Soil Acidification and Beech Bark Disease:

Influencing the Composition and Structure of Sugar Maple/Beech Forests

Summary Report

November 2017

Report Number 17-26

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.

Soil Acidification and Beech Bark Disease:
Influencing the Composition and Structure of Sugar Maple/Beech Forests

Summary Report

Prepared for

New York State Energy Research and Development Authority

Albany, New York

Prepared by:

E&S Environmental Chemistry, Inc.

Timothy J. Sullivan
Todd C. McDonnell

in cooperation with

U.S. Geological Survey

Gregory B. Lawrence,
Michael R. Antidormi

State University of New York College of Environmental Sciences and Forestry

Martin Dovciak
Michael R. Zarfos

USDA Forest Service Hubbard Brook Experiment Station

Scott W. Bailey

NYSERDA Report 17-26 NYSERDA Contract 41874 November 2017

Notice

Abstract

The research reported here determined the associations among acidic deposition, soil base cation supply, and the responses of key tree species in the Adirondack Park. The park is an excellent location for investigating the effects of atmospheric sulfur and nitrogen deposition on forest vegetation because decades of acidic deposition have altered forest soils by decreasing the availability of calcium (Ca) in the soil. Throughout the period of high levels of acidic deposition in the Adirondack region, beech bark disease (BBD) has been infecting beech (*Fagus grandifolia*) trees. The disease often results in aggressive beech regeneration that creates a dense understory of beech seedlings and saplings. To investigate the combined effects of acidic deposition and BBD on forest stand composition and structure, we utilized measurements of soils, canopy, sub-canopy, and seedlings. Base saturation in the upper B horizon was found to be strongly correlated ($p < 0.01$) with base-cation surplus values measured in the streams of these watersheds. Interacting effects of acidic deposition and BBD have left a legacy in terms of stand composition and structure in the Adirondack hardwood forest. In watersheds where soil Ca and other base cations were depleted below 17% base saturation, the threshold for aluminum (Al) mobilization was crossed, thereby impairing growth and regeneration of sugar maple (*Acer saccharum* Marsh.) trees. Where soil base saturation falls below the 17% threshold, the ongoing dominance of beech in the understory and competition from more acid-tolerant species for gaps may limit expansion of sugar maple at these sites, even with favorable changes in soil chemistry.

Keywords

Acidification, Adirondack Mountains, sugar maple, beech bark disease, forest, beech

Acknowledgements

Support for this work was provided by the New York State Energy and Research and Development Authority (NYSERDA) through a contract with E&S Environmental Chemistry, Inc. We thank Rachel Riemann for assistance with Adirondack Forest Inventory and Analysis (FIA) data and Ivan Fernandez for his helpful manuscript review.

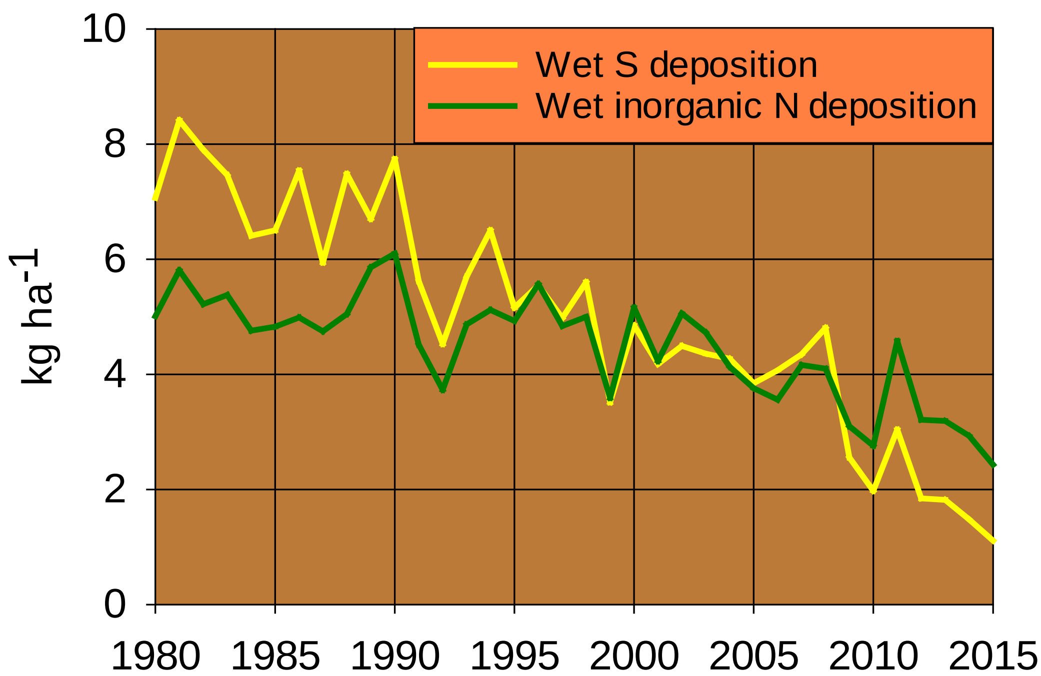
Table of Contents

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 sugar maple (*Acer saccharum* Marsh.) trees as affected by sulfur (S) and nitrogen (N) deposition and soil acidification in northern hardwood forests of the Adirondack Mountains (Sullivan et al. 2013b). Sugar maple was selected because it is an important biological resource that is sensitive to damage caused by air pollution. Interest in the other tree species in the Adirondacks led to the analysis presented in this report, which focuses on the response of the entire tree community to S and N deposition. This region has historically received relatively high levels of S and N deposition, although deposition levels have declined substantially during recent decades (Figure 1). Acidic deposition has reduced the acid-buffering capacity of soils by depleting soil reserves of the important nutrients calcium (Ca) and magnesium (Mg) at many locations, especially in the southwestern portion of the region. The research reported here determined the associations among acidic deposition, soil base cation supply, and the responses of key tree species.

Figure 1. Annual (calendar year) wet atmospheric deposition of S and inorganic N (NO3- plus NH4+) at the National Atmospheric Deposition Program site near Newcomb, NY (NY29)



The Adirondack Park, the largest state park in the United States, is an excellent location for investigating the effects of atmospheric S and N deposition on forest vegetation because it includes large spatial variations in soil-acid buffering capacity and has experienced high levels of acidic deposition. The legacy of historical acid (S, N) and nutrient (N) deposition now gains new significance as the deposition increasingly interacts with the 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.

2 Context

Sugar maple is an abundant and highly valued tree species in the forests of the Adirondack Park (Figure 2). It has experienced decline from soil-Ca depletion caused by acidic deposition over the last half century. Over the same period of time (mid-20th century to the present), beech (*Fagus grandifolia*) has been severely afflicted with beech bark disease (BBD). Because beech is a co-dominant with sugar maple in many northeastern U.S. hardwood forests, the effects of acidic deposition and BBD are likely to have a strong influence on these forests. However, the combined effects of these two harmful factors on the condition of northern hardwood forests has received minimal attention.

Figure 2. Sugar maple is the dominant canopy tree species across much of the study region

Some sugar maple in this region are several hundred years old, including the example in the image with a project researcher measuring its diameter.

Photo credit: S. Bailey.

Decades of acidic deposition (acid rain) have altered forest soils throughout eastern North America by decreasing the availability of Ca while increasing the mobility of aluminum (Al) in the rooting zone (Lawrence et al. 1995, Johnson et al. 2008, Warby et al. 2009). Sugar maple has a high-Ca demand relative to most other tree species in northern hardwood forests (Long et al. 2009), making it particularly vulnerable to the effects of acidic deposition. Research on sugar maple has linked decreased soil Ca to elevated mortality, poor stand health, impaired regeneration, and reduced growth in Quebec (Duchesne et al. 2002) and the northeastern U.S. (Schaberg et al. 2006, Long et al. 2009, Sullivan et al. 2013a).

Throughout the period of acidic deposition in the Adirondack region, BBD has been infecting beech trees (Figure 3) over much of their northern range (Houston 1994). In the northeastern U.S. and eastern Canada, beech trees are considered to be in the aftermath of the initial infection wave of BBD (Cale et al. 2015). The disease is spread by insects that introduce one of two species of fungi that eventually kills the tree (Cale et al. 2015). The mortality rate of BBD has been found to increase with tree size, but many trees survive long enough to grow into the canopy (Garnas et al. 2011). The disease often results in aggressive beech regeneration through root sprouts and seed production that create a dense understory of seedlings and saplings (Giencke et al. 2014). The high regeneration and mortality of larger trees has led to a shift toward smaller beech trees in the aftermath forest that are sufficiently abundant to maintain the pre-infection basal area of the species despite the BBD-induced mortality (Garnas et al. 2011).

Mobilization of Al is often harmful to plants, causing problems such as increased mortality of fine roots and impairment of Ca uptake (Cronan and Grigal 1995). The relationship between base saturation—a soil measure that relates concentrations of base cations to soil acidity (Al and H^+ concentrations)—and the Al mobilization threshold was defined in cation exchange modeling. The cation exchange modeling included identification of an abrupt shift in the dominance from Ca to Al in soil solutions when soil base saturation fell to between 15% and 20% (Reuss 1983). Limited field data also support Al mobilization in soil solutions below a base saturation of about 20% (Cronan and Schofield 1990), but further work was needed to identify the base saturation value at which the threshold for Al mobilization occurred.

The Al mobilization threshold is defined by an abrupt change from essentially no Al in solution to a linear increase in Al concentrations as conditions become increasingly acidic. However, the chemistry of soil solutions is difficult to determine. Instead, a chemical index of stream water termed the base-cation surplus (BCS) was used to estimate the soil base saturation value for this threshold. The BCS quantifies the relationship between concentrations of base cations and Al in stream water, but is also applicable to soil solutions. If values of BCS are greater than zero, then Al concentrations are essentially zero, which indicates that Al mobilization is not occurring in the watershed (Lawrence et al. 2007). Values of BCS less than zero have a negative linear relationship with stream concentrations of inorganic monomeric Al, the forms of Al that are mobilized by acidic deposition. By knowing the soil base saturation that relates to a BCS of zero, the soil acidification status can be quantified in terms of easily measurable soil chemistry.

Figure 3. Beech bark disease is apparent on most of the larger American beech trees in the Adirondacks

The beech tree in the image has beech bark disease. An uninfected beech tree has smooth, gray bark with few imperfections.

Photo Credit: G. Lawrence

3 Objectives

The objectives of this research are to (1) verify the relationship of base saturation to the Al mobilization threshold, (2) determine if the species composition of sugar maple-beech forests is related to base saturation, (3) evaluate how soil effects of acidic deposition and BBD combine to influence stand composition and structure, and (4) investigate temporal dynamics of a sugar maple-beech forest in an intensively monitored watershed where BBD is severe and the soil shows the beginnings of recovery from acidic deposition.

4 Methodology

To investigate the combined effects of acidic deposition and BBD on forest stand composition and structure, we utilized measurements of soils, canopy, sub-canopy, and seedlings previously collected in the Adirondack Sugar Maple Project (ASMP). The ASMP project collected data from 20 watersheds in the Adirondack region of New York State, where sugar maple and beech were the predominant canopy species. Results of the ASMP, published by Sullivan et al. (2013b) and Bishop et al. (2015), focused exclusively on sugar maple. In the ASMP study design, two or three plots (20 m by 50 m) were established in each of 20 small watersheds (< 1 km^2) that were selected to provide a wide range of Ca availability based on the chemistry of streams and soils determined in previous studies (Lawrence et al. 2008, Page and Mitchell 2008). Each of the 50 plots contained three or more sugar maple trees that were > 35 cm diameter at breast height (DBH) and of suitable form for coring to investigate growth responses. These criteria ensured that sugar maple trees were common in all study plots. Beech was also common in all 20 watersheds and occurred in all but one of the 50 plots, and BBD was identified in all of the 49 plots where beech trees were found.

This analysis also used soil and vegetation data from the 52-hectare (ha) South Tributary sub-watershed of the Buck Creek Long-Term Monitoring Watershed (hereafter the South Buck Watershed) located in the western part of the Adirondack region, near Inlet, NY (Lawrence 2002, Lawrence et al. 2011). Vegetation measurements in the South Buck Watershed were taken in 15 circular plots (9-m radii) distributed along 7 transects approximately perpendicular to the stream channel. All trees within the plots with DBH ≥ 5 cm were identified and measured for DBH in the growing seasons of 2000, 2005, 2010 and 2015.

On the ASMP plots, species, DBH, crown position, and canopy vigor were recorded for all trees larger than 10 cm DBH, following the protocols of the North American Maple Project (Cooke et al. 1998). One 10 by 10 m subplot was established within each plot for enumeration, by species, of saplings between 1 cm and 10 cm DBH. At each of five predetermined locations at 10-m increments along the centerline of the plot, a 1 m by 1 m subplot was established within which the number and species of each tree seedling (≤ 1.0 cm DBH) were recorded.

All soil data, including methods of collection and analysis, are available from the study conducted by Lawrence et al. (2017). This study focused on the upper 10 cm of the B horizon (an intermediate layer of soil) because fine roots were common in this depth increment, and by keeping the thickness constant, comparability among sampled locations was maximized. Furthermore, the upper B horizon is the layer within the soil profile where Al mobilization from acidic deposition is most prevalent, affecting both this horizon and organic-rich overlying horizons (Lawrence et al. 2015).

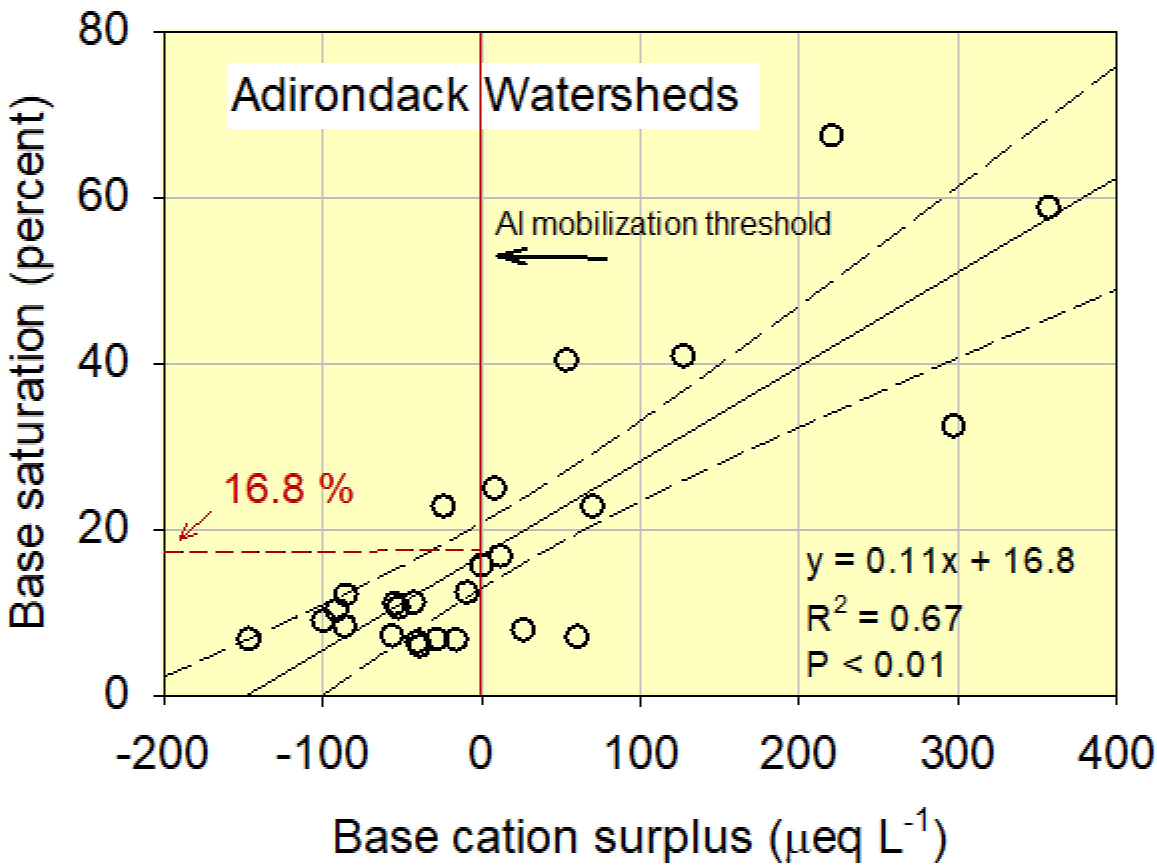
To relate BCS values in streams to base saturation in soils, data were compiled from several previous and ongoing U.S. Geological Survey projects (including the ASMP), to provide paired soil and stream data for 26 watersheds. Stream samples were collected from 19 of these watersheds in late March 2004 through the Western Adirondack Stream Survey (WASS; Lawrence et al. 2008) and data was available from one watershed in Christopher et al. (2006). Additional stream samples were collected in May 2011 in four ASMP watersheds that did not overlap with the WASS watersheds, and data from early April 2004 were included from the North and South Buck Watersheds. Further information on water chemistry in the North and South Buck Watersheds is available in the Lawrence et al. (2011) study.

5 Findings

Base saturation in the upper B horizon of the 26 watersheds used to relate base saturation to BCS was found to be strongly correlated ($p < 0.01$) with BCS values measured in the streams of these watersheds. Linear regression indicated that a BCS value of 0.0 microequivalents (μeq) L^{-1}, the value that defines the Al mobilization threshold, approximated a base saturation value of 17% (Figure 4). Confidence intervals showed that the intersection of base saturation with a BCS of 0.0 μeq L^{-1} ranged from 13.0% to 20.8% at $P < 0.05$.

Figure 4. Soil base saturation of the upper 10 cm of the soil B horizon as a function of the base-cation surplus (BCS) in stream water for 26 Adirondack watersheds

Negative BCS values indicate Al mobilization. The dashed lines indicate the 95% confidence interval.

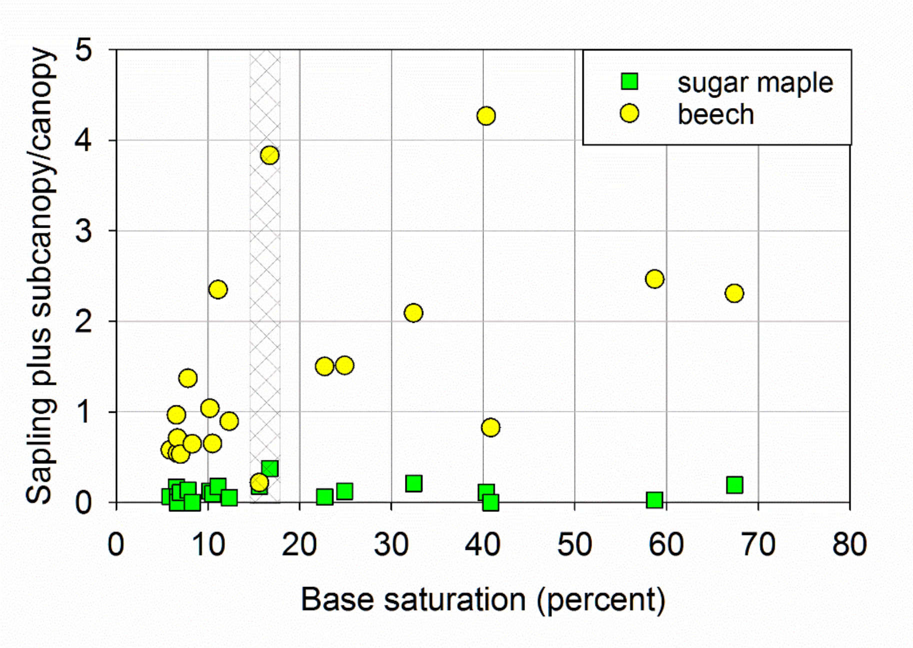


The base saturation value of 17% helped to define the species composition of both canopy trees and seedlings in the 20 watersheds with vegetation measurements. Values of base saturation in the upper B horizon varied widely among watersheds from 4.4% to 67.4%, with base saturation in 11 of the watersheds less than 17%, and therefore subject to Al mobilization, 2 watersheds with values that approximated the threshold value of 17%, and seven watersheds with base saturation values sufficiently high to prevent Al mobilization. Sugar maple and beech dominated the study watersheds in terms of number of trees, comprising an average of 44 and 40% of all measured trees greater than 10 cm DBH, respectively. However, basswood (*Tilia americana* L.), white ash (*Fraxinus americana* L.) and hophornbeam (*Ostrya virginiana* [Mill.] K. Kock), species known to prefer high-Ca soils, were not found below a base saturation of 17% with the exception of white ash in one plot that had average base saturation of 12.3%. Red maple (*Acer rubrum* L.) and black cherry (*Prunus serotina* Ehrh.), species known to prefer acidic soils, were not found above a base saturation of 17%. Measurements of canopy vigor and average DBH were both positively correlated ($P < 0.05$) with base saturation for sugar maple, but for beech these measurements were unrelated to base saturation. In low-base soils, effects on sugar maple of soil-Ca depletion and on beech mortality from BBD appeared to create opportunities for gap-exploiting species such as red maple and black cherry. In high-base soils, sugar maple dominated the canopy.

The canopy vigor rating (which increases with improving canopy condition) averaged by watershed was positively correlated with base saturation for sugar maple ($P = 0.03$; $R = 0.50$) and was significantly higher (indicating better health) at base saturation values above 16.8% than below ($P = 0.016$). The canopy vigor rating for beech was not correlated with base saturation nor were there differences when watersheds were grouped based on the Al mobilization threshold ($P > 0.10$). The canopy vigor rating was significantly higher for beech than sugar maple in six of 11 watersheds with base saturation values below 17%, but in only two of nine watersheds with base saturation values above 17%. The ratio of sapling plus sub-canopy trees to canopy trees was lower for sugar maple than beech over the full range of base saturation values, but at base saturation values above the Al mobilization threshold, the difference was considerably greater (Figure 5). Because the abundance of beech saplings and sub-canopy trees was not related to base saturation, the result suggested that beech was less effective at competing for canopy space where soils had base saturation values above the Al mobilization threshold than below the threshold. However, the low values for sugar maple indicated weak regeneration.

Figure 5. The ratio of saplings plus sub-canopy trees to canopy trees, as a function of base saturation of the upper 10 cm of the B horizon

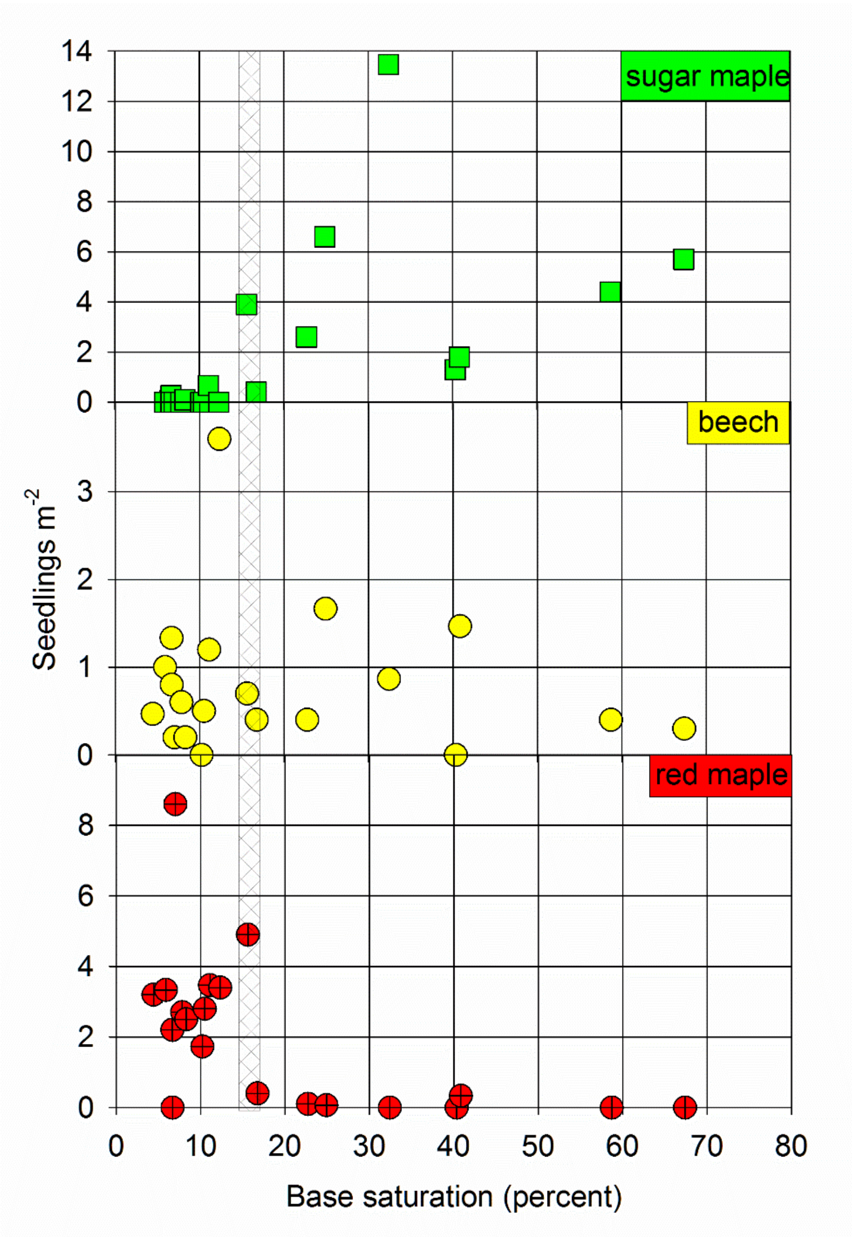
The base saturation range where the Al mobilization threshold occurs is indicated by vertical cross hatching.



Seedling abundance of beech was not related to base saturation (Figure 6). However, seedling abundance for sugar maple was substantially higher in watersheds where Al mobilization did not occur ($P < 0.01$) than where it did occur, and was positively correlated with base saturation ($P = 0.056$; $R = 0.43$). In sharp contrast, red maple seedling abundance was substantially higher where Al mobilization did occur than where it did not occur ($P < 0.01$), and was negatively correlated with base saturation ($P < 0.01$; $R = -0.57$). Red maple seedlings were nearly absent in the watersheds where Al mobilization did not occur (Figure 6).

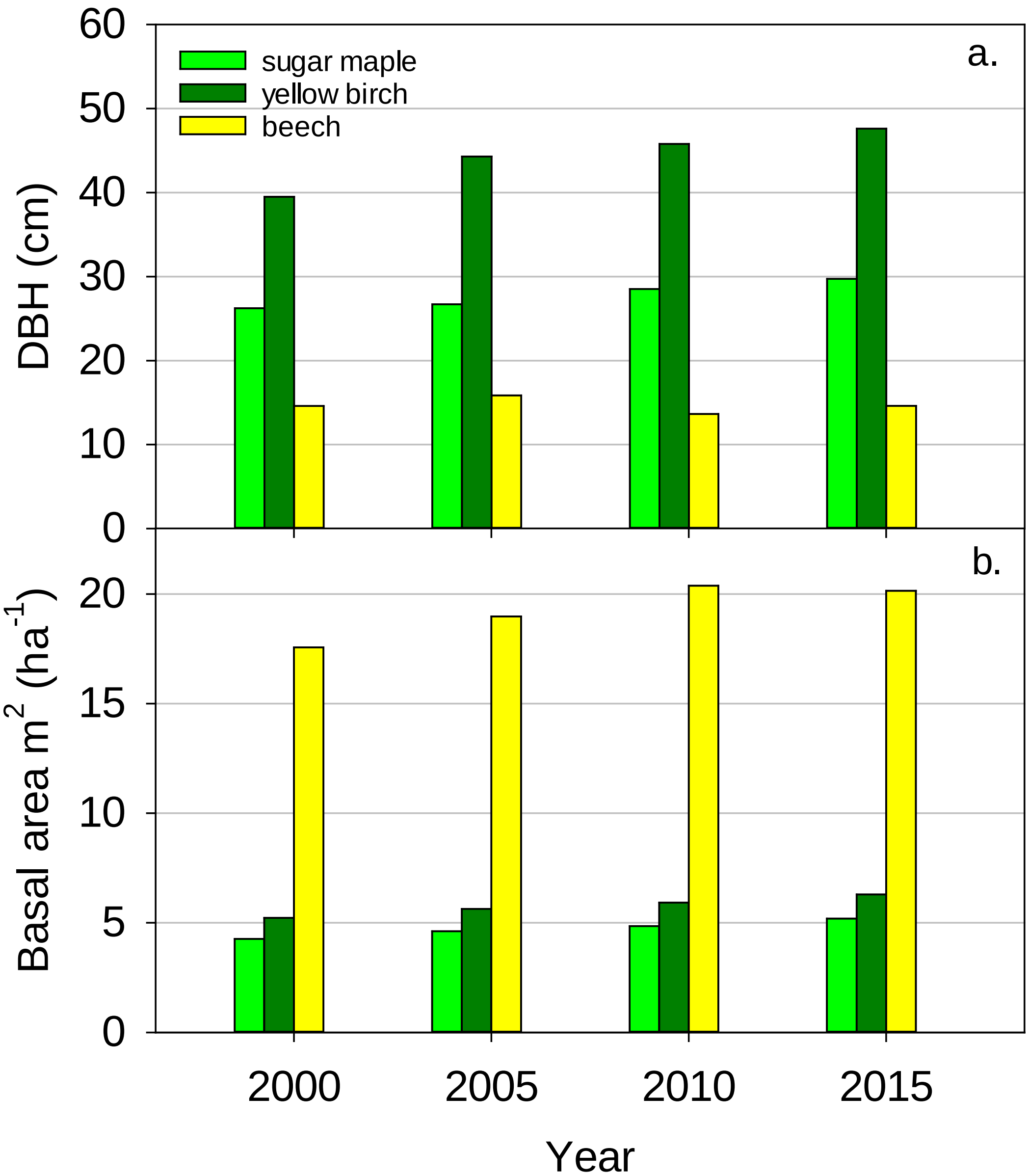
Figure 6. Seedling abundance as a function of base saturation of the upper 10 cm of the B horizon for sugar maple, beech, and red maple

The base saturation range where the Al mobilization threshold occurs is indicated by vertical cross hatching.



In South Buck Watershed, where soils were beginning to recover from acidic deposition effects, sugar maple average DBH and basal area increased progressively from 2000 to 2015 whereas average DBH of beech did not change during that period (Figure 7a). Progressive increases in basal area were also observed over this period for yellow birch, but beech only showed increases between 2000 and 2010, then leveled off between 2010 and 2015 (Figure 7b).

Figure 7. Average diameter at breast height (DBH) (a) and basal area (b) for the three major tree species in the South Buck Watershed from 2000 to 2015



6 Implications

Base saturation appeared to be an important factor determining the presence of some tree species, but not others. White ash, basswood, and hophornbeam, species recognized as calciphilic (Mitchell et al. 2003), occurred only in watersheds with base saturation values high enough to prevent Al mobilization (with the exception of white ash in one watershed below the threshold). In contrast, red maple and black cherry, species considered to favor acidic soils (Burns and Honkala 1990), were found only in watersheds where Al mobilization occurred. The occurrence of sugar maple, beech, and yellow birch in almost all watersheds, over nearly the full range of base saturation, indicated that these species were likely to have been common to abundant in all these watersheds before acidic deposition. Trees of these species were able to survive during the period of high-acidic deposition, although elevated mortality of sugar maple may have occurred on sites having low-base soils. These results likely reflected a combination of varying soil chemical tolerances and competitive species interactions. Despite the occurrence of mature sugar maple on both sides of the Al mobilization threshold, lower canopy vigor and smaller DBH where base saturation was less than 17% suggested that sugar maple growth was suppressed by Al mobilization. The study of Bishop et al. (2015) also showed that sugar maple diameter growth in these plots was negatively correlated with exchangeable Al concentrations and positively correlated with exchangeable Ca concentrations. In beech, the lack of direct relationships to base saturation in terms of canopy vigor, DBH, and regeneration suggests that its increased dominance in low-base soils is more a response to the decline of other species than a preference of beech for more acidic soils.

7 Conclusions

Interacting effects of acidic deposition and BBD have left a legacy in terms of stand composition and structure in the Adirondack hardwood forest. Because these factors co-exist in much of the hardwood forests of eastern North America, results of this study are potentially applicable across a large region. Where soil Ca and other base cations were depleted below 17% base saturation, the threshold for Al mobilization was crossed, thereby impairing growth and regeneration of sugar maple. However, decreasing acidic deposition provides an opportunity for sugar maple to rebound in low-base sites such as the South Buck Watershed if the decreases in acidic deposition are sufficient to stop Al mobilization. Marked decreases in surface water concentrations of harmful forms of Al and recent results of soil monitoring suggest that Al mobilization in soils is on a downward trend. However, in soils with base saturation less than 17%, the ongoing dominance of beech in the understory and competition from more acid-tolerant species for gaps may limit expansion of sugar maple at these sites, even with favorable changes in soil chemistry. Where base-rich soils occur, sugar maple may continue their canopy dominance as BBD continues to weaken the ability of beech to compete for upper canopy space, but only if sugar maple seedlings (Figure 8) and saplings can regenerate in the presence of the dense beech understory.

Figure 8. High densities of sugar maple seedlings observed in watershed

High densities of sugar maple seedlings such as seen in the image were observed in watersheds with soils buffered against Al mobilization, but were nearly absent in all watersheds where Al mobilization did occur in soils.

Photo Credit: G. Lawrence

8 References

Bishop, D.A., C.M. Beier, N. Pederson, G.B. Lawrence, J.C. Stella, and T.J. Sullivan. 2015. Regional growth decline of sugar maple (Acer saccharum) and its potential causes. Ecosphere 6(10):1-14. 10.1890/ES15-00260.1.

Burns, R.M. and B.H. Honkala. 1990. Silvics of North America: 1. Conifers; 2. Hardwoods. Agriculture Handbook 654. USDA Forest Service, Washington, DC.

Cale, J.A., S.A. Teale, M.T. Johnston, G.L. Boyer, K.A. Perri, and J.D. Castello. 2015. New ecological and physiological dimensions of beech bark disease development in aftermath forests. For. Ecol. Manage. 336:99-108. http://dx.doi.org/10.1016/j.foreco.2014.10.019.

Christopher, S.F., B.D. Page, D.H. Campbell, and M.J. Mitchel. 2006. Contrasting stream water NO3- and Ca2+ in two nearly adjacent catchments: the role of soil Ca and forest vegetation Glob. Chang. Biol. 12:364-381. 10.1111/j.1365-2486.2006.01084.x.

Cooke, R., B. Pendrel, C. Barnett, and D. Allen. 1998. North American Maple Project Cooperative Field Manual. USDA Forest Service, Northeastern Area, State and Private Forestry, Durham, NH.

Cronan, C.S. and C.L. Schofield. 1990. Relationships between aqueous aluminum and acidic deposition in forested watersheds of North America and northern Europe. Environ. Sci. Technol. 24:1100-1105.

Cronan, C.S. and D.F. Grigal. 1995. Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. J. Environ. Qual. 24:209-226.

Duchesne, L., R. Ouimet, and D. Houle. 2002. Basal area growth of sugar maple in relation to acid deposition, stand health, and soil nutrients. J. Environ. Qual. 31:1667-1683.

Garnas, J.R., M.P. Ayres, A.M. Liebhold, and C. Evans. 2011. Subcontinental impacts of an invasive tree disease on forest structure and dynamics. J. Ecol. 99(2):532-541. 10.1111/j.1365-2745.2010.01791.x.

Giencke, L.M., M. Dovčiak, G. Mountrakis, J.A. Cale, and M.J. Mitchell. 2014. Beech bark disease: spatial patterns of thicket formation and disease spread in an aftermath forest in the northeastern United States. Can. J. For. Res. 44(9):1042-1050. 10.1139/cjfr-2014-0038.

Houston, D.R. 1994. Major new tree epidemics: beech bark disease. Annu. Rev. Phytopathol. 32:75-87.

Johnson, A.H., A.J. Moyer, J.E. Bedison, S.L. Richter, and S.A. Willig. 2008. Seven decades of calcium depletion in organic horizons of Adirondack forest soils. Soil Sci. Soc. Am. J. 72:1824-1830. doi:10.2136/sssaj2006.0407.

Lawrence, G.B., M.B. David, and W.C. Shortle. 1995. A new mechanism for calcium loss in forest-floor soils. Nature 378:162-165.

Lawrence, G.B. 2002. Persistent episodic acidification of streams linked to acid rain effects on soil. Atmos. Environ. 36:1589-1598.

Lawrence, G.B., J.W. Sutherland, C.W. Boylen, S.A. Nierzwicki-Bauer, B. Momen, B.P. Baldigo, and H.A. Simonin. 2007. Acid rain effects on aluminum mobilization clarified by inclusion of strong organic acids. Environ. Sci. Technol. 41(1):93-98.

Lawrence, G.B., K.M. Roy, B.P. Baldigo, H.A. Simonin, S.B. Capone, J.W. Sutherland, S.A. Nierzwicki-Bauer, and C.W. Boylen. 2008. Chronic and episodic acidification of Adirondack streams from acid rain in 2003-2005. J. Environ. Qual. 37:2264-2274.

Lawrence, G.B., H.A. Simonin, B.P. Baldigo, K.M. Roy, and S.B. Capone. 2011. Changes in the chemistry of acidified Adirondack streams from the early 1980s to 2008. Environ. Pollut. 159:2750-2758.

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

Lawrence, G.B., T.J. Sullivan, S.W. Bailey, J.J. McDonnell, and M.R. Antidormi. 2017. Adirondack New York soil chemistry data, 1997-2014: U.S. Geological Survey data release; https://doi.org/10.5066/F78050TR

Long, R.P., S.B. Horsley, R.A. Hallett, and S.W. Bailey. 2009. Sugar maple growth in relation to nutrition and stress in the northeastern United States. Ecol. Appl. 19(6):1454-1466.

Mitchell, M.J., C.T. Driscoll, S. Inadar, G.G. McGee, M.O. Mbila, and D.J. Raynal. 2003. Nitrogen biogeochemistry in the Adirondack Mountains of New York: hardwood ecosystems and associated surface waters. Environ. Pollut. 123:355-364.

Page, B.D. and M.J. Mitchell. 2008. Influences of a calcium gradient on soil inorganic nitrogen in the Adirondack Mountains, New York. Ecol. Appl. 18:1604-1614.

Reuss, J.O. 1983. Implications of the calcium-aluminum exchange system for the effect of acid precipitation on soils. J. Environ. Qual. 12(4):591-595.

Schaberg, P.G., J.W. Tilley, G.J. Hawley, D.H. DeHayes, and S.W. Bailey. 2006. Associations of calcium and aluminum with the growth and health of sugar maple trees in Vermont. For. Ecol. Manage. 223:159-169.

Sullivan, T.J., G.B. Lawrence, S.W. Bailey, T.C. McDonnell, C.M. Beier, K.C. Weathers, G.T. McPherson, and D.A. Bishop. 2013a. Effects of acidic deposition and soil acidification on sugar maple in the Adirondack Mountains, New York. Environ. Sci. Technol. 47:12687-12694. 10.1021/es401864w.

Sullivan, T.J., G.B. Lawrence, S.W. Bailey, T.C. McDonnell, and G.T. McPherson. 2013b. 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.

Warby, R.A.F., C.E. Johnson, and C.T. Driscoll. 2009. Continuing acidification of organic soils across the northeastern USA: 1984 - 2001. Soil Sci. Soc. Am. J. 73(1):274-284.

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