PROTOCOL FOR ASSESSMENT AND MAPPING OF FOREST SENSITIVITY TO ATMOSPHERIC S AND N DEPOSITION

New England Governors/Eastern Canadian Premiers

Acid Rain Action Plan

2001

Action Item 4: Forest Mapping Research Project

Prepared by: NEG/ECP Forest Mapping Group

PREFACE

In June 1997, the Conference of the New England Governors and Eastern Canadian Premiers (NEG/ECP) recognized that acidic deposition is "*a joint concern for which a regional approach on research and strategic action is required*" and that "*state and provincial monitoring efforts and analysis remain a high priority within their respective programs*". The Conference charged its Committee on the Environment to present specific policy recommendations at their next meeting, June 1998. A draft framework for the Acid Rain Action Plan was subsequently developed by representatives of the New England states and Eastern Canadian provinces. This draft was refined following the NEG/ECP Workshop on Acid Rain and Mercury in February, 1997 in Portland, Maine, and the final work plan was approved in October, 1999.

The New England/Eastern Canadian Acid Rain Action Plan identifies steps to address those aspects of the acid rain problem in northeastern North America that are within the region's control. Specifically, the action plan includes:

- a comprehensive and coordinated plan for further reducing emissions of sulphur dioxide and oxides of nitrogen which contribute to the problem of long-range transport of air pollutants, acidic deposition, and nutrient enrichment of marine waters in the region
- a research and monitoring agenda targeted at both improving the state-of-the-science for this environmental problem, and increasing regional cooperation in sharing research and data in order to better understand the impact of acidic deposition on the region and analyze the effectiveness of current control programs on sensitive ecosystems
- a public education and outreach agenda to ensure that the public continues to be educated and mobilized towards the overall goal of protecting the natural environment.

The action plan contains 22 recommendations for specific actions that the provinces and states can undertake to ensure that significant progress is realized in reducing the effects of acidic deposition on ecosystems.

The NEG/ECP Committee on the Environment has appointed a steering committee to coordinate and prioritize the implementation of the action items, and a forest mapping group to carry out Action Item 4 on the forest mapping research project. Action Item 4 concerns the mapping of forest sensitivity to acidifying sulphur (S) and nitrogen (N) pollutants for upland forests in northeastern North America.

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1. PROJECT GOALS

1.1. Problem statement

As a result of SO_2 abatement legislation, sulphur emissions have decreased across North America. However, current emissions of both sulphur (S) and nitrogen (N) compounds are expected to have continuing negative impacts on forest soils, and forest health and productivity (Driscoll et al. 2001). Upland forests, as opposed to marshy wetlands, are expected to be impacted most: acid buffering capacities of upland soils are generally low compared to down-slope locations, and such soils typically do not receive acid-buffering seepage water from higher ground or from upwelling subsurface flows. Over time, the ability or the potential of the upland *forest soil/vegetation complex* to buffer acidic deposition is expected to decrease, and soil nutrient supplies for sustainable tree growth are expected to become depleted and/or imbalanced. The most sensitive forest ecosystems are likely to be in mountainous regions where glacial till and soils are thinnest, and where atmospheric deposition rates are highest (Miller et al. 1993).

In general, assessing forest sensitivity to acidic deposition is a complex task, and doing so in a reliable, yet practical manner requires a scientifically acceptable protocol to:

- Identify, quantify and map those parameters that best capture the ability or potential of each major upland soil-vegetation combination to buffer against increasing soil acidification
- Develop a criterion for determining the level of acidic deposition above which upland forest soils are no longer protected against increasing soil acidification and consequent base cation depletion (*sustainable acidic deposition*)
- Determine whether current and projected atmospheric S and N deposition rates exceed *sustainable acidic deposition*.

1.2. Objectives

The overall goal of this project is to generate maps of eastern Canada and the northeastern United States that identify those forest areas that are most sensitive to acidic deposition. Sensitive areas are those where current or projected acidic deposition potentially exceeds *sustainable acidic deposition rates*. Sustainable acidic deposition rates are those that would maintain forest ecosystem health and related productivity indefinitely based on S and N deposition inputs. Sustainable acidic deposition rates can be determined from analyzing existing information on geology, soils, vegetation, and land-use history. Therefore, the specific objectives of this project are to:

1. Estimate sustainable acidic deposition rates and exceedances for upland forests representative of the New England States and of the Eastern Canadian Provinces, using site-specific data, and ecozone subdivisions
2. Produce maps of sustainable acidic deposition rates and associated exceedances
3. Relate potential exceedance of sustainable acidic deposition to forest productivity and health, based on existing information.

The purpose of this document is to outline the procedures and methodologies that will be used to calculate sustainable acidic deposition rates and the related exceedances. Specifically:

- Section 2 (*Methods for estimating sustainable acidic deposition rate*) defines equations and assumptions used to estimate sustainable acidic deposition using a steady-state mass balance approach.
- Section 3 (*Data requirements for model application and validation*) lists data required to make site-specific calculations and to compare the site-specific to the ecological unit approach.
- Section 4 (*Mapping Methodologies*) outlines database development for the ecological unit approach and the related mapping methodologies.
- Section 5 (*Data Management Protocol*) describes the approach for standardizing data for the ensuing mapping effort.
- Appendices addressing: sustainable acidic deposition, soil base saturation, soil weathering, soil N accumulation, nutrient uptake, atmospheric deposition, impacts of exceedance of sustainable deposition on forest health, and project administration.

2. METHODS FOR ESTIMATING THE SUSTAINABLE ACIDIC DEPOSITION RATE

2.1. Background on sustainable deposition and critical loads

The procedures to be used generally follow the steady-state mass balance approach (SMB), as documented by Posch et al. (1995), the Mapping Manual (UBA, 1996), and Posch et al. (1999) for the calculations and mapping of critical soil acidification loads in Europe. In that context, a critical load was 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*" (Nilsson and Grennfelt 1988). As noted by Posch et al. 1999:

"The first critical loads to be calculated were for acidity, and - in the negotiations for the 1994 Sulphur Protocol - a "sulphur fraction" was used to derive a critical deposition of sulphur from the acid critical load (Downing et al., 1993; Hettelingh et al., 1995). In preparations for the negotiations for a "multi-pollutant, multi-effect" protocol, nitrogen became the focus, and thus critical loads of N had to be defined as well. This led to a revision of the Mapping Manual (UBA, 1996)".

The approach described in this protocol, however, differs from the European Critical Load concept by defining a *sustainable acidic deposition rate* that maintains or enhances the current level of soil base saturation such that soil reserves of plant nutrients can be maintained under given forest management practices and/or natural disturbance regimes, for the foreseeable future (e.g., several forest rotations). In contrast, the European critical load concept includes several chemical threshold concentrations above or below which damage to the functioning of organisms and ecosystems is thought to occur. One chemical criterion is the concentration of soil aluminum (Al), which is solubolized by acid, with threshold values for water-soluble Al in the soil solution ranging from 6 to 25 mg L^{-1} (or 0.1 to 0.4 meq L^{-1}; de Vries 1991, Posch et al. 1995). Another soil acidification criterion is the molar ratio of base cations to aluminum (*BC:Al*) in the soil solution. This criterion was selected because excessive amounts of Al ions in soil solution interfere with plant uptake of Ca, Mg and/or K ions (Shortle and Smith 1988). For the BC:Al criterion, a molar ratio of 1 is generally used, because that is at or near the threshold for inducing nutritional Ca, Mg or K deficiencies in tree seedlings (Warfvinge and Sverdrup 1995). These specifications, however, become problematic in terms of scaling up from observed tree seedling responses under controlled laboratory or greenhouse conditions (from which the physiological thresholds values have been derived) to the complexity of conditions in the forest. Soils rarely provide a uniform rooting medium and span a continuum of soil properties varying both laterally and vertically at the scale of a single tree. Often, the standard deviation of any soil property is as large as the mean value of that property (Arp 1984, Arp and Krause 1984). Therefore, a factor of 10 has been suggested as a safety factor to ensure that the soil conditions do not deteriorate under varying conditions and episodic acidification events (Arp et al. 1996). Many questions arise when scaling greenhouse results to the field, including: Is the critical concentration threshold for soluble Al that causes physiological damage to tree roots in the field the same as that in the greenhouse or hydroponic solution? Given the substantial vertical variation in solution Al, to which part of the rooting space should the threshold be assigned? Do tree roots simply adapt by avoiding soil pockets or individual soil layers with high soluble Al? To what extent do soil organic matter and dissolved organic matter render water soluble Al non-toxic via complexation?

Adopting the concept of a sustainable acidic deposition rate to protect against soil acidification and subsequent base cation depletion eliminates the difficulties of setting and accepting physiological thresholds and the related uncertainties as part of the forest sensitivity assessment. Moreover, focusing on the base status of soils is helpful in ensuring that the overall viability of forests and forest soils is maintained via sustainable nutrient capitals. Such an analysis will demonstrate whether nutrient pools can be maintained by primary means (e.g. soil weathering, atmospheric deposition), or by artificial means (e.g. forest fertilization). This protocol also addresses actual and anticipated disturbance regimes which can affect the sustainable acidic deposition rate. Uncertainties in the calculation of sustainable acidic deposition are caused by difficulties in quantifying:

? Inputs of primary nutrients into the soil (atmospheric deposition, soil weathering)
? Extent of nutrient retention within the soil and by the vegetation
? Effective depth of rooting zone
? Changes in individual nutrient pools within soil and vegetation, caused by changes in climate, forest management, or land use

The proposed methodology will allow for sensitivity assessments that specifically deal with these uncertainties.

In Appendix 1, the term *sustainable acidic deposition* - hereafter referred to as *Sustainable Deposition* or *SD* - is defined in terms of a simple mass balance calculation, for (i) the soil alone, (ii) the soil-vegetation complex (the forest), and (iii) the soil-vegetation-atmosphere complex (the ecosystem). It is important to note that the SD is calculated based on inputs of S and N deposition and does not include deposition of other pollutants such as ozone, or the effects of other factors detrimental to forest health, such as pests. Therefore the SD should reflect the level of S and N deposition an upland forest can tolerate in the absence of other impacts. The SD must be considered the *potentially* sustainable level of S and N deposition when other pollutants or forest health impacts are significant. The overall intent of this protocol is to provide a conservative estimate of the SD – the highest value of SD that will maintain the overall soil base status within the context of current or expected acidic deposition loads and related exceedance.

An important objective of this project is to relate the exceedance of SD to forest production and health. In an assessment of critical acidification loads in the Turkey Lake Watershed of northeastern Ontario, preliminary evaluations of data have revealed that many permanent sample plots that were located in regions with high acid exceedances showed symptoms of decline: trees have reduced growth, visible signs of damage, and increased canopy transparencies (Moayeri et al. *in press*). Declines of red spruce at high elevations have been linked to imbalances in soil nutrients and high concentration of acid-mobilized aluminum in the soil (Environment Canada 1997, Schaberg et al. 2000). Another study has shown strong correlations between forest decline symptoms and local acidification exceedances (Ouimet et al. 2000). There is increasing evidence that essential nutrients, such as calcium and magnesium, are being lost from soils exposed to acidic deposition (Environment Canada 1997, Alewell et al. 2000, Driscoll et al. 2001). In addition, air pollution damage to trees influences ecological processes such that the trees become more susceptible to other stressors such as insects and diseases, both directly and indirectly (Hall et al. 1998).

2.2. The steady-state mass balance (SMB)

The steady-state mass-balance approach uses a simplified, steady-state input/output description of the most important biogeochemical processes that affect soil acidification.

Ecosystem inputs include:

1. Atmospheric deposition of S, N, Ca, Mg, K
2. Soil base cation weathering rate (Ca. Mg, K, Na, P)
3. N fixation, where significant.

Ecosystem retention and output processes lead to:

1. Net nutrient accumulation in the soil (N, S, Ca, Mg, K, P)
2. Net nutrient storage in above-ground biomass by uptake (N, S, Ca, Mg, K, P)
3. Net removal of nutrients by forest harvesting or other disturbance (N, S, Ca, Mg, K, P)
4. Nutrient loss through soil leaching (N, S, Ca, Mg, K)
5. Denitrification (N).

Based on the above ecosystem processes, a mass-balance framework is used to calculate sustainable rates of acidifying sulphur and nitrogen deposition for upland forest soils, in order to maintain or enhance the current level of soil base saturation. The background and computational framework dealing with maintaining soil base saturation of ecosystems receiving acidic deposition is presented in Appendix 2.

2.3. Maximum sustainable deposition of acidifying sulphur

The maximum sustainable sulphur deposition rate to maintain the current soil base cation status is given by:

$$SD_{max}(S) = BC_{dep} + BC_{w} - BC_{u} - ANC_{le}(SD) \qquad (1)$$

where:

BC_{dep} - sum of Ca + Mg + Na+ K deposition rate (eq ha^{-1} yr^{-1})

BC_w - soil weathering rate of Ca + Mg + K + Na (eq ha^{-1} yr^{-1})

BC_u - net Ca + Mg + K uptake rate (eq ha^{-1} yr^{-1}) ultimately removed by harvest or disturbance

$ANC_{le}(SD)$ - sustainable acid neutralizing capacity (ANC) leaching rate (eq ha^{-1} yr^{-1}).

Atmospherically deposited base cations are acid-neutralizing. The soil weathering process whereby Ca, Mg, K, and Na ions are released into the soil solution is also acid neutralizing. In contrast, base cation uptake is considered acidifying (because plants release H^+ ions during base cation uptake to maintain charge neutrality on either side of the soil-root interface). In these calculations, Na can be neglected except for the Na component of soil weathering. Most of the incoming Na is lost from the ecosystem by leaching, because of low Na retention.

The relationship between soil acidity and base cation status is based on the ion exchange equilibrium by way of the BC:Al ratios of ion exchange sites and in soil solution (Appendix 2). In particular, the maintenance of the soil base saturation is closely linked with what constitutes a sustainable base cation leaching rate. This rate can be calculated from

$$ANC_{le}(SD) = -1.5\frac{BC_{dep} + BC_w - BC_u}{(BC/Al)_{SD}} - Q^{2/3}\left(1.5\frac{BC_{dep} + BC_w - BC_u}{(BC/Al)_{SD}K_{gibb}}\right)^{1/3} \qquad (2)$$

where:

$(BC:Al)_{SD}$ - ratio of base cations to Al (eq/eq) in the soil percolate which would be consistent with maintaining a particular base saturation level

K_{gibb} - gibbsite dissolution constant that controls Al solubility (m^6 eq^{-2}) the multiplication factor 1.5 arises from the conversion from moles to equivalents

Q - rate of soil percolation (combined lateral and downward), which can be assumed equal to streamwater flux (m yr^{-1}).

For background on setting $(BC:Al)_{SD}$, see Appendix 2. For background on determining soil weathering rates, see Appendix 3.

2.4. Minimum sustainable deposition of acidifying nitrogen

As long as the deposition of N stays below the minimum sustainable acidic deposition rate of nitrogen, i.e.,

$$N_{dep} \leq N_a + N_u + N_{de} = SD_{\min}(N) \qquad (3)$$

where:

N_{dep} - atmospheric N deposition rate (eq ha^{-1} yr^{-1})

N_a - net N accumulation rate in the soil (eq ha^{-1} yr^{-1})

N_u - net N uptake rate (i.e., increment of nutrient in biomass; eq ha^{-1} yr^{-1})

N_{de} - soil denitrification rate (eq ha^{-1} yr^{-1})

then all deposited N is consumed by N sinks within the ecosystem (N accumulation in soil, N uptake by the vegetation) or lost via denitrification. In this case, $SD_{max}(S)$ alone determines the maximum sustainable acidic deposition rate.

All of the above fluxes of N are expressed as net annual quantities, but net soil accumulation of N may vary significantly from location to location, because it is affected by long-term site history (old growth, intensively managed, fire, and other natural disturbances). Current estimates for net N accumulation vary from 0 to 5 kg ha^{-1} yr^{-1} (0 to 350 eq ha^{-1} yr^{-1}). For further background, see Appendix 4.

Equation 3 accounts not only for N_a and N_u, but also for denitrification. However, for upland forest soils, denitrification rates are small to negligible (Binkley et al. 1995; Appendix 1), hence N_{de} is set to 0. Assuming denitrification to be negligible gives a conservative estimate of SD (i.e., SD would be higher if denitrification were assumed to be greater than 0).

2.5. Maximum sustainable deposition of acidifying nitrogen

The maximum allowable sustainable acidic deposition rate of N (for the case of no S deposition) is given by:

$$SD_{\max}(N) = SD_{\min}(N) + SD_{\max}(S) \qquad (4)$$

In this equation the SD_{max} for N is the sum of the sinks for N in the ecosystem and the maximum deposition rate.

2.6. Sustainable deposition of nutrient nitrogen

In addition to the acidifying effect of nitrogen deposition, excess N deposition can cause water quality problems including eutrophication of surface water (the prolific growth of unwanted nitrophilic species in otherwise N-limited ecosystems), and deterioration of drinking water supplies and subsequent human health problems (Fisher et al. 1988, Nilsson and Grennfelt 1988, Skeffington and Wilson 1988). More significantly, excess N deposition can lead to plant nutrient imbalances and forest health decline (Agren and Bosatta 1988, Aber et al. 1998, Dehayes et al. 1999, Schaberg et al. 2000). Upland forests initially respond positively to the fertilizing effect of additional N deposition until they reach N saturation (Aber et al. 1989). Once a forest reaches N saturation, acidification from N deposition increases, nitrate leaching increases, and plant nutrient imbalances may occur. When there is excess available nitrogen, other nutrient elements such as Ca, Mg, K and P become growth limiting (Schulze 1989). The nitrogen leaching rate, N_{le}, is the eutrophication limit for surface waters or the maximum acceptable leaching rate (the maximum leaching rate for an ecosystem that is not at N saturation). This leaching rate is given by

$$N_{le[acc]} = Q[N]_{eut} \tag{5}$$

where:

$N_{le[acc]}$ - acceptable leaching of N

$[N]_{eut}$ - that N concentration in the soil solution above which it would be considered detrimental to ecosystem or soil

The sustainable deposition rate for nitrogen with respect to ecosystem eutrophication can then be expressed as

$$SD_{nut}(N) = N_a + N_u + N_{de} + N_{le} \tag{6}$$

In view of both the acidification and eutrophication issues, the maximum allowable N deposition can then be obtained from $\min\left[SD_{\max}(N), SD_{nut}(N)\right]$.

2.7. Sustainable acidic deposition (SD)

Since both S and N deposition contribute to acidity, they are both included in the calculation for the sustainable acidic deposition rate. For a given forest, it is therefore possible to determine those combinations of S and N deposition that will not exceed the sustainable acidic deposition rate. The various combinations of S and N deposition that do add up to the maximum sustainable acidic deposition rate therefore delineate the **sustainable acidic deposition region within the S_{dep} - N_{dep} deposition continuum** (i.e., the shaded area in Figure 1).

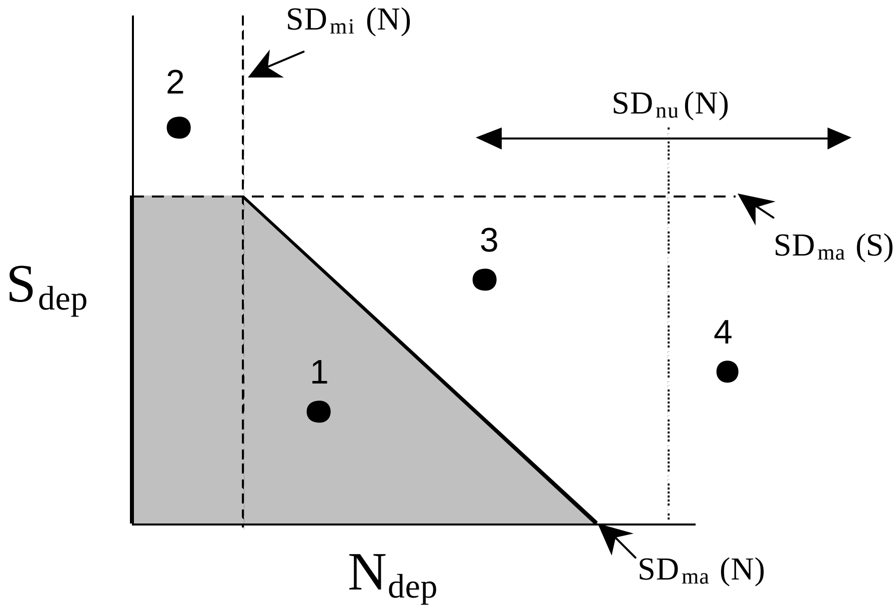

Figure 1. Relationship between atmospheric S and N deposition and the sustainable acidic deposition rate SD(S) + SD(N) for upland forest soils. For each point lying in the shaded area (e.g., Point 1), there is no exceedance of the sustainable acidic deposition rate. Points lying outside the shaded area exceed the sustainable deposition rate. For Point 2, S deposition is larger than the maximum acceptable rate for S deposition, and N deposition is less than the amount that the forest ecosystem can retain [$N_{dep} < SD_{min}(N)$]. This means that the system would not be saturated with respect to N, and, in this case, there would be an exceedance of sustainable S acidification but no exceedance of N acidification. For Points 3 and 4, there would be sustainable acidification exceedances due to the combined effects of S and N deposition. For Point 4, there would be a soil acidification exceedance as well as a N nutrient exceedance (the associated vertical line can be moved to the right or the left depending on one's choice about $[N]_{eut}$). Notes: see text for $SD_{max}(S)$, $SD_{max}(N)$, and $SD_{min}(N)$. The slope of the shaded area is -1 for the case of upland forests, when denitrification is considered negligible.

2.8. Forest biomass production and N uptake

In order to determine the sustainable deposition rate, mean annual forest biomass production rate or mean annual increment (MAI) is calculated. The MAI that can be sustained is a function of: (1) atmospheric deposition, (2) soil weathering, (3) the maintenance of current soil base status, (4) existing or anticipated nutrient availabilities, and (5) forest disturbance regimes, including harvesting and fire. The sustainable MAI can be derived once sustainable N concentrations in the above-ground forest biomass (leaves, branches, bark, stemwood) are specified using steady-state conditions for N accumulation and biomass.

Since

$$[N]_{biomass} = N\ content\ \textit{(kg N)} \,/\, Biomass\ \textit{(tonne)} = N_u / MAI \qquad (8)$$

one obtains the MAI using N uptake (defined below) and N concentration in biomass

$$MAI = N_u / [N]_{biomass} \qquad (9)$$

where:

- Biomass - above-ground forest biomass
- N content - accumulation of N in biomass
- MAI - mean annual increment, is equivalent to above-ground biomass divided by rotation length (years), or average period of recurring disturbance regime
- $[N]_{biomass}$ - wheighted/whole-tree concentrations of N (in kg N /tonne).

The MAI-based calculations are used to estimate the sink for nutrients in vegetation over a forest rotation. Coarse and fine roots usually remain on site. Thus, mean annual increment calculations and related N_u estimates can be restricted to the increment in above-ground vegetative components which will be removed by harvesting.

N uptake for mean annual leaf, branch, bark, and stemwood production is computed from

$$N_u = season\_length\_factor * \min\{X\ supply\ [N]_{biomass} / [X]_{biomass}\ , N\ availability\} \qquad (10)$$

where:

- season_length_factor - the fraction of the year during which nutrients are absorbed by the soil-vegetation complex (i.e., the growing season)

X_{supply} - the long-term mean annual supply rate of Ca, Mg, K, and P. Square brackets denote weighted, whole-tree concentrations of X for each major tree type.

$N_{availability}$ is the net sum of inputs from deposition and N fixation and losses to soil N accumulation

$$N_{availability} = N_{dep} + N_{fix} - N_a, \tag{11}$$

and X_{supply} is the sum of inputs from deposition and mineral weathering

$$X_{supply} = X_{dep} + X_w \tag{12}$$

Note that equation 10 makes use the limitation of X and N availability to calculate biomass growth and therefore uptake. Long-term N uptake is considered Ca, Mg, K, or P limited if

$$N_{availability} \text{ (in eq)} > X_{supply} \cdot [N]_{biomass} / [X]_{biomass} \tag{13}$$

Otherwise, N uptake is only limited by N availability. Ecosystems for which biomass growth is X-limited are at N saturation. In contrast, ecosystems for which biomass growth is N-limited have not reached N saturation (Aber et al. 1998). Note that because $[N]_{biomass} / [X]_{biomass}$ is fixed, sustainable deposition rates are calculated for conditions under which nutrient imbalances are not expected to occur.

In the above equations, S uptake does not contribute to the calculated sustainable acidic deposition rate, because S:N ratios in vegetative tissues are approximately 0.1. If S uptake were included in the calculation, then SD would increase very slightly.

The overall accuracy of this approach is a function of the accuracy of the N and X uptake estimates, and on the presumed constancy of the N:X ratios. While the nutrient ratios are considered constant, they are plastic in nature, thereby requiring ratio-specific sensitivity analysis of the model-calculated SD and related exceedance values. For details regarding X_u and N_u and related species-specific concentration values and nutrient ratios in foliage, branches, bark, and stemwood, see Appendix 5.

2.9. Exceedances of sustainable acidic deposition

Sustainable acidic deposition rates, once defined and calculated, can be compared with current or expected rates of acidic deposition (wet + dry). An exceedance of sustainable deposition can then be defined as follows (Appendix 2):

$$\text{Exceedance} = S_{dep} + \max\{N_{dep} - SD_{min}(N), 0\} - SD_{max}(S) \qquad (14)$$

For background and details regarding the estimation of local S, N, Ca, Mg, and K deposition rates, see Appendix 6. For background on observed or expected effects of exceedance on forest growth, see Appendix 7.

3. DATA REQUIREMENTS FOR MODEL APPLICATION AND VALIDATION

The goal of this project is to calculate and map SD based on detailed, site-specific data from locations throughout eastern Canada and the northeastern U.S. An approach similar to the one proposed here has already been used in a preliminary assessment of exceedance of critical loads in parts of Eastern Canada (Arp et al. 1996, Ouimet et al. 2000, Moayeri et al. *in press*), but that approach has not yet been applied to large regions. The overall intent of that assessment was to calibrate and validate the SMB model by comparing field observations of forest biomass increment, nutrient uptake, and soil ion leaching with corresponding model calculations. The data can also be used to evaluate underlying model assumptions. For example, it will be important to evaluate the sensitivity of the sustainable acidic deposition rate to uncertainty and variability related to tree nutrient uptake, soil N accumulation, N fixation, soil base weathering, etc., as affected by species composition, site conditions, harvest regimes, natural site disturbances (including fire), stand age, and biomass.

3.1. Site selection

Site selection for model calibration and validation is based on the distribution of stand types in the region and the ability to meet the data requirements for the SD calculations. There are three categories of sites:

<u>Level 1 site</u>: all necessary data are available

<u>Level 2 site</u>: some data are unavailable, but missing data can be modeled or extrapolated with confidence (e.g., atmospheric deposition)

<u>Level 3 site</u>: many data are unavailable and must be modeled or extrapolated.

3.2. Basic information requirements

Basic information of reference sites consists of:

- Political jurisdiction
- Number of the site (running by jurisdiction)
- Name of the site
- Geographical coordinates (degrees, minutes, seconds)
- Elevation
- Size of the site (ha)
- Long-term average temperature (ºC)
- Average length of vegetation period (day yr^{-1}). This represents the mean air temperature > 5 ºC for 5 consecutive days
- Land-use history.

3.3. Atmospheric deposition

Atmospheric deposition is made up of dry deposition (gaseous and particulate compounds) and wet deposition (snow and water deposition). The interception of mountain cloud water and coastal fog may also contribute to total deposition. In general, information on the chemistry of wet deposition is available from specialized meteorological networks. The precipitation rate is measured at a large number of locations. Dry deposition is more difficult to evaluate. Air concentrations of dry depositing species are available from a relatively small number of observing stations. Deposition velocity estimates can be obtained from deposition models (or from throughfall sampling for S only). Cloud and fog water deposition estimates require fog collectors and deposition models.

Data for the five most recent years should be reported for deposition chemistry. The mandatory parameters for deposition chemistry are:

- Specification of deposition origin (1-Wet deposition only, 2-Bulk deposition, 3-Wet + dry + fog deposition)
- Specification of deposition measurements (1- Samplers, 2-Models (or maps), 3- Samplers and models).
- Long term average precipitation amount (mm)
- Long term runoff (mm)
- Average percentage of precipitation as snow (%)
- pH
- Specific conductivity ($m S m^{-1}$)
- SO_4^{2-}-S (sulphate as sulphur mmol S L^{-1} or mol ha^{-1})

- NO_3^--N (nitrate as nitrogen mmol N L^{-1} or mol N ha^{-1})
- NH_4^+-N (ammonium as nitrogen mmol N L^{-1} or mol N ha^{-1})
- Cl (Chloride mmol Cl L^{-1} or mol Cl ha^{-1})
- Na (Sodium mmol L^{-1} or mol Na ha^{-1})
- K (potassium mmol L^{-1} or mol K ha^{-1})
- Ca (calcium mmol L^{-1} or mol Ca ha^{-1})
- Mg (magnesium mmol L^{-1} or mol Mg ha^{-1})
- Dates for which the chemistry data are averaged (e.g. 1988-1993).

For Level 2 and 3 sites, the data can be estimated from spatial data coverages for acidic deposition available from NATChem (National Atmospheric Chemistry Database and Analysis System, Atmospheric Environment Service of Environment Canada) or the HRDM (High Resolution Deposition Model, Ecosystems Research Group, Ltd.).

3.4. Soil characteristics

The soil parameters required provide information about soil quality and acidification impacts of S and N deposition and the potential nutrient imbalance/eutrophication impact of N deposition. Soil information should be reported to the bottom of the B horizon, which is considered to be the extent of the rooting zone.

- Soil type (according to the American (Soil Survey ref) or Canadian Soil Classification System (Soil Classification Working Group, 1988))
- Soil profile description (this information may be found using site soil sampling, pedological, or ecological surveys)
- Humus form (Mor, Moder, Mull)
- Forest floor thickness (cm)
- Horizon designation and depth (cm)
- Rooting depth (cm)
- Parent material type. This information can be found from soil sampling or from pedological, geomorphological or ecological surveys.
- Mineralogy and/or total element content (% P_2O_5, K_2O, CaO, MgO, Na_2O, Al_2O_3, Fe_2O_3, SiO_2) to the bottom of the B horizon, or for soil substrate. This information can be found from total soil analysis ($HClO_4$-HNO_3 digestion), from pedological surveys, or from geological surveys. See Appendix 3.

- Properties describing the acid and N status of the soil, e.g. pH, cation exchange capacity (CEC; cmol (+) kg^{-1}), percent base saturation (BS), N (%), and exchangeable base cation concentrations (K, Ca, and Mg in ppm). This information can be obtained from site soil sampling or pedological surveys.
- Background properties that determine soil acidity and nutrient status, i.e. organic matter content (%) and particle size distribution (texture: proportion of sand, silt, and clay in % of weight of combined soil minerals =2 mm in size). This information can be found from site soil sampling or pedological surveys.
- Parameters necessary for calculating soil chemistry pools, i.e. soil bulk density (<2 mm soil fraction, g cm^{-3}) and coarse fragment content (>2 mm soil fraction, %). This information can be found from site soil sampling or pedological surveys.
- Dates of sampling (yr).

3.5. Stand characteristics

This information is used for estimation of nutrient uptake or increment by the stand:

- Stand type (e.g. deciduous, coniferous)
- Species forming the stand and stand table:

  For each tree species:

  number of stems (number ha^{-1})

  average diameter at breast height (cm)

  total volume (m^3 ha^{-1} and/or – preferably – total biomass when dry (tonnes ha^{-1})

  wood density of dry wood (kg m^{-3})

  stand age (years)
- If available, N, K, Ca, and Mg concentrations in the wood, bark, branches, and leaves for each major tree species (ppm).

3.6 Data for model verification and forest health impact assessment

In addition to the input parameters, some parameters will be used for model verification including: ion leaching loss, mean annual increment, denitrification rates, nitrogen fixation rates, and ion concentrations in the soil solution. Additional information may be used to evaluate forest health including: foliage transparency, crown density, dieback, incidence of insects and disease, areas of forest decline, diversity and abundance of understory vegetation and lichens.

4. MAPPING METHODOLOGIES

4.1. Overview

At least two methodologies will be used for SD mapping (Arp et al. *in press*). For the first approach -- termed the ***site-specific approach*** -- as many sites as possible will be considered. However, not all sites will have all required information for the calculation. Sites that do have all required information are designated *Level 1* sites. There are presently about 20 Canadian sites and 15 American Level 1 sites. As already stated, sites with few missing variables are termed *Level 2* sites. The ARNEWS sites (108 sites) are Level 2 sites. These sites have the potential to become Level 1 sites with little effort, or have enough data that can be used to generate the missing information. Sites that have some useful data but fall short of having sufficient data are termed *Level 3* sites. The NAMP sites (147 sites), EMAN sites (38 sites) and FIA sites fall into this category. In all, there are about 325 sites within the study region for establishing a basic site-based mapping grid for the region of interest, i.e. all eastern provinces (Ontario east to Newfoundland) and the seven northeastern states. Level 3 sites can also be used to evaluate how the missing data for these sites can best be determined, either through examining and analyzing existing data bases for these sites or, if necessary, by further data collection at the sites.

The second approach--termed the ***ecological unit approach***--uses established terrestrial ecozone maps for the region of interest. In Canada, there are fifteen ecozones altogether. These units are subdivided into ecoregions and ecodistricts. Each ecodistrict has its own combination of physical environmental parameters (i.e. soils, water, and climate) and forest type. The ecological unit approach, therefore, is a means for ecosystem-level SD mapping, at the ecodistrict level (Wiken et al. 1996).

The two approaches will be compared in order to assess uncertainties associated with SD mapping. Comparisons will be made between the values in the site specific and ecological unit approaches for (1) input parameters such as deposition, (2) SD estimates, and (3) indicator parameters, such as ANC of streamwater nitrate, at sensitive sites.

4.2. Building the required databases

For the site-specific approach, Level 1, 2, and 3 sites will be considered: The ecological unit approach will make use of the following geospatial databases:

Canada

- Acid deposition coverage – (from NATChem, MSC)
- Climate data coverage (from CFS)
- Actual Evapotranspiration (AET) - (calculated)
- National Forest Inventory - 1:20,000,000 (from CFS)
- Provincial Forest Inventories – 1 km grid based on 1:12,000 (from Nfld)
- Soil Landscape of Canada - 1:1,000,000 (from CANSIS, AAFC)
- Geological Map of Canada - 1:5,000,000 (from NRCan)
- National Topographic Database 1:250,000 (from NRCan)
- Digital Elevation Model - 1 km grid (from NRCAN)
- Ecodistricts 1:2,000,000 (from AAFC)
- VMap Level 0 (Digital Chart of the World) – 1:1,000,000 (from NIMA)

United States

- Acid deposition coverages - (from NATChem and HRDM, Ecosystems Research Group, Ltd.)
- Climate data coverage - (from NE Regional Climate Center, and UNH model)
- Actual Evapotranspiration - (calculated from NE Regional Climate Center and UNH climate model, and VT Reference Evapotranspiration model)
- Forest Inventory and Assessment - (state level FIA) 1:250,000
- Soil Landscape - (from STATSGO, NRI) 1:250,000
- Geological map - (from VGS and VMC) 1:250,000; (regional map from USGS) 1:500,000
- Source Till map - (calculated from geologic map information)
- Topographic database - (from USGS digital elevation model) 1:250,000
- Ecological Units-Subsection - (from USFS) 1:1,000,000

The ecological unit approach will examine all upland areas within each ecodistrict to establish upland polygon areas for the model. Each upland polygon, which is to be based on existing soil drainage mapping, will be given a unique identifier and associated ecodistrict class. All input data will be cross-referenced to these polygon numbers. Tree species data, soil data, acidic deposition, and climate data will be determined for each upland polygon area from the existing spatial data sets and by way of GIS analysis techniques. Tree nutrient data will be estimated based on data gathered from the ARNEWS program and from intensive research sites in the U.S.A. The geo-referenced data will be compiled as a series of spreadsheets, which – in turn – will be accessed by the SMB model, one eco-unit at a time (each eco-unit is represented by one unit-referenced row of data).

The following steps outline the mapping method:

1. Acquire all spatial data sets and prepare the data for analysis
2. Develop upland forest polygons, by dominant tree type
3. Estimate atmospheric deposition and climate date, including actual evapotranspiration (AET), for each upland polygon
4. Estimate soil weathering rates for each upland polygon
5. Input data and run the SMB model for likely forest disturbance scenarios (including old-growth condition and repeat harvesting)
6. Use model to estimate nutrient uptake
7. Use model to estimate tree biomass production (mean annual increments) and cross check with field estimates
8. Use model to estimate soil leaching rates and cross check with field estimates
9. Reparameterize model if needed
10. Map forest sensitivity to acidic deposition on both a site and ecodistrict basis

For Eastern Canada, ecological and environmental characteristics of the landscape will be mapped at the ecodistrict scale, polygon by polygon. For the New England states, ecological and environmental characteristics of the landscape will be mapped in a raster GIS at scales of 90 to 30 meter ground resolution. This mapping scheme is chosen to represent the conditions of the complex, mountainous topography of the New England states in the most explicit manner. High-resolution mapping is necessary to capture the full range of conditions (soils, forest type, atmospheric deposition), at the resolution at which these conditions change. Sustainable deposition rates, as calculated for individual grid cells can - in turn - be aggregated by ecological unit to provide map representations more directly comparable with the results from the Canadian provinces.

4.3 Comparison of approaches

Both the site-specific and the ecological unit approach have advantages and disadvantages. Since the site-specific approach uses actual data, there are fewer assumptions associated with model input. However, regional interpretations are limited by the relatively small number of sites with the required information in comparison to the size of the study area. In addition, site data may not adequately represent all major regional and local soil, climate, and forest combinations. In contrast, the ecological unit approach utilizes existing spatial data, thus basing the resulting sustainable deposition calculations on known soil, climate, and forest distributions. Its main limitation is that the input data per mapping unit are numerically derived from other data, i.e., they are not measured *per se*. This approach also differs from the European approach since all input data are keyed and mapped deterministically on an ecodistrict or high-resolution grid cell basis rather than statistically on a coarse grid-cell basis (Posch et al. 1999).

Ideally, the combination of both approaches will facilitate a self-correcting mapping approach, such that the site-specific mapping effort can be used to evaluate and re-parameterize the ecologically-based mapping methodology. Alternatively, the ecologically-based mapping methodology can be used as a means to infer the spatial representativeness of the site-specific analyses. By using both approaches, the work group will be able to compare results and will have independent quality control as well.

During the pilot phase of the project, Newfoundland, Nova Scotia, and Vermont will be used to develop and test mapping methodology for the ecological unit and site-specific approach. Part of the pilot phase of this project is to compare the two approaches and determine why results differ. The lessons learned will then be applied to the region-wide mapping effort to allow policy and decision makers to make informed decisions about the spatial extent of the acid rain problem in the northeastern part of North America.

5. DATA MANAGEMENT PROTOCOL

A serious hurdle in making sustainable deposition calculations for a large region with many jurisdictions is the compilation and standardization of the data for cross-boundary mapping purposes. The purpose of the data standardization and management protocol is three-fold, to:

1. ensure that data compiled from each jurisdiction represent the same measures in the same way
2. minimize differences in data handling by different individuals by creating a roadmap which will guide the data-handler through the series of assumptions necessary to convert the data to the form used to calculate SD
3. ensure proper documentation of the data, data origin, and assumptions made at each step of the data handling.

While data relating to meteorology and atmospheric deposition are easily standardized, the same is not true for extensive datasets of soil and forest cover type. In addition, for model validation, soil leaching data are relatively sparse, and may include considerable variability based on collection method.

In all cases, decisions will be made about how existing information from various organizations can be transformed into common model input. These decisions ultimately depend on what data will actually be available and on the modeling objectives. For example, sustainable deposition rates can be mapped for given areas by species (e.g., balsam fir, sugar maple, red spruce), by group of species (e.g. fir, maple, spruce), or by forest cover type (e.g. softwood, mixed, hardwood).

While the data management protocol will necessarily be lengthy and the process of documenting assumptions time-consuming, the documentation produced will be invaluable both in evaluating the methods (especially in comparing the two approaches) and interpreting the results.

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