most of the stakeholder consultations have occurred within the pilot state and province, regional outreach has been conducted in both Canada and the United States. Additional outreach of results is planned for the general public.

9. Conclusions

The maps and analysis presented for Vermont and Newfoundland demonstrate the usefulness of the overall Forest Mapping Project approach for estimating the forest area that is sensitive to acidic deposition inputs. These results will be useful both in the policy context for determining the need for further emissions reductions, and in the forest resource management context for identifying potentially sensitive forest areas. Identification of sensitive forest areas

facilitates selection of sites where the consequences of future (elevated or reduced) deposition levels can most effectively be monitored.

Several factors may co-occur that cause the critical load to be exceeded by the current deposition: the mineral weathering rate may be low (and soils may be thin), the vegetation may have a high nutrient cation demand, and deposition levels may be high. Certain forest types (e.g. red spruce-balsam fir) more often have deposition levels which exceed the critical load because they tend to occur at higher elevations where deposition levels are higher, and on low weathering rate soils. Comparisons between ecological indicators of forest health and productivity and critical loads suggest that forest health is poorer where critical loads are exceeded. The results of the pilot phase indicate that a relatively small increase in deposition levels will increase sensitive forest area substantially, while reduction in deposition levels will reduce the sensitive forest areas.

Next Steps 2003 – 2004

The results of the Pilot Phase study will be used to guide Phase II of the Forest Mapping Project which will include assessment and maps for Connecticut, Massachusetts, Maine, New Hampshire, Rhode Island, New Brunswick, Nova Scotia, and Québec. Some of the work in Phase II is already underway (Figure 8) and timely completion of Phase II is contingent on funding.

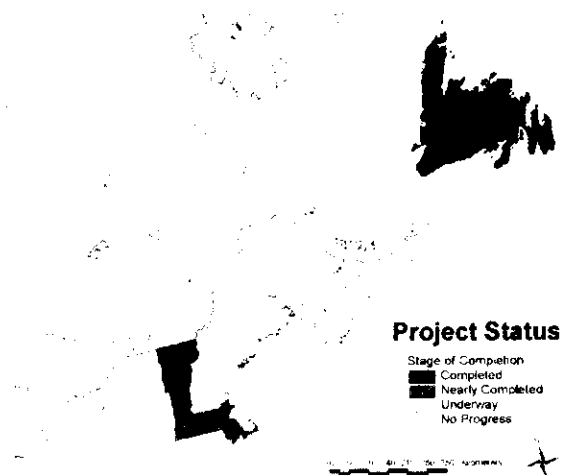


Figure 8. Status of the Forest Mapping Project

In the US and Canada, the additional work includes: (1) development of GIS data layers; (2) data synthesis and calculations for individual sites; (3) assembly and evaluation of ecological health indicators with respect to critical loads; (4) assessment of the impact of future emissions reduction (and increase) scenarios on the extent of sensitive forests; (5) estimation of the time until forest health and productivity are compromised; (6) outreach of pilot project results; and (7) additional stakeholder consultations throughout the region. The data synthesis will include compiling all available data on deposition, vegetation, harvesting rates and soil parameters into a permanent database for critical loads calculations and other regional

assessments. The ecological indicator assessment will include development of data layers for several forest health indicators and evaluation of forest health at sites where the critical load has been exceeded. In the US, the development of GIS layers will include literature review, data synthesis, modeling, mapping, and ground-truthing fieldwork required for the soil, vegetation, harvesting rate, and deposition data layers. In Canada, additional work will include assisting Environment Canada in drafting the 2004 Canadian Acid Rain Assessment Report.

10. Acknowledgments

The Forest Mapping Working Group would like to acknowledge our funding partners: Environment Canada, Forestry Newfoundland, Forestry Québec, Joint Conference of New England Governors and Eastern Canadian Premiers, Massachusetts Department of Environmental

Protection, Natural Resources Canada – Canadian Forest Service, Northeast States for Coordinated Air Use Management, US Environmental Protection Agency, USDA-Forest Service Northeastern Ecosystem Research Cooperative, and Vermont Agency of Natural Resources. We would like to thank Debra Avalone-King, Holly Carlson, Phil Girton, John Henderson, J. Edward Hurley, Wendy Leger, Tom Luther, Elisabeth McLane, Scott Payne, Rhéal Poirier, Peter Ryan, Angela Shea, and Dick Ziegler who have made significant contributions to this project.

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