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Spatial Relationships Between Sugar Maple (*Acer saccharum* Marsh), Sugar Maple Decline, Slope, Aspect, and Atmospheric Deposition in Northern Pennsylvania

Patrick Drohan, Susan Stout, and Gary Petersen[1]

Popular Summary

Sugar maple decline began to affect Allegheny Plateau forests in the early to mid-1980s. The forests of the region were exposed to several stresses in the period from 1985-1996, including droughts during 1988, 1991, and 1995. Additionally, both native and exotic insects reached epidemic levels during this period (see, for example, Rhoads, 1993). Other documented stresses in the region include past and present harvesting practices (Allen and others 1992), herbivory by deer (Tilghman 1989), and low soil nutrient availability (Long et al. 1997, DeWalle and Swistock 1997) possibly associated with soil acidification (Hendershot and Jones 1989).

Examination of sites experiencing sugar maple decline has yielded much valuable information about the potential causes of decline but has not provided estimates of the relative abundance of declining sugar maple sites or their spatial distribution within northern Pennsylvania. Nor did these studies provide an opportunity to contrast declining sugar maple stands with those that are not declining across a large geographic area. These estimates are desirable from both policy and scientific perspectives.

The long-term goal of our research is to characterize sites with sugar maple decline across northern Pennsylvania. In this preliminary work, our objectives were:

- to determine if the decline could be detected using data collected by the USDA Forest Service Forest Inventory and Analysis program (FIA) between 1978 and the late 1980s (Alerich 1993); and,
- to characterize the relative abundance of sugar maple decline and the sites on which declining and healthy sugar maple was found in the late 1980s across northern Pennsylvania.

This paper reports preliminary results from our study.

Methods

We limited our study to the Pennsylvania portions of the Northern Unglaciated Allegheny Plateau Section (212G) and the Northern Glaciated Allegheny Plateau Section (212F) of Bailey's Ecoregions and Subregions of the United States (Bailey and others 1994). These regions are characterized by northern hardwood forests and encompass the range of reports documenting sugar maple decline within Pennsylvania (Laudermilch 1995; McWilliams et al. 1996).

We excluded points in which overall basal area fell below the threshold of continuous forest cover (9.2 m^2 ha^{-1}) and those in which sugar maple basal area was insufficient for analysis (2.3 m^2 ha^{-1}). We found that 248 plots met these criteria (Figure 1); 140 plots were located in unglaciated Section 212G and 108 in glaciated Section 212F. Locations recorded at the center of each FIA plot were entered into a geographic information software program to create a map of stand locations and to provide points for later analysis.

FIA plot coordinates for this preliminary study consisted of actual longitudes and latitudes rounded to the nearest 100 seconds. The imprecision of FIA plot locations limited our preliminary analysis to variables (such as slope and aspect) measured directly at sample locations by FIA or to variables whose spatial resolution was compatible with plot location accuracy.

Several variables were chosen from the FIA database to determine the health status of the sugar maple population as measured in 1989. These variables were sugar maple basal area mortality in 1989 (SMBAM) and sugar maple basal area change 1978-1989 (SMBAC-we added any sugar maple basal area cut during the period to the 1989 value). We also calculated the percent dead sugar maple basal area (PDSMBA) (sugar maple basal area mortality as a percent of total living and dead sugar maple basal area), and percent sugar maple basal area change (PSMBAC) (sugar maple basal area change as a percent of basal area in 1979).

We used K Means Cluster Analysis (Minitab Inc. 1994) with these four variables to determine whether the data would cluster into healthy and declining subpopulations with sufficient separation for analysis. For slope and aspect, we tested for differences between clusters and between glacial regions as well as within region using the non-parametric Kruskal-Wallis test. Kruskal-Wallis contrasts use variable ranks rather than variable values in tests of significance. Therefore, we examined the differences in medians wherever rank difference suggested statistical significance to determine whether the differences were likely to be biologically meaningful (Minitab Inc 1994).

Wet deposition data, based on a spatially explicit model for Pennsylvania (Lynch et al. 1995), were obtained in digital format for 1987-1989 (NO_3, NH_4, SO_4, H, Ca, and Mg (kg ha^{-1} yr^{-1})). We used the mean deposition over the three-year period for each element for our tests. Again, the Kruskal-Wallis test was used to contrast the deposition rankings of healthy and declining clusters across the state and within each glacial region.

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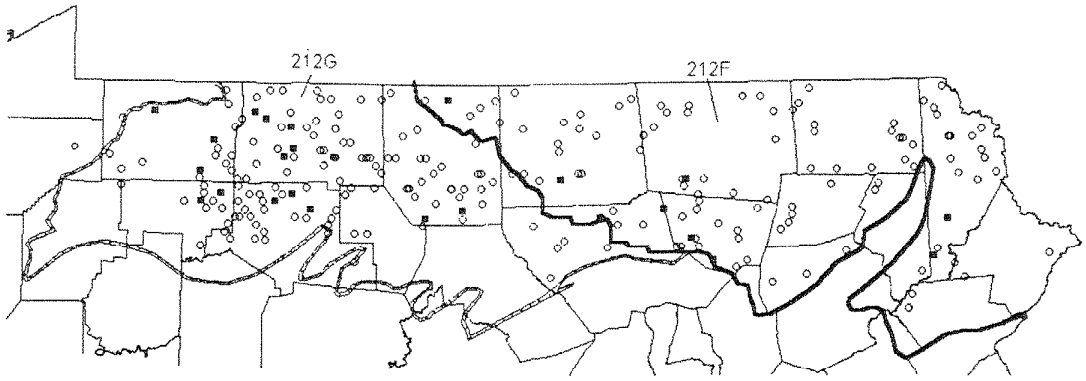

Figure 1.—Map showing the 248 FIA plot locations and the health status assigned by K-means cluster analysis (○healthy cluster, ■declining cluster). The map shows political boundaries and ecoregion boundaries (the solid line shows the boundary of glaciated Section 212F and the thin double line shows the boundary of unglaciated Section 212G).

Results and Discussion

Clustering for Health Status

Our best separation using cluster analysis resulted in the two populations seen in Figure 1 (223 healthy stands and 25 declining stands). This was achieved with all four standardized health variables (SMBAM, F=298; SMBAC, F=111; PDSMBA, F=458; PSMBAC, F=31) in the cluster analysis. Percent dead sugar maple basal area (PDSMBA) was the strongest variable contributing to the clustering. There were 123 members of the healthy cluster and 17 members of the declining cluster (about 12%) in Ecoregion 212G, the unglaciated section, and 100 members of the healthy cluster and 8 (about 7%) members of the declining cluster in Ecoregion 212 F, the glaciated area. While this difference suggests that there is a tendency towards a higher proportion of declining cluster members in the unglaciated section, the difference is not significant (p=0.22).

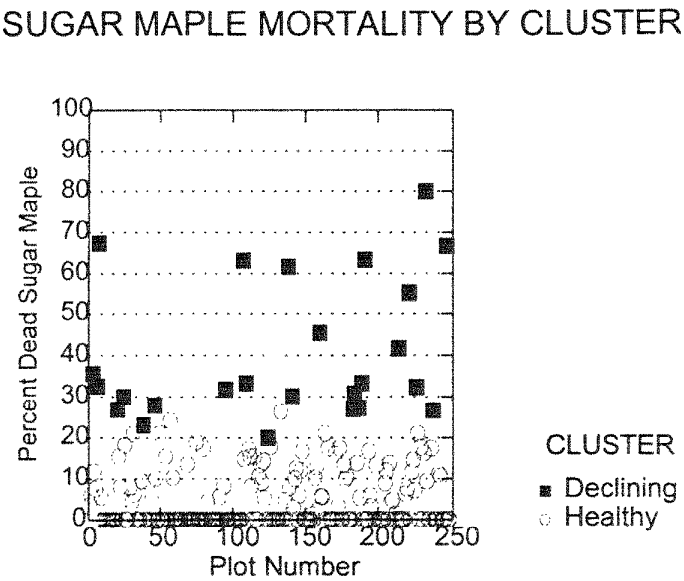

Figure 2.—Percent dead sugar maple basal area in the healthy and declining clusters (○healthy cluster, ■declining cluster).

The declining cluster included stands with 1989 measurement period basal areas ranging from 9.2 $m^2 ha^{-1}$ to 38.9 $m^2 ha^{-1}$, with a median of 25.9 $m^2 ha^{-1}$ (Table 1). Percent dead sugar maple basal area ranged from 20 to 80 percent, with a median of 33 percent. In the healthy cluster, 1989 measurement period basal area ranged from 9.2 $m^2 ha^{-1}$ to 41.7 $m^2 ha^{-1}$, with a median of 25.9 $m^2 ha^{-1}$. In this cluster, percent dead sugar maple basal area ranged from 0 to 26 percent, with a median of 0 percent. Figure 2 shows percent dead sugar maple basal area in the two clusters plotted against their case number in the file.

Both the proportion of the stands with decline and the characteristics of the declining cluster are comparable to results found by Horsley et al. (this volume) in their study of topographic gradients in northern Pennsylvania and southwestern New York. Six of the 43 plots that they examined (14%) were declining; all of these plots had a percent dead sugar maple basal area in excess of 20 percent, and all the plots in their healthy cluster had percent dead sugar maple basal area less than 20 percent. All of the plots in the Horsley et al. declining cluster occurred within the unglaciated region, but our analysis detected no difference in the rate of decline between regions. Our study area extends further east and west than the Horsley et al. study, specifically including a larger portion of the glaciated region.

Table 1.—Medians, means (± standard deviation) of selected characteristics as measured or calculated from data collected during the 1978 and 1989 measurement cycle from plots in the healthy and declining clusters used for this analysis. SMBA = Sugar maple basal area.

Cluster	Basal area (m^2 ha^{-1})	SM BA (m^2 ha^{-1})	Change in SM BA (m^2 ha^{-1})	SM BA mortality (m^2 ha^{-1})	% change, SM BA	% Dead SM BA
All stands medians	25.9	6.9	1.2	0.0	14	0
means (±SD)	25.6(±7.3)	8.0(±5.2)	1.4(±2.2)	0.7(±1.2)	24(±46)	8(±14)
1 – healthy medians	25.9	7.0	1.4	0.0	17	0
means (±SD)	25.6(±7.2)	8.3(±5.3)	1.7(±1.8)	0.4(±0.6)	30(±46)	4(± 6)
2 – declining medians	25.9	4.4	2.1	2.8	-21	33
means (±SD)	25.2(± 8.2)	5.2(± 3.3)	-2.3(± 1.9)	3.3(± 1.9)	-22(± 16)	41(± 17)
212F-glaciated medians	24.5	6.3	1.7	0.0	18	0
means (±SD)	24.7(±7.6)	8.3(±5.8)	1.7(±2.1)	0.5(±1.0)	33(±56)	6(±12)
212G-unglaciated medians	26.7	7.0	0.9	0.2	10	3
means(±SD)	26.4(±7.0)	7.8(±4.8)	1.1(±2.2)	0.8(±1.3)	18(±36)	10(±15)

Table 2.—Percent of sugar maple plots on each aspect by ecological subsection.

Region	Aspect			
	North	South	East	West
Entire State	39	14	31	16
Glaciated 212F	38	12	29	21
Unglaciated 212G	39	16	33	11

Table 3.—Median deposition for several ions for healthy and declining clusters, and the p value for the Kruskal Wallis test of differences between clusters. For the Kruskal-Wallis test, the values of a variable are transformed to ranks (ignoring group membership) to test that there is no shift in the center of the groups (that is, the centers do not differ). Thus, a low p value indicates that the groups differ in rank for a particular deposition variable.

Ion deposited	Median deposition, healthy cluster (kg ha^{-1} yr^{-1})	Median deposition, declining cluster (kg ha^{-1} yr^{-1})	Kruskal Wallis p
Ammonium	2.6	2.9	0.02
Calcium	1.1	1.3	0.04
Hydrogen	0.66	0.74	0.02
Magnesium	0.21	0.22	0.23
Nitrate	18.7	20.5	0.02
Sulfate	29.4	33.7	0.02

Slope and Aspect

Sugar maple distribution across four main aspects (N, S, E, and W) was similar for all three areas studied: the entire state, the glaciated region, and the unglaciated region (Table 2). North and east aspects contained 70 percent of the sugar maple plots across the two regions.

Plots in this study occurred on slopes ranging from 0 to 62 percent (median = 16). In the glaciated region, percent slope ranged from 0 to 52 percent (median = 15) and in theunglaciated region, 0 to 62 percent (median = 17). No differences were detected between the distributions of slope steepness (percent) (p=0.645) or aspects (p=0.291) by glacial region. Nor were there significant differences across the state (slope p=0.283, aspect p=0.291), within the glaciated region (slope p=0.958, aspect p=0.863), or within the unglaciated region (slope p=0.214, aspect p=0.313) in the distributions of slope or aspect between healthy and declining populations of sugar maple. These results are consistent with the observations of Whitney (1990) and Abrams and Ruffner (1995) who found increases in sugar maple abundance from presettlement times to the present. Comparisons are difficult because of slight differences in data form and organization. Using data from the early settlement period in a study area that spanned the glacial, ecoregional border, Abrams and Ruffner (1995) found that sugar maple preferred stream valleys and north-facing coves. Whitney (1990), working with presettlement data from the Allegheny National Forest (ANF), within the unglaciated ecoregion, found that sugar maple had a marked preference for plateau top landscape positions with slopes [8 percent. In an old-growth area on the ANF, Hough and Forbes (1943) found that sugar maple was more abundant on north-facing slopes.

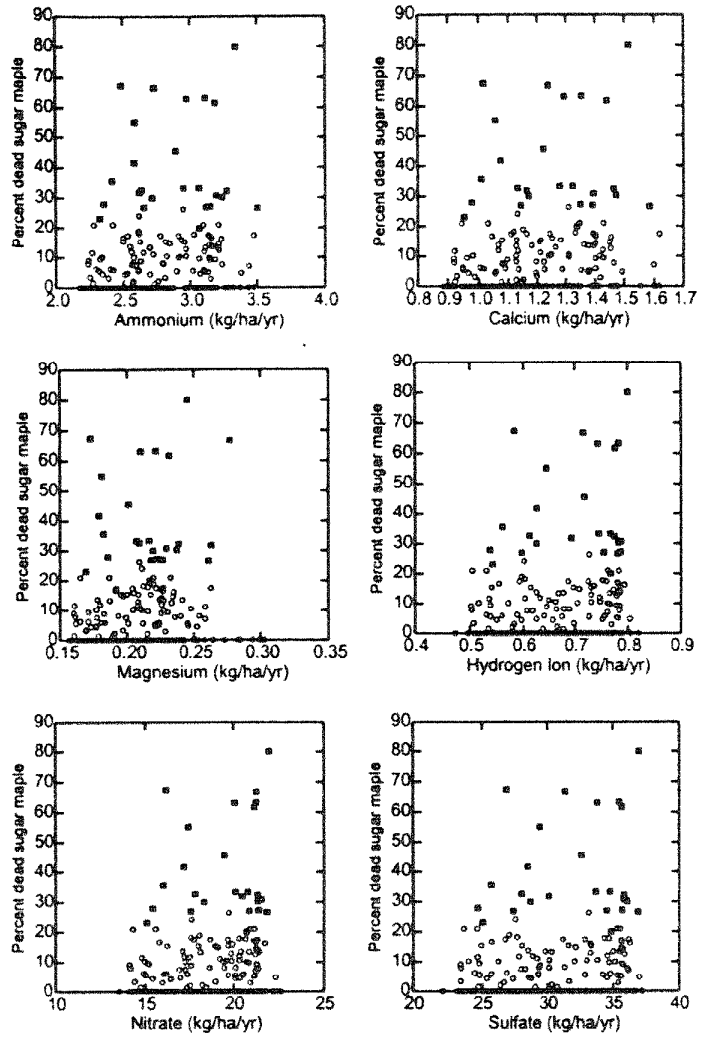

Figure 3.—Percent dead sugar maple basal area vs. each of the deposition variables examined in this study (○healthy cluster, ■declining cluster). Deposition values are mean annual kg ha $^{-1}$ for the period 1987-1989.

Deposition Variables

Nitrate, ammonium, sulfate, and calcium deposition falls on a distinct gradient from high levels in northwestern Pennsylvania to lower levels in northeastern Pennsylvania (Lynch et al. 1995). The spatial pattern of magnesium deposition is different from that of other elements, with a secondary peak deposition level near the eastern end of the Northern Tier.

Significant differences were found across the state between healthy and declining stands for all deposition variables (p=0.02 through 0.04) except magnesium (p=0.23). Median differences in deposition values were small in all cases (Table 3). The same pattern was found within the unglaciated region. Within the glaciated region, differences between plots in the healthy cluster and those in the declining cluster were not significant (p= 0.296). Figure 3 shows the relationship between dead sugar maple basal area and each of the deposition variables for both ecoregions, including healthy and declining cluster plots.

This exploratory analysis of the correlation between deposition levels and sugar maple decline showed relationships that achieved statistical significance, but are associated with differences in actual deposition values that are unlikely to have biological meaning.

Future Work

Future work on this project will include both additional analysis at the large geographic scale reported here and analysis of intensive field-sampled data from a subset of these plots. At the large scale, we plan to test for differences between declining and healthy plots with respect to historical defoliations, elevation, and topographic position with the 248 plots. We also plan to develop much more intensive site characterizations for a sub-sample of these plots. During the summer of 1998, a crew from the Pennsylvania State University collected data at thirty of the 248 plots used in this study. They sampled soil and vegetation at 15 plots with various levels of percent dead sugar maple basal area and 15 plots with no dead sugar maple.

At each plot, the crew remeasured basal area following the methods set by the FIA program during the previous survey in 1989, collected foliage for chemical analysis, and collected cores from three trees. Other data included: slope and aspect (8-pt. scale), topographic position, tree vigor, dieback and transparency, forest floor and soil characteristics, and ground vegetation. Analysis of soil and rock physical and chemical properties and foliar chemistry will allow us to detect much more specific characteristics that distinguish plots in the healthy cluster from those in the declining cluster.

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Factors Associated with Rapid Mortality of Sugar Maple in Pennsylvania

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Abstract

Mortality of sugar maple and red maple was observed throughout Pennsylvania in 1995 following an outbreak in 1994 by forest tent caterpillar and elm spanworm on sugar maple and red maple, respectively. Symptoms of leaf anthracnose caused by *Discula campestris* (Pass.) were observed during the refoliation period from July through September 1994; the refoliation of crowns of affected trees was extremely poor or almost non-existent. Subsequent mortality and tree condition were monitored in 15 sugar maple stands located in Bedford, Blair, Lycoming, Potter, Sullivan, Susquehanna, Tioga, and Wayne counties from 1995-1997. Initial mortality was 12.3% in 1995; by 1997 cumulative mortality was 19.9% (salvaged timber excluded). The role of multiple stress factors in relation to mortality is discussed.

Introduction

Unusual levels of sugar maple (*Acer saccharum* Marsh.) crown dieback and tree mortality have been observed across the northern-tier counties of Pennsylvania since the early to mid-1980s (Kolb and McCormick 1993, Quimby 1997). In some cases, tree decline has been characterized by slow crown deterioration and eventual mortality occurring over five or more years; in other cases the crown dieback and mortality process occurs relatively rapidly in only a year or two. Defoliation, drought, and other climatic events have been associated with decline and mortality of sugar maple elsewhere (Giese et al. 1964, Gross 1991, Bauce and Allen 1991, Allen et al. 1992a and 1992b, Payette et al. 1996, Robitaille et al. 1995, Auclair et al. 1997). Recently, we had an opportunity to document a sequence of events which resulted in rapid mortality of sugar maple in Pennsylvania.

In May-June 1994, an outbreak of forest tent caterpillar (*Malacosoma disstria* Hhbner) on sugar maple was responsible for extensive defoliation of northern hardwood stands throughout Pennsylvania. Affected areas included the northern-tier counties of Bradford, Columbia, Luzerne, Lycoming, McKean, Sullivan, Susquehanna, Tioga, and Wayne and the southcentral counties of Blair and Bedford. Based on estimates from aerial surveys conducted by the Pennsylvania Bureau of Forestry (Quimby 1995 and 1996), forest tent caterpillar defoliated approximately 283,000 hectares. An additional 93,280 hectares were defoliated in areas infested by both forest tent caterpillar and elm spanworm (*Ennomos subsignaria* Hubner) on sugar maple and red maple, respectively. Subsequent refoliation of trees in affected stands was poor; trees exhibited extensive crown dieback, and foliage transparency in the range of 80 to 95+% was estimated.

In August 1994 visual inspection of foliage from affected sugar maple and red maple trees revealed symptoms of anthracnose presumably caused by the fungal pathogen *Discula campestris* (Pass.) (Hall 1995). Symptoms observed during the refoliation period were leaf blight, expansive necrotic leaf lesions characteristic of anthracnose, leaf cupping, extensive necrosis of succulent twig and bud tissue, lack of terminal bud formation, and extensive twig and branch dieback. In 1994 a study was initiated to evaluate the impact of the defoliation by forest tent caterpillar followed by anthracnose on sugar maple mortality in the years following the initial outbreak.

Methods

In November 1994, plots were established in 15 sugar maple stands for a multiyear monitoring study to record changes in tree crown condition and mortality following heavy (30-50%) to severe (50+%) defoliation by forest tent caterpillar and damage by *Discula campestris*, the sugar maple anthracnose fungus, during the subsequent refoliation period. Verification of damage by *Discula campestris* was based on the presence of bud and twig symptoms on samples taken from sugar maples within or near each study plot between September and late October 1994. Twig samples were collected and incubated in a moist chamber to induce fungal sporulation; subsequent cultures of *Discula campestris* were made from symptomatic twigs. Isolates of *Discula campestris* were tested for pathogenicity on sugar maple seedlings. After confirmation of anthracnose damage within a stand, a study plot, including 30 to 50 sugar maple trees that had been damaged by both forest tent caterpillar and *Discula campestris*, was established. Most of the sampled trees were of either dominant or codominant crown class. A total of 546 trees among the 15 plots was monitored. These plots were revisited in late May and early June 1995, 1996, and 1997 to collect data on tree mortality, percent crown dieback, percent live crown cover, foliage condition, foliage distribution and size, insect defoliation, and anthracnose activity.

Results

Only tree mortality and crown dieback are presented. Table 1 lists annual and cumulative mortality for 1995-97. In 1995, sugar maple mortality among all plots was 12.3% (67 of 546 trees), though initial tree mortality was high in four stands located in Lycoming, Sullivan, and Wayne Counties. Most residual tree crowns were damaged, and many were in fair to poor condition in most stands. Two plots located in

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Table 1.—Percentage of sugar maple mortality associated with 1994 defoliation by *Malacosoma disstria* and anthracnose caused by *Discula campestris* for 15 stands located in eight* Pennsylvania counties.

Mortality category	Year 1995	1996	1997
Annual	12.3 (67/546)**	8.1 (39/479)	0.7 (3/427)
Cumulative	12.3 (67/546)	19.4 (106/546)	19.9 (109/546)
Salvage healthy	-	-	2.7 (15/546)
Salvage unhealthy	-	-	15.2 (83/546)
Total salvage	-	-	17.9 (98/546)

*Bedford, Blair, Lycoming, Potter, Sullivan, Susquehanna, Tioga, and Wayne.
**Actual mortality figures presented for each category with the numerator representing dead trees and the denominator representing the study population.

Table 2.—Percentage of crown dieback in sugar maple due to the 1994 outbreak of forest tent caterpillar and anthracnose caused by *Discula campestris* on 15 study plots in Pennsylvania.

Dieback class*	Percent crown dieback by year 1995	1996	1997
0-15%	48.9**	57.7	79.9
20-30%	9.9	14.9	13.1
35+%	41.2	27.4	7.2

*Dieback class based on Sugar Maple Management Highlights for the Region from the North American Maple Project (Anonymous 1997).
**Percentage based on the number of standing live trees at the time of data collection; salvaged trees are not included.

Table 3.—Percentage of crown dieback in sugar maple stands* due to the 1994 outbreak of forest tent caterpillar and anthracnose where cumulative tree mortality was below 2%.

Dieback class**	Percent of crown dieback 1995	1996	1997
0-15%	74.2*** (242/326)	74.5 (240/322)	78.7 (251/319)
20-30%	11.3 (37/326)	11.8 (38/322)	9.7 (31/319)
35+%	13.2 (43/326)	9.9 (32/322)	9.7 (31/319)

*Data reflects nine stands which remain under study beyond 1997.
**Dieback class based on Sugar Maple Management Highlights for the Region from the North American Maple Project (Anonymous 1997).
***Percentage based on the number of standing live trees at the time of data collection.

Sullivan County on the Wyoming State Forest (Dry Run and Slab Run) each with 50 trees had 13 and 36 dead trees, respectively. Of the remaining live trees, 18 and 11 trees, respectively, had crown dieback of 80% or more. Only three additional trees died in these stands in 1996, but crown dieback was 80% or more in 22 and 8 trees, respectively. By 1996, 52 trees were dead, 30 trees had crown dieback >80%, and only 8 trees were healthy with dieback <25%. These stands were subsequently marked for salvage and removed from the current study after 1996. One plot in Wayne County on Pennsylvania State Game Lands #159 was the location where forest tent caterpillar and anthracnose were first observed and confirmed in 1994. Of the 30 trees in this plot, 4 died in 1995 and 7 in 1996. Crown dieback was >80% on 22 of 30 trees in 1995 and 14 of 19 living trees in 1996. The latter plot was marked for salvage in 1996 and removed from this study.

In 1995 two plots with 30 trees each, one in private ownership at Franklin Forks, Pennsylvania, in Susquehanna County and the other owned by the Rockport Gun Club in Wayne County, had only 1 dead tree among the 60; crown dieback of >80% was observed on 7 and 4 trees, respectively. In 1996 salvage at the Franklin Forks stand resulted in removal of 4 healthy trees and 12 trees in poor health; salvage at the Rockport Gun Club resulted in removal of 8 healthy trees, though some showed symptoms of crown dieback. These plots also were removed from the study in 1996.

Table 1 lists mortality data for the study to date. Total cumulative mortality due to natural causes for the 15 plots was 109 trees out of 546 sampled trees (19.9%). Salvage operations in 1996 and 1997 removed 98 of 546 trees (17.9%) of which 15 (2.7%) were healthy and 83 (15.2%) were in poor health. Natural mortality and salvage of trees with extensive dieback resulted in the removal of 35.1% (192/546) of the study population within three years of the forest tent caterpillar and anthracnose outbreak.

To illustrate the impact of insect defoliation and anthracnose on crown dieback, we used information developed through the North American Maple Project (NAMP) to categorize tree health among easily determined dieback classes (Anonymous 1997). Table 2 shows the tree distribution

among three crown dieback classes. Trees in the 0-15% dieback class represent those with the greatest probability of long-term survival, while those with >35% dieback have a lower probability of survival. From 1995 to 1997, the proportion of trees in the 0-15% dieback class increased, while those in the >35% dieback class decreased.

Table 3 illustrates crown dieback distribution for 1995-97 among the nine stands which remained under study after 1997. Tree mortality in these stands was low. In 1995, only 4 dead trees were observed among the remaining study population of 326 trees; 3 additional trees died in 1996 and 3 more in 1997. Cumulative mortality for 1995-97 was 3%, and incidence of trees with severe dieback (>80%) for the 1995-97 period was 4.9%. Over the three years of data collection, tree crowns had less dieback and appeared to be recovering. Since 1994 there has been little or no additional insect defoliation or anthracnose damage. However, a severe drought from late June through September 1995 may have contributed to tree mortality and crown damage expression in 1996.

Discussion

High mortality and extensive crown dieback were evident within ten months of the initial defoliation. Subsequent crown recovery in residual trees was apparent by 1996 and has since improved throughout the remaining 9 stands under study. Many factors may interact to account for apparently high mortality rates following defoliation (Houston 1981). These include site factors such as soils that are excessively or poorly drained, high stand density, prior defoliation (Houston 1981, Bauce and Allen 1991), and defoliation followed by anthracnose outbreaks (Heichel et al. 1972). Unfortunately, these factors along with predefoliation crown condition could not be determined in this study. Adverse environmental factors such as drought or frost also may contribute to tree mortality following defoliation (Houston 1981). While defoliations occurred in May and June, previous research has shown that June defoliations were the most severe, resulting in the fastest and greatest amount of crown damage (Wargo 1981). In the current study, defoliation was followed by precipitation patterns that ensured moist conditions over an extended period, providing a favorable environment for anthracnose infestations (Heichel et al. 1972, Neely and Himelick 1963). During subsequent refoliation attempts, emergent leaves and subtending twigs were attacked by the anthracnose fungus which prevented any significant canopy refoliation until seasonal leaf drop in early November 1994. Therefore, affected trees with insufficient photosynthetic leaf area might not produce sufficient carbohydrate reserves to survive the winter and produce new foliage in the next growing season (Wargo 1981). Alternatively, trees with sufficient carbohydrate reserves that were not consumed during initial foliation and refoliation might survive, but would be expected to exhibit damage to residual crowns.

Other maple decline studies have noted mortality or increased crown dieback associated with secondary organisms such as the root and collar rotting fungus *Armillaria mellea* (Vahl:Fr.) P. Kumm. or the twig and branch fungus *Steganosporium ovatum* Corda. Both of these organisms may hasten the death or increase the amount of crown dieback of already stressed trees (Wargo 1981, Houston et al. 1990). There are no previous reports of the interaction between forest tent caterpillar and *Discula campestris* with the fungus acting to accelerate mortality. However, Heichel et. al. (1972) describes a field experiment where red oak and red maple saplings were manually defoliated to simulate gypsy moth or elm spanworm defoliation; during the subsequent refoliation period, emergent leaves and twigs exhibited anthracnose symptoms followed by severe twig dieback in both species. The observations of Heichel et al. (1972) suggest that insect defoliation and anthracnose can occur simultaneously to cause severe damage to tree crowns and could be a contributing factor when assessing tree decline. Given the difficulty of examining and sampling the crowns of mature trees, the role of anthracnose diseases may have been previously overlooked or attributed to other factors, including insect defoliation.

While there are many reports of long-term sugar maple mortality, only a few studies have monitored mortality rates during decline events. In the Allegheny National Forest, 340 stands surveyed in 1994, approximately ten years after initiation of sugar maple decline, revealed 28% of the sugar maple basal area (trees >2.5 cm dbh) were dead (McWilliams et al. 1996). Precise mortality rates cannot be calculated because no pre-decline data was available from these plots. Averaged across seven states and four provinces, the six-year average annual mortality rate for sugar maple in all crown classes was 0.9% for 165 plots located in sugarbushes and nonsugarbushes monitored in the North American Maple Project (Allen et al. 1995). In New England, annual mortality rates (over ten years) for sugar maple in northern hardwood stands ranged from 0.14% to 2.75% or 0.0009 to 0.0204 m^2yr^{-1} of basal area (Solomon 1977). In our study, mortality was greatest (12.3%) the year following the defoliation and anthracnose infestations; average annual mortality was 6.6% from 1995 to 1997. By 1997, annual mortality was only 0.7%, suggesting that the 1995 and 1996 mortality was episodic and by 1997 rates had returned to those found by Allen et al. (1995) and Solomon (1977). Periodic occurrences of high levels of annual mortality will influence forest composition, age structure, and stand density with irregular patterns in time and space across the landscape. Long-term annual monitoring of tree health may help to understand the influence of specific stressor events on mortality patterns.

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Impact of Forest Liming on Growth, Vigor, and Reproduction of Sugar Maple and Associated Hardwoods

Robert P. Long, Stephen B. Horsley and Paul R. Lilja[1]

Popular Summary

Introduction

In 1985 a long-term study was initiated by the Pennsylvania Bureau of Forestry and the Northeastern Research Station to evaluate factors impeding regeneration of Allegheny hardwoods (Auchmoody, unpublished). The major factors suspected of limiting regeneration were high soil aluminum levels associated with low soil pH (typically 3.6 to 4.2 in surface mineral soils), deer browsing, and interfering vegetation such as hayscented fern (*Dennstaedtia punctilobula* (Michx.) Moore) and striped maple (*Acer pensylvanicum* L.). At that time, overstory sugar maple (*Acer saccharum* Marsh.) decline was just beginning to become a serious problem on the Allegheny Plateau. Subsequently, sugar maple decline became widespread across the unglaciated Allegheny Plateau in northwestern and north central Pennsylvania. A secondary objective of the study was to determine the effects of treatments on the growth and vigor of the three principal overstory species, sugar maple, American beech (*Fagus grandifolia* L.), and black cherry (*Prunus serotina* Ehrh.), and to evaluate the effects of treatments on sugar maple flower and seed production, and seedling regeneration. Results of this study through 1993 have been reported elsewhere (Long et al. 1997), and this report will summarize results through 1996 or 1997.

Methods

Four replications of the study are located in the Susquehannock State Forest in Potter County,Pennsylvania on the unglaciated Allegheny Plateau. The study design was a split-plot with fencing (to exclude deer) the whole plot treatment and dolomitic lime (22.4 megagrams per hectare), herbicide (glyphosate), lime+herbicide, and untreated controls as the subplot treatments. Each of the 32 subplots was 45 meters X 45 meters. Herbicide to control interfering vegetation was applied with a backpack mist blower at a rate of 2.2 kg a.i. per hectare in August 1985. In October 1985, dolomitic limestone was applied with a tractor-spreader. In winter of 1985-1986, all stands were thinned to 50 percent relative density to provide lighting conditions sufficient to stimulate growth of regeneration, and in spring 1986 the electric fencing was installed.

Changes in soil chemistry were monitored by sampling soils in all 32 subplots by 2.5 centimeter increments to a depth of 15 centimeters in each year from 1986-1989 and in 1993 and 1996. Similarly, overstory growth and vigor were measured each year from 1986 to 1990 and in 1993, 1996 (growth and vigor), and 1997 (vigor only). Sugar maple flower and seed crops were evaluated each spring and fall since 1987. Mid-crown foliage chemistry was evaluated by sampling overstory sugar maples (27 trees in limed plots, 27 trees in unlimed plots) in August 1994. Sugar maple seedling regeneration was monitored in nine permanently marked 1.13 meter radius plots in each treatment plot. Where tests of statistical significance are mentioned, 0.05 was the nominal indicator of significance.

Results

Soil Chemistry

Soil chemistry was dramatically altered by the dolomitic limestone application. To simplify presentation, results are summarized for the 0-5 centimeter depth, the 5-10 centimeter depth, and the 10-15 centimeter depth. Exchangeable Ca increased in the 0-5 cm depth in 1986 to 1873 mg kg^{-1} in limed plots compared with 340 mg kg^{-1} in unlimed plots. By 1996, exchangeable Ca concentration was 2800 mg kg^{-1} in limed plots compared with 360 mg kg^{-1} in unlimed plots at the 0-5 centimeter depth. Similarly, exchangeable Mg at the 0-5 centimeter depth increased to 337 mg kg^{-1} in limed plots compared with only 50 mg kg^{-1} in unlimed plots in 1986; Mg continued to increase in limed plots to a high of 929 mg kg^{-1} in 1996. There was a downward wave of changes in elemental concentrations in limed plots induced by direct addition of Ca and Mg or by pH changes. KCl extractable Al was reduced significantly only in the upper 0-5 centimeter depth in the first few years of the study, but by 1993 and 1996 there was evidence of decreasing Al concentrations even at the deeper depths. Exchangeable Mn also decreased in response to increased soil pH in the limed plots, although there was an anomalous increase in Mn at the 0-5 centimeter depth for unlimed plots in 1996. Both P and K decreased in response to liming, but only at the 0-5 centimeter depth. Soil pH responded rapidly to lime addition, increasing to 5.28 in limed plots in 1986 compared with only 3.70 in unlimed plots. Acidity changes also were evident at the 5-10 cm depths by 1987 in limed plots. By 1996, the upper 5 centimeter pH value averaged 6.30 in limed plots and 3.70 in unlimed plots.

Vigor and Growth Responses

Overstory crown vigor was estimated by two observers and rated on a scale from 1=dead to 6=healthy using the system of Mader and Thompson (1968). For American beech and black cherry, liming did not improve vigor (Figure 1). Beech bark disease was detected in the plots early in the study and trees started to die by 1987 or 1988. There also were droughts in 1988, 1991, and 1995 which likely affected tree vigor, and these were followed by elm spanworm (*Ennomos subsignaria* Hubner) defoliations in 1993 and 1994. While

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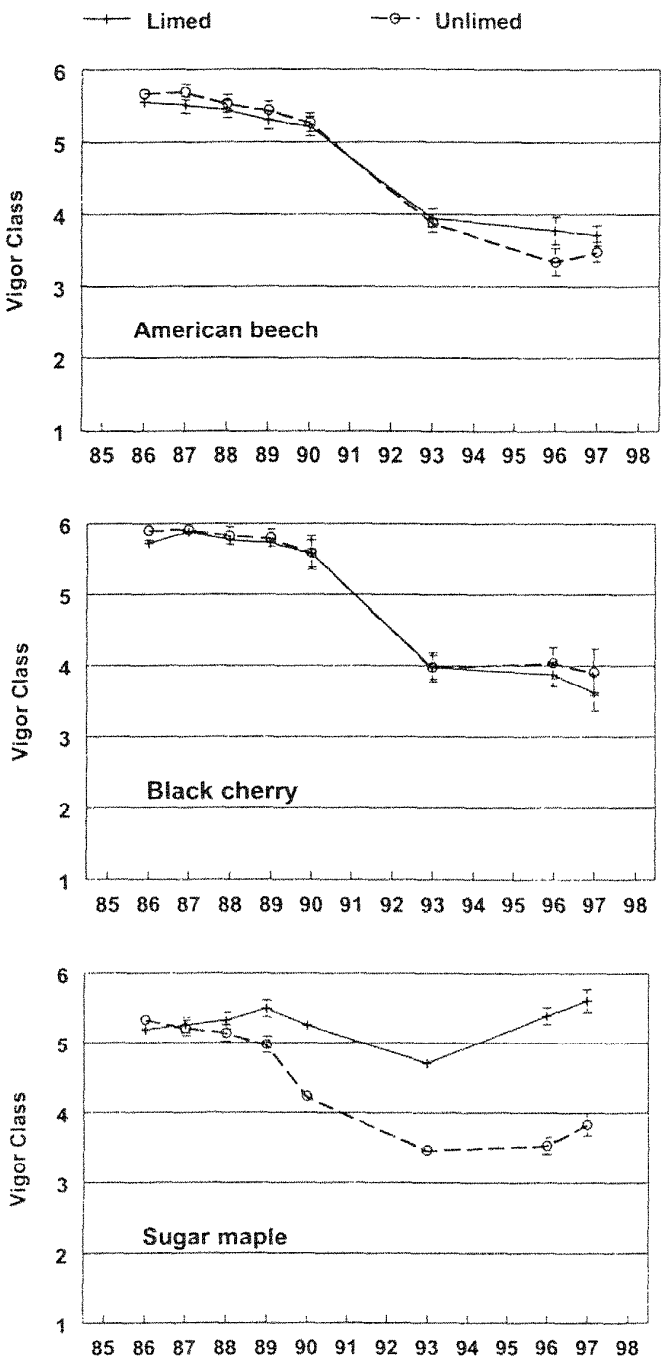

Figure 1.—Mean vigor ratings in limed and unlimed plots.

elm spanworm has a broad host range, beech is a preferred species for spanworm feeding. Overall beech vigor decreased from 5.6 in 1986 to 3.5 in 1997 (Figure 1). Black cherry has suffered similarly, with mean vigor averaging 5.7 through 1988 and then declining to 5.5 by 1990 and to 3.8 in 1993 as a result of elm spanworm defoliation. In addition, black cherry was affected by cherry scallop shell moth (*Hydria prunivorata* Ferguson) in 1995 and trees were slow to recover through 1997.

Sugar maple vigor shows a different response (Figure 1). There was some initial indication of an increase in sugar maple vigor for limed trees from 5.1 in 1986 to 5.3 in 1989, but this was not statistically significant ($p>0.05$). However, by 1990, a trend of decreasing sugar maple vigor was evident for both limed and unlimed trees, but the limed trees maintained significantly higher vigor by 1993. By 1996 and 1997, vigor for both limed and unlimed sugar maple increased. For limed trees mean vigor in 1997 was 5.6, the highest mean vigor for the duration of the study, compared with 3.8 for unlimed trees. As with beech and black cherry, sugar maple vigor of both limed and unlimed trees was negatively affected by droughts in 1988, 1991, and 1995 and by elm spanworm defoliations in 1993 and 1994. We speculate that in the absence of these stressors, sugar maple in limed plots would have continued to increase in vigor after 1989.

The progression of mortality in the course of the study is similar to the vigor results. By 1997 (12 years after treatment applications), mean mortality based on plot means shows sugar maple mortality in the unlimed plots was 18% while in limed plots it was only 9%. For beech there was no significant difference in mean mortality between limed plots (14 percent) and unlimed plots (17 percent). For black cherry, mean mortality was 15 percent on limed plots and only 10 percent on unlimed plots, but these differences were not statistically significant.

Cumulative mortality, by 1997, based on individual tree data rather than plot means showed sugar maple mortality on unlimed plots was 24 percent compared with only 9 percent on limed plots. For beech cumulative morality was 25 percent on limed plots and 24 percent on unlimed plots. Black cherry mortality was higher on limed plots, 11 percent, compared with unlimed plots, 4 percent, suggesting that liming may be deleterious to black cherry.

Growth responses indicate that liming did not significantly affect mean basal area increment of beech or black cherry through 1996 (Figure 2). However, for black cherry, there is again the suggestion that limed trees have been growing more slowly. For sugar maple, basal area growth for limed and unlimed trees started to diverge as early as 1990, but was not significantly different until 1993 when limed trees averaged 890 square centimeters of basal area and unlimed trees

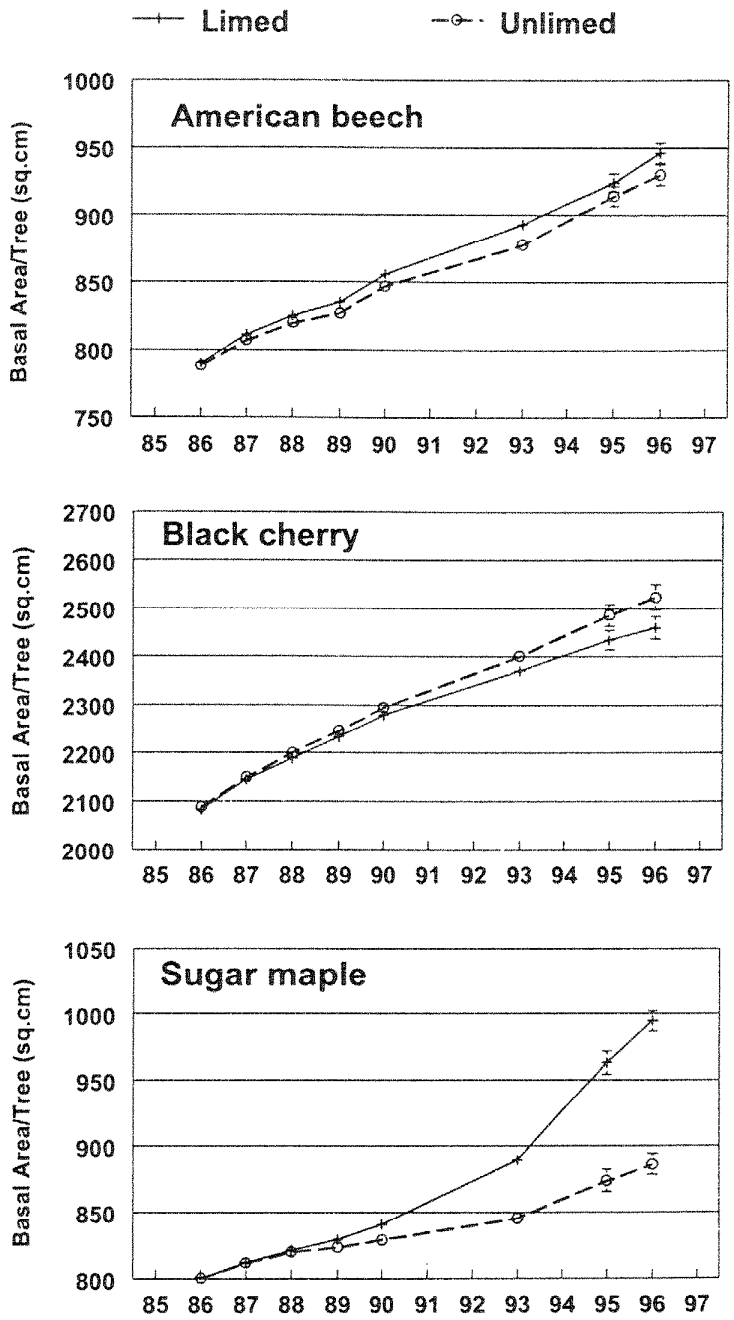

Figure 2.—Mean basal area per tree in limed and unlimed plots from 1986 to 1996. Plotted values are corrected by covariance analysis for differences in initial basal area.

averaged 845 square centimeters of basal area. By 1995, unlimed sugar maple increased slightly in growth rate, while limed trees continued to accelerate in growth rate (Figure 2). Over the course of the study (1986-1996), limed sugar maple increased in basal area by 24 percent and unlimed trees by only 11 percent, and mean annual basal area increment for sugar maple averaged 19.5 square centimeters per year for limed trees and 8.6 for unlimed trees.

Foliage Chemistry

In 1994, mid-crown foliage samples were obtained from 54 sugar maple trees, 27 in limed and 27 in unlimed plots. Foliage chemistry reflected many of the changes observed in soil chemistry. Foliar Ca levels were doubled to 8777 mg kg^{-1} in limed trees compared with only 4031 mg kg^{-1} in unlimed trees, and Mg concentrations increased fourfold to 2655 mg kg^{-1} in limed trees compared with only 617 mg kg^{-1} in unlimed trees. Both Al and Mn concentrations were reduced in foliage from limed trees compared with unlimed trees, likely due to the pH-induced decrease in availability of these cations. Foliar P concentrations were unaffected by liming, while K concentrations decreased from 7136 mg kg^{-1} in unlimed trees to 4811 mg kg^{-1} in limed trees. The decreased foliar K concentration probably indicates soils were overlimed, and, based on results from other studies, K may now be nearing a deficiency threshold in limed plots. Molar ratios of Ca:Al were 75 in foliage from unlimed trees and 233 from limed trees.

Correlations between soil and foliage nutrients provide some additional insights into nutrient relationships. There were significant positive correlations between exchangeable K, Ca, Mg, Mn and Al and corresponding foliar chemical concentrations. Correlations of overstory vigor measurements from sampled trees with soil chemical constituents revealed a negative correlation between vigor and soil Al concentrations ($r=-0.59$) while soil Ca and Mg were positively correlated with vigor ($r=0.52$ and 0.54, respectively). The foliar molar Ca:Al ratio was also positively correlated with overstory vigor ($r=0.64$) suggesting that low Ca:Al ratios are associated with low sugar maple vigor.

Flower and Seed Crops

Sugar maple flower and seed crops were also affected by liming, but not by fencing or herbicide. Lime increased the size, but not the frequency of sugar maple flower and seed crops. Three sugar maple flower crops were initiated during the study in 1988, 1989 and 1992. The 1988 flower crop did not develop into an appreciable seed

crop though differences between limed and unlimed trees were statistically significant ($p<0.001$ for flower crops; $p=0.13$ for seed crops). To assess flower crops, the percent of crown with flowers was rated on about 200 trees, using a scale where 0=no flowers present, 1 percent=trace flowering, and 5-100 percent estimated to the nearest 5 percent class. In 1989 and 1992, the percent of crown with flowers increased from 22 percent (1989) to 225 percent (1992) in trees on limed plots compared with unlimed trees. Seed crops were rated with a different scale where 0=no seed, 1=trace-5 percent, 2= 6-25 percent, 3=26-50 percent, 4=51-75 percent, and 5=76-100 percent of crown with seed. Lime increased the mean seed crop rating from 2.8 (unlimed trees) to 3.8 (limed trees) in 1989 and from 0.6 to 2.8, respectively, in 1992. Sugar maple seed crop frequency was unaffected by lime application; over the past 31 years area-wide seed crops have appeared the year following summer drought events when the mean June-July Palmer Drought Severity Index (PDSI) became more negative than -1. Seed crop size, even on limed plots, was only 5 to 15 percent of that found in the Lake States and New England (Curtis 1959, Godman and Mattson 1976, Graber and Leak 1992). Thus, seed supply appears to be an important factor influencing sugar maple regeneration.

Sugar Maple Regeneration

Prior to 1990, there were few sugar maple seedlings on plots in any treatment; those present typically were <5 centimeters tall and did not survive from year to year. Cohorts of sugar maple seedlings occurred on study plots in 1990 and 1993 following the seed crops in 1989 and 1992, respectively. These seeds fell into vegetation established 5 to 8 years earlier. Unfenced areas typically were dominated by ferns, grass, striped maple and birch (*Betula spp.*), which are all species that are low in preference to deer or resilient to repeated deer browsing. Fenced areas were dominated by a variety of tree species and by *Rubus*.

Establishment of sugar maple seedlings was positively correlated with overstory sugar maple basal area and with grass abundance. There was more sugar maple basal area on unfenced than on fenced plots; basal area was equally distributed on lime and herbicide treatment plots. There was more grass ground cover on unfenced, limed, and herbicided plots than on fenced, unlimed, and unherbicided plots. Sugar maple seedlings were more abundant on unfenced and limed plots; herbicide made no difference.

Survival of sugar maple seedlings during the 24 months following cohort appearance in 1990 and 1993 was affected by liming and herbicide, but not by fencing. Survival was higher on limed and herbicided treatments.

Mean height of the tallest sugar maple seedling was also increased by lime application; fencing and herbicide had no effect. Seedlings on both limed and unlimed plots were buried in vegetation established prior to sugar maple seedling appearance, so the data probably do not reflect the growth potential of sugar maple.

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Sugar Maple Seedling Anatomy and Element Localization at Forest Sites with Differing Nutrient Levels

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Abstract

Sugar maple (*Acer saccharum* Marsh.) seedlings often have poor survival on acidic unglaciated portions of the Allegheny Plateau. Greater survival is found after lime treatment of unglaciated sites or on glaciated areas of the Plateau. The difference in survival rate may depend in part on the acidity or chemical composition of the soil. From a 1993 seedling cohort, survival after 2 years was 70 percent on limed plots (surface mineral soil pH=5.4) compared with 35 percent on more acidic unlimed plots (surface mineral soil pH=3.8) (Horsley and Long, unpublished data). A third site, Dodge Hollow (DH), on nearby glaciated soils had an abundant 1993 sugar maple seedling cohort and surface mineral soil pH was 4.0. Comparison of foliar nutrient levels showed significantly higher concentrations of base cations in foliage from seedlings on limed plots but significantly higher Mn and a lower Ca:Al ratio in foliage from unlimed plots (Horsley and Long, unpublished data). At DH foliar base cation concentrations were similar to those from the limed plot, but high foliar Mn concentration and a low Ca:Al ratio was comparable to foliage from the unlimed plot. An anatomical study was conducted to compare differences in mycorrhizal colonization, root and foliar anatomy, and the location of potentially toxic elements (Mn, Al) in seedlings from these 3 forest sites with differing soil chemical characteristics. In June and August 1996, 10 seedlings each from limed, unlimed, and DH sites were collected. Root and foliar tissues from each seedling were chemically processed for examination by light and transmission electron microscopy, and by energy-dispersive x-ray microanalysis. Remaining root systems (>80 percent of total) were chemically preserved in the field for later mycorrhizal assessment. Roots and foliar tissues for transmission electron microscopy and x-ray analysis were thin-sectioned and examined in a JEOL transmission electron microscope coupled with a Link Systems x-ray analyzer. In June, mycorrhizal colonization of roots was highest at the limed site, lowest at the unlimed site, and intermediate at DH (66, 21 and 45 percent, respectively). In August, colonization at the unlimed and DH sites was similar (approximately 35 percent) but lower than colonization at the limed site (61 percent). By light microscopy, roots from the unlimed site had an irregular outline and contained increased amounts of dense compounds in endodermal and stele cells compared to roots from the other sites. Dense staining is often associated with accumulation of phenolics or defensive compounds. Precipitates analyzed by x-ray analysis in root xylem and cortical cells (June collection) from the unlimed site were composed of Mn, and dense material observed by transmission electron microscopy in leaf chloroplast membranes was similar to Mn toxicity injury observed in sugar maple seedlings under controlled conditions (McQuattie and Schier, unpublished data). Aluminum was detected in mycorrhizal fungal hyphae (associated with P) in roots from the unlimed site and occasionally at DH. Precipitates containing Al in petiole and midvein vascular cells were found in foliage collected from the unlimed site only. In contrast, Ca and/or Si precipitates were found in foliar and root cell walls in seedlings from all sites, indicating a common chemical composition in these cellular sites. By transmission electron microscopy, starch grains were observed in leaf chloroplasts from all sites in June, whereas in August starch was prominent only in leaf blades from the unlimed site. In August, large starch grains were seen in roots of seedlings from DH. Starch grains were not observed in roots from limed and unlimed plots possibly indicating starch storage had not commenced for these seedlings. Overall, potential indicators of stress were most often seen in seedlings from the unlimed site: low early-season mycorrhizal colonization, Mn compounds in root cells, Al precipitates in leaf cells, and altered patterns of starch accumulation in leaves and roots.

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Factors Contributing to Sugar Maple Decline Along Topographic Gradients on the Glaciated and Unglaciated Allegheny Plateau

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Popular Summary

In the early to mid 1980s, foresters began to notice a reduced level of sugar maple health characterized by unusual mortality of large trees, decreased crown vigor and crown dieback. Affected trees most often were located on the upper slopes of unglaciated sites; sugar maple on the lower slopes of unglaciated sites and in any landscape position on glaciated sites seemed less affected or unaffected. These observations were made against a background of unusual levels of insect defoliation and untimely climatic events (Drohan and Stout this volume).

During the past 30 years, declines of sugar maple have been reported in Massachusetts, Ontario, Quebec, Vermont, New York and Pennsylvania (Kolb and McCormick 1993). While defoliation and other stress factors also seem to be involved in each of these situations, nutrient deficiencies, particularly of base cations including Ca, Mg and K, seem to be a common thread in all of these declines. Recently, Long et al. (1997; this volume) reported that addition of dolomitic limestone at four high elevation unglaciated sites in north central Pennsylvania resulted in significantly increased sugar maple survival, crown vigor, diameter and basal area increment, flower and seed crop production. Black cherry and American beech were unaffected by lime addition. Lime significantly increased foliar concentrations of Ca, Mg, the Ca:Al and Mg:Mn molar ratios and decreased foliar concentrations of potentially toxic Al and Mn. On unlimed plots, trees with high crown vigors had higher foliar concentrations of Ca and Mg than trees with moderate crown vigor. And for all trees, mean BAI was positively correlated with foliar concentrations of Ca and Mg and negatively correlated with foliar concentrations of Al and Mn. Overall, the study showed that Ca and Mg supplies and perhaps those of potentially toxic ions like Al and Mn were important for health and growth of sugar maple.

Northwestern and north central Pennsylvania and southwestern New York lie at the boundary of the Wisconsin and earlier glacial advances. Areas to the north were glaciated as recently as 12,000 to 21,000 years ago; those south of the terminal moraine are older and have not been glaciated. Soils on glaciated portions of the Allegheny Plateau are Inceptisols and generally have higher supplies of base cations than the Ultisols found on unglaciated areas, but the distribution of Ca, Mg, Al and Mn with topographic position was not known.

In the present study, we investigated the relationship between sugar maple health and 1) glacial history, 2) topographic or physiographic position, 3) site (elevation, aspect) and stand characteristics (species composition, structure, density), 4) disturbance history (management, defoliation), and 5) foliar nutrition.

Methods

A series of plots was established in stands along topographic gradients at 19 sites across the glaciated and unglaciated portions of the Allegheny Plateau in northwestern and north central Pennsylvania and southwestern New York. In 1995, plots were established on upper, mid- and lower topographic positions at 5 sites; these were supplemented in 1996 with plots on upper and lower topographic positions at 14 additional sites. In all there are 43 stands; 18 on glaciated soils and 25 on unglaciated soils. In each stand, we identified 5 dominant or co-dominant sugar maple trees that were judged to be healthy by lack of crown dieback. These trees were used for mid-crown foliage collection during the last 2 weeks in August. Foliar levels of N, P, K, Ca, Mg, Al and Mn were determined for each tree, then averaged for each stand. The foliage sample trees became the locus for plots to evaluate other site and stand characteristics.

Health of all trees including sugar maple was measured in mid- to late July on three 400 m^2 plots in each stand using North American Maple Project protocols (Cooke et al. 1996). Four parameters were calculated for sugar maple which gave an estimate of sugar maple health over different time scales: % Dead sugar maple basal area (PDEADSM), crown vigor index (SMVIG), crown dieback (SMDIE) and crown transparency (PTRANS). Cluster analysis was used to determine which health variable best discriminated healthy from unhealthy stands. PDEADSM, the best health measure, separated the 43 stands into a healthy group of 37 stands with 0 - 11% dead sugar maple basal area and an unhealthy group of 6 stands with 21 - 56% dead sugar maple basal area.

Stand species composition, structure and density were calculated from data obtained on the three 400 m^2 plots. Species composition was evaluated as the percent of the total basal area that was sugar maple and the percent of the total basal area that was black cherry. Relative sugar maple diameter was the measure of stand structure and expresses the relative position of sugar maple in the diameter distribution of the stand. Relative density was used as the measure of stand density.

At each site, aspect was estimated with a compass and elevation was determined from 7.5 minute topographic maps after geolocating the sites with a GPS unit.

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Information on disturbance histories was determined from two sources: 1) annual layers of digitized defoliation sketch maps were queried to determine the timing, severity and agent of defoliation, and 2) land managers who were responsible for each stand were contacted and queried concerning stand management history and additional information on stand defoliation history.

Results

Thirty-three of the 43 stands were on north and east facing slopes; 4 (12%) were unhealthy. The remaining 10 stands were on south and west facing slopes; 2 (20%) were unhealthy. All of the unhealthy stands were at elevations >500 m, but there was not a precise relationship between sugar maple health and elevation.

Health of sugar maple varied with glacial history and topographic position. Sugar maple were uniformly healthy and there were no trends with topographic position on glaciated sites. But on unglaciated sites, PDEADSM was higher on upper than lower topographic positions. Health on the lower slopes of unglaciated sites was indistinguishable from that on glaciated sites. Each stand was categorized according to its physiographic position. Summits, shoulders and upper backslopes represent the positions in the landscape where the soils are most leached and the driest; mid- and lower backslopes have moderate leaching potential and higher moisture. Foot and toe slopes and enriched sites such as those with concave microtopography, benches or seeps have the least potential for leaching; soil moisture is variable depending upon position in the landscape and the nature of enrichment. On unglaciated sites, stands with unhealthy sugar maple were located on summits, shoulders and upper backslopes. But, all stands in these physiographic positions were not unhealthy. Stands on mid- and lower backslopes, on foot or toe slopes or on enriched sites remained healthy.

Among the stand variables, competitive effects of black cherry, which forced sugar maple into a lower crown position and a lower relative diameter, seem to be the most important. The proportion of sugar maple in the stand and the stand relative density had little relationship with sugar maple health. Overall, the effects of stand parameters on sugar maple health were relatively small.

Disturbances caused by stand management activities also had little effect on sugar maple health. Thinning was the only management activity at the study sites over the past 20 years. Eleven of the 43 stands were thinned from 4 - 20 years previously. The remaining 32 stands had no management activity in the past 20 years. Thinning did not predispose or protect sugar maple from decline in the long term. Two thinned and four unthinned stands were among the six stands with unhealthy sugar maple.

Defoliation disturbance played a key role in determining which stands were unhealthy. We evaluated the number of defoliation events and defoliation severity for the 10 and 20 year period prior to overstory health evaluation. A defoliation severity index was constructed by assigning a value of 3 to a heavy defoliation where >60% of the foliage was lost, a 2 to moderate defoliations where 30 - 60% of the foliage was lost and a 1 to a light defoliation where <30% of the foliage was lost. These values were summed over the 10 or 20 year period prior to health evaluation. The most recent 10 year period proved to be the most important. The upper slopes of unglaciated sites were defoliated more often and more severely than the lower slopes of unglaciated sites or any topographic position on glaciated sites. Both the number and severity of defoliation events had an effect on sugar maple health. Stands with unhealthy sugar maple were those defoliated 2 or more times during the past 10 years with a defoliation severity index of 4 or more, representing two moderate defoliations. However, all stands with these defoliation history characteristics did not have unhealthy sugar maple, suggesting that there must be something which makes trees in some stands more resilient to repeated defoliation.

There were important relationships between foliar levels of Ca, Mg, Al and Mn and glacial history, topographic position, physiographic position and sugar maple health. Foliar chemistry data were expressed on concentration, content and leaf area bases. There were no differences in interpretation of the results among these expressions. There also were no relationships between foliar N, P and K and sugar maple health.

Comparison of the foliage chemistry of healthy sugar maple on glaciated and unglaciated sites showed that trees on glaciated sites had more Ca and Mg and higher molar ratios of Ca:Al, Ca:Mn and Mg:Mn, similar amounts of Al and less Mn than trees on unglaciated sites. There were few differences in foliar values between upper and lower slopes of glaciated sites; trees in upper slope stands had similar levels of Ca, Mg, and Al and molar ratios of Ca:Al, Ca:Mn, and Mg:Mn and more Mn than trees in lower slope stands. On unglaciated sites, there were important differences. Foliage from trees in upper slope stands had less Ca and Mg, lower molar ratios of Ca:Al, Ca:Mn, and Mg:Mn and more Al and Mn than foliage from trees in lower slope stands. Similar trends in foliar nutrition were found when each stand was assigned to a physiographic position.

Foliar nutrition was correlated with sugar maple health and with defoliation disturbance history. Foliar Mg, Mn and the Mg:Mn molar ratio were significantly correlated with PDEADSM and the Ca:Al molar ratio was marginally correlated with PDEADSM. Foliar Mg content showed a strong relationship with PDEADSM. Stands with less than threshold amounts of foliar Mg became unhealthy, if the stands had had $^{3}2$ moderate or severe defoliations (defoliation severity index $^{3}4$) during the past 10 years. Stands with greater than threshold levels of foliar Mg could withstand greater numbers and severity of defoliation and still remain healthy. Foliar Mn alone could not be used to distinguish healthy from unhealthy sites. All stands which became unhealthy had relatively high foliar Mn content, but in some stands, trees with foliar Mn as high or higher than those which became unhealthy remained healthy; these

trees had greater than threshold amounts of Mg. The molar ratio of Mg:Mn did not distinguish healthy from unhealthy stands as well as foliar Mg alone.

Discussion

Our work confirms the observations of practicing foresters that sugar maple is healthy on glaciated sites and the lower slopes of unglaciated sites. Unhealthy sugar maple was found on unglaciated upper slopes in the summit, shoulder and upper backslope physiographic positions. These sites had the lowest foliar Ca and Mg, the highest Al and Mn, and were defoliated more often and more severely than any other landscape position. Poor base cation status of upper slope sites probably is the result of long-term weathering of initially base-poor substrates, which may be aggravated by acid deposition. Flowpaths of water which is in contact with Ca and Mg-containing bedrock may explain the higher base cation status of lower slope unglaciated sites (Bailey et al. this volume).

Foliar Mg was the key ion associated with sugar maple health. Healthy trees had greater than threshold amounts of foliar Mg. Mg interacted with defoliation stress. Unhealthy trees were those with low Mg AND two or more moderate or severe defoliations in 10 years. Sugar maple remained healthy on low Mg sites if defoliation stress was low. This is corroborated by the fact that sugar maple with low foliar Ca and Mg and low stress in New England remained healthy (Hallett et al. this volume). Furthermore, trees with greater than threshold foliar levels of Mg were more resilient to stress, withstanding greater numbers and severity of defoliation. Foliar levels of Mn seem to be important only when there is inadequate Mg; at present, the role of Mn in sugar maple decline is unclear.

The decline of sugar maple fits the definition of a decline-disease: a syndrome of canopy-dominant trees characterized by gradual deterioration in health and vigor which leads to death (Manion 1991; Houston 1992). Decline-diseases seem to result from complex interactions of factors that predispose or weaken trees, followed by inciting or triggering events that result in dieback and mortality. Our study suggests that sugar maple decline occurs as a result of an interaction between imbalanced Mg nutrition and excessive defoliation stress. Sugar maple with low foliar levels of Mg (and Ca) photosynthesize at a lower rate than those with higher levels of these cations (Liu et al. 1997). The level of storage carbohydrates accumulated by trees growing on base cation-poor sites likely is less than those growing on base cation-rich sites. Thus, trees growing on base cation-poor sites are predisposed to be less resilient to stress because they have less carbohydrate reserves to maintain living tissue and repair damaged tissue. Stresses such as defoliation, particularly those that are severe enough to cause refoliation, and to a lessor extent drought, trigger or incite decline because they result in a substantial drain on storage carbohydrates (Wargo this volume). Under these circumstances, trees first dieback, reducing the amount of living tissue that is supported by storage carbohydrates. If stress continues trees often die, either as a result of carbohydrate starvation or from the action of secondary organisms such as *Armillaria*, which invade the weakened trees (Wargo and Harrington 1991).

For land managers, the implication of our study is that unglaciated upper slope sites in northwestern and north central Pennsylvania are sensitive sites where sugar maple and other high base cation-demanding species may be at risk during stress events such as insect defoliations. They are areas where land managers should focus insect monitoring and suppression activities and consider management activities that favor species with lower base cation requirements.

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Influence of Geologic and Pedologic Factors on Health of Sugar Maple on the Allegheny Plateau

Scott W. Bailey, Stephen B. Horsley, Robert P. Long and Richard A. Hallett[1]

Popular Summary

Decline of sugar maple (*Acer saccharum* Marsh.) has been a problem on the Allegheny Plateau of Pennsylvania since the mid-1980's (Kolb and McCormick 1993; McWilliams et al. 1996). Horsley et al. (this volume) found that declining stands were distinguished from non-declining stands by a combination of repeated insect defoliation and low foliar calcium and magnesium concentrations. Stands that exhibited only one of these two conditions remained healthy. Information is needed (1) to determine whether low foliar nutrient concentrations are related to soil quality, (2) to determine key parameters and threshold values that describe soil conditions which might predispose a stand to decline, and (3) to develop methods to predict the distribution of susceptible sites across the landscape. Furthermore, information about the role of acid deposition in inducing soil fertility problems remains elusive.

The present study was initiated to examine soil factors leading to sugar maple decline on the Allegheny Plateau. Soil description and sampling were conducted at a number of plots, spanning the geographic range of the Plateau in northwestern and north-central Pennsylvania and adjacent southwestern New York. Plots include a range of stand heath conditions, landscape positions, and bedrock and glacial geologic influences.

Methods

Study plots were established at 19 sites described by Horsley et al. (this volume) across the Allegheny Plateau from Chautauqua County, New York in the west to Tioga County, Pennsylvania in the east. Study plots span a wide range of soil parent materials and geologic influences found on the Allegheny Plateau. At each site, two or three plots were established to span the elevational distribution of sugar maple. County soil surveys and reconnaissance observations were used to locate one representative sampling pit per plot. Pedon description, according to National Resource Conservation Service methods, was conducted to a depth of at least 130cm, unless bedrock was encountered at a shallower depth. Samples for chemical analysis were collected by genetic horizon. Additional forest floor samples (O and A horizons) were collected by the pin-block technique (Federer 1984) at three locations in each plot. This provided information on spatial variability in surficial horizons as well as the ability to express nutrient levels on a landscape area basis. Soil samples were analyzed for pH, extractable cations and organic matter content generally following the methods of Robarge and Fernandez (1987). Forest composition and health measurements are described in Horsley et al. (this volume).

Results

Surveyed sugar maple stands were located on all physiographic positions from summit to footslope, on soils that ranged from moderately deep to very deep, well drained to poorly drained, and included soils of four orders (Inceptisols, Spodosols, Alfisols, and Ultisols). All declining stands were located on summit, shoulder or upper backslope physiographic positions on Ultisols. Declining stands had lower extractable calcium and magnesium and higher exchangeable aluminum than non-declining stands. Subsoil horizon chemistry was a better predictor of decline than chemistry of the forest floor or upper mineral horizons.

Overall, a great variety of nutrient conditions was measured. For example, extractable concentrations of calcium, magnesium and aluminum each ranged over a factor of 250. Further analysis is planned to determine which chemical parameters for which horizon or sequence of horizons best correlates with foliar chemistry and health parameters.

Soils in unglaciated upper landscape positions contained lower concentrations of extractable nutrient base cations compared with other landscape positions. Soils on upper and lower landscape positions of glaciated sites and in lower landscape positions on unglaciated sites had similar moderate to high base cation content. Mineralogy also played a role in site nutrient status. Plots influenced by calcareous bedrock, such as the Oswayo and Huntley Mountain Formations, contained the highest concentrations of soil extractable base cations. Some plots at mid to lower physiographic positions contained seeps. Chemistry of seep water corroborated site nutrient status indicated by soil extractable cations. No declining stands were located on plots containing seeps; seeps did not occur in landscape positions where decline was observed.

Discussion

Nutrition appears to be a predisposing factor in sugar maple decline on the Allegheny Plateau. Declining stands are marked by low foliar calcium and magnesium concentrations, which follow low concentrations of extractable pools of these elements in the soil. The variation in site quality across the Plateau might be explained by a model that considers the location of weathering reactions and the effect of landscape position on delivery of weathering products to the rooting zone.

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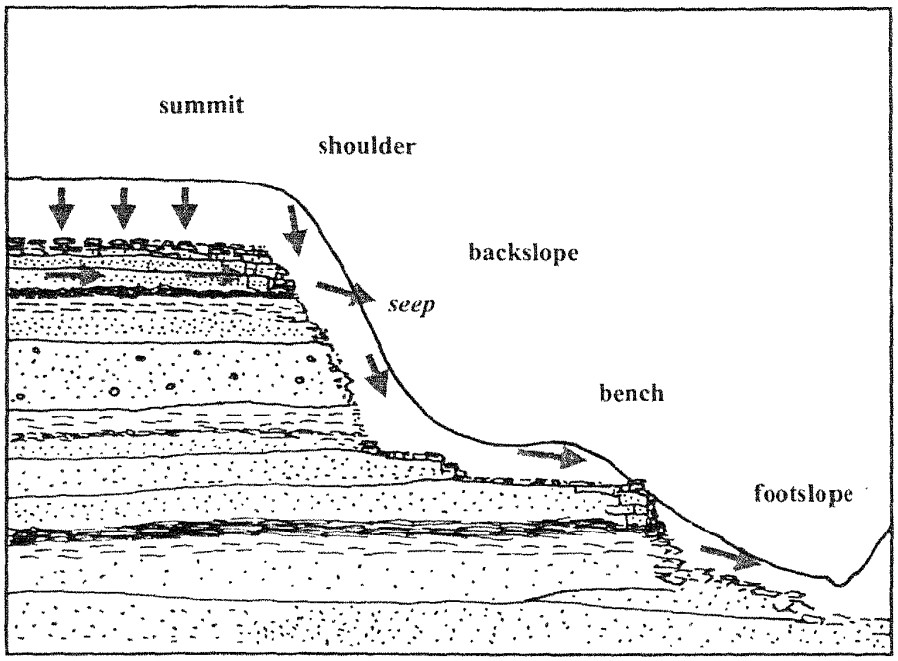

Figure 1.—Schematic cross section of the unglaciated portion of the Allegheny Plateau. Patterned areas represent interbedded sandstone, siltstone and shale bedrock. Soils are developed in relatively thick, weathered residuum, colluvium and alluvium shown as the unpatterned area above the bedrock. General locations of physiographic positions where sugar maple plots occurred are labeled. Arrows indicate generalized hydrologic flowpaths.

Mineralogy of unglaciated soils is dominated by primary minerals such as quartz and muscovite, which are resistant to weathering, and secondary minerals such as kaolinite and illite, which are stable in the soil environment. Weatherable minerals are confined to lower portions of the regolith well below the rooting zone or within bedrock. Thus the delivery of weathering products, such as calcium or magnesium ions, to the rooting zone is limited to portions of the landscape where water flowpaths bring ions released from bedrock or deeper regolith to the soil (Figure 1). Such locations may be those where water that has percolated into the bedrock is forced laterally back into the regolith by a strata of low permeability, thereby influencing soil chemistry and in some cases creating seeps. On other portions of the landscape, particularly unglaciated summits, shoulders and upper backslopes, nutrient inputs are confined to atmospheric inputs; nutrient conservation by biomass cycling is particularly important on these sites.

In contrast, on glaciated portions of the Plateau, much of the weathered regolith was removed by glacial erosion. Soils are developed in glacial till (Figure 2), which incorporates relatively unweathered material freshly exposed by glacial erosion. Thus, weathering reactions occur within the rooting zone, creating less contrast in weathering inputs by landscape position. However, even on glaciated sites weathering in the rooting zone may be limited where glacial till is largely derived from bedrock units with few weatherable minerals.

Although none of the soils investigated contained carbonate minerals, weathering of carbonate-bearing bedrock may contribute to soil fertility at both unglaciated and glaciated sites in mid to lower landscape positions on certain bedrock formations. Some of the highest concentrations of base cations in soil and seep water occur in this situation. These sites may be best suited to management of relatively high nutrient-demanding species such as sugar maple and white ash. Further analysis is planned to develop predictive tools for identifying site quality.

The role of acid deposition in contributing to sugar maple decline remains unclear. Acid deposition has been shown to reduce extractable base cations in soil based on theoretical grounds and in laboratory studies (Lawrence et al. this volume). Long-term depletion of exchange pools has been documented by retrospective studies (Shortle and Bondietti 1992; Lawrence et al. this volume) and in field-based mass balance studies (Bailey et al. 1996; Likens et al. 1998). However in the present study, the base cation-poor sites where sugar maple decline has occurred are located in landscape positions and on bedrock formations that one would expect to have the lowest nutrient levels, based on

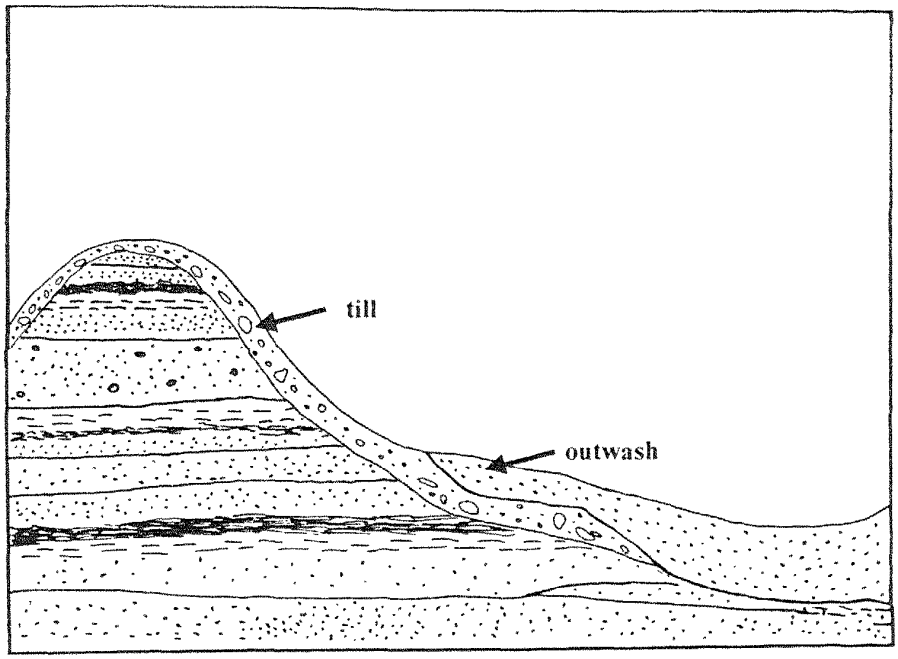

Figure 2.—Schematic cross section of the glaciated portion of the Allegheny Plateau. Soils on glaciated portions have developed in relatively thin glacial till on upper portions of the landscape and in glaciofluvial deposits (e.g. outwash) in lower valleys.

lack of weatherable minerals in the rooting zone and lack of hydrologic pathways to deliver weathering products from deeper sources. Given the available evidence, one would reasonably hypothesize that nutrient depletion due to acid deposition has increased the portion of the landscape with nutrient values below a critical, but as yet undetermined, threshold. However, in light of the great variety of nutrient concentrations attributable to landscape position, mineralogy and soil development, the extent that sugar maple decline is due to acid deposition remains speculative.

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Foliar Chemistry of Sugar Maple: A Regional View

Richard A. Hallett, Stephen B. Horsley, Robert P. Long, Scott W. Bailey, and Thomas J. Hall[1]

Abstract

Forest health and monitoring issues have become major focus of scientists and research institutions in Europe and North America during the last decade because of widespread forest decline symptoms in Europe, high elevation spruce/fir decline in eastern North America and sugar maple (*Acer saccharum* Marsh.) decline in Quebec, and the United States. Foliar concentrations of Ca, Al, K, Mg, N, and P are highly correlated with tree growth, health, and physiological function for a wide range of species. Other studies have shown that foliar Ca and Ca:Al ratios are correlated with dark respiration rates and basal area increment on sites that are affected by acid deposition or are susceptible to cation depletion. Further work in Pennsylvania and New York has linked decline of overstory sugar maple trees to multiple insect defoliations in stands with low foliar nutrient status. These results have implications for forest management agencies across the northeastern United States.

In order to understand sugar maple productivity and health at a regional scale, 75 plots representing a wide range of soil types, spanning the northeastern United States have been established. A suite of soil chemical and physical variables will be measured along with health and productivity. Results from the chemical analysis of sun leaves from 3 to 5 healthy, dominant or co-dominant sugar maple trees per plot are presented here. Foliar Ca fell below putative minimum values (5000 ppm) on 24% of the plots region wide. Foliar Mg fell below putative minimum values (700 ppm) on 22% of the plots region wide. Low Ca and Mg values can indicate deficiencies of these elements. Maximum Mn values were 3740 ppm, much higher than the putative maximum of 1630 ppm reported in the literature. High foliar Mn may indicate toxicity in sugar maple. Other elements (Al, P, K and N) were not at levels that could be considered deficient or toxic. Sugar maple decline symptoms exist in PA and NY but are not widespread in NH and VT. However, foliar chemistry data show that many stands in NH and VT are at least as nutrient poor as affected stands in PA and NY. This data set in conjunction with other data collected on these plots will allow us to understand the linkages between soil chemistry, foliar nutrition, and sugar maple health at a regional scale. In addition this study will allow us to provide tools for forest managers that can be used to identify sugar maple stands that may be vulnerable to decline.

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Nutritional Factors Associated with Decline in Canada

Benoît Côté[1]

Abstract

Forest decline in eastern Canada was particularly severe in the early 1980's and is still prevalent in some areas (Bowers and Hopkin 1997). Early public and scientific opinions on the causes of forest decline were often not based on sound scientific knowledge. Factors such as acidic precipitation and ozone were most often mentioned as direct causes of forest decline in the early stages. Although standards of nutrition for sugar maple (*Acer saccharum* Marsh.) were not known at the time, some common nutrient deficiencies were identified: K in the Eastern Townships, Mg on some sandy soils, and P on some sites with mull humus. More than 10 years after the onset of decline, we now have a better understanding of the nutritional problems associated with forest decline. The problem was complex as many combinations of nutrients were found to be deficient. Most common combinations of deficient nutrients were in descending order of importance: K+Ca (31%), K+N (23%), K+Ca+N (11%), K (9%), P (8%), and K+Ca+Mg+N (3%).

Nutrient deficiencies were corrected through diagnostic fertilization. Diagnoses were usually made using DRIS indices. Typical application rates ranged from 400 to 800 kg ha^{-1}. Fertilizers were applied manually or by air. Terrestrial applications were slightly more efficient. Fertilization was found to have long-term effects (> 5 years) in many instances. The use of diagnostic fertilization rather than the use of general fertilizer guidelines should be favored in declining stands as nutrient imbalances can easily be exacerbated with an inappropriate fertilizer mixture.

As mentioned before, the forest is still declining in some areas. Based on nutrient status, our results suggest that many forest stands are "walking on a tight rope" in that most of their nutrients are at critical levels. Any perturbation of the nutrient cycle in these stands is likely to trigger nutrient imbalances and deficiencies in one or more nutrients. This is in agreement with the recent publication of the critical loads for eastern Canada (Bowers and Hopkin 1997) which suggests that large tracts of forest have soils that are susceptible to nutrient leaching and soil acidification via acidic deposition.

Forest management can also lead to soil acidification. Some species are known to improve soil fertility. Birch (*Betula* spp.) and basswood (*Tilia americana* L.) are well known as soil improvers. Sugar maple, which has been favored in most sugar bushes to the detriment of other hardwoods, has leaf litter characteristics that suggest a strong potential for soil acidification (Côté and Ouimet 1996). Among all common hardwoods of eastern Canada, red and sugar maple have the most acidic leaf litters and their C:N ratios are high. Leaf litter N concentrations are low in maples and other nutrients are generally lower than in basswood. Clear evidence of soil acidification under maple was provided by comparing soil acidity under 27 year-old plantations of white pine (*Pinus strobus* L.), white spruce (*Picea glauca* (Moench) Voss), yellow birch (*Betula allegheniensis* Brit. and maple(*Acer* spp.) (France et al. 1989).

Although forest decline does not make the news anymore in Canada, it is still present and many sites are in a precarious state with regard to nutrient status. Some ecosystems may require a bit of help to fully recover and become more resilient to natural and anthropogenic stress factors. Diagnostic fertilization and sound management of forest composition may be what is required.

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Trends in Growth Rates of Vermont Sugar Maples from 1953-1992 in Relation to Stand Nutrition

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Abstract

Growth of sugar maple (*Acer saccharum* Marsh.) in 7 northern Vermont stands managed for sap production and 22 unmanaged stands distributed around the state was studied for the period 1953-1992 in relation to stand nutrition and other site factors. In 4 managed stands where at least 25% of the trees had 10% or greater crown dieback, average annual basal area increment (BAI) for 1953-1992 in codominant trees averaged 17.5 cm^2 compared to 32.3 cm^2 in 3 managed stands where less than 10% of the trees had 10% or greater crown dieback. Soil surface horizons of slower growing stands were characterized by significantly lower pH and Ca, ($p < 0.05$) marginally lower Mg and marginally higher Al than faster growing stands, while soil P and K were not different. Foliar Ca was lower ($p < 0.01$) in slower growing stands (6,400 mg kg^{-1}) than faster growing stands (12,200 mg kg^{-1}) but other foliar nutrients did not differ significantly. No other stand characteristics, including age, basal area, stem density, elevation or aspect were apparently related to differences in growth rates and crown condition between these two groups. A 49% decline in BAI of the faster growing trees from the mid-1970's to 1992 was noted, but the small sample size precluded interpreting this as a region-wide growth decline.

In a second study, 22 hardwood stands composed of at least 1/3 sugar maple, and not thinned since 1943 were identified on state and federal lands in the Green Mountains and the Vermont Piedmont east of the mountains. Twelve sugar maples per stand 27 cm in diameter or greater were cored in 1993, and surface soil horizons were sampled around each tree. Average annual stand BAI for the period 1953-1992 ranged from 8.9 cm^2 to 26.9 cm^2. Stand growth rates were not correlated with stand basal area (range = 20.7 - 28.3 m^2 ha^{-1}), tree density (range = 197 - 388 stems > 15 cm dbh ha^{-1}) , slope (range = 5 - 69%) or elevation (range = 195 - 807 m). There was a negative correlation between soil pH and average stand dieback ($p < 0.01$), but, unlike the managed stands in northern Vermont, base cation availability and soil pH in soil upper horizons were not well correlated with growth rates on either a stand or tree basis, although soil P was negatively correlated with stand growth ($p < .05$). Other site factors that were not examined, such as soil depth, water-holding capacity, and soil nutrient pools in deeper horizons may have had an overriding influence on stand growth rates.

A moderate growth decline over the period 1979-1992 was observed across most of the 22 unmanaged stands. Average annual BAI for trees that were canopy codominants in 1953 (30-46 cm DBH) was approximately 22 cm^2 between 1953 and 1977, but declined to 15.6 cm^2 by 1992. A period of defoliation by forest tent caterpillar (*Malacosoma disstria* Hubner) over much of the state from 1978-1982 was a likely inciting factor in this decline, as was an outbreak of pear thrips (*Taeniothrips inconsequens* Uzel) in 1988. Records from Vermont weather stations did not indicate long-term changes in growing season precipitation between 1953-1992. Continued monitoring is needed to determine whether this change in growth rate was due to stand closure or other factors, and if growth rates will recover to previous levels. It is notable that the average annual BAI of nearly 15 cm^2 in 1992 for all trees at all sites was near or above the average growth rate for sugar maple reported from other parts of its range.

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