

# SUGAR MAPLE DECLINE AND LESSONS LEARNED ABOUT ALLEGHENY PLATEAU SOILS AND LANDSCAPES

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## Insights for Managers

- A long-term forest liming study showed the critical importance of base cations for sustaining sugar maple crown health, growth, and survival.
- A topographic gradient study examined the distribution of base cations on the landscape in relation to sugar maple health and found that unglaciated summits, shoulders, and upper backslopes had the most crown dieback and mortality.
- Foliar calcium and magnesium were lowest on the unglaciated upper landscape stands and, combined with two or more moderate to severe defoliations in the preceding 10 years, cause extensive sugar maple dieback and mortality.
- Bedrock parent material and hydrologic flow paths were important factors that affected where sugar maple declined on unglaciated sites.
- A 30-year retrospective study that used archived soils from four forested and undisturbed sites originally sampled in 1967 showed that changes in soil base cation status and acidity over 30 years was a predisposing stressor for sugar maple.
- This multidisciplinary research produced a new understanding of the factors that led to the widespread sugar maple decline episode.

## INTRODUCTION

Sugar maple (*Acer saccharum* Marsh.) decline was a major forest health challenge in northern Pennsylvania starting in the mid- to late 1980s and continued through the mid-1990s. During this time sugar maple suffered extensive crown dieback and rapid mortality, primarily on the unglaciated Allegheny Plateau in northwestern and north-central Pennsylvania (Drohan et al. 2002, Horsley et al. 2000). Declining trees exhibited a slow loss of vigor and increased fine twig dieback, which was followed by large branch mortality. This frequently ended in tree death (Kolb and McCormick 1993). Surveys conducted as part of the North American Maple Project found sugar maple healthy in most parts of its range, though declines in Quebec were noted in the mid- and late 1980s (Allen et al. 1992, 1995, 1999). In northern Pennsylvania a series of stressors, which included insect defoliators and extreme drought, played a significant role in accelerating crown dieback and mortality.

Historically, sugar maple declines have not been limited to northern Pennsylvania; other declines have been reported in parts of New England, the Lake States, and Quebec and Ontario (Bal et al. 2015). A common theme in these declines is the interaction with nutrient

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stress. Across these regions, nutrients implicated with sugar maple dieback included nitrogen (N), calcium (Ca), magnesium (Mg), phosphorus (P), and potassium (K) (Bal et al. 2015). Additionally, soil acidification caused the potentially toxic cations aluminum (Al) and manganese (Mn) to become more readily available in soils, which created an additional stressor that affected sugar maple health and growth (Bal et al. 2015, Halman et al. 2013). Several studies also showed sugar maple growth to be related to soil base cation supplies; sugar maple growth decreased on sites with poor base cation status (Bishop et al. 2015, Duchesne et al. 2002, Long et al. 2009).

Our research began in 1993 and continued into the 2000s. Portions of our work covered a broad geographic range of sugar maple sites in the northeastern United States from northern Pennsylvania to New York, Vermont, and New Hampshire (Hallett et al. 2006). Three major related research projects and their results will be described here:

- Long-term forest liming impacts on northern hardwoods
- Sugar maple health and growth along topographic gradients
- Long-term changes in forest soil chemistry

In combination, these research efforts led to conclusive findings regarding the principal factors for sugar maple decline and mortality in Pennsylvania. Recommendations and management tools were developed to help foresters and land managers select sites where sugar maple could be sustained even if severe stressors such as drought and defoliation occurred.

## RESEARCH PROJECTS

### Forest Liming Impacts on Northern Hardwoods

The lime study was initiated in 1985 in cooperation with the Pennsylvania Department of Conservation and Natural Resources, Bureau of Forestry, to determine whether deer or acidic deposition, or both, were responsible for difficulty in regenerating more diverse species (primarily red and sugar maples) in north-central Pennsylvania (Auchmoody 1985). Dolomitic lime was applied in fall 1985, at a high rate ( $22.4 \text{ mg ha}^{-1}$ ), to reduce potential Al toxicity associated with acidic deposition and promote diverse seedling regeneration in fenced and unfenced plots at four unglaciated locations (Long et al. 1997). An herbicide treatment was also overlaid on the lime treatment to control interfering plants, but this treatment had no effect on overstory responses and is not considered here (Long et al. 1997). Stands at all four replications were thinned to 50 percent relative density in the winter of 1985–86 to provide sufficient light for regeneration. Sugar maple seedling regeneration was only temporarily improved by liming but was ultimately unaffected by lime application or fencing (Long et al. 1997). Concurrent with the initiation of this study was the widespread crown dieback and mortality of sugar maple in the unglaciated parts of northern Pennsylvania (Horsley et al. 2000). This event shifted the focus of the study to the overstory community (Long et al. 1997), which was composed of sugar maple, American beech (*Fagus grandifolia* Ehrh.), and black cherry (*Prunus serotina* Ehrh.).

By 1992 the only notable results were significant increases in exchangeable Ca and Mg and decreases in acidity, Al, and Mn in the upper 15 cm of mineral soil (Fig. 1) (Long et al. 2015). By 1995 it was evident that sugar maple growth and crown vigor were sustained in limed plots compared with trees in unlimed plots. In cooperation with the Pennsylvania Bureau of Forestry, overstory diameter growth and crown health, along with soil and foliar nutrients, were intensively monitored through 2008 (Long et al. 2015).

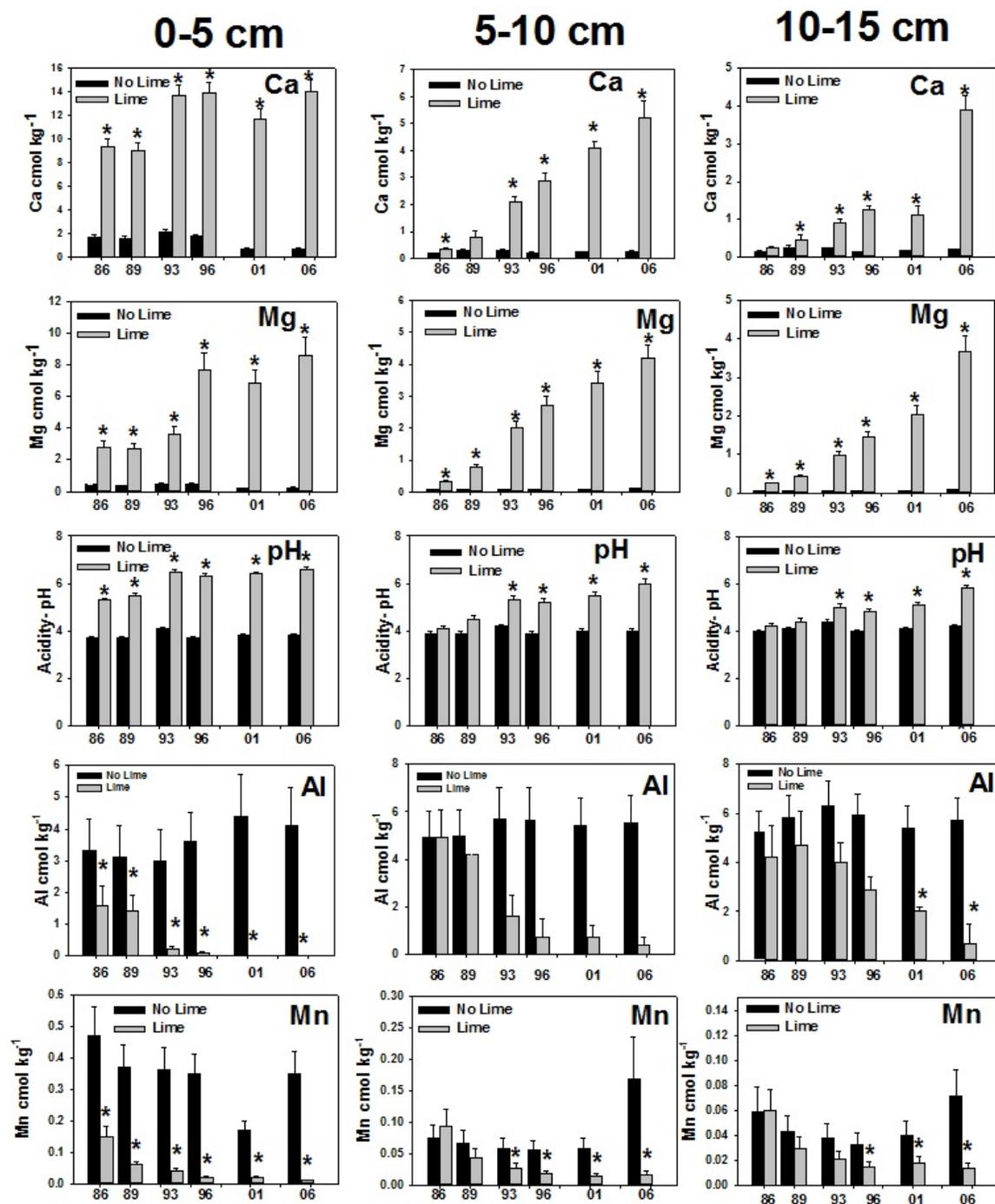


Figure 1.—Least square means from repeated measures analysis of lime treatment effects on soil-exchangeable Ca, Mg, Mn, Al, and pH in 1986, 1989, 1993, 1996, 2001, and 2006. Separate analyses were conducted for depths of 0–5, 5–10, and 10–15 cm. All elements and pH had significant ( $\alpha \leq 0.05$ ) lime  $\times$  year interactions and Tukey-Kramer pairwise comparisons. Significant differences between lime and no lime treatments are noted by an asterisk (\*).

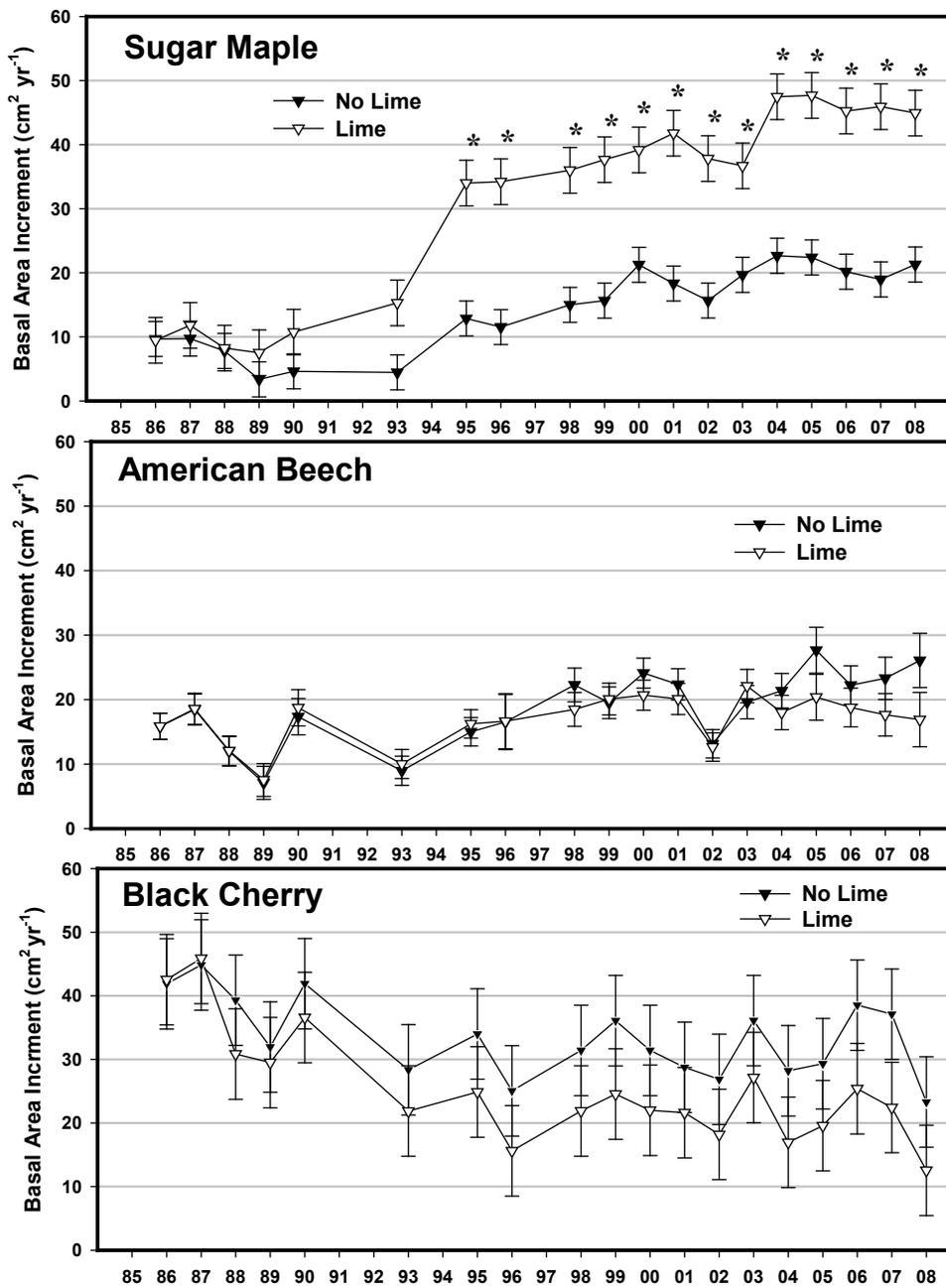


Figure 2.—Least square means of mean annual basal area increment (cm<sup>2</sup> yr<sup>-1</sup>) for sugar maple, American beech, and black cherry, 1986 to 2008. Asterisks indicate a significant ( $P \leq 0.05$ ) pairwise difference based on the Tukey-Kramer adjustment for multiple comparisons because of year x lime treatment interaction. Pairwise comparisons were not significantly different for American beech or black cherry, but black cherry BAI averaged across all time periods was 25.3 cm<sup>2</sup> yr<sup>-1</sup> in limed plots, significantly ( $P = 0.026$ ) less than the BAI of 33.4 cm<sup>2</sup> yr<sup>-1</sup> in unlimed plots.

### Growth Responses

The long-term impact of a single 22.4 Mg ha<sup>-1</sup> application of dolomitic lime remained evident in 2008, 23 years after its application, in these four northern hardwood stands (Fig. 2). Major effects of the lime treatment were the sustained increase in sugar maple basal area increment (BAI) in limed plots compared with unlimed plots and the detection of a negative growth response of black cherry to lime application. American beech growth was unaffected by lime treatment.

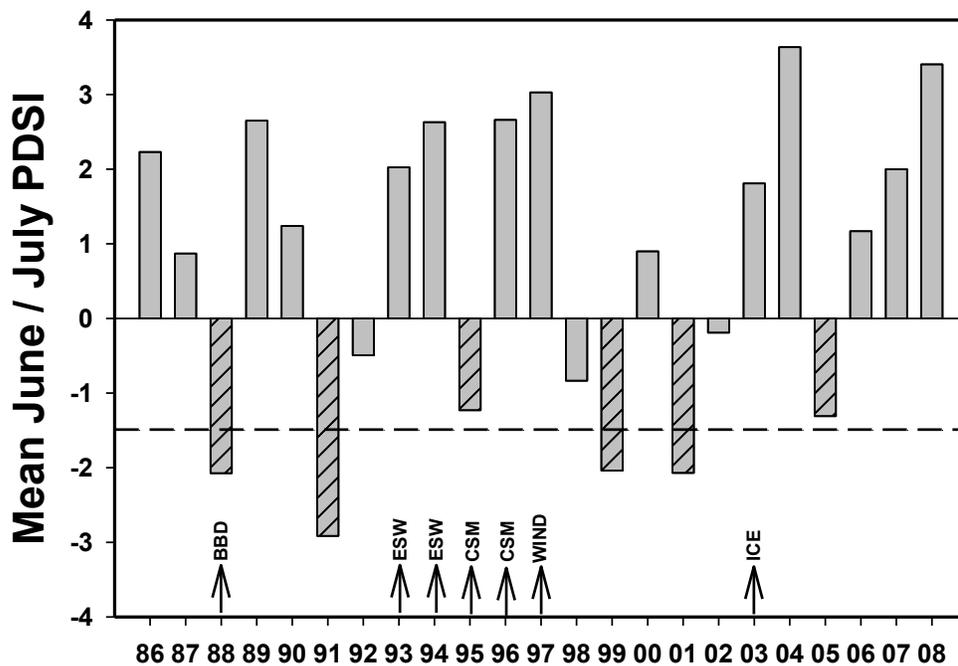


Figure 3.—Disturbance diagram showing drought (mean June–July PDSI for Pennsylvania climate division 10), disease (BBD = beech bark disease initiation), defoliation (ESW = elm spanworm, CSM = cherry scallop shell moth), and ice and wind events affecting the study plots. Dashed horizontal line at  $-1.5$  shows the threshold for mild drought based on the PDSI; cross-hatching on bars shows the years when the PDSI was  $< -1$  (incipient drought).

Average BAI growth for sugar maple trees in limed plots since 2004 has averaged  $> 40 \text{ cm}^2 \text{ yr}^{-1}$ , a large increase over values observed in the first 8 years of the study when BAI averaged  $12.7 \text{ cm}^2 \text{ yr}^{-1}$  for limed trees (Fig. 2) (Long et al. 2011). Sugar maple trees in limed plots have maintained elevated BAI despite the background of disturbance events, which could negatively affect growth (Fig. 3). The droughts of 1988 and 1991 affected crown health and growth, as did the defoliations in 1993 and 1994. Subsequent droughts in 1999 and 2001 were not as severe as the 1991 drought, and no additional defoliations occurred through 2008. As stressors have abated to some degree, limed and unlimed trees have sustained BAI increases, though at a much higher level for limed trees.

American beech BAI (Fig. 2) was unaffected by lime applications, but results may be obscured by the effects of beech bark disease. However, black cherry BAI was negatively affected by lime applications. The negative effect of lime on black cherry growth was not evident in earlier results and may be related to longer-term nutrient imbalances caused by lime application. This result must be interpreted cautiously; black cherry was analyzed on only two of the four replications because of the small number of trees on the other two replications (four remaining black cherry trees on each replication). Black cherry mean BAI on unlimed plots was  $33.4 \text{ cm}^2 \text{ yr}^{-1}$ , or 32 percent greater than mean BAI of limed trees,  $25.3 \text{ cm}^2 \text{ yr}^{-1}$ .

Although it is tempting to attribute the decrease in black cherry growth to an improved competitive status for sugar maple, on-the-ground observations of stand structure do not support this interpretation. Black cherry remains in a dominant crown position in the two replications where it is abundant. Sugar maples are not noticeably crowded or competing with the black cherry, because the thinning left sufficient room for these trees to continue to grow for some time without directly competing.

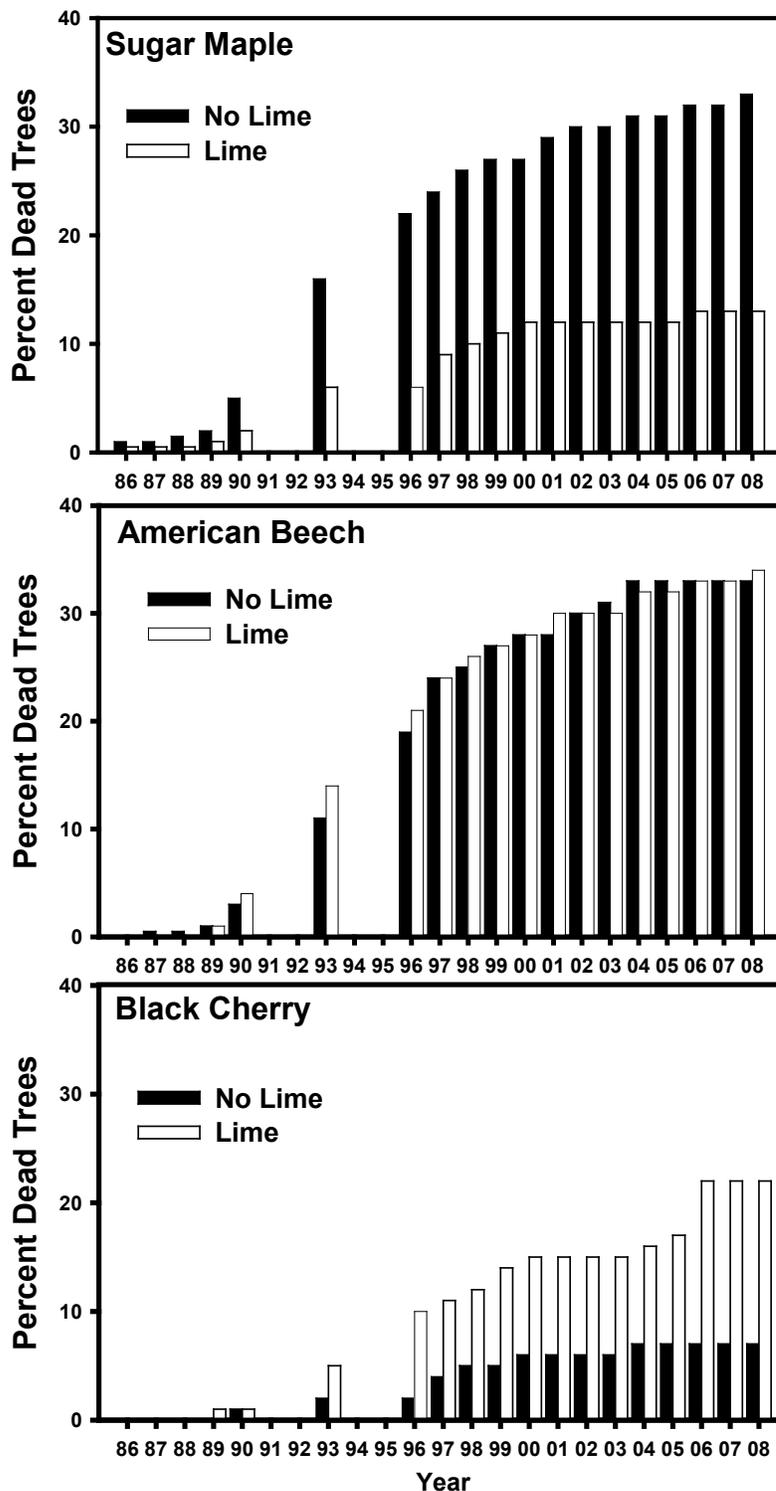


Figure 4.—Cumulative mortality (unadjusted) by year for sugar maple, American beech, and black cherry, 1986–2008.

### Mortality

Mortality patterns for all three overstory species show that the highest mortality rate occurred from 1988 to 2001, during multiple droughts and defoliations (Fig. 4). Starting in 2000, the mortality rate leveled off for sugar maple and American beech in limed and unlimed plots but increased abruptly in 2006 for black cherry in limed plots (Fig. 4). Reasons for this increase are not evident but may be related to the drought conditions (mean June–July Palmer drought severity index [PDSI] = -1.31) that prevailed in 2005. Black cherry has been shown to grow less on high base cation sites than on low base cation sites (Long et al. 2009).

**Table 1.—Sugar maple and black cherry mean foliage element concentrations in mg kg<sup>-1</sup> (standard error) and t-test probability levels for comparisons based on means from each block in limed and unlimed plots in 2006**

| Element | Sugar Maple  |              |                    | Black Cherry  |              |                    |
|---------|--------------|--------------|--------------------|---------------|--------------|--------------------|
|         | No Lime      | Lime         | T-test Prob. level | No Lime       | Lime         | T-test Prob. level |
| Ca      | 3,913 (191)  | 9,519 (549)  | <0.001             | 4,952 (72.7)  | 8,485 (354)  | 0.010              |
| Mg      | 646 (39)     | 2,855 (113)  | <0.001             | 2,279 (1.7)   | 4,688 (359)  | 0.094              |
| P       | 1,140 (61)   | 1,268 (119)  | 0.373              | 1,380 (19)    | 1,420 (27)   | 0.343              |
| K       | 7,657 (204)  | 6,133 (93)   | <0.001             | 11,821 (1038) | 8,226 (753)  | 0.107              |
| Al      | 38 (1)       | 30 (1)       | 0.002              | 27 (3)        | 30 (4)       | 0.560              |
| Mn      | 2,946 (221)  | 426 (76)     | <0.001             | 2,160 (70)    | 627 (77)     | 0.005              |
| Fe      | 59 (4)       | 44 (1)       | 0.008              | 53 (1)        | 51 (1)       | 0.175              |
| N       | 19,329 (356) | 18,906 (172) | 0.326              | 23,979 (585)  | 21,972 (372) | 0.101              |

American beech mortality caused by beech bark disease exceeded 30 percent in limed and unlimed plots during the study (Fig. 4). Sugar maple mortality also exceeded 30 percent on unlimed plots but was only 14 percent on limed plots. Mortality of black cherry remained the lowest of the three overstory species; unlimed plots had the lowest mortality, 6.1 percent, over the 23 years of the study; on limed plots mortality was 21.2 percent (Long et al. 2011).

### Foliar Chemistry

Foliar chemistry provides some insights into the differential responses of sugar maple and black cherry in response to liming. The effects of liming on sugar maple foliar chemistry remained apparent in 2006 when the last samples were taken, 21 years after lime application. Increased foliar concentrations of Ca and Mg and reduced concentrations of Al and Mn were maintained for sugar maple foliage from limed trees. Foliar Ca concentrations for limed sugar maples, 21 years after lime application, were 9,519 mg kg<sup>-1</sup>; foliage from unlimed plots had 3,919 mg kg<sup>-1</sup>. Similarly, foliar Mg from trees on unlimed plots was 646 mg kg<sup>-1</sup>, compared with 2,855 mg kg<sup>-1</sup> for trees in limed plots (Table 1) (Long et al 2011).

In our research, high Mn levels have been associated with decline and poor crown health of sugar maple. High foliar Mn concentration in sugar maple impairs photosynthesis and high late season antioxidant enzyme activity in foliage of dominant and codominant trees (St. Clair et al. 2005). Other cellular symptoms, such as discrete electron-dense areas in the chloroplast thylakoid membranes, delayed transport of starch out of chloroplasts to the roots. Other carbohydrate storage areas may indicate a mechanism for impaired photosynthetic processes (McQuattie and Schier 2000).

In addition to Ca, Mg, Mn, and Al, black cherry may be influenced by N and K. Black cherry foliar N and K levels were reduced by liming in 2006, though differences were not statistically significant (Table 1). Black cherry is a high N-demanding species (Auchmoody 1982). Based on fertilization studies with N-P-K additions in sapling black cherry stands, these reductions of N and K in limed plots may be sufficient to influence black cherry growth (Auchmoody 1982). Although no specific K requirement has been established for black cherry, the lowest foliar K level in untreated sapling stands was 9,200 mg kg<sup>-1</sup>, which is 1000 mg kg<sup>-1</sup> higher than observed in foliage from black cherry in limed plots. Similarly, the lowest N concentration from untreated sapling black cherry foliage was 24,300 mg kg<sup>-1</sup>, and black cherry foliage in our limed plots was about 22,000 mg kg<sup>-1</sup> in 2006. Deficiencies of N and K in limed plots may account for the reduced black cherry growth.

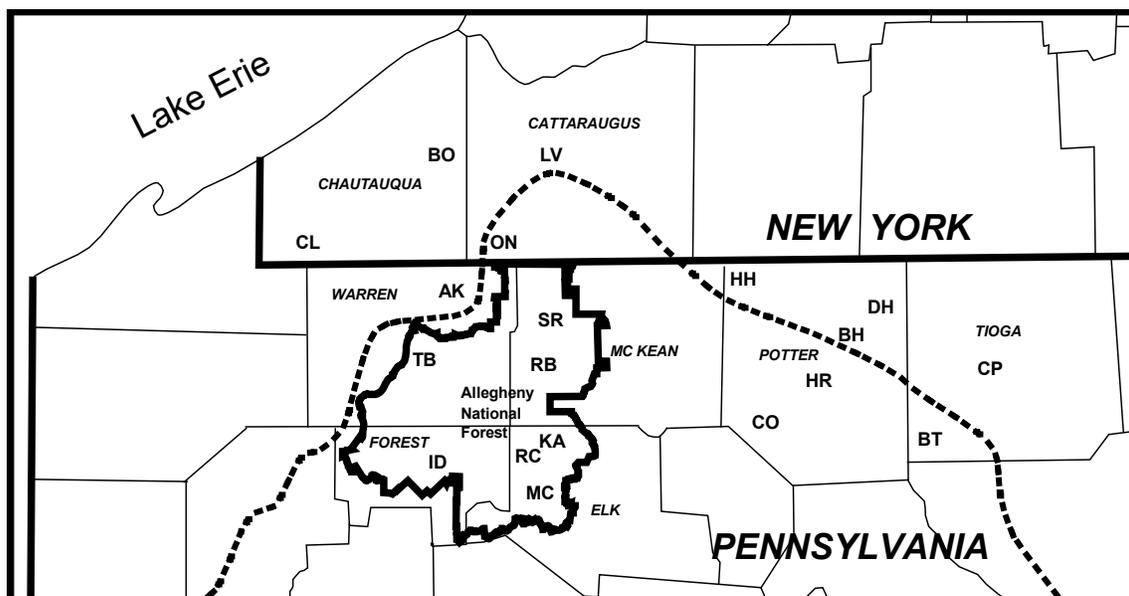


Figure 5.—Location of study sites in northwestern Pennsylvania and southwestern New York. The dashed line represents the southern extent of the Wisconsin glacial advances in the area. Study sites: AK = Akeley, BH = Baldwin Hollow, BO = Boutwell Hill, BT = Brooks Trail, CL = Clymer, CO = Costello, CP = Colton Point, DH = Dodge Hollow, HH = Hemlock Hollow, HR = Hardwood Ridge Trail, ID = Indian Doctor, KA = Kane Experimental Forest, LV = Little Valley, MC = Mill Creek, ON = Onoville, RB = Red Bridge, RC = Russell City, SR = Sugar Run, TB = Tanbark Trail.

Each of the three principal overstory species responded differently to the lime treatment. Sugar maple benefitted from liming with improved crown condition, BAI growth, and survivorship compared with trees in unlimed plots (Long et al. 2011). American beech BAI and crown condition were unaffected by the lime treatment, and beech bark disease resulted in significant beech mortality in limed and unlimed plots. Black cherry had a negative response to liming with lower BAI growth and greater mortality for trees in limed plots compared with black cherry in unlimed plots. Liming proved beneficial for sugar maple but, as shown in this study, different species respond differently to the changing soil chemical environment.

### Sugar Maple Health and Growth along Topographic Gradients

Based on our early findings from the lime study and input from foresters and other researchers, Horsley et al. (2000) initiated a study in 1995 to determine how Ca and Mg were distributed in sugar maple stands across an 18 000-km<sup>2</sup> area in northern Pennsylvania and southwestern New York. The influence of glaciation, topographic position, foliar chemistry, defoliation history, and stand characteristics (species composition, structure, and density) on the health of sugar maple was evaluated in 43 stands at 19 sites from Chautauqua County, New York, in the west to Tioga County, Pennsylvania, in the east (Fig. 5). These stands span a wide range of soil parent materials and geologic influences found on the Allegheny Plateau. At each site, two or three stands were sampled along the local elevational distribution of sugar maple. In each stand, five dominant or codominant sugar maples, presumed healthy by lack of symptoms of crown dieback, were selected for foliage sampling. Foliar chemistry of healthy trees was used as a bioassay of site nutritional quality because of its ability to integrate horizontal and vertical differences in soil nutrition within stands. Foliar chemistry was determined for each tree and averaged by stand. Three 0.1-acre sampling plots were established to assess stand composition and tree health. Defoliation incidence and severity were determined for each stand for the most recent 10-year period from 1987 to 1996. Annual

**Table 2.—Sugar maple foliar concentrations (mg kg<sup>-1</sup>) of Ca, Mg, Al, and Mn (standard error of the mean) by physiographic position for 43 stands on glaciated and unglaciated sites. n = number of stands represented by each mean.**

| Element           | Physiographic position |                |                  |                |                |
|-------------------|------------------------|----------------|------------------|----------------|----------------|
|                   | Summit/<br>shoulder    | Upper back     | Mid-back         | Lower back     | Enriched       |
| Glaciated sites   |                        |                |                  |                |                |
|                   | n = 2                  | n = 4          | n = 2            | n = 3          | n = 7          |
| Ca                | 11 800<br>(2000)       | 9300<br>(2900) | 11 100<br>(2000) | 7800<br>(300)  | 9600<br>(1100) |
| Mg                | 1160<br>(90)           | 1160<br>(170)  | 1290<br>(200)    | 1110<br>(70)   | 1380<br>(100)  |
| Al                | 26<br>(4)              | 38<br>(8)      | 26<br>(4)        | 30<br>(5)      | 30<br>(5)      |
| Mn                | 1780<br>(10)           | 1690<br>(350)  | 1270<br>(220)    | 1220<br>(170)  | 1140<br>(60)   |
| Unglaciated sites |                        |                |                  |                |                |
|                   | n = 9                  | n = 3          | n = 3            | n = 3          | n = 7          |
| Ca                | 4500<br>(300)          | 7300<br>(2500) | 7100<br>(1200)   | 9400<br>(2100) | 8800<br>(900)  |
| Mg                | 630<br>(60)            | 1150<br>(250)  | 1060<br>(180)    | 1170<br>(60)   | 1260<br>(100)  |
| Al                | 37<br>(2)              | 28<br>(5)      | 23<br>(2)        | 24<br>(1)      | 29<br>(4)      |
| Mn                | 2770<br>(170)          | 1740<br>(310)  | 1720<br>(340)    | 1220<br>(120)  | 1280<br>(200)  |

layers of digitized sketch maps were used to determine the timing, agent, and severity of defoliation and allowed development of a defoliation severity index (DSI) for each stand. One representative soil pit was sampled in each stand using Soil Survey Staff (1993) protocols. Pedons were sampled to at least 130 cm, unless bedrock was encountered at a shallower depth (Bailey et al. 2004). Root density, depth to a root-restricting layer, and depth to redoximorphic features were recorded for each soil pit. Soil samples for chemical analyses were collected by genetic horizon and were analyzed to determine pH, exchangeable cations (Ca, Mg, Na, and K), and exchangeable Al and acidity (see Bailey et al. 2004 for details).

We used percent dead sugar maple basal area (%DEADSM) as the measure of health and found that all moderately to severely declining stands were on unglaciated summits, shoulders, or upper backslopes. Stands on glaciated sites and unglaciated lower topographic positions were not declining when evaluated in this study. Foliar nutrients, particularly of Ca, Mg, and Mn, and defoliation stress during the preceding 10 years, were the most important factors associated with sugar maple health. The lowest foliar Mg, highest foliar Mn, and highest number and severity of insect defoliations were associated with stands on unglaciated summits, shoulders, and upper backslopes (Table 2). Across the sampled region, glaciation, topographic and physiographic position, and elevation were surrogates for foliar nutrition of Ca and Mg and appear to delineate landscape positions with inadequate base cation supply where sugar maple may be vulnerable to other stressors. All six stands with unhealthy sugar maple (> 22 percent %DEADSM) were associated with unglaciated landscapes on summits,



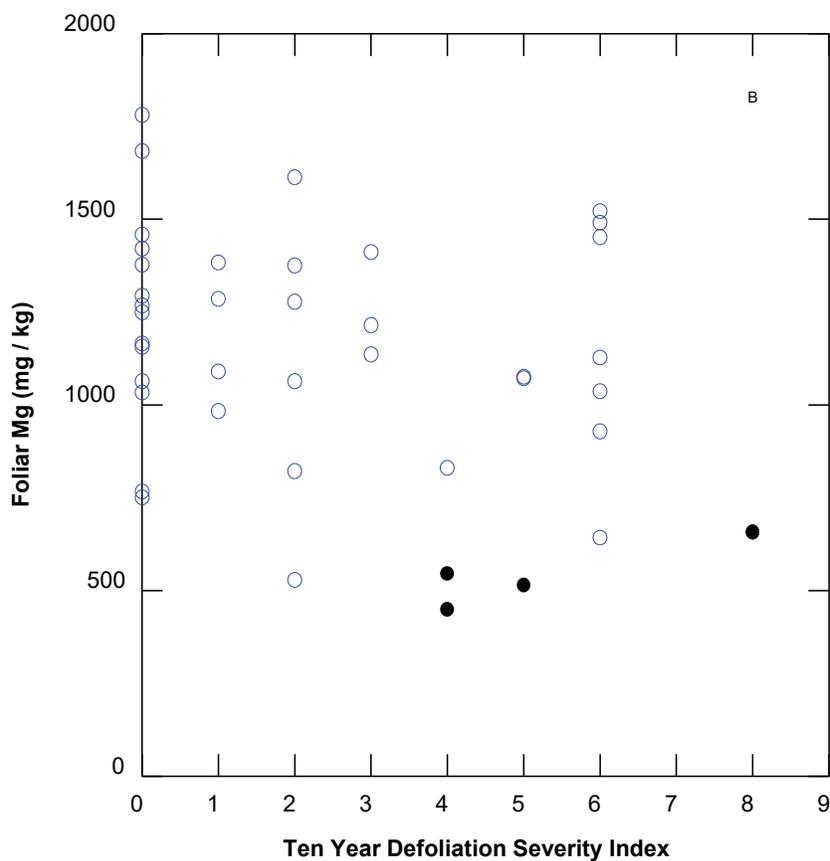
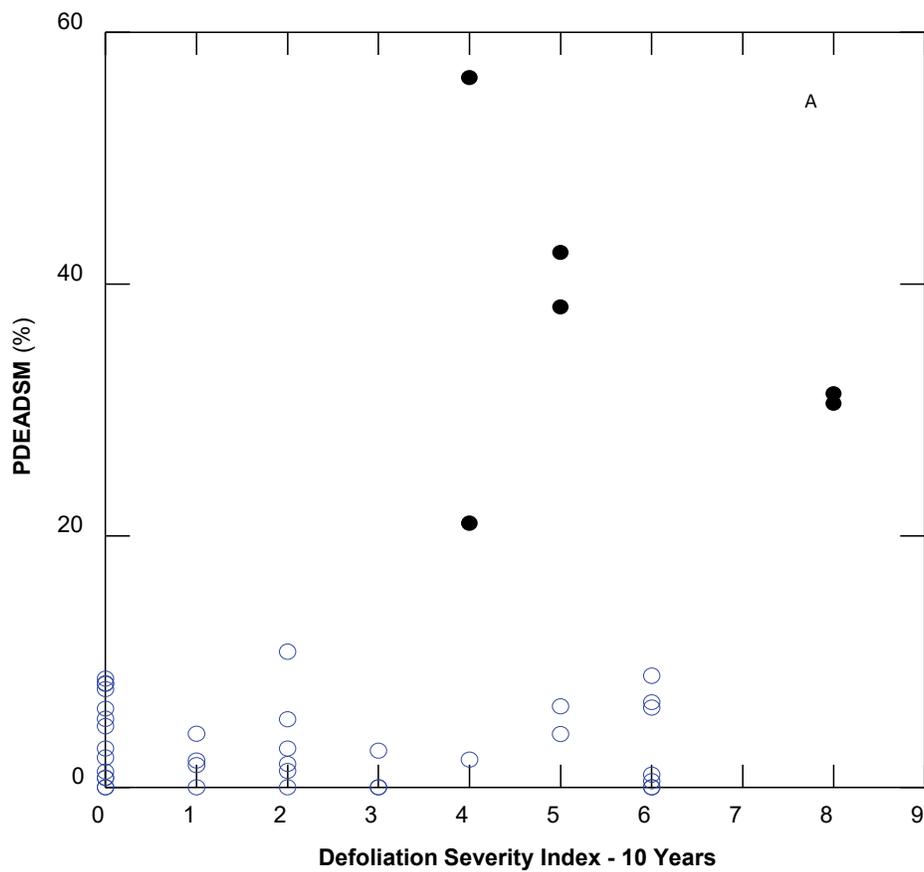


Figure 7.—(A) Relationship between sugar maple health as measured by %DEADSM and the DSI in the 10 years from 1987 to 1996 ( $R^2 = 0.158$ ,  $P = 0.008$ ); (B) relationship between foliar Mg ( $\text{mg kg}^{-1}$ ) and the DSI for the previous 10 years. Solid symbols show stands with moderate to severe decline. Open symbols show nondeclining stands.

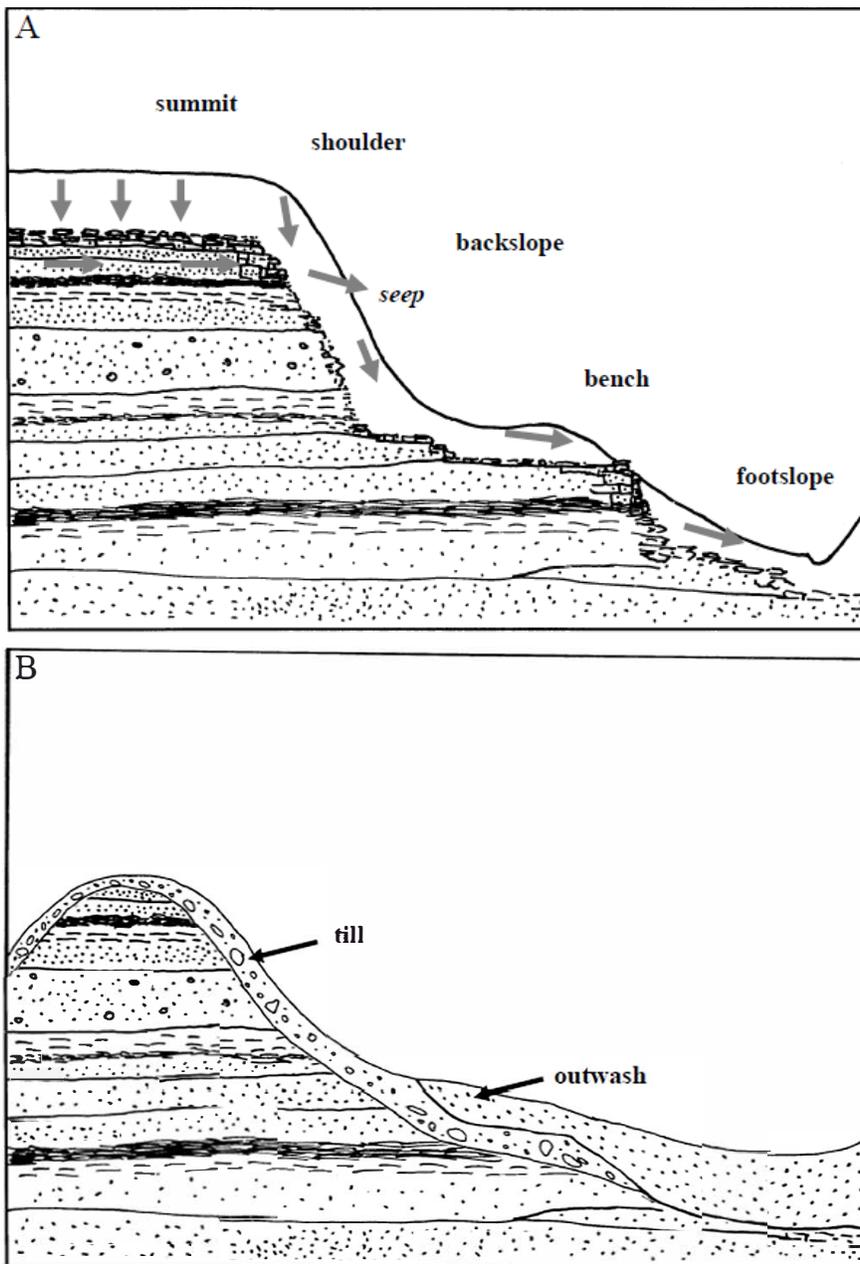


Figure 8.—Schematic cross sections of (A) unglaciated and (B) glaciated portions of the Allegheny Plateau. Patterned areas represent interbedded sandstone, siltstone, and shale bedrock. Soils on the unglaciated section are developed in relatively thick, weathered residuum, colluvium, and alluvium shown as the unpatterned area above the bedrock. Arrows suggest general direction of water flow in unglaciated soils and bedrock. Soils on the glaciated section are developed in relatively unweathered glacial till and outwash.

Foliar Ca and Mg were significantly correlated with many soil variables. Soil base saturation, which was dominated by Ca and Mg because of low concentrations of Na and K, also showed significant correlations with foliage values. The best predictors of foliar chemistry were made by regressions that considered soil chemistry across the depth of the B horizon, suggesting the importance of looking at more than one depth to assess nutrition (Bailey et al. 2004).

An important aspect of the soils research highlighted the differences between glaciated and unglaciated soils. On unglaciated sites, particularly on upper landscape positions, weatherable minerals are confined to the lower parts of the regolith well below the rooting zone, or within underlying bedrock. Thus, the delivery of weathering products, such as Ca or Mg ions, to the rooting zone is limited to parts of the landscape where water flow paths bring ions released from bedrock or deeper regolith to the solum where roots are active (Fig. 8A) (Bailey et al. 2004). In contrast, on glaciated portions of the Allegheny Plateau, much of the weathered regolith was removed by glacial erosion (Fig. 8B). Soil developed in glacial till incorporates

relatively unweathered material freshly exposed by glacial erosion. Thus, weathering reactions occur within the rooting zone and create less contrast in base cation levels by landscape position (Bailey et al. 2004).

These findings allowed for a more explicit application of Manion's decline spiral model (Manion 1991). Site nutrition, as influenced by glaciation and landscape position, affects the availability of Ca, Mg, and Mn. Thus, poor base cation nutrition is a predisposing factor that makes sugar maple more susceptible to decline. Insect defoliations and other less well-quantified stressors such as drought are the inciting factors that cause crown dieback and mortality for susceptible trees. For sugar maple, contributing stressors (the actual mortality agents) included *Armillaria* fungi, the sugar maple borer (*Glycobius speciosus*), and other organisms (Hallett et al. 2006, Horsley et al. 2002).

## Long-term Changes in Forest Soil Chemistry

Why did sugar maple decline occur during the late 1980s and early 1990s? The conceptual decline model described above relates the sequence of stressors that affected sugar maple health and mortality during this period. However, the timing of the decline coincident with the high levels of acid deposition inputs suggested that losses from these soils could have affected soil base cation status and sugar maple health. To assess changes in forest soils, we conducted a unique retrospective study that used archived soils sampled in 1967 from four forested sites on the Allegheny National Forest along with new contemporary samples (Bailey et al. 2005). In 1997, four new pits were established 10 m north, south, east, and west of the original 1967 pit. These were sampled by genetic horizon to 1 m or greater depth at each site to assess spatial variability and to compare long-term changes in soil base status. All four sites supported mature fully stocked second- and third-growth northern hardwood or mixed-oak forests that originated following forest removal between 1890 and 1930 (Marquis 1975). All sites were in the plateau top physiographic position near the local height of land and had been mostly undisturbed (no active management) since the 1960s.

The 1967 soils were subsampled and reanalyzed with contemporary analytical methods, and results were compared with the original 1967 analyses. Comparisons to 1967 showed a slightly lower pH in reanalyzed samples, but there was still a high correlation between the two ( $r = 0.87$ ). Ca, Mg, and Al concentrations in reanalyzed 1967 samples were highly correlated with the original values with all correlations  $>0.92$  (Bailey et al. 2005).

Comparisons of 1967 archived soils and 1997 soil samples showed long-term decreases in pH, exchangeable Ca and Mg, and increased exchangeable Al (Fig. 9) (Bailey et al. 2005). Changes in pH and exchangeable Ca and Mg were evident at all depths sampled up to 150 cm; changes in Al were mainly in the upper 30 to 50 cm (Bailey et al. 2005). Soil pools of Ca, Mg, and Al were calculated based on measured cation concentrations, horizon thickness, volumetric rock content, and bulk density. Values from the 1967 pits were similarly calculated for comparisons. We used three 400-m<sup>2</sup> vegetation plots at each site to estimate biomass storage of Ca and Mg in all trees 10 cm diameter at breast height and larger in 1997. We also used equations compiled by Jenkins et al. (2003) to divide biomass of each tree into foliage, stem wood, stem bark, branches, and coarse roots. The biomass storage in 1967 was estimated using data from eight fully stocked stands in a thinning study to estimate growth rates (Nowak 1996). We used the growth data to estimate the tree diameters in our plots in 1967 and then calculated the amounts of Ca and Mg stored in the biomass in 1967. This amount was then subtracted from the 1997 biomass values to provide the amount of Ca and Mg stored in trees from 1967 to 1997 (Bailey et al. 2005). The difference between the 1997 and 1967 biomass Ca and Mg represented a conservative estimate of what was sequestered in trees over 30 years.

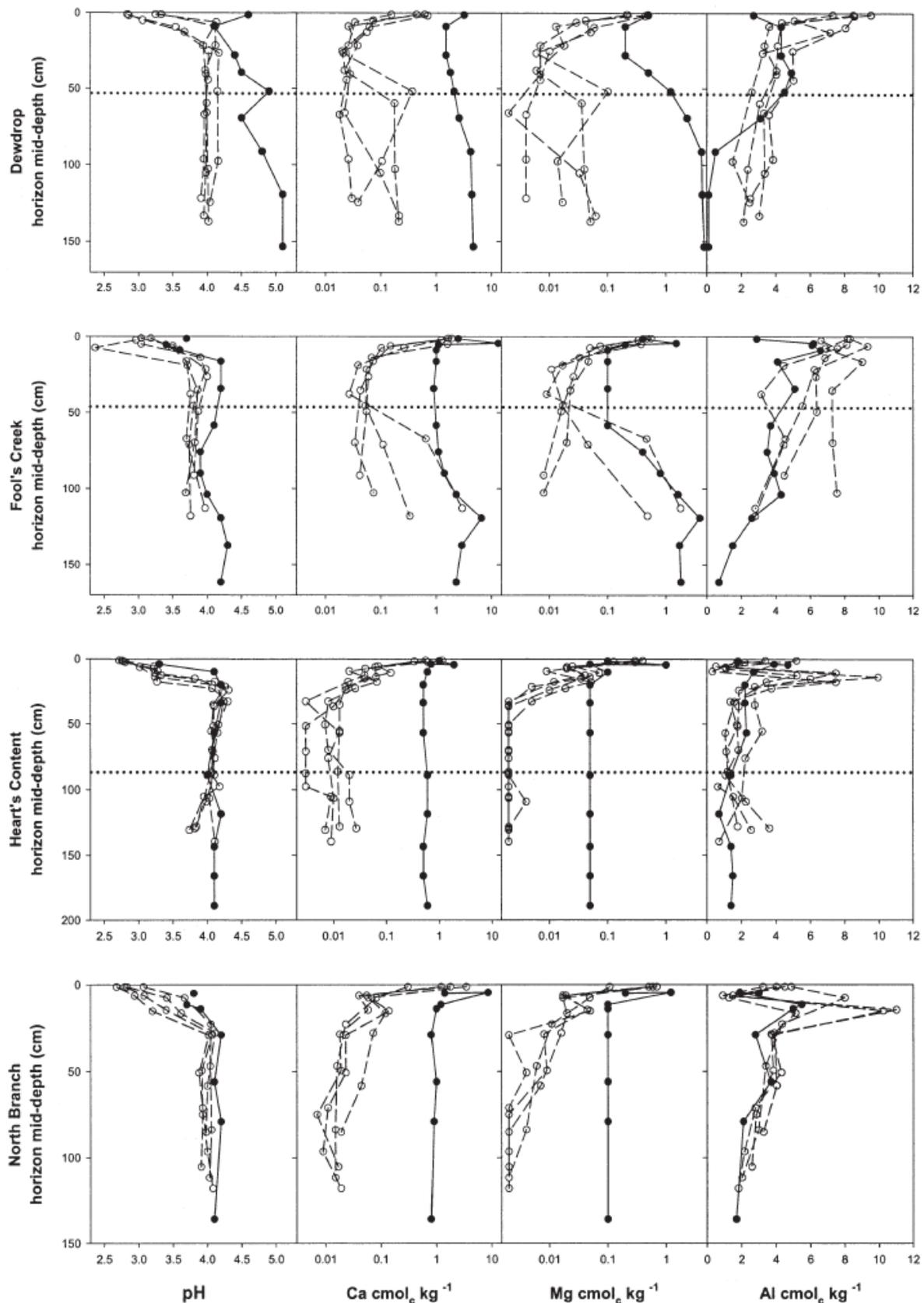


Figure 9.—Depth profiles of pH (standard units) and exchangeable Ca, Mg, and Al (cmol<sub>c</sub> kg<sup>-1</sup>) at each of four study sites. The closed circles represent the data collected from the original pit dug in 1967. The open circles represent the data collected from four pits dug in 1997, located 10 m from the original pit, in each of the four cardinal directions. The dotted horizontal line shows the average depth of the top of the fragipan, where present. A fragipan was found at three of the five pits at DD, all five pits at FC, and one of the five pits at HC.

Comparison of soil pool changes with net biomass accumulation suggest that many of the changes in exchangeable Ca and Mg in these soils cannot be accounted for by forest growth, implying off-site leaching (Bailey et al. 2005). These findings were consistent with those from other studies that found acid deposition induced significant losses of exchangeable base cation pools by hydrologic leaching (Fernandez et al. 2003, Huntington et al. 2000, Likens et al. 1996).

Because deposition inputs vary from year to year, we also examined short-term temporal variation by sampling forest floor organic layers (Oi, Oe, Oa/A) over 3 years (1997–99) at all four sites. The very thin Oa horizons could not be sampled separately, so Oa and A horizons were combined for analyses. Overall, short-term variability was minor and within an expected range. Changes between 1997 and 1999 samples were slight compared with values in 1967. As in the deeper mineral soils, pH was much lower, about 3.0 in 1997–99 samples compared with 1967 pH about 4.0. Similarly, Ca and Mg were much lower in 1997–99 organic layers compared with 1967 concentrations. Al concentrations were much higher in 1999–97 organic layers than in 1967 concentrations (Bailey et al. 2005).

This unique study showed that changes in soil base cation status and acidity over 30 years was a predisposing stressor for sugar maple and likely accounts for the timing of the maple decline in the late 1980s and 1990s. The addition of inciting stressors such as defoliating insects added the critical components that caused sugar maple crowns to die back and for trees to die from attacks by secondary organisms.

## CONCLUSIONS

Our studies in Pennsylvania, New York, and New England over more than a decade led to new insights regarding sugar maple health and nutrition. A key aspect of this research was the multidisciplinary team that conducted the research. The scientific collaboration across the disciplines of soil science and geology, forest ecology, plant physiology, and forest pathology accelerated progress in understanding the causes of sugar maple decline. Each scientist brought unique skills and expertise that enabled us to synthesize the factors that affected sugar maple health and led to substantial new findings. A key lesson is that diverse levels of scientific expertise accelerate the achievement of new knowledge and understanding.

Along with this work, guidelines and tools for land managers were developed. These included:

- Choose appropriate sites to culture sugar maple—sites with adequate Ca and Mg.
- Use indicator plants to help select sites with adequate Ca and Mg nutrition (see Horsley et al. 2008).
- Monitor and record stressor events and their effects—especially defoliations and droughts.
- Supplement nutrition—consider adding lime where feasible.
- Protect base cations on sensitive sites—leave treetops and don't fertilize to conserve Ca and Mg.
- On low base cation sites, emphasize species that are not responsive to base cations—for example, red maple and black cherry.

The lime study findings in the mid-1990s were important for identifying the key role of base cation nutrition for sustaining sugar maple health, even when trees were stressed by defoliations and drought. The differential responses of American beech and black cherry also highlight the complexity of forest nutrient and tree growth interactions and that nutrient

requirements vary by species. The gradient study was initially a pilot project to determine how Ca and Mg were distributed on the landscape and whether this was related to sugar maple health. Expanding this work across a broader geographic area and gathering additional stand history information keyed us to the finding that glaciation, landscape position, and the number and severity of defoliations were important factors in determining where on the landscape sugar maple was most likely to decline. Initial findings that Ca and Mg were lowest on unglaciated upper landscape positions and that these were the sites with the most sugar maple mortality led to more intensive assessment of soil nutrition at all 43 stands. Understanding the critical influence of bedrock parent materials and hydrologic flow paths on unglaciated sites helped explain the site variability that affected changes in sugar maple health. The retrospective soil nutrient study used four sites on the Allegheny National Forest and showed substantial losses of Ca and Mg throughout the soil profile from 1967 to 1997 as a result of deposition inputs. Base cation losses and soil acidification likely influenced the timing of the sugar maple decline. The stressors affecting sugar maple came together in the mid- and late 1980s and caused extensive dieback and mortality. However, since this period, deposition inputs have decreased, and insect defoliations have been less frequent. These factors allow many sugar maples to survive and recover.

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