NEW YORK STATE OF OPPORTUNITY | NYSERDA

# Acidification and Forest Understory Plant Communities in the Adirondack Mountains

## Summary Report

November 2017

Report Number 17-27

# NYSERDA's Promise to New Yorkers:

NYSERDA provides resources, expertise, and objective information so New Yorkers can make confident, informed energy decisions.

## Mission Statement:

Advance innovative energy solutions in ways that improve New York's economy and environment.

## Vision Statement:

Serve as a catalyst – advancing energy innovation, technology, and investment; transforming New York's economy; and empowering people to choose clean and efficient energy as part of their everyday lives.

# Acidification and Forest Understory Plant Communities in the Adirondack Mountains

***Summary Report***

Prepared for:

**New York State Energy Research and Development Authority**

Albany, New York

Prepared by:

**E&S Environmental Chemistry, Inc.**

T.J. Sullivan
T.C. McDonnell

in cooperation with

**U.S. Geological Survey**

G.B. Lawrence

and

**State University of New York College of Environmental Sciences and Forestry**

M. Dovciak

M.R. Zarfos

NYSERDA Report 17-27 NYSERDA Contract 50773 November, 2017

# Notice

# Abstract

This project focuses on relationships between understory vegetation and soil properties as influenced by acidic deposition in Adirondack Mountain forests. Acidic deposition has reduced the acid-buffering capacity of soils by depleting soil reserves of the important nutrients, calcium and magnesium, at many locations. The research reported here determined the associations between acidic deposition and soil base cation supply and understory plant community responses that reflect aspects of biodiversity. During an earlier field study of *Acer saccharum* (sugar maple) trees and soil chemistry, 50 study plots within 20 small Adirondack watersheds were sampled and evaluated for soil acid-base chemistry and *A. saccharum* growth, canopy condition, and regeneration. For this follow-up study, we characterized how understory plant community composition changed at these same sampling locations across deposition and soil acidification gradients using ordination analysis—nonmetric multidimensional scaling (NMDS). Trees growing on soils with poor acid-base chemistry that received relatively high levels of atmospheric sulfur and nitrogen deposition exhibited minimal to no *A. saccharum* seedling regeneration, relatively poor canopy condition, and short- to long-term growth declines compared with study plots having better soil condition and lower levels of acidic deposition. Understory species richness was positively related to both exchangeable calcium concentrations and base saturation in both the $O_a$ and upper B soil horizons. Several plant species were strongly and positively correlated with Axis 1 of the NMDS, suggesting positive responses to increases in pH, base saturation, and availability of plant base cation nutrients. Other plant species were negatively correlated with Axis 1, and richness decreased with acidic deposition and soil acidification. Results of this research suggested that plant understory richness in Adirondack hardwood forests was controlled significantly by acidic deposition and soil acid-base chemistry. Both bivariate and multivariate analyses clearly illustrated an association between the base status of the $O_a$ and upper B soil horizons and plant understory richness and species composition.

# Keywords

acidification, forest understory, vegetation, Adirondack Mountains, acidic deposition

# Acknowledgments

This research was funded by a contract between E&S Environmental Chemistry, Inc. and the NYSERDA Environmental Monitoring, Evaluation, and Protection Program under the direction of Greg Lampman.

# Table of Contents

# List of Figures

# 1 Project Focus

An earlier project was conducted by E&S Environmental Chemistry, Inc. on behalf of the New York State Energy Research and Development Authority (NYSERDA) to measure and report the health, growth, and regeneration of *Acer saccharum* (sugar maple) trees as affected by sulfur and nitrogen deposition and soil acidification in northern hardwood forests of the Adirondack Mountains (Sullivan et al. 2013). *A. saccharum* was selected because it is an important biological resource sensitive to damage caused by air pollution. This follow-on project focuses on relationships between understory vegetation and soil properties as influenced by acidic deposition in these same forests.

The Adirondacks has historically received relatively high levels of sulfur and nitrogen deposition, although deposition levels have declined substantially during recent decades. Acidic deposition has reduced the acid-buffering capacity of soils by depleting soil reserves of the important nutrients, calcium and magnesium, at many locations, especially in the southwestern portion of the region. The research reported here determined the associations between acidic deposition and soil base cation supply and understory plant community responses that reflect aspects of biodiversity. Plant species that can serve as indicators of high or low base supply were identified. Findings were placed in the context of critical and target loads of atmospheric deposition required to protect or restore sensitive biological resources and ecosystems.

The Adirondack Park is an excellent location for investigating the effects of atmospheric sulfur and nitrogen deposition on forest understory vegetation because the park is one of the largest protected areas in the eastern United States. It has experienced pronounced spatial and temporal gradients in acidic deposition and has been comparatively unaffected by forest fragmentation, land management, or invasions of non-native plants. The legacy of historical acid (sulfur, nitrogen) and nutrient (nitrogen) deposition now gains new significance as the deposition increasingly interacts with confounding effects of climate change, which imposes additional temperature, moisture, and snowpack-related pressures on plant communities. These pressures compound the effects associated with the acid and nutrient status of the soils.

The herb layer of hardwood forests in the eastern United States is an under-appreciated component of the forest ecosystem. On average, across the eastern United States, for every tree species in the forest, there are approximately six species present in the herbaceous layer of the vegetation (Gilliam 2007). In addition, the herb layer often responds to relatively low levels of disturbance (Roberts and Gilliam 2003, Gilliam 2006). Competition from herbaceous and shrub species, and among the seedlings of tree species that partly make up the forest herb layer, can influence the regeneration of overstory species and ultimately forest canopy composition.

# 2 Context

Acidic deposition is comprised of multiple forms of sulfur and nitrogen that are emitted into the atmosphere from such sources as power-generating facilities that burn coal, oil, or natural gas; motor vehicles; agricultural activities; and industry. The term “acid rain” refers to the wet components of the deposition contained in rain and snow. There are also dry components that are comprised of gasses and particles that are scavenged from the air largely by vegetation surfaces. Acidic deposition causes a wide range of environmental impacts, including acidification of soil and drainage water; toxicity to fish and other aquatic biota; depletion of soil nutrient bases, such as calcium and magnesium; reduced growth and regeneration of various plant species; and changes in species composition and biodiversity. Such impacts have been especially prevalent, and some have been well-studied in the Adirondack Mountain region of New York (Driscoll et al. 2001a, Sullivan et al. 2006b, Sullivan et al. 2014, Sutherland et al. 2015).

Atmospheric deposition of sulfur and nitrogen can cause two different kinds of environmental impact: acidification of soil and drainage water and nutrient enrichment (also called eutrophication). Each type of impact can occur in both aquatic and terrestrial ecosystems. These effects can have both environmental and economic consequences. Acidification in the Adirondacks is caused mainly by sulfur, although nitrogen can also be involved and is becoming proportionally more important as sulfur deposition decreases markedly. Nutrient enrichment can be caused by nitrogen deposition, but usually not by sulfur deposition. Nitrogen and sulfur air pollution impacts are governed by 1) pollutant emissions into the atmosphere, 2) deposition processes that govern the movement of pollutants within and from the atmosphere to the earth surface, and finally 3) by the suite of transformations and processes that occur within the soil and drainage water and that control ecosystem responses.

Forest ecosystems worldwide are experiencing decreases in biodiversity in response to human actions. Biodiversity is important to ecosystem structure, function, stability, processes, and services. However, environmental change caused in part by air pollution has contributed to loss of biodiversity at many locations in the United States. Principal measures of plant biodiversity, especially species richness (number of species present), can be affected by ecosystem acidification and/or nutrient enrichment stresses. In the study reported here on the effects of acidic deposition in the Adirondack region, we determined the extent to which the base status of watershed soils is associated with understory plant community composition (species occurrence, relative abundance, cover, and plant community richness).

The Adirondack region hosts a large diversity of plant life. These forests also support wildlife, timber production, and clean water supplies, often closely linked to the health, diversity, and abundance of plants. These natural resources provide the foundation for tourism and fishing economies and attract millions of visitors who participate in seasonal recreation as they enjoy the flora and fauna of the region, including the aesthetics of autumn foliage colors. More than a century of high levels of air pollution has negatively affected these resources. Even though there have been Federal and State efforts over several decades to reduce air pollutant emissions from power plants, motor vehicles, and industry (and pollution levels have decreased substantially), legacy effects on the environment persist.

Emissions of sulfur and nitrogen into the atmosphere at locations upwind from the Adirondacks increased severalfold during the late 19th and the 20th centuries to levels high enough to impact sensitive terrestrial and aquatic ecosystems. In more recent years, Federal and State rules and legislation have reduced sulfur and nitrogen emissions and deposition, and some ecosystem recovery has been documented (Lawrence et al. 2013).

Aquatic effects of sulfur and nitrogen deposition in the Adirondacks have been well studied for the past three decades (cf., National Acid Precipitation Assessment Program 1991, Driscoll et al. 2001a, b, Sullivan et al. 2006a, Jenkins et al. 2007, Lawrence et al. 2008, Sullivan 2015). Such studies have included long-term monitoring, process investigations, and mathematical modeling of ecosystem responses and target loads. Terrestrial responses in the Adirondacks have been somewhat less studied. However, Sullivan et al. (2006b) reported soil acid-base chemistry found at about 200 sites across the region, and Sullivan et al. (2013) documented effects on *A. saccharum* health and regeneration, both reports supported by research funding from NYSERDA. Scientists now know a great deal about the effects of atmospheric deposition on sensitive natural resources in New York State, especially in the Adirondack Mountains. Additional key questions relate to effects on terrestrial resources other than trees, anticipated resource recovery under decreasing levels of deposition, and critical and target deposition loads needed to affect ecosystem recovery. NYSERDA funds much of the research in this region intended to address these issues.

The Adirondack Park contains over 1,000 lakes, an extensive network of streams radiating from high-elevation areas, abundant wetlands, and diverse forests. The Adirondack Mountains, especially the southwestern portion of the region, have experienced relatively high levels of both sulfur and nitrogen deposition, with levels peaking during the late 20th century. In addition, ecosystem sensitivity in this region is very high (Sullivan 2015). Several environmental factors contribute to high ecosystem sensitivity to acidification damage, including slow weathering of bedrock and geological glacial deposits, shallow and naturally acidic soils, and steep slopes. However, soil acid buffering capacity varies across space with soil and bedrock characteristics. Even in the Adirondacks, despite the generally high ecosystem sensitivity to acidification, some watersheds—and the lakes and streams that drain them—are better able to buffer incoming atmospheric acid precursors. Thus, not all water systems have been heavily impacted to date.

Processes of soil and water acidification are of substantial concern to natural resource managers in the Adirondack region because of the potential for damage to sensitive terrestrial and aquatic resource receptors and ecosystem services, such as aspects of soils, vegetation, and aquatic life. As the chemistry of impacted soils changes in response to acidic deposition, several effects are of direct relevance to native plant communities. First, the supply of nutrient base cations in the soil, in particular, calcium and magnesium, can become depleted, causing increased stress for species that require considerable available base cations in the soil to support plant nutrition and optimal plant physiological functioning. The potential for negative effects of base cation depletion on plants can be characterized by the soil base saturation (BS) measurements and calculations. Second, aluminum can be mobilized by acidic deposition from soil particles into soil solution, where it can adversely affect the roots and nutrient uptake of sensitive plant species. Third, the supply of nitrogen can increase, causing some species to grow more vigorously and outcompete other species that are less able to take advantage of the added nitrogen.

As soil chemistry changes in response to decades of acidic deposition, species that are unable to tolerate high acidity, high aluminum, and/or low base cation supply may be at risk, becoming increasingly susceptible to insect infestation, disease, or other stressor(s). As a result, the species may show decreased health, regeneration, and/or growth and be gradually eliminated from the ecosystem. Another set of species may gain competitive advantage in acidified and/or nitrogen enriched soils, often drawn from a relatively small pool of species capable of successfully competing with the majority of native understory forest plant species under such conditions, thus leading to an impoverished and altered plant community as well as other associated biological communities. These environmental impacts are more thoroughly described, together with key scientific principles, by Gilliam (2006), Sullivan et al. (2011, 2012), Sullivan and Jenkins (2014), Driscoll et al. (2001a), Burns et al. (2011), and Sullivan (2015).

# 3 Goals and Objectives

This summary report addresses key findings of the recently completed Adirondack forest understory biodiversity study (Sullivan et al. 2017). It is targeted to land managers, policy makers, non-specialist environmental scientists, and nonscientists who must make decisions related to the effects of air pollution and acidic deposition on natural ecosystems in New York State. Selected aspects of plant understory responses to acidic deposition and soil acidification are discussed in an effort to inform decision-making and understanding of the complexities of ecosystem responses to acidic deposition and nutrient stress.

The goal of the study is to identify relationships between plant understory biodiversity and soil acidification presumably caused by sulfur and nitrogen deposition in the Adirondack northern hardwood forest, an important forest type in this region. Major objectives include the following:

- identify understory plant indicators of base nutrient-rich and base nutrient-poor (acidified) forest stands
- describe relationships among acidic deposition, soil chemistry, and understory plant diversity

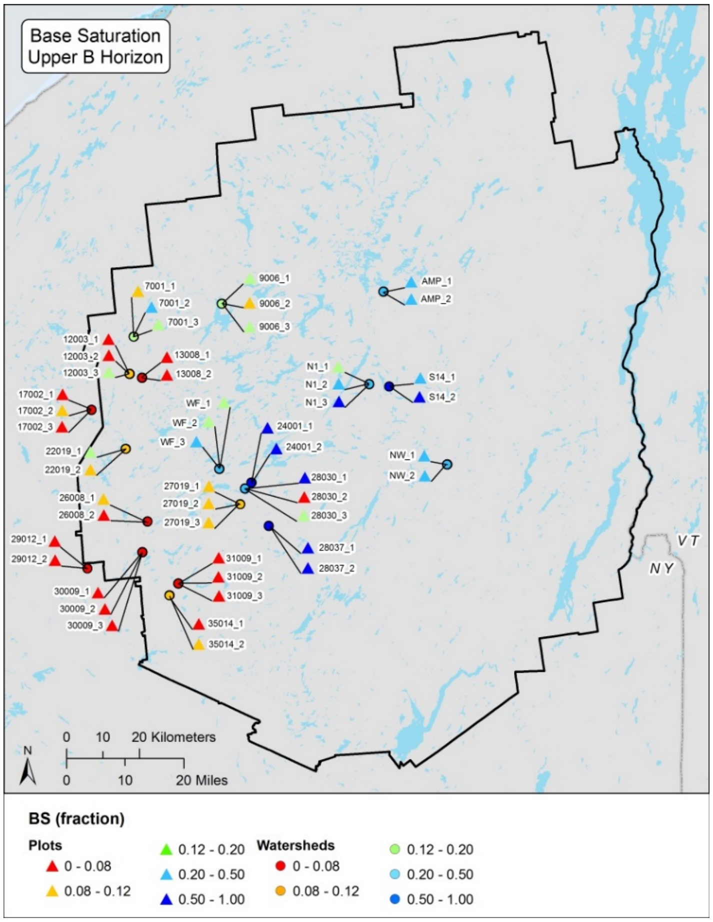
Scientific perspectives presented here will help to inform land managers and decision-makers who are tasked with developing and implementing environmental policy. The text is supported by photographs and charts illustrating key concepts and results. The intent is to educate interested citizens and policy makers regarding the potential impacts of acid and nutrient deposition on the understory plant communities of Adirondack northern hardwood forests that contain *A. saccharum*, *Fagus grandifolia* (American beech), *Betula alleghaniensis* (yellow birch), and other tree species. There are other effects of air pollution in the State that are not considered here, including effects on human health, visibility, ozone formation, water acidification, water eutrophication, and climate change.

# 4 Study Methodology

During the earlier field study of *A. saccharum* trees and soil chemistry, 50 study plots within 20 small Adirondack watersheds were sampled and evaluated for soil acid-base chemistry and *A. saccharum* growth, canopy condition, and regeneration (Figure 1). This research built upon the sampling design and data collected during the NYSERDA-sponsored Western Adirondack Stream Survey (WASS) conducted by the U.S. Geological Survey. The WASS provided an assessment of stream acidification for small watersheds through the sampling of 200 streams selected from the regional population of 565 streams. Low-order stream watersheds were used to integrate watershed response. To select the 50 study plots for the *A. saccharum* project, the 200 WASS watersheds were ranked by the stream water base cation surplus value (an indication of acid-base status of drainage water) and divided into 20 groups (strata) that maintained watershed rankings. One watershed was selected for sampling from each group. Thus, results are broadly applicable to low-order stream watersheds in the southwestern portions of the Adirondack Park. Landscape characteristics of each watershed were evaluated through the use of geographic information system (GIS) databases, aerial photography and field reconnaissance to select two or three plot locations in each watershed that were generally representative of the watershed and included *A. saccharum* trees. At these locations, *A. saccharum* seedlings and saplings were counted, identified, and measured, and wood cores were collected from mature trees for dendrochronological analysis. Crown vigor index, percent branch dieback, and percent crown transparency were estimated for each tree. Soil samples were collected from soil pits (one per plot) from discrete horizons to represent the organic (O and A horizons) and mineral (upper and lower B and C horizons) soil. These samples were dried and analyzed at the U.S. Geological Survey laboratory for a suite of chemical variables that reflected the acid-base chemistry of the soil. Analyses focused in particular on the concentration in the soil of exchangeable calcium and the soil base saturation. Exchangeable calcium is important for the *A. saccharum* condition because this species performs best in soils with relatively large amounts of calcium and because calcium has been depleted from the soil in the Adirondacks by acidic deposition. Soil base saturation expresses the percent of the soil cation exchange sites that are occupied by base cations (including calcium, magnesium, and others) as opposed to acid cations (including aluminum, which is toxic to tree roots). Base saturation is the common summary chemical variable often used to represent soil acid-base chemistry (U.S. EPA 2009).

**Figure 1. Map showing soil base saturation (BS) in the upper B horizon, aggregated by plot (triangles) and by watershed (circles), in the Adirondack Park**

The solid line represents the boundary of the Adirondack Park.




Soil analyses for this understory plant assessment focused largely on the $O_a$ organic horizon because most understory plants are shallow-rooting. Additional analyses focused on the upper B mineral horizon because this horizon can be important for supporting trees, shrubs, and herbaceous plants that have deeper roots and because process-based dynamic modeling of watershed response often relies on upper B horizon data (Sullivan et al. 2006a, Sullivan et al. 2013).

Each plot was visited twice in the summer of 2015, during the period May–June and again during July–August, to account for variable timing of species growth during the growing season. On each visit, plants in the understory vegetation layer were surveyed in established subplots (Figure 2), tabulated, and identified to species where possible. The herb layer includes resident species (herbaceous and woody) that are not taller than 1.5 m as well as tree seedlings, sprouts, and small saplings that may eventually grow into the higher strata of the forest. Within each 20 × 50-m plot, 15 subplots (1 × 1 m) were established on a 5 × 5-m grid. Topographic moisture indices were calculated, and the light environment was characterized.

**Figure 2. Field crew visually estimating understory plant cover of species on a 1 × 1 m subplot**

*Photo credit: J. Wason*

Plant species richness varies spatially and can therefore be influenced by the area sampled (Fridley et al. 2005). Thus, surveys of the 750 subplots in this study did not capture some of the rarer species. Subplot surveys were therefore supplemented with an inventory approach whereby each plot was examined to identify all additional understory plant species that were not present on subplots (thereby yielding a complete species inventory for each plot). The subplot-based approach provided quantitative measurements of herbaceous plant cover (%) and tree seedling density on subplots (averaged for each plot), and relative frequency estimates (based on species absence versus presence on each subplot) for each species on each plot. Plant cover on subplots was visually estimated within 1.5 m above the ground following Daubenmire (1959). The inventory approach identified some of the less common species missed by the subplots and enabled more accurate estimates of species richness on each plot.

Grasses and sedges (collectively called graminoids) were excluded due to their rarity (average subplot cover only 0.4%) and because most were not flowering at the time of the field surveys and therefore could not be accurately identified to species. Species richness per plot was calculated as the total number of unique non-graminoid plant understory species identified on the survey subplots plus those tabulated in the plot searches for each plot and watershed.

Plant species richness on each plot was analyzed relative to its expected drivers (measured soil characteristics, light environment, soil moisture index, and atmospheric deposition of sulfur and nitrogen) using scatterplots and associated correlation and regression analyses. In addition, we classified all plots based on three richness levels (high, intermediate, and low) and tested to see if the ecological drivers varied across those levels. We also characterized how plant community composition changed across deposition and soil acidification gradients using ordination analysis—nonmetric multidimensional scaling (NMDS). The NMDS was based on the frequency of plant species occurrence calculated as the number of 1×1-m subplots in which a species occurred during either survey period (May–June and July–August) divided by the total number of subplots in the watershed. Rare species, occurring in only one or two watersheds, were excluded from the ordination analysis.

Following the NMDS ordination that characterized overall plant community compositional gradients, we performed a complementary indicator species analysis (ISA), using the procedures of Dufrêne and Legendre (1997) and Peck (2010) to identify those species most closely associated with upper B horizon base saturation above or below 12% at each study watershed. We selected a base saturation value of 12% to differentiate soils where vegetation responses may have been clearly affected by soil acidification (BS $< 12\%$), and soils where vegetation responses to acidification were less likely, based on the previous work on *A. saccharum* (Sullivan et al. 2013). The ISA was conducted on the same primary matrix used in NMDS with a secondary matrix of binary values indicating average base saturation in the upper B horizon in each watershed as either $> 12\%$ or $<12\%$ and species indicator values were calculated as products of relative abundance and relative frequency of each species in each group (i.e., employing a general threshold of BS $>12\%$ or $<12\%$) divided by 100. Monte Carlo randomization tests were performed with 4999 iterations for each final indicator value and the indicator values were considered statistically significant at $\alpha = 0.05$. A significant indicator value for a species suggests that the species is more abundant and constant in a particular group (BS $>$ or $<$ 12%) than would be expected by chance.

# 5 Project Findings

The earlier *A. saccharum* tree assessment showed that trees growing on soils with poor acid-base chemistry (low exchangeable calcium and base saturation) that received relatively high levels of atmospheric sulfur and nitrogen deposition exhibited little to no *A. saccharum* seedling regeneration, relatively poor canopy condition, and short- to long-term growth declines compared with study plots having better soil condition and lower levels of acidic deposition. *A. saccharum*, followed by *Fagus grandifolia*, was the dominant tree species in all study plots. Nevertheless, *A. saccharum* sapling abundance was low, with nearly half of the study plots having no *A. saccharum* saplings. *A. saccharum* seedling abundance was also low on most plots during both assessments, especially compared with *F. grandifolia*. While all plots contained mature *A. saccharum* trees in the canopy, plots that contained *A. saccharum* seedlings had significantly higher soil base saturation and exchangeable calcium compared with plots that lacked *A. saccharum* seedlings. *A. saccharum* seedling abundance was lowest on plots with upper B horizon soil base saturation less than 12% and highest on plots with base saturation greater than 20%.

Results from the analysis showed that understory species richness was positively related to both exchangeable calcium concentrations and base saturation in both the $O_a$ and upper B horizons (for example, Figure 3). Some plant species showed pronounced patterns in the relationship between soil base saturation and percent plant cover (Figure 4), with either increasing (i.e., *A. saccharum*) or decreasing (i.e., *Dryopteris intermedia*) cover with increasing soil base saturation. Soil base saturation was not the only plausible driving variable since it was closely correlated with several other functionally related variables—positively with soil pH and calcium (Ca) and magnesium (Mg) concentrations, and negatively with the deposition levels (S, N) and Al concentrations—that described various aspects of the composite gradient of soil acidification across the studied watersheds (Figure 7) and lead to several alternative and equally plausible models explaining variation in understory plant richness. Cover of two plant groups (ferns and club mosses) showed higher percent cover on the study plots that had relatively low soil base saturation (Figure 5). Tipping points for cover were near 10-20% for the base saturation of the upper B soil horizon.

**Figure 3. Plots of understory richness versus base saturation of the $O_a$ horizon and upper B horizon (transformed by Box-Cox, -0.5) of the soil. P-value for each model < 0.001**

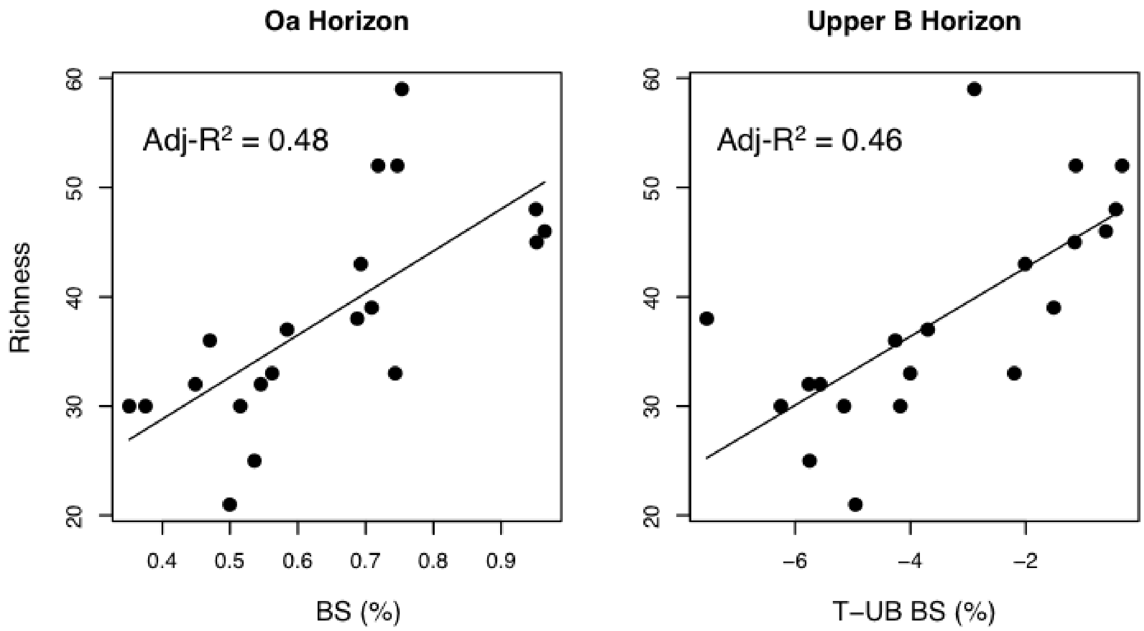



**Figure 4. Percent cover of selected individual plant species as functions of base saturation of the $O_a$ soil horizon (left) and upper B soil horizon (right)**

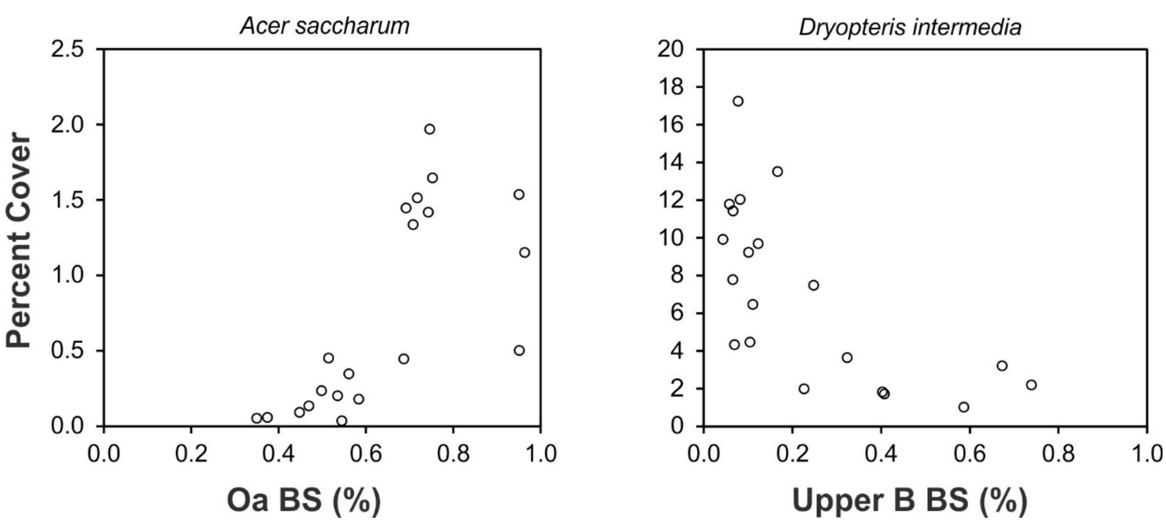


**Figure 5. Plot-level percent cover of selected plant types versus the base saturation (BS) of the upper B soil horizon**

Other plant types did not show evidence of clear relationships with base saturation.

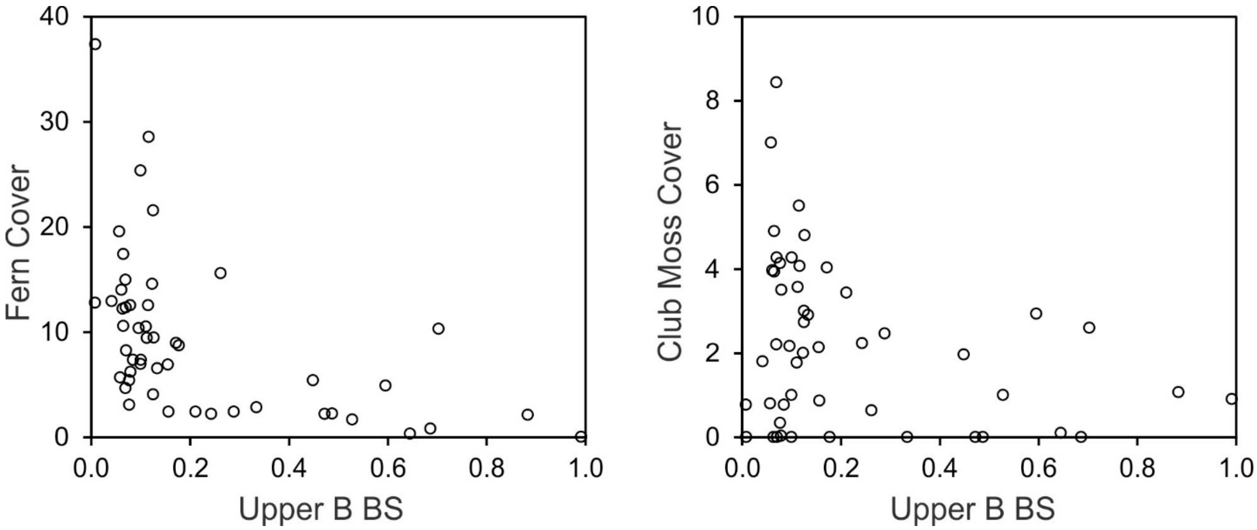


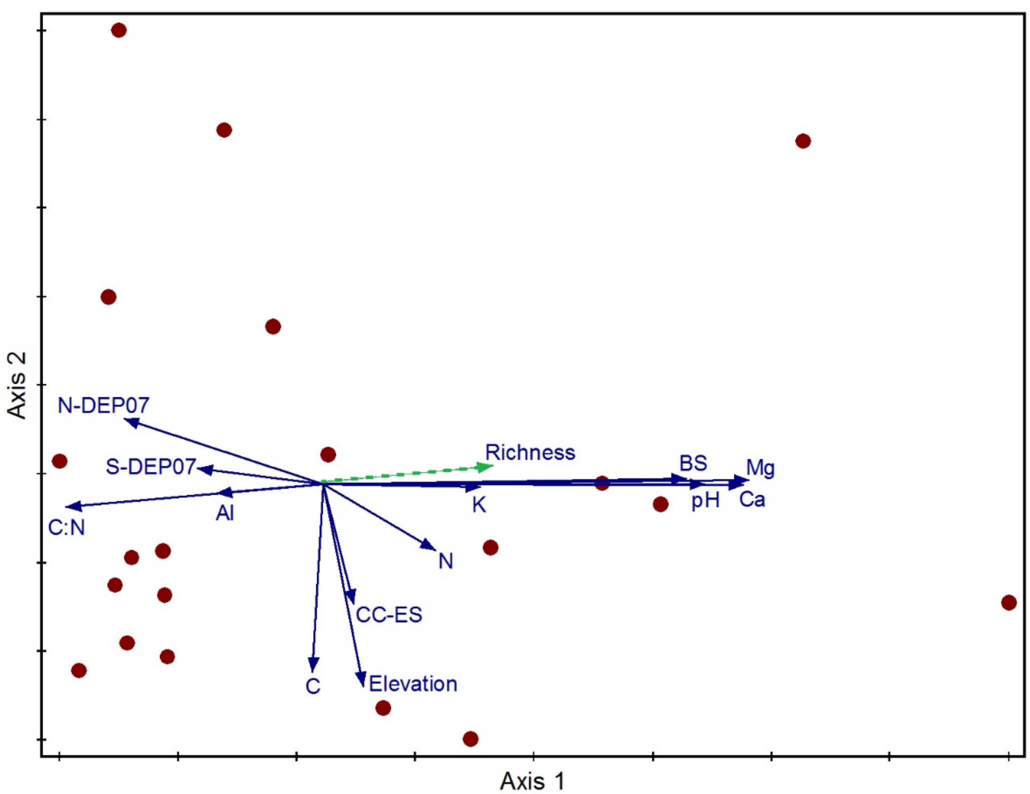

Figure 6 shows photographs of example plots having high and low understory plant richness and cover. The final two-dimensional NMDS ordination model (Figure 7) was highly significant ($p \leq 0.01$) in representing differences in species composition across the study watersheds. The two identified statistical axes explained 63.3% and 27.8%, respectively, of the variation in plant species composition (total 91.1% explained). Each axis was related to clear environmental gradients. Axis 1 reflected a soil acidity-acidic deposition gradient. Thus, soil pH, base saturation, and the exchangeable nutrient base cations Ca and Mg were strongly positively correlated with the acidity gradient axis, whereas aluminum, carbon-to-nitrogen ratio, and sulfur deposition were negatively correlated with this axis. Axis 1 is represented by soil acid-base chemistry, with vectors of base saturation, pH, and exchangeable base cations (magnesium, calcium) to the right (positive relationship) and sulfur deposition and aluminum to the left (negative relationship). Axis 2 is negatively related to total percent carbon and percent canopy cover, which reflect aspects of nutrition and carbon cycling. Total soil nitrogen correlated similarly well with both axes, likely because total soil nitrogen can be positively affected by plant nutrition and carbon cycling in addition to the effects of atmospheric deposition (deposited nitrogen has to be taken up by plants or microbes or it is largely leached from the soil system). Plant understory richness was strongly correlated ($r=0.609$) with Axis 1 (green line, Figure 7), but unrelated to Axis 2, suggesting that understory richness in the herb layer of these forests was mainly controlled by acid-base chemistry and sulfur deposition.

**Figure 6. Example plots with a) high richness, b) high cover, and c) low richness and cover**

*Photo credit: M.R. Zarfos*


**Figure 7. Vectors showing correlations of species richness and abiotic variables with NMDS ordination of species composition across watersheds**

Only correlations having p ≥ 0.4 are shown. The length of each vector is drawn proportional to the strength of the respective correlation. This chart shows that Axis 1 is represented by soil acid-base chemistry, with vectors of base saturation (BS), pH, and exchangeable base cations (Mg, Ca) to the |right (positive relationship) and sulfur deposition (S-DEP07) and aluminum (Al) to the left (negative relationship). Axis 2 is negatively related to total percent carbon (C) and percent canopy cover (CC-ES), which reflect aspects of nutrition and carbon cycling. Deposition estimates are three-year averages centered on 2007. Watersheds are represented by filled circles.



Several plant species (e.g., *Arisaema triphyllum, Fraxinus americana, A. saccharum,* and *Tiarella cordifolia*) were strongly and positively correlated with Axis 1, suggesting positive responses to increasing pH, base saturation, and availability of plant base cation nutrients. Other plant species (e.g., *D. intermedia, Acer pennsylvanicum, Acer rubrum,* and *Dennstaedtia punctilobula*) were negatively correlated with Axis 1 and increased with acidic deposition and soil acidification.

Indicator Species Analysis values and species indicative of the two soil upper B horizon base saturation groups (watersheds with average base saturation below or above 12%) are displayed in Table 1 and Table 2 based on 95% confidence intervals. Photographs of the identified indicators are shown in Figure 8 and Figure 9. The indicator values (and their associated p-values) given in the tables highlight the strength of the association between a given species and an environmental condition. Thus, *D. punctilobula* had the strongest association with the occurrence of relatively low upper B horizon base saturation. The ratio of number of plant species identified as indicators of relatively high base saturation in the upper B soil horizon (> 12%) divided by the number of indicators of low base saturation (< 12%) decreased with increasing sulfur and nitrogen deposition (Figure 10). Apparent tipping points were near 12 kg/ha/yr of both sulfur and nitrogen deposition (based on deposition data centered on 2001).

**Table 1. Indicators of base saturation < 12% in the upper B horizon**

| Species | Indicator Value | P-value |
|---|---|---|
| *Dennstaedtia punctilobula* | 77.6 | 0.004 |
| *Acer rubrum* | 71 | 0.0094 |
| *Acer pennsylvanicum* | 65.4 | 0.018 |
| *Dryopteris intermedia* | 59.6 | 0.0058 |

**Table 2. Indicators of base saturation > 12% in the upper B horizon**

| Species | Indicator Value | P-value |
|---|---|---|
| *Arisaema triphyllum* | 81.6 | 0.0016 |
| *Fraxinus americana* | 80.0 | 0.0012 |
| *Acer saccharum* | 78.6 | 0.0004 |
| *Viola rotundifolia* | 64.1 | 0.0466 |
| *Prenanthes sp.* | 60.0 | 0.0116 |
| *Tiarella cordifolia* | 56.6 | 0.0182 |
| *Lonicera canadensis* | 56.4 | 0.0116 |
| *Viola renifolia* | 50.0 | 0.0336 |
| *Galium triflorum* | 50.0 | 0.0304 |

**Figure 8. Indicators of upper B horizon base saturation < 12%: a) *Acer pennsylvanicum*, b) *Acer rubrum*, c) *Dennstaedtia punctilobula*, and d) *Dryopteris intermedia***

*Photo credit: M.R. Zarfos*

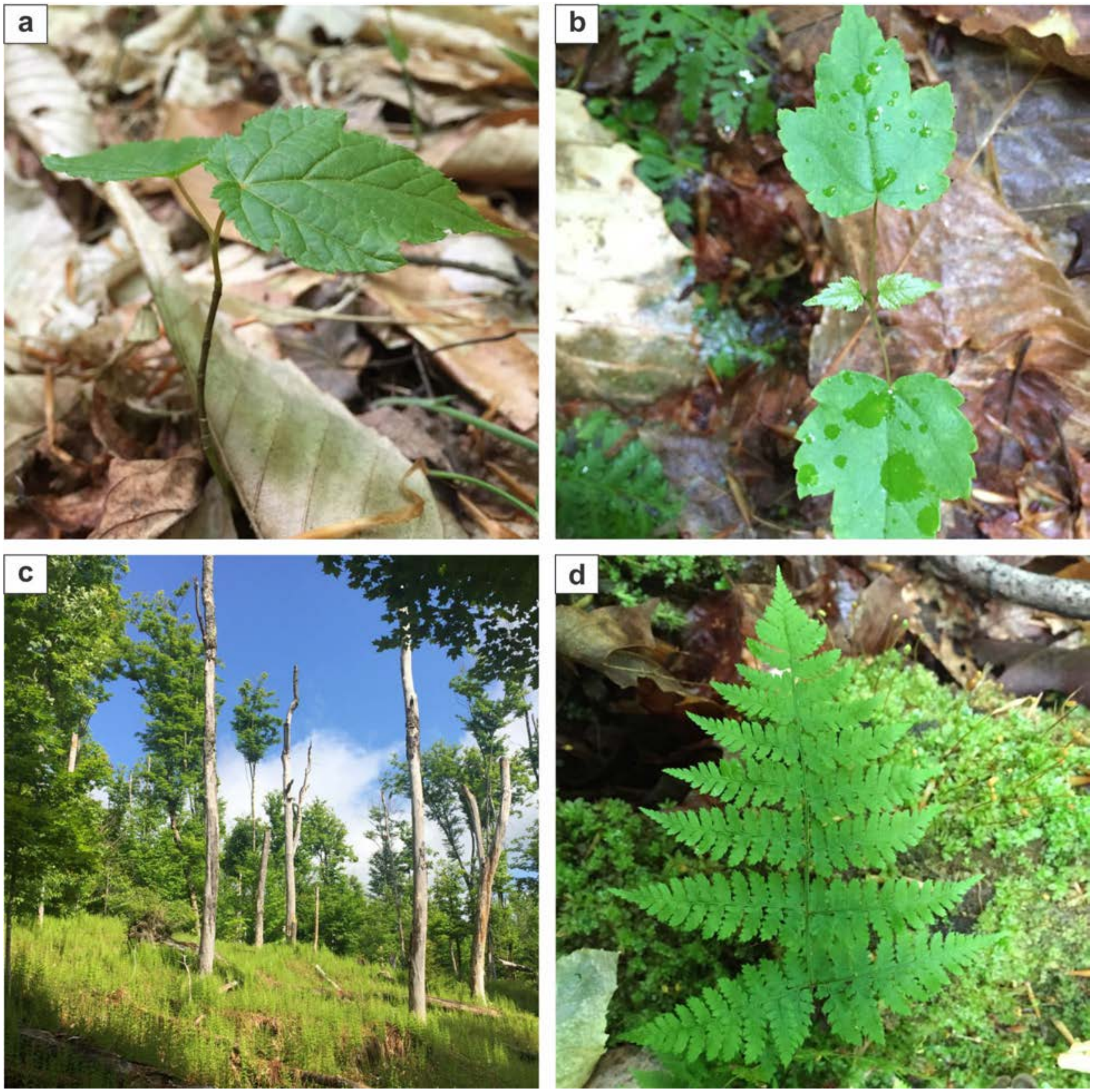


**Figure 9. Indicators of upper B horizon base saturation > 12%: a) Acer saccharum, b) Arisaema triphyllum, c) *Fraxinus americana*, d) *Galium triflorum*, e) *Lonicera canadensis*, f) *Prenanthes* sp., g) *Tiarella cordifolia*, h) V*iola renifolia*, and i) *Viola rotundifolia***

*Photo credit: M.R. Zarfos*

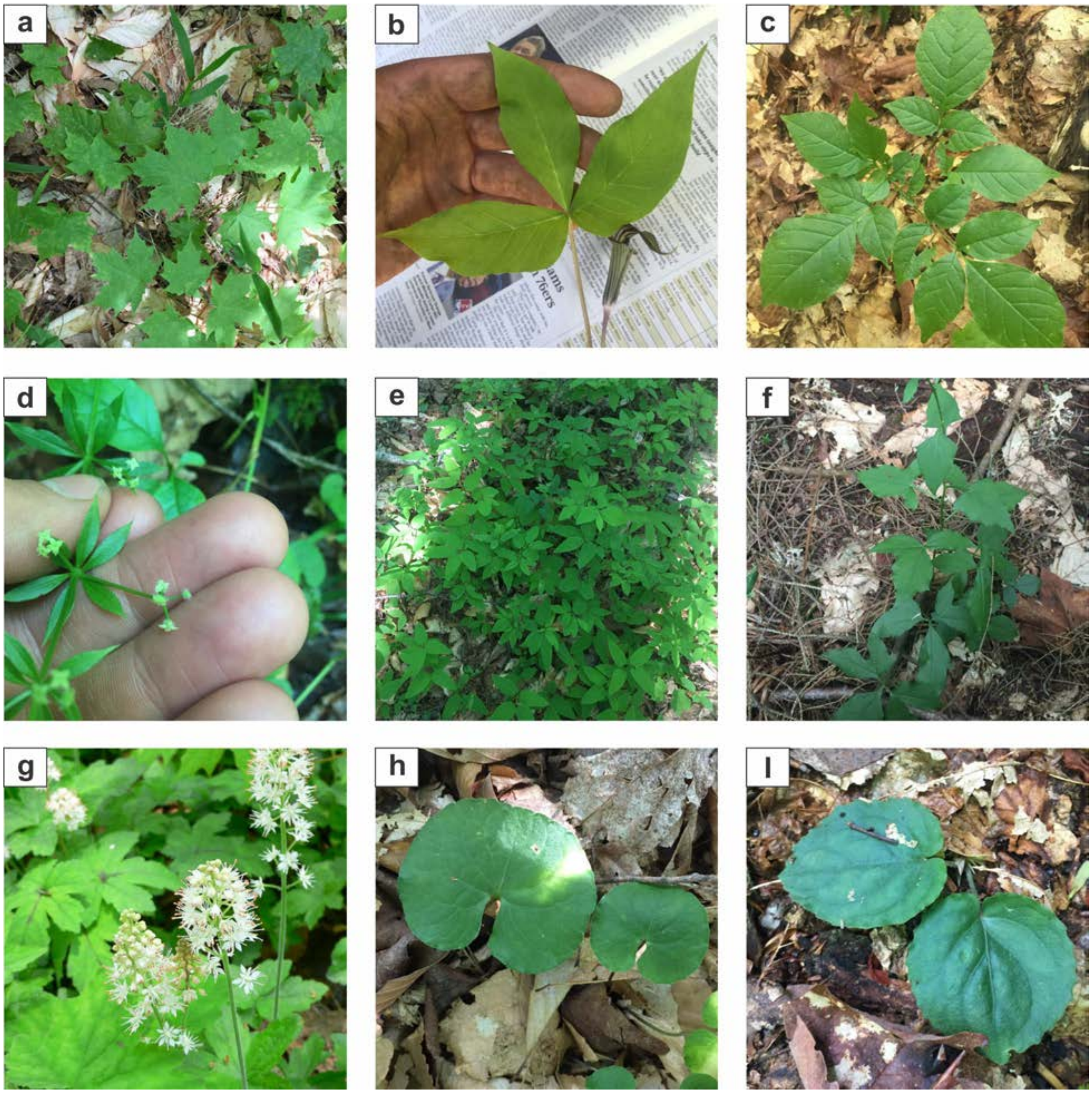
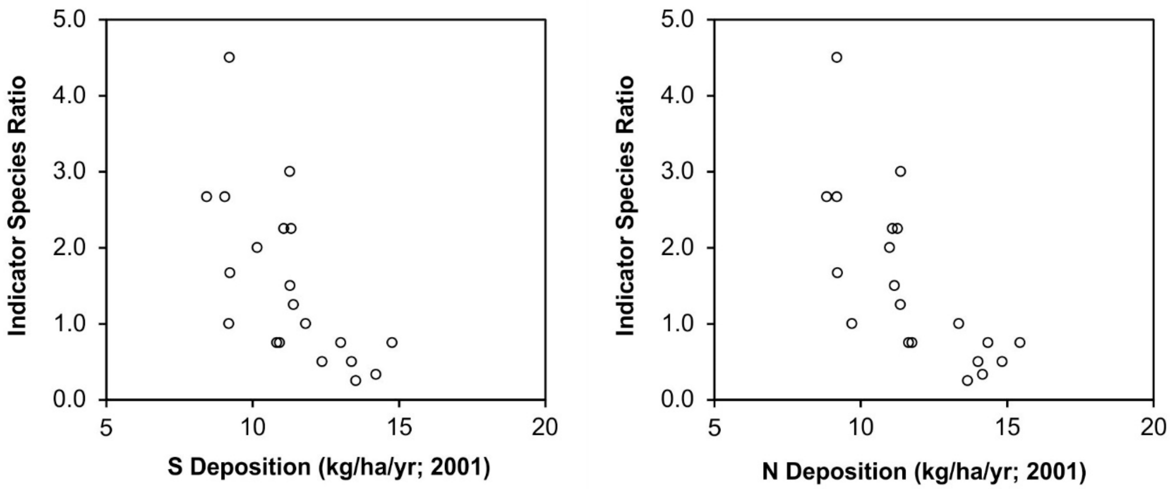


**Figure 10. Indicator species ratio versus sulfur (S) deposition (left) and nitrogen (N) deposition (right) during the period 2000-2002**

The indicator species ratio was calculated, by watershed, as the number of plant species indicators of base saturation > 12% divided by the number of plant species indicator of base saturation < 12%.



# 6 Project Implications

This research contributes to the scientific foundation for determining the extent to which northern hardwood forests and their soils in the western Adirondack Mountains have been impacted by acidic deposition. It also provides context for estimating the degree to which impacted forests might recover, both chemically (soils) and biologically (vegetation), following recent and perhaps future reductions in acidic deposition. This information will help policy makers better understand and evaluate the impact of efforts to reduce acidic deposition in New York State and to determine locations where forest recovery is not likely to occur in the absence of restoration activities (e.g., watershed liming, plant-species reintroductions).

Watersheds differ in the extent to which they are sensitive to excess acidity or nutrient availability. Such differences are reflected in critical and target loads, which illustrate the thresholds of atmospheric sulfur and/or nitrogen deposition as well as the level (above or below) that harmful ecological effects are or are not expected. The critical load is usually calculated to reflect a long-term, steady-state condition far into the future. The target load is usually specific to a particular management time frame. Details of critical and target load calculations, which can be complex and confusing, are summarized by Sullivan and Jenkins (2014) and Burns and Sullivan (2015). Calculation of either requires specification of what will be protected (e.g., *A. saccharum* regeneration or herbaceous plant species composition), the critical indicator of protection (e.g., base saturation in the upper B soil horizon), the level to which the indicator will be protected (e.g., higher than 12%), where the protection will occur (e.g., northern hardwood forests in the Adirondack Park), and the time frame of protection (e.g., year 2050). Each ecosystem will have many critical and target loads. An empirical critical load can be developed using an empirical approach based on spatial or temporal gradient studies (cf., Simkin et al. 2016) or experimental manipulations of pollutant inputs (cf., Gilliam 2006).

Results of this study of forest understory plant community relationships with soil chemistry and acidic deposition can be used in developing chemical and biological thresholds for analysis of critical and target loads. A chemical threshold is a value of the chemical criterion (e.g., base saturation in upper B horizon) beyond which the biological receptor of interest is negatively impacted (Aherne et al. 2001). The biological receptor is a biological element (e.g., understory richness or the presence of the indicator species) that is impacted by the conditions created by acidic or nutrient deposition.

Analysis of the relationship between sulfur deposition and species richness of Adirondack understory plants illustrates a limitation of the empirical critical load approach. Because acidic deposition in the Adirondacks has changed substantially during recent years, the deposition levels at which changes in richness become evident depends on the time frame of the analysis, although the spatial distribution of locally high and low deposition have likely changed only marginally. Nevertheless, watersheds that exhibited the lowest species richness were consistently those that received highest sulfur and nitrogen deposition (Figure 11 and Figure 12). The extent to which deposition levels have changed over recent years can be seen in the maps depicted in Figure 13 and Figure 14 for total sulfur and nitrogen deposition, respectively. These maps compare Total Deposition (TDEP; Schwede and Lear 2014) estimates for an early three-year average period of relatively high deposition (2000-2002, earliest available TDEP estimates) with a more recent period of comparatively low deposition (2011-2013). During the earlier period, all of the study watersheds for this project exhibited nitrogen deposition higher than 8 kg N/ha/yr and seven watersheds received more than 12 kg N/ha/yr. During the latter period, most watersheds exhibited nitrogen deposition lower than 8 kg N/ha/yr. It is likely that understory plants are in fact responding to the cumulative input of nitrogen and sulfur over a sustained period that is unknown and variable across species. Thus, atmospheric deposition as it affects plants is a moving target. This same limitation applies to calculation of critical- and target-load exceedances, which indicate the extent to which ambient deposition exceeds the critical and target loads.

**Figure 11. Total sulfur (S) deposition received by study watersheds in three richness classes during the three-year periods centered on 2001 and 2012 and for the full period of record (2000-2013)**

Low, intermediate, and high richness watersheds are classified into classes 1 (n=21-32), 2 (n=33-43), and 3 (n=45-59), respectively.

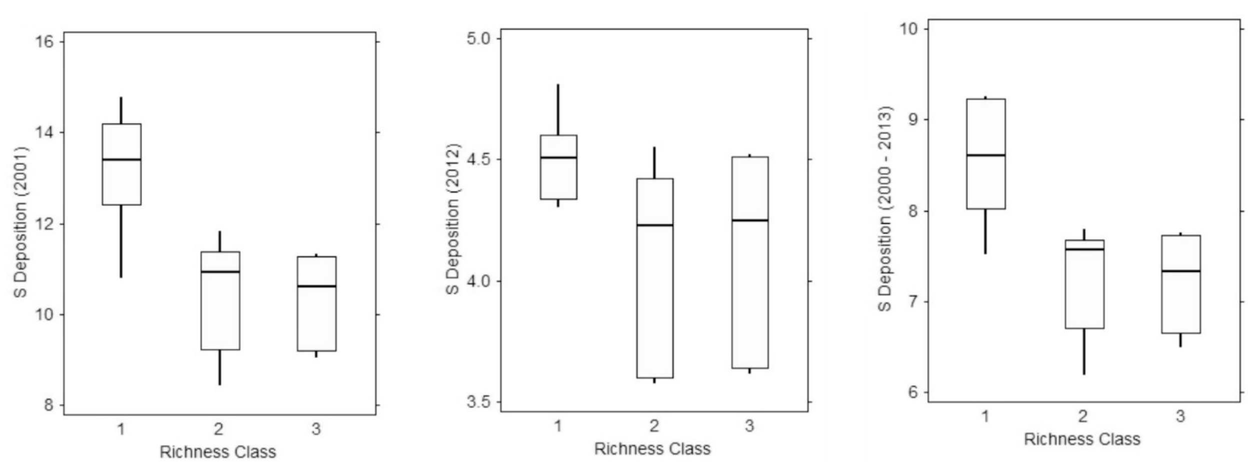


**Figure 12. Total nitrogen (N) deposition received by study watersheds in three richness classes during the three-year periods centered on 2001 and 2012 and for the full period of record (2000-2013)**

Low, intermediate, and high richness watersheds are classified into classes 1, 2, and 3, respectively.

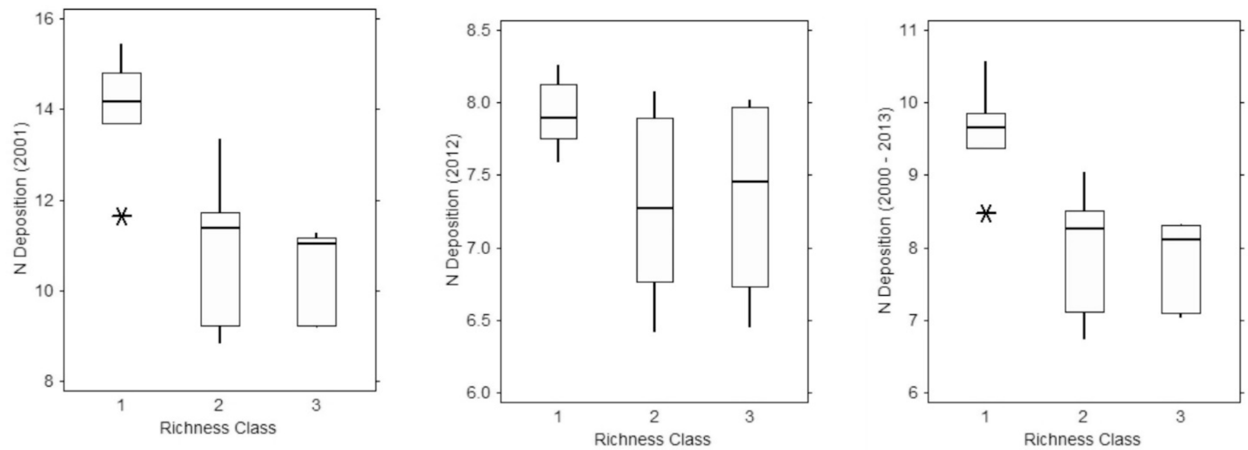



**Figure 13. Three-year average total atmospheric sulfur deposition estimates across the study region, centered on 2001 (left) and 2012 (right)**

*Source of data: Schwede and Lear (2014)*

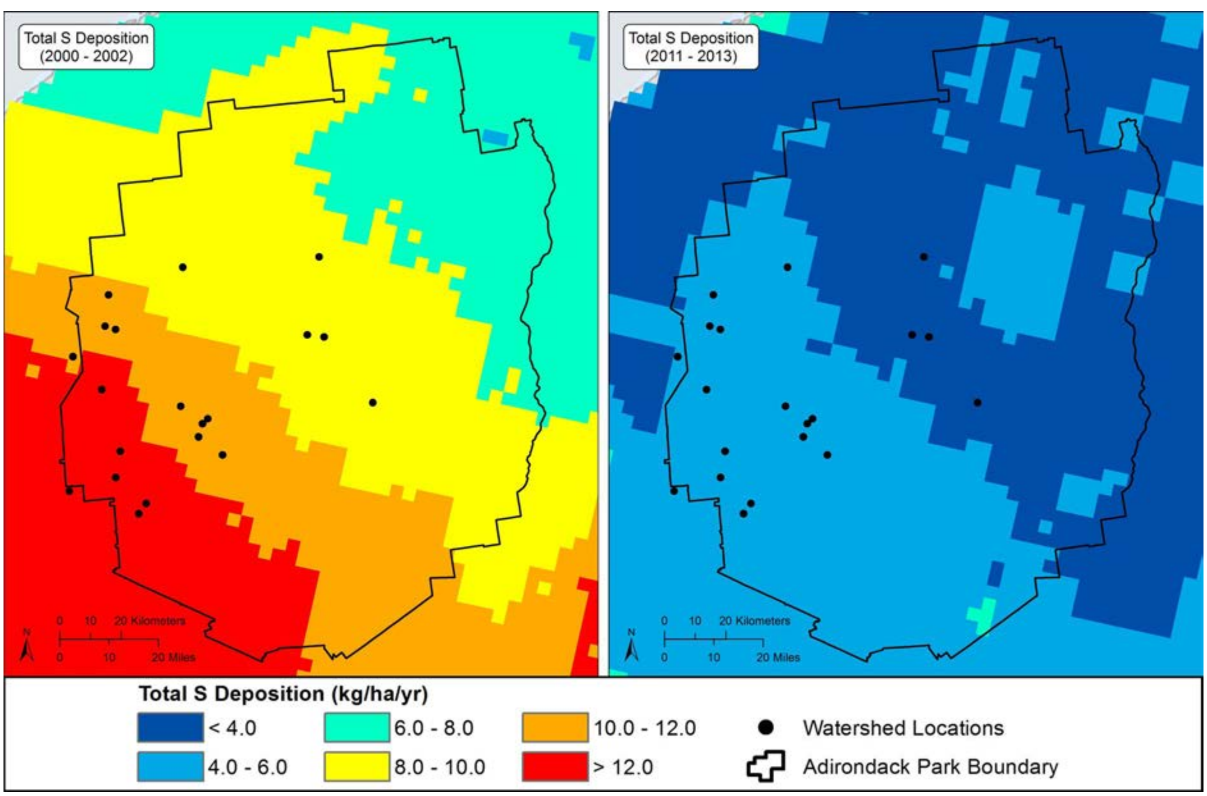
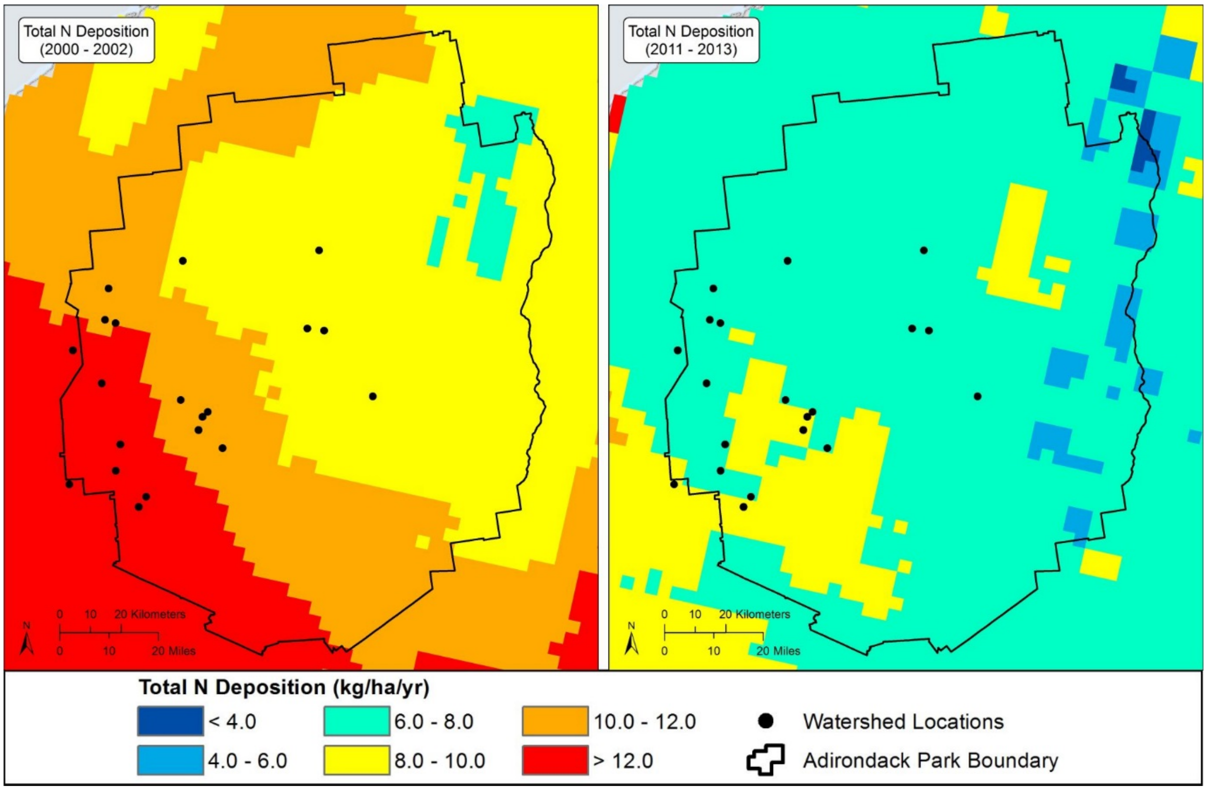


**Figure 14. Three-year average total atmospheric nitrogen deposition estimates across the study region, centered on 2001 (left) and 2012 (right)**

*Source of data: Schwede and Lear (2014)*




Soil acidification and base cation deficiency can interact with other plant stressors, including drought, insect defoliation, and cold temperatures (cf., Horsley et al. 1999). The presence of non-native plant species can magnify the impacts on the plant community because some non-native species commonly outcompete native species in the presence of high nitrogen supply (Bobbink et al. 2010). Herbaceous plant indicators of soil acid-base and/or nutrient status can provide diagnostic tools for land managers to ascertain where *A. saccharum*, for example, are likely at risk for harm caused by stressful conditions. Such information can inform decisions about the likelihood of a successful insect control program or other management action. Thus, indicator species information might be used to prioritize pest-suppression activities (Horsley et al. 2008) and may, in some cases, serve as an inexpensive substitute for a soil chemistry survey.

# 7 Conclusions

Results of this research suggested that plant understory richness in Adirondack hardwood forests was controlled significantly by acidic deposition and soil acid-base chemistry. Both bivariate and multivariate analyses clearly illustrated an association between the base status of the $O_a$ and upper B soil horizons and plant understory richness, cover, and species composition. In particular, richness is lower where soil base saturation is relatively low and both sulfur and nitrogen deposition are/were relatively high. Species that indicate either relatively low (< 12%) or high (> 12%) base saturation were identified. These findings will assist in the development of critical and target loads of acidic deposition for protecting plant biodiversity in the Adirondacks, a highly sensitive and impacted region. Models with which to accomplish this are under development (Belyazid et al. 2011a, 2011b, Reinds et al. 2014, Bonten et al. 2016, McDonnell et al. 2018 a, b).

# 8 Glossary

***Acidic deposition*** is the collective contribution of acidifying compounds (sulfur, nitrogen) via rain, snow, hail, fine particles, fog, ground-level clouds, and gasses that deposit from the atmosphere to the surface of the earth and cause acidification of soils, soil water, lakes, and streams. Wet deposition in rain and snow is measured by a network of precipitation monitors. Dry deposition is estimated using models that consider measured air concentrations of contaminants and the morphology of vegetation surfaces.

***Biodiversity*** typically reflects the varying organisms of a particular type (taxa; usually expressed as species), such as, for example, trees or forest herbaceous understory plants, that occur in an ecosystem. Diversity is largely represented by richness, which describes the number of different taxa (species) present on a plot or in a forest.

***Base Cation Nutrition****:* Plants require adequate amounts of available positively charged, nutrient-base cations, including calcium, magnesium, and potassium to sustain their growth and health. These base cation nutrients are largely supplied by the slow breakdown of geologic materials in the process called weathering and are stored on exchange sites within the soil (especially clay minerals and soil organic matter). The cation supply can be diminished by acid deposition to the extent that mobile negatively charged anions supplied by acid deposition (sulfate and nitrate) are charge balanced in the drainage water that flows through a watershed by basic, as opposed to acidic, cations. The latter include aluminum and hydrogen, both of which can be toxic. The extent of base cation depletion is commonly reflected by the soil base saturation measurement or the amount of exchangeable calcium and/or magnesium.

***Chemical and Biological Impacts****:* Ecosystem damage caused by atmospheric deposition and subsequent resource recovery can be expressed as chemical and/or biological indicators and impacts. Chemical effects might, for example, be quantified as a change in the base saturation or the carbon-to-nitrogen ratio of a particular soil horizon. Measurement of a biological response might include the richness of the plant community or the presence or absence of a particular indicator species that is known to be associated positively or negatively with adverse impacts. Measurement of chemical effects or chemical recovery is often more straight-forward and less complicated than measurement of biological effects.

***Critical load*** is informally defined as the threshold of atmospheric deposition below which specified harmful ecological effects should not occur (Porter et al. 2005). The critical load is often calculated or estimated as a long-term, steady-state condition many years into the future. Estimates specific to a management time frame such as, for example, the year 2050 are called target loads or dynamic critical loads. Critical and target loads can be estimated empirically from the results of gradient or experimental studies or using a process model.

***Environmental Management and Policy****:* Adoption of effective environmental management options and development of environmental policy reflect a balance among competing visions of how and to what extent human activities affect natural ecosystems as well as the costs and benefits of protecting those ecosystems (Burns and Sullivan 2015). Environmental science can help inform the development of sound management strategies and policy. Plant community biodiversity, the presence or absence of indicator species, and critical and target loads offer useful concepts and metrics that aid in the development of sound policy and management actions.

# 9 References

Aherne, J., E.P. Farrell, J. Hall, B. Reynolds, and M. Hornung. 2001. Using multiple chemical criteria for critical loads of acidity in maritime regions. Water, Air and Soil Pollution: Focus 1(1):75-90. 10.1023/a:1011578311375.

Belyazid, S., D. Kurz, S. Braun, H. Sverdrup, B. Rihm, and J.-P. Hettelingh. 2011a. A dynamic modelling approach for estimating critical loads of nitrogen based on plant community changes under a changing climate. Environ. Pollut. 159:789-801.

Belyazid, S., H. Sverdrup, D. Kurz, and S. Braun. 2011b. Exploring ground vegetation change for different deposition scenarios and methods for estimating critical loads for biodiversity using the ForSAFE-Veg model in Switzerland and Sweden. Water Air & Soil Pollution 216:289-317.

Bobbink, R., K. Hicks, J. Galloway, T. Spranger, R. Alkemade, M. Ashmore, M. Bustamante, S. Cinderby, E. Davidson, F. Dentener, B. Emmett, J.-W. Erisman, M. Fenn, F.S. Gilliam, A. Nordin, L. Pardo, and W. DeVries. 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecol. Appl. 20(1):30-59.

Bonten, L.T.C., G.J. Reinds, and M. Posch. 2016. A model to calculate effects of atmospheric deposition on soil acidification, eutrophication and carbon sequestration. Environ. Model. Software 79:75-84. http://dx.doi.org/10.1016/j.envsoft.2016.01.009.

Burns, D.A., J.A. Lynch, B.J. Cosby, M.E. Fenn, J.S. Baron, and U.S. Environmental Protection Agency - Clean Air Markets Division. 2011. National Acid Precipitation Assessment Program Report to Congress 2011: An Integrated Assessment. National Science and Technology Council, Washington, DC.

Burns, D.A. and T.J. Sullivan. 2015. Critical loads of Atmospheric Deposition to Adirondack Lake Watersheds: A Guide for Policymakers. New York State Energy Research and Development Authority, Albany, NY. 14 pp.

Daubenmire, R. 1959. A canopy-coverage method of vegetation analysis. Northwest Sci. 33:43-64.

Driscoll, C.T., G.B. Lawrence, A.J. Bulger, T.J. Butler, C.S. Cronan, C. Eagar, K.F. Lambert, G.E. Likens, J.L. Stoddard, and K.C. Weathers. 2001a. Acidic deposition in the northeastern United States: sources and inputs, ecosystem effects, and management strategies. BioScience 51(3):180-198.

Driscoll, C.T., G.B. Lawrence, A.J. Bulger, T.J. Butler, C.S. Cronan, C. Eagar, K.F. Lambert, G.E. Likens, J.L. Stoddard, and K.C. Weathers. 2001b. Acid Rain Revisited: Advances in Scientific Understanding Since the passage of the 1970 and 1990 Clean Air Act Amendments. Vol. 1, No. 1. Hubbard Brook Research Foundation. Science Links Publication, Hanover, NH.

Dufrêne, M. and P. Legendre. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecol. Monogr. 67(3):345-366. 10.1890/0012-9615(1997)067[0345:SAAIST]2.0.CO;2.

Fridley, J.D., R.K. Peet, T.R. Wentworth, and P.S. White. 2005. Connecting fine- and broad-scale species–area relationships of southeastern U.S. flora. Ecology 86(5):1172-1177. 10.1890/03-3187.

Gilliam, F.S. 2006. Response of the herbaceous layer of forest ecosystems to excess nitrogen deposition. J. Ecol. 94(6):1176-1191.

Gilliam, F.S. 2007. The ecological significance of the herbaceous layer in temperate forest ecosystems. BioScience 57(10):845-858.

Horsley, S.B., R.P. Long, S.W. Bailey, R.A. Hallet, and T.J. Hall. 1999. Factors contributing to sugar maple decline along topographic gradients on the glaciated and unglaciated Allegheny Plateau. *In* S.B. Horsley and R.P. Long (Eds.). Sugar Maple Ecology and Health: Proceedings of an International Symposium. Radnor (PA): U.S. Department of Agriculture, Forest Service. General Technical Report NE-261. pp. 60-62.

Horsley, S.B., S.W. Bailey, T.E. Ristau, R.P. Long, and R.A. Hallett. 2008. Linking environmental gradients, species composition, and vegetation indicators of sugar maple health in the northeastern United States. Can. J. For. Res. 38:1761-1774.

Jenkins, M.A., S. Jose, and P.S. White. 2007. Impacts of an exotic disease and vegetation change on foliar calcium cycling in Appalachian Forests. Ecol. Appl. 17(3):869-881.

Lawrence, G.B., B.P. Baldigo, K.M. Roy, H.A. Simonin, R.W. Bode, S.I. Passy, and S.B. Capone. 2008. Results from the 2003-2005 Western Adirondack Stream Survey. Final Report 08-22. New York State Energy Research and Development Authority (NYSERDA).

Lawrence, G.B., J.E. Dukett, N. Houck, P. Snyder, and S. Capone. 2013. Increases in dissolved organic carbon accelerate loss of toxic Al in Adirondack lakes recovering from acidification. Environ. Sci. Technol. 47(13):7095-7100. 10.1021/es4004763.

McDonnell, T.C., G.J. Reinds, T.J. Sullivan, C.M. Clark, L.T.C. Bonten, J.P. Mol-Dijkstra, G.W.W. Wamelink, and M. Dovciak. 2018a. Feasibility of coupled empirical and dynamic modeling to assess climate change and air pollution impacts on temperate forest vegetation of the eastern United States. Environ. Pollut. 234:902-914. doi.org/10.1016/j.envpol.2017.12.002.

McDonnell, T.C., S. Belyazid, T.J. Sullivan, M. Bell, C. Clark, T. Blett, T. Evans, W. Cass, A. Hyduke, and H. Sverdrup. 2018b. Vegetation dynamics associated with changes in atmospheric nitrogen deposition and climate in hardwood forests of Shenandoah and Great Smoky Mountains national parks, USA. Environ. Pollut. 237:662-674. doi.org/10.1016/j.envpol.2018.01.112

National Acid Precipitation Assessment Program. 1991. Integrated Assessment Report. National Acid Precipitation Assessment Program, Washington, DC.

Peck, J.E. 2010. Multivariate Analysis for Community Ecologists: Step-by-Step using PC-ORD. MjM Software Design, Gleneden Beach, OR.

Porter, E., T. Blett, D.U. Potter, and C. Huber. 2005. Protecting resources on federal lands: implications of critical loads for atmospheric deposition on nitrogen and sulfur. BioScience 55(7):603-612.

Reinds, G.J., J. Mol-Dijkstra, L. Bonten, W. Wamelink, W. deVries, and M. Posch. 2014. VSD+PROPS: Recent developments. Chapter 4. *In* J. Slootweg, M. Posch, J.-P. Hettelingh and L. Mathijssen (Eds.). Modelling and Mapping the Impacts of Atmospheric Deposition on Plant Species Diversity in Europe. CCE Status Report 2014. Coordination Centre for Effects, Bilthoven, The Netherlands. pp. 47-53.

Roberts, M.R. and F.S. Gilliam. 2003. Response of the herbaceous layer to disturbance in eastern forests. *In* F.S. Gilliam and M.R. Roberts (Eds.). The Herbaceous Layer in Forests of Eastern North America. Oxford University Press, New York. pp. 302-320.

Schwede, D.B. and G.G. Lear. 2014. A novel hybrid approach for estimating total deposition in the United States. Atmos. Environ. 92:207-220. http://dx.doi.org/10.1016/j.atmosenv.2014.04.008.

Simkin, S.M., E.B. Allen, W.D. Bowman, C.M. Clark, J. Belnap, M.L. Brooks, B.S. Cade, S.L. Collins, L.H. Geiser, F.S. Gilliam, S.E. Jovan, L.H. Pardo, B.K. Schulz, C.J. Stevens, K.N. Suding, H.L. Throop, and D.M. Waller. 2016. Conditional vulnerability of plant diversity to atmospheric nitrogen deposition across the United States. Proceedings of the National Academy of Science 113(15):4086-4091. 10.1073/pnas.1515241113.

Sullivan, T.J., C.T. Driscoll, B.J. Cosby, I.J. Fernandez, A.T. Herlihy, J. Zhai, R. Stemberger, K.U. Snyder, J.W. Sutherland, S.A. Nierzwicki-Bauer, C.W. Boylen, T.C. McDonnell, and N.A. Nowicki. 2006a. Assessment of the Extent to Which Intensively-Studied Lakes Are Representative of the Adirondack Mountain Region. Final Report 06-17. New York State Energy Research and Development Authority, Albany, NY.

Sullivan, T.J., I.J. Fernandez, A.T. Herlihy, C.T. Driscoll, T.C. McDonnell, N.A. Nowicki, K.U. Snyder, and J.W. Sutherland. 2006b. Acid-base characteristics of soils in the Adirondack Mountains, New York. Soil Sci. Soc. Am. J. 70:141-152.

Sullivan, T.J., B.J. Cosby, C.T. Driscoll, T.C. McDonnell, and A.T. Herlihy. 2011. Target loads of atmospheric sulfur deposition to protect terrestrial resources in the Adirondack Mountains, New York against biological impacts caused by soil acidification. J. Environ. Stud. Sci. 1(4):301-314.

Sullivan, T.J., B.J. Cosby, C.T. Driscoll, T.C. McDonnell, A.T. Herlihy, and D.A. Burns. 2012. Target loads of atmospheric sulfur and nitrogen deposition for protection of acid sensitive aquatic resources in the Adirondack Mountains, New York. Water Resour. Res. 48:doi:10.1029/2011WR011171.

Sullivan, T.J., G.B. Lawrence, S.W. Bailey, T.C. McDonnell, and G.T. McPherson. 2013. Effects of Acidic Deposition and Soil Acidification on Sugar Maple Trees in the Adirondack Mountains, New York. NYSERDA Report No. 13-04. New York State Energy Research and Development Authority, Albany, NY.

Sullivan, T.J., B.J. Cosby, C.T. Driscoll, T.C. McDonnell, A.T. Herlihy, and D.A. Burns. 2014. Critical Loads of Sulfur and Nitrogen for Protection of Acid Sensitive Aquatic and Terrestrial Resources in the Adirondack Mountains. Summary Report. New York State Energy Research and Development Authority (NYSERDA). 14-11. E&S Environmental Chemistry, Corvallis, OR.

Sullivan, T.J. and J. Jenkins. 2014. The science and policy of critical loads of pollutant deposition to protect sensitive ecosystems in NY. Ann. NY Acad. Sci. 1313:57-68. doi: 10.1111/nyas.12407.

Sullivan, T.J. 2015. Air Pollutant Deposition and Its Effects on Natural Resources in New York State. Cornell University Press, Ithaca, NY. 307 pp.

Sullivan, T.J., M.R. Zarfos, M. Dovciak, T.C. McDonnell, and G.B. Lawrence. 2017. Effects of Acid Deposition on the Biodiversity of Forest Understory Plant Communities in the Northern Hardwood Forests of the Adirondack Mountain Region. Final Technical Report. New York State Energy Research and Development Authority (NYSERDA), Albany, NY.

Sutherland, J.W., F.W. Acker, J.A. Bloomfield, C.W. Boylen, D.F. Charles, R.A. Daniels, L.W. Eichler, J.L. Farrell, R.S. Feranec, M.P. Hare, S.L. Kanfoush, R.J. Preall, S.O. Quinn, H.C. Rowell, W.F. Schoch, W.H. Shaw, C.A. Siegfried, T.J. Sullivan, D.A. Winkler, and S.A. Nierzwicki-Bauer. 2015. Brooktrout Lake case study: Biotic recovery from acid deposition 20 years after the 1990 Clean Air Act Amendments. Environ. Sci. Technol. 49(5):2665-2674. 10.1021/es5036865.

U.S. Environmental Protection Agency. 2009. Risk and Exposure Assessment for Review of the Secondary National Ambient Air Quality Standards for Oxides of Nitrogen and Oxides of Sulfur: Final. EPA-452/R-09-008a. Office of Air Quality Planning and Standards, Health and Environmental Impacts Division, Research Triangle Park, NC.

NYSERDA, a public benefit corporation, offers objective information and analysis, innovative programs, technical expertise, and support to help New Yorkers increase energy efficiency, save money, use renewable energy, and reduce reliance on fossil fuels. NYSERDA professionals work to protect the environment and create clean-energy jobs. NYSERDA has been developing partnerships to advance innovative energy solutions in New York State since 1975.

To learn more about NYSERDA's programs and funding opportunities, visit nyserda.ny.gov or follow us on Twitter, Facebook, YouTube, or Instagram.

**New York State Energy Research and Development Authority**

17 Columbia Circle
Albany, NY 12203-6399

**toll free:** 866-NYSERDA
**local:** 518-862-1090
**fax:** 518-862-1091

info@nyserda.ny.gov
nyserda.ny.gov

NEW YORK STATE OF OPPORTUNITY™ | NYSERDA

**State of New York**
Andrew M. Cuomo, Governor

**New York State Energy Research and Development Authority**
Richard L. Kauffman, Chair | Alicia Barton, President and CEO