Susceptibility of Forests in the Northeastern U.S. to Nitrogen and Sulfur Deposition and Implications for Forest Health

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1. INTRODUCTION

Anthropogenic activities caused emissions of sulfur (S) and nitrogen (N) to increase dramatically in the middle of the 20th century (Driscoll et al. 2001). Although S emissions have since decreased significantly as a result of SO_2 control programs (Driscoll et al. 2001), projected emissions of acidifying S and N compounds are expected to have continuing negative impacts on forests. Atmospheric S and N deposition have contributed to acidification of soils and surface waters, export of nutrient cations, and mobilization of aluminum (Al) in soils (Reuss 1983, Reuss and Johnson 1985), which can be toxic to plants and other biota. When exports of nutrient cations are greater than inputs to an ecosystem, soil nutrients may decrease to inadequate levels, a condition known as *cation depletion*. Cation depletion may result in a wide range of forest health problems: reduced growth rates and increased susceptibility of forests to climate, pest and pathogen stress, which results in reduced forest health, reduced timber yield, increased mortality, and eventual changes in forest species composition (Schaberg et al. 2001, Bailey et al. 2005). In addition to these acidification impacts, excess N deposition can lead to N saturation, the condition when N inputs exceed biotic demand (Aber et al. 1989, 1998). Excess N may result not only in elevated N leaching and further stream and soil acidification, but may also lead to plant nutrient imbalances, which ultimately lead to similar forest health problems as cation depletion (Pardo et al. 2011c). In northeastern North America, where N and S deposition are relatively high (NADP 2009), these N and S emissions, therefore, present long−term threats to forest health and productivity.

The primary objective of this study was to assess forest susceptibility to atmospheric deposition in the northeastern U.S. The *critical load* is the level of deposition below which no harmful ecological effects occur for a forest ecosystem over the long term (Nilsson and Grennfelt 1988). We calculated the critical load for S + N, the critical load for nutrient N, and the *exceedance* (the difference between the current deposition and the critical load; UBA 2004). We calculated the critical load using a steady−state, ecosystem mass balance for nutrient cations (calcium (Ca), magnesium (Mg), and potassium (K)) (NEG/ECP 2001). A secondary objective of this study was to relate measures of forest susceptibility to atmospheric deposition with indicators of forest health. We compared

current ecological indicators (crown health, growth, and mortality) at the plot level to exceedance across the New England states – Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont – and New York.

This study contributed to a larger forest sensitivity mapping project for New England and Eastern Canada. The larger project was an initiative of the New England Governors/Eastern Canadian Premiers (NEG/ECP) to map forests sensitive to atmospheric deposition in New England and Eastern Canadian (NEG/ECP Forest Mapping Group 2001, NEG/ECP Forest Mapping Group 2003, http://www.fs.fed.us/ne/durham/4352/critical_loads/Critical_loads_webs/home.htm). The NEG/ECP Forest Mapping Project includes involvement at the state level, as well as support in disseminating the information to a wide audience of stakeholders (federal, state, private land managers, environmental groups).

Due to intensive data demands, the scope of critical loads estimates has often been limited. In this assessment, however, we used datasets available on a regional scale that could be adapted for use in critical loads calculations. Using simple models to extrapolate data allowed us to estimate critical loads for many locations in the northeastern U.S. To evaluate forest susceptibility to acidic deposition, we assembled information on pollution loading to forest landscapes, plant nutrient requirements and removal through harvesting, the ability of soils to buffer acid inputs and replenish nutrients lost due to acidification, and indicators of forest health. After estimating deposition rates required to maintain forest health and productivity (critical loads) and identifying specific plots susceptible to continued S and N deposition (by calculating exceedance), we compared current health status with exceedance at the plot level. We used plot data from Forest Health Monitoring (FHM)/Forest Inventory and Analysis (FIA), North American Maple Program (NAMP), the Vermont Hardwood Health Survey (HHS), and the Vermont Monitoring Cooperative Forest Health Plots (VMC–FH). Data from soil pits from county soil surveys (Soil Survey Staff 2003) and additional research sites in Vermont were also included. The forest health data were collected between 1989 and 1997. NAMP data were collected from 1989–1997; FIA data were collected in 1994–95.

Various measures of forest health are used to assess the current condition of forest ecosystems. Determining forest health is an important part of most regional forest assessments; monitoring forest health is necessary to determine the extent of response to various forest stressors. These stressors can include biotic factors such as pests and disease, as well as abiotic factors such as climate change, air pollution, and storms.

The Forest Health Monitoring (FHM) program was a national initiative developed by the USDA Forest Service to monitor the status of and trends in indicators of forest condition in the United States (http://fhm.fs.fed.us/). The FHM program has assembled data collected using a standard protocol (USDA Forest Service 2006) from ground plots and surveys, aerial surveys (FHM 2005), and other biotic and abiotic datasets since 1990. Parameters in the FHM database used in this study include forest health indicators such as tree mortality, damage, and growth, regeneration, and crown condition, plant diversity, vegetation structure, down woody debris, and ozone damage (Coulston et al. 2005). Additional parameters include lichens and fuel loadings. The FHM plots are sampled as part of Forest Inventory and Analysis' (FIA) annual surveys.

2. METHODOLOGY

2.1 Site Description

Vegetation survey sites, soil survey pits, and additional research sites were used in this analysis. The FIA program's Forest Monitoring Survey, a three phase sampling approach used to track status and trends in forest extent, cover, growth, mortality, removals, and overall health, is described in detail below. Phase 1 consists of remote sensing to identify the location of forested land (not used here). Phase 2 consists of sampling one site per 2,428 hectares of forest (P2 plots). On P2 plots, field crews collect data on forest type, site attributes, tree species, tree size, and general forest structure. Phase 3 consists of sampling a subset of P2 plots (P3 plots), which are measured for a broader suite of parameters, including crown health conditions such as crown position, crown density, crown dieback, foliage transparency, and crown defoliation. There are approximately 125,000 P2 plots laid out on a 5 km grid across the U.S. and 8,000 P3 plots on a 22 km

grid (1 for every 16 P2 plots). These plots consist of a cluster of four circular subplots spaced in a fixed pattern, for a total area of 0.067 ha. Due to the grid layout, not all of the FIA plots are forested; only plots with some forested area were included in this analysis. More details on FIA plot layout and sampling protocols can be found at: http://www.fia.fs.fed.us.

The VMC−FH plots, located on Mount Mansfield and at Lye Brook Wilderness Area in Vermont (http://sal.snr.uvm.edu/vmc/), are laid out and are sampled according to FIA P3 plot protocol (see http://www.fia.fs.fed.us.). The NAMP plots (1.0 ha area) are located either in managed sugarbushes or sugar maple−dominated northern hardwood stands. The Vermont HHS sites (1 ha area) were sampled as a ground survey carried out to compliment aerial color infrared photography conducted by the Vermont Department of Forestry, Parks, and Recreation in collaboration with the U.S. Forest Service Forest Health Protection. The forest health measurements for these surveys include canopy transparency, crown density, defoliation, crown dieback, and mortality.

The sites based on county soil surveys were identified by searching the NRCS National Soil Survey Center (NSSC) database, which consists of pedon data associated with soil samples, for forested sites with latitude and longitude coordinates (Soil Survey Staff 2003). Forested sites were defined by either the presence of an organic layer or the absence of an Ap horizon combined with a record of forest vegetation. Forested pedons with evidence of gleying (indicating wet soil) were excluded from our analysis.

The Additional Research Sites in Vermont include plots for which sufficient data were available to estimate critical loads. These include plots on Camel's Hump, Mount Ascutney, and 75 other plots throughout the state (C. Cogbill unpublished data). Species composition and some limited soil data (parent material and soil series; in some cases, soil depth) were available for the Additional Research sites.

Only sites for which digitized soil maps were available are included in this analysis (Table 1, Map 1), which limited the extent of coverage.

Table 1. Distribution of sites by state

Site Group	CT	MA	ME	NH	NY	RI	VT	Total
FIA (P2 plots)	231	116	631	552	1012	99	509	**3150**
FHM (P3 plots)	12	3	31	22	402	4	17	**491**
VMC−FH							19	**19**
NAMP	10	10	18				35	**73**
VT HHS							62	**62**
NRCS	27	56	33	37		2	61	**216**
VT Additional Research Sites							75	**75**
Total	**280**	**185**	**713**	**591**	**1414**	**103**	**778**	**4064**

2.2 Critical Load Calculations

2.2.1 Critical load for acidity (S+N)

Calculations of critical loads are based on a simple, mass balance model for nutrient cations of inputs (atmospheric deposition, soil mineral weathering) and outputs (nutrient removal via biomass extraction, leaching). Calculation methods are described in detail elsewhere (UBA 2004, Pardo 2010); the simplified equation for calculating critical loads is:

$$\textit{Critical Load (S+N)} = BC_{dep} + BC_{W} - Bc_{u} + N_i + N_u + N_{de} - ANC_{le_{crit}} \qquad (1)$$

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}) removed by harvest or disturbance

N_i = acceptable immobilization (accumulation) of N in soil

N_u = N uptake (removal of N by harvest or fire)

N_{de} = export of N via denitrification

$ANC_{le_{crit}}$ = acceptable acid neutralizing capacity (ANC) leaching rate (eq ha^{-1} yr^{-1}).

The acceptable ANC leaching rate, $ANC_{le_{crit}}$, is calculated based on the critical chemical criteria of no change in base saturation according the NEG/ECP Forest Mapping Group Protocol (NEG/ECP 2001). In order to achieve the condition of no change in base saturation, a BC/Al_{crit} ratio of 10 (mol/mol) was used (NEG/ECP 2001, Ouimet et al. 2006).

$$ANC_{le,\,crit} = -Q^{\frac{2}{3}} \times \left(1.5 \times \frac{BC_{dep}+BC_w-BC_u}{K_{Gibb} \times \left(\frac{BC}{Al_{crit}}\right)}\right)^{\frac{1}{3}} - 1.5 \times \frac{BC_{dep}+BC_w-BC_u}{\frac{BC}{Al_{crit}}} \qquad (2)$$

Where: Q = precipitation surplus or streamflow ($m^3\ ha^{-1}\ y^{-1}$)

$K_{Gibb} = 10^9\ (mol\ L^{-1})^2$

The most susceptible 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). We refer to these sites as *upland sites* and, in our calculations, we assume soils in these regions do not receive acid–buffering seepage water from higher ground or from upwelling subsurface flows. Over time, the potential of the upland forest soil/vegetation complex to buffer acidic deposition is expected to decrease. Soil nutrient supplies for maintaining healthy tree growth are expected to become depleted and/or imbalanced.

These calculations involve multiple steps and require extensive data. Both measured and modeled data were used as inputs for deposition, climate, vegetation, and soils parameters. Access to geographic coordinates for FIA and FHM plots is strictly limited by law in order to protect the privacy of private landowners who permit sampling on their land (http://www.fia.fs.fed.us/library/papers–presentations/). Therefore, we worked closely with an FIA GIS Specialist to model the missing climate data and to overlay the geographic coordinates of individual plots with digitized county soil survey maps (Soil Survey Geographic (SSURGO) Database) to estimate the missing soil input data. The methods employed were developed during the Pilot Phase of the NEG/ECP Forest Mapping project (Duarte et al. *In prep.*; Vermont Site–Specific Report; http://www.fs.fed.us/ne/durham/4352/critical_loads/Critical_loads_webs/home.htm)

We used the "fuzzed and swapped" coordinates publicly available from FIA to display the results for FIA plots. In order to conceal the true location of the plots, the coordinates may be switched with those for a similar plot within the county (swapped) and they may be altered by approximately 0.5 miles (fuzzed). These changes should not alter the

patterns at the regional scale. For FHM plots, there were no publicly available coordinates. Therefore, FHM plots are not included in the maps, but are included in the figures. According to FIA protocol, the publicly available coordinates for all New York FIA plots are the geographic center of the county within which the plot is located (county centroid). Therefore it was not possible to show spatial patterns within the county. Instead, we plotted the mean of the county for the entire county, in order to give a general idea of the larger scale, regional spatial patterns.

2.2.2 Critical load for nutrient N

The critical load for nutrient N is the rate of N deposition below which nutrient imbalances or other detrimental consequences of N deposition do not occur. Nitrogen saturation is the condition when N inputs exceed biotic demand (Aber et al. 1989). Upland forests initially exhibit a growth response to the fertilizing effect of additional N deposition as they move toward the condition of N saturation (Aber et al. 1989). As a forest approaches N saturation, acidification from N deposition increases, nitrate leaching increases, and plant nutrient imbalances may occur. More discussion on the concept of a critical load for nutrient N can be found in the NEG/ECP Forest Mapping Group Protocol (NEG/ECP 2001) and the European Critical Loads Mapping Manual (UBA 2004).

The critical load for nutrient N is defined as the level of deposition that would balance the acceptable accumulation and export of N in the forest ecosystem. The critical load for nutrient N is the sum of the net N accumulation in the soil, net N uptake by vegetation, denitrification, and acceptable N leaching. The acceptable net N accumulation is not a measured value, but is set based on the accumulation of N in soil that would be considered unlikely to lead to disruptions in the N cycle (UBA 2004, Pardo 2010). In these calculations, we used an acceptable soil N accumulation rate of 2 kg ha^{-1} yr^{-1}. There is little research in the U.S. upon which to base the values for acceptable soil N accumulation and acceptable nitrate leaching; even the established critical load approach in Europe notes that there is no consensus on sustainable long–term rates of soil N accumulation (UBA 2004). In this study, in order to avoid setting the critical load too low, we used a conservative (low) value for the acceptable nitrate leaching term and a

higher value for the acceptable soil N accumulation term. Based on the values for Q in this analysis, this provides us with an intermediate value for the critical load. The critical load for nutrient N tends to be extremely low compared, for example, to the empirical CL based on a response of nitrate leaching for the region (Pardo et al. 2011b) since nitrate leaching represents the main output of the input/output budget on which the steady-state mass balance equation (Equation 3) is based. Thus, we concluded that we were more likely to underestimate the critical load than to overestimate it. The calculation of net N uptake is described in Section 3.2. For upland forest soils, denitrification rates are small to negligible (Binkley et al. 1995), hence denitrification is set to 0. Assuming denitrification to be negligible gives a conservative estimate of critical load (i.e., the critical load would be higher if denitrification were assumed to be greater than 0). The acceptable N leaching rate is the eutrophication limit for surface waters or the maximum acceptable leaching rate for an ecosystem that is not at N saturation.

The acceptable nitrate leaching rate, N_{le}, is the maximum acceptable leaching rate for an ecosystem that is not at N saturation. This leaching rate is given by:

$$N_{le(acc)} = Q*[N]_{crit} \quad (3)$$

where:

$N_{le(acc)}$ = acceptable nitrate leaching

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

$[N]_{crit}$ was set at 0.2 g N/m^3, per the ICP Mapping and Modelling Manual (http://www.rivm.nl/en/themasites/icpmm/manual-and-downloads/index.html; UBA, 2004).

$CL_{nut}(N)$ can then be expressed as:

$$CL_{nut}(N) = N_i + N_u + N_{de} + N_{le(acc)} \quad (4)$$

In view of both the acidification and N saturation issues, the maximum critical load for N deposition should be determined by $CL_{max}(N)$ (the maximum deposition rate of N if there were no S deposition) or $CL_{nut}(N)$, which ever had the lowest value.

2.3 Overview of input data

2.3.1 Climate and Deposition

Climate and deposition data are used at several stages of critical loads calculations. Climate values are used to calculate soil mineral weathering rate. Base cation deposition data are used to calculate the critical load. Nitrogen and S deposition data are used to calculate the exceedance.

We used the ClimCalc model to calculate the required climate and deposition parameters (Ollinger et al. 1993; http://www.pnet.sr.unh.edu/climcalc). ClimCalc is a model of physical and chemical climate for New England and New York derived from statistical analysis of weather station data and data from atmospheric deposition monitoring networks (such as the National Atmospheric Deposition Program, NADP) and combined with a digital elevation model (USGS 1987). The model estimates mean monthly values for precipitation volume, solar radiation, and minimum and maximum monthly temperature as well as wet deposition of S and N compounds, Cl^-, H^+, Ca^{2+}, Mg^{2+}, K^+, and Na^+ ions and dry deposition of S and N compounds. ClimCalc was designed to capture the dominant regional patterns in climate and atmospheric deposition and does not address some local factors such as rain shadow effects, proximity to large water bodies, cloud and fog inputs, elevation effects on dry deposition, and stand species composition (Ollinger et al. 1993). Required inputs are latitude, longitude, and elevation.

ClimCalc was developed using precipitation volume data from 1950–1980 and wet deposition data from the time period of 1980–1991 from 26 NADP stations across the northeastern U.S. Wet deposition datasets from each site range from 3 to 11 years in length (mean 6.7 years). Data from two coastal NADP sites were omitted due to high concentrations of Na^+, Cl^-, Mg^{2+}, and K^+ from inputs of sea spray.

Dry deposition was inferred by combining atmospheric concentrations of NH_4^+, NO_3^-, HNO_3 (for N), and SO_4^{2-} and SO_2 (for S) with estimates of deposition velocity. Data for the dry deposition estimates came from 13 sites, 11 from the National Dry Deposition

Network, NDDN (1989−1990), one site at Huntington Forest in the Eastern Adirondacks (1986−1988), and one site in southeastern New York (IES, 1988−1990). Mean annual deposition velocities characteristic of a deciduous forest were used and it was assumed that wind speed did not vary substantially across the region.

ClimCalc was developed using deposition rates for an earlier time period, 1980−1991, and may underestimate deposition inputs at certain sites. However, it is publicly available and easy to use, which was a requirement for the FIA GIS Specialist. The GIS Specialist used the true geographic coordinates and elevation for each FIA and FHM plot as input to the ClimCalc model, then provided us with truncated (rounded) monthly precipitation volume and air temperature, as well as annual total (wet+dry) deposition rates. The monthly precipitation volume and air temperature were combined with soil attributes (Section 2.1.3) in a simple model that estimates annual evapotranspiration (Miller pers. Communication, see Miller 2011 for details).

2.3.2 Nutrient Removal

Removal of biomass from forest ecosystems by harvesting or fire results in the removal of nutrient base cations and N. As fire is not significant in this region (Richburg and Patterson 2000), we calculated only nutrient removal via harvesting. In order to calculate the nutrient uptake and removal for each site, we estimated biomass (kg) by above−ground compartment (stem, branch, bark) and multiplied that by nutrient concentration (%) by compartment.

All of the required data for calculating annual merchantable removals of growing stock trees on timberland are available in the publicly accessible FIA database (http://www.fia.fs.fed.us/tools-data). For the P2 plots, the sample years used varied by state due to FIA's sampling cycles (Table 2). The data for the P3 plots in the New England states were provided to us by FIA and are from 1994−1995 (prior to the 1999 merger of FHM and FIA). Data for the New York P3 plots were from years 1993 and 2004. We summarized the data using algorithms outlined in the FIA Database Documentation (Table 5, Chapter 4; http://www.fia.fs.fed.us/library/database-

documentation/historic/ver1/gtr_nc218.pdf). These current removal rates at the county level were combined with chemistry data from the Tree Chemistry Database (Pardo et al. 2005; http://www.treesearch.fs.fed.us/pubs/9464) to calculate the annual nutrient removal rates. The Tree Chemistry Database includes information on nutrient concentration by compartment (stem, branch, bark, foliage) for tree species found in the northeastern U.S.

Table 2. Sample years used for FIA (P2) plot data, by state

	CT	MA	ME	NH	NY	RI	VT
Year	1998	1998	1995, 2003	1997	1993, 2004	1998	1997

Although removal rates were available only for FIA sites, species composition and DBH data (used for calculating biomass) were available for the other vegetation survey sites and additional research plots. Saw timber harvest was considered to be the dominate harvest type for New England and New York, and estimates of tree wood and bark were made using allometric equations (Jenkins et al. 2003, Vermont Site–Specific Report, http://www.fs.fed.us/ne/durham/4352/critical_loads/Critical_loads_webs/home.htm, Duarte et al. *In prep.*). Estimates of tree wood and bark biomass were combined with compartment–specific nutrient concentrations in order to estimate the nutrient content in saw timber. Annual biomass extraction rates for saw timber compiled from FIA data and tabulated by county, land–ownership category (public, private) and gross forest type (softwood, hardwood, mixed) were then used to estimate the nutrient removal from these non–FIA sites, except the NRCS sites.

For the NRCS sites, which have no vegetation data, we assumed no biomass removal. The resulting critical loads for acidity for these sites may therefore be too high, as we assumed that there is no base cation removal for these sites. The resulting critical loads for nutrient N for these sites may be too low, as we assumed that there was no N removal.

2.3.3 Soil Mineral Weathering Rates

Mineral weathering represents the most significant term in the critical loads calculations. It is not possible to measure the rate of mineral weathering directly. Instead it is modeled either using complex models based on soil mineralogy or simple models based on soil

type. We used a simple model for this analysis. Estimates for weathering rates were made for the rooting zone; when we had information that indicated a root limiting layer, we included only horizons above that layer.

In order to identify the primary soil series for each plot, the FIA GIS Specialist overlaid the true geographic coordinates of the FIA and FHM plots on the digitized soil county survey maps (Soil Survey Geographic (SSURGO) Database; http://soils.usda.gov/survey/geography/ssurgo). Regions for which digitized soil maps were not available were excluded from this analysis (Map 1). A database of parameters associated with each soil series, based on NSSC soil pit data (Soil Survey Staff 2003) was used to calculate an NSSC mean by soil series and, where data were extensive, by state. The Official Soil Series Descriptions (OSSD) were used to assign minimum, mid, and maximum values for the required soil parameters (depth, clay percent, texture, moisture, substrate type) for each soil series. In order to reduce an unrealistic skewing of the minimum weathering rate towards zero, we eliminated the lowest 20% of the range of values reported in the OSSD and used this adjusted value as the minimum weathering rate. The "mid" value was calculated by taking the midpoint of the range ($\text{maximum}_{\text{reported}} - \text{minimum}_{\text{adjusted}}$) of OSSD parameters for each soil type.

Soil depth, texture, and moisture data were used with monthly precipitation volume and air temperature (Section 2.3.1) to model annual evapotranspiration (AET). Soil depth, clay percent, substrate type (see Duarte et al. 2011 for substrate classification of soil series), and mean annual air temperature were used to estimate mineral weathering rates using the clay percent/substrate type method (Ouimet et al. 2006, McNulty et al. 2007, Sverdrup et al. 1990). These calculations were done using minimum, maximum, midpoint, and NCCS mean soil parameters, resulting in minimum (min), maximum (max), midpoint (mid), and mean mineral weathering values. The clay percent/substrate type method uses three categories of soil substrate: acidic, intermediate, and basic. *Acidic soil substrates* include granites, gneiss, sandstones, and felsic rocks; *intermediate soil substrates* include diorite, granodiorite, conglomerates, and most sedimentary rocks other than sand stone; *basic soil substrates* include mafic rocks, sedimentary rocks with

low carbonate content, and carbonate rocks. We were limited to this method for estimating soil mineral weathering rates because it requires the fewest data and is the easiest method to use. The FIA GIS Specialist made mineral weathering calculations and provided us with truncated values for each plot.

2.4 Exceedance Calculations

The exceedance is the amount of current deposition in excess of what the ecosystem can tolerate. Exceedance for acidity is calculated as the current S+N deposition minus the critical load for S+N. Exceedance for nutrient N is calculated as the current N deposition minus the critical load for nutrient N. We used the annual deposition rates provided from ClimCalc (Section 2.3.1) to calculate the exceedance for each plot.

2.5 Ecological Indicators

Ecological indicators used in this analysis were restricted by the availability of data at a state or regional basis. Original methodologies called for comparing critical load and exceedances with a broad suite of biological criteria: ecosystem health and vitality, productive capacity, water resources, and global carbon cycles (NEG/ECP Forest Mapping Group 2001). For this analysis, ecosystem health and vitality was measured using indicators of tree health: canopy transparency, crown density and dieback, growth rate, and vigor. These ecological indicators were employed to assess the current health status at each site and were then compared with the exceedance by species. We excluded trees with damage caused by logging. We analyzed FIA P3, HHS, NAMP, and VMC-FH data from 1995. We analyzed FIA P2 data from inventory years 1994 to 1998.

The ecological indicator data included in our analysis is from tree measurements at individual ground plots. We included only measurements made for dominant, co−dominant, and open grown trees because these trees are less likely to decline due to confounding stand dynamics; it is therefore easier interpret forest health decline as related to acidic deposition. We excluded intermediate and overtopped trees. We compared critical load exceedance with forest health indications using the Spearman's rank correlation analysis (α =0.05) using SAS software.

2.5.1 Definitions of ecological indicators

The majority of the ecological indicators used are measurements of crown condition (Table 3). Tree crown condition is considered a good indicator of forest health because foliage is the driver of net primary productivity in forest ecosystems (Kozlowski et al. 1991). Crown condition is highly correlated with tree growth, survival, and reproduction, and the canopy often shows the first indications of stresses on a tree. *Canopy* (or *foliage*) *transparency* refers to the amount of sunlight visible through the live crown. *Crown density* is the amount of light blocked by branches and foliage in a live crown. *Dieback* refers to branch mortality beginning at the terminal portion of a limb and progressing toward the stem. Crown indicators are measured to the nearest 5% of the crown area (estimated visually).

Table 3. Definitions of ecological indicator

Indicator	Class definition
Canopy transparency	• *Heavy:* Percent of overstory trees with greater than 25% transparency
Crown density	• *Low*: percent of overstory trees with less than 40% crown density
Die back	• *High*: percent of overstory trees with greater than 15% dieback
Decline/Vigor	• *Moderate−Severe*: percent of overstory trees with Moderate−Severe decline or vigor
Growth rate	• *For FIA (P2) plots only:* net annual merchantable growth of growing stock trees

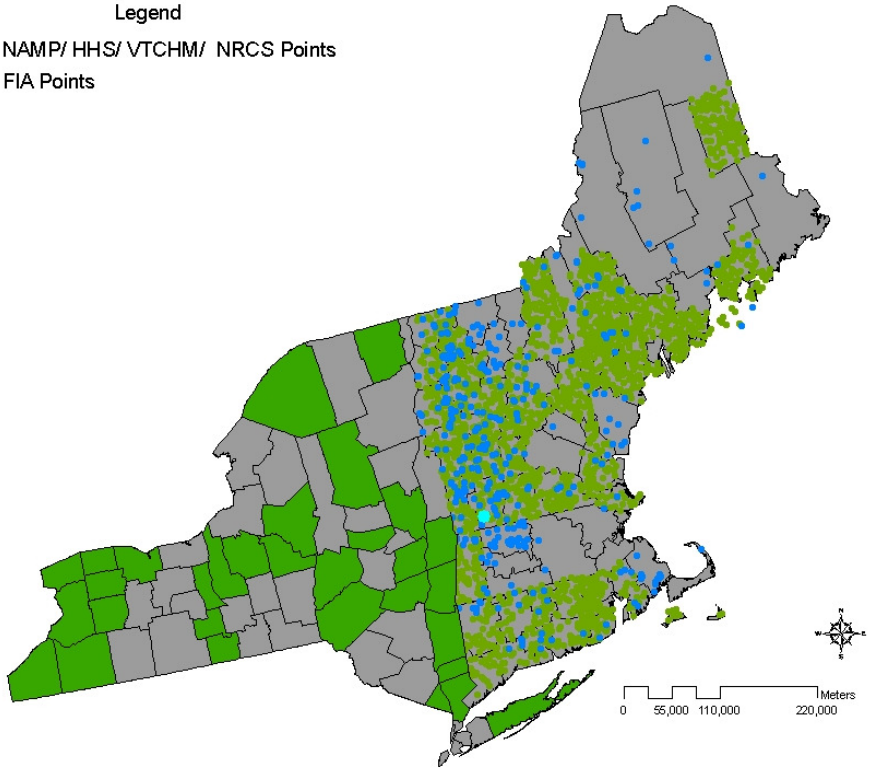
Crown decline or vigor is a more general indicator used only on the NAMP and HHS plots and is rated in relatively broad classes of percent of the crown affected by discoloration, dwarfed leaves, and branch and twig dieback or mortality. The definition of crown decline or vigor may also include estimates of crown area missing based on presence of old snags or severe bole damage. The acceptable error of decline and vigor ratings is plus−or−minus one class, which may represent 25 to 50% of the crown area (see Table 4). Mortality and decline in growth rate are the only ecological indicators measured on the FIA P2 plots. We used the parameter GROWCFGS, the net change in cubic foot volume per year reported by tree, to compare growth to exceedance by species. FIA parameters are described in the FIA Database Documentation (Table 5, Chapter 4;

http://www.fia.fs.fed.us/library/database-documentation/historic/ver1/gtr_nc218.pdf). We did not include mortality versus exceedance comparisons in our final analysis, as we could not determine the crown class of trees with mortality data.

Table 4. Vigor rating used in Forest Health Assessments on NAMP & HHS plots

Vigor Rating	Vigor Assessment	Vigor Definition
1	Healthy	<10% of crown has branch or twig mortality, discoloration, or dwarfed leaves present
2	Light decline	10–25% of crown has branch or twig mortality, discoloration, or dwarfed leaves present
3	Moderate decline	26–50% of crown has branch or twig mortality, discoloration, or dwarfed leaves present
4	Severe decline	>50% of crown has branch or twig mortality, discoloration, or dwarfed leaves present
5	Dead, natural	Standing dead
6	Dead, removed or dropped	Tree has been sawed or girdled by humans

Subsequent sections of this report provide details on the input data (atmospheric, nutrient removal, and mineral weathering rates), the results of critical load and exceedance calculations, the patterns of forest health, and the correlation between exceedance and forest health.



Map 1. Site location in New England and New York Only sites for which digitized soil maps were available are included in this analysis. These include plots from the North American Maple Program (NAMP), the Vermont Hardwood Health Survey (HHS), and the Vermont Monitoring Cooperative Forest Health Plots (VMC−FH) and Natural Resources Conservation Service soil surveys (NRCS). U.S. Forest Service Forest Inventory and Analysis (FIA) P2 plots are indicated using the publicly available (not true) coordinates (see section 2.1). Because only county center coordinates are publicly available for New York, counties where digitized soil maps are available are indicated in blue. FHM (P3) plots do not have publicly available coordinates and are not shown on this map (see section 2.1).

3. CRITICAL LOADS INPUT DATA

3.1 Climate and Deposition

Climate and deposition data are used at several stages of critical loads calculations: climate values are used to calculate the soil mineral weathering rate, base cation deposition data are used to calculate the critical load, and N and S deposition data are used to calculate the exceedance. As explained in section 2.2.1, FHM plots are not included in the maps, and New York FIA values are mapped as the mean by county.

Precipitation volume across New England and New York ranges from 64 to 209 cm (mean 112 cm; Map 2). Annual evapotranspiration ranges from 3 to 74 cm (mean 33 cm). Sulfur deposition ranges from 242 to 1,154 eq ha^{-1} yr^{-1} (Map 3a) or 3.8–18.5 kg S ha^{-1} yr^{-1} (Map 3b); N deposition ranges from 256 to 920 eq ha^{-1} yr^{-1} (Map 4a) or 3.6–12.8 kg N ha^{-1} yr^{-1} (Map 4b), with higher deposition rates in New York and southwestern New England (Map 5). Base cation deposition rates range from 62 to 286 eq ha^{-1} yr^{-1} (Map 6). Table 5 summarizes the mean annual precipitation volume, mean AET, and deposition rates calculated using the ClimCalc model. In order to comply with FIA's strict privacy regulations, data are presented as mean, minimum and maximum values by state.

Table 5. Summary of modeled climate and deposition inputs for plots in New England and New York

		CT	MA	ME	NH	NY	RI	VT
Precipitation Volume (cm)								
All Sites Except FHM	Min	103	103	91	92	64	111	79
	Mean	**117**	**123**	**107**	**117**	**106**	**118**	**117**
	Max	140	175	165	209	152	125	163
FHM	Min	111	108	98	104	66	116	94
	Mean	**117**	**121**	**106**	**116**	**110**	**117**	**113**
	Max	131	131	141	132	149	118	136
AET (cm)								
All Sites Except FHM	Min	24	18	3	4	7	24	13
	Mean	**40**	**31**	**20**	**28**	**45**	**40**	**30**
	Max	64	61	67	74	63	55	69
FHM	Min	28	28	13	16	4	25	25
	Mean	**37**	**31**	**23**	**29**	**29**	**37**	**41**
	Max	44	35	46	43	46	42	53

		CT	MA	ME	NH	NY	RI	VT
S Deposition (eq ha^{-1} yr^{-1})								
All Sites Except FHM	Min	706	592	242	532	492	681	496
	Mean	**787**	**763**	**475**	**640**	**800**	**728**	**701**
	Max	1073	974	702	950	1154	759	966
FHM	Min	737	624	303	559	505	703	605
	Mean	**798**	**744**	**464**	**650**	**817**	**723**	**695**
	Max	872	840	630	766	1149	729	846
S Deposition (kq ha^{-1} yr^{-1})								
All Sites Except FHM	Min	11.3	9.5	3.9	8.5	7.9	10.9	7.9
	Mean	**12.6**	**12.2**	**7.6**	**10.2**	**12.8**	**11.7**	**11.2**
	Max	17.2	15.6	11.2	15.2	18.5	12.1	15.5
FHM	Min	11.8	10.0	4.8	8.9	8.1	11.3	9.7
	Mean	**12.8**	**11.9**	**7.4**	**10.4**	**13.1**	**11.6**	**11.1**
	Max	14.0	13.4	10.1	12.3	18.4	11.7	13.5
N Deposition (eq ha^{-1} yr^{-1})								
All Sites Except FHM	Min	610	530	256	466	423	305	428
	Mean	**669**	**650**	**435**	**553**	**659**	**622**	**594**
	Max	858	800	594	779	920	649	791
FHM	Min	637	552	307	490	430	612	518
	Mean	**678**	**635**	**428**	**561**	**673**	**626**	**589**
	Max	727	701	542	647	916	629	704
N Deposition (kg ha^{-1} yr^{-1})								
All Sites Except FHM	Min	8.5	7.4	3.6	6.5	5.9	4.3	6.0
	Mean	**9.4**	**9.1**	**6.1**	**7.7**	**9.2**	**8.7**	**8.3**
	Max	12.0	11.2	8.3	10.9	12.9	9.1	11.1
FHM	Min	8.9	7.7	4.3	6.9	6.0	8.6	7.3
	Mean	**9.5**	**8.9**	**6.0**	**7.9**	**9.4**	**8.8**	**8.2**
	Max	10.2	9.8	7.6	9.1	12.8	8.8	9.9
Cl Deposition (eq ha^{-1} yr^{-1})								
All Sites Except FHM	Min	42	75	32	40	13	123	23
	Mean	**118**	**108**	**63**	**69**	**49**	**135**	**56**
	Max	143	214	94	100	154	154	97
FHM	Min	102	91	47	49	14	129	39
	Mean	**119**	**96**	**66**	**71**	**48**	**141**	**56**
	Max	138	102	84	98	114	148	81
BC Deposition (eq ha^{-1} yr^{-1})								
All Sites Except FHM	Min	135	142	80	105	62	192	75
	Mean	**193**	**187**	**128**	**143**	**125**	**208**	**133**
	Max	216	286	175	209	224	224	205
FHM	Min	176	170	104	120	64	203	105
	Mean	**194**	**175**	**130**	**145**	**127**	**213**	**131**
	Max	209	179	150	180	204	219	172

3.2 Nutrient removal

Nutrient uptake and storage by vegetation become factors in calculations of critical load when the vegetation biomass is removed from the ecosystem. At steady state, for the ecosystem as a whole, there is no ***net*** change in standing biomass and therefore no ***net*** annual nutrient requirement. In this scenario, any nutrient uptake is assumed to be released in litter in the same year. When forests are harvested, all or part of the nutrient pool in the aboveground biomass is removed. The amount of nutrients removed depends on the intensity and frequency of harvest; there are also variations in harvesting practices on privately and publicly owned lands. For the FIA and FHM plots, biomass of merchantable growing stock removed from the plots was used to calculate nutrient removal where there was harvest. For the rest of the sites, except the NRCS sites, biomass of potentially harvestable saw timber was used to calculate nutrient removal. For the NRCS sites, we assumed no biomass removal, because we did not have any data about vegetation and potential removal rates.

There were 2215 sites throughout New England and New York that were assumed to have no biomass removals via harvest (Table 6). For the sites with biomass removal, the N removal ranged from 1 to 891 eq ha^{-1} yr^{-1} (mean 61; Table 6; Map 7) or up to 12.5 kg N ha^{-1} yr^{-1}; base cation removals ranged from 1 to 2083 eq ha^{-1} yr^{-1}(mean 97; Table 6; Map 8).

Table 6. Summary of the range of N and base cation removal rates for plots with biomass removal in New England and New York

		CT	MA	ME	NH	NY	RI	VT
Number of sites without harvest		**209**	**162**	**36**	**442**	**1024**	**80**	**471**
Number of sites with harvest		**60**	**22**	**676**	**177**	**383**	**24**	**283**
N removal (eq ha^{-1} yr^{-1})								
All Sites Except FHM	Lowest	2	1	2	2	1	5	4
	Mean	67	66	16	95	19	92	158
	Highest	385	239	34	680	99	214	891
FHM	Lowest	8	149	25	11	6	17	1
	Mean	21	249	80	35	113	41	14
	Highest	30	349	190	111	232	79	87

		CT	MA	ME	NH	NY	RI	VT
BC removal (eq ha^{-1} yr^{-1})								
All Sites Except FHM	Lowest	7	1	3	4	2	6	7
	Mean	164	176	29	192	42	237	325
	Highest	1083	695	62	1516	258	660	2083
FHM	Lowest	20	318	61	31	14	38	1
	Mean	57	682	248	99	333	107	41
	Max	86	1046	576	320	886	205	249

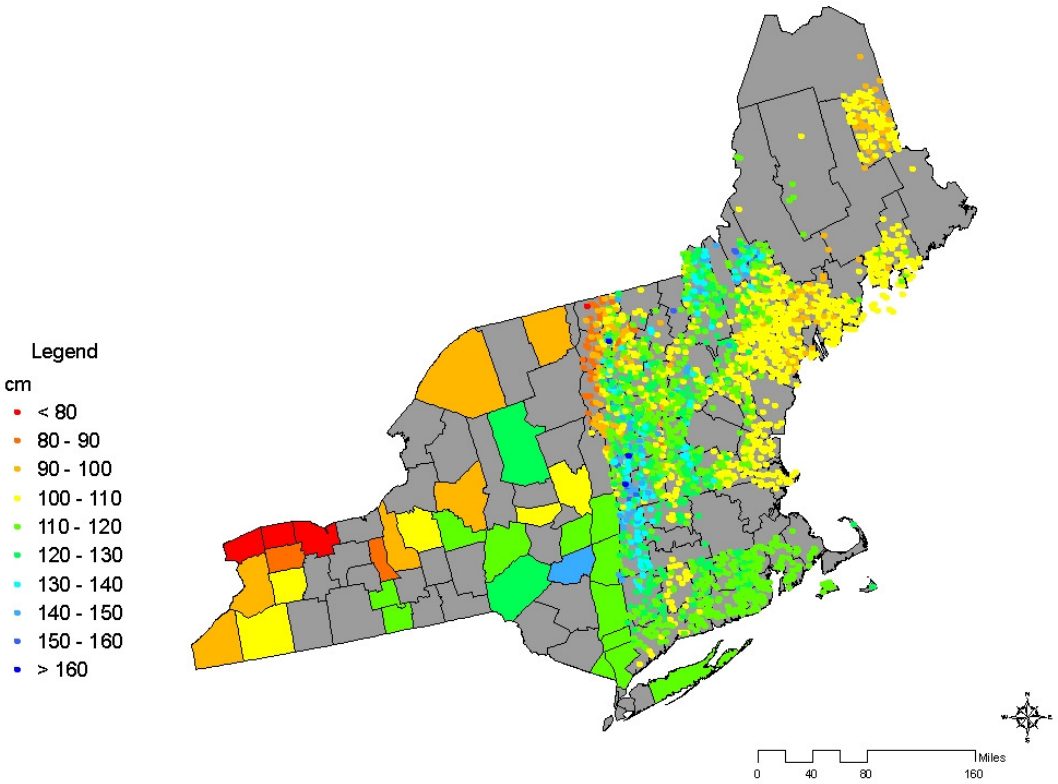
3.3 Soil mineral weathering

Soil mineral weathering, the primary means of replenishing base cations lost from the soil due to leaching caused by acidic deposition, is often the most important parameter in the critical load model and is difficult to estimate. The soil mineral weathering rate is determined by the types of minerals present in the bedrock or substrate, soil physical properties, and the local climate (air temperature and precipitation). The substrate type/clay content method was used to estimate soil mineral weathering rates (Sverdrup et al. 1990, NEG/ECP 2001) for minimum, maximum, midpoint, and NCCS mean soil values as described in section 2.3.3.

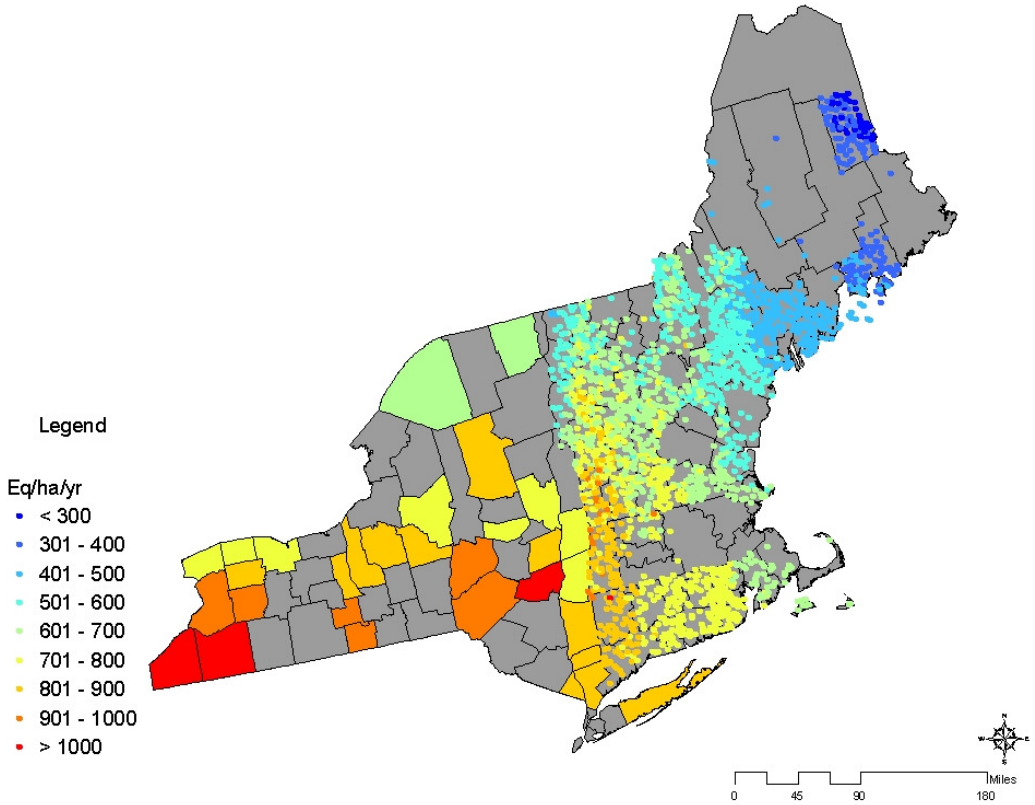
The NSSC soil pit data (Soil Survey Staff 2003) were averaged across New England to generate mean values for the soil input parameters by soil series. We took the mean of the NCCS soil pit data to constrain the range of possible values (from the OSSD) to better reflect the observed range in the region. However, the number of pits per soil series and state was so limited that it was difficult to assess how representative these plots were. We nonetheless report NSSC mean weathering rates for most sites. For some soil series, soil data were not available from the NSSC soil database. For plots with these soil series, only minimum, maximum and midpoint mineral weathering rates were calculated (based on the Official Soil Series Description). Mineral weathering rates are summarized by state for all sites (Table 7; Maps 9–12).

Table 7. Summary of mean soil mineral weathering rates for plots in New England and New York

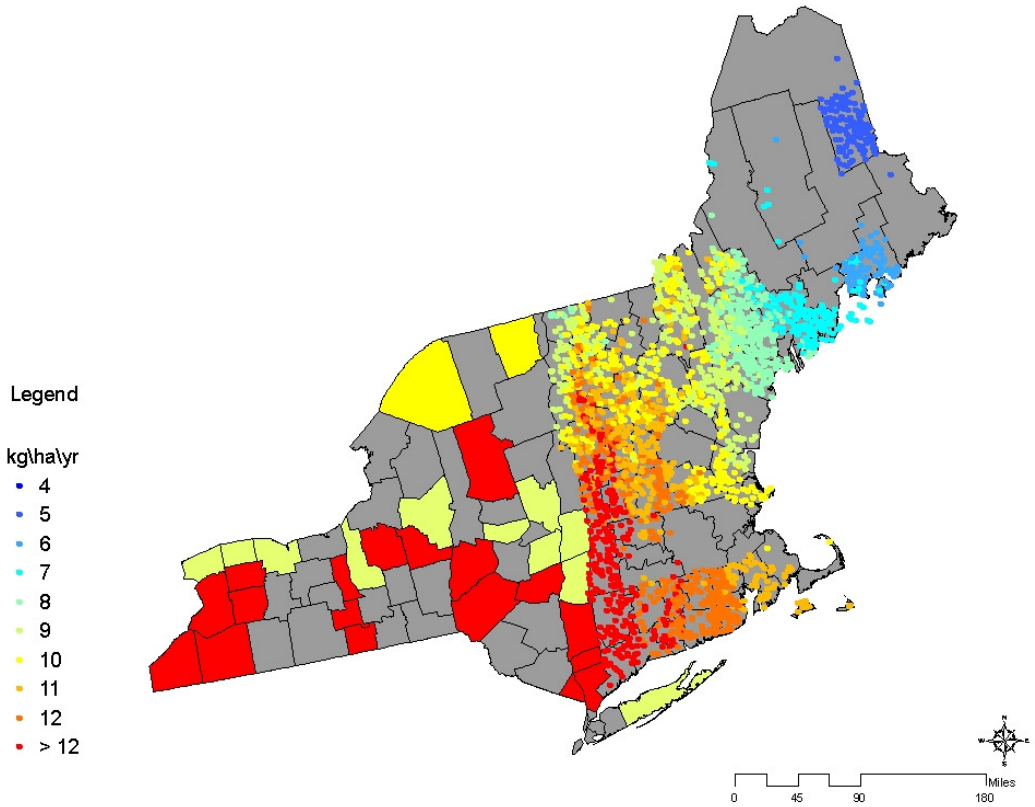
		CT	MA	ME	NH	NY	RI	VT
Soil mineral weathering rate (eq ha^{-1} yr^{-1})								
All Sites Except FHM	***Min***	358	321	275	282	324	365	287
	Mid	**939**	**678**	**753**	**758**	**925**	**1012**	**764**
	Max	1940	2355	3985	2123	4890	2650	8327
	NSSC Mean	314	183	133	160	274	312	168
FIA−FHM	***Min***	359	275	288	303	310	422	300
	Mid	**1015**	**777**	**832**	**855**	**884**	**1209**	**859**
	Max	1923	1601	3878	1672	4733	2369	1637
	NSSC Mean	254	150	103	180	202	538	176



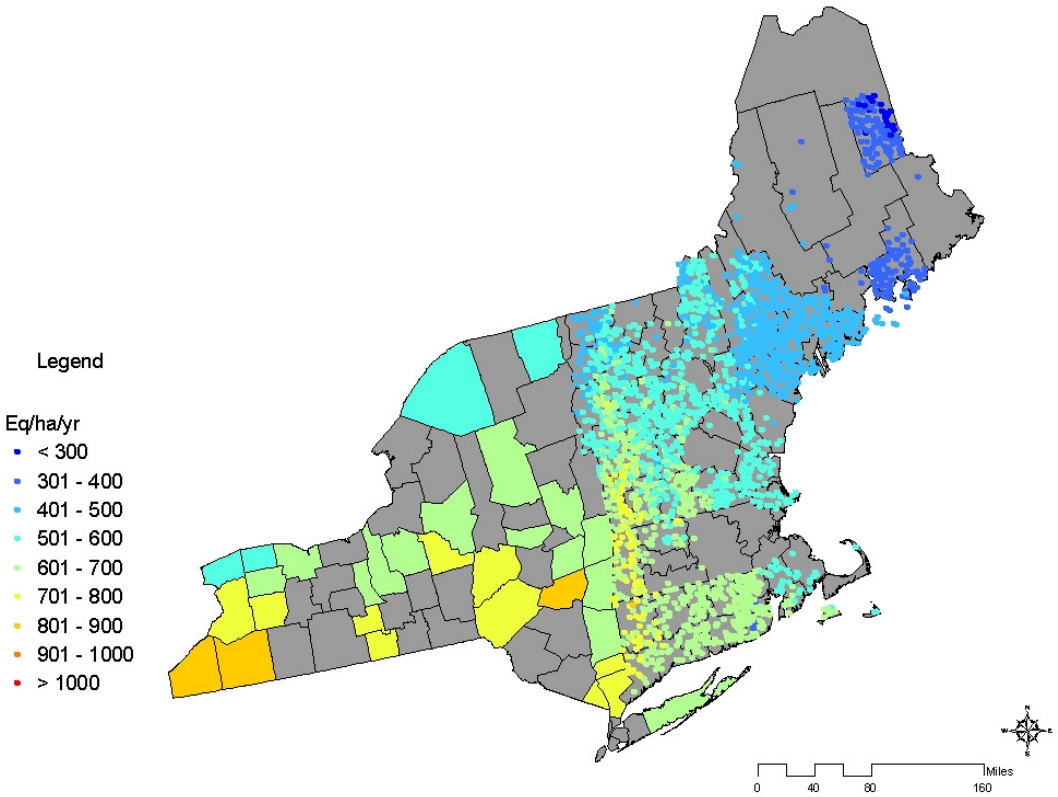
Map 2. Precipitation volume modeled by ClimCalc for sites in New England and New York



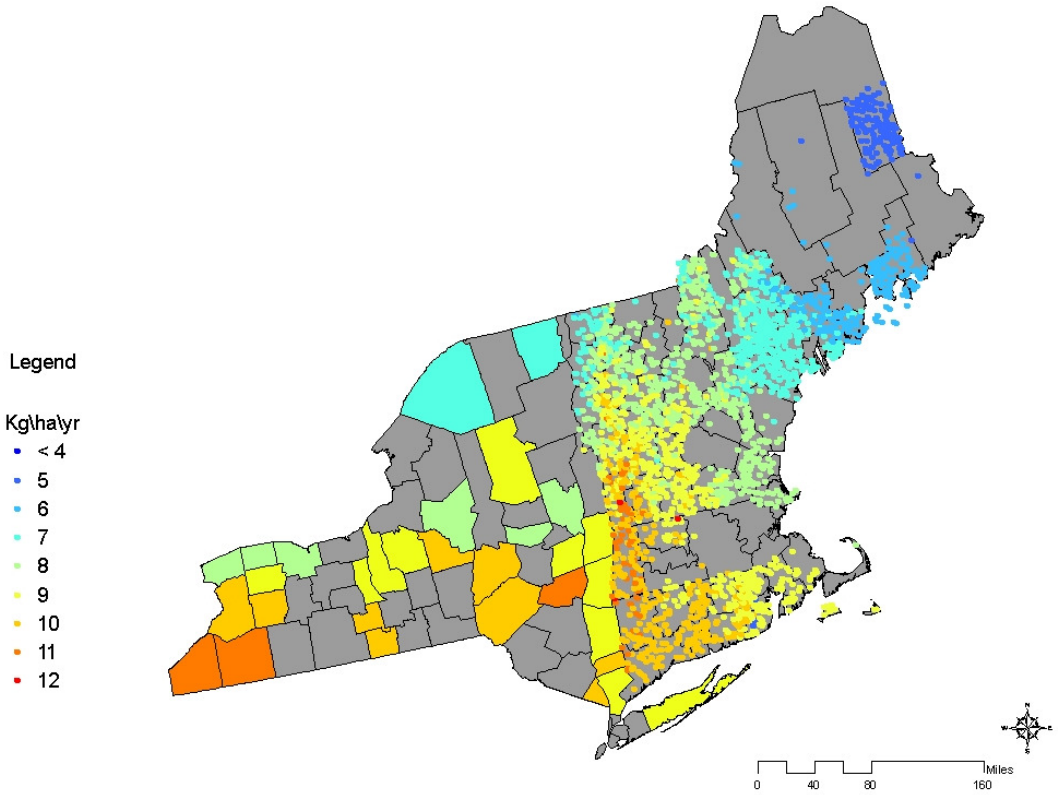
Map 3.a S deposition rates (wet + dry) modeled by ClimCalc for sites in New England and New York (eq ha^{-1} yr^{-1})



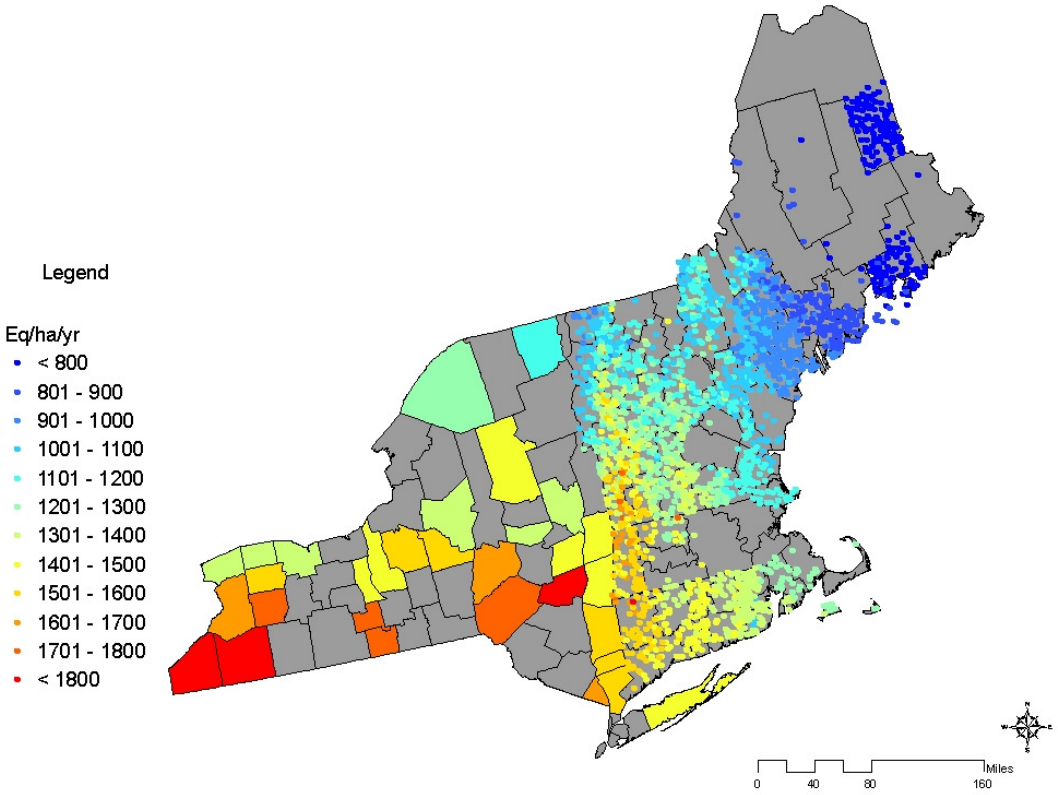
Map 3.b S deposition rates (wet + dry) modeled by ClimCalc for sites in New England and New York (kg ha^{-1} yr^{-1})



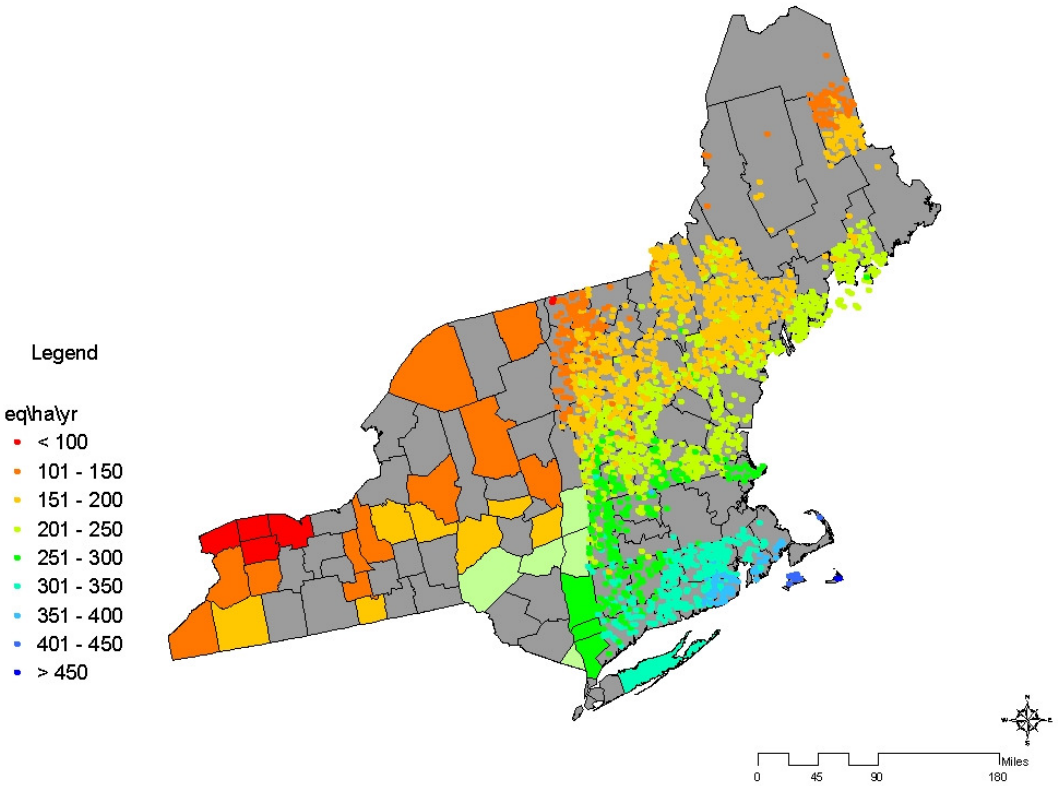
Map 4.a N deposition rates (wet + dry) modeled by ClimCalc for sites in New England and New York (eq ha^{-1} yr^{-1})



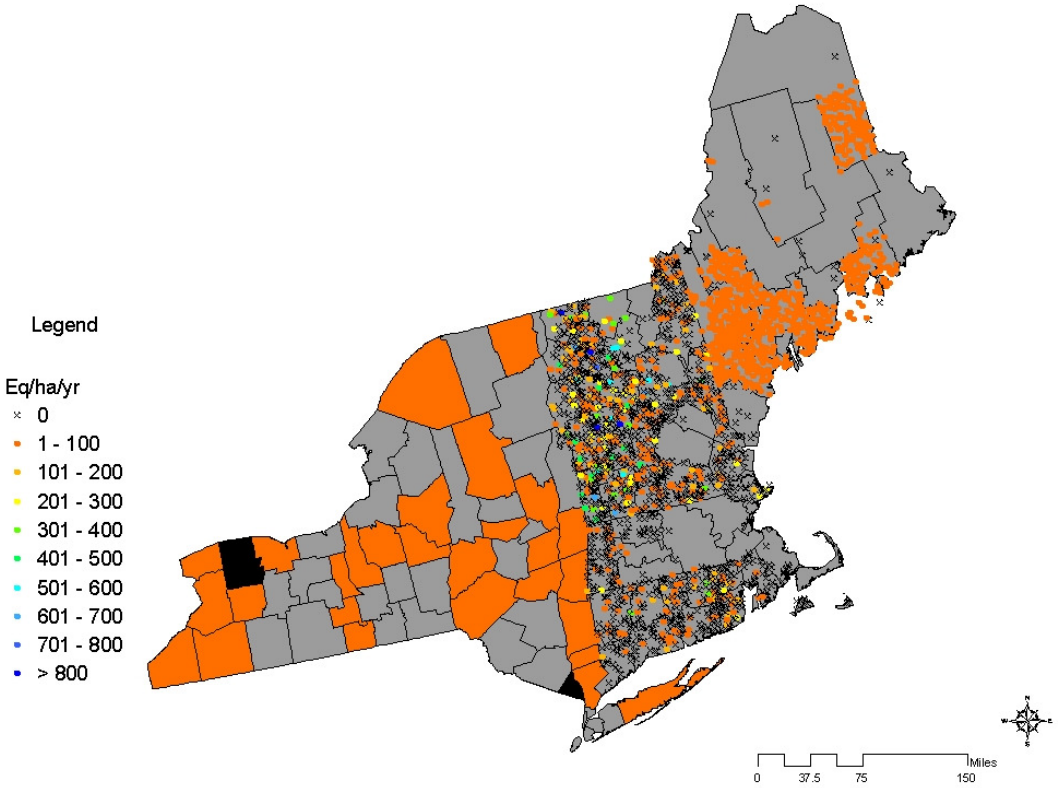
Map 4.b N deposition rates (wet + dry) modeled by ClimCalc for sites in New England and New York (kg ha^{-1} yr^{-1})



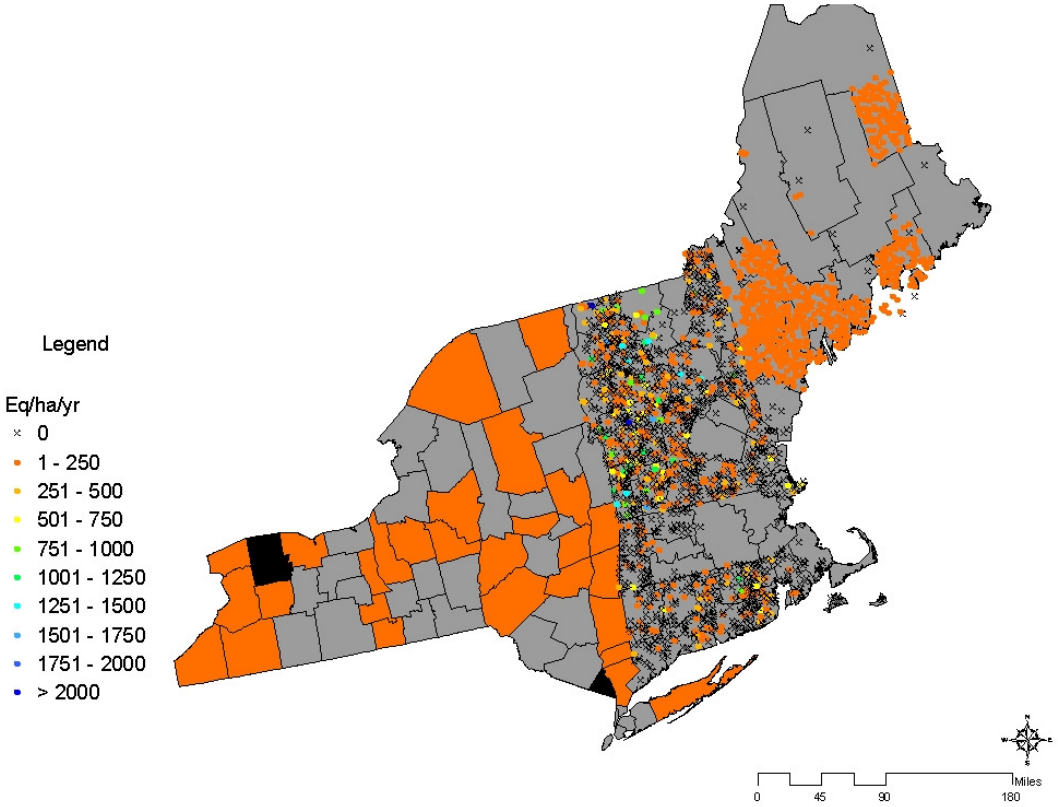
Map 5. S+N deposition rates (wet + dry) modeled by ClimCalc for sites in New England and New York (eq ha^{-1} yr^{-1})



Map 6. Base cation deposition rates (wet only) modeled by ClimCalc for sites in New England and New York (eq ha^{-1} yr^{-1})

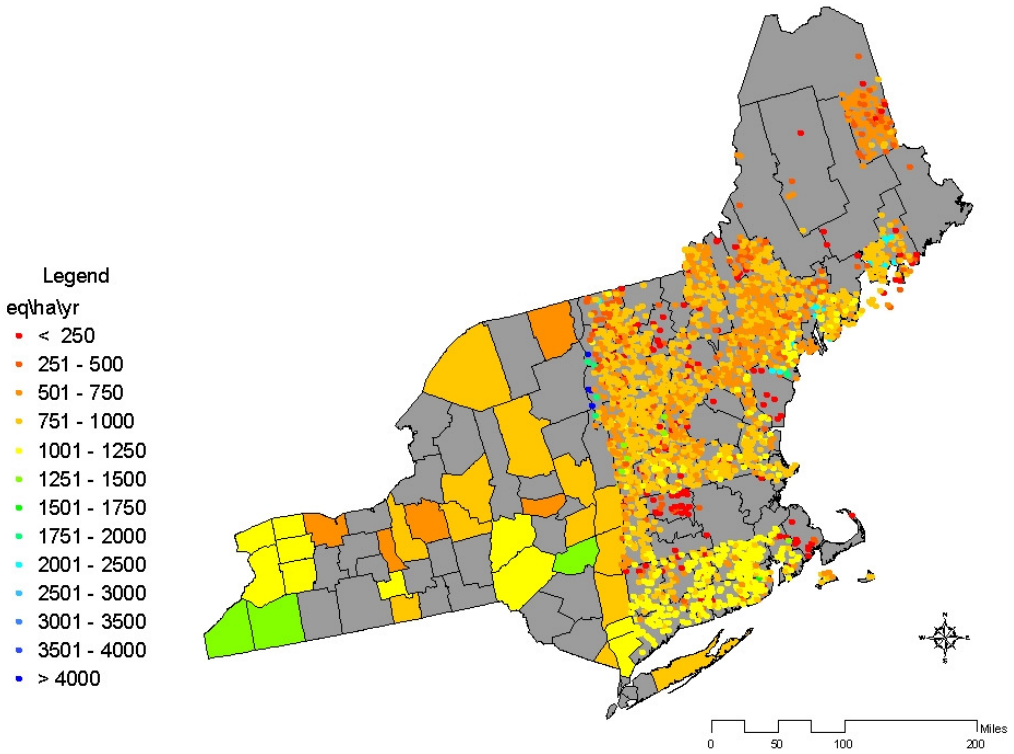


Map 7. N removal rates in biomass for sites in New England and New York
Sites with no biomass removal are indicated with a black "x" or black fill (for NY). Biomass removal is shown in (eq ha^{-1} yr^{-1}).

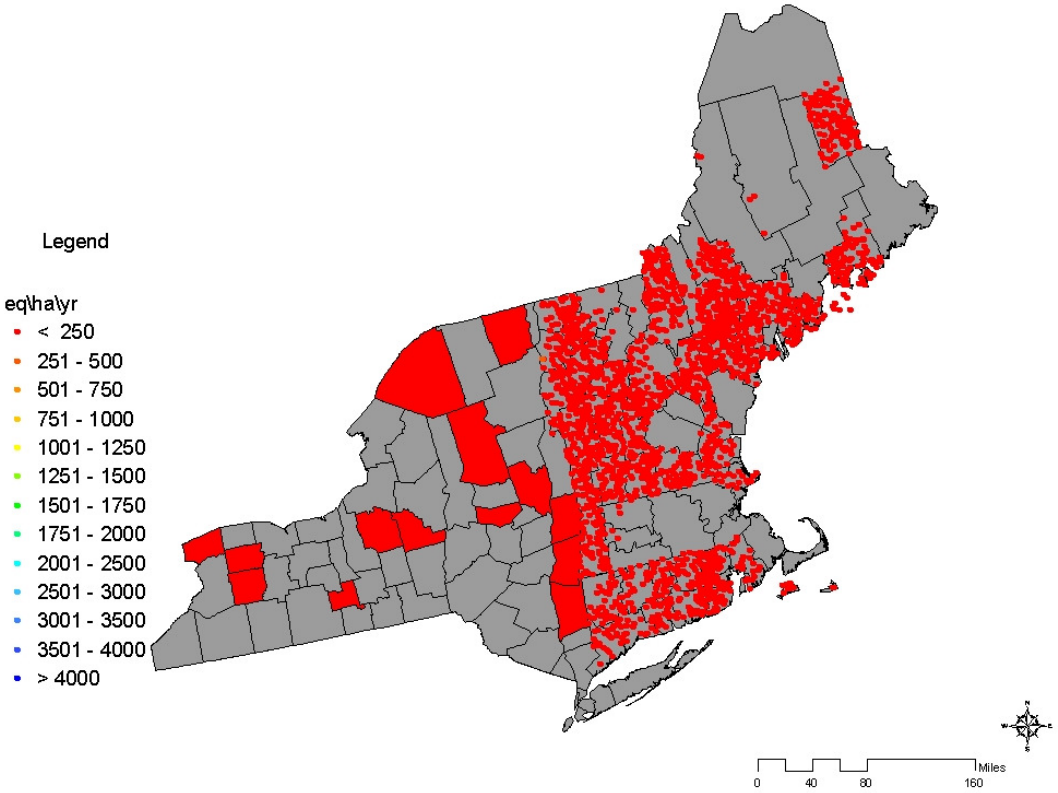


Map 8. Base cation removal rates in biomass for sites in New England and New York FIA

Sites with no biomass removal are indicated with a black "x" or black fill (for NY). Biomass removal is shown in (eq ha^{-1} yr^{-1}).

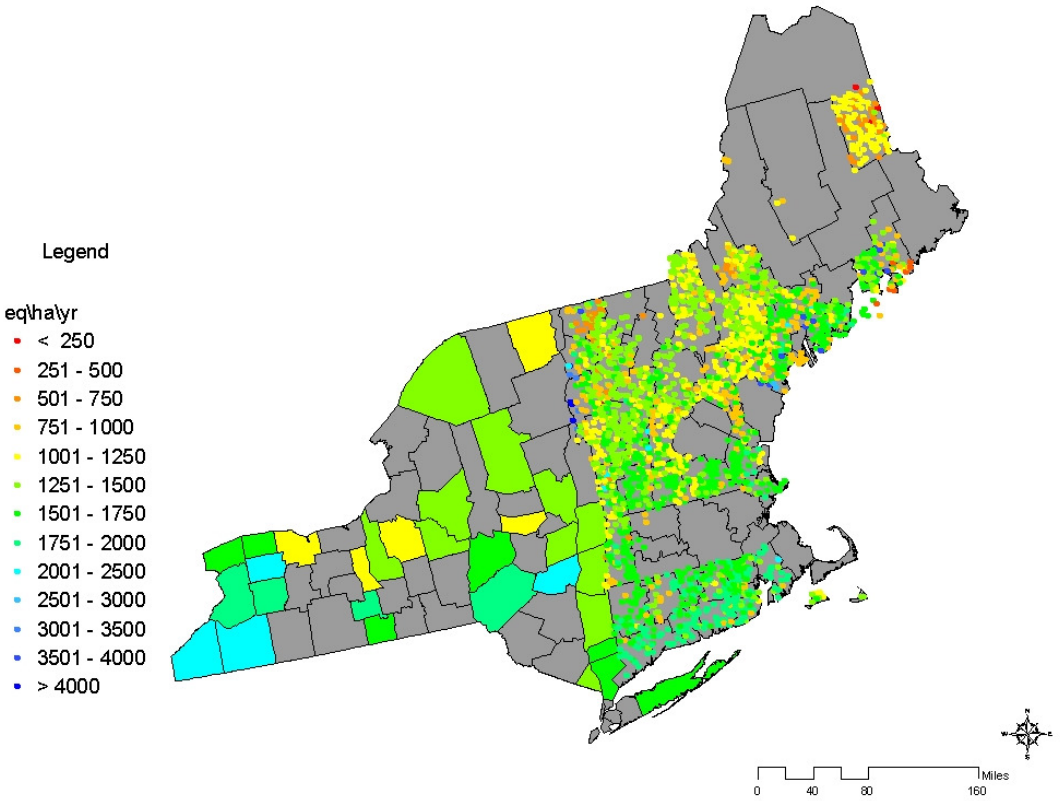


Map 9. Midpoint mineral weathering rates for sites in New England and New York
Midpoint of the range of minimum and maximum weathering rates (eq ha^{-1} yr^{-1}) calculated using the clay percent and substrate type method, with data from the Official Soils Series Descriptions and county soil surveys (described in Section 2.3.3).



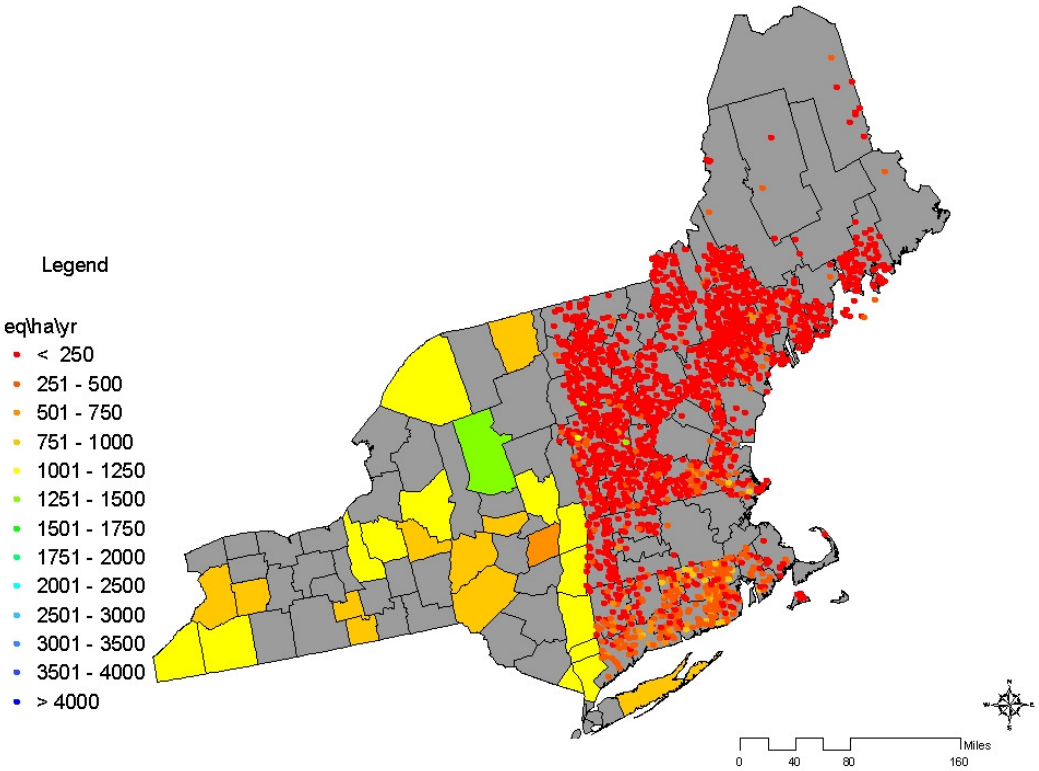
Map 10. Minimum mineral weathering rates for sites in New England and New York

Minimum weathering rates (eq ha^{-1} yr^{-1}) calculated using the clay percent and substrate type method, with data from the Official Soils Series Descriptions and county soil surveys (described in Section 2.3.3).



Map 11. Maximum mineral weathering rates for sites in New England and New York

Maximum weathering rates (eq ha^{-1} yr^{-1}) calculated using the clay percent and substrate type method, with data from the Official Soils Series Description and county soil surveys (described in Section 2.3.3).



Map 12. NSSC mean mineral weathering rates for sites in New England and New York

Mean weathering rates (eq ha^{-1} yr^{-1}) calculated using the clay percent and substrate type method, with data from National Soil Survey Characterization soil pits and county soil surveys (described in Section 2.3.3).

4. CRITICAL LOADS RESULTS AND DISCUSSION

The susceptibility of forest ecosystems to negative impacts from acidic deposition was assessed by making calculations of critical load for acidity (S+N) and for nutrient N (N_{nut}). Sites where the deposition rate exceeds the critical load are considered susceptible to negative impacts from N and S deposition.

We calculated the critical load for acidity (S+N) using the minimum, mid−point and maximum weathering rates, as well as a regional mean by soil type (NSSC mean; as described in Section 3.3). The critical load, and therefore the exceedance, varied depending on the weathering rate scenario used, resulting in worst case (using minimum weathering rates), mid, best case (using maximum weathering rates) and NSSC mean scenarios for each site. It is important to note that the critical load and exceedance were calculated only for effects of S and N deposition. The critical load for acidity does not address impacts of deposition of other pollutants (such as ozone), climate change, or the effects of other factors detrimental to forest health, such as pests. Therefore the critical load reflects the level of S and N deposition that an upland forest can tolerate in the absence of other impacts. In order to address the complex interaction of multiple stressors, the critical load would need to be adjusted, likely with the aid of dynamic modeling.

4.1 CL(S+N)

The critical load tended to be lowest in northern New England, with higher values reported in southern New England, coastal areas, and parts of New York (Map 13). For example, in Connecticut and Rhode Island, most critical loads using the mid−point weathering rates (~80%) fell in the range of 1500−2000 eq ha^{-1} yr^{-1}; while in Maine, New Hampshire, and Vermont, approximately 65% of critical loads were less than 1500 eq ha^{-1} yr^{-1}. In order to evaluate patterns in the critical loads, we determined the percentage of plots that fell between the lower and upper inflection points on the cumulative frequency plots (Figures 1−8). This represents the majority of the sites in each state and eliminates the tails of the distribution, which can be quite broad. Critical loads calculated using the mid−point weathering rates mostly (>80%) fell between 850 and

2050 eq ha^{-1} yr^{-1}, the total range was 11 to 6,540 eq ha^{-1} yr^{-1} (Map 13 and Figure 1.a). Critical loads in the worst case scenario, calculated using the minimum weathering rates, were considerably lower, with 90% falling below 1085 eq ha^{-1} yr^{-1}; they ranged from 9 to 2,386 eq ha^{-1} yr^{-1} (Map 14 and Figure 1.a). Critical loads for the best case scenario, calculated using the maximum weathering rates, were highest; 90% were greater than 1050 eq ha^{-1} yr^{-1}. Critical loads in the best case scenario ranged from 0 to 10,544 eq ha^{-1} yr^{-1} (Map 15 and Figure 1.a). The critical loads calculated using the mean weathering rates based on data from NSSC soil pits were consistently lower than for the other scenarios. For all states except New York, more than 80% of plots fell into the range 200–780 eq ha^{-1} yr^{-1}; when New York was included, the upper end of the range increased to 1150 eq ha^{-1} yr^{-1}. The mean critical loads ranged from 0 to 2,202 eq ha^{-1} yr^{-1} (Map 16 and Figure 1.a). Data from FHM plots are not mapped for any of the input parameters or calculated values, as there are no publicly available coordinates for these plots. According to FIA protocol, the publicly available coordinates for all New York FIA plots are the geographic center of the county within which the plot is located (county centroid). Therefore it was not possible to show spatial patterns within the county. Instead, we plotted the mean of the county for the entire county, in order to give a general idea of the larger–scale, regional spatial patterns. Thus, it is difficult to compare the spatial patterns in New York to the rest of the region.

Connecticut: When critical loads were summarized by state (Table 8), the largest range for the mean critical load calculated was for Connecticut, suggesting that these soil pits represented a greater portion of the variability in that state than the NSSC soil pits did in other states. Critical loads calculated using the mid–point weathering rates range from 375 to 1,963 eq ha^{-1} yr^{-1} (Figure 2.a, Map 13). Critical loads in the worst case scenario, calculated using the minimum weathering rates, range from 50 to 1,364 eq ha^{-1} yr^{-1} (Figure 2.a, Map 14). Critical loads in the best case scenario, calculated using the maximum weathering rates, range from 0 to 2,806 eq ha^{-1} yr^{-1} (Figure 2.a, Map 15). Critical loads calculated using the mean weathering rates range from 0 to 1,568 eq ha^{-1} yr^{-1} (Figure 2.a, Map 16).

Massachusetts: Critical loads calculated using the mid−point weathering rates range from 305 to 2347 eq ha^{-1} yr^{-1} (Figure 3.a, Map 13). Critical loads in the worst case scenario, calculated using the minimum weathering rates, range from 85 to 1,176 eq ha^{-1} yr^{-1} (Figure 3.a, Map 14). Critical loads in the best case scenario, calculated using the maximum weathering rates, range from 66 to 3,428 eq ha^{-1} yr^{-1} (Figure 3.a, Map 15). Critical loads calculated using the mean weathering rates range from 0 to 1,309 eq ha^{-1} yr^{-1} (Figure 3.a, Map 16).

Maine: Critical loads calculated using the mid−point weathering rates range from 238 to 3,644 eq ha^{-1} yr^{-1} (Figure 4.a, Map 13). Critical loads in the worst case scenario, calculated using the minimum weathering rates, range from 30 to 1,481 eq ha^{-1} yr^{-1} (Figure 4.a, Map 14). Critical loads in the best case scenario, calculated using the maximum weathering rates, range from 307 to 5,657 eq ha^{-1} yr^{-1} (Figure 4.a, Map 15). Critical loads calculated using the mean weathering rates range from 0 to 1,141 eq ha^{-1} yr^{-1} (Figure 4.a, Map 16).

New Hampshire: Critical loads calculated using the mid−point weathering rates range from 64 to 2,011 eq ha^{-1} yr^{-1} (Figure 5.a, Map 13). Critical loads in the worst case scenario, calculated using the minimum weathering rates, range from 91 to 1,336 eq ha^{-1} yr^{-1} (Figure 5.a, Map 14). Critical loads in the best case scenario, calculated using the maximum weathering rates, range from 0 to 2,942 eq ha^{-1} yr^{-1} (Figure 5.a, Map 15). Critical loads calculated using the mean weathering rates range from 0 to 1,255 eq ha^{-1} yr^{-1} (Figure 5.a, Map 16).

New York: Critical loads calculated using the mid−point weathering rates range from 98 to 4,064 eq ha^{-1} yr^{-1} (Figure 6.a, Map 13). Critical loads in the worst case scenario, calculated using the minimum weathering rates, range from 21 to 1,665 eq ha^{-1} yr^{-1} (Figure 6.a, Map 14). Critical loads in the best case scenario, calculated using the maximum weathering rates, range from 0 to 6,318 eq ha^{-1} yr^{-1} (Figure 6.a, Map 15). Critical loads calculated using the mean weathering rates range from 0 to 1,720 eq ha^{-1} yr^{-1} (Figure 6.a, Map 16).

Rhode Island: Critical loads calculated using the mid−point weathering rates range from 580 to 2,360 eq ha^{-1} yr^{-1} (Figure 7.a, Map 13). Critical loads in the worst case scenario, calculated using the minimum weathering rates, range from 286 to 1,328 eq ha^{-1} yr^{-1} (Figure 7.a, Map 14). Critical loads in the best case scenario, calculated using the maximum weathering rates, range from 1,241 to 3,561 eq ha^{-1} yr^{-1} (Figure 7.a, Map 15). Critical loads calculated using the mean weathering rates range from 0 to 1,451 eq ha^{-1} yr^{-1} (Figure 7.a, Map 16).

Vermont: Critical loads calculated using the mid−point weathering rates range from 11 to 6,540 (Figure 8.a, Map 13). Critical loads in the worst case scenario, calculated using the minimum weathering rates, range from 9 to 2,386 eq ha^{-1} yr^{-1} (Figure 8.a, Map 14). Critical loads in the best case scenario, calculated using the maximum weathering rates, range from 0 to 10,544 eq ha^{-1} yr^{-1} (Figure 8.a, Map 15). Critical loads calculated using the mean weathering rates range from 0 to 2,202 eq ha^{-1} yr^{-1} (Figure 8.a, Map 16).

Table 8. Summary of mean critical loads calculated using minimum, mid, maximum, and mean soil mineral weathering rates (eq ha^{-1} yr^{-1}) for plots in New England and New York

		CT	MA	ME	NH	NY	RI	VT
All sites except FHM	***Min***	893	858	726	756	780	910	734
	Mid	1618	1279	1375	1350	1538	1732	1267
	Max	2415	2259	1967	1931	2143	2462	1840
	Mean	691	530	386	425	575	685	374
FHM	***Min***	902	810	520	679	865	902	722
	Mid	1747	1226	1203	1407	1379	1926	1443
	Max	2442	1012	1794	1984	1955	2799	2014
	Mean	617	44	121	369	394	873	412

4.2 Exceedance (S+N)

For the mid−point weathering scenario, deposition exceeded the critical load in 45% of plots (Table 9; Figure 1.b). For the worst case scenario, that value rose to 98%, while for the best case scenario, deposition exceeded the critical load only in 15% of plots. Exceedance of critical loads calculated using the mid−point weathering scenario mostly (>85%) fell between −500 and 1100 eq ha^{-1} yr^{-1}; the total range was −5,340 to 3840

eq ha^{-1} yr^{-1} (Map 17 and Figure 1.b). Exceedance in the worst case scenario ranged from −1,186 to 4,889 eq ha^{-1} yr^{-1} (Map 18 and Figure 1.b). Exceedance in the best case scenario ranged from −9,343 to 3,026 eq ha^{-1} yr^{-1} (Map 19 and Figure 1.b). Exceedance in the mean scenario ranged from −657 to 1,760 eq ha^{-1} yr^{-1} (Map 20 and Figure 1.b). A negative exceedance value means that the deposition is lower than the critical load.

The percentage of plots in each state where the critical load was exceeded for the mid−point weathering scenario ranged from 13−62%. For the worst case scenario, the percentage of plots by state where the critical load was exceeded ranged from 91−100% (Table 9). For the best case scenario, the percentage of plots by state where the critical load was exceeded ranged from 1−27% (Table 9). For the mean scenario, the percentage of plots by state where the critical load was exceeded ranged from 99−100% (Table 18). When exceedance was summarized by state (Table 10), the ranges of mean values were similar for all states.

Table 9. Percent of plots where the critical load (S+N) is exceeded, by minimum, mid−point, maximum, and mean weathering rate scenarios

	Min (Worst case)	Mid	Max (Best case)	Mean
Connecticut	100	24	6	99
Massachusetts	100	56	9	99
Maine	91	15	3	99
New Hampshire	100	35	3	100
New York	100	62	27	100
Rhode Island	100	13	1	100
Vermont	99	56	20	99
New England and New York	98	45	15	>99

Connecticut: Exceedance calculated using the mid−point weathering rates ranged from −488 to 1,732 eq ha^{-1} yr^{-1} (Figure 2.b, Map 17). Exceedance in the worst case scenario, calculated using the minimum weathering rates, ranged from 471 to 2,219 eq ha^{-1} yr^{-1} (Figure 2.b, Map 18). Exceedance in the best case scenario, calculated using the maximum weathering rates, ranged from −1,319 to 1,664 eq ha^{-1} yr^{-1} (Figure 2.b, Map

19). Exceedance calculated using the mean weathering rates ranged from −33 to 1,482 eq ha^{-1} yr^{-1} (Figure 2.b, Map 20).

Massachusetts: Exceedance calculated using the mid−point weathering rate ranged from −1,001 to 1,565 eq ha^{-1} yr^{-1} (Figure 3.b, Map 17). Exceedance in the worst case scenario, calculated using the minimum weathering rates, ranged from 230 to 2,071 eq ha^{-1} yr^{-1} (Figure 3.b, Map 18). Exceedance in the best case scenario, calculated using the maximum weathering rates, ranged from −2,083 to 1,209 eq ha^{-1} yr^{-1} (Figure 3.b, Map 19). Exceedance calculated using the mean weathering rates ranged from −64 to 1,700 eq ha^{-1} yr^{-1} (Figure 3.b, Map 20).

Maine: Exceedance calculated using the mid−point weathering rates ranged from −2,753 to 882 eq ha^{-1} yr^{-1} (Figure 4.b, Map 17). Exceedance in the worst case scenario, calculated using the minimum weathering rates, ranged from −622 to 1,033 eq ha^{-1} yr^{-1} (Figure 4.b, Map 18). Exceedance in the best case scenario, calculated using the maximum weathering rates, ranged from −4,734 to 381 eq ha^{-1} yr^{-1} (Figure 4.b, Map 19). Exceedance calculated using the mean weathering rates ranged from −305 to 1,247 eq ha^{-1} yr^{-1} (Figure 4.b, Map 20).

New Hampshire: Exceedance calculated using the mid−point weathering rates ranged from −759 to 2630 eq ha^{-1} yr^{-1} (Figure 5.b, Map 17). Exceedance in the worst case scenario, calculated using the minimum weathering rates, ranged from 272 to 2,939 eq ha^{-1} yr^{-1} (Figure 5.b, Map 18). Exceedance in the best case scenario, calculated using the maximum weathering rates, ranged from −1,690 to 2,472 eq ha^{-1} yr^{-1} (Figure 5.b, Map 19). Exceedance calculated using the mean weathering rates ranged from 11 to 1,346 eq ha^{-1} yr^{-1} (Figure 5.b, Map 20).

New York: Exceedance calculated using the mid−point weathering rates ranged from −2,042 to 1,936 eq ha^{-1} yr^{-1} (Figure 6.b, Map 17). Exceedance in the worst case scenario, calculated using the minimum weathering rates, ranged from 135 to 2,309 eq ha^{-1} yr^{-1} (Figure 6.b, Map 18). Exceedance in the best case scenario, calculated using the

maximum weathering rates, ranged from –4,296 to 1,916 eq ha^{-1} yr^{-1} (Figure 6.b, Map 19). Exceedance calculated using the mean weathering rates ranged from 141 to 1,665 eq ha^{-1} yr^{-1} (Figure 6.b, Map 20).

Rhode Island: Exceedance calculated using the mid–point weathering rates ranged from –929 to 769 eq ha^{-1} yr^{-1} (Figure 7.b, Map 17). Exceedance in the worst case scenario, calculated using the minimum weathering rates, ranged from 280 to 1,472 eq ha^{-1} yr^{-1} (Figure 7.b, Map 18). Exceedance in the best case scenario, calculated using the maximum weathering rates, ranged from –2,130 to 187 eq ha^{-1} yr^{-1} (Figure 7.b, Map 19). Exceedance calculated using the mean weathering rates ranged from 17 to 1,427 eq ha^{-1} yr^{-1} (Figure 7.b, Map 20).

Vermont: Exceedance calculated using the mid–point weathering rates ranged from –5,340 to 3,840 eq ha^{-1} yr^{-1} (Figure 8.b, Map 17). Exceedance in the worst case scenario, calculated using the minimum weathering rates, ranged from –1,186 to 4,889 eq ha^{-1} yr^{-1} (Figure 8.b, Map 18). Exceedance in the best case scenario, calculated using the maximum weathering rates, ranged from –9,343 to 3,026 eq ha^{-1} yr^{-1} (Figure 8.b, Map 19). Exceedance calculated using the mean weathering rates ranged from –657 to 1,760 eq ha^{-1} yr^{-1} (Figure 8.b, Map 20).

Table 10. Summary of mean exceedance (eq ha^{-1} yr^{-1}) calculated using minimum, mid, maximum, and mean critical loads for plots in New England and New York

		CT	MA	ME	NH	NY	RI	VT
All sites except FHM	***Worst case***	674	669	250	582	818	548	821
	Mid	–68	187	–399	–46	61	–289	189
	Best case	–863	–741	–990	–639	–544	–1017	–431
	NSSC Mean	856	930	640	862	1013	766	1018
FHM	***Worst case***	674	1634	512	632	961	540	660
	Mid	–171	965	–229	–96	226	–483	–60
	Best case	–865	447	–820	–673	–358	–1357	–631
	NSSC Mean	959	1365	848	938	1164	582	971

4.3 Critical Load for nutrient N

Across the region, critical loads for nutrient N were low; over 90% ranged from 200 to 300 eq ha^{-1} yr^{-1}. Critical loads for nutrient N ranged from 163 to 1,121 eq ha^{-1} yr^{-1} (Map 21 and Figure 9.a). When critical loads were summarized by state (Table 11), the lowest values were calculated for New York and the highest values were calculated for Vermont. For Connecticut, critical loads range from 209 to 624 eq ha^{-1} yr^{-1} (Figure 10.a, Map 21). For Massachusetts, critical loads range from 210 to 597 eq ha^{-1} yr^{-1} (Figure 10.b, Map 21). For Maine, critical loads range from 201 to 448 eq ha^{-1} yr^{-1} (Figure 10.c, Map 21). For New Hampshire, critical loads range from 197 to 878 eq ha^{-1} yr^{-1} (Figure 10.d, Map 21). For New York, critical loads range from 163 to 535 eq ha^{-1} yr^{-1} (Figure 10.e, Map 21). For Rhode Island, critical loads range from 242 to 461 eq ha^{-1} yr^{-1} (Figure 10.f, Map 21). For Vermont, critical loads range from 175 to 1121 eq ha^{-1} yr^{-1} (Figure 10.g, Map 21).

Table 11. Summary of mean critical load for nutrient N (eq ha^{-1} yr^{-1}) calculated for plots in New England and New York

	CT	MA	ME	NH	NY	RI	VT
All sites except FHM	226	275	280	292	237	274	315
FHM	226	518	329	299	288	302	261

4.4 Exceedance $(N)_{nutrient}$

Deposition exceeded critical loads for nutrient N for 98.5% of the plots across the region; the percentage of plots by state where the critical load was exceeded ranged from 94–100% (Table 12). Exceedance of critical loads for nutrient N range from –649 to 668 eq ha^{-1} yr^{-1} (Map 22 and Figure 9.b).

Table 12. Percent of plots where the critical load for nutrient N is exceeded

CT	MA	ME	NH	NY	RI	VT	New England and New York
100	99	99	98	100	98	94	98

The lowest mean values of exceedance for nutrient N were calculated for Maine where deposition is lowest; the highest values were calculated for New York (Table 13).

For Connecticut, exceedance ranged from −1 to 620 eq ha^{-1} yr^{-1} (Figure 11.a, Map 22). For Massachusetts, exceedance ranged from −46 to 493 eq ha^{-1} yr^{-1} (Figure 11.b, Map 22). For Maine, exceedance ranged from −42 to 295 eq ha^{-1} yr^{-1} (Figure 11.c, Map 22). For New Hampshire, exceedance ranged from −333 to 411 eq ha^{-1} yr^{-1} (Figure 11.d, Map 22). For New York, exceedance ranged from 145 to 668 eq ha^{-1} yr^{-1} (Figure 11.e, Map 22). For Rhode Island, exceedance ranged from −90 to 392 eq ha^{-1} yr^{-1} (Figure 11.f, Map 22). For Vermont, exceedance ranged from −649 to 467 eq ha^{-1} yr^{-1} (Figure 11.g, Map 22).

Table 13. Summary of mean exceedance of critical load of nutrient N (eq ha^{-1} yr^{-1}) calculated for plots in New England and New York

	CT	MA	ME	NH	NY	RI	VT
All sites except FHM	402	368	142	260	440	344	277
FHM	411	108	92	262	387	321	328

4.5 Deposition Reduction

We considered three different deposition reduction scenarios: (1) 20% reduction of both S and N deposition, (2) 50% reduction in S and 26% reduction in N, (3) 48% reduction in S and 32% reduction in N. The number of sites in exceedance of the critical load for acidity (S+N) in the mid scenario decreased from 45% based on ClimCalc modeled deposition to 23% under the first scenario and to 13% under the second and third scenario. Exceedance of the critical load for acidity (S+N) for the NSSC mean weathering rate was not decreased substantially when deposition was reduced overall. In the worst case weathering rate scenario, the more stringent reduction scenarios (2 and 3) reduced exceedance from over 90% to about 30% in Maine and Rhode Island; regionally, the exceedance was reduced to 74−77%.

For nutrient N, deposition reductions did not significantly alter the proportion of sites where the critical load was exceeded, which included nearly all sites in the region.

Table 14. Percent of plots where the critical load (S+N) is exceeded, by worst, mean, mid, and best case scenarios, under ClimCalc deposition and three deposition reduction scenarios

No Deposition Reduction				
	Worst Case	**Mean**	**Mid Case**	**Best Case**
Connecticut	100	>99	24	6
Massachusetts	100	99	56	9
Maine	91	99	15	3
New Hampshire	100	100	35	3
New York	100	100	62	27
Rhode Island	100	100	13	1
Vermont	99	99	56	20
New England and New York	98	>99	45	15
Reduction Scenario 1: 20% reduction of both S and N deposition				
	Worst Case	**Mean**	**Mid Case**	**Best Case**
Connecticut	100	96	16	2
Massachusetts	99	99	40	3
Maine	71	99	8	2
New Hampshire	100	99	11	2
New York	99	99	33	13
Rhode Island	100	87	3	0
Vermont	99	99	32	12
New England and New York	94	98	23	8
Reduction Scenario 2 (2015): 50% S reduction and 26% N deposition				
	Worst Case	**Mean**	**Mid Case**	**Best Case**
Connecticut	80	88	11	<1
Massachusetts	67	98	33	1
Maine	36	98	5	1
New Hampshire	76	99	9	1
New York	93	98	14	5
Rhode Island	32	87	3	0
Vermont	96	98	22	7
New England and New York	77	97	13	4
Reduction Scenario 3 (2018): 48% S reduction and 32% N deposition				
	Worst Case	**Mean Scenario**	**Mid Case**	**Best Case**
Connecticut	69	86	10	<1
Massachusetts	66	98	33	1
Maine	32	98	5	1
New Hampshire	69	99	8	1
New York	92	97	13	5
Rhode Island	28	87	3	0
Vermont	93	98	21	7
New England and New York	74	97	13	3

Table 15. Percent of plots where the critical load for nutrient N is exceeded, under ClimCalc deposition and three deposition reduction scenarios

	ClimCalc Deposition	Reduction Scenario 1: 20% reduction N	Reduction Scenario 2: 2015: 32% N reduction	Reduction Scenario 3: 2018: 26% N reduction
Connecticut	>99	99	99	99
Massachusetts	99	98	97	98
Maine	99	84	59	80
New Hampshire	98	95	93	95
New York	100	100	96	99
Rhode Island	98	97	93	96
Vermont	94	90	87	89
New England and New York	98	94	87	93

4.6 Discussion

Using different mineral weathering rate scenarios to calculate critical loads led to a very broad range of critical loads. Similarly, for exceedance, there was little overlap between the extreme scenarios: in the worst case scenario, nearly all sites were exceeded (98%), while for the best case scenario, only a relatively low proportion (15%) of the sites were exceeded. The broad range spanned by the best case and worst case scenarios is not especially useful in a management or policy context. For assessing potential effects of atmospheric deposition, the mid scenario is the most valid, because it is most likely to represent the typical condition of the region. However, the mean scenario, which is based on actual soil samples collected in the region, may be informative as well. In this section, we compare these critical loads estimates with other published values, explore the causes for the patterns observed in critical load and exceedance and factors that confound the patterns, and discuss ways in which critical load and exceedance estimates could be improved.

<u>Comparisons to other critical loads estimates</u>

The critical loads for acidity (S+N) that we report for the mid scenario fell into similar ranges with other assessments. Critical loads for New England based on a detailed spatial analysis and modeling were reported in a similar range as this assessment, with the bulk of those values <3000 eq ha^{-1} yr^{-1} (NEG/ECP 2003, Miller 2005, Miller 2006a, b). Critical loads were lower in southern New England and coastal areas (Miller 2005, Miller 2006a, b). In a national assessment, the majority of the area in the Northeast had critical loads between 149 and 2000 eq ha^{-1} yr^{-1} (McNulty et al. 2007), although there were many more values in the 2000–4000 eq ha^{-1} yr^{-1} range in their assessment. Ouimet et al. (2006) report a median critical load for Eastern Canada of 599 eq ha^{-1} yr^{-1}, with a reported range of 200 to >2000 eq ha^{-1} yr^{-1}.

Our estimated critical load for nutrient N spanned a much narrower range of values and was much lower than the critical load for acidity, as has been reported in other assessments (Reinds et al. 2008). The critical loads for nutrient N tend to be extremely low compared, for example, to the empirical critical load based on a response of nitrate

leaching for the region (Pardo et al. 2011b). Empirical critical loads for N in the Northeast were from >215 to ~800 eq ha^{-1} yr^{-1} for declines in growth and survivorship for some species, 570 eq ha^{-1} yr^{-1} for increased nitrate leaching and < 1850 eq ha^{-1} yr^{-1} for increased mortality and changes in species composition (Gilliam et al. 2011, Pardo et al. 2011a, b).

Causes for patterns observed in critical loads

The most important parameter in determining the critical load for N+S is the mineral soil weathering rate (Whitfield et al. 2006, Slootweg et al. 2007), which essentially is a measure of how much a soil can buffer/neutralize acid input each year. If the mineral weathering rate is high, the critical load will tend to be high. Weathering, in this analysis, typically represents about 80% of the critical load for acid inputs independent of N, called $CL(S)_{max}$. One significant factor that affects mineral weathering rate is soil depth, as the weathering rate per unit area is multiplied by soil depth. If the soil at a given site is deeper than was assumed, the actual weathering rate will be higher than that calculated. Soil depth, like other soil characteristics is very spatially heterogeneous. Finally, the removal of base cations via harvesting will lower the critical load. At sites where harvesting is limited (above a certain elevation or on protected lands), the critical load will be slightly higher than it would if there were harvesting. For over 2400 sites, the nutrient removal of base cation and N was assumed to be zero. The base cation nutrient removal term, when it was not zero, tended to represent a fairly small fraction of the critical load; the average of the non−zero values was 132 eq ha^{-1} yr^{-1}. The N nutrient removal term would increase the critical load for S+N; the average of the non−zero values, 61 eq ha^{-1} yr^{-1}, was lower than that for base cation removal.

The main drivers in the equation used to calculate the critical load for nutrient N are differences in acceptable N leaching rate and N removal rates. Because denitrification was assumed to be negligible and the acceptable rate of soil N accumulation is fixed (2 kg N ha^{-1} yr^{-1} or 143 eq ha^{-1} yr^{-1}), these parameters do not vary by site. The acceptable N leaching rate is a product of streamflow or precipitation surplus (Q) and the acceptable nitrate leaching concentration. As the acceptable nitrate leaching concentration is fixed,

as Q increases, the critical load will increase. Thus a drier site would be expected to have a lower critical load than a wetter site.

Regional factors affecting the critical load and exceedance

In addition to the site characteristics discussed above, certain regional factors would be expected to drive critical load values, because certain soil and ecosystem characteristics vary systematically across the region. For example, at higher elevations, soils are often shallower, which would lead to lower weathering rates and therefore lower critical loads. Similarly, as forest type shifts moving north across the region from central hardwood to northern hardwood to spruce fir, the critical load tends to decrease due to changes in multiple parameters, including decreases in soil depth, nutrient uptake (which would decrease the N removal term), and differences in soil type. Soil type can influence the weathering rate. For example, in Connecticut, high clay percent coupled with deeper soils led to high weathering rates, which resulted in some of the highest critical loads. Similarly, in Vermont, sites with clay soil had high weathering rates and extremely high critical loads.

The exceedance is expected to be higher at higher elevations both because deposition tends to increase with elevation and because the critical loads often decrease with elevation. Exceedance would be expected to be lower on certain soil types, such as calcareous soils or soils with high clay percent. In this analysis, because cloud and fog inputs were not included, the reported exceedances at sites where cloud and fog inputs are significant will underestimate the actual exceedance. Note that the S deposition used for this analysis is higher than current values. There has been no significant change in N deposition over time. In general, deposition decreases along a gradient to the northeast (Ollinger et al. 1993; Map 5).

Certain species may be more susceptible to effects of S and N deposition. This assessment does not have a mechanism for directly addressing differences in species that are not expressed via soil type. Thus, the only way to make sure that the critical load

would be protective of more sensitive species is by making sure that the critical thresholds are selected to protect the most sensitive species.

Sources of variability in critical loads estimates

One challenge in estimating critical loads at the regional scale is that detailed data are not available on that scale, thus it is necessary to estimate or model many of the key input parameters. We used the official soil series descriptions based on SSURGO maps, because these were the most comprehensive data available to us at the time of the analysis. Because there is a large range between maximum and minimum values reported for each soil series, the resulting critical loads had an extremely large range.

The most significant example of this is for the mineral weathering rate. Accurate determination of the mineral weathering rate is difficult, because it requires specific information about the types and quantities of different minerals present (Hodson and Langan 1999). Given the spatial heterogeneity of soils in the northeastern U.S. (Lathrop et al. 1995), the weathering rate is highly variable and difficult to predict or model. There was considerably more variability in this parameter within each county than in other parameters. The range of weathering rates between the minimum and maximum scenarios can be quite large (in some cases more than 2000 eq ha^{-1} yr^{-1}). The differences in the minimum and maximum potential clay percent can range from 5% for a loamy sand textured soil up to 40% for a clay textured soil. If a soil texture ranges from silty clay to clay, the difference in minimum and maximum clay percents can be as much as 60%. Similarly, the differences in the minimum and maximum range for soil depth across the 326 soil types used in this analysis ranged from 15 cm to 152 cm with a mean difference of 50 cm. Because of these large ranges, we consider the mid scenario, based on the mid−point of the weathering rate range, to be most representative of the general patterns in the region.

We initially planned to use the NSSC soil pit mean as the main scenario, since we assumed that using actual soil samples would constrain the ranges of the parameters so that the range observed would be considerably narrower than that between the best case and worst case scenarios. Instead, we found instead that all the NSSC soil pits clustered

on the low end of the range for critical load or weathering based on soil series, often lower than the worst case scenario. This could be because the official soil series description is not representative of the soils that occur in New England and New York—i.e., that the soils in the Northeast are more sensitive than the soils series description indicates. Or, it may simply mean that the soil pit locations used by the NSSC are skewed towards sensitive sites and are not representative of the region. It is not possible to assess which explanation is correct based on the information that we have. However, given that the NSSC soil pits were randomly located and not sited to select for sensitive sites, one cannot ignore the possibility that the soils in the region may be considerably more sensitive to atmospheric deposition than the official soil series suggests. Note that only FIA plots in areas with digitized soil maps were included (Map 1), which also makes the plots less representative than if all FIA plots had been included.

Other methodological issues may have affected the accuracy of the results. The most significant of these is the method used to estimate weathering. The clay percent–substrate method allows for separation of sites into weathering classes based on soil texture and mineral substrate (Ouimet et al. 2006, Sverdrup et al. 1990). In general, the clay percent method has been found to track weathering rates calculated using the PROFILE model (Hodson and Langan 1999, Whitfield et al. 2006). The clay percent method was also used by Ouimet et al. (2006) in their analysis of critical loads for Eastern Canada as part of the NEG/ECP forest mapping group. Because our application of the clay percent method was based on soil series data rather than site specific data, this represents a general approach; it cannot capture the spatial heterogeneity that exists across the landscape.

In order to determine the nutrient removal via harvesting, we assumed saw timber harvest. If, in fact, a whole tree harvest were used, significantly more biomass would be removed, lowering the critical load for S+N and increasing critical load for nutrient N. In addition, when mean or median scenarios are used, the most sensitive sites are overlooked. Thus, this type of analysis is best used to evaluate where the most sensitive sites are likely to lie so that further more intensive studies can be conducted in those areas. It is also useful for identifying which sites are very unlikely, either by virtue of soil

type or deposition input, to be susceptible to acidic deposition.

Finally, certain sites may deviate from expectations. For example, a high elevation site on Mt Mansfield, Vermont, for which we had field measurements, had deeper soils than would be expected, resulting in a higher critical load and lower exceedance. In contrast, poor soils at low elevation would lead to a lower critical load than expected.

Improving critical loads and exceedance estimates

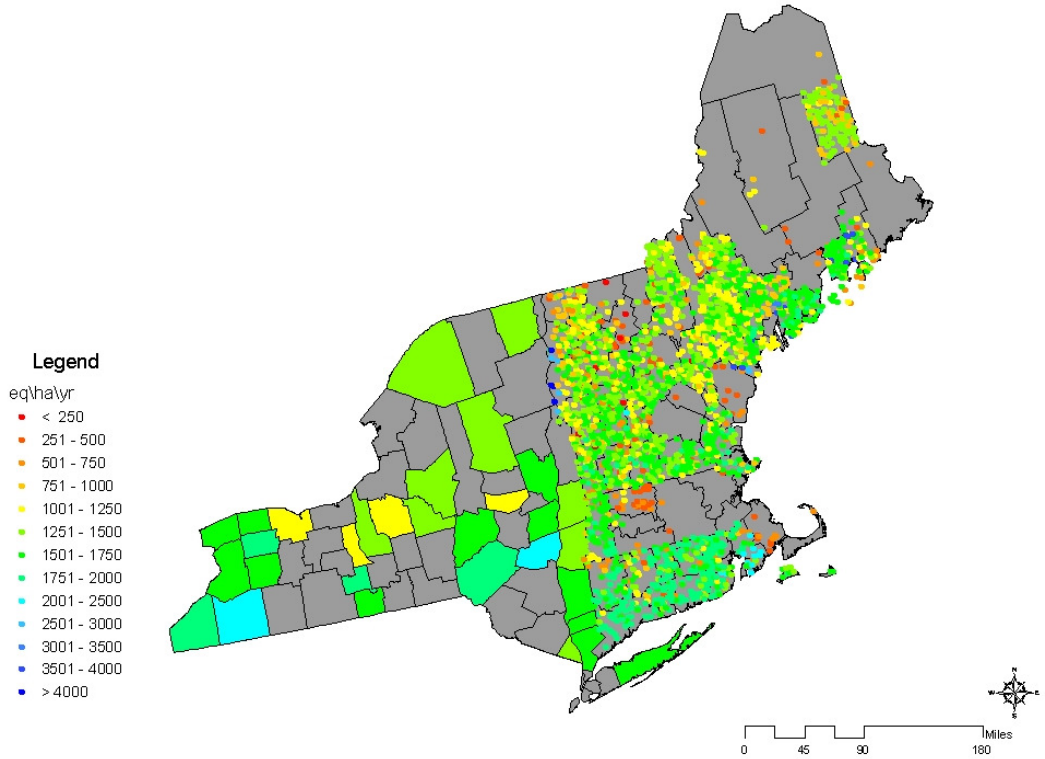
The main limitations to the accuracy of the critical loads estimates are due to shortcomings in soil weathering rate data, thus the biggest gains could be made by increasing the accuracy of these data. Several steps would facilitate this. Integrating detailed soil sampling and soil chemical/mineralogical analysis into a national assessment program such as FIA would significantly increase available soil data paired with other site parameters. Soil samples would need to be collected by horizon and to bedrock (or at least rooting depth). In Sweden, where there is an extensive network of soil pits with mineralogy information (>60,000 sites), estimates of mineral weathering rates can be made with certainty (Akselssen et al. 2004). Changing the scale at which soil maps are made, to account for smaller landscape units, would constrain the ranges of parameters which would in turn contribute greatly to increasing the resolution at which critical loads calculations could be applied. Increasing the accuracy of soil depth alone could increase the accuracy of the modeled soil weathering rates tremendously. Using these suggested improved datasets in a dynamic model such as PROFILE (Warfvinge and Sverdrup 1992) would result in improved estimates of soil mineral weathering rates.

For estimating exceedance, the main limitation (beyond the accuracy of the critical load estimates), is the accuracy of deposition measurements. The deposition model that we used in this analysis, ClimCalc (Ollinger et al. 1993), will not capture the highest deposition values because cloud and fog deposition are not included and the impact of elevation and tree species on deposition are not modeled. For example, the High Resolution Deposition Model (HRDM; Miller 1993), which includes these factors, predicts hotspots in N deposition in southern Vermont of > 30 kg ha^{-1} yr^{-1}, while

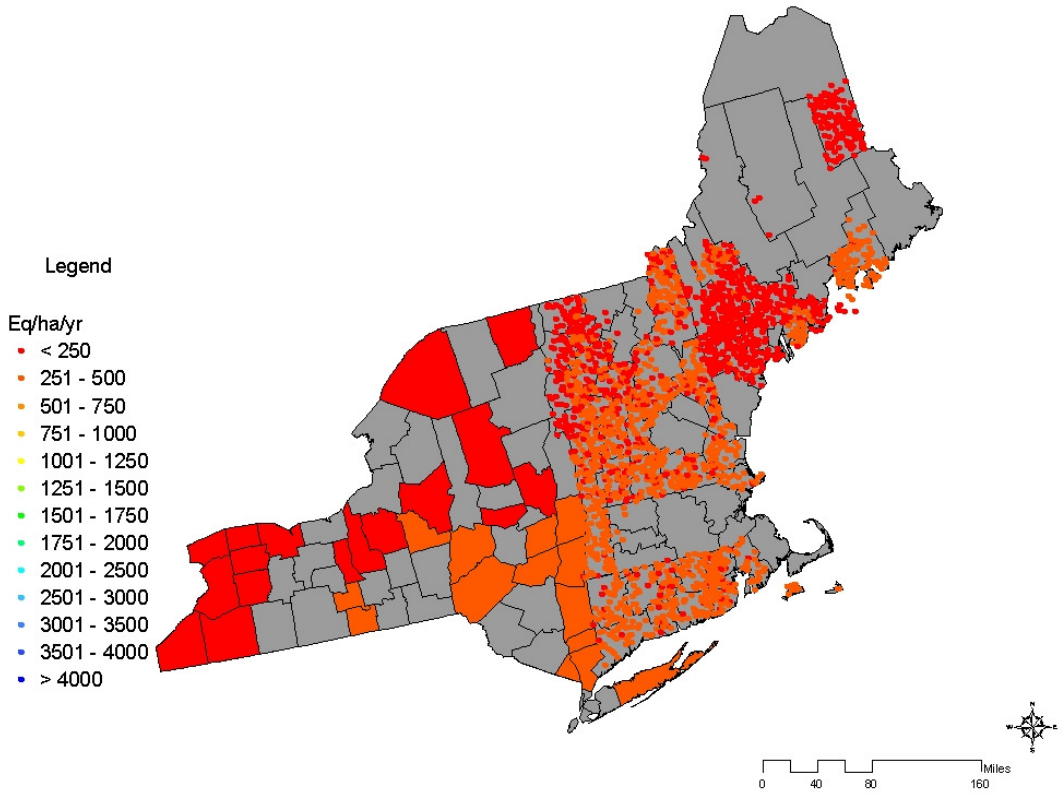
ClimCalc predicts <12 kg ha^{-1} yr^{-1} (Ollinger et al. 1993), and NADP maps wet−only deposition in the region as 4−6 kg ha^{-1} yr^{-1} (NADP, 2003). Clearly this range of deposition values would have a dramatic effect on the level of exceedance reported.

Another way that this process could be improved would be to refine the critical thresholds used in calculating the critical load, especially those used for the acceptable ANC leaching term (Aherne et al. 2001, Hall et al. 2001, Reinds et al. 2008, UBA 2004). Refining the values used for the BC:Al threshold for different forest types based on observed physiological responses would strengthen the link between critical load and ecosystem response. Similarly, as has been done in the Netherlands (de Vries et al. 2007), evaluating the relationship between soil solution nitrate [NO_3^-] and detrimental physiological responses in different ecosystem types would improve estimates of the nutrient N critical load.

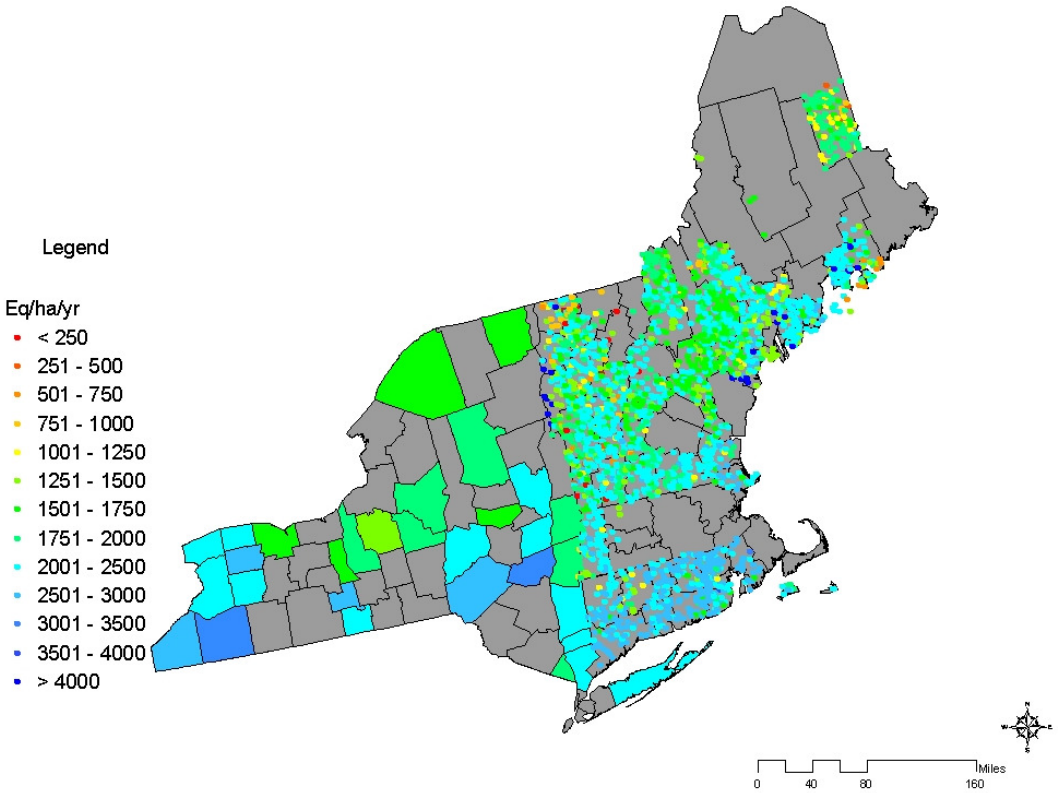
If there were better information about the distribution of values within the soil series (i.e., an approach to narrow the range of possible values of soil characteristics), it might be useful to do probabilistic modeling to assess the likely distribution of combinations of characteristics. Although this would still not allow direct calculation of the critical load of a specific location, it might give a better indication of the area likely to be most sensitive and would increase the accuracy of estimates made in the absence of extensive site−specific data.



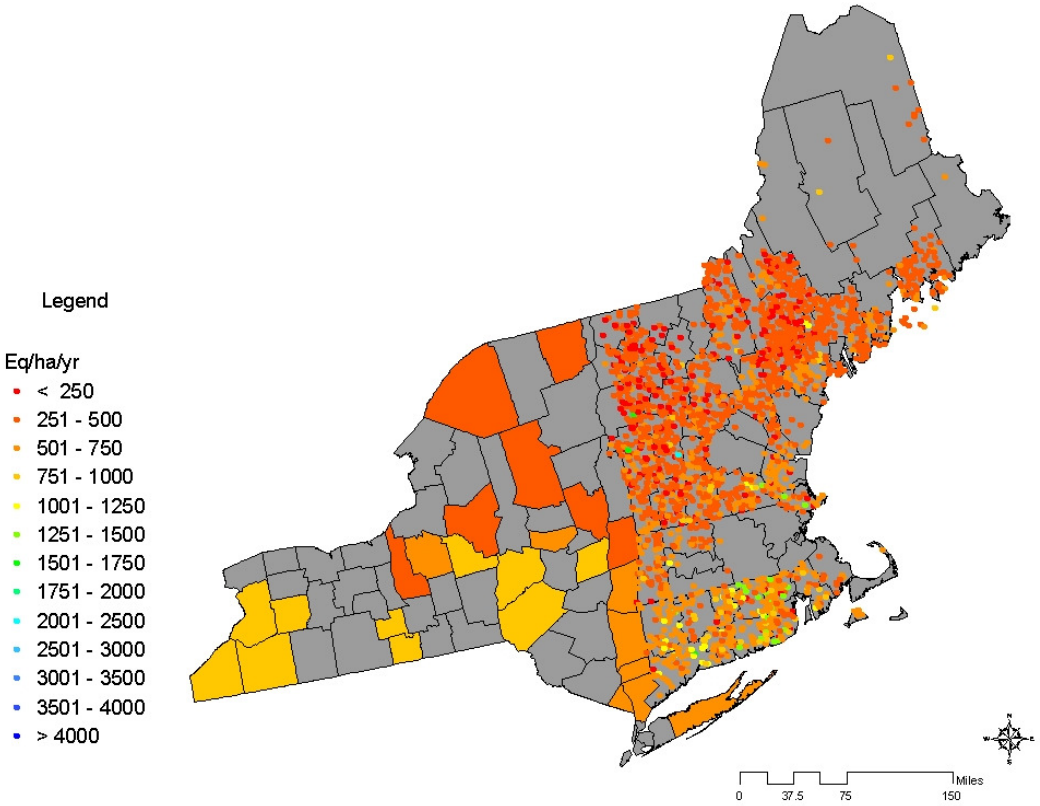
Map 13. Mid critical loads for acidity (S+N) for sites in New England and New York FIA



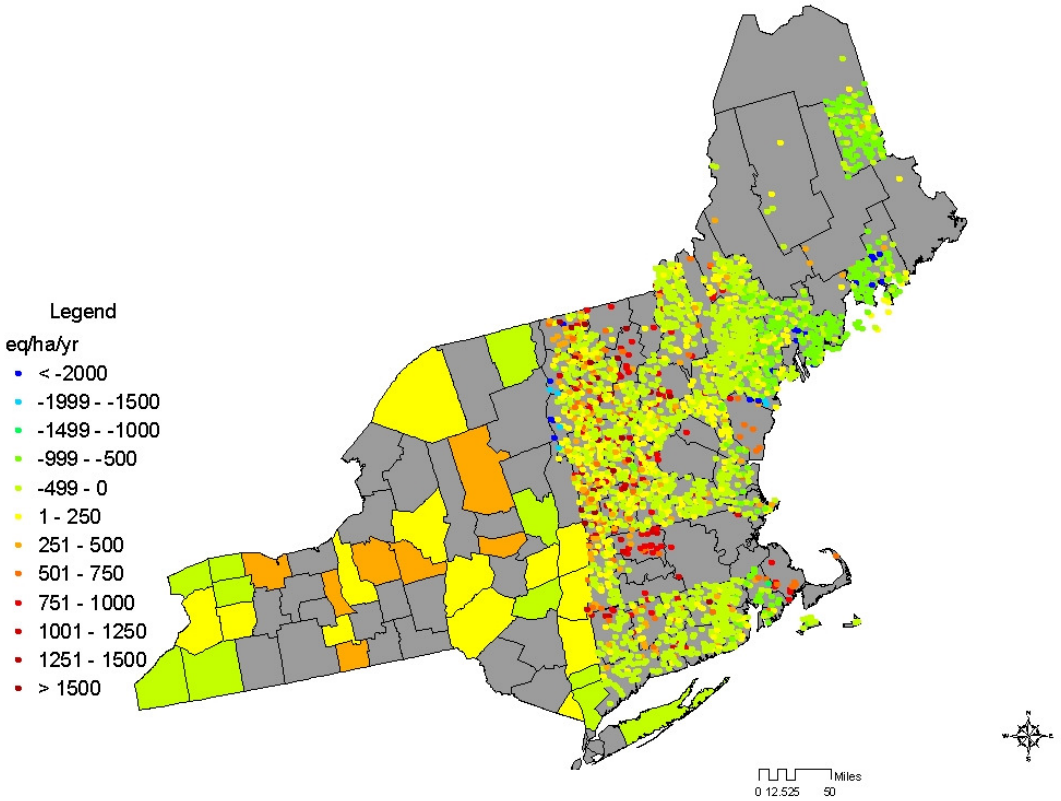
Map 14. Worst case scenario critical loads for acidity (S+N) for sites in New England and New York FIA



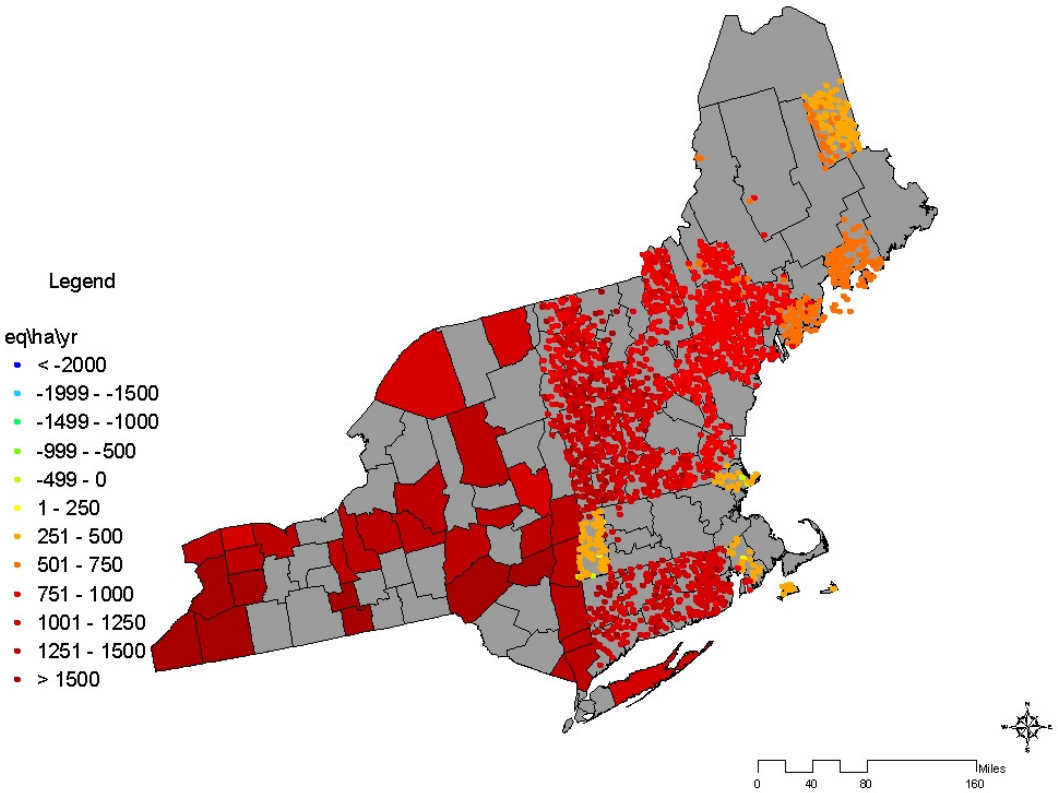
Map 15. Best case scenario critical loads for acidity (S+N) for sites in New England and New York FIA



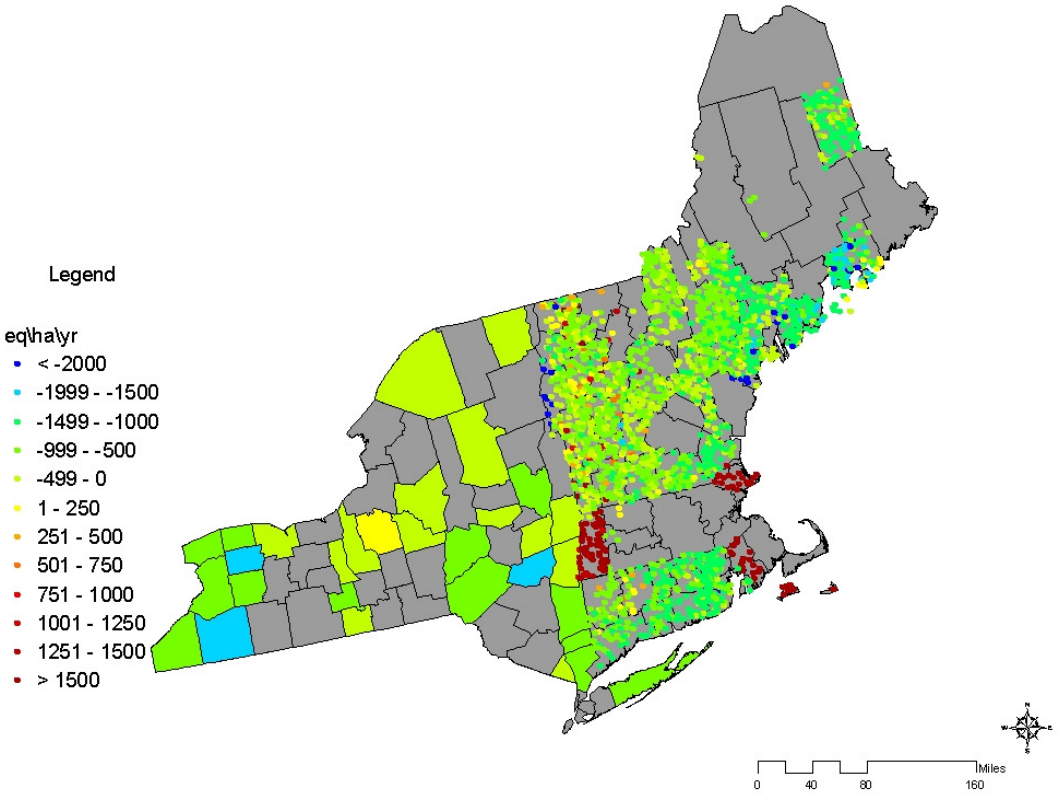
Map 16. Mean critical loads for acidity (S+N) for sites in New England and New York FIA



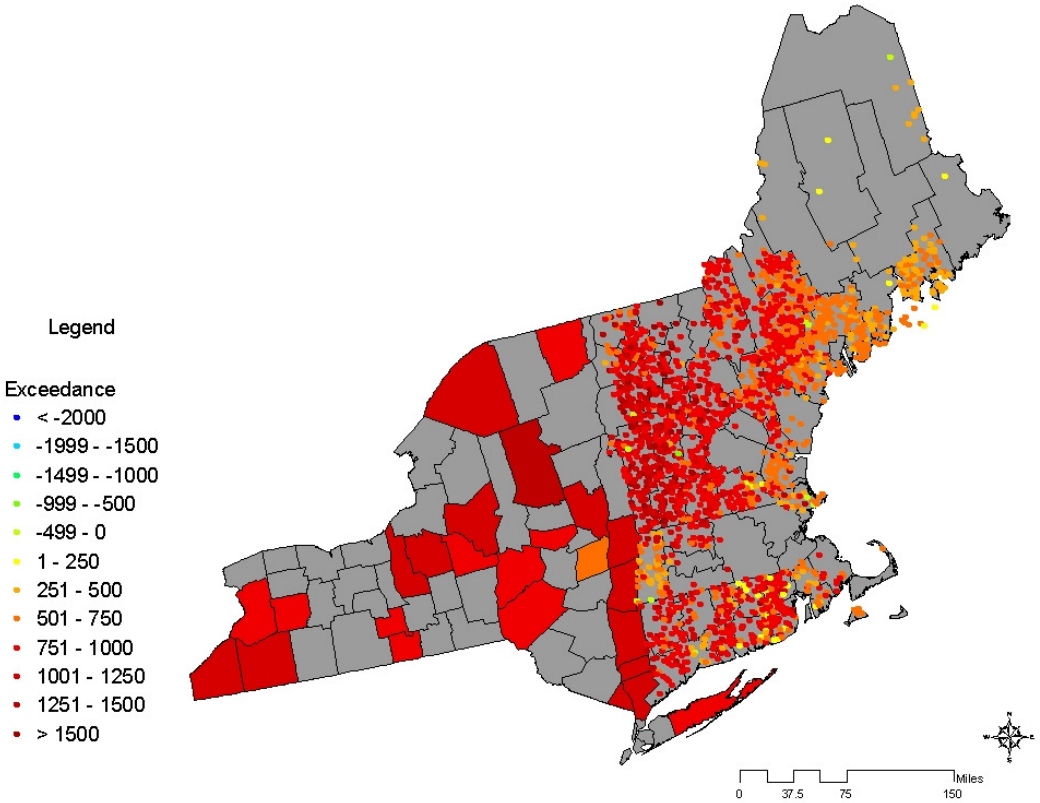
Map 17. Mid exceedance for acidity (S+N) for sites in New England and New York FIA



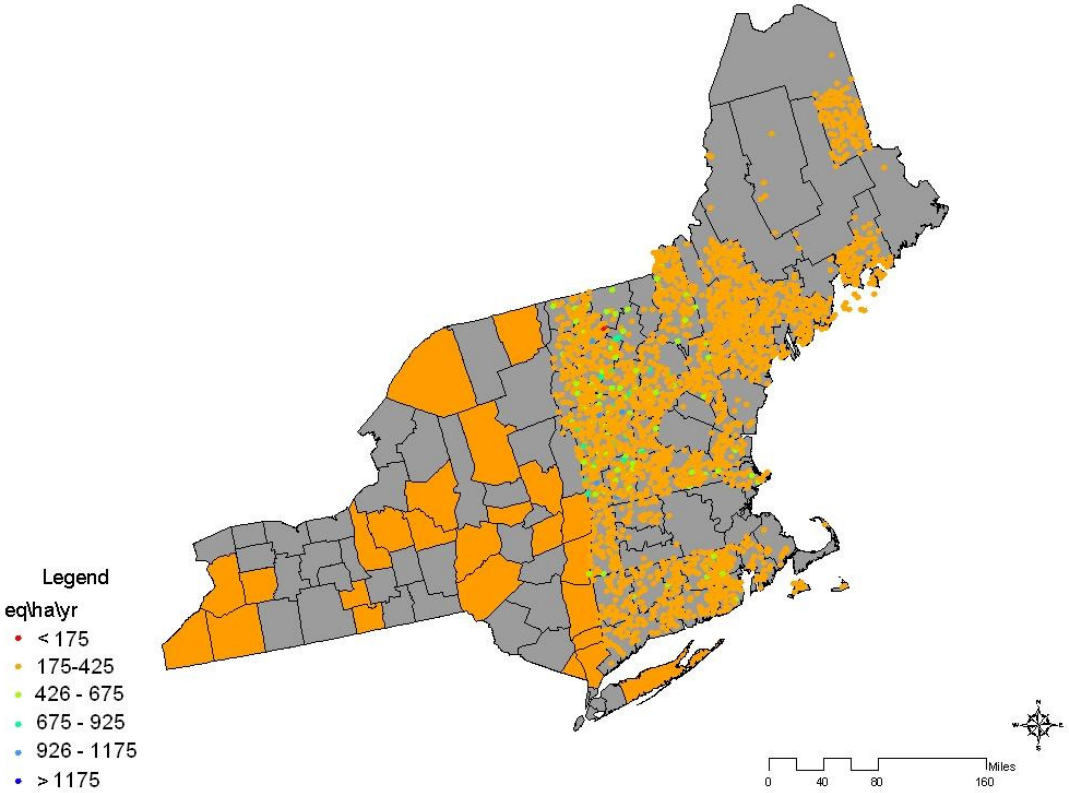
Map 18. Worst case scenario exceedance for acidity (S+N) for sites in New England and New York FIA



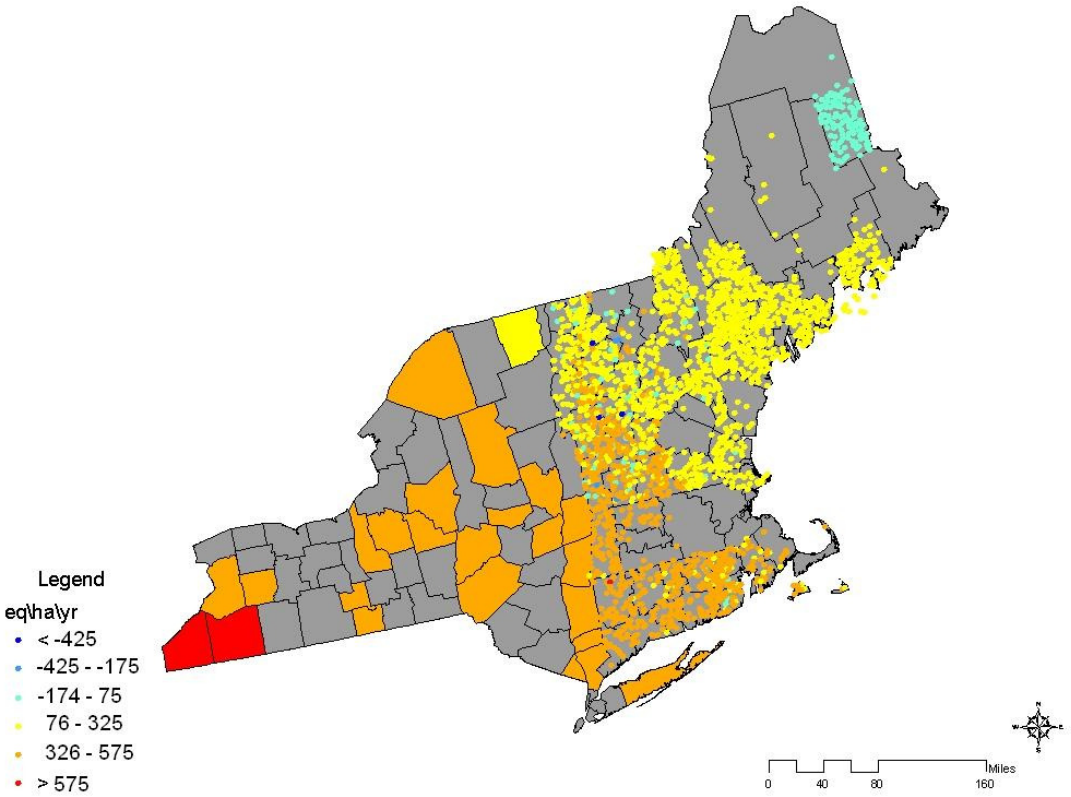
Map 19. Best case scenario exceedance for acidity (S+N) for sites in New England and New York FIA



Map 20. Mean exceedance for acidity (S+N) for sites in New England and New York FIA



Map 21. Critical loads for nutrient N for sites in New England and New York FIA



Map 22. Exceedance for nutrient N for sites in New England and New York FIA

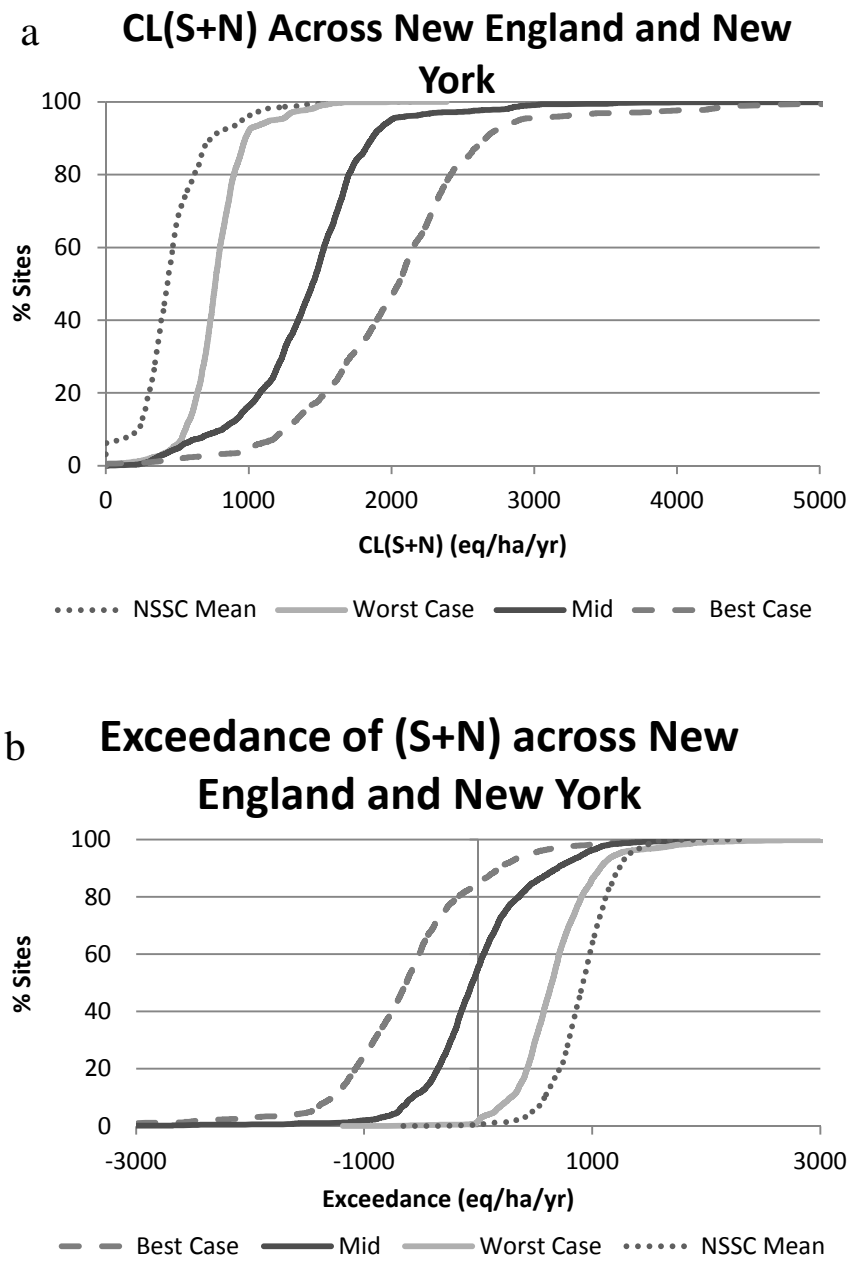


Figure 1. Cumulative frequency of mid, worst case, best case, and NSSC mean (a) critical loads for acidity (S+N) and (b) exceedance of critical load for acidity for New England and New York

Calculated using mid–point, minimum, maximum, and NSSC mean soil mineral weathering rates. The critical load axis (a) does not display the full range, which extends to 10,544; neither does the exceedance axis (b) display the full range, which extends from –9343 to 4889.

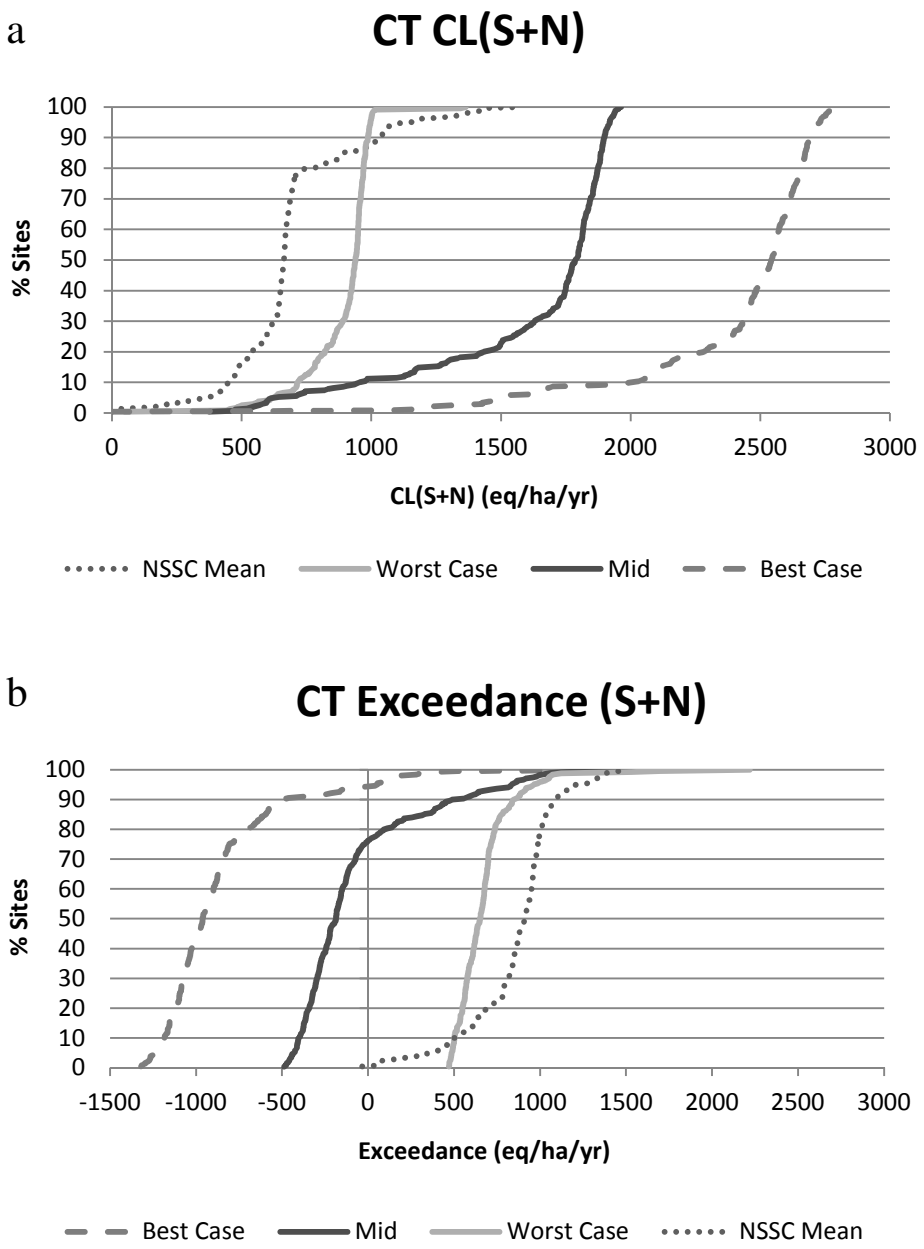
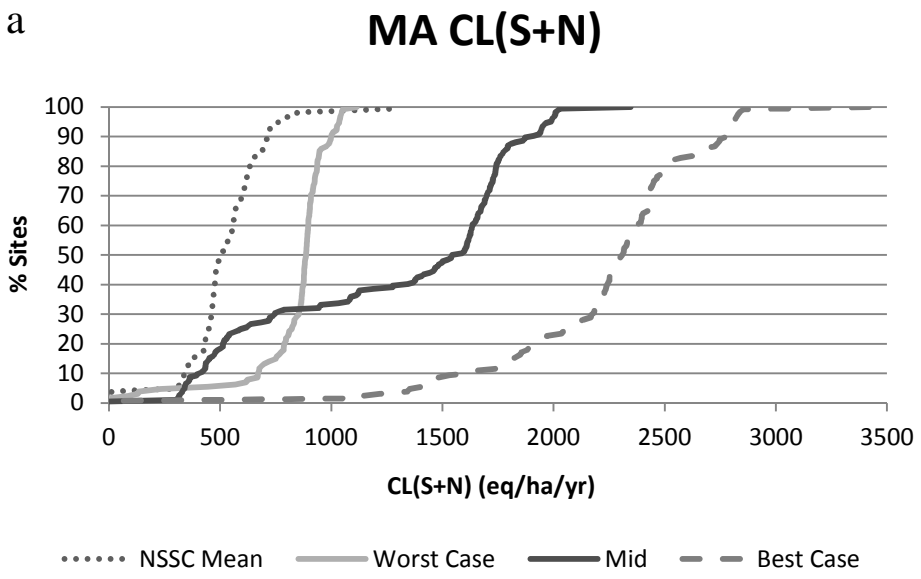


Figure 2. Cumulative frequency of mid, worst case, best case, and NSSC mean (a) critical loads for acidity (S+N) and (b) exceedance of critical load for acidity for plots in Connecticut

Calculated using mid–point, minimum, maximum, and NSSC mean soil mineral weathering rates.

a



b

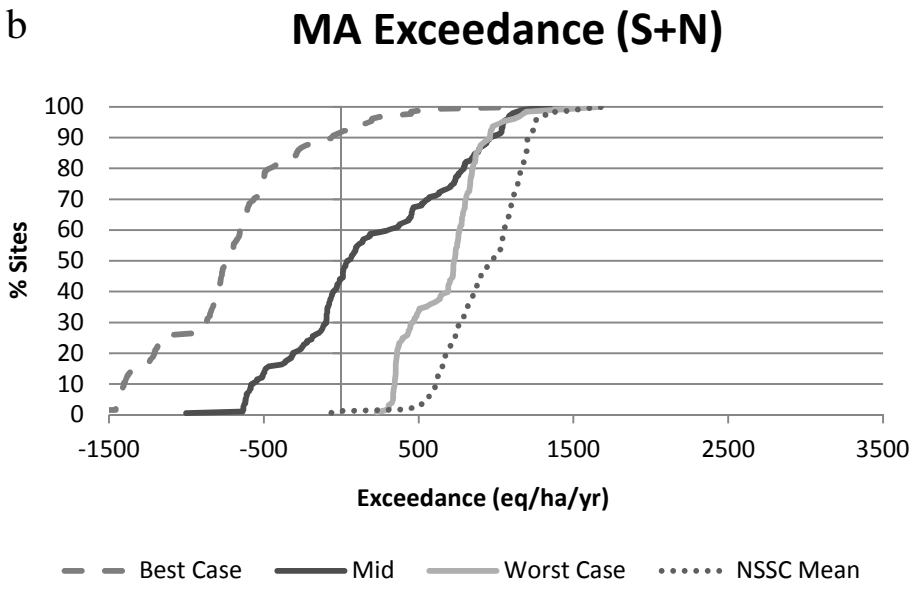


Figure 3. Cumulative frequency of mid, worst case, best case, and NSSC mean (a) critical loads for acidity (S+N) and (b) exceedance of critical load for acidity for plots in Massachusetts

Calculated using mid–point, minimum, maximum, and NSSC mean soil mineral weathering rates.

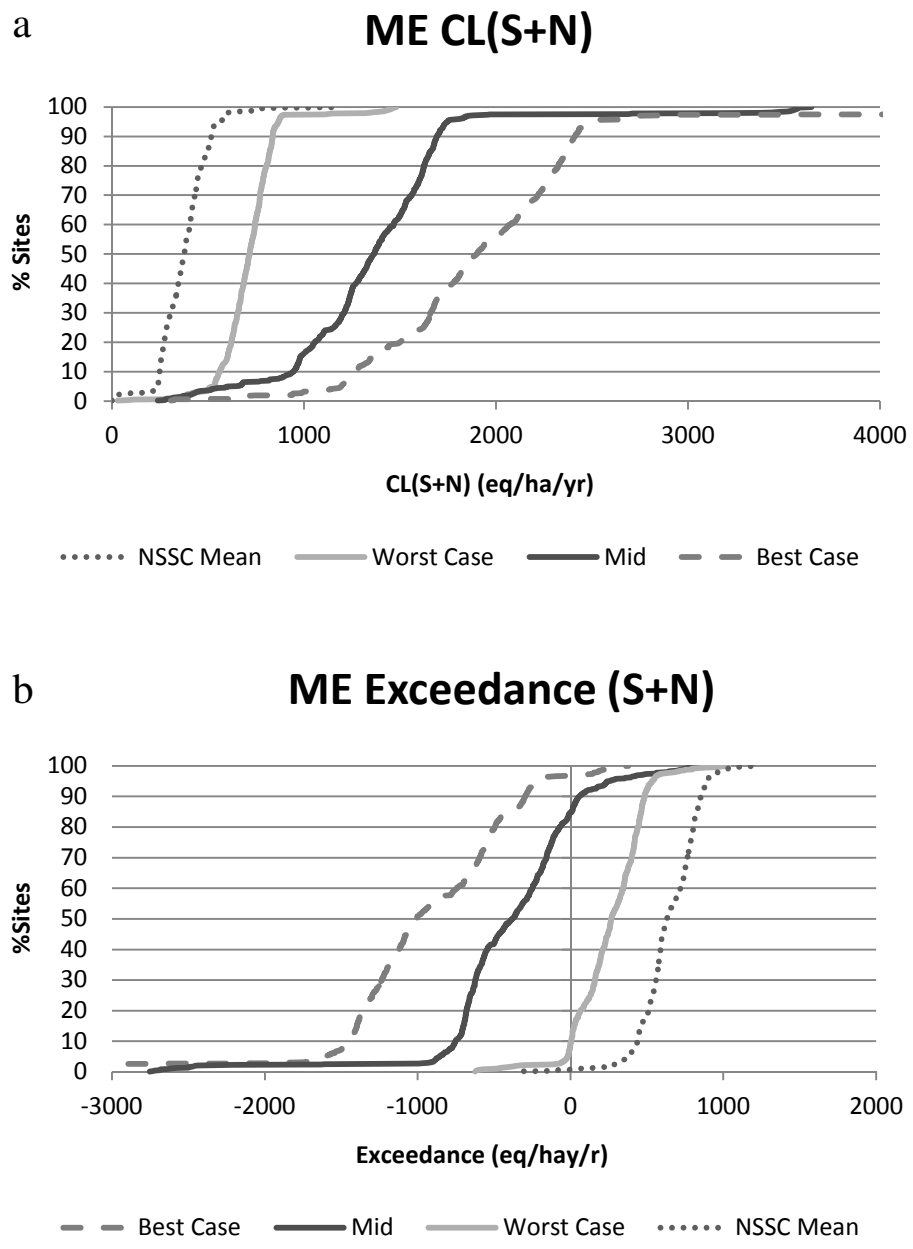


Figure 4. Cumulative frequency of mid, worst case, best case, and NSSC mean (a) critical loads for acidity (S+N) and (b) exceedance of critical load for acidity for plots in Maine

Calculated using mid–point, minimum, maximum, and NSSC mean soil mineral weathering rates. The critical load axis (a) does not display the full range, which extends to 5657; neither does the exceedance axis (b) display the full range, which extends to –4734.

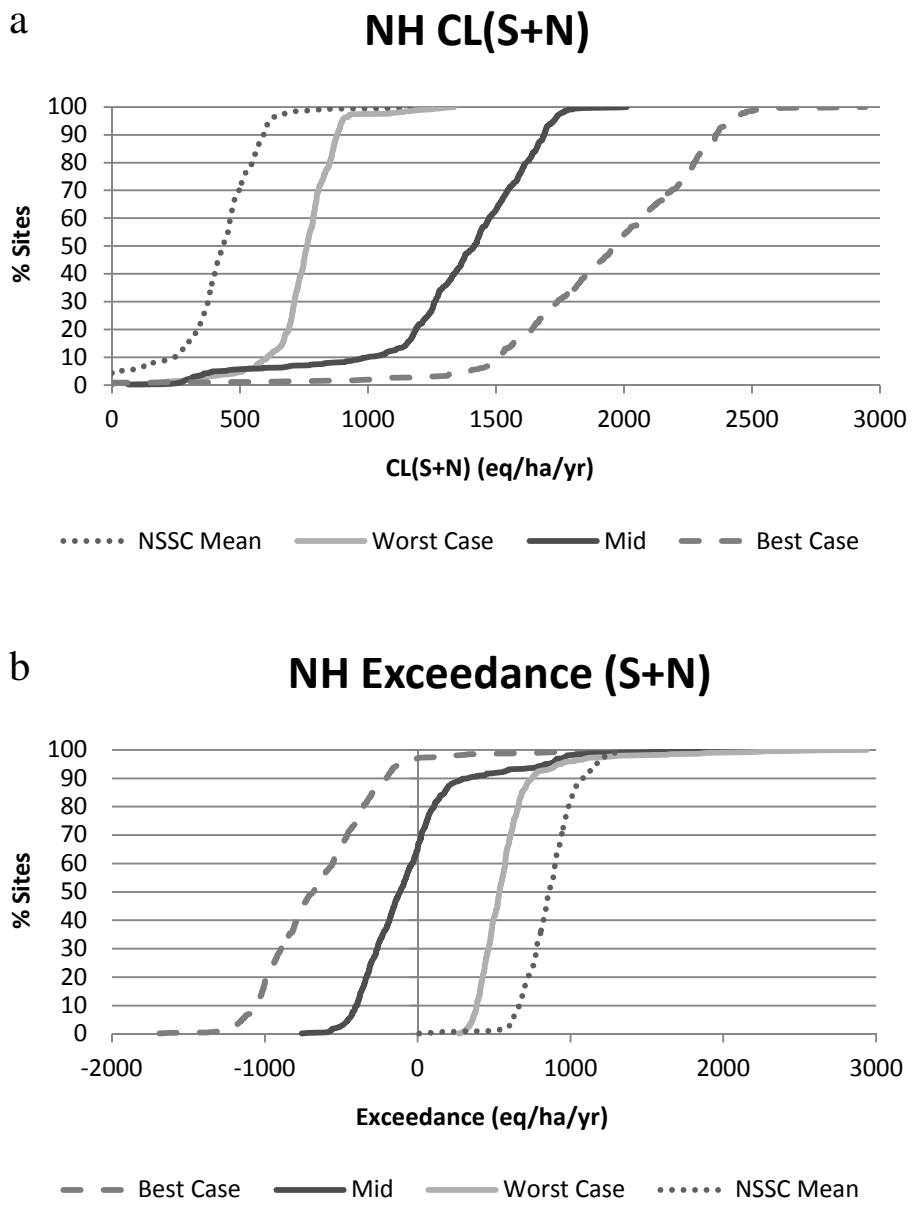


Figure 5. Cumulative frequency of mid, worst case, best case, and NSSC mean (a) critical loads for acidity (S+N) and (b) exceedance of critical load for acidity for plots in New Hampshire
Calculated using mid–point, minimum, maximum, and NSSC mean soil mineral weathering rates.

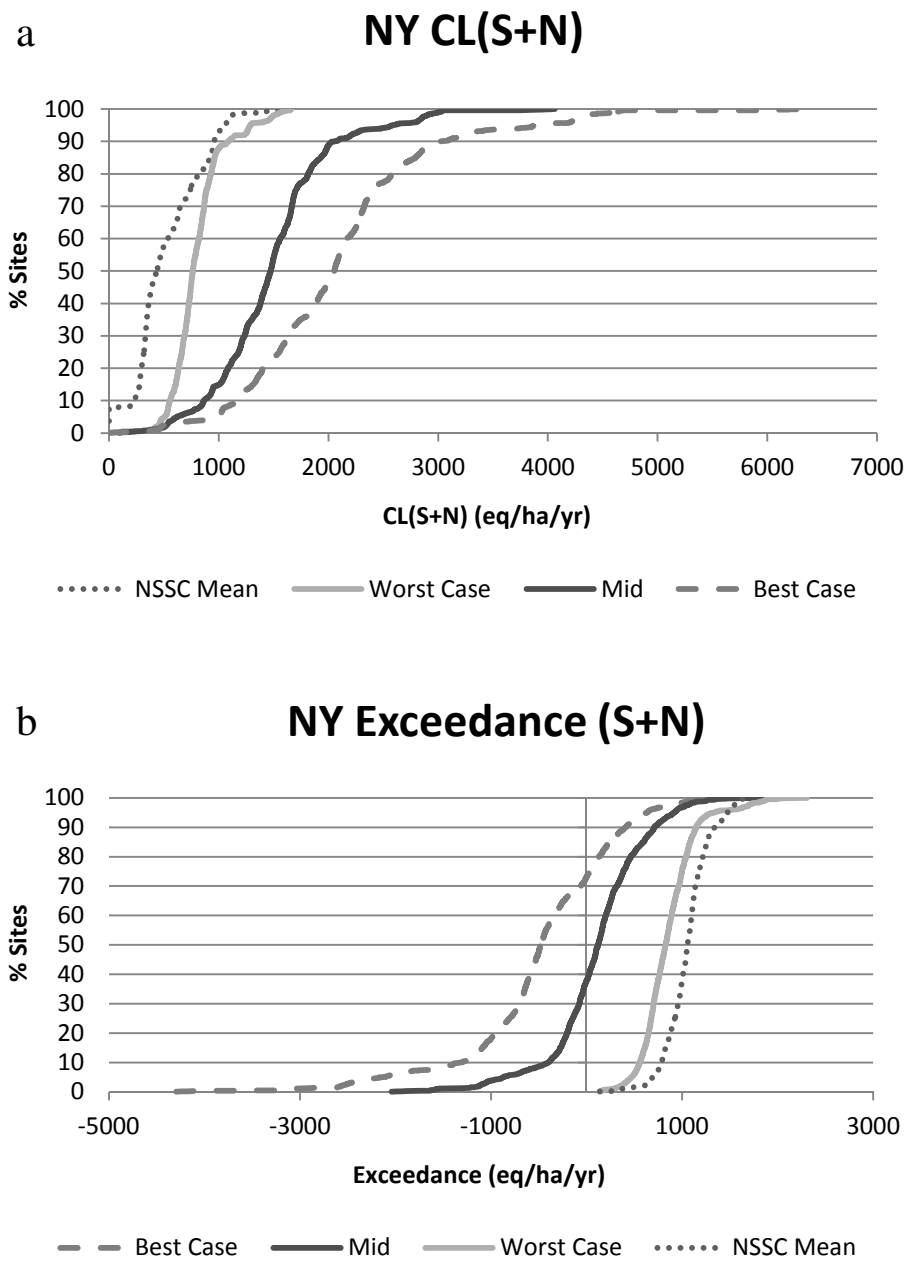
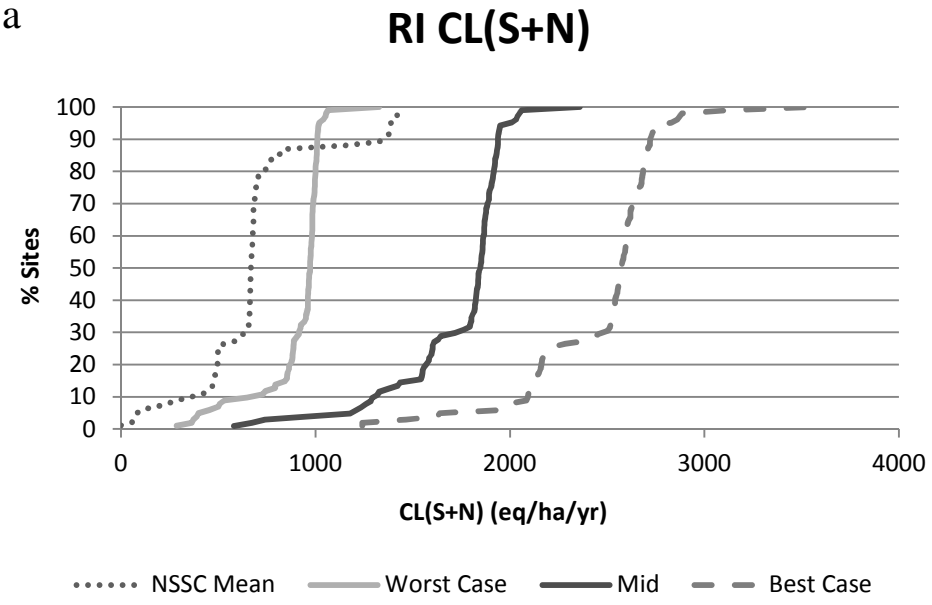


Figure 6. Cumulative frequency of mid, worst case, best case, and NSSC mean (a) critical loads for acidity (S+N) and (b) exceedance of critical load for acidity for plots in New York
Calculated using mid–point, minimum, maximum, and NSSC mean soil mineral weathering rates.

a



b

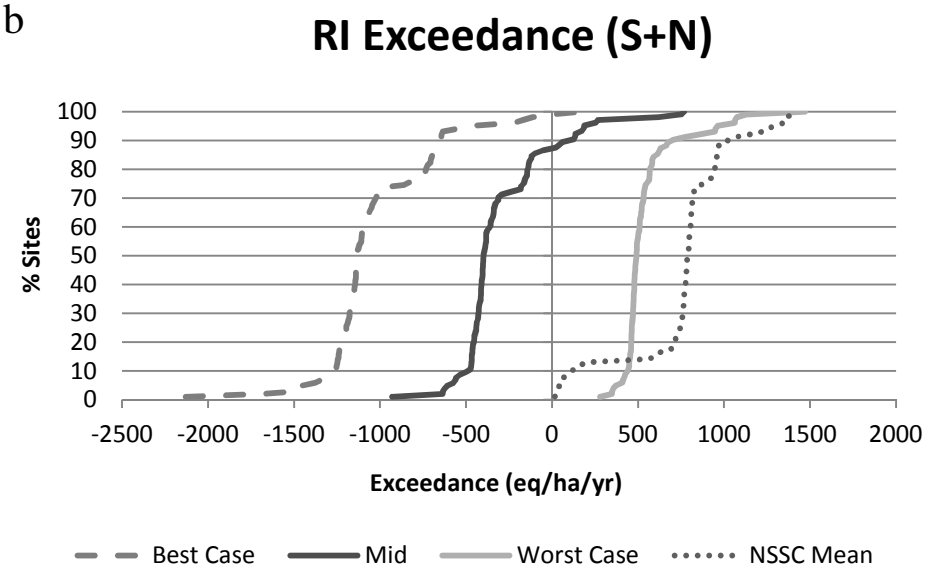


Figure 7. Cumulative frequency of mid, worst case, best case, and NSSC mean (a) critical loads for acidity (S+N) and (b) exceedance of critical load for acidity for plots in Rhode Island

Calculated using mid–point, minimum, maximum, and NSSC mean soil mineral weathering rates.

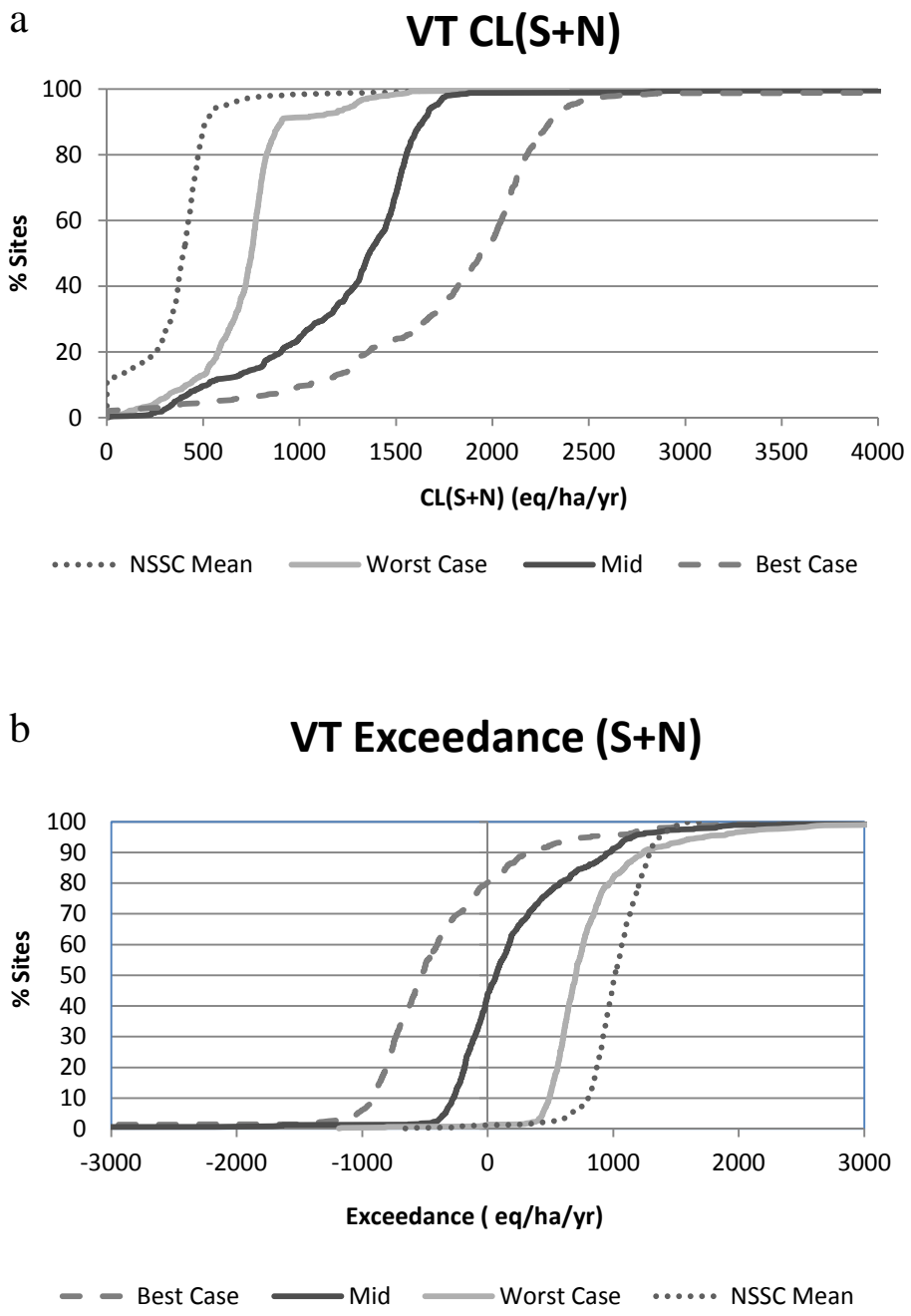
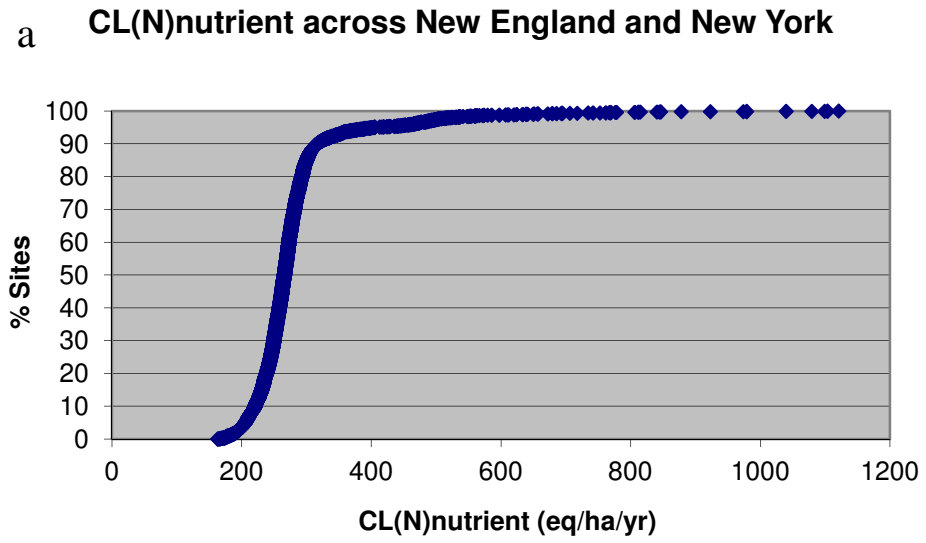


Figure 8. Cumulative frequency of mid, worst case, best case, and NSSC mean (a) critical loads for acidity (S+N) and (b) exceedance of critical load for acidity for plots in Vermont

Calculated using mid–point, minimum, maximum, and NSSC mean soil mineral weathering rates. The critical load axis (a) does not display the full range, which extends to 10,544; neither does the exceedance axis (b) display the full range, which extends from –9343 to 4889.

a



b

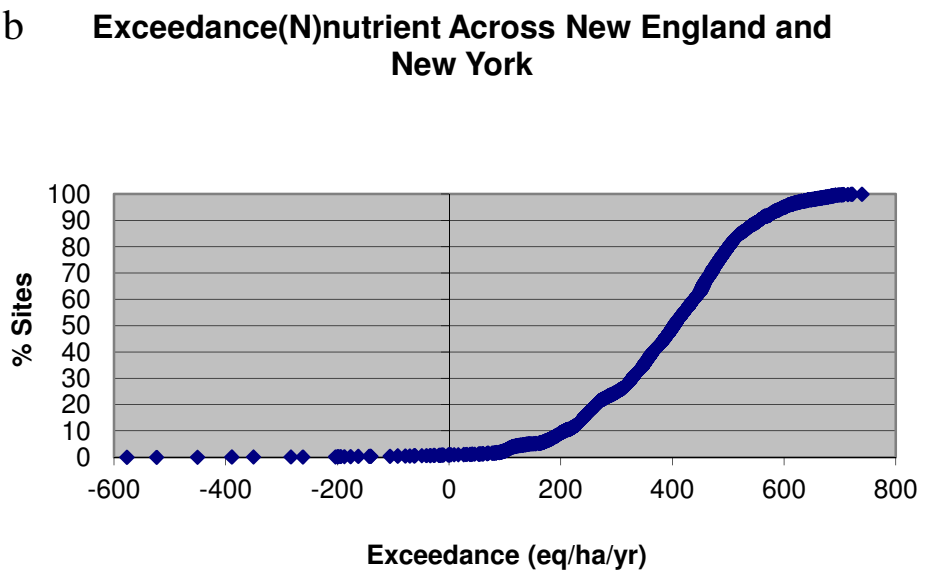


Figure 9. Cumulative frequency of (a) critical loads for nutrient N and (b) exceedance of critical load for nutrient N for plots in New England and New York

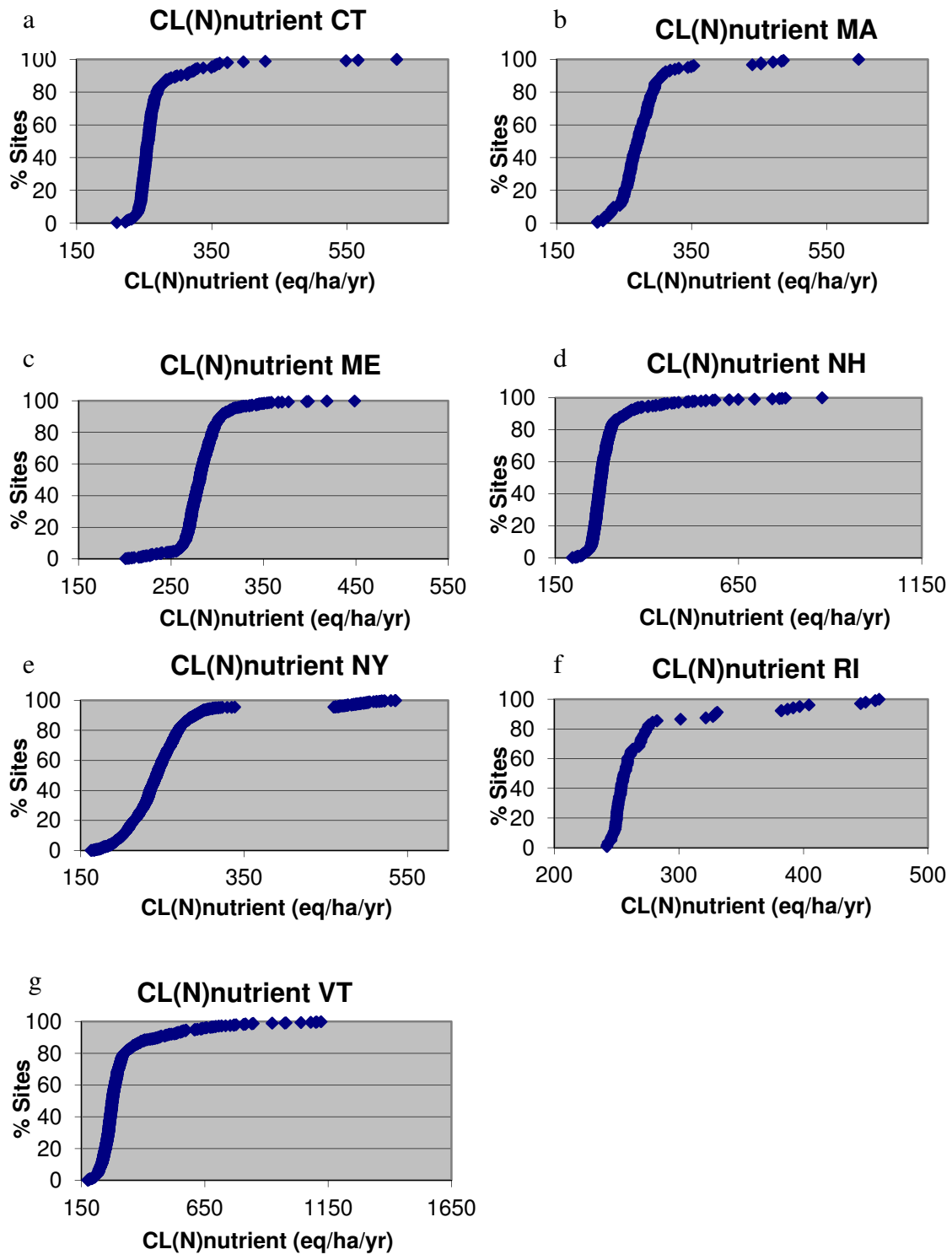


Figure 10. Cumulative frequency of critical loads for nutrient N for plots in (a) Connecticut, (b) Massachusetts, (c) Maine, (d) New Hampshire, (e) New York, (f) Rhode Island, (g) Vermont

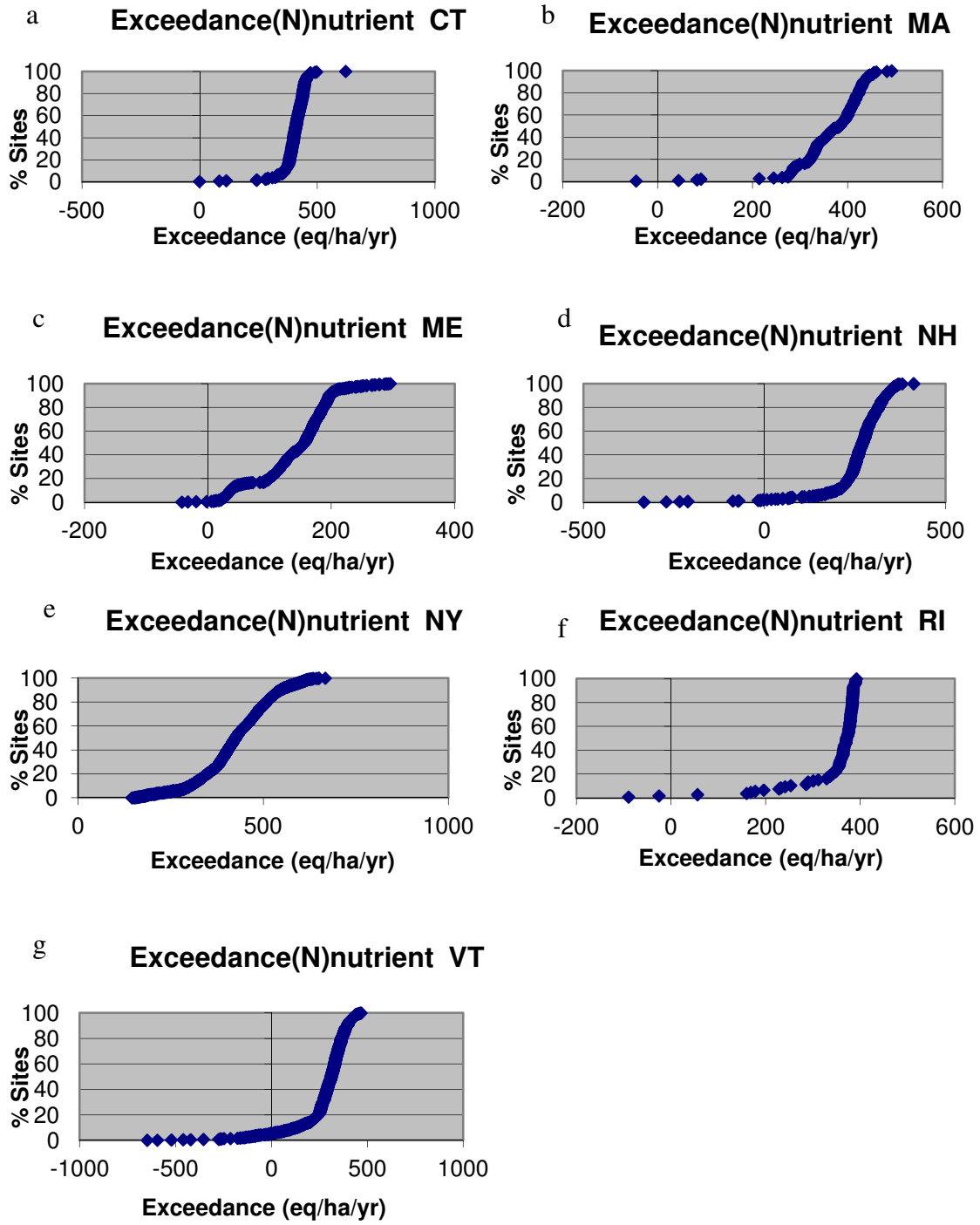


Figure 11. Cumulative frequency of exceedance of critical load for nutrient N for plots in a) Connecticut, (b) Massachusetts, (c) Maine, (d) New Hampshire, (e) New York, (f) Rhode Island, (g) Vermont

5. FOREST HEALTH RESULTS AND DISCUSSION

The objective of the forest health analysis was to determine whether forest ecosystem susceptibility to N and S deposition as quantified by critical load exceedance was related to measureable declines in forest health. We found significant negative correlations between critical load exceedance and growth for 17 species, with the highest growth rates for individual trees primarily at sites where the critical load was not exceeded (Table 16; Figure 12). The slight negative trend for sugar maple (*Acer saccharum)* was not significant (n = 3310, p=0.06). Four species had positive correlations between growth and exceedance; for pignut hickory (*Carya glabra)*, white spruce (*Picea glauca)*, and yellow poplar (*Liriodendron tulipifera)* the growth rates were highest at sites where the critical load was not exceeded, while growth rates for Norway spruce (*Picea abies)* were highest at sites with critical load exceedance (Table 16; Figure 12). Balsam fir (*Abies balsamea)*, quaking aspen (*Populus tremuloides),* and red maple (*Acer rubrum)* had significant positive correlations for increased crown dieback (Table 17; Figure 13) and canopy transparency (Table 18; Figure 14) with exceedance, as well as significant negative correlations for crown density with exceedance (Table 19; Figure 15). Quaking aspen, red spruce (*Picea rubens)*, and balsam fir had the strongest correlations (>0.4) for increased crown dieback, the most reliable health indicator, with exceedance (Table 17; Figure 13). American beech (*Fagus grandifolia)* and red spruce had significant positive correlations for increased crown dieback and canopy transparency with exceedance (Tables 17 and 18; Figures 13 and 14); paper birch (*Betula papyrifera)* had significant positive correlations for increased crown dieback with exceedance and significant negative correlations for crown density with exceedance (Tables 17 and 19; Figures 13 and 15). Significant results for sugar maple were not consistent: crown dieback was negatively correlated with exceedance (Table 17; Figure 13), while canopy transparency was positively correlated with exceedance (Table 18; Figure 14). Eastern hemlock (*Tsuga canadensis)* had significant negative correlations for increased dieback with exceedance and positive correlations for crown density with exceedance. Cherry (*Prunus),* ash (*Fraxinus)*, American beech, and sugar maple had positive correlations between exceedance and vigor class (as the vigor class increases health decreases; Table 20). Most species with decreased forest health also showed decreased growth with exceedance.

Table 16. Growth versus exceedance by species for FIA (P2 plots) using Spearman's rank correlation analysis. Results are for all species with n > 30. The first section of the table lists species with significant correlations (α≤0.05).

Species	Latin name	Spearman correlation	α	n
American beech	*Fagus grandifolia*	-0.077	0.003	1449
Balsam fir	*Abies balsamea*	-0.332	<0.0001	499
Bigtooth aspen	*Populus grandidentata*	-0.250	<0.0001	280
Black cherry	*Prunus serotina*	-0.070	0.024	1026
Black oak	*Quercus velutina*	-0.176	0.005	257
Black spruce	*Picea mariana*	-0.436	0.004	41
Chestnut oak	*Quercus prinus*	-0.279	<0.0001	238
Eastern hemlock	*Tsuga canadensis*	-0.072	0.020	1055
Eastern white pine	*Pinus strobus*	-0.195	<0.0001	1464
Northern red oak	*Quercus rubra*	-0.115	<0.0001	1533
Norway spruce	*Picea abies*	0.381	<0.0001	148
Paper birch	*Betula papyrifera*	-0.266	<0.0001	574
Pignut hickory	*Carya glabra*	0.437	0.014	31
Red maple	*Acer rubrum*	-0.111	<0.0001	3861
Red spruce	*Picea rubens*	-0.090	0.025	616
Scarlet oak	*Quercus coccinea*	-0.260	0.001	170
Sweet birch	*Betula lenta*	-0.119	0.011	460
White ash	*Fraxinus americana*	-0.175	<0.0001	1256
White spruce	*Picea glauca*	0.235	0.020	97
Yellow birch	*Betula alleghaniensis*	-0.122	0.002	669
Yellow poplar	*Liriodendron tulipifera*	0.352	0.015	47
American basswood	*Tilia americana*	-0.014	0.836	230
American elm	*Ulmus americana*	0.116	0.122	179
Black locust	*Robinia pseudoacacia*	-0.160	0.117	98
Black walnut	*Juglans nigra*	0.205	0.231	36
Black willow	*Salix nigra*	0.103	0.497	46
Butternut	*Juglans cinerea*	-0.298	0.104	31
Eastern cottonwood	*Populus deltoides*	-0.271	0.100	38
Eastern hophornbeam	*Ostrya virginiana*	-0.246	0.112	43
Gray birch	*Betula populifolia*	-0.033	0.748	100
Green ash	*Fraxinus pennsylvanica*	0.258	0.062	53
Hickory spp.	*Carya*	-0.081	0.223	231
Larch (introduced)	*Larix spp.*	0.062	0.649	57
Northern white cedar	*Thuja occidentalis*	0.086	0.284	158
Pitch pine	*Pinus rigida*	-0.157	0.077	128
Quaking aspen	*Populus tremuloides*	-0.038	0.375	545
Red pine	*Pinus resinosa*	0.040	0.571	206
Scotch pine	*Pinus sylvestris*	-0.092	0.378	94
Silver maple	*Acer saccharinum*	0.013	0.932	44
Sugar maple	*Acer saccharum*	-0.033	0.058	3310
Tamarack (native)	*Larix laricina*	-0.047	0.677	82
White oak	*Quercus alba*	-0.105	0.109	234

Table 17. Crown dieback versus exceedance by species for FHM (P3 plots), HHS, NAMP, and VMC-FH using Spearman's rank correlation analysis. Results are for all species with n > 30. The first section of the table lists species with significant correlations (α≤0.05).

Species	Latin name	Spearman	α	n
American beech	*Fagus grandifolia*	**0.116**	0.009	502
Balsam fir	*Abies balsamea*	**0.556**	<0.0001	161
Eastern hemlock	*Tsuga canadensis*	**-0.236**	0.004	148
Paper birch	*Betula papyrifera*	**0.134**	0.021	300
Quaking aspen	*Populus tremuloides*	**0.437**	0.0004	61
Red maple	*Acer rubrum*	**0.100**	0.005	767
Red spruce	*Picea rubens*	**0.427**	<0.0001	168
Sugar maple	*Acer saccharum*	**-0.043**	0.011	3466
Ash	*Fraxinus*	**0.057**	0.441	188
Cherry	*Prunus*	**-0.013**	0.929	46
Eastern white pine	*Pinus strobus*	**-0.050**	0.421	258
Fir	*Abies*	**0.185**	0.303	33
Northern red oak	*Quercus rubra*	**0.091**	0.191	208
Sweet/black birch	*Betula lenta*	**-0.078**	0.651	36
White ash	*Fraxinus americana*	**0.137**	0.141	117
Yellow birch	*Betula alleghaniensis*	**0.029**	0.558	403

Table 18. Canopy transparency versus exceedance by species for FHM (P3 plots), HHS, NAMP, and VMC-FH using Spearman's rank correlation analysis. Results are for all species with n > 30. The first section of the table lists species with significant correlations (α≤0.05).

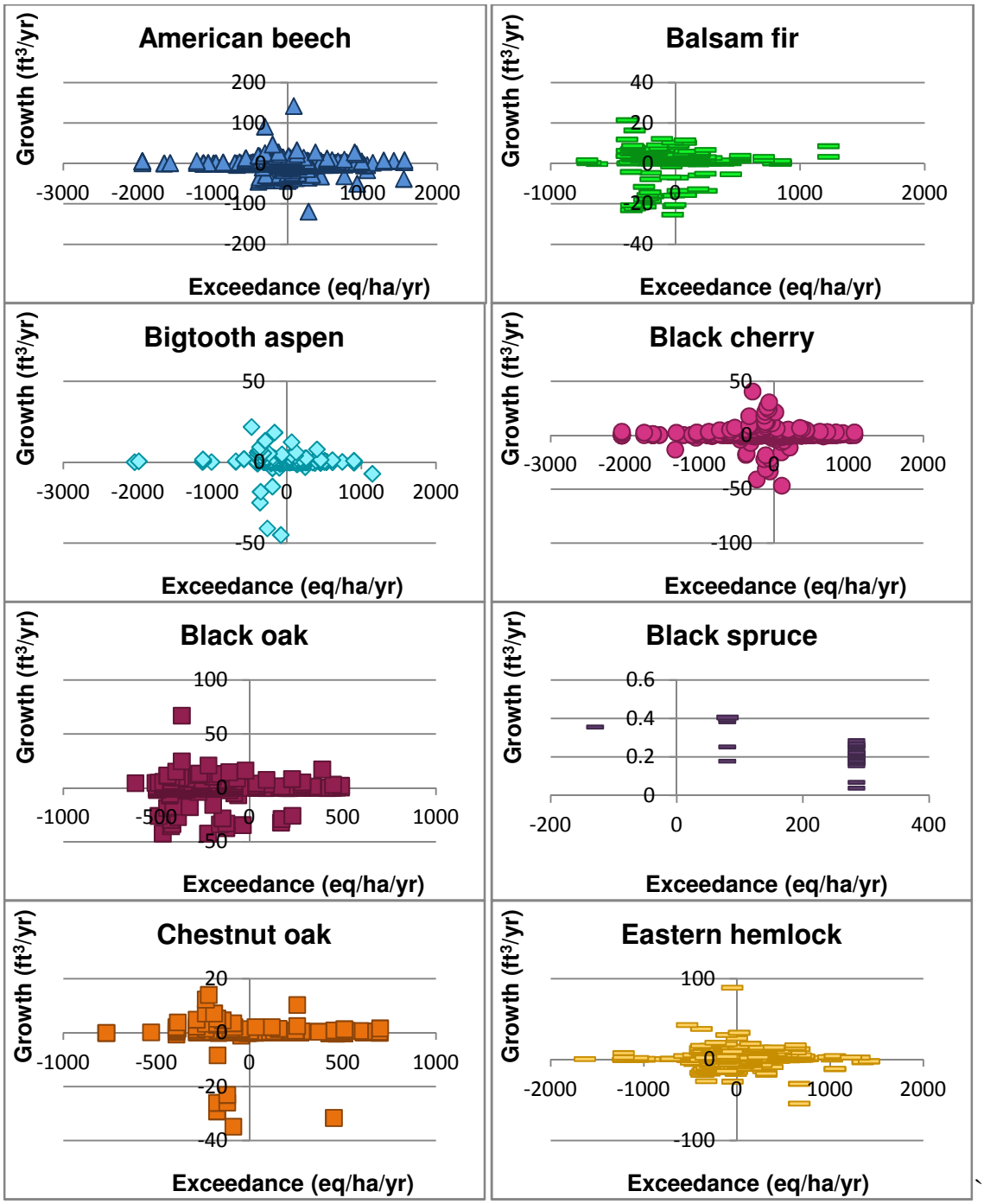
Species	Latin name	Spearman	α	n
American beech	*Fagus grandifolia*	**0.300**	<0.0001	502
Balsam fir	*Abies balsamea*	**0.183**	0.020	161
Fir	*Abies*	**-0.363**	0.038	33
Northern red oak	*Quercus rubra*	**0.266**	0.0001	208
Quaking aspen	*Populus tremuloides*	**0.403**	0.001	61
Red maple	*Acer rubrum*	**0.185**	<0.0001	767
Red spruce	*Picea rubens*	**0.606**	<0.0001	168
Sugar maple	*Acer saccharum*	**0.122**	<0.0001	3467
Ash	*Fraxinus*	**0.004**	0.962	188
Cherry	*Prunus*	**0.137**	0.364	46
Eastern hemlock	*Tsuga canadensis*	**-0.147**	0.074	148
Eastern white pine	*Pinus strobus*	**0.064**	0.304	258
Paper birch	*Betula papyrifera*	**0.044**	0.452	300
Sweet/black birch	*Betula lenta*	**0.200**	0.241	36
White ash	*Fraxinus americana*	**0.018**	0.847	117
Yellow birch	*Betula alleghaniensis*	**0.095**	0.057	403

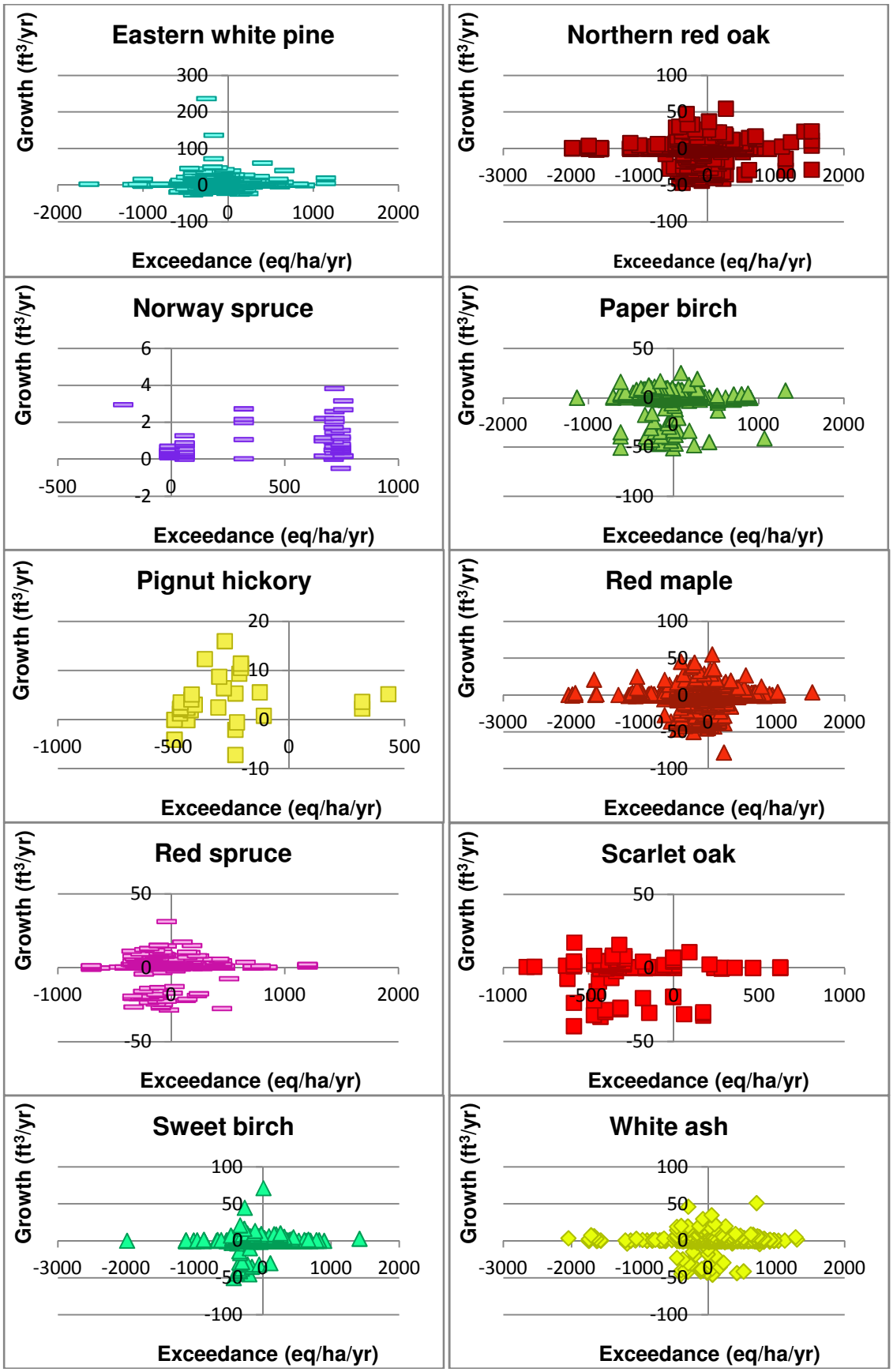
Table 19. Crown density versus exceedance by species for FHM (P3 plots), HHS, NAMP, and VMC-FH using Spearman's rank correlation analysis. Results are for all species with n > 30. The first section of the table lists species with significant correlations (α≤0.05).

Species	Latin name	Spearman	α	n
Balsam fir	*Abies balsamea*	**-0.232**	0.003	161
Eastern hemlock	*Tsuga canadensis*	**0.362**	0.001	82
Paper birch	*Betula papyrifera*	**-0.293**	0.001	125
Quaking aspen	*Populus tremuloides*	**-0.556**	<0.0001	61
Red maple	*Acer rubrum*	**-0.159**	0.004	337
Red spruce	*Picea rubens*	**0.200**	0.032	115
American beech	*Fagus grandifolia*	**0.129**	0.244	83
Eastern white pine	*Pinus strobus*	**0.055**	0.429	210
Northern red oak	*Quercus rubra*	**0.129**	0.238	86
Sugar maple	*Acer saccharum*	**0.040**	0.621	152
Sweet/black birch	*Betula lenta*	**0.151**	0.380	36
White ash	*Fraxinus americana*	**0.124**	0.314	68
Yellow birch	*Betula alleghaniensis*	**-0.120**	0.267	88

Table 20. Vigor versus exceedance by species for FHM (P3 plots), HHS, NAMP, and VMC-FH using Spearman's rank correlation analysis. Results are for all species with n > 30. The first section of the table lists species with significant correlations (α≤0.05).

Species	Latin name	Spearman	α	n
American beech	*Fagus grandifolia*	**0.134**	0.005	433
Ash	*Fraxinus*	**0.216**	0.003	189
Cherry	*Prunus*	**0.327**	0.025	47
Sugar maple	*Acer saccharum*	**0.057**	0.001	3408
White ash	*Fraxinus americana*	**-0.322**	0.024	49
Eastern hemlock	*Tsuga canadensis*	**-0.192**	0.111	70
Eastern white pine	*Pinus strobus*	**0.110**	0.432	53
Fir	*Abies*	**-0.303**	0.086	33
Northern red oak	*Quercus rubra*	**0.015**	0.868	123
Paper birch	*Betula papyrifera*	**0.119**	0.109	183
Red maple	*Acer rubrum*	**-0.048**	0.317	436
Red spruce	*Picea rubens*	**-0.038**	0.785	53
Yellow birch	*Betula alleghaniensis*	**-0.053**	0.344	323


American beech
Growth (ft3/yr)
200
100
0
-100
-200
-3000
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Balsam fir
Growth (ft3/yr)
40
20
0
-20
-40
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Bigtooth aspen
Growth (ft3/yr)
50
0
-50
-3000
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Black cherry
Growth (ft3/yr)
50
0
-50
-100
-3000
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Black oak
Growth (ft3/yr)
100
50
0
-50
-1000
-500
0
500
1000
Exceedance (eq/ha/yr)
Black spruce
Growth (ft3/yr)
0.6
0.4
0.2
0
-200
0
200
400
Exceedance (eq/ha/yr)
Chestnut oak
Growth (ft3/yr)
20
0
-20
-40
-1000
-500
0
500
1000
Exceedance (eq/ha/yr)
Eastern hemlock
Growth (ft3/yr)
100
0
-100
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)


Eastern white pine
Growth (ft3/yr)
300
200
100
0
-100
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Northern red oak
Growth (ft3/yr)
100
50
0
-50
-100
-3000
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Norway spruce
Growth (ft3/yr)
6
4
2
0
-2
-500
0
500
1000
Exceedance (eq/ha/yr)
Paper birch
Growth (ft3/yr)
50
0
-50
-100
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Pignut hickory
Growth (ft3/yr)
20
10
0
-10
-1000
-500
0
500
Exceedance (eq/ha/yr)
Red maple
Growth (ft3/yr)
100
50
0
-50
-100
-3000
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Red spruce
Growth (ft3/yr)
50
0
-50
-1000
0
1000
2000
Exceedance (eq/ha/yr)
Scarlet oak
Growth (ft3/yr)
50
0
-50
-1000
-500
0
500
1000
Exceedance (eq/ha/yr)
Sweet birch
Growth (ft3/yr)
100
50
0
-50
-100
-3000
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)
White ash
Growth (ft3/yr)
100
50
0
-50
-100
-3000
-2000
-1000
0
1000
2000
Exceedance (eq/ha/yr)

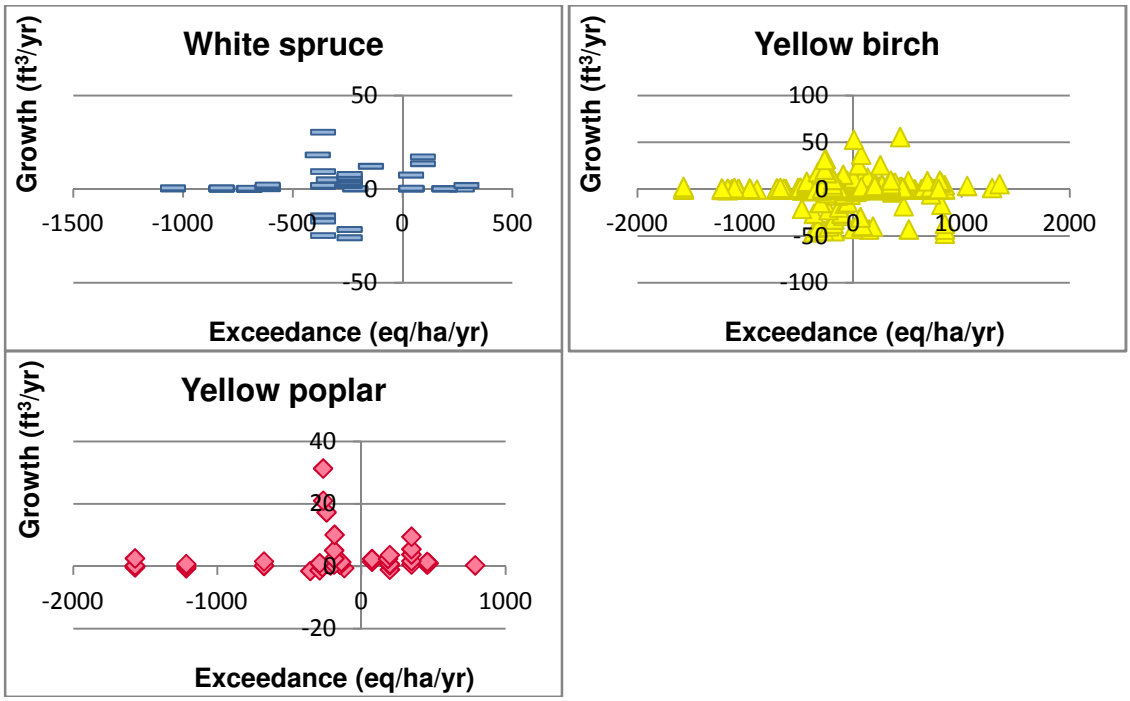


Figure 12. Growth (ft^3/yr) versus exceedance (eq/ha/yr) for species with significant ($\alpha \leq 0.05$) correlations using Spearman's rank correlation analysis.

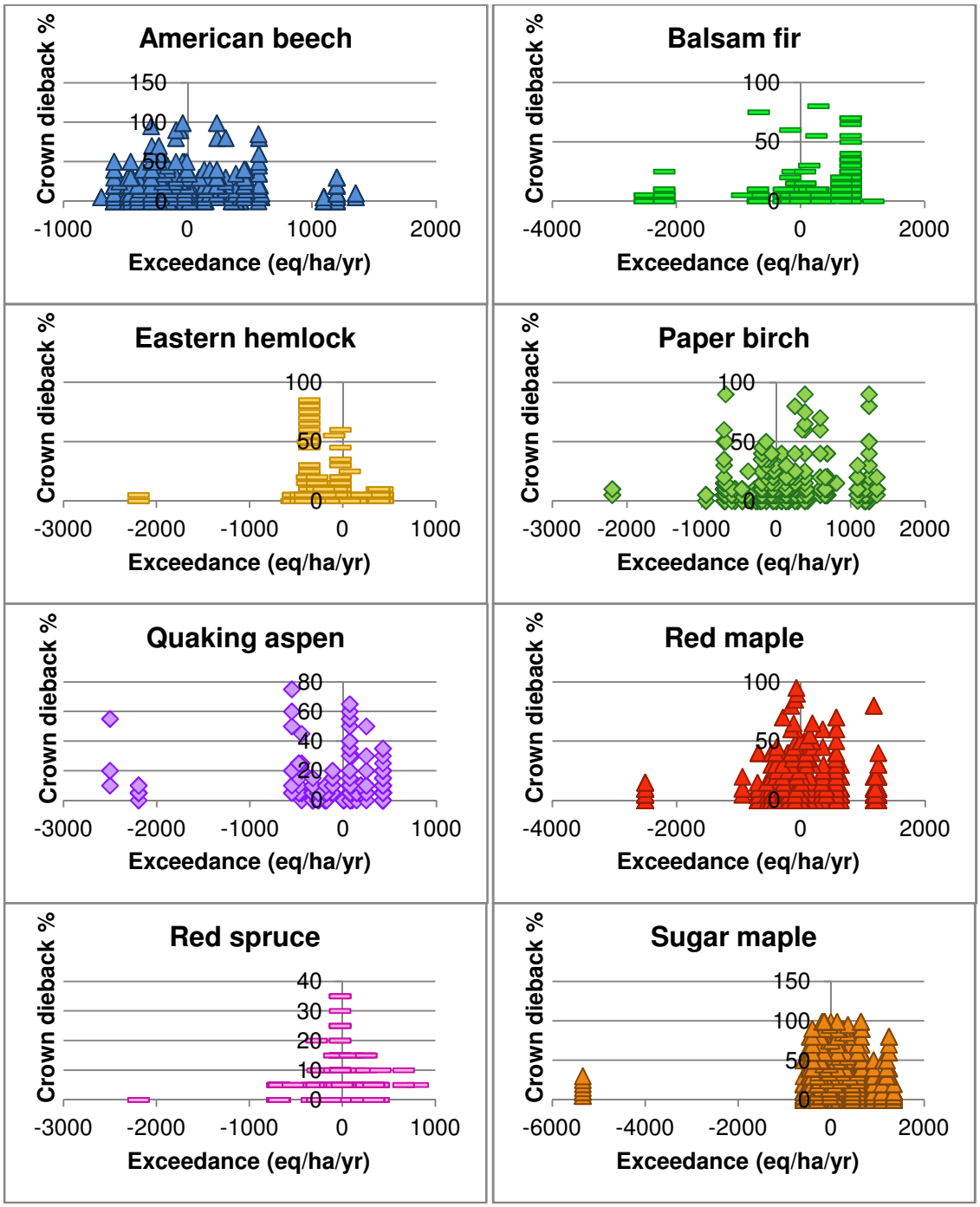


Figure 13. Crown dieback versus exceedance (eq/ha/yr) for species with significant ($\alpha \leq 0.05$) correlations using Spearman's rank correlation analysis.

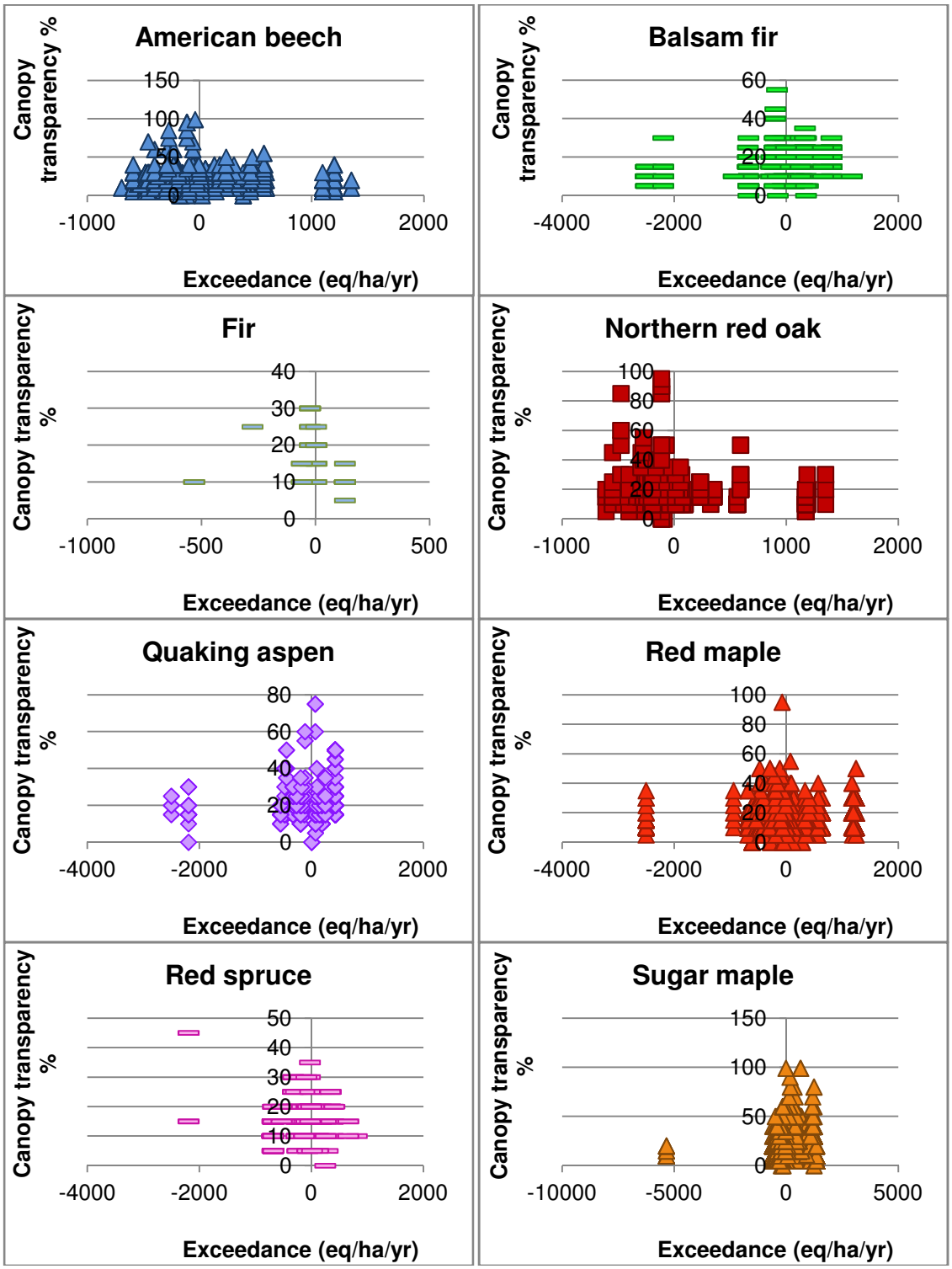


Figure 14. Canopy transparency versus exceedance (eq/ha/yr) for species with significant ($\alpha \leq 0.05$) correlations using Spearman's rank correlation analysis.

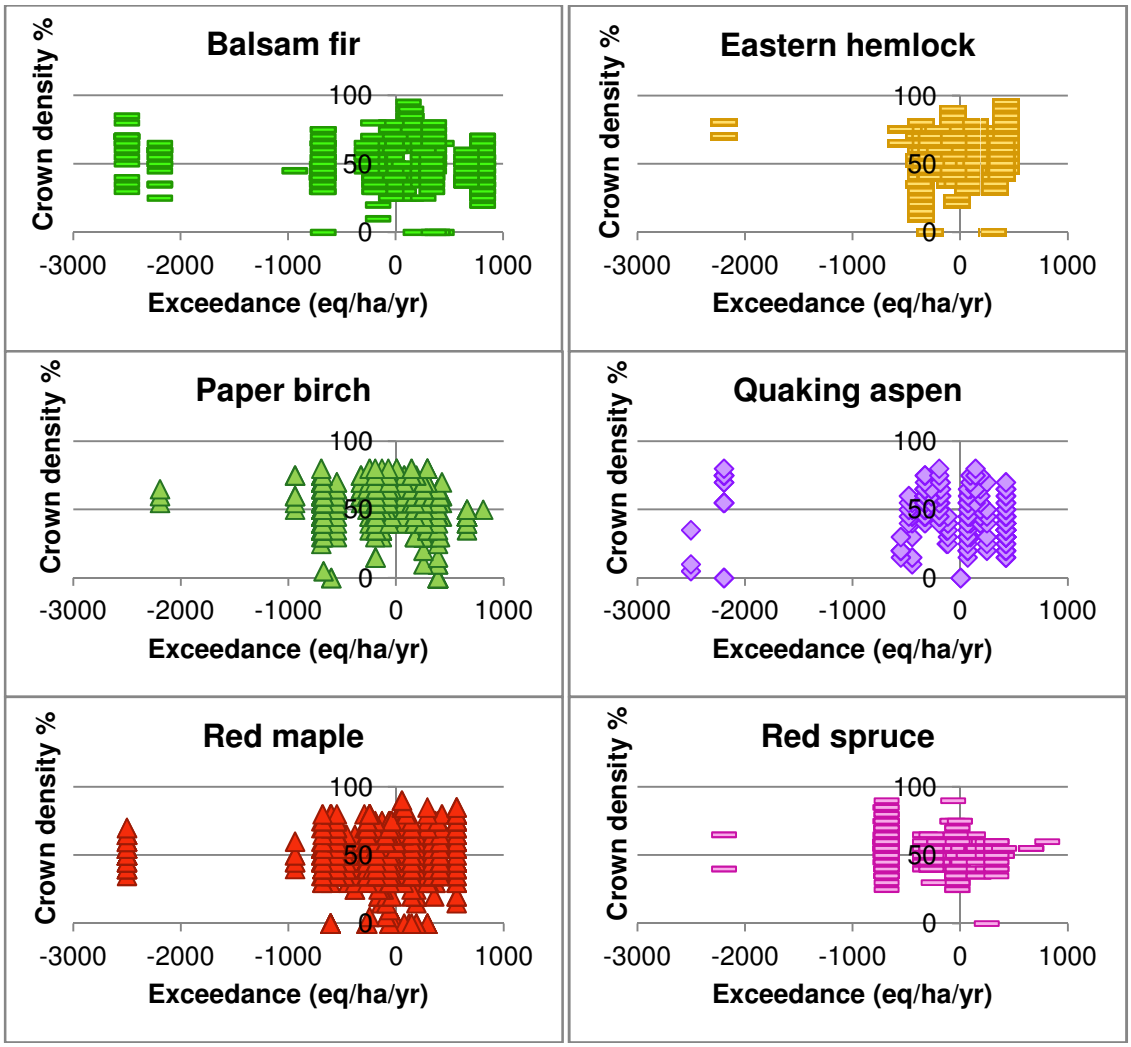


Figure 15. Crown density versus exceedance (eq/ha/yr) for species with significant ($\alpha \leq 0.05$) correlations using Spearman's rank correlation analysis.

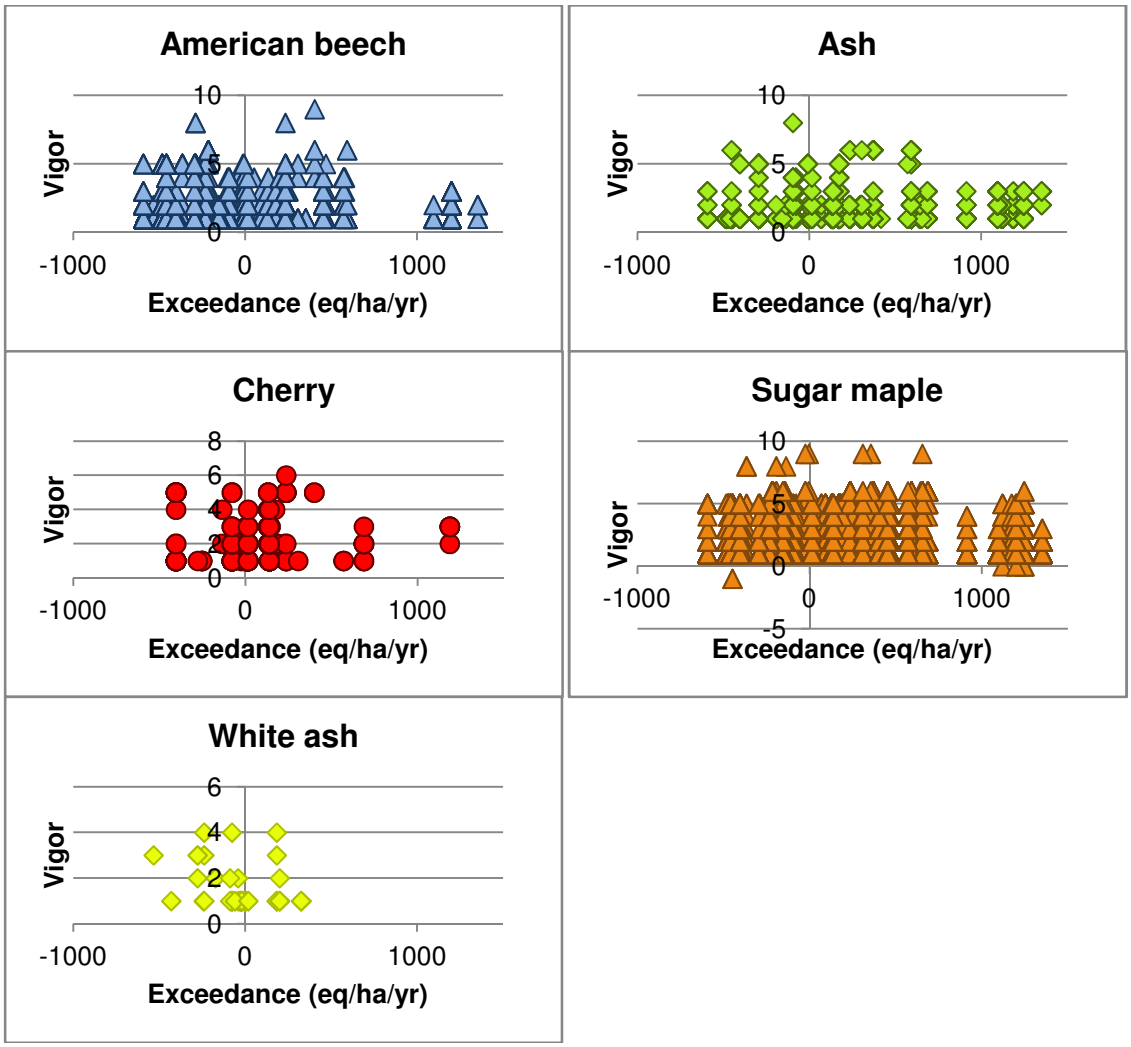


Figure 16. Vigor versus exceedance (eq/ha/yr) for species with significant ($\alpha \leq 0.05$) correlations using Spearman's rank correlation analysis.

Twenty-one tree species in the northeastern U.S. exhibit detrimental impacts from atmospheric deposition as shown by the correlation between exceedance and forest health indicators (Tables 16-20). Some studies have identified relationships between growth or crown damage and exceedance (Nelleman and Frogner 1994, Ouimet et al. 2001), while others have found only weak or non-significant relationships (Augustin et al. 2005). Because the critical loads equations are steady-state mass balances, they give no information about the timing of detrimental impacts. Thus, while sites with damage caused by atmospheric deposition should show exceedance, not all sites that have

exceedance will necessarily exhibit the detrimental effects currently. The most likely mechanism for these impacts of atmospheric deposition is the sequence of ecosystem changes caused by acidification and cation depletion which lead to plant nutrient deficiencies and imbalances.

Plant nutrition regulates growth directly (Marschner 1995), but is also important in plants' ability to respond to environmental stresses. Several species that occur in the northeastern U.S. have well-documented mechanisms by which they are harmed as a result of the cation depletion that occurs with acidification. In many cases, nutrient deficiencies predispose trees to a secondary stress—which may vary with species. For red spruce, soil calcium depletion leads to reduced stress signaling capability and makes red spruce more susceptible to damage from winter injury (Halman et al. 2008, Hawley et al. 2006, Schaberg et al. 2001). The high correlation of crown dieback with exceedance for red spruce confirms that spruce on the poorer sites are already being impacted by atmospheric deposition. Sugar maple is a commercially important species that grows across much of the region. At sites with low soil calcium, sugar maple has been shown to be susceptible to secondary stresses (Bailey et al. 2004, 2005, Bernier and Brazeau 1988a,b,c, Horsley et al. 2000); these stresses include pest defoliation (Horsley et al. 2000) and drought (Bauce and Allen 1991, Allen et al. 1992). Because of its commercial value for maple syrup, sugar maple is retained at suboptimal sites and managed more heavily than many species, which may make the patterns with exceedance more difficult to discern. Paper birch on sites with low soil calcium availability and high extractable soil aluminum in Vermont showed higher foliar loss, reduced fine branching of twigs, and increased tree mortality after the secondary stress of an ice storm (Halman et al. 2011).

Several nutrient-loving species: ash, cherry, sugar maple, and quaking aspen (Burns and Honkala 1990), as might be expected, showed more detrimental effects when exceedance was higher (at poorer sites); this was particularly evident for quaking aspen (Tables 17, 18, and 19). Quaking aspen survivorship was also reported to be negatively impacted by N deposition (Thomas et al. 2010) which may indicate that detrimental responses occur for both acidification and N saturation.

Improving northern red oak regeneration in the Northeast has been the object of considerable management effort (Buckley et al. 1998, Dey et al. 2007). These results suggest that northern red oak may not be viable on poor sites, a finding which is supported by an analysis in the Monongahela National Forest in West Virginia, in which declines in basal areas from 1989-2000 were attributed to atmospheric deposition (Elias et al. 2009). A prior study had reported that low availability of Ca and K and high availability of Al combined with drought led to increased mortality and reduced growth of northern red oak in Pennsylvania (Demchik and Sharpe 2000).

The high positive correlation for crown dieback and crown transparency and negative correlations for growth and crown density that we observed for balsam fir suggest that it may be at greater risk from atmospheric deposition than has been assumed. Balsam fir is cold tolerant, in contrast to red spruce, with which it often co-occurs (DeHayes et al. 1999). Thus, little research has focused on the susceptibility of balsam fir to atmospheric deposition. One study, however, in which chlorophyll fluorescence was measured, indicates that balsam fir is stressed by low soil calcium availability (Boyce 2007). Similarly, Van Doorn et al. (2011) report high mortality of balsam fir in an assessment across the Hubbard Brook Valley, New Hampshire. The secondary stress, mechanism, or condition that has led to this decline is unknown and merits further investigation.

Attributing causes for forest decline remains complex because many factors at local, regional, and global scale may influence forest health. For example, Van Doorn et al. (2011) observed a significant decrease in growth of yellow birch across the Hubbard Brook Valley which they attribute to secondary succession. The negative correlations for yellow birch that we observed between growth and exceedance (Table 16) and that Thomas et al. (2010) report between survivorship and N deposition, however, suggest that atmospheric deposition is implicated, to some extent, in this decline. While most of the significant growth response had a negative correlation with exceedance, four species had positive correlations. In addition, some species, including eastern hemlock, had positive correlations for forest health and exceedance. One possible explanation for the

positive correlation of growth and forest health with exceedance is that some species may be benefitting from the declines of the species with which they co-occur. Certainly, climate change and N deposition have been shown to increase growth of some tree species (Dietze et al. 2011, Thomas et al. 2010, Zhang et al. 2012) across the Northeast.

6. CONCLUSIONS

In trying to estimate critical loads for a broad region, there are inevitable tradeoffs between trying to cover a large area (with few site-specific data) and accurately representing a specific location. This assessment does a better job of capturing the typical values than in identifying the most susceptible ecosystems. Thus, caution should be taken in interpreting values to give specific information at a point in space. Improving regional soil datasets would most improve critical loads and exceedance estimates. Nonetheless, the strong relationships between forest health indicators and exceedance indicate that atmospheric deposition continues to detrimentally impact forest health in the northeastern U.S. The species most affected are balsam fir, red spruce, and quaking aspen, followed by American beech, paper birch, and red maple.

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