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A Nutrient-Sustainable Harvest Assessment Tool for Nova Scotia Acadian Forests

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Abstract

Nova Scotia forest soils have been severely impacted by acidic deposition and base cation depletion to the point where mean percent base saturation levels for many dominant soil series are below 10%. Given these conditions, it is critical that nutrient budget assessments be integrated into timber harvest planning to ensure site-specific harvest removals are nutrient sustainable. The Nova Scotia Department of Natural Resources and Renewables has partnered with researchers in the Faculty of Forestry and Environmental Management at the University of New Brunswick to develop a locally calibrated forest nutrient budget model (NBM-NS) that can be used to assess the nutrient sustainability of proposed harvest prescriptions before operations begin. Using model inputs derived from ecosystem-based vegetation and soil classification units, a series of sustainable mean annual increment (SusMAI) tables have been generated that list current nutrient-sustainable growth rates (equals potential harvest rates) based on estimated tree species nutrient demands and local soil/site supply rates. These SusMAI tables can be used to assess the nutrient sustainability of any proposed harvest removal on upland Acadian forest sites where stand-level vegetation type, soil type, merchantable volume, and age data are known.

Key words: Forest soils, nutrients, sustainability, acid rain, model

1.0 Introduction and Background

The Nova Scotia Department of Natural Resources and Renewables (Department) is involved with several projects related to forest soil assessment and maintenance of site productivity. Results from two of these projects (*Forest Nutrient Budget Model Project* and *Provincial Soil Sampling Program*) have supported development of a tool that can assess the nutrient sustainability of proposed harvest prescriptions in all Acadian forest types in Nova Scotia. This report provides an overview of the two projects and discusses development and use of the sustainability assessment tool. A related overview of acidic deposition impacts on base cation nutrient levels in Nova Scotia forest soils is also provided.

The need for a nutrient sustainability assessment tool to guide timber harvest planning in Nova Scotia is directly related to the historic and in some cases ongoing impacts of acidic deposition (i.e., acid rain) on forest soils across the province (NEG-ECP, 2007). In a five-volume series published by Springer Verlag, Reuss and Walthall (1990 Volume 4) provided a comprehensive overview of the mechanisms and impacts of acidic deposition on non-calcareous forest soils. At the same time, Tomlinson et al. (1990) produced a comprehensive review of acidic deposition impacts on European and North American forests. The overview below is based largely on these two references.

1.1 Acid Rain and Base Cation Depletion

There are several pH-buffering mechanisms in soil that are associated with different pH ranges. In general, soils are mainly buffered through silicate mineral weathering (i.e., base cation(1) release) when pH is between about 6.2 and 5.0. This changes to mainly base cation exchange buffering when pH is between 5.0 and 4.2, and then aluminum (Al) and/or iron (Fe) hydroxide buffering when pH is about 4.2 or less (Tomlinson et al., 1990). Using several forest soil samples from eastern Canada, Clark and Hill (1964 *in* Reuss & Walthall, 1990) showed pH to be relatively consistent (between 4.0 and 5.0) over a large range of calcium (Ca) and magnesium (Mg) percent saturation values (20% to 90%), thus indicating the dominance of base cation exchange in buffering pH in these soils.

In soils that have been impacted by acidic deposition, concentrations of sulphate (SO_4^{2-}), nitrate (NO_3^-), and hydrogen (H^+) ions are increased. If increases in mobile SO_4^{2-} and NO_3^- anions are not offset by plant and microbial uptake (SO_4^{2-} and NO_3^-) and mineral soil adsorption (SO_4^{2-}), they will be leached from the soil. Given the requirement for electro-neutrality in aqueous

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[1] Base cations are calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+).

solutions, cations must also be leached with excess anions, and when soil pH is in the range associated with cation exchange buffering (i.e., about 4.2-5.0), base cations will make up most of the required positive charge in soil leachate (having been displaced by increased H^+ and Al^{3+} concentrations). If these base cation losses are not offset by inputs from soil weathering and atmospheric deposition, then base cation depletion will occur – the overall impact of which depends on initial base cation stores, the rate of loss, and the crossing of deleterious thresholds.

1.2 Base Cation Depletion and Aluminum Stress

Base cation depletion and associated decreases in soil pH will eventually lead to increased Al^{3+} in solution via two mechanisms. As noted above, when soil pH drops into the low 4.0 range, further acid buffering becomes more and more associated with release of Al^{3+} from hydroxide minerals (simplistically represented by: $3H^+ + Al(OH)_3 \leftrightarrow Al^{3+} + 3H_2O$) rather than through cation exchange, thereby increasing the concentration of exchangeable Al^{3+} in soil while also limiting the drop in pH. Despite this increase in available Al^{3+}, lower charged base cations can still be dominant in soil solution due to the stronger affinity of trivalent Al^{3+} for cation exchange sites. However, when percent base saturation (%BS)(2) drops to about 15%-20%, release of Al^{3+} into solution increases significantly (Reuss & Johnson, 1985 *in* Reuss & Walthall, 1990) and Al^{3+} becomes a major component of soil solution and leachate.

Increases in bioavailable Al^{3+} can cause stress and growth loss in plants as well as high inputs of Al^{3+} into surface waters (with related toxicity impacts). Reduced plant growth is due mainly to reduced nutrient availability or imbalances, Al^{3+} interference with base cation nutrient uptake, and reduced fine root growth from Al^{3+} toxicity (Rengel, 1992; Ouimet & Camiré, 1995; Godbold et al., 2003; Lawrence et al., 2005; de Wit et al., 2010).

2.0 Forest Nutrient Budget Model

The forest nutrient budget model (NBM-NS) project was initiated in 2008 and led by Dr. Paul Arp, University of New Brunswick (UNB) Faculty of Forestry and Environmental Management. NBM-NS was initially designed to be a decision support tool to assess the suitability of forest sites for biomass harvesting by assessing potential impacts on soil nutrient levels. The project was funded through the Nova Scotia Community Development Trust and the model is property of the Nova Scotia Government. A Master of Science in Forestry thesis was produced as part of

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[2] %BS is the percentage of base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) versus total cations in a soil. It provides a relative measure of base cation content versus less desirable hydrogen (H^+) and aluminum (Al^{3+}) acid cation content.

this project (Noseworthy, 2011) which described model development and sample output for Kejimkujik National Park. After receiving the beta version of the model in 2011, the Department worked with UNB for several years to validate, update, and correct model components as needed. The main problems identified were related to area weighting calculations for atmospheric deposition values, the need for a bark correction factor in mean annual increment (MAI) calculations, the preponderance of suspect soil data found, and coding problems that generated false increases in sustainable MAI (SusMAI) values in soils with low %BS values. All this work culminated in a journal paper that discussed how the model was developed, model assumptions and limitations, and a case-study application (Keys et al., 2016).

2.1 Model Overview

NBM-NS is an input-output model for nutrients – specifically calcium (Ca), magnesium (Mg), potassium (K), nitrogen (N), and sulphur (S). It estimates nutrients going into upland forest ecosystems (i.e., deposits) and nutrients going out (i.e., withdrawals). Inputs are from soil weathering and atmospheric deposition, while outputs are from timber harvesting and acid leaching. Weathering, deposition, and leaching are all fixed, current estimates for a given location based on best available information related to soils and local atmospheric inputs. Harvesting outputs are estimated based on user-defined harvest scenarios (volume, species, diameter, biomass component, and average tree age). Critical components of this harvest calculation are the species-specific nutrient concentrations found in biomass components (stemwood, bark, branches, foliage), and the species percentages within each stand.

The model generates a sustainable mean annual increment (SusMAI) value in $m^3ha^{-1}yr^{-1}$ for a given vegetation type (VT) and soil type (ST) combination that reflects what the nutrient-sustainable growth rate is based on estimated VT demand for, and soil/site supply of, the most limiting nutrient. Harvest sustainability is then related to whether estimated nutrient inputs are currently equal to or greater than estimated outputs for a given harvest scenario. A "no reduction" in %BS is also integrated into sustainability assessments.

Like any model, the more accurate the data are going in, the more realistic and representative the data are coming out. During model development, the only soil chemistry data available were from historic Nova Scotia soil survey reports (1940s-1990s). As noted in Noseworthy (2011) and later Keys et al. (2016), these data were found to be incomplete and/or non-representative of current forest soil conditions. Similarly, tree tissue nutrient concentration data sourced during model development (Noseworthy, 2011) came from a compilation of research studies from across North America (Pardo et al., 2005). While useful, these data are not necessarily representative of Nova Scotia conditions since tree nutrient concentrations are generally correlated with availability and not always reflective of regional values (Tremblay et al., 2012; Paré et al., 2013). It was these known and suspected problems with soil and tree tissue data that led to the provincial soil sampling program.

3.0 Provincial Soil Sampling Program

The provincial soil sampling program was initiated in 2015 after it became clear that available soil chemistry data for use in forest nutrient budget assessments were incomplete and/or outdated. The objectives of this ongoing program are:

- To provide current chemical and physical data for dominant soil series across the province for use in site productivity assessment and nutrient budget modelling.

- To provide benchmark data for ongoing forest soil and ecosystem monitoring with respect to impacts from management activities, climate change, and pollution stress.

- To enhance nutrient budget modelling by also acquiring tree nutrient concentration data directly linked to Nova Scotia soil/site conditions.

The program was designed to use forest inventory permanent sample plots (PSPs) as potential sampling locations. The initial goal was to sample as many as 360 plots found on dominant soil associations across the province over a five-year period. Soil horizons chosen for sampling are based on the dominant forest floor (one) and mineral soil horizons (two) found within the top 50 cm of mineral soil (total of three samples per plot). Soil parameters assessed provide the most interpretive value for assessment and monitoring and were chosen in consultation with the Northeastern Soil Monitoring Cooperative(3) (Table 1).

Wood (sapwood only) and bark samples are taken at breast height from healthy, co-dominant trees found at each plot location. When possible, samples are collected from two separate trees and pooled for analysis by species. Foliage is also collected from some trees when the canopy is accessible. For softwood trees, 1-year old shoots are collected to reduce variability associated with new shoots. For hardwoods, only summer foliage is collected.

Analysis work is being carried out at the Dalhousie University Faculty of Agriculture in Truro, NS, the Canadian Forest Service Laurentian Forestry Centre in Quebec City, and the Laboratory for Forest Soils and Environmental Quality at the University of New Brunswick in Fredericton, NB.

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[3] For information on the Northeastern Soil Monitoring Cooperative, see (http://www.uvm.edu/~nesmc/).

Table 1. List of parameters analyzed in mineral soil and forest floor samples.

pH	Exchangeable Acidity/Al
Total C/N/S	Available Phosphorous (P)
Loss on Ignition (%OM)	Cation Exchange Capacity
Exchangeable Ammonium (NH_4)	Base Saturation
Available Nitrate (NO_3)	Bulk Density
Exchangeable Ca/Mg/K/Na	Texture (mineral soil only)

To ensure randomness in spatial plot selection and related statistical rigour, sample PSPs were selected using a generalized random tesselation stratified (GRTS) design realized through the *spsurvey* package (ver. 2.4) within *R* (ver. 2.15.1). (Fig. 1).

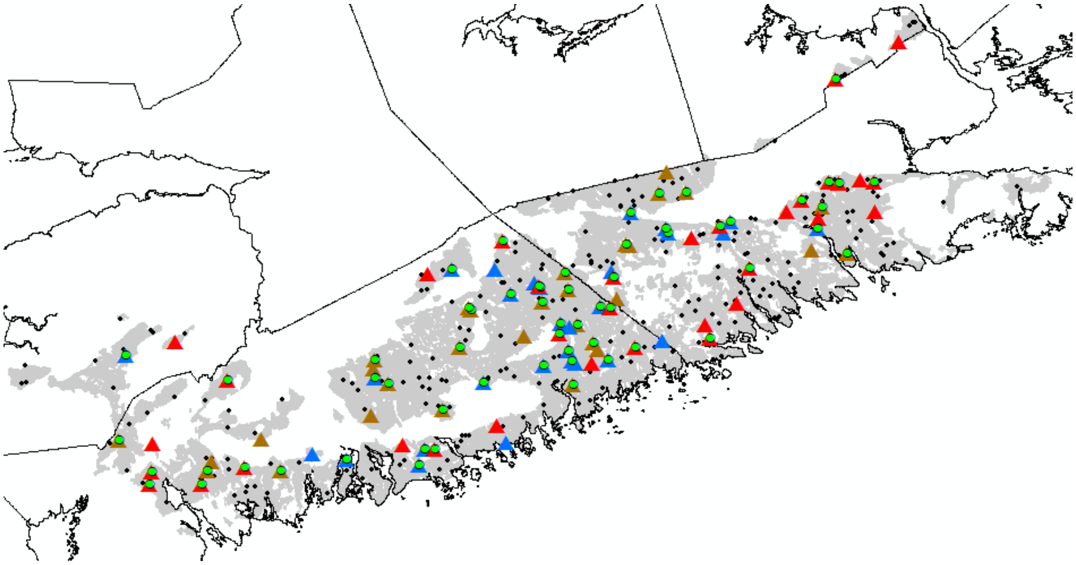

Fig. 1. Example of GRTS-derived sampling scheme for Halifax association soils (grey shading) in central Nova Scotia. Triangles represent eligible mature inventory PSPs (Blue = well drained softwood, Brown = imperfectly drained softwood, Red = well drained mixedwood/hardwood). Green dots show *spsurvey* selected sample plots (30 selected plus 30 oversample). Black dots show ineligible PSPs.

To date, 676 soil samples and 523 tissue samples have been collected from 211 plots across the province. Soil associations targeted for initial sampling were Halifax, Gibraltar, Thom, and Queens which make up more than 55% of the target survey area (Table 2). Other soil series that have been partially sampled include Cobequid, Wolfville, Bridgewater, and Kirkhill. Several samples were also recently collected from Highland areas classed as Rough Mountain Land in Cape Breton.

Table 2. Top four soil associations by area associated with the Nova Scotia soil sampling program. Associations include well and imperfectly drained soils derived from the same parent material.

Rank	Soil Association	Total area (ha)	% of Survey Area
1	Halifax	723,997	19.3
2	Gibraltar	700,860	18.7
3	Thom	335,449	9.0
4	Queens	329,027	8.8

Although fewer plots have been sampled than anticipated, the program is ongoing, and more sampling is planned. In addition, most soil samples have been archived and stored for future use as needed. Verified data are being compiled in a spreadsheet database and updated on a regular basis for use by Department staff and other researchers.

3.1 Soil Data

With respect to soil health and nutrient sustainability, the most significant finding to date has been confirmation of low mineral soil %BS values (as discussed in Keys et al., 2016), especially in coarse-textured Gibraltar soils (Table 3). Except for some Queens soils, all soils sampled to date had BS levels below 20%, with mean values for all soils below 10%. This indicates significant base cation depletion in these soils and related aluminum stress in associated ecosystems – as also indicated by mean pH levels hovering around 4.0 (Table3).

Table 3. Percent base saturation (%BS) data for Gibraltar (Ga), Halifax (Hx), Thom, (Th), Queens (Qe), Bridgewater (Bw), Cobequid (Cd), Kirkhill, (Kh), Millbrook (Mi), and Wolfville (Wv) association mineral soils sampled as part of the Nova Scotia provincial soil sampling program. Data are for B-horizons only where most mineral soil rooting occurs.

Statistic	Ga	Hx	Th	Qe	Bw	Cd	Kh	Mi	Wv
Mean BS%	1.9	3.1	4.2	7.6	4.5	3.6	3.8	5.6	7.9
Stdev	1.4	2.6	4.2	8.1	2.9	1.6	1.8	3.1	3.8
Min. BS%	0.3	0.2	0.5	0.8	2.0	1.5	1.8	1.9	2.7
Max. BS%	6.8	16.4	19.4	40.8	8.7	7.1	5.8	9.8	12.9
n	56	78	29	46	6	11	6	6	6
Mean pH	4.0	4.0	4.0	3.8	4.0	4.0	4.0	3.7	3.9

Other soil data incorporated into updated NBM-NS data sets were percent clay content, percent organic matter content, mineral soil bulk density, and relative Ca/Mg/K fractions. Having representative percent clay data is particularly important because weathering functions in NBM-NS (and therefore calculated nutrient inputs) are directly linked to soil clay content (Keys et al., 2016).

3.2 Tissue Data

As suspected, most tree tissue nutrient data used to initialize NBM-NS were not representative of Nova Scotia conditions (Table 4). Regional mean nutrient values by species and biomass component were much lower overall than those reported by Pardo et al. (2005), as shown by the preponderance of negative percent difference (%Diff) values in Table 4. In addition, some species nutrient concentrations were found to vary by region across the province which allowed for even more fine-tuning of model inputs (data not shown). A tree species list is provided in Appendix 1.

3.3 Atmospheric Deposition Data

Atmospheric deposition data used in NBM-NS development came from available 2002 Environment Canada datasets (Noseworthy, 2011). Since that time there have been significant decreases in annual deposition of sulphate (SO_4^{2-}) and nitrate (NO_3^-) across northeastern North America. Updated datasets are not available for Nova Scotia, but available National Atmospheric Deposition Program (NADP) data from Maine, USA, showed approximately 66% and 28% decreases in SO_4^{2-} and N deposition respectively between 2002 and 2016 (based on regression analysis) (Fig. 2). This is in keeping with local trends reported in Keys et al. (2016).

To update S and N deposition rates across the province, slightly more conservative decreases of 60% and 25% were applied to current values in NBM-NS. Atmospheric deposition rates for base cations (Ca^{2+}, Mg^{2+}, K^+) remain essentially the same and were unchanged in the model.

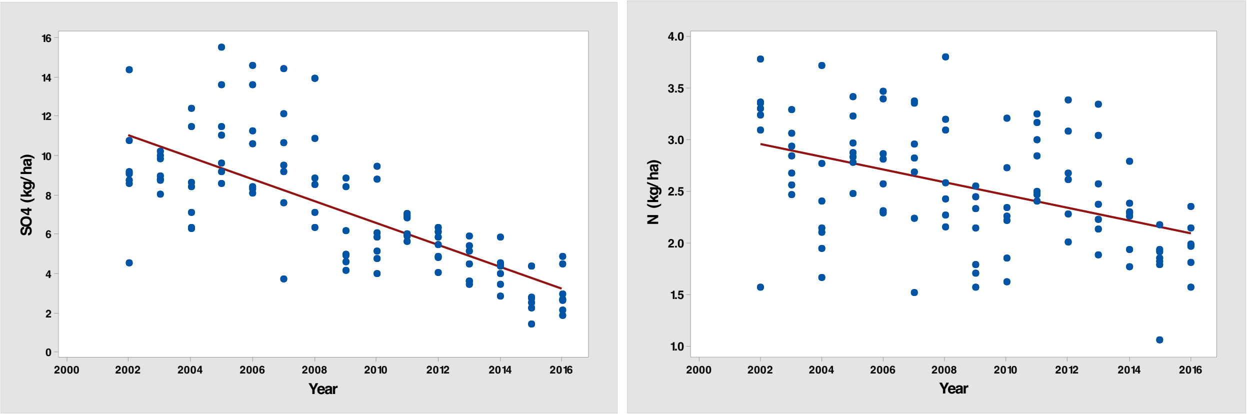

Fig. 2. Atmospheric deposition for sulphate (SO_4^{2-}) and nitrogen (N) from seven sites in Maine, USA (derived from available National Atmospheric Deposition Program (NADP) data).

Table 4. Sample nutrient fractions in wood and bark by tree species. Original = original values used in NBM-NS derived from Pardo et al. (2005). Updated = updated values from trees sampled on Gibraltar and Halifax association soils in central and western Nova Scotia (all species except sugar maple) and Thom association soils in central and eastern Nova Scotia (sugar maple). % Diff. = percentage difference between original and updated values.

		Wood				Bark			
Species	**NBM**	**Ca** (fraction)	**Mg** (fraction)	**K** (fraction)	**N** (fraction)	**Ca** (fraction)	**Mg** (fraction)	**K** (fraction)	**N** (fraction)
RS (nW=38) (nB=20)	Original	0.000690	0.000096	0.000220	0.000640	0.006685	0.000445	0.001635	0.002773
	Updated	0.000752	0.000102	0.000161	0.000394	0.006103	0.000383	0.000680	0.001841
	% Diff.	**9.0**	**6.3**	**-26.8**	**-38.4**	**-8.7**	**-13.9**	**-58.4**	**-33.6**
EH (nW=4) (nB=4)	Original	0.000704	0.000112	0.000868	0.000770	0.007368	0.000295	0.001523	0.002673
	Updated	0.000796	0.000116	0.000602	0.000425	0.002946	0.000162	0.000160	0.001717
	% Diff.	**13.0**	**3.6**	**-30.7**	**-44.8**	**-60.0**	**-45.1**	**-89.5**	**-35.8**
WP (nW=7) (nB=7)	Original	0.000516	0.000101	0.000324	0.000780	0.004223	0.000613	0.001473	0.003544
	Updated	0.000340	0.000100	0.000189	0.000357	0.001100	0.000209	0.000171	0.001584
	% Diff.	**-34.0**	**-1.0**	**-41.6**	**-54.2**	**-73.9**	**-65.9**	**-88.4**	**-55.3**
BF (nW=24) (nB=11)	Original	0.000823	0.000204	0.000921	0.000918	0.007394	0.000636	0.002566	0.004616
	Updated	0.000609	0.000162	0.000468	0.000425	0.006150	0.000610	0.001694	0.002871
	% Diff.	**-26.0**	**-20.5**	**-49.2**	**-53.7**	**-16.8**	**-4.2**	**-34.0**	**-37.8**
BS (nW=15) (nB=11)	Original	0.000874	0.000138	0.000342	0.000630	0.009966	0.000555	0.001542	0.002400
	Updated	0.000789	0.000101	0.000145	0.000356	0.006425	0.000348	0.000642	0.001974
	% Diff.	**-9.7**	**-26.5**	**-57.6**	**-43.5**	**-35.5**	**-37.3**	**-58.4**	**-17.8**
RM (nW=44) (nB=22)	Original	0.001121	0.000204	0.000803	0.000885	0.013016	0.000468	0.001985	0.004332
	Updated	0.000675	0.000144	0.000477	0.000555	0.010802	0.000499	0.000985	0.004353
	% Diff.	**-39.8**	**-29.5**	**-40.6**	**-37.3**	**-17.0**	**6.5**	**-50.4**	**0.5**
SM (nW=15) (nB=4)	Original	0.001301	0.000198	0.000691	0.000976	0.022280	0.000600	0.003119	0.005114
	Updated	0.000742	0.000211	0.000379	0.000724	0.014823	0.000892	0.001265	0.003948
	% Diff.	**-42.9**	**6.5**	**-45.1**	**-25.8**	**-33.5**	**48.6**	**-59.4**	**-22.8**
YB (nW=7) (nB=7)	Original	0.000701	0.000155	0.000433	0.001026	0.010283	0.000423	0.001243	0.005672
	Updated	0.000464	0.000147	0.000236	0.000675	0.007313	0.000358	0.000693	0.003671
	% Diff.	**-33.8**	**-5.4**	**-45.6**	**-34.3**	**-28.9**	**-15.3**	**-44.2**	**-35.3**
WB (nW=8) (nB=5)	Original	0.000775	0.000185	0.000514	0.000924	0.006846	0.000413	0.001201	0.003639
	Updated	0.000436	0.000142	0.000182	0.000516	0.002338	0.000170	0.000231	0.003450
	% Diff.	**-43.7**	**-23.2**	**-64.6**	**-44.1**	**-65.9**	**-58.9**	**-80.8**	**-5.2**
RO (nW=7) (nB=7)	Original	0.000557	0.000057	0.001093	0.001257	0.024273	0.000380	0.001290	0.003958
	Updated	0.000256	0.000020	0.000593	0.000783	0.016710	0.000269	0.000586	0.002723
	% Diff.	**-54.0**	**-64.7**	**-45.8**	**-37.7**	**-31.2**	**-29.2**	**-54.6**	**-31.2**

RS = red spruce, EH = eastern hemlock, WP = white pine, BF = balsam fir, BS = black spruce, RM = red maple, SM = sugar maple, YB = yellow birch, WB = white birch, RO = red oak. nW = number of wood samples. nB = number of bark samples.

4.0 Modelling Methods

Although the provincial soil sampling program is ongoing, enough data have been collected to allow integration of NBM-NS output into Crown land harvest planning. This is being accomplished by generating a series of sustainable mean annual increment (SusMAI) look-up tables for all upland Acadian forest sites across the province that can then be compared with proposed harvest prescriptions to determine if they are nutrient sustainable. This work was completed using a five-step protocol:

- Mean, adjusted atmospheric S and N deposition values were calculated for each of the province's ecodistricts (excluding Sable Island) along with mean base cation deposition values.

- Soil series distribution within each ecodistrict (Neily et al., 2017) was related to representative forest ecosystem classification (FEC) soil types, and their attributes adjusted (as needed) based on available soil sampling data. For soil series that have not yet been sampled, interim adjustments were made based on expert opinion using data from similar soil series.

- To acquire mensuration data for model use, known FEC vegetation type (VT), soil type (ST), and ecosite combinations (Neily et al., 2013) associated with each ecodistrict were identified and representative stands were "grown" using the Nova Scotia Growth and Yield Model (NSGNY) (NSDNR, 2006). Representative stocking adjustments were later made to NSGNY output based on inventory PSP data.

- NBM-NS was run to generate SusMAI estimates for each VT/ST combination in each ecodistrict using updated deposition data, updated soil data, updated tree tissue data, and NSGNY output as NBM-NS inputs.

- To integrate NBM-NS output more efficiently into operational planning, ecodistricts that showed similar SusMAI values (± 0.2 $m^3ha^{-1}yr^{-1}$) for the same VT/ST combinations were combined for reporting and implementation purposes.

At this time, SusMAI values have been generated for all known upland VT/ST combinations in Acadian ecodistricts. Work is ongoing for Maritime Boreal sites.

5.0 Results and Discussion

A total of 16 tables containing SusMAI values for VT/ST combinations found in 32 Acadian ecodistricts are provided as a supplemental spreadsheet.(4) These SusMAI values are associated with merchantable stemwood plus bark, foliage and branch removals were not included in any model calculations.

5.1 Overview

Predicted SusMAI values range from 0.1 $m^3ha^{-1}yr^{-1}$ to more than 8 $m^3ha^{-1}yr^{-1}$. In general, the lowest SusMAI values are associated with coarse and/or stony soils (associated with lower potential nutrient inputs) combined with VTs containing significant hardwood fractions (associated with greater nutrient demand).

Within softwood dominated VTs, those with significant pine fractions generally have higher SusMAI values due to the nutrient efficiency (i.e., lower nutrient concentrations) associated with pine compared to other softwood species. In hardwood dominated VTs, higher sugar maple and aspen fractions tend to lower SusMAI values due to higher nutrient demands associated with these species.

For all scenarios, Ca was usually the predicted limiting nutrient in coarser soils, while N was often the predicted limiting nutrient in finer soils. Potassium was only close to being limiting for some VT/ST combinations where basalt was a major constituent in soil parent material (ecodistrict 920), while Mg was never close to being limiting in any scenario.

5.2 Model Settings and Assumptions

Several key settings and working assumptions that affect model output are discussed below.

1. Given that forest ecosystems tend to naturally acidify over time, and that Ca^{2+} concentrations in base-poor soils in Nova Scotia were probably already decreasing before the accelerated losses from acidic deposition (as suggested by Leys et al., 2016), Nova Scotia forest soils will likely never return to “pre-acid rain” base cation levels without the use of remedial amendments (e.g., dolomitic lime). In addition, any natural recovery will be slow as discussed

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[4] These SusMAI tables are associated with VT/ST units described in the original FEC guide (Neily et al., 2013). Tables associated with the updated 2023 FEC guide will be available from NSDNRR when completed.

by Lawrence et al. (2015) and supported by a 20-year soil reassessment study in Kejimkujik National Park (Keys, 2018).

It is therefore critical that timber harvest operations do not exacerbate the lingering impacts of acid deposition on soil base cation levels. To this end, the default %BS value for all NBM-NS calculations was set to 30%.(5) This approach allows for some level of timber harvesting while theoretically allowing soil base cation levels to gradually rebuild to more healthy levels over time.

The significance of using a 30% BS value in model runs is evident when comparing output based on current %BS levels with outputs using the higher 30% threshold (Table 5).

Table 5. Estimated sustainable mean annual increment (SusMAI) values using current mean percent base saturation (%BS) found in Gibraltar soils (2%) and higher threshold BS (30%) for example stands in western Nova Scotia (ecodistricts 720/770/780). See Neily et al. (2017) for information on ecodistricts and Neily et al. (2013) for information on vegetation type (VT) and soil type (ST) units.

VT	ST	SusMAI ($m^3ha^{-1}yr^{-1}$) with current 2% BS	SusMAI ($m^3ha^{-1}yr^{-1}$) with default 30% BS	Percent Difference in SusMAI
SH3	ST2	3.1	2.1	- 32%
SH3	ST2-L	3.6	3.1	- 14%
SH5	ST2	3.5	2.5	- 29%
SH5	ST2-L	4.1	3.7	- 10%
SP5	ST2	3.1	2.4	- 23%
SP5	ST2-G	2.8	1.9	- 32%
SH4	ST2	4.9	3.9	- 20%
SH4	ST2-G	4.5	3.1	- 31%

Since NBM-NS has a “no reduction” in %BS criterion integrated into sustainability assessments, using a default 30% BS reduces estimated SusMAI values by 10% to 32% depending on VT/ST combination (Table 5). These decreases reflect the variable losses in site productivity associated with acidic deposition impacts across different forest sites and highlights the importance of accurate stand assessment for appropriate application of NBM-NS output.

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[5] Driscoll et al. (2001) suggest 20% BS as a general value for assessing chemical recovery from acidic deposition, and this can be considered an initial recovery target for soil monitoring purposes. A 20% BS value could have been used in NBM-NS calculations, but a more conservative 30% value was chosen because it provides an additional buffer against possible leaching losses not directly accounted for in the model.

2. Using average VT and ST conditions in model calculations may not accurately represent percent cover and soil conditions in every associated stand, but this approach allows for efficient integration of NBM-NS output into harvest planning and should be reasonably representative of overall site-type conditions. This approach also allows for identification of VT/ST combinations with SusMAI values that may not be amenable to any level of sustainable harvest. Stands associated with these combinations can then be removed from harvest consideration upfront which facilitates management planning and wood supply modeling. Indeed, this was the case for VTs found on very coarse ST1-S and ST1-GS soils, as well as most shallow soils, which had negative SusMAI values. As a result, no timber harvesting would be recommended on these soils and SusMAI tables do not contain any output for these soil types.

3. As outlined in Keys et al. (2016), weathering rate functions in NBM-NS are related, in part, to soil substrate class which reflects the relative weatherability of different soil parent material types. There are four substrate class options in NBM-NS: acidic, intermediate, basic, and calcareous – with relative weathering rates increasing with each class step. Based on their parent material constituents, all but a few forest soils in Nova Scotia would be classed as either acidic, intermediate, or somewhere in between. However, given the uniformly low soil %BS found across the province, and the uncertainty about where some soil parent materials fall on the acidic-intermediate continuum, all non-basic and non-calcareous soils were classed as acidic to avoid overestimating weathering inputs.

4. In theory, imperfectly drained soils would have a shallower potential rooting zone than well drained soils which would decrease model generated SusMAI values (all other factors being equal). However, extensive field work associated with development of Nova Scotia's FEC system has shown that moist (i.e., imperfectly drained) ecosites are equally or slightly more productive than fresh (i.e., well drained) ecosites (Neily et al., 2013). This is mainly due to seepage inputs offsetting decreases in potential rooting zone depth. Since NBM-NS cannot account for seepage inputs (Keys et al., 2016), the same SusMAI outputs for well drained soils were assigned to their imperfectly drained associates.

5. Increased organic matter content in soils is generally associated with higher fertility, but also with lower bulk density values which, in turn, is related to weatherable soil mass. Since organic matter is not considered a primary source of nutrients in NBM-NS,(6) the model will predict slightly lower SusMAI values in soils that have less dense Ah or Ap horizons compared with otherwise similar soils that have denser Ae or Ahe horizons. To account for this somewhat

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[6] Primary nutrient inputs are new "deposits" into the nutrient bank account from weathering and deposition. Nutrients in organic matter that cycle within ecosystems are analogous to "transfers" between bank accounts rather than new deposits, until they become "withdrawals" associated with harvesting or leaching.

anomalous output, ST8/ST9 soils and ST11/ST12 soils with Ah or Ap horizons were assigned the same SusMAI values as their non-Ah/Ap counterparts (ST2-L/ST3-L and ST5/ST6)

6. NBM-NS was not run for poorly drained soils and their associated VTs, nor were SusMAI values estimated for wet ecosites. NBM-NS was not designed to model nutrient inputs into poorly drained sites where seepage and/or groundwater chemistry dictate nutrient availability much more than soil weathering.

5.3 Interpreting SusMAI Values

To those familiar with forest growth and yield analysis, the SusMAI values predicted for some VT/ST combinations may seem surprisingly low. This is because SusMAI values do not necessarily reflect current growth rates on any given site, only what is estimated to be the current sustainable nutrient removal rate for a given VT/ST combination.

For example, a vegetation type may be growing at a rate of 5.0 $m^3ha^{-1}yr^{-1}$ on a particular soil type at a particular location and so would be predicted to have up to 250 m^3ha^{-1} after 50 years at full stocking. This growth rate reflects many factors (e.g., species physiology, moisture availability, nutrient availability, etc.). In the absence of harvesting, this stand will succumb to disturbance or senescence and either renew itself or transition to a different VT with its own site-specific growth rate. In this case, except for some natural leaching loses, the nutrient bank account that has accrued over time is still largely in place.

Introduce timber harvesting into this scenario and instead of just having nutrient cycling between accounts, you start to also have nutrient withdrawals. If these periodic nutrient withdrawals are greater than natural inputs from weathering and atmospheric deposition, then nutrient capital will decrease overtime. How long this takes and at what point it leads to reduced ecosystem health and productivity will vary by site, but by definition, it means that the associated harvest rate is not sustainable. SusMAI reflects what the current nutrient sustainable growth rate is for a given VT/ST combination based on estimated VT demand for, and soil/site supply of, the most limiting nutrient – it may be lower than, similar to, or greater than the current actual growth rate at a given site.

6.0 Model Limitations and Use

Development of NBM-NS started in 2008 when critical loads modeling was the main approach used to estimate potential impacts of acidic deposition on forest ecosystems (see for example NEG-ECP, 2007). As outlined above, NBM-NS uses a similar mass balance or budget calculation approach to estimate SusMAI values. However, it has been suggested that this mass balance approach is too uncertain and/or too simplistic to be the basis for spatially explicit biomass harvesting decisions (Paré & Thiffault, 2016; Löfgren et al., 2021). These concerns are discussed below.

6.1 Model Limitations

One of the main areas of uncertainty for all geochemical models is estimation of soil weathering rates (Futter et al., 2012). However, it was shown in Keys et al. (2016) that the method used in NBM-NS to estimate base cation inputs produced similar values as other studies in the region. This does not eliminate the uncertainty associated with NBM-NS estimates, but it provides confidence that results are at least reasonable.

NBM-NS is indeed a relatively simple model. It is not a process-based model with the ability to estimate variable nutrient fluxes and availability over time, nor can it account for other potential sources of nutrients not associated with silicate mineral weathering or atmospheric deposition (e.g., Ca from phosphate minerals like apatite: Yanai et al., 2005; or N from N-fixation: Keys et al., 2016). In this regard, NBM-NS output may be conservative with respect to nutrient supply estimates, especially under partial harvest scenarios where post-harvest leaching losses are expected to be reduced.

As noted by Paré and Thiffault (2016), most nutrient budget models are calibrated at the watershed scale and assume that soils are homogenous, both of which limit stand-level applicability. With use of NBM-NS, these limitations are somewhat offset by calibration of the model with local data, and by use of FEC units to assign average stand or site-type conditions. This allows for reasonable application of model output within ecologically defined units.

While some of the inherent limitations of nutrient budget models have been addressed in this case, NBM-NS is still an environmental model based on empirical data. Therefore, anticipated impacts from regional climate change mean that SusMAI values will need future updates since nutrient supply and demand relationships will also change with changing climate drivers.

For example, warmer average temperatures will tend to promote soil weathering and base cation inputs. However, impacts on precipitation (and related soil moisture) may be quite variable, adding to or subtracting from the positive temperature influence. Climate change is expected to result in significant changes to watershed hydrology in northeastern North America (Campbell et al., 2009), including: (i) increased winter precipitation, (ii) reduced snowpack and shortened snow season, and (iii) increased likelihood and severity of damaging rainstorms

(Frumhoff et al., 2007). In addition to affecting weathering rates, these changes could lead to increased leaching of base cations outside of the growing season and/or during storm events (Huntington et al., 2009), all of which affects nutrient supply estimates. Tree species assemblages and growing degree day patterns in Nova Scotia are also expected to change over time (e.g., Bourque et al., 2008; Steenberg et al., 2013), leading to changes in nutrient demands as well as supplies.

6.2 Appropriate Use

Given the model limitations outlined above and the assumptions discussed in Section 5, how should SusMAI values be interpreted and used?

- SusMAI values represent sustainable growth rates for different VT/ST combinations based on current estimated supply and demand of the least available nutrient (Ca, Mg, K, N). Values also address (as much as is possible within model constraints) the historic impacts of acidic deposition and past harvesting on soil base cation stores by incorporating a “recovery” value of 30% base saturation for all forest soils in the province.
- SusMAI values also represent current maximum harvest rates that do not remove more nutrients (in particular Ca) than the average site can currently supply through soil weathering and atmospheric deposition (inputs from organic matter are not included here because they are secondary nutrient supplies originally obtained via primary sources like weathering and deposition).
- SusMAI values can be used to identify sensitive VT/ST combinations and/or to group VT/ST combinations with similar SusMAI values for management purposes.
- Given that accelerated climate change is expected to affect future nutrient supply and demand rates, current SusMAI values are not valid over the long-term, and will need to be updated as new data and/or modelling capabilities are acquired. However, using SusMAI values to inform current harvest prescriptions will ensure future stand management decisions are not handicapped by past overharvesting.
- SusMAI values represent average site-types and may not be representative of individual stand conditions. However, given the need to increase base cation levels in most forest soils, it is recommended that current harvest rates should not exceed associated SusMAI values for any stand (unless use of soil amendments is planned). Also, if current health conditions in individual stands warrant, recommended harvest levels can (or should) be lower than the maximum levels associated with SusMAI values.

6.3 Applying SusMAI Output

SusMAI values can be used to assess the nutrient sustainability of current harvest prescriptions when merchantable volumes (m^3ha^{-1}) and representative stump ages (yr) are known for stands described by unique VT/ST combinations. This is achieved by calculating the proposed harvest MAI (HarMAI) and comparing it with the applicable SusMAI for each stand. If HarMAI is less than or equal to the SusMAI, the proposed harvest is considered nutrient sustainable. If HarMAI is greater than SusMAI, the proposed harvest level needs to be reduced to be compatible with the SusMAI value. This includes using cumulative harvest volumes for SusMAI comparisons when a partial harvest is planned before a later final harvest.

Example 1.

VT: MW4 (Balsam fir – Red maple / Wood sorrel - Goldthread)
ST: ST2-L (Fresh – Medium-Coarse textured – Loamy phase)
Ecodistrict: 440 (Eastern Interior)
SusMAI: **4.1** $\mathbf{m^3ha^{-1}yr^{-1}}$ (from SusMAI tables)

Proposed harvest: 160 m^3ha^{-1}
Stand/cohort age: 60 yr
HarMAI: 160 m^3ha^{-1} ÷ 60 yr = **2.7** $\mathbf{m^3ha^{-1}yr^{-1}}$
HarMAI < SusMAI : The proposed harvest is nutrient sustainable.

Example 2.

VT: SP5 (Black spruce / Lambkill / Bracken)
ST: ST2-G (Fresh – Medium-Coarse textured – Granite phase)
Ecodistrict: 720 (South Mountain)
SusMAI: **1.9** $\mathbf{m^3ha^{-1}yr^{-1}}$ (from SusMAI tables)

Proposed harvest: 130 m^3ha^{-1}
Stand/cohort age: 60 yr
HarMAI: 130 m^3ha^{-1} ÷ 60 yr = **2.2** $\mathbf{m^3ha^{-1}yr^{-1}}$
HarMAI > SusMAI : The proposed harvest is not nutrient-sustainable.
Maximum harvest removal would be 1.9 $m^3ha^{-1}yr^{-1}$ x 60 yr = 114 m^3ha^{-1}

Example 3.

Commercial thinning at 40 yr followed by planned final harvest at 70 yr.

VT: SH5 (Red spruce – Balsam fir / Schreber's moss)
ST: ST3 (Moist – Medium-Coarse textured)
Ecodistrict: 380 (Central Uplands)
SusMAI: **4.2** $\mathbf{m^3ha^{-1}yr^{-1}}$ (from SusMAI tables)

Current proposed harvest: 50 m^3ha^{-1} (commercial thin)
Predicted final harvest: 170 m^3ha^{-1}
Stand age at final harvest: 70 yr
HarMAI: 220 m^3ha^{-1} ÷ 70 yr = **3.1** $\mathbf{m^3ha^{-1}yr^{-1}}$
HarMAI < SusMAI : The proposed harvest regime (commercial thin plus predicted final harvest) is nutrient sustainable.

7.0 Conclusion

After several years of development and refinement, the Department’s forest nutrient budget model (NBM-NS) and ongoing provincial soil sampling program now give forest managers a localized, ecosystem-based decision-support tool to estimate nutrient-sustainable timber harvest levels for all Acadian ecosites across Nova Scotia.

A series of sustainable mean annual increment (SusMAI) tables have been generated that list current nutrient-sustainable growth rates (equated here to maximum potential harvest rates) based on estimated tree species demands for, and soil/site supply of, Ca, Mg, K, and N. These SusMAI tables can be used by all forest landowners and managers to assess the nutrient sustainability of current harvesting prescriptions in stands where vegetation type, soil type, merchantable volume, and cohort age data are known.

Use of SusMAI values to inform timber harvest prescriptions should help promote forest ecosystem health and related recovery of base cation levels in Nova Scotia forest soils. However, these SusMAI values are only a first approximation that should be validated or adjusted based on regular monitoring (e.g., through the provincial soil sampling program) and/or incorporation of improved modelling approaches as they are developed.

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References

Bourque, C.P.-A., Hassan, Q.K., & Swift, D.E. (2008). *Modelled potential species distribution for current and projected future climates for the Acadian Forest region of Nova Scotia, Canada*. Nova Scotia Department of Natural Resources.

Campbell, J.L., Rustad, L.E., Boyer, E.W., Christopher, S.F., Driscoll, C.T., Fernandez, I.J., Groffman, P.M., Houle, D., Kiekbusch, J., Magill, A.H., Mitchell, M.J., & Ollinger, S.V. (2009). Consequences of climate change for biogeochemical cycling in forests of northeastern North America. *Can. J. For. Res. 39*: 264-284.

Clark, J.S. & Hill, R.G. (1964). The pH-percent base saturation relationships of soils. *Soil Sci. Soc. Am. J. 28*(4): 490-492.

de Wit, H.A., Eldhuset, T.D., & Mulder, J. (2010). Dissolved Al reduces Mg uptake in Norway spruce forest: Results from a long-term field manipulation experiment in Norway. *Forest Ecol. Manag. 259*: 2072-2082.

Driscoll, C.T., Lawrence, G.B., Bulger, A.J., Butler, T.J., Cronan, C.S., Eagar, C., Lambert, K.F., Likens, G.E., Stoddard, J.L., & Weathers, K.C. (2001). *Acid rain revisited: Advances in scientific understanding since the passage of the 1970 and 1990 Clean Air Act Amendments*. Hubbard Brook Research Foundation. Science Links Publication. Vol. 1, No.1.

Frumhoff, P.C., McCarthy, J.J., Melillo, J.M., Moser, S.C., & Wuebbles, D.J. (2007). *Confronting climate change in the U.S. Northeast: Science, impacts, and solutions*. Synthesis report of the Northeast Climate Impacts Assessment (NECIA). Cambridge, MA.

Futter, M.N., Klaminder, J., Lucas, R.W., Laudon, H., & Kohler, S.J. (2012). Uncertainty in silicate mineral weathering rate estimates: Source partitioning and policy implications. *Environ. Res. Lett. 7*.

Godbold, D.L., Fritz, H.-W., Jentschke, G., Meesenburg, H., & Rademacher, P. (2003). Root turnover and root necromass accumulation of Norway spruce (*Picea abies*) are affected by soil acidity. *Tree Physiol. 23*: 915-921.

Huntington, T.G., Richardson, A.D., McGuire, K.J., & Hayhoe, K. (2009). Climate and hydrologic changes in the northeastern United States: Recent trends and implications for forested and aquatic ecosystems. *Can. J. For. Res. 39*: 199-212.

Keys, K., Noseworthy, J.D., Ogilvie, J., Burton, D.L., & Arp, P.A. 2016. A simple geospatial nutrient budget model for assessing forest harvest sustainability across Nova Scotia, Canada. *Open Journal of Forestry 6*: 420-444. (http://dx.doi.org/10.4236/ojf.2016.65033).

Keys, K. (2018). *Forest soil re-sampling project, Kejimkujik National Park, Nova Scotia, Canada.* Nova Scotia Department of Natural Resources.

Lawrence, G.B, Lapenis, A.G., Bergren, D., Aparin, B.F., Smith, K.T., Shortle, W.C., Bailey, S.W., Varlyguin, D.L., & Babikov, B. (2005). Climate dependency of tree growth suppressed by acid deposition effects on soils in northwest Russia. *Environ. Sci. Technol. 39*: 2004-2010.

Lawrence, G.B., Hazlett, P.W., Fernandez, I.J., Ouimet, R., Bailey, S.W., Shortle, W.C., Smith, K.T., & Antidormi, M.R. (2015). Declining acidic deposition begins reversal of forest soil acidification in the northeastern U.S. and eastern Canada. *Environ. Sci. Technol. 49*: 13103-13111.

Leys, B.A., Likens, G.E., Johnson, C.E., Craine, J.M., Lacroix, B., & McLauchlan, K.K. (2016). Natural and anthropogenic drivers of calcium depletion in a northern forest during the last millennium. *PNAS 113(25)*: 6934-6938.

Löfgren, S., Stendahl, J., & Karltun, E. (2021). Critical biomass harvesting indicator for whole-tree extraction does not reflect the sensitivity of Swedish forest soils. *Ecol. Indic. 132* (https://doi.org/10.1016/j.ecolind.2021.108310).

NEG-ECP. (2007). *Mapping forest sensitivity to atmospheric acid deposition. Forest Mapping Group 2006-2007 Annual Report*. The Committee on the Environment of the Conference of New England Governors and Eastern Canadian Premiers.

Neily, P., Keys, K., Quigley, E., Basquill, S., & Stewart, B. (2013). *Forest ecosystem classification for Nova Scotia (2010)*. Report FOR 2013-1. Nova Scotia Department of Natural Resources.

Neily, P., Basquill, S., Quigley, E., & Keys, K. (2017). *Ecological land classification for Nova Scotia*. Report FOR 2017-13. Nova Scotia Department of Natural Resources.

Noseworthy, J. (2011). *A mass balance, biogeochemical framework for assessing forest biomass harvest sustainability*. MScF thesis. Faculty of Forestry and Environmental Management. University of New Brunswick.

NSDNR. (2006). *Growth and yield model (software)*. Nova Scotia Department of Natural Resources. (https://novascotia.ca/natr/forestry/programs/gny2004/growthandyield.asp).

Ouimet, R. & Camiré, C. (1995). Foliar deficiencies of sugar maple stands associated with soil cation imbalances in the Quebec Appalachians. *Can. J. Soil Sci. 75*: 169-175.

Pardo, L.H, Robin-Abbott, M., Duarte, N., & Miller, E.K. (2005). *Tree chemistry database (Version 1.0)*. General Technical Report NE-324. Northeastern Research Station, USDA Forest Service.

Paré, D., Bernier, P., Lafleur, B., Titus, B.D., Thiffault, E., Maynard, D.G., & Guo, X. (2013). Estimating stand-scale biomass, nutrient contents, and associated uncertainties for tree species of Canadian forests. *Can. J. For. Res. 43*: 599-608.

Paré, D. & Thiffault, E. (2016). Nutrient budgets in forests under increased biomass harvesting scenarios. *Curr. For. Rep. 2*: 81-91. doi:10.1007/s40725-016-0030-3.

Rengel, Z. (1992). Role of calcium in aluminum toxicity. *New Phytot. 121*: 499-513.

Reuss, J.O. & Johnson, D.W. (1985). Effect of soil processes on the acidification of water by acid deposition. *J. Environ. Qual. 14*: 26-31.

Reuss, J.O. & Walthall, P.M. (1990). Soil reaction and acidic deposition. In Norton, S.A., Lindberg, S.E., & Page, A.L. (Eds.), *Acidic precipitation Volume 4: Soils, aquatic processes, and lake acidification* (pp. 1-33). Springer-Verlag, New York.

Steenberg, J.W.N., Duinker, P.N., & Bush, P.G. (2013). Modelling the effects of climate change and timber harvest on the forests of central Nova Scotia, Canada. *Ann. Forest Sci. 70*: 61-73.

Tomlinson, G.H., Tomlinson, F.L., Grennfelt, P., Hüttl, R., Hüttermann, A., Mehne, B.M., & von Tiedemann, S. (1990). *Effects of acid deposition on the forests of Europe and North America*. CRC Press Inc.

Tremblay, S., Ouimet, R., Houle, D., & Duchesne, L. (2012). Base cation distribution and requirement of three common forest ecosystems in eastern Canada based on site-specific and general allometric equations. *Can. J. For. Res. 42*: 1796-1809.

Yanai, R.D., Blum, J.D., Hamburg, S.P., Arthur, M.A., Nezat, C.A., & Siccama, T.G. (2005). New insights into calcium depletion in northeastern forests. *J. Forest. 103(1)*: 14-20.

Appendix 1. Tree species list

Aspen	*Populus spp*.
Balsam fir	*Abies balsamea* (L.) Mill
Black spruce	*Picea mariana* (Mill) B.S.P.
Eastern hemlock	*Tsuga canadensis* (L.) Carr
Red maple	*Acer rubrum* L.
Red oak	*Quercus rubra* L.
Red spruce	*Picea rubens* Sarg.
Sugar maple	*Acer saccharum* Marsh.
White birch	*Betula papyrifera* Marsh.
White pine	*Pinus strobus* L.
Yellow birch	*Betula alleghaniensis* Britton